CleanEra

a collection of

RESEARCH PROJECTS *for*

SUSTAINABLE AVIATION

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RESEARCH PROJECTS *for* SUSTAINABLE AVIATION

by The CleanEra Team

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IOS Press BV
Nieuwe Hemweg 6b
1013 BG Amsterdam
The Netherlands
tel: +31 20 688 3355 info@iospress.nl
fax: +31 20 687 0019 www.iospress.nl

Published online with help of the
TU Delft - Open Access Fund

Printed in the Netherlands

ISBN 978-1-61499-590-6 (print)
ISBN 978-1-61499-591-3 (online)
DOI 10.3233/978-1-61499-591-3

ACKNOWLEDGEMENTS
The CleanEra project got underway in 2007 with the goal of developing revolutionary ideas for Civil Air Transport. Over the next five years, we learned a tremendous amount from all the people involved in CleanEra. Now, in 2015, we are proud to present our findings in book form for the first time.

The CleanEra Project would like to express its great appreciation to:

Charlotte de Kort **Etnel Straatsma**

Ingmar van Dijk **Koon Tang**
Ritesh Sharma **Tanuj Dora**
Jochem Kuiper **Zeger van der Voet**
Farid Talagani **Erik van Berkel**
Pjotr Sillekens **Kristian Schmidt**
Remco Zwinderman

Advice given by **Kees de Koning** and **Bart Korff** has been of great help in determining the course of the project.

Finally, CleanEra would like to specially thank the following companies for their assistance and support of the project. Without them it would not have been possible:
Frits van der Jagt, Daden voor Delft
Henri Artz, ZEFT model building
Willemijn van der Werf, KLM
Particularly grateful to both **Frank Jansen** and **Sjoerd Keizerwaard** of the Netherlands Aerospace Group.

Our sponsors for ZEFT:
NAG, Dutch-Shape, AmEuro, Aleris, KLM

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Foreword

by Ben Droste

When I came to Delft in 2003 I had a vision. It was to radically overturn contemporary aerospace design practice. To start afresh and come up with an aircraft design that was low-noise, zero-emission, super-efficient and ultra-comfortable. In short, this aircraft of the future would have to be completely green.

To achieve this, I quickly realised, we had to look to the young, to our MSc and PhD students. Why the young? Because at no other point in life than in youth can one be so unencumbered, free of spirit and full of wild new ideas. It is these ideas I wished to harvest.
At the same time, this was an excellent opportunity to bring together all the disciplines within our renowned Faculty of Aerospace Engineering in one great collaborative effort. Therefore, every chair was invited to select one PhD candidate to dedicate his or her efforts to the undertaking.

The outcome was the CleanEra project, a group of young (prospective) engineers and scientists from a varied international background, ready to take on the challenge, share the dream and create something new. To maximise the usefulness beyond academic output, Dutch industry and research institutes were also invited to take part. Among others, this led to the appointment of a project director from an such a background. But the journey from vision to reality takes years of meticulous research and design. That our radically new plane has not arrived (yet) was not caused by lack of effort. Nor by lack of inspiration, for our CleanEra participants surprised us and the outside world with their ideas and unconventionality.

The need for sustainable solutions is now greater than ever, not only from an environmental point of view, but also from perspectives of cost-efficiency, image, and ultimately survival. This book offers you just that: a set of technological solutions aimed at making aviation low-noise, zero-emission, super-efficient and ultra-comfortable. In other words: truly sustainable. Individually, they can be applied to existing aircraft.

But this book is more; it is also a presentation of the work of a group of young scientists fuelled by the same ambition. I hope this publication will inspire industry, government and the scientific community to continue that ambition and help aviation enter a new, clean era.

— Ben Droste
Founding partner of the Space Expedition Corporation (SXC)

Ben Droste served as a fighter pilot with the Royal Netherlands Air Force for 38 years and retired in March 2000 as Lieutenant General and Commander in Chief. He was then appointed Chairman of the Netherlands Agency for Aerospace Programmes (NIVR). In 2004-2008 he was dean of the Faculty of Aerospace Engineering of the Delft University of Technology.

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From pioneering to consolidating

Introduction

by Ronald van Gent

CLEANERA

CleanEra is an acronym for Cost-effective Low Emissions And Noise Effective Revolutionary Aircraft. The project started in May 2007 at the Aerospace faculty of the University of Delft. On average ten PhD students, aided by a number of master students, researched technologies to make aircraft more energy and cost-efficient, to reduce aircraft noise and pollution and to look for alternative strategies to expand aviation infrastructure.
The group was led by a project manager from industry and backed-up by the knowledge available at the faculty of Aerospace Engineering.

Fast, flexible, cost-effective and safe; aviation outclasses other modes of travel in many aspects. With cruise speeds of 1,000 kilometers per hour, aircraft leave even the fastest high-speed trains far behind. Aviation is the cheapest mode of transport for long distances, and often even for shorter distances. Flying involves high speeds and high altitudes, very lightweight constructions and high-energy propulsion systems. Despite these potential dangers it is the safest mode of mass transport. As to flexibility, the slogan of the Aircraft Owners and Pilot Association (AOPA) says it all: "A mile of road leads nowhere and a mile of runway leads everywhere!"

The safety of flying is extra remarkable, considering passengers and crew have to be protected from:

- **High kinetic energy, meaning crashes are often deadly;**
- **Hostile environments. At 10 km altitude the environment is extremely cold (ranges of -50 C) with not enough air for humans to breathe in. Exposure would lead to certain death witin minutes;**
- **Explosive and highly flammable systems. The kerosene engines needed to reach flying speeds make the system potentially very flammable or even explosive;**
- **Minimum amount of structural protection. Aircraft design is continuously seeking ways of reducing excess structural mass, leading to a minimization of surplus strength. (It is even said that a well-designed aircraft should break up in its component parts when its structural ultimate load is achieved.)**

PRODUCT LIFE CYCLE OF AVIATION

Aviation achieved all this in record time. Dating back just over one hundred years, it is the latest kid in transport town. So how did aviation get to this point? Let us look at that from the point of view of a Product Life Cycle. A product is anything capable of

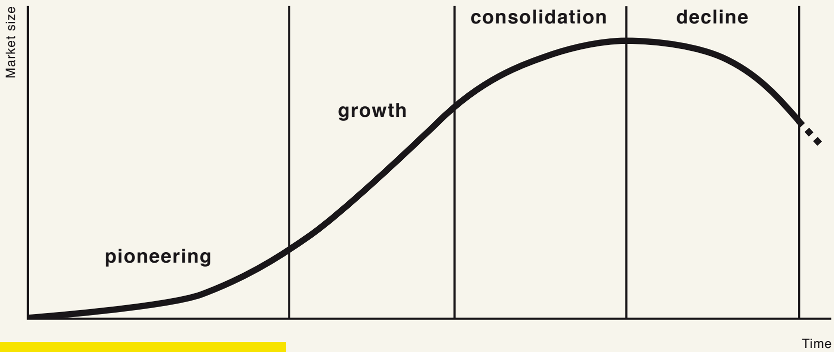


Fig. 1. A typical product life cycle.

achieving a customer's needs. A product can be an object, a service, or in this case, a mode of transport. A typical Product Life Cycle (PLC) has four stages: pioneering, growth, consolidation and decline.

PIONEERING STAGE (PRE-WORLD WAR 2)

During the pioneering stage a product's market share and growth are slight. The emphasis is on research and development. It is an experimental phase in which little or no profits are made. For aviation this is the period before the Second World War. Aviators try to make some money flying postal packages and the wealthier and more adventurous passengers. Mostly though, they are building a diversity of civil aircraft in small numbers. The stories of Charles Lindbergh, Antony Fokker, Howard Hughes and Juan Trippe tell of the fast-changing aircraft and services within a small market. There is the Fokker F.VII, a high-wing plywood laminate monoplane that comes in single-engined and three-engined varieties. Other three-engined planes are the all-metal, high wing Ford Trimotor and the low wing Junkers JU 52. For long-range trans-Atlantic and trans-Pacific flights flying boats such as the Martin M130 and the Boeing 314 are developed. A real breakthrough is the Douglas DC 3, with its retractable gear, autopilot, de-icing equipment, and other technological innovations. A mature, comfortable airliner has now entered the arena of passenger transport.

GROWTH STAGE (POST-WORLD WAR 2 – 1970)

The growth stage is less experimental than the pioneering stage. High expectations of new technologies will lead to substantial investments. It is a time of rapid market expansion and considerable profits. Civil aviation really takes off after the Second World War, profiting from technological advances made in military aviation and the availability of airfields and airports. Efficient engines ranging from high-performance piston engines to turbo-props and jet engines make their way into civil aircraft. Modern construction methods and pressure fuselages are introduced. Aircraft start flying higher to avoid bad weather and long-range flying becomes less adventurous (i.e. dangerous) and more affordable for the general public. In the pressurized Lockheed Constellation with its flying speed of over 500 km/h, for example. The first successful jet airliner is the Boeing 707. Its most striking design feature – four engines mounted in pylons beneath the wings – is still in use today. Speed is one objective in civil aircraft design; size is another. The more a plane can carry over larger distances, the better the business case for airlines, especially on long haul routes. Aircraft companies such as Douglas, Lockheed and Boeing start working on so-called wide-body aircraft. Examples are the three-engine Douglas DC-10, the very similar looking Lockheed Tristar, and the four-engine gigantic Boeing 747, also known as the Jumbo Jet. Douglas and Boeing made their wide bodies successful, enabling ever more people to travel by air. By the 1960s commercial aviation has matured.

TRIAL AND ERROR

Not all aircraft developed in the post-war boom era were resounding successes. The Lockheed Electra was the first turbo prop airliner. It could fly even higher and faster than the Lockheed Constellation. However, badly designed engine mounts lead to two fatal accidents, and its fame was short-lived. A similar fate was in store for the de Havilland Comet, the first jet airliner put into service in 1952. A number of fatal accidents due to metal fatigue prevented the Comet from becoming really successful.

SUPERSONIC BUST

In the 1950s the US, USSR and Europe started designing SuperSonic Transport aircraft, or SSTs. Only the British-French Concorde and the Russian Tupolev Tu-144 saw regular service. SSTs were plagued with enormous development costs resulting in outrageously high fare prices. Moreover, supersonic flight was very noisy, on account of the use of afterburners for the necessary acceleration, and – more importantly – the sonic boom it produced. This led to growing resistance. Supersonic flight was soon regarded as unacceptable over land, leaving just the possibility of supersonic flight over the Atlantic Ocean. Only Concorde made it into significant commercial operation (the TU-144 having logged only 55 commercial flights) and remained the fastest airliner for 27 years. Following a fatal accident in 2000 Concorde was retired in 2003.

CONSOLIDATION STAGE (1970 – NOW)

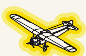
During the consolidation stage competition is usually intense. The market is extensive, but margins are low. Marketing and finance therefore become key activities. Research and development are restricted to product modification and improvement, and production efficiency and quality. In 1978 the United States federal Airline Deregulation Act comes into being. This brought an end to the governmental regulation of airline fares and routes. In effect this leads to an open market for the airline industry. Deregulation is eventually adopted (almost) worldwide and civil aviation becomes the mass transport system as we know it today.

From the 1970s onwards, commercial aviation has to deal with stiff competition, low margins and a huge market. Research and development are primarily aimed at improving the efficiency. Aircraft concepts are beginning to resemble one another more and more: a cylindrical fuselage, low wings with engines (most of the times only two) in pylons underneath and a conventional tail. The cylindrical fuselage makes it possible to create aircraft families by using plug extensions, thus creating longer versions of the same aircraft. Engines underneath the wing facilitate engine maintenance, upgrade or replacement. Most designs are derivatives of older designs. New designs mostly follow the trend already set. The introduction of computers in the cockpit means crews can be reduced to only two pilots. Aircraft like the Boeing 757, 767 and 777, Airbus 320, 330 340 and further developments of the Boeing 747 and 737 are all examples of the trend set. It is all about efficiency.

Legend

- no. of engines + type
- Y year of first flight
- no. of passengers
- cruise speed
- a►b range
- ceiling (max. altitude)
- wing span

Fig. 2. Timeline showing the most important civil aircraft of the various ‘stages’ of aviation and the important innovations they introduced in passenger transport.

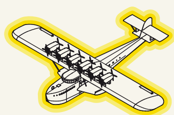


Fokker F VII
monoplane
plywood laminate

1(+2) recipr. prop
Y 1924
8
170 km/h
a►b 900 km
4267 m
21.70 m

Ford Trimotor
all metal

3 recipr. prop
Y 1926
10
145 km/h
a►b 885 km
5640 m
23.72 m



Dornier DO-X
semi cantilever monoplane
flying boat, sponsons
duralumin hull

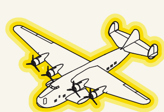
12 recipr. prop
Y 1929
100
175 km/h
a►b 1700 km
500 m
48.00 m

Junkers JU 52
low wing

3 recipr. prop
Y 1930
17
222 km/h
a►b 950 km
5200 m
29.25 m

Douglas DC-3
low wing cantilever
retractable gear, autopilot

2 reciprocating prop
Y 1935
28
240 km/h
a►b 1650 km
7300 m
29.00 m



Boeing 314
three tail flying boat
long range

4 recipr. prop
Y 1938
74
302 km/h
a►b 5896 km
5980 m
46.36 m

Lockheed Constellation
pressurized

4 reciprocating prop
Y 1943
95
547 km/h
a►b 8700 km
7620 m
38.47 m

de Havilland DH 106 Comet
first commercial jet airliner

4 turbojet
Y 1949
81
800 km/h
a►b 5190 km
12800 m
35.00 m

Fokker F27 Friendship

2 turboprop
Y 1955
56
460 km/h
a►b 2600 km
7620 m
29.00 m

Boeing 707

4 low-bypass turbofan
Y 1957
179
1000 km/h
a►b 8704 km
13000 m
39.90 m

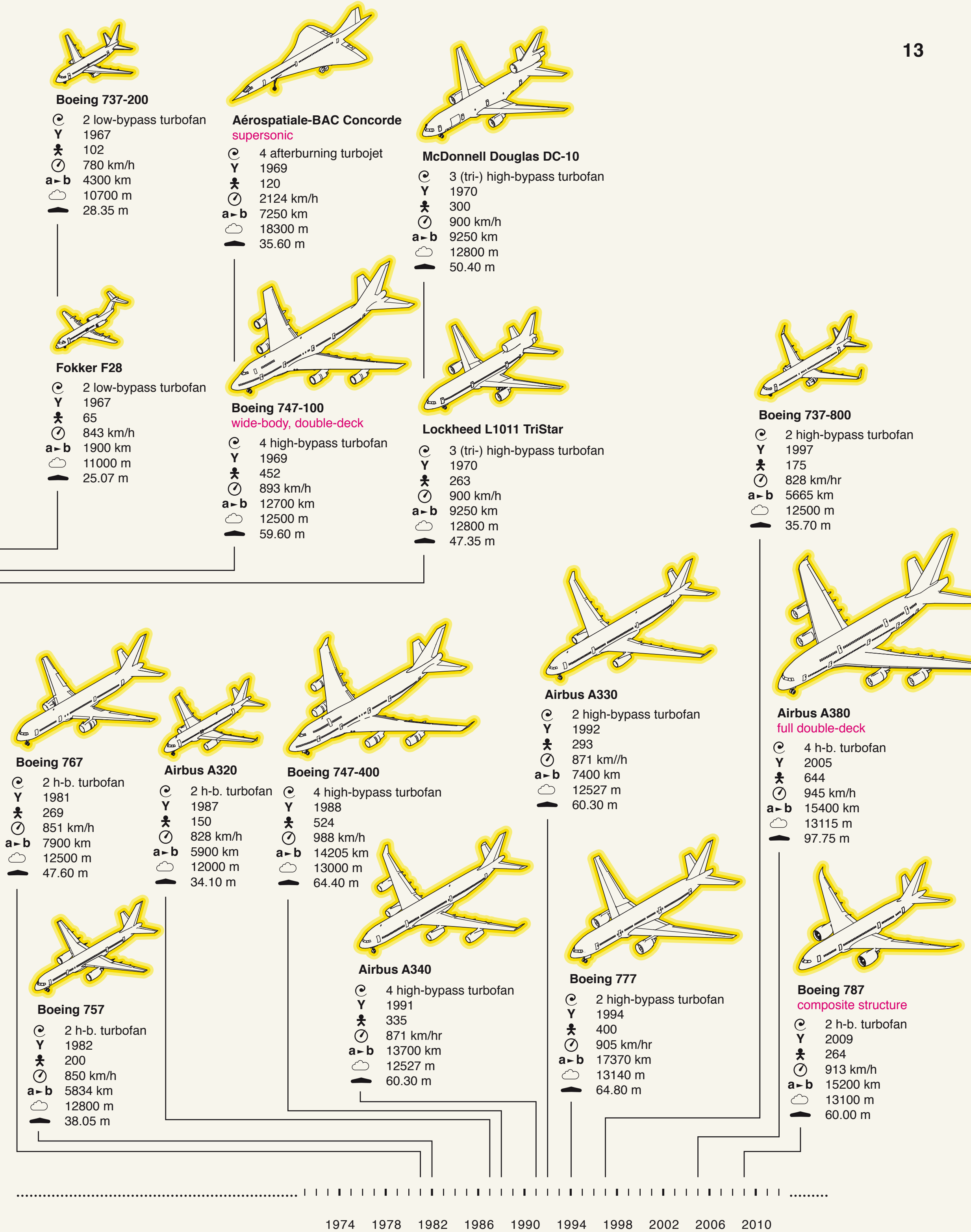
Lockheed L188C Elektra

4 turboprop
Y 1957
98
600 km/h
a►b 3540 km
8665 m
30.18 m

w.w. II

1922 1926 1930 1934 1938 1942 1946 1950 1954 1958 1962 1966 1970

pioneering **growth**



consolidation

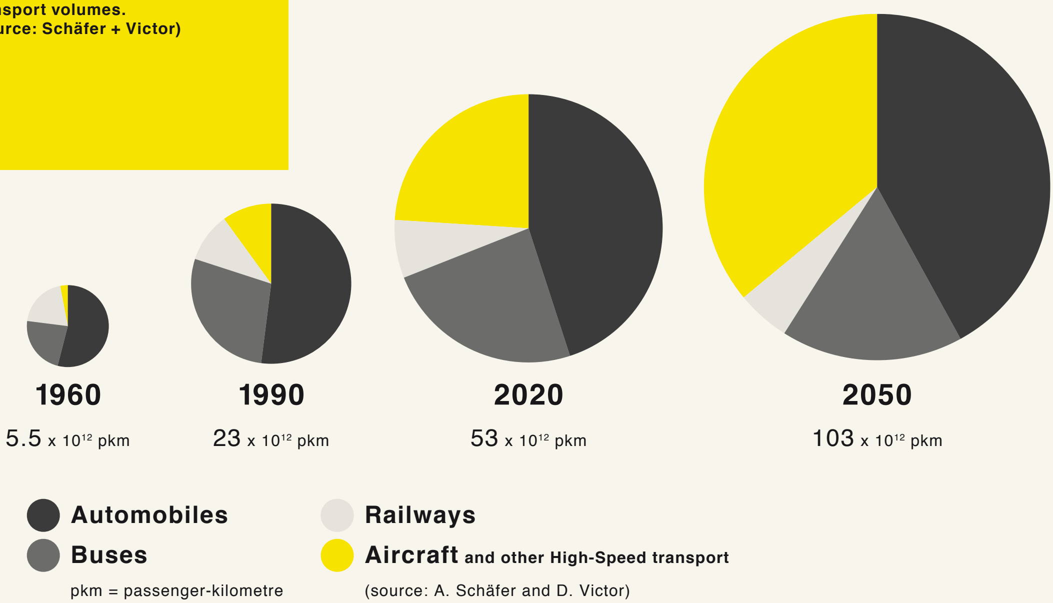
During the 1970s Supreme Court Justice Stephen Breyer worked with Senator Ted Kennedy on airline deregulation. The open market does come with its own problems, as he explains in an article in Business Week magazine of January 2011:

"What does the industry's history tell us? Was this effort worthwhile? Certainly it shows that every major reform brings about new, sometimes unforeseen, problems. No one foresaw the industry's spectacular growth, with the number of air passengers increasing from 207.5 million in 1974 to 721.1 million last year. As a result, no one foresaw the extent to which new bottlenecks would develop: a flight-choked Northeast corridor, overcrowded airports, delays, and terrorist risks consequently making air travel increasingly difficult. Nor did anyone foresee the extent to which change might unfairly harm workers in the industry. Still, fares have come down. Airline revenue per passenger mile has declined from an inflation-adjusted 33.3 cents in 1974, to 13 cents in the first half of 2010. In 1974 the cheapest round-trip New York-Los Angeles flight (in inflation-adjusted dollars) that regulators would allow: $1,442. Today one can fly that same route for $268. That is why the number of travelers has gone way up. So we sit in crowded planes, munch potato chips, flare up when the loudspeaker announces yet another flight delay. But how many now will vote to go back to the 'good old days' of paying high, regulated prices for better service? Even among business travelers, who wants to pay 'full fare for the briefcase?'"

DECLINE STAGE OR FURTHER GROWTH

Following the consolidation stage products and services often face a decline stage when consumers turn to alternatives leading to a shrinking market share. In the transport industry this has happened before. Trains replaced horses, because they were faster and cheaper. High-speed buses replaced trains, as they are more flexible. Cars in turn have replaced buses. Yet for longer distances the aircraft is still the preferred mode of transport and could remain so for a long time. Why? Because no suitable alternative has become available. Only an aircraft allows you to travel at speeds close to the speed of sound - the highest practically achievable speed, because of the 'sound barrier' and the associated sonic boom. Air travel demand is in fact expected to rise due to a growing world population and the increasing wealth of developing countries. Upcoming economies such as India and China show an impressive increase in air travel demand and this may well continue.

Fig. 3. History and prediction of transport volumes. (source: Schäfer + Victor)



Compared to 1990 world passenger traffic volume will multiply by more than a factor of two in the year 2020 and by a factor of 4 by 2050. Air travel and other high-speed transport accounted for 2% of world passenger traffic volume in 1960 and for 9% in 1990 and are projected to account for almost 25% in 2020 and 36% in 2050.

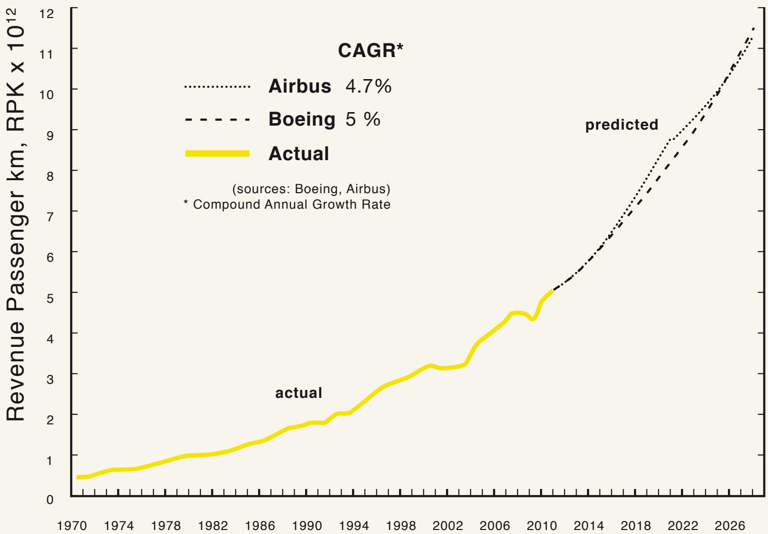


Fig. 4. Projected growth data for air travel (1970-2028) as predicted by the largest manufacturers in the aviation industry.

THE FUTURE IS BRIGHT?

With air transport revenues, passengers and miles expected to rise and rise, the future of commercial aviation seems bright. Yet there are threats on the horizon. If these are not dealt with, the industry could still enter a decline fase.

- Energy: the cost and availability of fuel.
- Environment: aviation noise and pollution and society's changing attitude towards these.
- Infrastructure: the room to fly and the airports to make aviation possible.

ENERGY

Our natural resources are diminishing. Somewhere in the coming decades 'peak oil' is expected to be reached– the moment of maximum oil production. After that, the rate of production will decline. Where other transport modes can potentially move towards electric propulsion, aviation remains dependant on hydrocarbon fuel, as this is weight-wise the most efficient fuel available. Lower oil production and higher prices can impact aviation severely. Aviation may well become the last sector to use hydrocarbons as an energy source.

ENVIRONMENT

Aviation affects the environment. First, aviation contributes to global warming and acid rain. Second, aircraft produce noise, and more and more people are affected by it. As a result, socio-cultural attitudes are changing and there is a growing resentment towards aviation.

A growing population means potential market growth, but also an increase in people experiencing noise and pollution. With other modes of transport going electric, aviation's relative contribution to pollution – now in the region of 3% – will only rise further. This could lead to a cycle of restrictions on airports and flights.

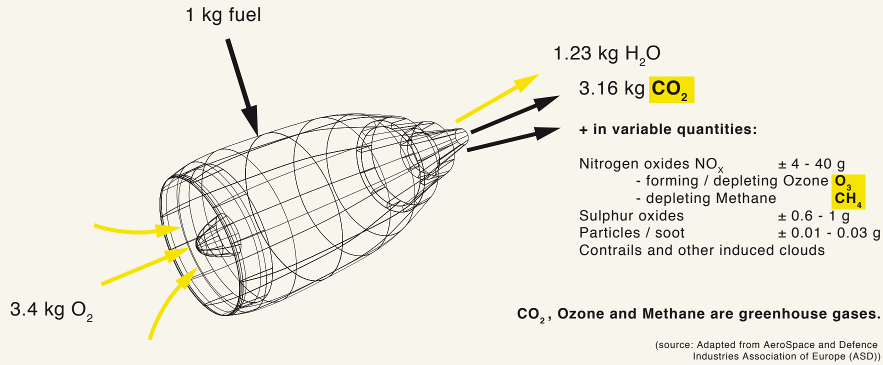
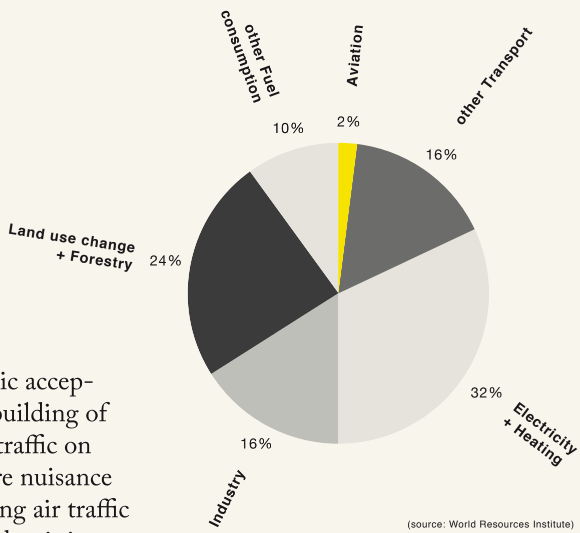


Fig. 5. Average chemical in- and output of a jet engine.

Fig. 6. Global man-made CO_2-emission sources.



INFRASTRUCTURE

The infrastructure – airspace and airports, in other words: room to fly – is another problem civil aviation will face in the future. A lack of public acceptance creates a problem for the building of new airports, and increasing air traffic on existing airports will lead to more nuisance from emissions and noise. Existing air traffic control systems are overburdened as it is. Infrastructure-wise a few hurdles have to be taken to accommodate growth in the sector.

ADAPT OR DIE

How can aviation avert such threats to its continued growth? By taking the example of others. Nike, Philips, Apple, Gillette and Ford: all successful companies that keep reinventing their products and strategies. They know that product innovation is the key to life cycle extension. Without it, customers will turn away and choose for alternatives.

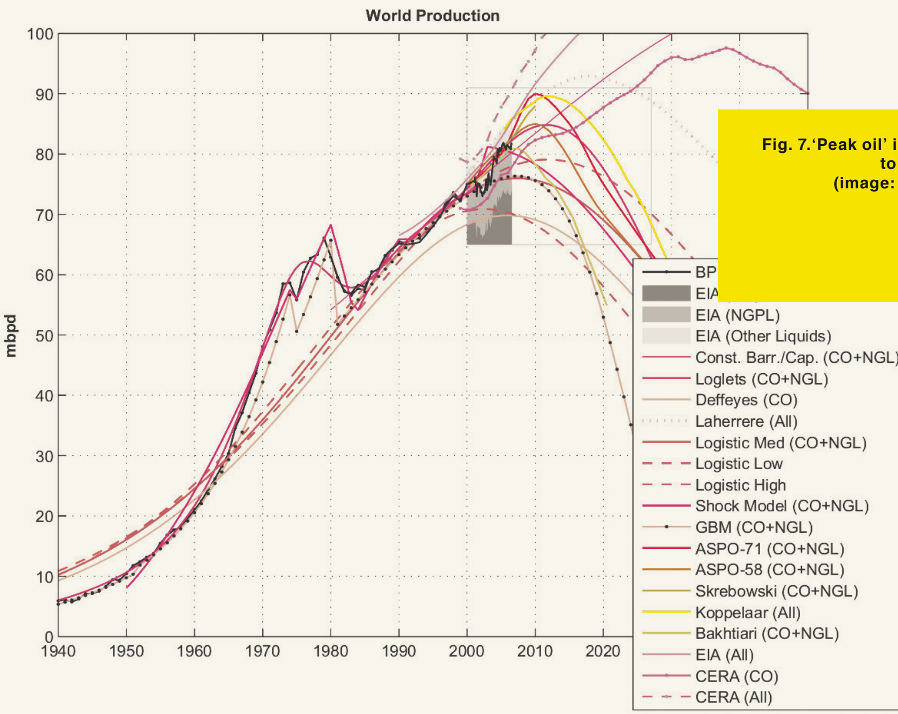


Fig. 7. 'Peak oil' in time according to various sources. (image: theoildrum.com)

It is true that aviation has no real alternative (yet), because it is still the fastest and most flexible mode of transport. Arguably, high speed trains are becoming an alternative, especially for short-to-middle range city pairs. But for long range and overseas travel, aviation is still the best option. However, the hurdles looming in the future are very real. Moreover, when the general public starts to focus more on the problems than on the benefits, air travel might lose its popularity and could even be taxed. The same thing happened to the tobacco industry. The industry can overcome the hurdles foreseen and overturn public opinion. How? – By making flying greener with the help of new technologies. CleanEra is therefore looking into ways to:

- Make aircraft significantly more efficient, so a minimum of fuel will be needed
  > *energy*
- Make aircraft nuisance free (considerably reducing noise and emissions)
  > *environment*
- Provide more airport and airspace capacity
  > *infrastructure*
- Make aircraft even more cost-efficient
  > *good business sense*

Innovation will allow civil aviation to enter a new century of clean and nuisance free expansion and in so doing attain new and greater heights. This is what CleanEra is all about.

THE CLEANERA MISSION:
"To develop new technologies for (a) revolutionary conceptual aircraft design(s) optimized for environment and passenger friendliness and investigate the feasibility of these technologies and their integration."

THIS BOOK
This book gives an overview of the technologies studied by the CleanEra project. Most of these technologies formed the basis for PhD theses, which can be read separately for more indepth coverage of the various subjects.
The first part of the book is organized according to the 'simplified Breguet range equation', which states that the range of an aircraft is related to the following factors:

- speed (V) or (aM) (speed of sound times Mach number of flight);
- the aerodynamic efficiency C_L/C_D (lift over drag);
- the weight of the aircraft at the beginning of the flight divided by the final weight of the aircraft after the flight (W_1/W_2); and
- thrust specific fuel consumption (c_T).

Applying the Breguet range equation, we see that to improve the efficiency of the aircraft we need better aerodynamics, lighter structures, and more efficient engines.

THE SIMPLIFIED BREGUET RANGE EQUATION

(by Louis Charles Breguet)

$$R = \frac{aM}{c_T} \frac{C_L}{C_D} \ln \frac{W_1}{W_2}!$$

R	=	range
M	=	Mach number aircraft is flying
a	=	speed of sound
c_T	=	thrust specific fuel consumption
C_L	=	Lift coefficient
C_D	=	Drag coefficient
W_1	=	Initial Weight
W_2	=	Final Weight

Aerodynamics are covered in the chapters "Shape up!", "Zapp the air" and "Metamorphosis" on the subjects of aerodynamic shape optimization, plasma controllers influencing the airflow, and novel high lift devices. Improving the aerodynamics of an aircraft will increase the lift-over-drag ratio, which means you can fly further with the same amount of energy.

Lighter structures are described in the chapters "Skin and bones", "Bubbles in the sky" and "Painting it green", which deal with novel composite structures, pressure vessels, and coatings to ensure light-weight and durable structures. With such lighter structures, more payload and/or more energy can be carried, within the limits of the maximum take-off weight of the individual aircraft.

More efficient engines are described in the chapters "No smoking", "Hushing jet-engines" and "Lean machine", covering several subjects concerning modern jet engines. In this section, the various energy carriers, the energy-to-work convertors and finally the various thrust producers are discussed, giving insight into the propulsion systems of today and what might be achievable in the future.

THE BIGGER PICTURE

An aeroplane, however efficiently designed, does not fly in isolation. In an ever busier air traffic environment there is room for improvement too. "Free flight" deals with a novel concept for aircraft control that allows for more efficient flying. With free flight, air traffic management can keep detours and suboptimal flight paths to a minimum. "A quiet approach" describes novel techniques that can lead to optimal noise abatement procedures. This is an important factor in a time when public acceptance is declining.
On the subject of stakeholder behaviour in general, the penultimate chapter "Design for sustainability" discusses the wider consequences of technological improvements.

Finally Jacco Hoekstra, Professor Communication, Surveillance, Navigation / Air Traffic Management, and former dean of the faculty of Aerospace Engineering, rounds up the various chapters and gives us his expectations of the future of flight.

Shape up!

Controlling drag through three-dimensional shape optimization

by Michiel Straathof

During the early development of aircraft, not much attention was paid to aerodynamic efficiency. Structural design did not yet allow for cantilever wings - wings that are only supported on one side. Instead, they had to be supported with numerous struts and wires, which caused huge amounts of parasitic drag. During WWI speed and range became important for fighters, bombers and observation aircraft. The drag of an aircraft increases with the square of its speed, so drag reduction came high on the agenda. The resulting advances in aerodynamic design can be seen in the Spirit of St. Louis, the aircraft with which Charles Lindbergh performed his famous flight across the Atlantic Ocean in 1927. It could fly non-stop for over 33 hours, covering a distance of almost 6500 km. Lindbergh's airplane shows a number of aerodynamic design

Fig. 8. Charles Lindbergh next to his Spirit of St. Louis.

features. First, the steel tube fuselage is covered with fabric to allow the air to flow past smoothly. Second, the struts are aerodynamically shaped for low drag and their number is kept to a minimum. In later versions a cowling (cover) was added to the propeller.

Towards the end of the 1920s wooden monocoque fuselages and wings appeared. These had much cleaner lines, but a few struts were still necessary to support the wings, as on the Fokker F.VII.

True aerodynamic optimization was first achieved in the 1930s with the Boeing 247 (1934) and the Douglas DC-2 (1935). Except for the propellers and the rear landing gear, the entire exterior of these aircraft consists of a smooth aluminum skin; even the engines are completely covered. This skin could carry part of the loads occurring during flight, so external struts were no longer required. Also, the intersection between the wings and the fuselage has been aerodynamically optimized, to prevent the air flow from separating[1]. The wings are tapered and swept backwards, which also decreases drag.

[1] **FLOW TRANSITION AND SEPARATION**

Air that flows past a surface can go through different stages. At the leading edge of a wing, the flow is usually laminar, meaning that it is very smooth and causes very little friction drag. For sail planes the area of laminar flow can extend all the way to the trailing edge, while for airliners it usually doesn't extend beyond about 15% of the wing chord. Instabilities in the flow – known as Tollmien-Schlichting waves - eventually cause the laminar flow to transition to a more chaotic state called turbulent flow. Turbulent flow causes considerably more friction drag than laminar flow, but it is less likely to separate due to its energetic nature. Separation generally occurs in areas where there is a strong positive pressure gradient, i.e. in areas of large curvature. This can be actual curvature in the geometry or induced curvature caused by a large angle of attack. On passenger aircraft, flow separation is always unwanted since it creates enormous amounts of pressure drag and could even lead to loss of lift and/or control of the aircraft.

Fig. 9. Laminar and turbulent flow.

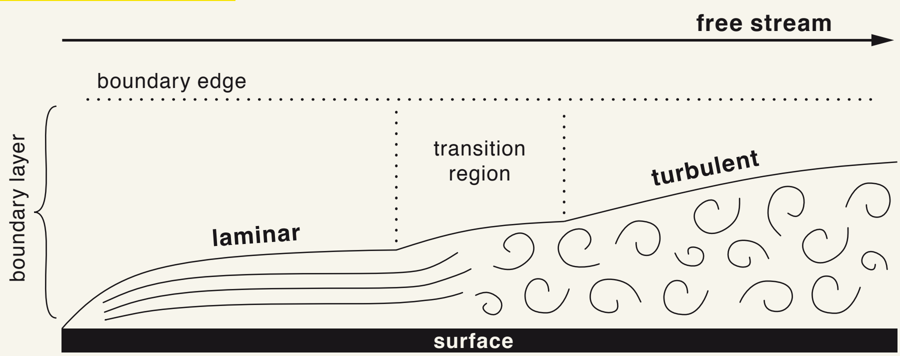


Fig. 10. The Douglas DC-2 in flight. (photo: Ed Coates collection)

Fig. 11. The Boeing 787 during turnaround. (photo: Tomoaki Inaba)

In December 2009, the latest airliner to enter production, the Boeing 787, took to the skies. Compare the B787 to the DC-2 and it is clear that over a period of 75 years, nothing changed in terms of aircraft configuration. That was not for lack of trying.

Over the years, various novel aircraft concepts have been considered, but none of them actually made it into production. One design that has been extensively studied is the joined-wing or box wing aircraft. Creating lift using two sets of wings, joined together at the tips, could dramatically reduce induced drag by weakening the wing tip vortices[2]. A promising concept, but a lot of structural challenges will have to be overcome, such as making the box-wing structure stiff enough.

Another novel configuration is the blended-wing-body aircraft. By merging the wings with the fuselage, the entire exterior surface of the aircraft contributes to the generation of lift. In a conventional aircraft, the fuselage only generates drag, without contributing to the lift. Challenges to overcome with this configuration mainly concern stability and control.

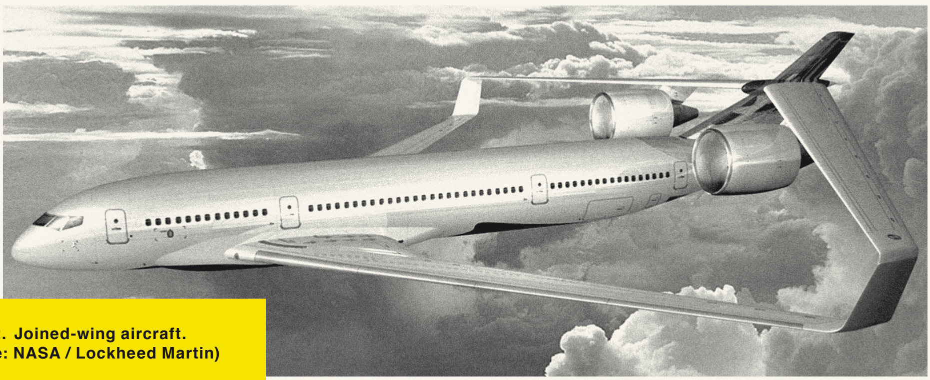


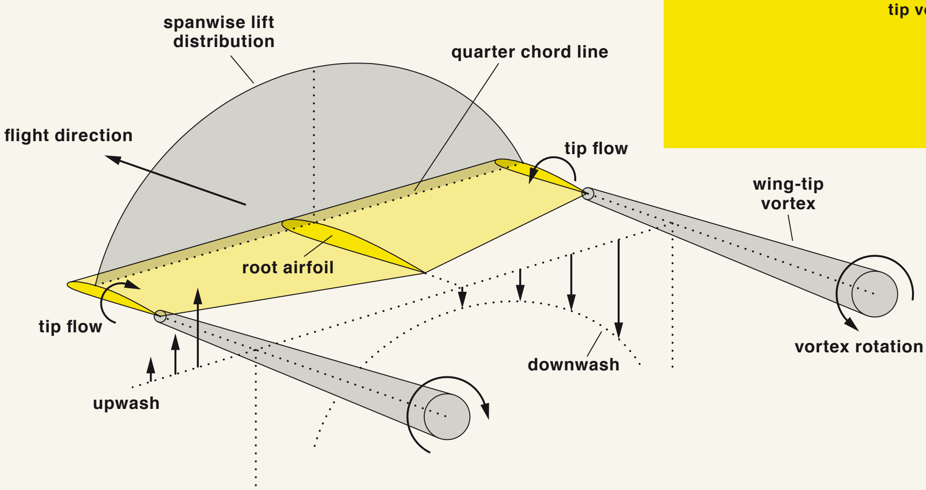
Fig. 12. Joined-wing aircraft. (image: NASA / Lockheed Martin)

Fig. 13. Blended-wing-body aircraft. (image: NASA / Boeing)

[2] **LIFT DISTRIBUTION**

The planform – the shape of the wing from above (or more likely, from below) – has a significant influence on the aerodynamic performance. It is one of the major factors determining the spanwise distribution of lift on the wing. During flight, the lower side of a wing experiences high pressure and the upper side low pressure; this causes an upward force: lift. At the wing tip, the high and low pressure regions come together and cause the air to flow from the lower side of the wing to the upper side and roll up into vortices. These vortices in turn cause a downwash at the leading edge of the wing, resulting in a rearward tilt of the lift vector. This vector now has a component opposite to the direction of travel, which is called induced drag. Induced drag is inevitable, but it can be reduced by modifying the wing planform.

Fig. 14. Induced drag due to wing tip vortices.



A wing with an elliptical planform experiences the least amount of induced drag for a given aspect ratio. Elliptical wings are difficult to manufacture, because of the required curvature in the leading and trailing edges. Tapered wings form a good alternative, but they produce up to 15% more drag. The number by which the induced drag exceeds that of the elliptical lift distribution is called the Oswald factor.
Another way of reducing induced drag is by increasing the aspect ratio of the wing. This will reduce wing tip vortices and hence induced drag. The aspect ratio is a measure of slenderness and can be expressed as: $AR = b^2 / S$, where b is the semi-wing span and S the wing area. Sailplanes typically have very high aspect ratios, resulting in extremely low induced drag.

Despite the lack of new configurations, a number of subtle differences can be distinguished between the DC-2 and the B787. The wings and tail surfaces of the B787 are very slender and highly tapered, lowering induced[2] and wave[3] drag. Additionally, the nose section of the B787 is more aerodynamically shaped and the landing gear is fully retractable. These characteristics give the B787 a much higher aerodynamic efficiency.

In general, a number of factors have led to the superiority of modern aircraft. One is the advancement in materials. The slender wings of the B787 could simply not have been produced 70 years ago. Another one is the availability of computer power. The design of the DC-2 was purely driven by the experience of the designers, validated by wind tunnel testing. These days, computer algorithms are used to accurately model the airflow around an aircraft and then to numerically optimize aircraft shapes. These powerful tools are capable of optimizing complete aircraft.

[3] **SHOCK WAVES**

As the speed of an aircraft increases, there comes a point where some of the air flow on the wing is supersonic, even though the aircraft itself is still flying at subsonic speed. An air particle moving over the wing will accelerate from subsonic to supersonic and decelerate back to subsonic speed again. This deceleration leads to a shock wave on top of the wing. Because it takes energy to form this shock wave, this process translates into a form of drag called wave drag. The strength of the shock wave and hence the amount of wave drag depends on the component of the flow velocity that is perpendicular to the wing. For a straight wing, this component is equal to the speed of the whole aircraft. For a swept wing it can be much smaller. That is why a swept-wing aircraft is able to travel much closer to the speed of sound, without the air flow becoming supersonic anywhere on the wing.

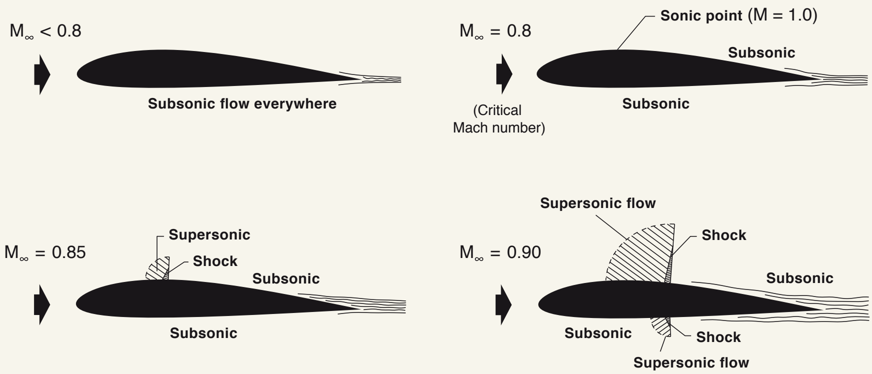


Fig. 15. Shock wave formation.

CFD

Calculating the flow of air around an object using computer algorithms is called computational fluid dynamics or CFD. This is done with the help of a set of equations named after French engineer Claude-Louis Navier and British mathematician George Gabriel Stokes: the Navier-Stokes (N-S) equations. These describe the motion of fluid substances. Unfortunately, no analytical solutions of the Navier-Stokes equations are known, meaning that the equations always have to be solved numerically. The most straightforward and time-consuming way of solving the N-S equations is a direct numerical simulation. This is however not (yet) feasible for use in aircraft design, because it simply takes too long to compute the flow. This problem can be solved by making a number of assumptions about the flow, such as that it is inviscid and/or incompressible.[4]

[4] **FLOW EQUATIONS**

The Navier-Stokes (N-S) equations describe the behavior of all fluids (including gases, such as air) at all scales. For incompressible, Newtonian fluids, the N-S equations can be written as:

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=$$
$$\rho g_x-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left[2\mu\frac{\partial u}{\partial x}+\lambda\nabla\cdot\mathbf{V}\right]+\frac{\partial}{\partial y}\left[\mu\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right]+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z}\right)\right]$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=$$
$$\rho g_y-\frac{\partial p}{\partial y}+\frac{\partial}{\partial y}\left[2\mu\frac{\partial v}{\partial y}+\lambda\nabla\cdot\mathbf{V}\right]+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)\right]+\frac{\partial}{\partial x}\left[\mu\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right]$$

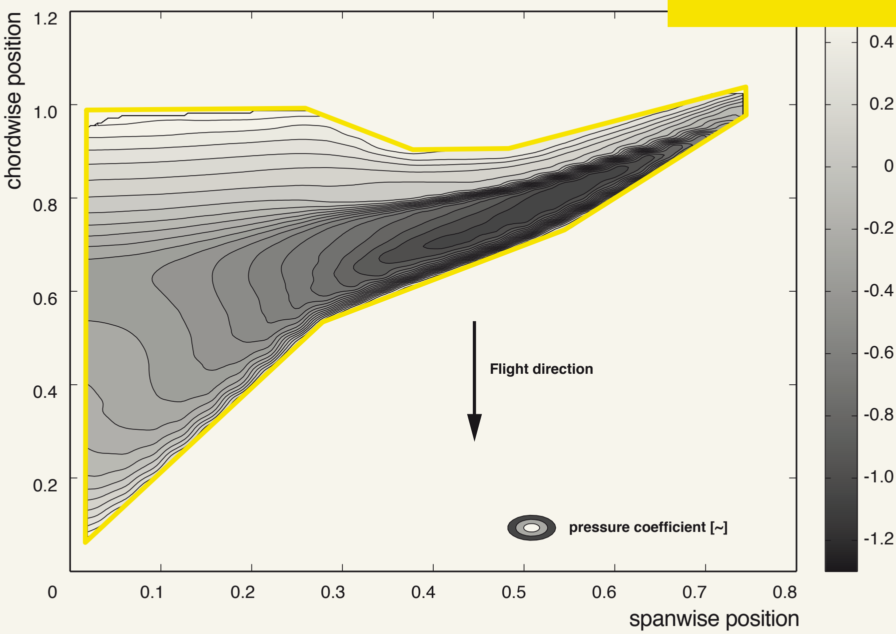
$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=$$
$$\rho g_z-\frac{\partial p}{\partial z}+\frac{\partial}{\partial z}\left[2\mu\frac{\partial w}{\partial z}+\lambda\nabla\cdot\mathbf{V}\right]+\frac{\partial}{\partial x}\left[\mu\left(\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z}\right)\right]+\frac{\partial}{\partial y}\left[\mu\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)\right]$$

As mentioned, no analytical solutions of the Navier-Stokes equations are currently known. In fact, a $1 million prize has been offered to the first person who finds an analytical solution or proves that no such solution exists. So for now, the only way to find a solution to the N-S equations is to solve them numerically. This can be done directly on the full set of equations (Direct Numerical Simulation or DNS) or one or more assumptions can be made about the flow to simplify the computation. Separating the turbulent velocity fluctuations from the mean velocity leads to the Reynolds-Averaged-Navier-Stokes (RANS) equations. Neglecting viscosity results in the Euler equations and assuming irrotational flow finally leads to the potential flow equations. Many commercial flow solvers are available to solve these simplified sets of equations. In my work I have used an Euler code that was developed at TU Delft.

Solving the N-S equations produces a velocity field; it describes the velocity of the flow at certain points in space. Interesting properties can be derived from this velocity field, such as the flow rate and aerodynamic forces and moments. CFD is also very useful for visualizing the flow around an object.

Many flow phenomena can be easily identified by looking at a plot of the pressure distribution on a wing or aircraft. Where the isobars (lines of constant pressure) lie close together and the pressure gradient is positive a shockwave is likely to form. Stagnation points can be found at locations where the pressure coefficient is equal to 1. Areas of low pressure on top of the wing

Fig. 16. Pressure contours on a blended-wing-body configuration.



(and high pressure below the wing) can give an indication about the aerodynamic moments involved. The list goes on, but an important conclusion is that computational fluid dynamics provides a powerful tool that gives insight into the flow around an aircraft in both a quantitative and a qualitative way.

PARAMETERIZATION

The shape of an object must be properly described in order to compute the flow around it. Finding a mathematical description of a shape is called parameterization. The first CFD algorithms that were used in the 1970s and 1980s were simple and thus required only simple ways of parameterizing a shape. However, as computer power grew and the flow solvers became more sophisticated, the need arose for novel parameterization methods. This is the primary focus of the CleanEra design work.

EXISTING METHODS

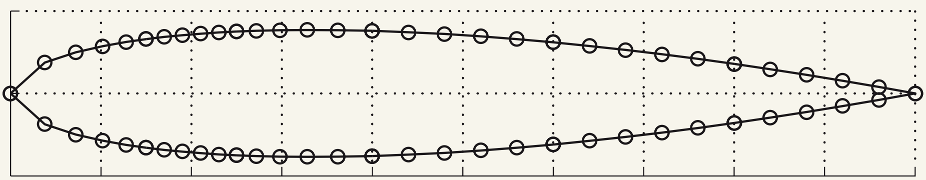


Fig. 17. Discrete parameterization.

The most straightforward way to parameterize a shape is by taking discrete points along its boundary and connecting those points with lines. This is not very efficient, as you need a lot of points to generate a smooth shape. Additionally, it is very difficult to maintain a smooth shape throughout the optimization process.

The number of variables required can be greatly reduced by using a polynomial representation, where the polynomial coefficients determine the shape. This results in a shape which is much smoother than with a discrete representation. A disadvantage is that in order to capture local deformations of a shape, the order of the entire polynomial needs to be increased, which could result in a high number of design variables after all.

Another alternative is to add up a number of special functions that together form the required shape. Different functions can be used for this purpose, such as Bernstein or Chebyshev polynomials[5].

[5] POLYNOMIAL BASIS FUNCTIONS

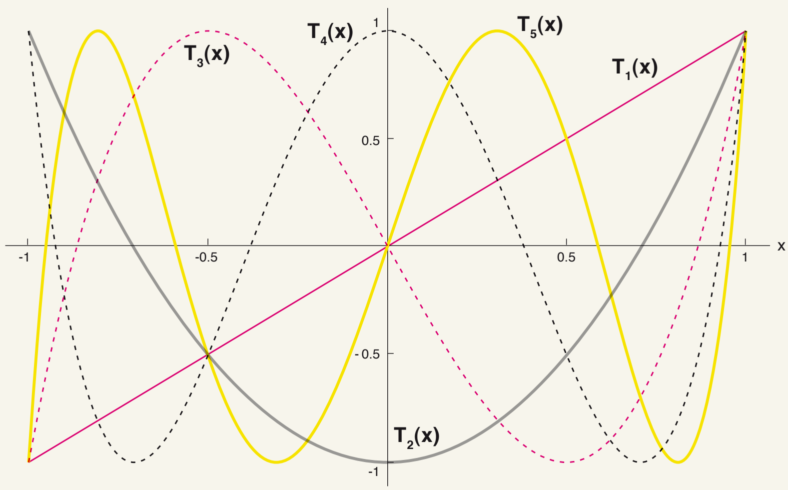
Instead of using a single polynomial to describe a curve, it is also possible to use a set of polynomial basis functions that form a smooth curve when added up.

One such set of basis functions are the so-called Chebyshev polynomials, which are defined by the following recurrence relationship:

$$T_0(x) = 1$$
$$T_1(x) = x$$
$$T_{n+1}(x) = 2xT_n(x) - T_{n-1}(x)$$

The curve is then given by multiplying each basis function with a coefficient and then adding them all up. This is described mathematically as:

$$f(x) = \sum_{n=0}^{p} a_n T_n(x)$$



Another popular set of basis functions are the Bernstein polynomials, which have the special property that their sum is always equal to 1. They are defined as follows:

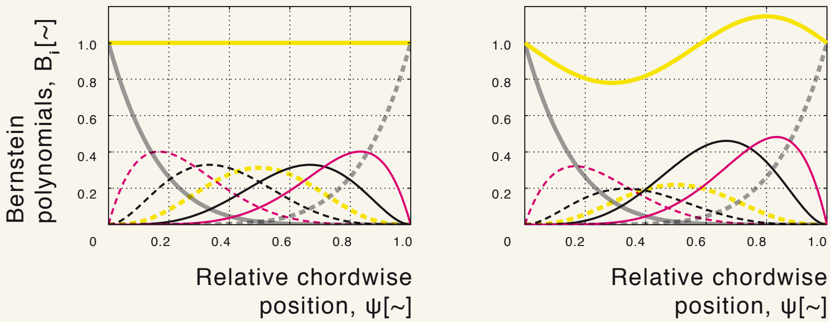
Fig. 18. (above) Chebyshev polynomials.

Fig. 19. (below) Bernstein polynomials.

$$B_{n,p_S} = \binom{p_S}{n} x^n (1-x)^{p_S - n}$$

The Bernstein curve is then described as:

$$f(x) = \sum_{n=0}^{p_S} b_n B_{n,p_S}(x)$$



CST METHOD

In 2008, a Boeing employee named Brenda Kulfan introduced a novel parameterization technique called the Class-Shape-Transformation (CST) method. This technique combines an analytical function, called the class function, and a set of Bernstein polynomials, called the shape function. The class function represents a basic class of shapes, such as an airfoil or a fuselage cross-section, while the shape function represents the deviation from this basic shape[6].

[6] **CLASS-SHAPE-TRANSFORMATION (CST) METHOD**

The CST method as developed by Kulfan describes the shape of a curve as the product of a class function C and a shape function S:

$$f(x) = C(x) \cdot S(x)$$

The class function is given by the following analytical function:

$$C(x) = x^{N1}(1-x)^{N2}$$

By varying the coefficients $N1$ and $N2$, different classes of shapes can be generated, from typical round nose/sharp trailing edge airfoils to fuselage cross-sections.

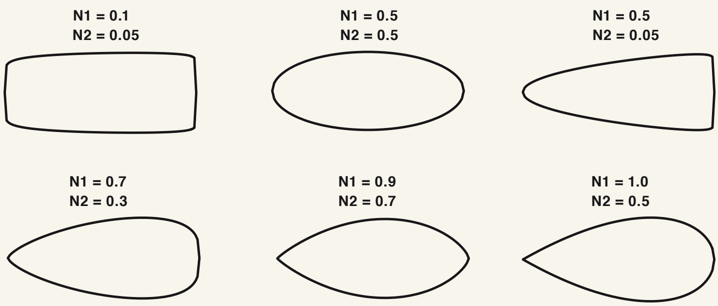


Fig. 20. Possible class functions.

The shape function consists of a set of Bernstein polynomials and can thus be described as follows:

$$S(x) = \sum_{n=0}^{p_S} b_n \binom{p_S}{n} x^n (1-x)^{p_S - n}$$

The main advantage of the CST method is that the final shape always belongs to the class of shapes determined by the class function. For example, if $N1$ = 1 and $N2$ = 0.5, then the CST curve will always have a rounded nose and a sharp trailing edge, independent of the shape function. The shape function merely describes the deviation from the class function.

This method proved to be very useful because of its ability to handle many different airfoil and wing shapes with a relatively low number of design variables. Another advantage of the CST method is that the round nose of the airfoil is completely defined as a result of the square root term in the class function. This causes problems for most other parameterization methods.

The CST method has one big limitation: it cannot handle local deformations efficiently. When more detail is required in a specific area, the order of the entire shape function needs to be increased. This problem can be solved by adding a third function based on B-splines.

CSRT METHOD

To be able to efficiently model local shape changes, an extension to the CST technique was developed at CleanEra, called the Class-Shape-Refinement-Transformation method. As the name suggests, an extra function was added: the refinement function. This function is based on B-splines[7], which are basically strings of lower order curves. Because of the piece-wise nature of B-splines, it is possible to deform only a particular region of the curve, while keeping the rest constant. This provides the possibility to increase the detail on a specific part of the shape, without having to increase the order of the whole shape function.

[7] **B-SPLINES**

As was the case for the shape function, a B-spline curve (and hence the refinement function) consists of a set of basis functions, multiplied by a set of coefficients. For a B-spline, this set of coefficients is represented by the coordinates of so-called control points that together form a control polygon, $\bar{\mathrm{P}}$. Mathematically, the B-spline is described as follows:

$$R(x) = \sum_{n=0}^{p_R} \bar{\mathrm{P}}_n N_{n,k}(x)$$

The B-spline basis functions are defined iteratively:

$$\begin{aligned} N_{n,1}(x) &= 1 \quad \text{if} \quad t_n \leq x \leq t_{n+1} \\ &= 0 \quad \text{otherwise} \end{aligned}$$

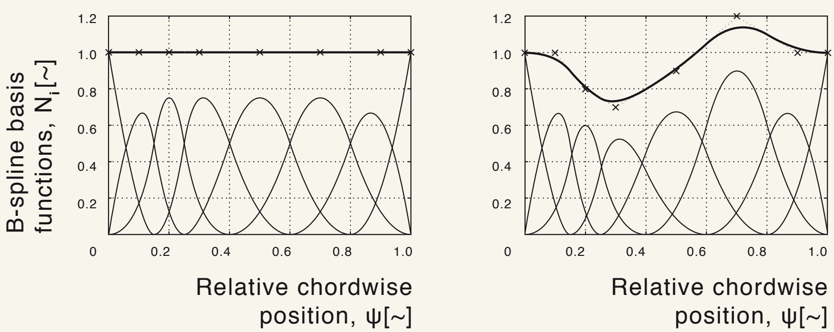
and:

$$N_{n,k}(x) = \frac{(x - t_n)N_{n,k-1}(x)}{t_{n+k-1} - t_n} + \frac{(t_{n+k} - x)N_{n+1,k-1}(x)}{t_{n+k} - t_{n+1}}$$

Where t_i are called the knot values, which relate the parametric variable x to the control points $\bar{\mathrm{P}}$. They are defined as follows:

$$\begin{aligned} t_i &= 0 && \text{if} \quad n < k \\ t_i &= n - k + 1 && \text{if} \quad k \leq n \leq p_R \\ t_i &= p_R - k + 2 && \text{if} \quad n > p_R \end{aligned}$$

Fig. 21. B-spline basis functions.



The CSRT method can now be described symbolically as:

$$f(x) = C(x) \cdot S(x) \cdot R(x) = x^{N1}(1-x)^{N2} \cdot \sum_{n=0}^{p_S} b_n B_{n,p_S}(x) \cdot \sum_{n=0}^{p_R} \bar{\mathrm{P}}_n N_{n,k}(x)$$

The methods mentioned so far are all used to parameterize two-dimensional shapes, such as airfoils. A three-dimensional shape can be treated as a stack of two-dimensional shapes with the points in between interpolated. This is how most aircraft wings are currently defined. This is an easy solution, also because production can be done in a similar fashion, with ribs representing the airfoil sections. However, the more complex the wing shape, the more airfoil sections have to be defined to describe the wing, rendering the method less efficient.

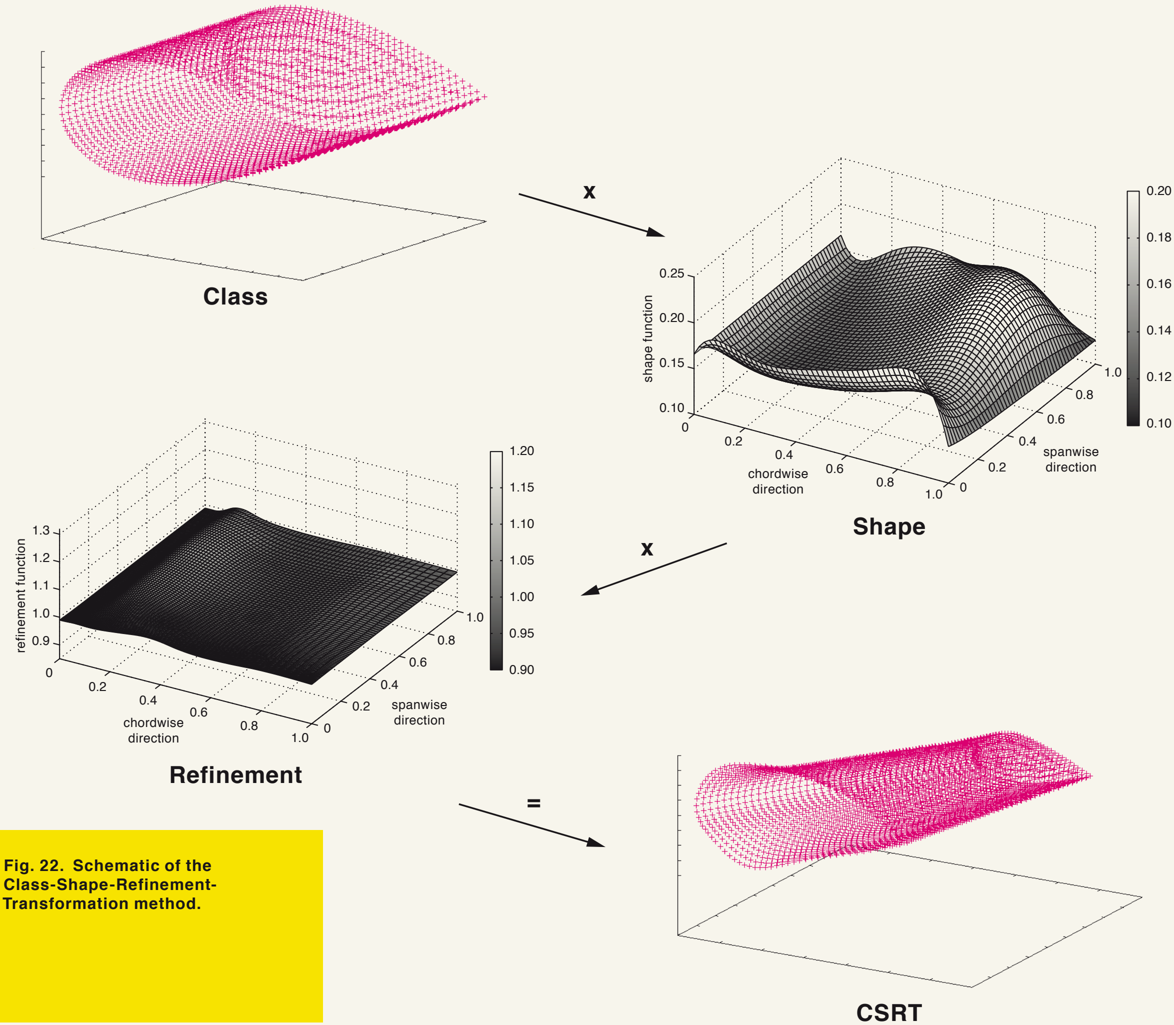


Fig. 22. Schematic of the Class-Shape-Refinement-Transformation method.

With more sophisticated production techniques and computers available, it is now possible to represent the entire three-dimensional shape as a mathematical surface. To do this with the CSRT method, the class, shape and refinement functions will have to represent surfaces instead of curves. For the class function this is straightforward, since it is an analytical function. For the shape and refinement functions this means that Bernstein and B-spline surfaces will have to be used. These require slightly more elaborate computations compared to Bernstein and B-spline curves, but they are well-defined and have the same advantageous properties.

OPTIMIZATION

Once a flow solver and a parameterization technique have been selected, they can be coupled to an optimization algorithm. At the heart of most optimization algorithms lies a so-called sensitivity analysis, which determines the gradients of the objective function with respect to the design variables. In other words, it finds out how the function to be optimized (e.g. lift-to-drag ratio) changes when you change the parameters that determine the shape. This can be done in a number of ways, but most of them require the flow solver to be run once for each gradient. This means that if a shape is parameterized using 100 variables, the flow solver will have to be run 100 times to find all gradients, which can take a very long time. However, there is one technique that can significantly reduce the required computation time: the adjoint equation method[8]. In my work, this technique has been successfully coupled to the CSRT method and to an Euler solver that was developed at TU Delft.

[8] ADJOINT EQUATION METHOD

First, let us assume some aerodynamic property J which is a function of the flow variables U and the geometry design variables $\mathbf{x}$:

$$J = J(\mathbf{U}, \mathbf{x})$$

The derivative of J with respect to a specific design variable x_i can be written as:

$$\frac{dJ}{dx_i} = \frac{\partial J}{\partial x_i} + \frac{\partial J}{\partial \mathbf{U}} \frac{\partial \mathbf{U}}{\partial x_i}$$

Note that this equation distinguishes between a change in objective function as a result of a variation in the flow solution $\partial \mathbf{U}$ and a variation due to the change in geometry ∂x_i. In order to solve this equation, a relationship between $\mathbf{U}$ and x is needed. Such a relationship is the steady state flow equation, i.e.:

$$\mathbf{R}(\mathbf{U}, x_i) = \mathbf{0}$$

Computing the derivative of $\mathbf{R}$ with respect to x_i gives:

$$\frac{d\mathbf{R}}{dx_i} = \frac{\partial \mathbf{R}}{\partial x_i} + \frac{\partial \mathbf{R}}{\partial \mathbf{U}} \frac{\partial \mathbf{U}}{\partial x_i} = \mathbf{0}$$

The adjoint method can be derived by introducing a vector of Lagrange Multipliers Λ. The steady state flow equation be added as a constraint to the sensitivity to obtain:

$$\begin{aligned}\frac{dJ}{dx_i} &= \frac{\partial J}{\partial x_i} + \frac{\partial J}{\partial \mathbf{U}}\frac{\partial \mathbf{U}}{\partial x_i} - \mathbf{\Lambda}\left(\frac{\partial \mathbf{R}}{\partial x_i} + \frac{\partial \mathbf{R}}{\partial \mathbf{U}}\frac{\partial \mathbf{U}}{\partial x_i}\right)\\ &= \frac{\partial J}{\partial x_i} - \mathbf{\Lambda}\frac{\partial \mathbf{R}}{\partial x_i} + \left(\frac{\partial J}{\partial \mathbf{U}} - \mathbf{\Lambda}\frac{\partial \mathbf{R}}{\partial \mathbf{U}}\right)\frac{\partial \mathbf{U}}{\partial x_i}\end{aligned}$$

The vector of Lagrange Multipliers can be chosen to satisfy the following adjoint equation:

$$\mathbf{\Lambda}\frac{\partial \mathbf{R}}{\partial \mathbf{U}} = \frac{\partial J}{\partial \mathbf{U}}$$

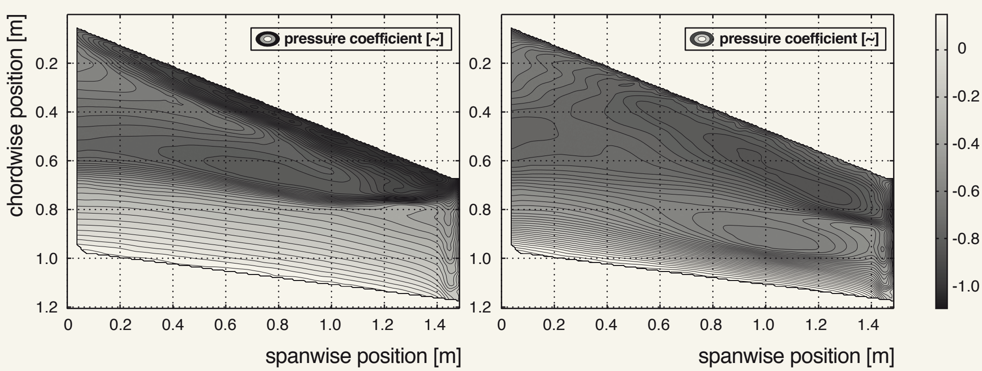
Combining the last two equations results in the elimination of the last two terms and hence:

$$\frac{dJ}{dx_i} = \frac{\partial J}{\partial x_i} - \mathbf{\Lambda}\frac{\partial \mathbf{R}}{\partial x_i}$$

Finding a solution to this system only requires solving as many equations as there are flow functionals. For most aerodynamic optimization problems, this number is much lower than the number of design variables. Hence, using the adjoint equation method can dramatically reduce the time required to compute the gradients.

The CSRT method, in two as well as three dimensions, allows for a two-step optimization approach. In the first optimization step, only the Bernstein coefficients of the shape function are used as variables. In the second refinement step, the B-spline coefficients are varied. Typical results indicate that the first optimization step significantly reduces the shockwave on a wing in transonic conditions, increasing its aerodynamic efficiency by about 20-30%. The refinement step usually results in a further improvement in the order of 5%.

Fig. 23. Pressure distribution before (left) and after (right) optimization.



These results can be visualized by looking at the pressure distribution on a wing before and after the optimization process. Putting an ordinary wing in transonic conditions will often lead to shock waves, indicated by strong positive pressure gradients. As a result of these shock waves, most of the lift will be located near the leading edge of the wing, causing an unwanted pitch-up moment. Looking at the optimized wing, a strong reduction of the shock waves can be identified. Additionally, a more even distribution of lift over the entire wing will lead to a lower pitch-up moment.

CONCLUSIONS

The CSRT method developed at CleanEra proved to be a very intuitive and effective way of parameterizing aircraft shapes, both in two as well as in three dimensions. The method allows for a two-step approach which has the potential to significantly increase the lift-to-drag ratio of various aircraft shapes. Using an adjoint algorithm provided the computational efficiency necessary to perform true three-dimensional shape optimization.

Future research will be focused on optimizing the complete design framework and investigating the applicability of the CSRT method to more diverse aircraft shapes.

Metamorphosis

Seamless high-lift systems

by Durk Steenhuizen

High-lift systems are an indispensable aerodynamic tool for modern civil airliners. Their function is to increase the maximum lift capability of an airliner's wing, which improves take-off and landing performance. In other words: at landing they allow for the decrease of speed and at take-off they make it easier for the plane to lift off the ground. During cruise flight, high-lift (HL) systems are usually stored away in order to keep their additional drag to a minimum.

The use of high-lift systems makes it possible to fly with a smaller wing with less drag. Without them, modern airliners would either have impractically high airspeeds at take-off and landing in order to be efficient in cruise, or their wings would be too large for efficient cruise flight. As such, they are a necessary evil, because they introduce extra weight and complexity to the aircraft design.

High-lift systems have been in use for many years and in many different configurations. New structural solutions are now being researched in order to further increase flight performance.

In the previous chapter the design of the overall aircraft wing was treated, while the present chapter will elaborate more on this necessary addition to the wing. While the focus here lies on traditional wing designs, the high-lift systems discussed can be considered for application to any potential future wing shape.

Fig. 24. High-lift systems in action on a Boeing 757-23A.

(photo: Krzysztof Ciapala)

TRADITIONAL HIGH-LIFT SYSTEMS

Traditionally, high-lift systems are rigid discrete surfaces on the aircraft wing. During cruise flight they are collapsed, so they form a closed aerodynamic shape with the main wing. For landing and take-off the system's panels are rotated and moved with respect to the main wing to increase the lifting potential of the wing. A measure for the maximum attainable lift of a wing is the so-called maximum lift-coefficient, or $C_{L\text{-max}}$.

High-lift systems make use of a number of aerodynamic effects:

- *Increase of camber*: the shape of the airfoil becomes more curved. An increased camber will add a constant amount of lift to the airfoil for every angle of attack in its operational envelope. This means that the C_L-alpha curve, i.e. the relation between angle of attack and the amount of lift, is moved towards a higher lift-coefficient. This implies that the $C_{L\text{-max}}$ is also increased.
- *Increase of chord*: the airfoil becomes longer. This increases the wing-area and its maximum lifting capacity.

TRAILING EDGE

The effects of increased camber and chord are often combined in fowler flaps: a trailing edge flap element that is extended to the rear and rotated downward.

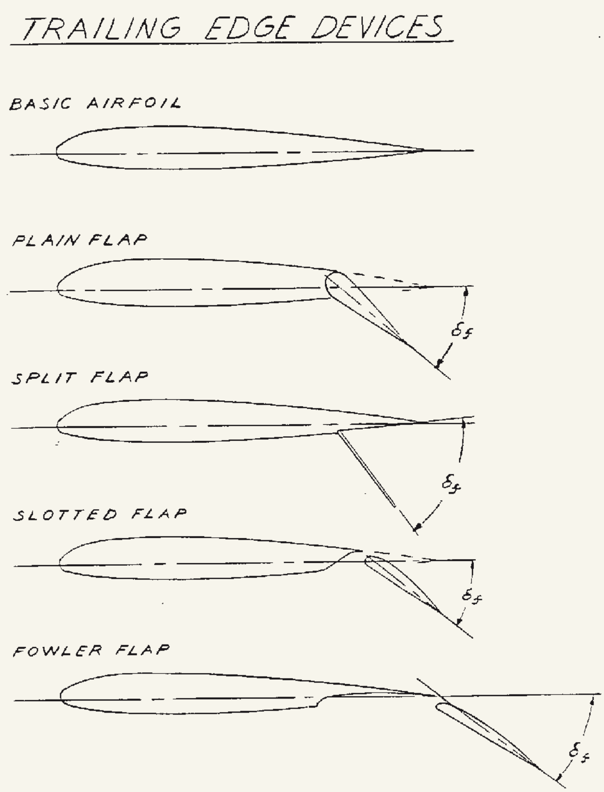


Fig. 25. Most common trailing edge devices.

(Dick Kita, 1985)

LEADING EDGE

At the leading edge moving HL panels are often added to increase the effective camber of the airfoil. These panels are also rotated downward, to move the front stagnation point to a beneficial location.

In high lift conditions the angle of attack is generally high, which causes this front stagnation point to move to the bottom wing surface, a few percent past the leading edge. This stagnation point is the divisor between the flow that passes via the top and bottom of the airfoil, so a part of the flow will reverse into a direction almost opposed to the free stream, curve around the leading edge (which is usually the part with highest curvature on any airfoil) and then follow its way via the top surface.

This flowing past the leading edge is a very tricky undertaking for the boundary layer, given the high curvature. It can result in suction peaks and a high tendency to separate from the wing surface, causing a premature (and violent) loss of lift. To avoid this effect under high angles of attack, it is best to move the leading edge to a position close to or slightly downstream of the stagnation point on the bottom airfoil surface. In this fashion, the upper surface flow will not have to pass the high curvature region, avoiding the risk of separation.

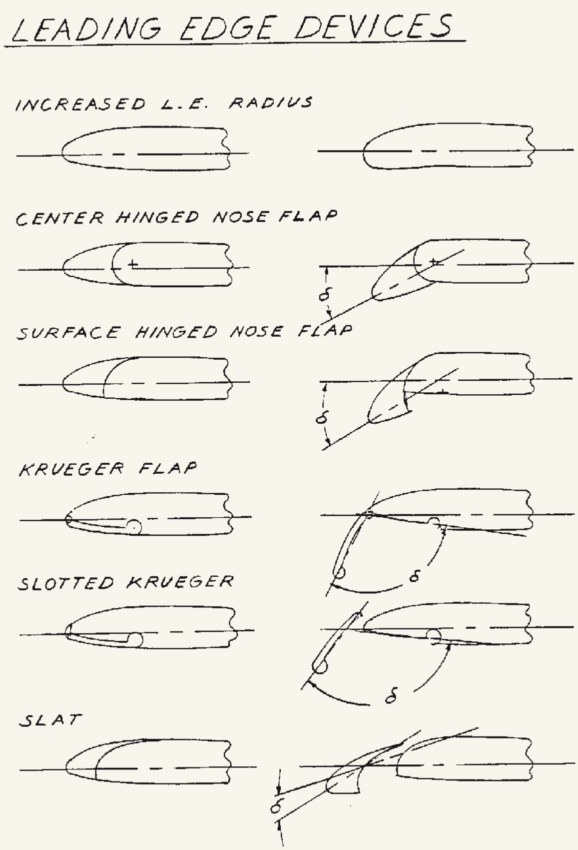


Fig. 26. Most common leading edge devices.

(Dick Kita, 1985)

SLOTS

A combination of several small airfoil elements has a higher maximum lift capacity than a single airfoil of the same chord length. So aerodynamic effects can be improved further by applying slots in the high-lift wing configuration.
These slots are typically formed by placing a high-lift system element at some distance from the main wing element, often in combination with a rotation. For the leading edge this effect is achieved by using slats, while for the trailing edge one or several slots can be used.

STRUCTURAL IMPLICATIONS OF HIGH-LIFT SYSTEMS

The use of high-lift systems influences the wing design. The originally closed cross-section of the wing is now split up into several disjointed wing-elements that together form the desired aerodynamic configuration. The required structural weight is higher than for an identical single element wing for two main reasons.

First, the high-lift system elements are only designed to carry the aerodynamic loads directly imparted on them; they do not contribute to the primary distribution of the total weight of the fuselage (including its payload) to the air washing over the wing. The aerodynamic load from the high-lift elements is initially transferred chordwise towards the main element torsion box. This then transfers the collective load of the spanwise station to its neighbors in a span wise direction, resulting in the transfer of weight to the flow. The spanwise load-carrying member - the main-element torsion box - has to have smaller chord-

Fig. 27. Airbus A320 wing with moveables extended.

wise dimensions (even when the wing is collapsed into cruise configuration) than an identical rigid, single-element airfoil.

Second, the need arises to transfer the load chordwise and all aerodynamic load must be transferred to the main-element. For aerodynamic reasons, this load transfer is implemented as a set of discrete load-carrying members, the flap and slat guide-tracks. By transferring the chordwise load in this fashion, the least amount of obstruction to the flow through the forward slot is achieved. Their dimensions are kept low, so their weight must be increased to cope with the reduced bending-resistance (or more precise: moments of inertia) of this implementation.

HIGH-LIFT SYSTEMS AND NOISE

Another issue in high-lift system design is noise. Aircraft engines have become increasingly quiet. Nowadays high-lift devices and landing gear often produce more noise in the final approach for landing than the engines, which are usually on a low thrust setting at that time.
The design alteration that has the most impact on approach noise is the omission of slots. A good example is the A380. This aircraft has simple slotless droop-nose devices for its inner LE high-lift devices, combined with only single-slotted fowler flaps. In spite of its size, this aircraft is remarkably quiet on and around an airport.
This consideration provides an incentive to avoid slotted devices whenever possible. In that case, the performance of a slotless alternative should not be worse than that required of a slotted device. Here, $C_{L\text{-max}}$ can be used for comparison of aerodynamic performance of alternative design solutions.

SIMPLER IS BETTER

Simpler design results in lower production and maintenance effort and cost and also in lower weight. Apart from the number of elements and slots, the complexity of a high-lift design is determined by its guide mechanism. This ensures the correct positioning of the high-lift surfaces, and safely transfers all imparted loads for each deflection-setting. Naturally, a guide mechanism will be more complex – and heavier – when multiple elements have to be choreographed.

In the past the aim was to keep increasing the $C_{L\text{-max}}$ that a high-lift system could generate, resulting in triple slotted flaps appearing on airliners around the 1970s. Nowadays there is a tendency to apply the simplest system layout possible that still generates sufficient $C_{L\text{-max}}$ for the desired field performance of the aircraft. Since the 1970s a steady simplification of high-lift systems can be seen. Often even later designs within a family of aircraft already have simpler systems than their predecessors.
Airbus is planning to take high-lift system simplicity another step further, with a dropped-hinge single slotted flap for its upcoming A350 XWB aircraft. A dropped-hinge extension mechanism consists of a single, fixed hinge-line that is offset to a point below and outside of the airfoil of the wing, omitting any translational movement, thus greatly simplifying the required mechanism.

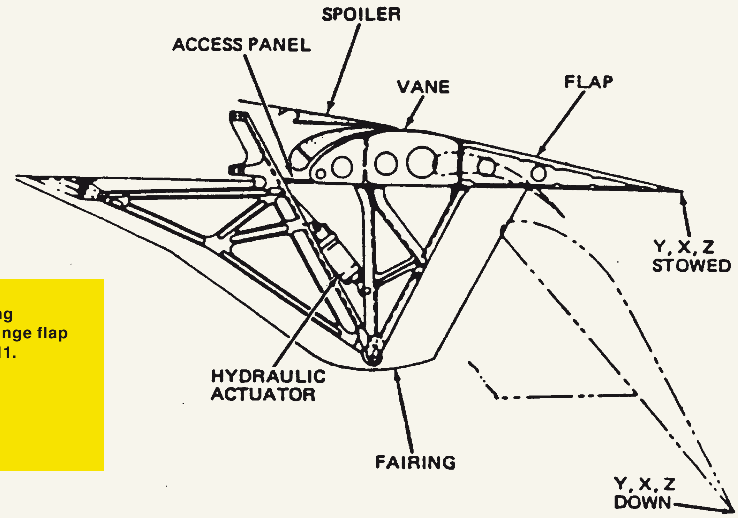
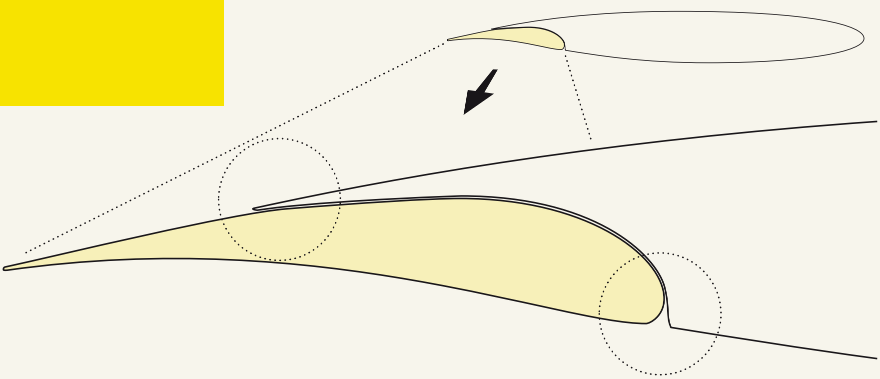


Fig. 28. Schematic working principles of a dropped-hinge flap on a Douglas DC-10 / MD-11.

NATURAL LAMINAR FLOW AND ITS DESIGN IMPLICATIONS

The use of current high-lift surfaces results in small gaps and seams in the combined aerodynamic wing surface that is washed by boundary layer flow. Usually, the boundary layer flow over a wing is of a turbulent nature, so the gaps and seams are not too critical to the total aircraft drag. They were therefore never treated as an unwanted feature. Current developments should result in a reconsideration of this practice: the application of natural laminar flow (NLF).

Fig. 29. Gaps and seams caused by a collapsed moveable panel.



NLF has been used successfully in single-seat glider designs for at least 30 years. But these have cruise speeds around 75 knots. It is an immense design challenge to achieve something even remotely similar for a passenger aircraft cruising at around 450 knots and accommodating some 300 passengers. No wonder, as the glider's cruise speed is only half of the airliner's landing approach speed.

LAMINAR FLOW AND AERODYNAMIC SURFACE

Any source of discontinuity or disturbance to the boundary layer could evolve into early transition of the laminar flow. It is therefore essential that the surface is smooth. But surface smoothness is broken by a high-lift system's gaps and seams, rivet-heads, division lines between skin panels, edges of HL and control surfaces, closed aerodynamic slots, and by doors, inspection panels, or even through fouling by insects. Composite structures show a promising potential to accommodate the strict requirements on surface quality.

Careful design of the wing surface details can remove quite a lot of these transition sources. The application of glued joints or composite structures can solve the problems caused by rivet heads. In this sense, the trend of increased application of composite structures in airliners is desirable, as this form of construction allows for highly integrated structures, with a low amount of parts and their mutual connectors. This greatly facilitates the desired surface smoothness. A similar trend has been observed for the already mentioned gliders, when from the 1970s onward, an increased application of composite structures was accompanied by a dramatic increase in aerodynamic performance.

Hinge lines that are formed by rotatable panels (spoilers, ailerons, etc.) can be covered in an elastomeric film that gives them an aerodynamically smooth surface when stored away. An adequate seal for division-lines between panels proves more challenging. For instance, the seams that are left by retracted high-lift panels are difficult to seal.

Also, hatches need to be provided that allow for periodic inspection of the wing's internal structure. Omission of passenger doors or inspection hatches is simply not an option, so the best approach is to move these as far downstream as possible, preferably downstream of the boundary layer transition point. That way, their negative impact on the NLF can be kept to a minimum.

Slots should preferably be left out altogether, in order to avoid discontinuities on the surface of the wing. However, this would come at a considerable price to landing performance, because of their large boosting effect on $C_{\text{L-max}}$. The best compromise is a modern slotless droop-nose device at the leading edge in combination with a single slotted fowler flap at the trailing edge. With a single slot an acceptable high-lift performance can still be achieved. The negative influence on the NLF is then kept to a minimum by the clean nose surface and the fact that the flap's slot is located relatively far aft towards the rear of the airfoil.

In this light, research is performed into structural concepts that accommodate this high-lift system layout while improving some design parameter, such as performance, cost, complexity, etc. However, the ideal high-lift system should accommodate NLF in cruise flight without compromise or trade-off.

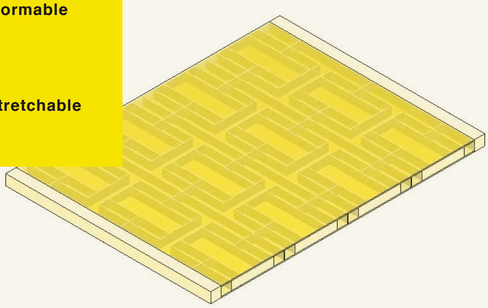
NOVEL APPROACHES IN HIGH-LIFT DEVICES

With the help of new materials we can now design high-lift leading edge devices that are smooth during cruise flight and that can deflect in a smooth, seamless fashion ('morph') during take-off and landing.

For the development of these devices, a distinction can be made between those that change a linear dimension of the wing and those that only deform through rotation.

Such a novel device that alters the linear dimension of the airfoil must be thought of as an aerodynamic element that varies its chord length smoothly, stretching the skin as it deforms. The lengthening of the chord will increase the $C_{L\text{-}max}$. This puts linear strains in the order of 100-300% on the skin. Research is on-going to find skin concepts that accommodate these high strain values. Elastomers or rubberlike substances are good candidates. Elastomers can stand the necessary levels of stretching and at the same time maintain a smooth, aerodynamically sealed skin surface.

However, an elastomer tends to behave like a membrane: it will bulge in or out the farther it is removed from a support point connecting it to the rigid wing structure. This effect is also dominated by the value and sign of the pressure difference. Whether the bulging is directed inwards or outwards depends on whether the pressure outside is higher than inside, or vice versa. Also, the greater the pressure difference, the more the elastomer will bulge. In order to circumvent this problem, skin bracing constructions can provide a 'backing' frame to the elastomeric material. Such constructions should have a relatively low extensional stiffness, but quite a high bending stiffness. Different backing structures can be used, but essentially this concept consists of a backing frame cast in an elastomeric material that provides pressure sealing.



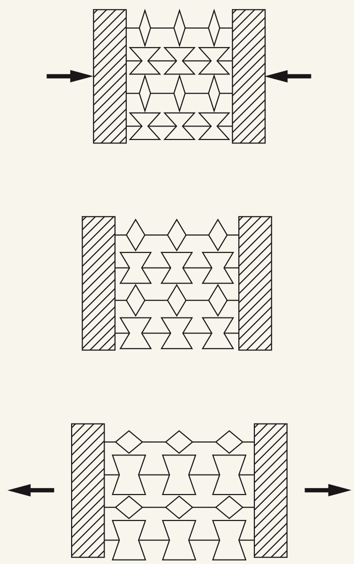


Fig. 30. (left) Smart Deformable Skin (SDS) concept.

Fig. 31. (right) Airbus stretchable skin concept.

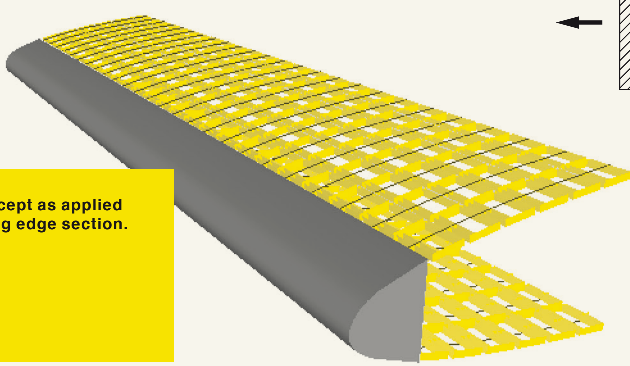


Fig. 32. SDS concept as applied to a wing's leading edge section.

On the other end of the spectrum of smoothly morphing high-lift devices is the type of device that changes its shape through pure rotation of its skin. In this implementation the skin of the device does not change its arc length considerably. Rather, by rotating the skin at various locations distributed along the arc length, a smooth-skinned device is obtained throughout the range of different deflection settings. For this high-lift concept the demands on the skin material are less stringent than for the variable chord implementation, therefore a lot more candidate skin materials are available.

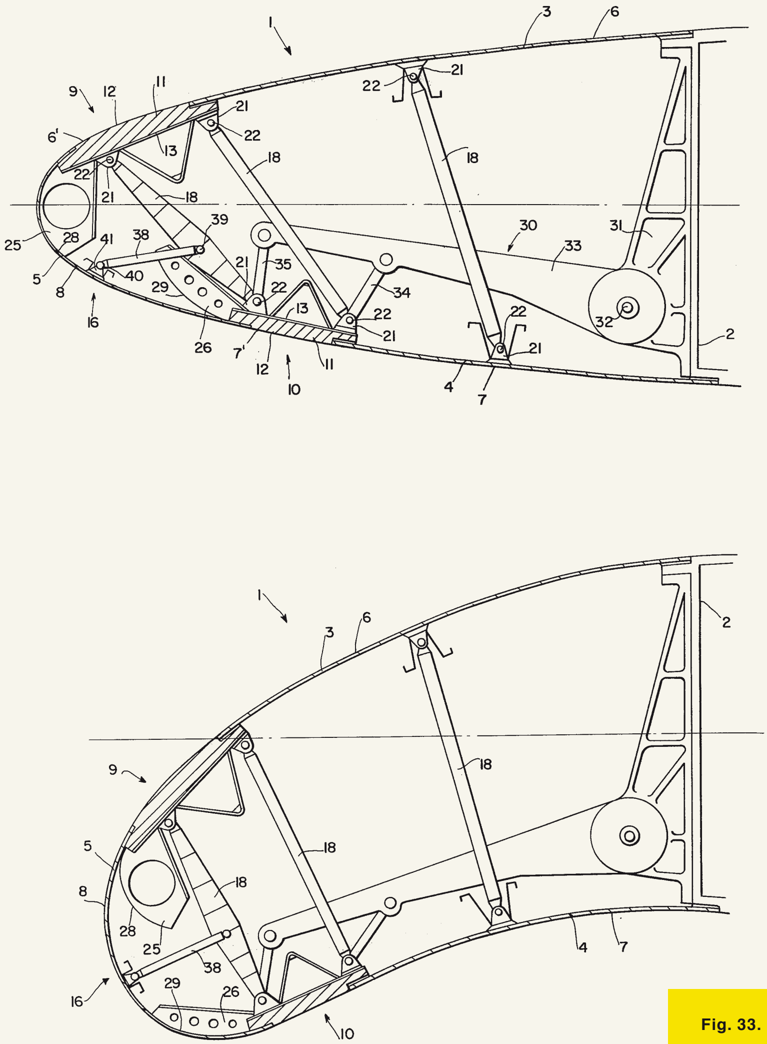
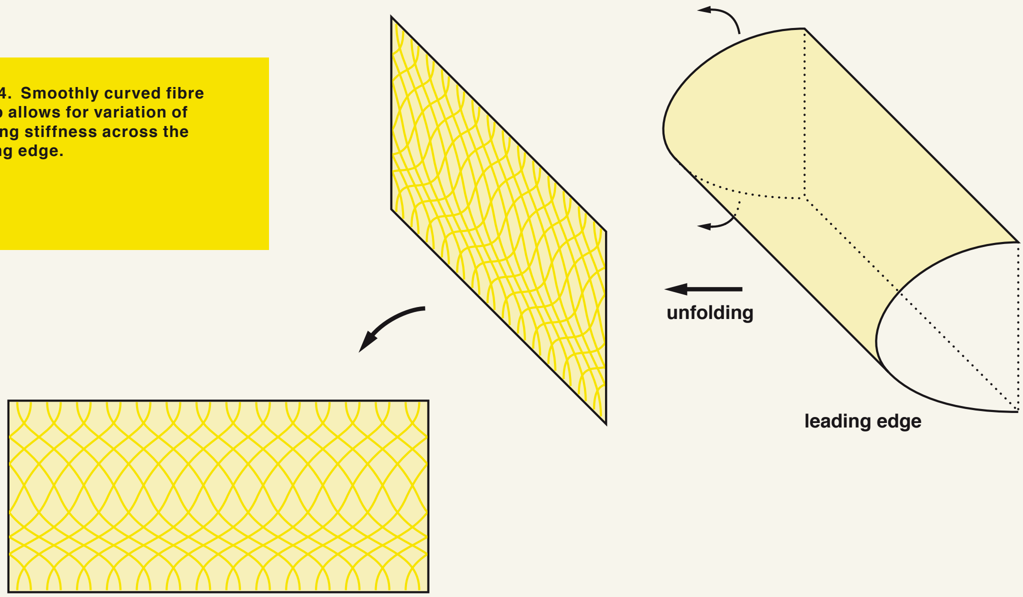


Fig. 33. Dornier smooth deforming LE concept (1981).

Fig. 34. Smoothly curved fibre lay-up allows for variation of bending stiffness across the leading edge.



Designing a high-lift leading edge device that is smooth in the cruise configuration and deflects in a seamless fashion ('morphs'), poses a number of new design challenges. In traditional LE devices the skin only has to hold a single, rigid cross-sectional shape. In morphing devices the skin has to assume at least two shapes and should be able to transition from one shape to the other. This calls for reduced stiffness of the skin, because the stiffness directly influences the forces and power required to deflect the skin. On the other hand, stiffness can not be reduced too much, as the skin will then start to act as a membrane, bulging in or out as a result of aerodynamic pressure differences. This bulging will have a negative effect on aerodynamic performance as it will cause early transition, precluding NLF. Therefore, too much stiffness of the material will result in heavy actuation systems, while too little will result in a heavy and complicated internal support structure.

Another issue is the actual wing size. It turns out that there is a lower limit to the skin thickness for such a device, dictated by strength and impact requirements. When scaling the morphing device to fit an increasingly lower wing chord, keeping the skin thickness at its minimum allowable value, there will be a point where the required strains will exceed the material limits for a given amount of shape variation. This means that for a given combination of cruise and high-lift nose shape, there will be a limit to the wing-chord to which it can still be applied. To reduce this chord further, a reduction in the amount of shape variation is needed. This can be achieved by reducing the downward deflection of the nose, but this can potentially reduce the $C_{L\text{-max}}$ of the wing.

WATCH THE BIRDIE

The primary design objective of a high-lift system is to allow a wing to change between a cruise, take-off and high-lift configuration. Additionally, there are several requirements imposed on the design of morphing high-lift systems. One of these is the bird strike requirement. The leading edge of the wing equipped with a morphing device should be able to withstand the impact of a given reference bird in flight. In absorbing the impact of this bird, not only pure material strength properties are a dominant factor, but also stiffness and toughness, as well as the geometry of the design. These factors all influence the way in which the impact energy will be dissipated through the rest of the structure.

SMOOTH FUTURE

Morphing high-lift systems will be seen on an increasing scale on future civil aircraft. While there are still a number of technological hurdles that need to be overcome, already a number of promising concepts have been investigated and are being developed. As experience with these devices increases, the most successful solutions will be identified and become standard implementations on the airliners of the next decades. CleanEra research into morphing high-lift systems should be another step into the direction of the ultra-smooth wings of the future.

Zapp the air!

Plasma actuators for flow control

by Marios Kotsonis

Airplanes are strange creatures. Their life is full of controversies. They need to be light yet strong, fast yet economic, safe yet immensely complex. All the features that a good aircraft must have, are dictated by the problems it tries to solve. And most of the times the solution to one of these problems is another problem in itself. Aerodynamic drag is such case. It is the force that the surrounding air is applying on the airplane during flight. It is always opposed to the airplane's movement and it is exactly this force that the engines must overcome with their thrust. As expected, drag is almost entirely dependent, either directly or indirectly, on the shape of the airplane. But the shape is also defined by weight limitations, passenger capacity and many more factors.
Tricky business..

Engineers have long searched for ways to reduce the aerodynamic drag without compromising other properties such as structural complexity or weight. Several solutions have been searched. Less have been applied. But a great improvement has been achieved over a hundred years of flight. The radical change in the shape of aircraft is clearly shown from a mere comparison between the Wright Flyer and the latest Airbus and reveals the vast improvement in drag reduction.

The shape change of aircraft brought drag down a long way. Streamlining enabled modern aircraft to have an almost optimum shape for the conditions they are required to operate in. But this is not enough. Drag still exists and it is now more challenging than ever to find space for improvement. Radical changes are needed. For drag, two major pathways lie ahead: (1) the complete change of the aircraft shape, a kind of "reboot" of the design philosophy and (2) flow control. New aircraft shapes are discussed in the "Shape up" chapter. Here, we discuss CleanEra's efforts and visions on flow control for drag reduction.

Modern airplanes are extremely efficient as aerodynamic shapes. This is the result of the extensive research that has gone into drag reduction in the last 50 years. Yet room for improvement exists. Aerodynamic drag can be separated into different components accordingly to the source mechanisms that are causing it. The four major components are pressure drag, friction drag, induced drag and shock wave drag. A great deal of work on pressure drag and shock wave drag has reduced these two components drastically through shape changes. The familiar streamlined swept-wing configuration is the outcome of this effort. Together, pressure and shock wave drag account to no more than 20% of the total drag in airplanes nowadays. The remaining 80% is caused equally by friction drag and induced drag. CleanEra's flow control efforts are aimed, but not limited, at reducing the skin friction drag.

AERODYNAMIC DRAG

Aerodynamic drag is defined as the sum of forces, parallel to the flight direction, that are applied on an aircraft by the surrounding air. It is always opposed to the movement of the airplane. Several classifications of drag exist based on varying criteria. Here, drag is separated into components based on the source mechanism. Four major components exist.

1. **Pressure drag - is caused by the deflection of the air around the shape of the aircraft and the creation of a wake behind it. This effectively creates regions of higher pressure in front of the aircraft than behind it, which, if integrated over the frontal area, give the pressure drag component. Streamlined cylindrical shapes with carefully designed trailing edge minimize pressure drag significantly. In modern airliners it accounts for almost 10% of total drag.**
2. **Wave drag - is caused by the development of shock waves on the aerodynamic surfaces of the aircraft. Airliners usually fly at high subsonic speeds, though flow can accelerate to supersonic velocities over the wing. Due to compressibility effects, shock waves are created which present large pressure differences before and after the formation region. The integral of the pressure difference gives the wave drag component. The use of swept wings mitigates the effect since the velocity component experienced by the wing section is geometrically reduced. Wave drag accounts for almost 10% of total drag.**
3. **Induced drag - is caused by the existence of strong vortices created by the wing especially at the tip. The so-called wingtip vortices induce a downwash on the wing, which diverts the main velocity component downwards. This effectively changes the angle of attack. Based on this new, induced angle of attack a part of the lift component is translated to the induced drag component. Since the tip vortices are a product of the lift, induced drag is also known as drag due-to-lift. Increased aspect ratio and wingtip devices such as winglets are found to reduce induced drag. Nevertheless it occupies almost 40% of the total drag component.**
4. **Skin friction drag - is alternatively called viscous drag. The friction of the air with the solid aerodynamic surface causes it. For all internal and external wall bounded flows a boundary layer develops at the wall. The relative velocity of the air at the wall is always zero while it increases gradually with distance from the wall to the freestream value. The shear stress that is developed at the wall causes the friction drag component. Major effort is given in sustaining laminar flow over turbulent since it presents almost 1 order of magnitude less friction drag. Nevertheless, friction drag still consists about 40% of the total drag.**

FLOW CONTROL

Flow control is a general term for a group of actions that aim to manipulate the flow of air around an object in order to improve its aerodynamic performance. In a very general framework, the wing can be considered as a flow control device in itself. It deflects flow downwards while creating a relatively small wake thus creating lift with minimum drag. Flow control can be separated into two major categories, namely, passive and active. Passive methods involve any action that does not require input of external energy for the flow manipulation, while the exact opposite applies for active methods.

Passive flow control was always in the minds of engineers. Even from the early days of aviation a variety of aerodynamic devices was used to improve the aircraft performance. One of the most typical examples is the use of vortex generators. These are usually small vanes or fins placed on the wing much like the fins of sharks or dolphins. They create localized small vortices, which stir and mix the air making it more energetic. With more energy, flow can follow the surface of the wing easier and in more extreme situations. One of these is in landing conditions where the angle of the aircraft is large and the danger for stalling is imminent. With vortex generators the flow can stay attached even for theses large angles of attack, decreasing the stall velocity to levels that are safe for landing. Other passive flow control techniques involve Gurney flaps for the increase of lift, dogtooth leading edge for separation control, canard fins for delta wing configurations and many more.

In contrast to passive means, active flow control changes the external flow via some mechanical or electric device with the use of external energy. A classic example of active flow control is the application of suction on the top-side of the wing in order to delay transition. By uniform suction through microscopic holes on the surface of the wing, the thin layer of slow air near the surface is changed and becomes more resilient to transition to turbulence. By delaying transition, the laminar flow is extended over the wing, which effectively decreases friction drag. Other active control techniques involve unsteady blowing and suction for turbulent drag reduction, synthetic jets for separation control, and various electromechanical devices that are able to control the flow. More recently, a new kind of actuators based on plasma discharges has found extensive use. CleanEra is particularly focused on these actuators as will be explained further down.

PLASMA ACTUATORS

Plasma actuators have recently gone under the magnifying lens of the research community. They combine qualities that make them ideal for flow control applications. They do not have any mechanical or moving parts. They do not protrude in the flow and do not disturb it. They consume very little power and they are extremely easy to manufacture. But, as with pretty much everything else, they come with some drawbacks. Their effect on the flow is usually small and local. In other words one cannot use them to propel an aircraft. Yet a large variety of exciting opportunities are presented to the imaginative engineer.

Plasma actuators work by ionizing the air. This is achieved by the application of the High-Voltage (HV) difference between two thin electrodes that are separated by a dielectric layer. The high-electric field that is created causes the plasma to be formed much like a small lightning or spark. This plasma cloud is basically normal air filled with free running electrons and ions. As the plasma cloud moves over the dielectric layer it crashes into the free air and pushes it around. One can imagine this as a small and local gravity force which acts on the air in a certain direction. We call this a Coulombian body force. Under the body force, the external air accelerates and the so called ionic wind is created. This body force can be used for a large number of flow control ideas.

Due to their simplicity, plasma actuators can be applied to virtually any part of the wing. They can be used for laminar turbulent transition as will be shown later. They can be employed near the trailing edge for separation control during landing and take-off. They can serve as simple vortex generators which can be activated on-demand while being completely unobtrusive when they are inactive. The possibilities seem endless. Yet, much work must be done in optimizing their performance for the task at hand. CleanEra has focused on the understanding and improvement of these actuators.

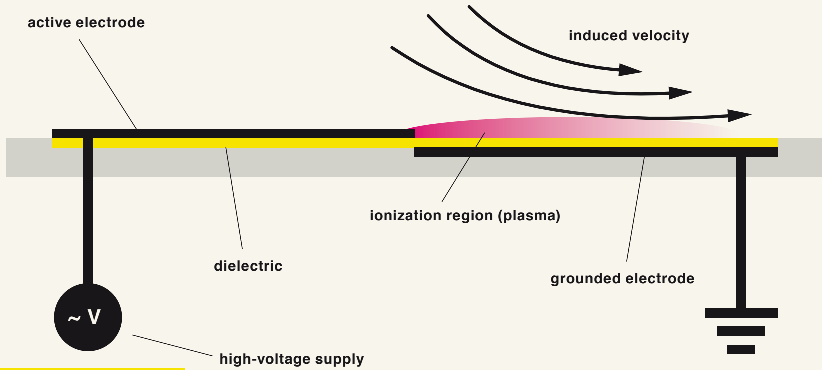


Fig. 35. The plasma actuator geometry and operation.

Another important issue is the modeling of these actuators. In other words it is necessary to find simple and universal ways of describing and representing their action. This can be used in Computational Fluid Dynamics (CFD) studies.

DIELECTRIC BARRIER DISCHARGE ACTUATORS

DBD actuators are a special kind of the Dielectric Barrier Discharge device, which is currently used in a variety of applications ranging from plasma TVs to air purifiers. What separates it from conventional DBD devices is the asymmetric configuration of the two electrodes. These are flat metallic strips which are placed on the aerodynamic surface. They are separated by either a thin polyimide layer or a thicker layer of polymer plastic (usually PMMA) that acts as a dielectric. Alternating (AC) High Voltage (HV) is applied to the exposed electrode while the covered electrode is kept at ground potential. Typical values for the HV are in the order of tens of kV while the alternation frequency is on the kHz range. Due to the large difference in potential, a strong electric field is created at the vicinity of the electrodes which, in turn, creates a local plasma region.

In the plasma a large number of charged particles consisting of positive and negative ions and free electrons exist. This is a highly volatile region where several coexisting processes take place. More specifically ionization processes create positive ions from neutrals, attachment processes create negative ions while recombination and dissociative attachment processes create neutrals. The entirety of the charge particles move under the influence of the Coulombian forces exerted on them by the electric field. Heavier particles such as ions collide with the neutral particles of the external flow and impart momentum on them. Due to the asymmetry between the two electrodes and the existence of the dielectric this momentum transfer is different between the positive and negative half cycle of the HV alternation. This difference is translated into a bias in momentum transfer which is always towards the direction of the covered electrode. Because the plasma-flow interaction region is a volume above the dielectric surface, the event can be modeled by the existence of a directional volume body force, which is exerted by the actuator on the flow.

DIAGNOSTICS

Plasma actuators are a young technology. As such, many issues regarding their fundamental working principles are still unclear. The first part of research conducted by CleanEra on plasma actuators involved an advanced diagnostic campaign. Using several techniques the actuators where measured for strength and power consumption. An experimental parametric study was made on the operation of plasma actuators. Several experiments were carried out. Multiple measurement techniques were combined with state-of-the art equipment in order to provide the best possible description of the actuators.

More specifically, three main groups of experiments were done. Firstly the velocity of the ionic wind was measured using Hot Wire Anemometry (HWA). Secondly the actuators where mounted on a load balance and their body force was measured. Finally, time resolved Particle Image Velocimetry (PIV)

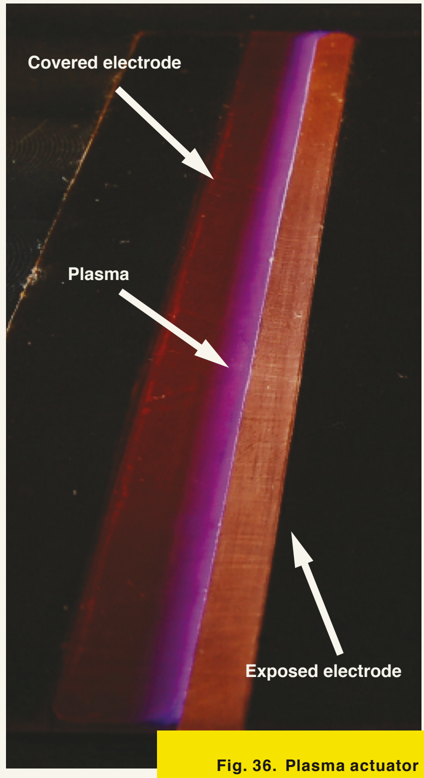


Fig. 36. Plasma actuator during operation.

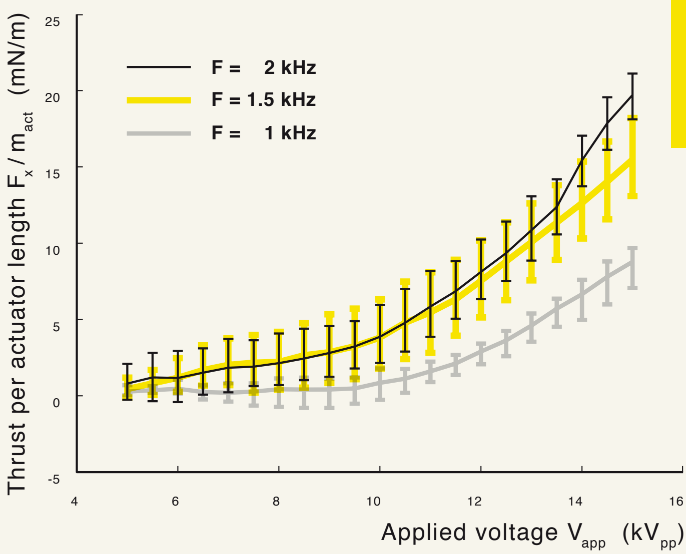
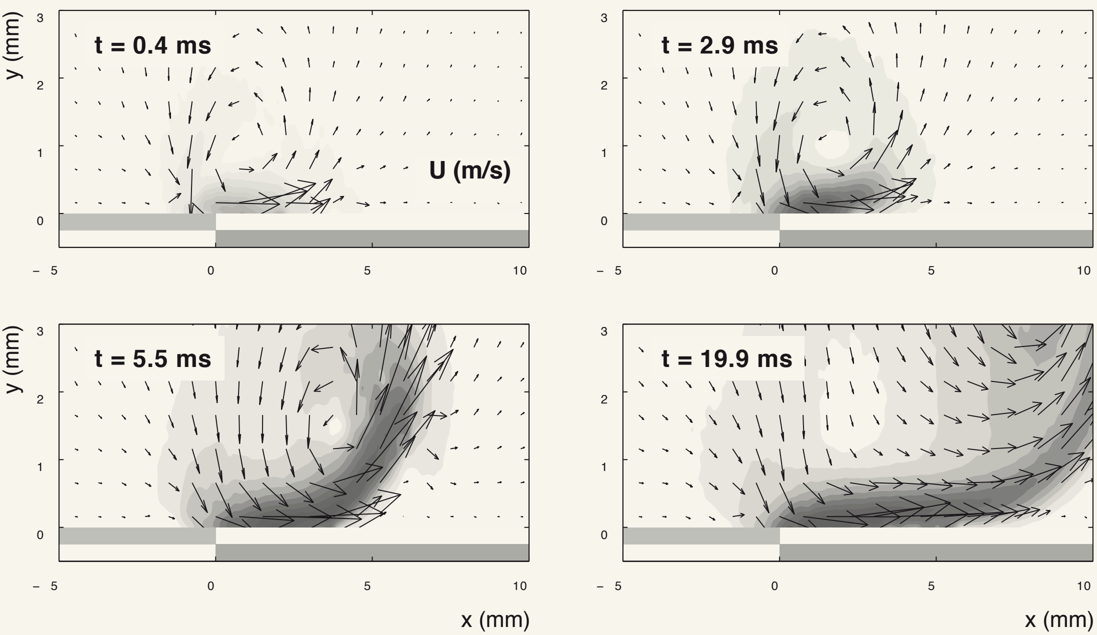


Fig. 37. The thrust of the actuator as function of applied voltage and frequency.

measurements where made to accurately visualize the field of ionic wind. During all these runs the voltage and current supplied to the actuators was also measured in order to calculate their power consumption. The study on time-averaged velocity revealed the dependence of the induced flow field on geometrical properties such as geometric



configuration of the electrodes and thickness of the dielectric layer. Several electrical operational conditions were also studied. A direct relation between maximum velocity and applied voltage and frequency was identified. For pulsed operation, which is extremely important in active flow control, the induced velocities were found to depend directly on the duty cycle of the modulating voltage signal. Finally, a selected group of cases in continuous and pulsed actuation was tested using time resolved PIV. The flowfield information further verified the findings of the other two test groups.

One of the most important findings of the parametric study campaign is the inherently unstable nature of the forcing due to the plasma actuator. In other words the body force is not constant during the HV cycle. This is generally due to the discharge asymmetry between the positive and negative half cycles of applied voltage. This is very important for flow control since the "strong" and "weak" forces can be used individually to manipulate instabilities. In order to further investigate this topic a second experimental campaign was performed based on advanced high speed PIV measurements. Furthermore, four different applied voltage waveform shapes were tested in order to understand how the unsteady force is related to the waveform shape of the High Voltage.

The results of this study were suggestive of ways to improve the performance of the plasma actuators. The key seems to be the forward stroke which is the part of the AC cycle where voltage is negative. It was found that a change in waveform shape could also change the discharge characteristics. This was applied, resulting in plasma actuators which are 30% stronger and consume 20% less power than conventional actuators.

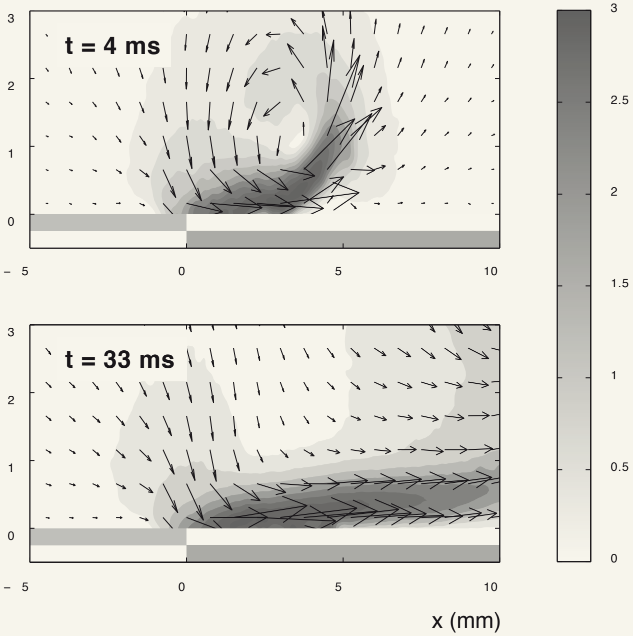


Fig. 38. The start-up sequence of flow acceleration under plasma actuation.

Fig. 39. Unsteady velocity due to pulsed plasma actuation.

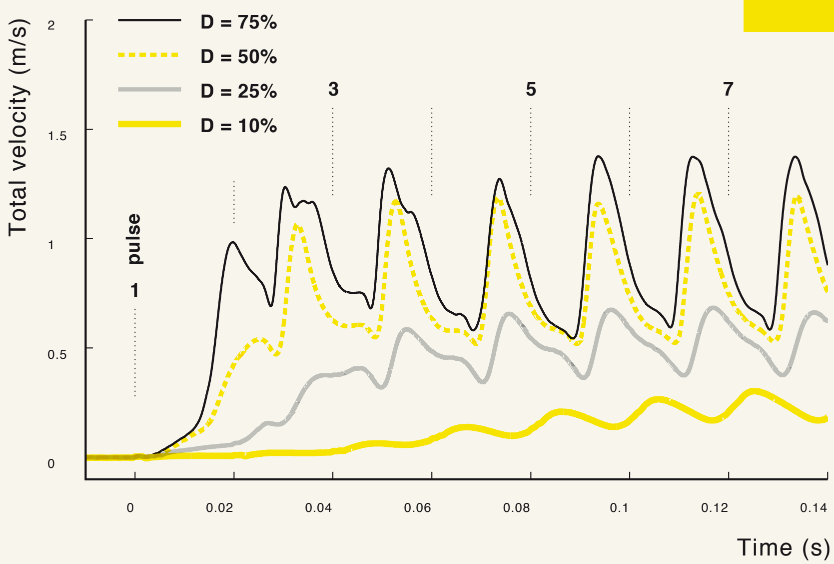
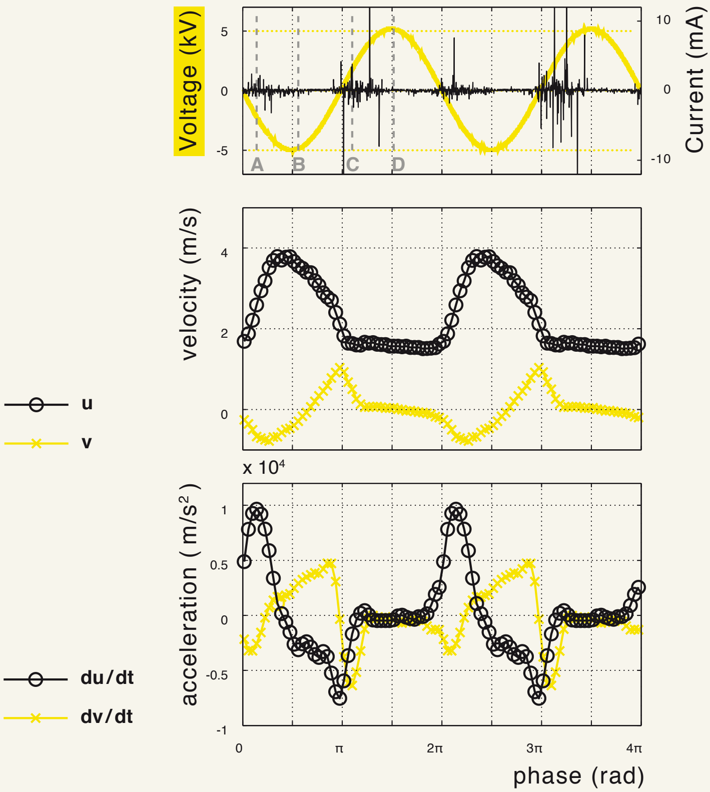


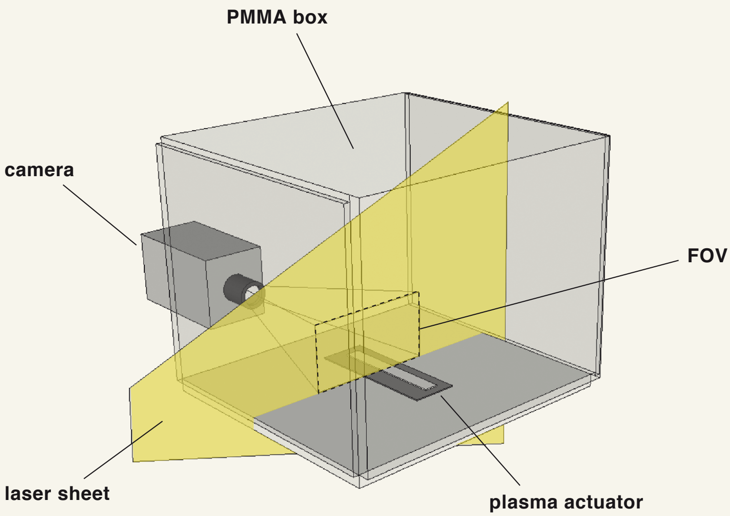
Fig. 40. The instantaneous forcing behaviour of plasma actuators.



ADVANCED FLOW DIAGNOSTICS

Hot Wire Anemometry (HWA) is one of the staple techniques used in experimental fluid mechanics. It is based on small heated sensors, which are placed in the flow to be measured. The sensor in its most traditional form is made of a thin tungsten or platinum wire supported between two metallic probes. Taking advantage of the Joule effect, the wire is heated by an electric current provided by a Wheatstone bridge circuit. Variations in external flow velocity produce an increase or decrease in the heat, which is transferred by the sensor to the fluid. This can be traced back to voltage variations, which, through proper calibration can be correlated with velocity.

Fig. 41. Typical PIV setup for plasma actuator characterization.



PIV is a nonintrusive technique that measures the velocity simultaneously at numerous points within a fluid volume or area using optical means. The fluid is injected (seeded) with non-transparent tracer particles that are assumed and considered to demonstrate two important properties:

- **the tracer particles do not influence or alter the motion of the fluid**
- **the tracer particles exactly follow the motion of the fluid**

The tracer particle position and displacement is established by illuminating and optically capturing the planar measurement domain twice in a short deterministic time interval. This successive illumination is provided by a pulsed laser sheet while the optical capture is performed using fast digital cameras. A statistical analysis is then conducted on the two captured image patterns in order to determine the most likely displacements of the particle ensemble and in extension the instantaneous velocity vector field.

MODELING

The second major involvement of CleanEra with plasma actuators involved the modeling of their operation. A plasma body force model is of great importance for a successful flow control application. Many ways exist in getting these models. One is to numerically model the entire plasma physics of the discharge. This is both complicated and time consuming. Another way is to make simple empirical relations based on experimental observations. This is relatively simple and fast but it lacks accuracy because it is not based on true physics.

CleanEra worked on a new model that combined both simplicity and accuracy. The research effort focused on the development of a novel experimental approach for determining the amplitude and spatial distribution of the body force. The method involved the use of time-resolved PIV data on the evolving flowfield during actuator operation. The force amplitude and spatial distribution were calculated through the estimation of the individual terms of the 2D incompressible Navier Stokes equations.

Here we include some equations:

$$\frac{\partial \mathbf{U}}{\partial t} + \mathbf{U} \cdot \nabla \mathbf{U} - \nu \, \nabla^{\mathbf{2}} \mathbf{U} = -\frac{\nabla p}{\rho} + \frac{\mathbf{F}}{\rho}$$

$$\frac{\partial^2 \mathbf{U}}{\partial t^2} + \frac{\partial (\mathbf{U} \cdot \nabla \mathbf{U})}{\partial t} - \nu \, \frac{\partial (\nabla^2 \mathbf{U})}{\partial t} = -\frac{\partial (\nabla p)}{\partial t} \cdot \frac{1}{\rho}$$

$$\int_0^t \left(\frac{\partial^2 \mathbf{U}}{\partial t^2} + \frac{\partial (\mathbf{U} \cdot \nabla \mathbf{U})}{\partial t} - \nu \, \frac{\partial (\nabla^2 \mathbf{U})}{\partial t}\right) dt = -\frac{\nabla p}{\rho} + A$$

The so called Navier Stokes (N-S) equations describe the movement of fluids under external forces such as pressure gradients or plasma body forces. If one knows the velocity then the force terms can be calculated using these equations.

We used PIV measurements to get the velocity. Then a dimensional analysis was performed on the temporal and spatial characteristics of the induced velocity. An initial period where pure acceleration was the dominant term was identified and the latter was expanded explicitly in body force terms. So the force was calculated only based on acceleration effectively making use of Newtons second law.

Fig. 42. Decomposition of the N-S equation's terms for the developing plasma actuator flowfield.

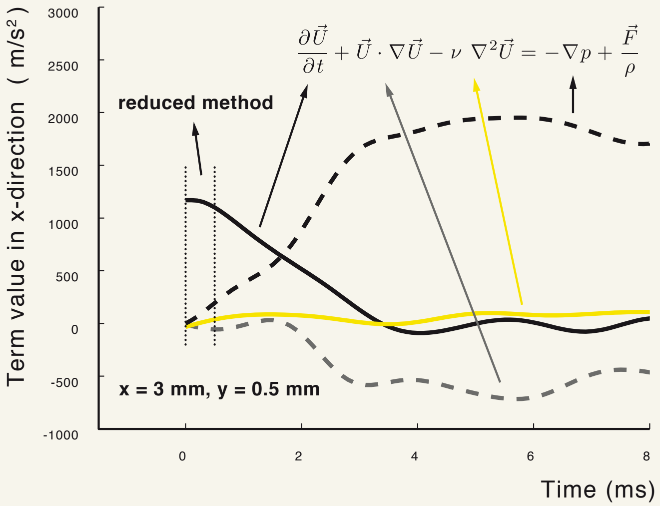
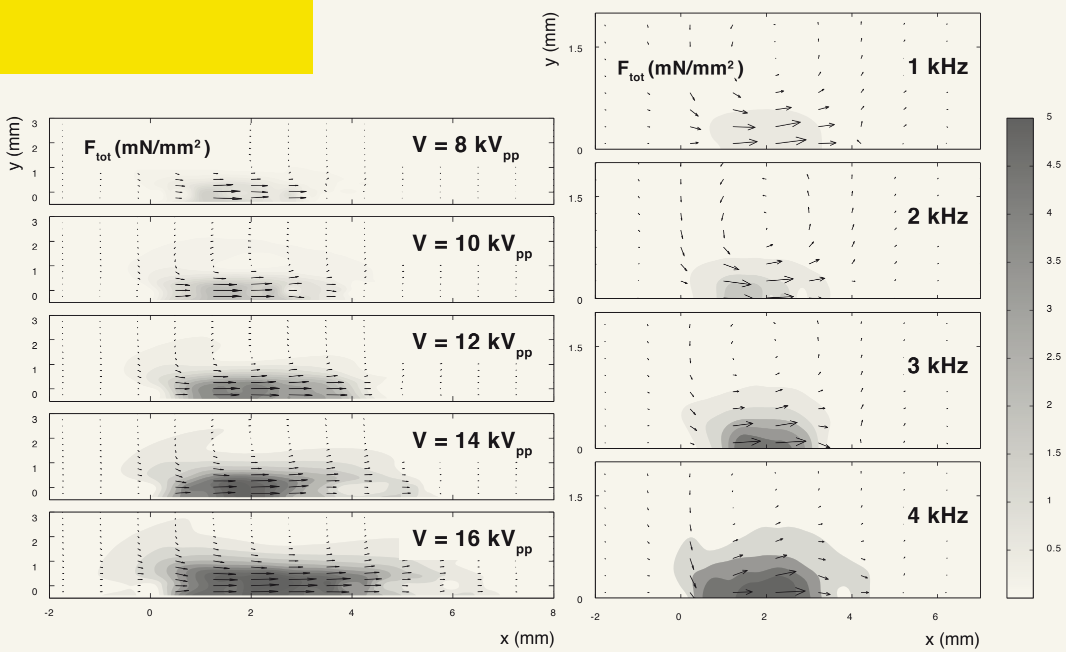


Fig. 43. The body force distributions as estimated by the developed techniques.



Moving even deeper we tried to use all the terms of the N-S equations. The problem here is that two unknowns exist. These are the pressure gradient and the body force that we are looking at. The decoupling between the force and pressure gradient terms was achieved based on several assumptions on the nature of the body force and the initial zero pressure gradient. The results from the tested methods were compared against well-established thrust measurement techniques and demonstrated good agreement. It was also the first time in reported literature that an accurate body force model based on experimental data was made.

Finally, the developed body force models where implemented and validated as DBD actuation models. The experimentally derived body force distributions where implemented in a CFD flow solver and the results where compared with the respective experimental cases. Good agreement between experimental and numerical results gave more confidence in the quality of the novel modeling techniques.

APPLICATION

Since plasma actuators have such favorable qualities for flow control, exciting possibilities open for possible utilizations. One of the core themes of CleanEra is aerodynamic drag reduction, and in this area the plasma actuators could be used extensively.

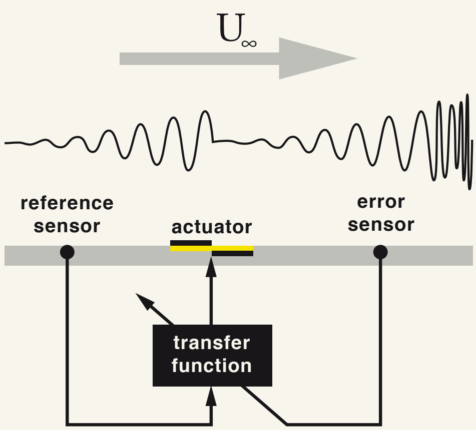


Fig. 44. Concept of a feedforward control loop for flow control.

One of the topics investigated by CleanEra in the area of drag reduction was the delay of laminar-turbulent transition. Laminar flow occurs over the initial parts of the aerodynamic surface such as the wing. Downstream (around one third of the distance from the wing leading edge) the flow becomes turbulent. The difference between the two flows is in the way the air moves. During laminar flow the movement of the air is smooth and predictable. On the other hand during turbulent flow the movement of the air is chaotic and unpredictable. What comes in between these two cases is the so-called laminar-turbulent transition. During transition instabilities form in the boundary layer much resembling waves on a beach.

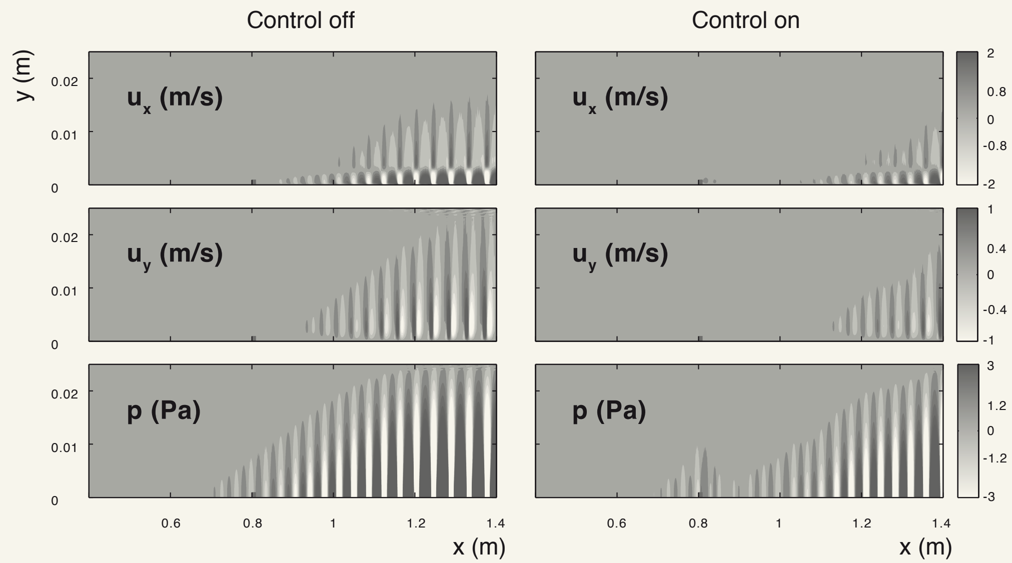
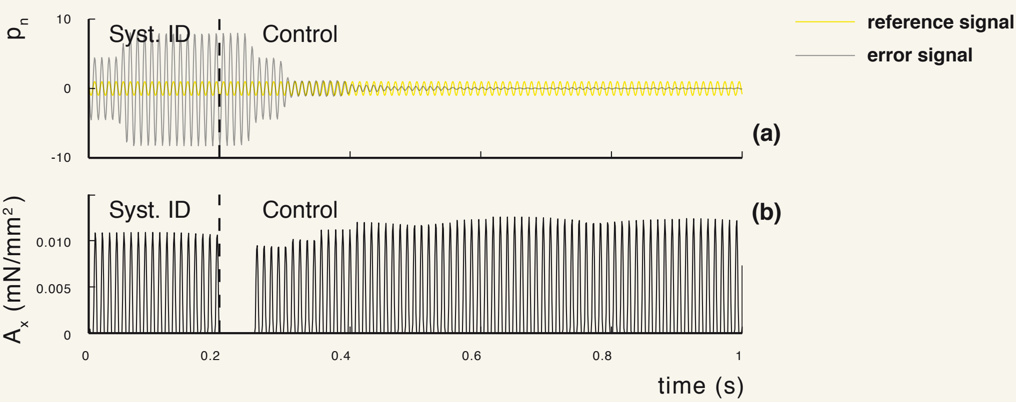


Fig. 45. (above) Numerical suppression of T-S waves using plasma actuation.

Fig. 46. (below) The performance of the T-S waves control system.

These are the Tollmien Schlichting (T-S) waves, which travel with the flow and grow. When they reach a specific growth, they break down into turbulence. The trick here is to find a way to reduce the amplitude of these waves in order to delay transition. The plasma actuator is ideal for this since its body force can be used to cancel these waves.



The concept was investigated numerically. The numerical framework involved the solution of the full unsteady 2D incompressible Navier-Stokes equations. Additionally an advanced adaptive control system was implemented in the solver. This way the actuator was able to actuate directly on the Tollmien Schlichting waves in the boundary layer. If the actuation is successful then T-S waves are cancelled and transition is delayed. Thereafter, two different sets of control test cases were simulated. Firstly, low Reynolds number (Re) cases at freestream velocity of 10 m/s. These involve two single-frequency cases and one multi-frequency case comprising a propagating wavetrain of T-S waves.

Considerable reduction in the T-S amplitude was registered in all cases. For the high Re number test cases an external velocity of 30 m/s was tested. Furthermore large amplitude T-S modes were used to demonstrate the capabilities of the actuator in adverse conditions. Two runs are tested with one single frequency and one multi frequency case. Again considerable reductions in amplitude were achieved. Several insights were gained into the process of T-S wave cancellation using plasma actuators.

T-S WAVE CANCELLATION

The flow over the initial parts of aerodynamic surfaces starts by forming a laminar boundary layer. Downstream, the boundary layer is subject to a receptivity process from external sources such as freestream turbulence, noise and surface roughness. Through receptivity, instabilities develop and amplify within the boundary layer and eventually brake down into turbulence. In order to postpone transition (and thus reduce turbulent friction drag) it is desirable to damp the growing instabilities prior to the turbulent breakdown. The major objective here is to use the DBD actuator in the laminar boundary layer as a "killer" of unstable modes. In these cases the primary unsteady modes are Tollmien-Schlichting (T-S) waves. A plasma control system must be able to autonomously operate with minimum user input. It is therefore necessary to employ an adaptive functionality in the active flow control framework in order to be able to work with random and arbitrary T-S waves. To this goal the naturally growing T-S waves are treated with the use of adaptive filtered-x LMS algorithm. The filtered-x LMS algorithm is a simple and robust tool initially developed for noise control. It involves the on-line measurement of reference and error signals (usually pressures at the wall) and the utilization of these to predict the optimal control signal sent to the actuator.

OUTLOOK

The field of flow control is rapidly expanding and the time when the first commercial applications will appear is near. Plasma actuators have all the necessary features to take a leading role in this near future. Within CleanEra several aspects of plasma actuators were investigated which have enhanced our knowledge and expertise. Yet, much needs to be done before we are able to develop a truly functional plasma flow control system. Two main directions should be followed. Firstly, the improvement of the existing actuators must be pursued through better understanding of the underlying physics, better manufacturing and innovative electrical engineering solutions. Secondly, aerodynamic flows must be analyzed and interpreted in order to find the exact control scenarios in which the plasma actuator truly excels.

Bubbles in the sky

Conformable pressurized structures

by François Geuskens

Today, fuel economy is aviation's innovation driver. A reduction in fuel consumption is primarily achieved by improving the aerodynamic, propulsive and structural efficiency. In other words, what the aircraft industry wants today is to transport more payload over longer distances at a transonic speed with less fuel. Sounds familiar? That is because this concept has been around since WWII. Think Hermann Göring, Hitler's demanding deputy, who would settle for no less than his 1000 x 1000 x 1000 - an aircraft capable of a range of 1000 kilometres, carrying 1000 kilograms of payload while travelling at 1000 kilometres per hour. In this respect, WWII created a boost for aviation. Designers were pushed into creating more speed, range and payload capacity.

The only way to achieve such outstanding fuel efficiency with the engine technology of that time was to create an aircraft that had tremendous aerodynamic efficiency and a very small operating empty weight. One fraternal team, the Horten brothers, came very close to realizing Göring's "3x1000" performance requirements and making it operational. Thinking big and birdlike, the Brothers achieved these goals by blending wings and fuselage into one integral vehicle. They designed and built the Horten H.IX (or HO 229), a flying wing design powered by two jet engines, that made its maiden

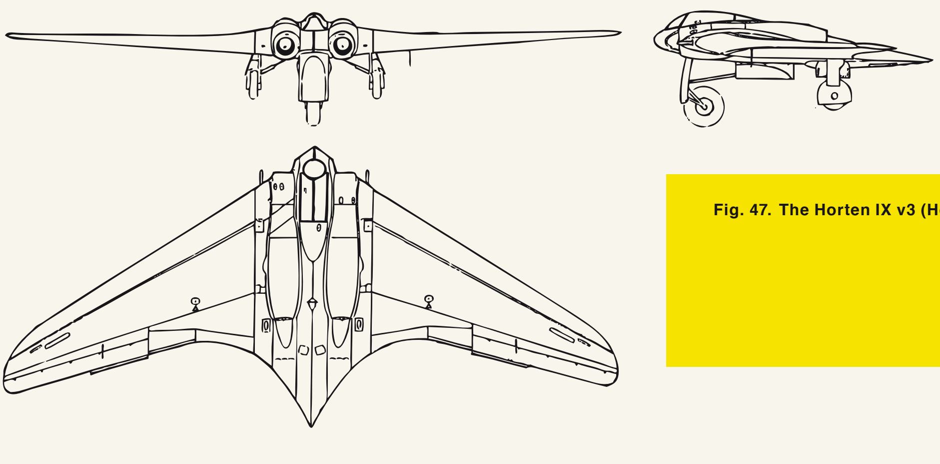


Fig. 47. The Horten IX v3 (Ho229).

flight in 1945. While the Horten Brothers were pioneers of the flying wing design, Burnelli was the pioneer in another interesting concept, the lifting body aircraft. A lifting body is a fixed-wing aircraft configuration in which the body itself produces lift. Between them, the Horton brothers and Burnelli thought up what we know now as the Blended Wing Body (BWB).

Fig. 48. The Burnelli UB-14 (1934).

A conventional aircraft is essentially a tube with highly efficient wings mounted on it. The problem is in the fuselage and tail: these do not contribute to keeping the aircraft airborne (the tail is used for stability and together with the fuselage does not produce lift) and only create parasitic drag.
The Blended Wing Body can almost totally eliminate parasitic drag. This will improve aerodynamic efficiency by up to 30%. The BWB design also distributes the payload in the loadbearing sections. This leads to lower bending and torque moments which is the overture to a lighter structure. So it is no surprise that the BWB idea was revisited in the 1990s by Robert Liebeck at the McDonnel Douglas Corporation (now Boeing). Though the concept was dropped for passenger airliners, it is successfully used for (unmanned) military aircraft.

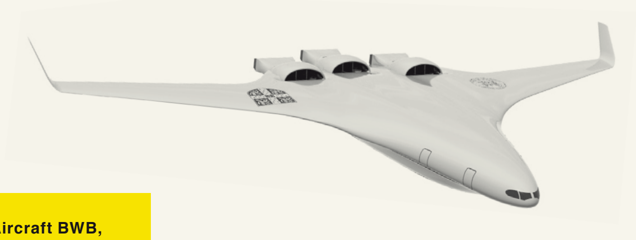


Fig. 49. The Silent Aircraft BWB, Design of the Cambridge University MIT institute.

The aerodynamic design and lighter structure render the BWB the green solution for the 21st century, as it delivers considerable savings on fuel and materials. To make the BWB suitable for passenger airliners the challenge is how to effectively pressurize it. A conventional tube-and-wing (TAW) aircraft has a very efficient shell structure. In contrast, the cabin cross section of the BWB is non-circular. CleanEra investigates how to design pressure cabins for Blended Wing Bodies that are comfortable for passengers.

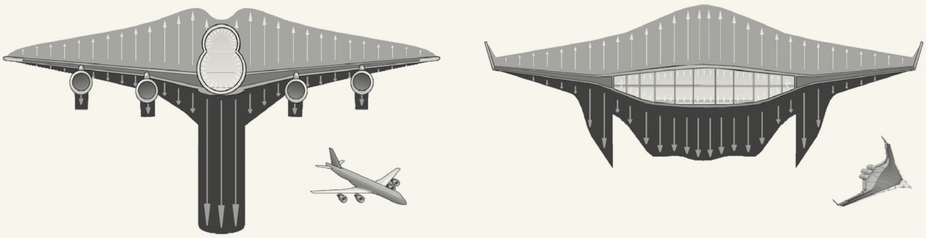


Fig. 50. Inertia and Lift Distribution for a Conventional versus a BWB aircraft. (image: Boeing)

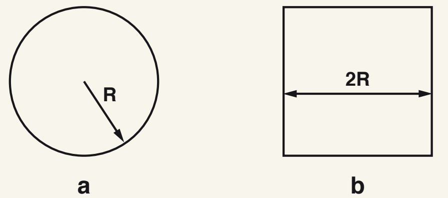
Fig. 51. (bottom) Bubbles.

SOAP BUBBLES

Who can resist making bubble-beards in the bathtub? More than just a bit of fun, understanding the mechanics of soap bubbles is the key to pressurising noncircular shapes effectively. Why is a soap bubble a sphere? This has to do with nature's tendency to configure itself in a state of minimum energy. Cohesive forces among the liquid molecules in the soap bubble create surface tension which make the layer of the bubble behave like an elastic sheet. In still air the soap bubble forms an almost perfect sphere. Only the weight of the surface layer distorts the geometry a bit.

But let’s first look at why the bubble’s cross-section is circular.

σ = order $[PR/t]$ $\qquad$ σ = order $[P(R/t)^2]$



A circular tube transfers the pressurization loads via in-plane loading, so only in-plane tensile stresses exist. These are equally distributed through the wall thickness.
A square tube carries the pressurization loads primarily via a bending moment. The inside of the wall experiences compressive stress and the outside experiences an equal and opposite tensile stress. The maximum stress varies quadratically with the width of the square tube.
The circular tube requires a much thinner wall to carry the pressurization loads. So structures subjected only to in-plane loading are structurally efficient. The energy required for the membrane to sustain pressurization is a lot lower. This is why the conventional tube and wing design is so efficient. Cross-sections that are not circular - such as an ellipse - combine in-plane stresses with bending stresses. These also require more energy to sustain pressurization loads.

All shells of revolution have circular cross-sections and are therefore only subjected to in-plane loading when pressurized. So why is a soap bubble spherical and not cylindrical? Let’s regard the soap bubble as a pressure vessel. The total potential energy is the energy stored in the complete spherical surface due to the pressure inside the sphere. The sphere has the lowest possible surface area for a given volume. The curvature is the same in all directions and so is the stress when pressurized.

The material properties for isotropic materials are also the same in all directions. If we think of soap as an isotropic material, it is intuitively not hard to understand that the soap bubble configures itself into a sphere. Foam is created when two or more bubbles merge. What you get is a multi-spherical pressure vessel with a common wall for structural integrity. The wall is also in a state of bi-axial stress, just as the spherical membrane. A cluster of soap bubbles is the perfect example of the spatial freedom the multi-sphere offers.

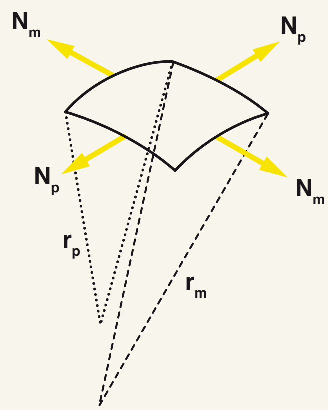
MEMBRANE FORCES

The membrane forces of a pressurized shell of revolution are defined as:

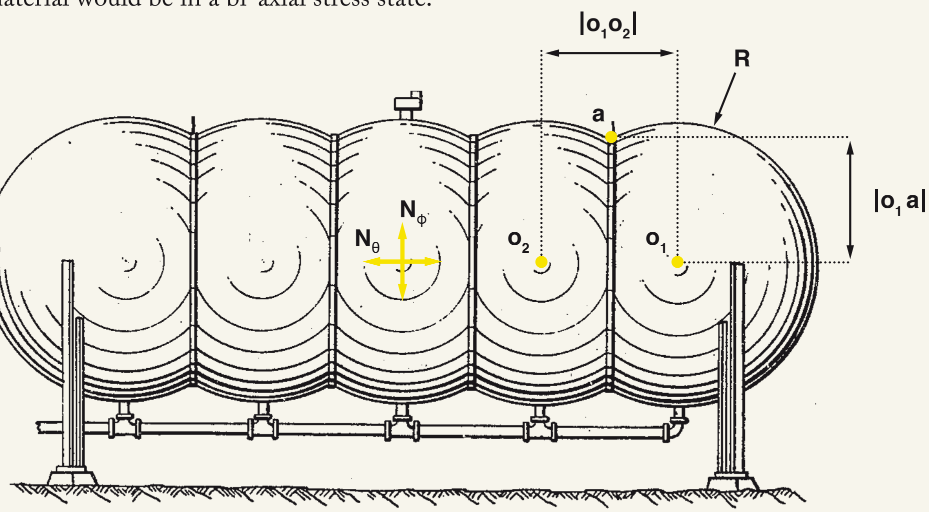
$$\frac{N_m}{r_m} + \frac{N_p}{r_p} = p$$

The meridional radius r_m and the radius of the parallel r_p define the doubly curved shell and N_m and N_p are respectively the tension in meridional and circumferential direction due to the pressure p.

The surface tension of a liquid membrane is a constant: small soap bubbles have a higher internal pressure than larger bubbles. This means that for coalescing soap bubbles, the common wall bulges into the larger bubble. For multi-spherical pressure vessels on the other hand, the pressure difference in between the cells is kept the same and the common wall is therefore straight.



In 1944 Jackson was inspired by soap bubbles and patented a multi-spherical tank structure. He replaced the classical cylinder by its multi-spherical alternative so the material would be in a bi-axial stress state.



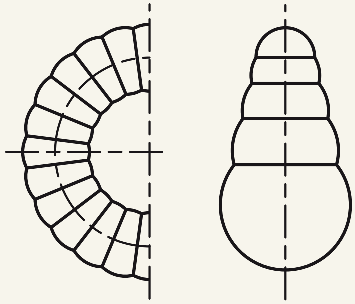
The tension ratio in a doubly curved shell is defined as:

$$\frac{N_p}{N_m} = 2 - \frac{R_p}{R_m}$$

This equation shows that isotropic materials are the ideal materials for a pressurized sphere, because the curvature is the same in both directions and so is the stress. It also follows that the stress ratio in a cylinder is 2, as the meridional radius is infinite.

Fig. 52. Multi-spherical tank patented by Jackson in 1944.

Fig. 53. Multi-cell reservoirs by Komarov who, after Jackson's multispherical tank, analyzed more complex multispherical structures.



When you replace the internal walls in a multi-spherical structure with external reinforcement rings, you create an open-cell multisphere. These rings are uni-axially loaded. Looking at the membrane stresses, any pressurized shell of revolution can be represented as a multi-sphere with an infinite number of spheres with rings at the intersection. The rings are divided along the surface and are responsible for a change in the stress distribution.

The membrane force in the circular discs of Jackson's tank reservoir is defined as:

$$F_s = \frac{p\left|o_1 o_2\right|}{2}$$

Where $\left|o_1 o_2\right|$ denotes the distance between the origins of the two spheres.

For the open cell configuration, the tensile load T in the ring is defined as:

$$T = F_s\left|o_1 a\right| = p \times \left[o_1 a o_2\right]$$

Where $\left[o_1 a o_2\right]$ denotes the area of the triangle governed by three points.

If we place an infinite number of spheres in an open cell configuration between o_1 and o_2 (meaning $o_2 = o_N$), we create a cylinder. In that case, $\left|o_1 a\right|$ will become R and the membrane force in the cylinder can be expressed as:

$$N_{\phi,c} = N_{\phi,s} + \frac{1}{\left|o_1 o_\infty\right|}\left(\lim_{n\to\infty}\sum_{i=1}^{n} T_i\right) = \frac{pR}{2} + \frac{pR \lim_{n\to\infty}\sum_{i=1}^{n}\left|o_i o_{i+1}\right|}{2\left|o_1 o_\infty\right|} = \frac{pR}{2} + \frac{pR}{2} = pR$$

These loads correspond with the membrane forces for cylinders. All other shells can in the same manner be reduced to an open cell multi-sphere because the interconnected spheres are not required to have the same diameter.

Before the 1970s, highly loaded aerospace structures were made of isotropic materials. The closed-cell multi-sphere was an interesting concept for large pressurized structures. This changed with the advent of composite materials. The bi-axial stress state was no longer a design driver. Composite cylinders could now be constructed from fibre reinforced materials of which all the fibres experienced the same stress levels. With composites all pressurized shells of revolution can have the same structural efficiency. This meant the multispherical reservoir was in danger of being overlooked. But for the pressurization of a BWB pressure cabin, we can now revive the concept.

Vasiliev has shown that the structural efficiency of a pressure vessel is optimal when the structure is in a state of uniform equal bi-axial strain. This simply means that the strain in meridional and circumferential direction is equal and the same over the entire shell. This condition applies for example to a pressurized sphere made of isotropic materials. The structural efficiency of the pressure vessel is defined as:

$$\frac{PV}{m} = \frac{\sqrt{\sigma_m^2 + \sigma_c^2}}{3\rho}$$

The structural efficiency is the ratio of the pressurised volume PV and the mass m of the pressure vessel. It depends on the density (ρ) of the material of the pressure vessel, and the allowable tensile stresses in the meridional and circumferential direction. This equation does not contain geometrical parameters. This means that the structural efficiency is the same for any pressurised shape when the material is in a state of uniform equal bi-axial extension. With composites, any shell of revolution (cylinders, torii, ellipsoids, etc.) can theoretically apply to this equation due to the tailorability of the fibres.

Pressure vessels need to have circular cross-sections. The tailorability of composites allow us to play with the curvature of their meridian. The Blended Wing Body however, needs a non-circular cross-section that is still able to carry the pressurization loads in the form of in-plane loading. After all, the operating empty weight of an aircraft needs to be as small as possible. The way to achieve this is to create a multi-bubble: an articulated pressurisable structure that is made up of sections with circular cross-sections. These can be cylindrical, spherical, toroidal or another type of membrane element. The simplest example of the multi-bubble is the air-mattress. Besides as pressure cabins for Blended Wing Body Aircraft, the multi-bubble can be used for inflatable space stations, submarines, conformable pressure vessels for liquid gasses (e.g. propane) or even cryogenic applications.

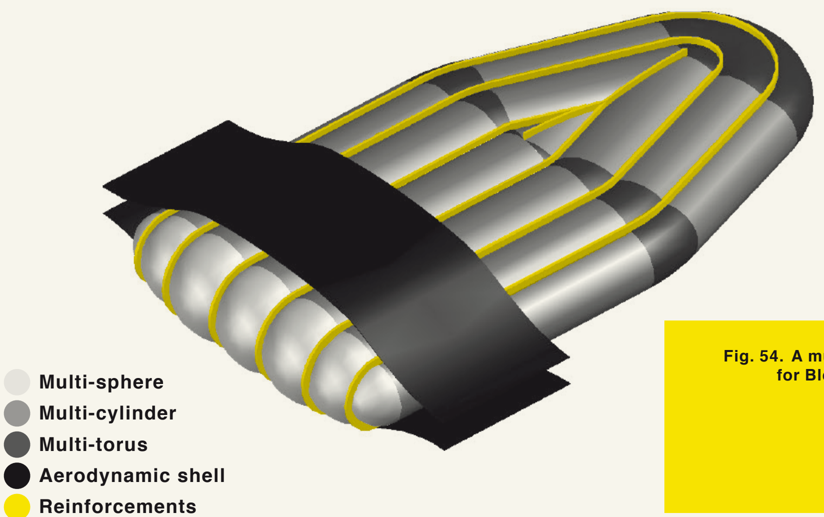
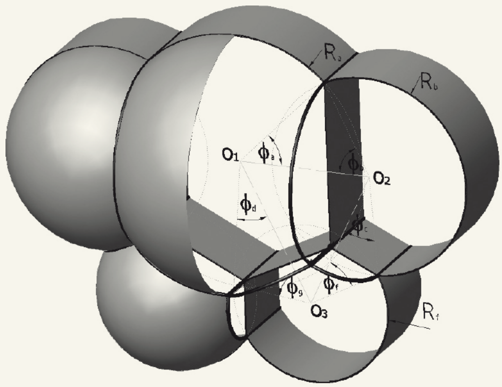


Fig. 54. A multi-bubble concept for Blended Wing Bodies.

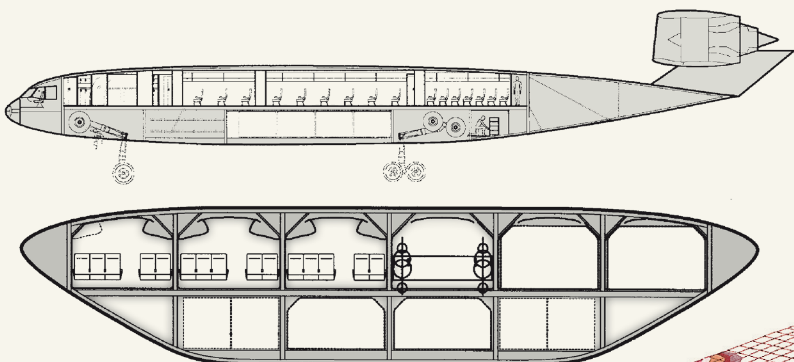
Just like the common walls in soap bubbles, reinforcement members are located at the intersections of the individual segments. The closed cell configuration has its reinforcement members inside the multi-bubble in the form of walls. This is an interesting option for pressure vessels. The open cell on the other hand has reinforcement members located outside the multi-bubble and is interesting for pressure cabins.

Fig. 55. Combination of an open-cell multisphere with a closed-cell multicylinder.



PRESSURE CABINS IN BLENDED WING BODIES

Structural issues to pressurize Blended Wing Bodies can be overcome. Yet a major consideration when exploring new concepts for aircraft is passenger acceptance. Passengers want to feel comfortable and be able to safely evacuate the aircraft. There are several concepts for BWB pressure cabins. - Which one is best?



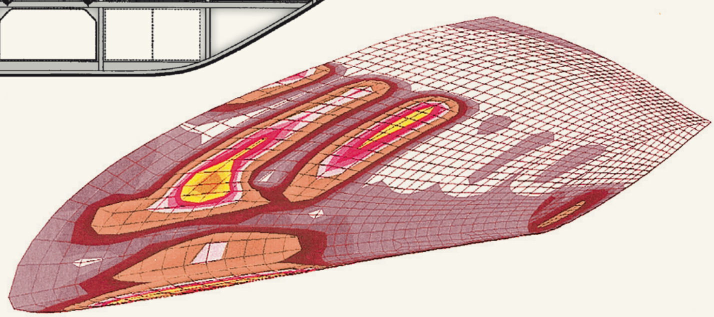


Fig. 56. (above) Liebeck's concept for the blended wing body cabin structure. (Boeing)

Fig. 57. (right) Exaggerated cabin skin deflection at 2x pressure in a blended wing body. (Boeing)

THE CONVENTIONAL OR INTEGRATED CONCEPT

Like in conventional aircraft, the aerodynamic fuselage and pressure cabin form one integrated module. By making use of the finite element method, Liebeck illustrated the deformation of the BWB while being pressurized. So theoretically it could work, but he had given only scant attention to passengers acceptance. Passengers had to sit between the interior walls, and had to look at video monitors showing the 'window view' for their orientation. This solution rendered the resulting spaces potentially claustrophobic and difficult to escape from. Eventually, the idea was dismissed.

BUBBLE TECHNOLOGY IN PRESSURE CABINS

In the segregated or double shell concept the multi-bubble carries the pressurization loads. It is separated from the rest of the structure that carries the aerodynamic and inertia loading. In order to create an unobstructed open space, the pressure-bearing walls are replaced by thin pillars and by beams that are located outside the cabin. However, these beams decrease the structural efficiency. A pressure cabin built up from open cell multi-spheres would avoid this. The choice between the multi-sphere and the multi-cylinder is a trade-off between structural efficiency and a more usable space with interior flexibility and manufacturability.

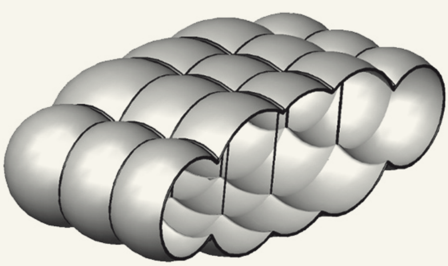
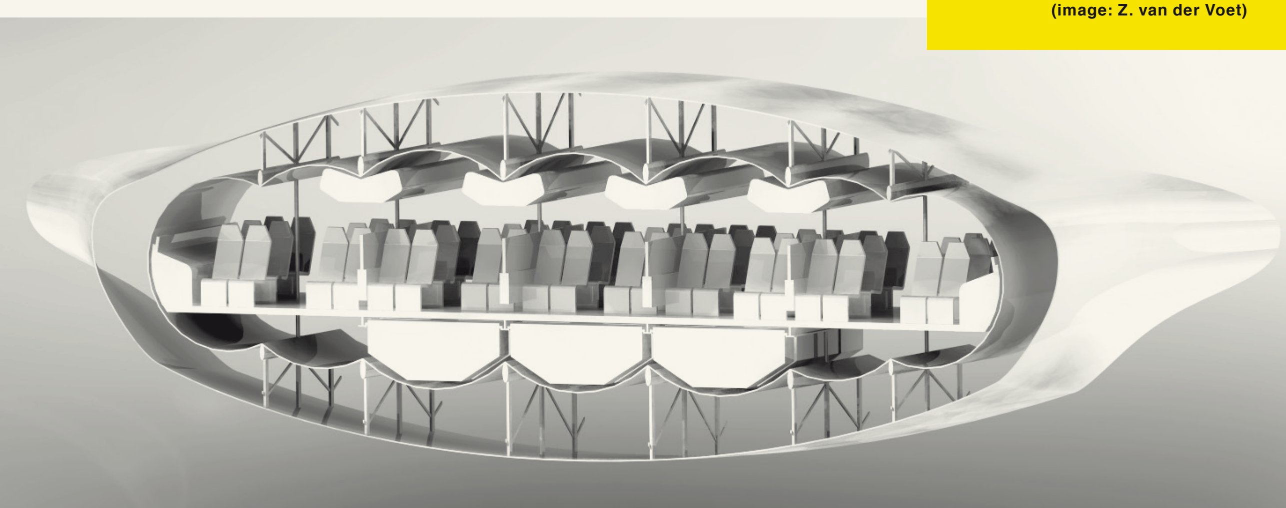


Fig. 58. Open-cell Multi-sphere.

Fig. 59. (below) Multi-cylinder pressure cabin. (image: Z. van der Voet)



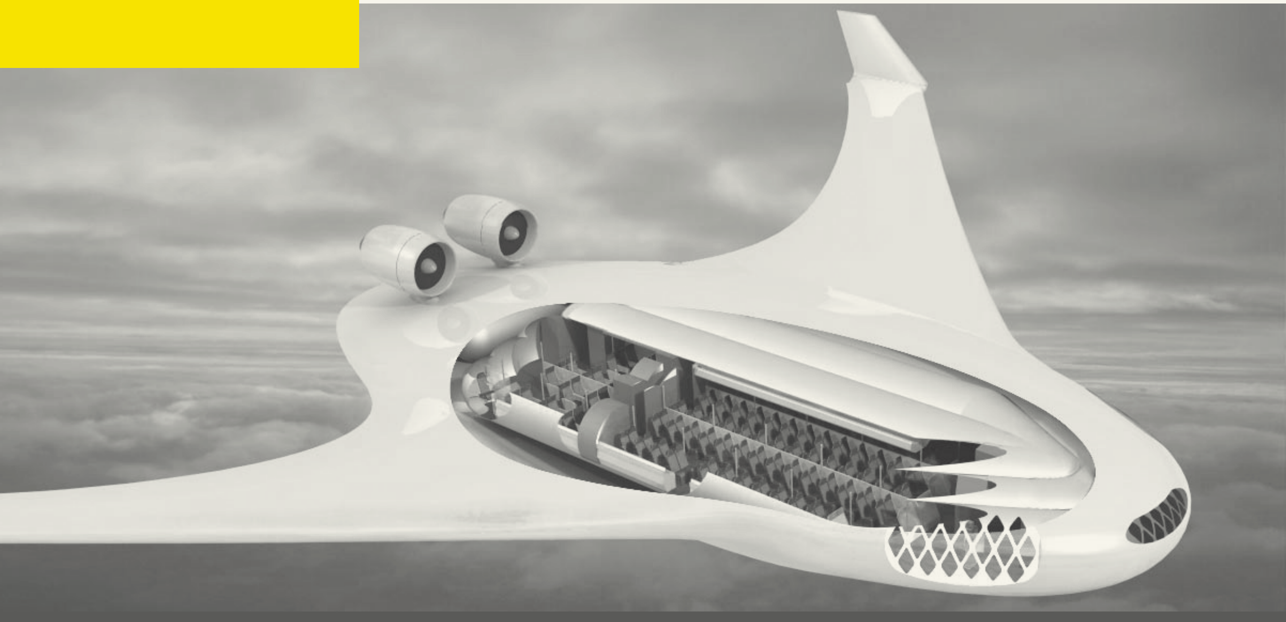
The integration of the multi-bubble with the aerodynamic shell is the biggest challenge for the segregated concept. The expansion of the multi-bubble requires joints that have the required strength and degrees of freedom or reinforcements that constrain the expansion. The concept of integrating the multi-bubble with the leading edge is structurally less efficient than the complete segregated multi-bubble, but it makes the integration less complicated and does not require a double amount of doors and windows in the leading edge of the centerbody.

SEA-LEVEL ALTITUDE

The pressure inside a multi-bubble needs to be kept at sea-level altitude. When a conventional aircraft makes a steep dive, the pressure outside the fuselage can be momentarily higher than that inside the pressure cabin. This leads to compressive stresses inside the wall of the fuselage. The thin membrane of the multi-bubble provides no buckling resistance, so under all circumstances the pressure inside the multi-bubble needs to be higher than outside.

Flying at 'sea-level' is a big advantage for passengers: babies will cry less and people with colds or sensitive ears won't suffer any discomfort. A higher pressure means that a larger mass of air needs to be transported at cruise altitude, so the structure must be stronger. This should lead to an additional weight penalty, but this is counteracted by the fact that the pressurized volume of the multi-bubble BWB is about 1/3 smaller than that of a conventional aircraft. The explanation is that the cargo space of a conventional aircraft exceeds the required luggage space when the aircraft is exclusively used for passenger transportation. The available floor area plays a large role in the capacity of passenger aircraft and the ratio of floor area to pressurized volume is higher for a multi-bubble than for conventional aircraft. The concept of an aerodynamic shell with pressurized cargo containers is promising for a BWB cargo carrier.

Fig. 60. Double shell concept by CleanEra, artist impression. (image: Z. van der Voet)



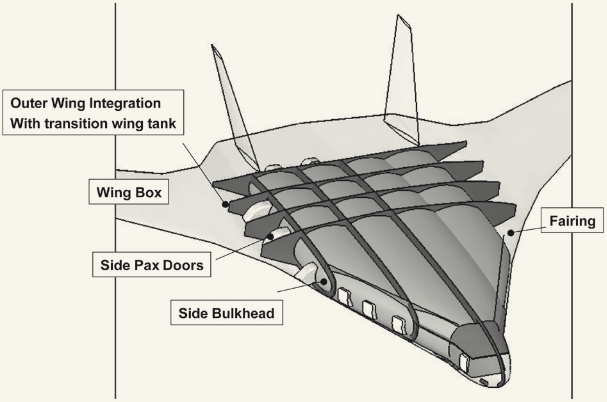


Fig. 61. Double shell concept by VELA.

The double shell concept is lighter than the integrated concept from Liebeck but not by an enormously significant amount. This is because the pressurization loads of the pressure cabin are not the only pressure loads the aircraft is subjected to. The dynamic pressure load causes the aircraft to become airborne but also creates pressure-induced bending moments in the aerodynamic shell of the Blended Wing Body. Under normal flight conditions these loads are very small, but in extreme situations they can become significant. Such extreme situations are exceptional and overall the segregated solution proves superior to the integrated concept. It allows the shell to maintain a better aerodynamic shape because there is less deflection of the panels under normal flight conditions. This in turn also reduces fatigue issues.

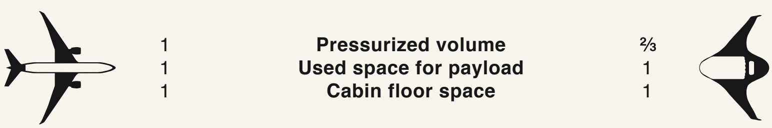


Fig. 62. Pressure-volume comparison between conventional aircraft and the BWB

THE OVAL CENTERBODY

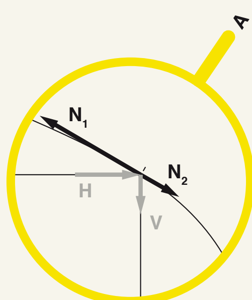
The integrated and the segregated concepts have in common that the pressure cabin fits in an outer surface that fulfils all requirements on handling characteristics and maximizes the aerodynamic efficiency. However, fuel efficiency also depends on operative empty weight and certain BWB configurations require a compromise between aerodynamic and structural efficiency.
When it comes to passenger acceptance other factors come into play. These don't fit in analytical formulae but they play a major role in the (commercial) success of any airplane.

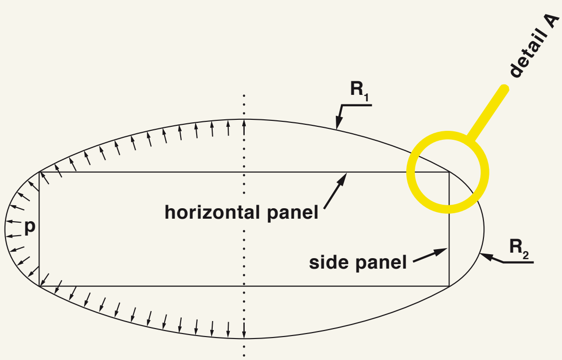
The pillars or walls for both BWB cabin concepts described put restrictions on cabin configuration. The positioning of chairs, galleys, toilets and other operational items is constrained by these structures that protrude into the cabin. They also spoil the spaciousness of the cabin, which is one of the attractive features of the BWB.

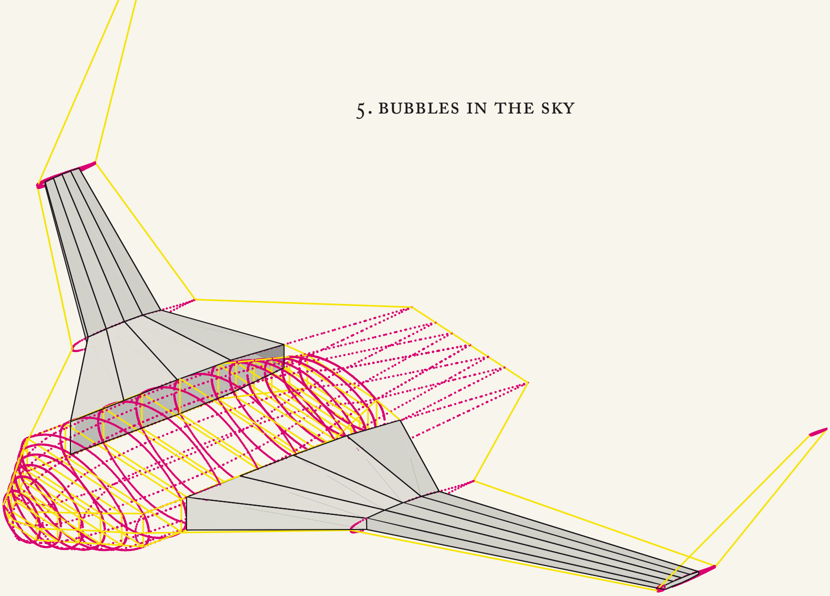
The oval BWB cross-section is a compromise between passenger acceptance and structural and aerodynamic efficiency. This shape is less complex than the double shell and has less structural components that protrude into the cabin. It is still able to carry the pressurization loads via in-plane loading, even taking the dynamic pressure into account. The cross-section consists of four connecting arcs, two at each side that are identical, one bottom arc and one top arc. Similar to soap bubbles, reinforcement members (i.e. panels) are needed at the intersections. When pressurized, the long horizontal panels are subject to a compressive load while the short panels on the side are subject to a tensile load.

Fig. 63. (right) Detail of force equilibrium at connecting nodes.

Fig. 64. (below) Cross-Section of the Oval Centerbody with identical top and bottom radius.





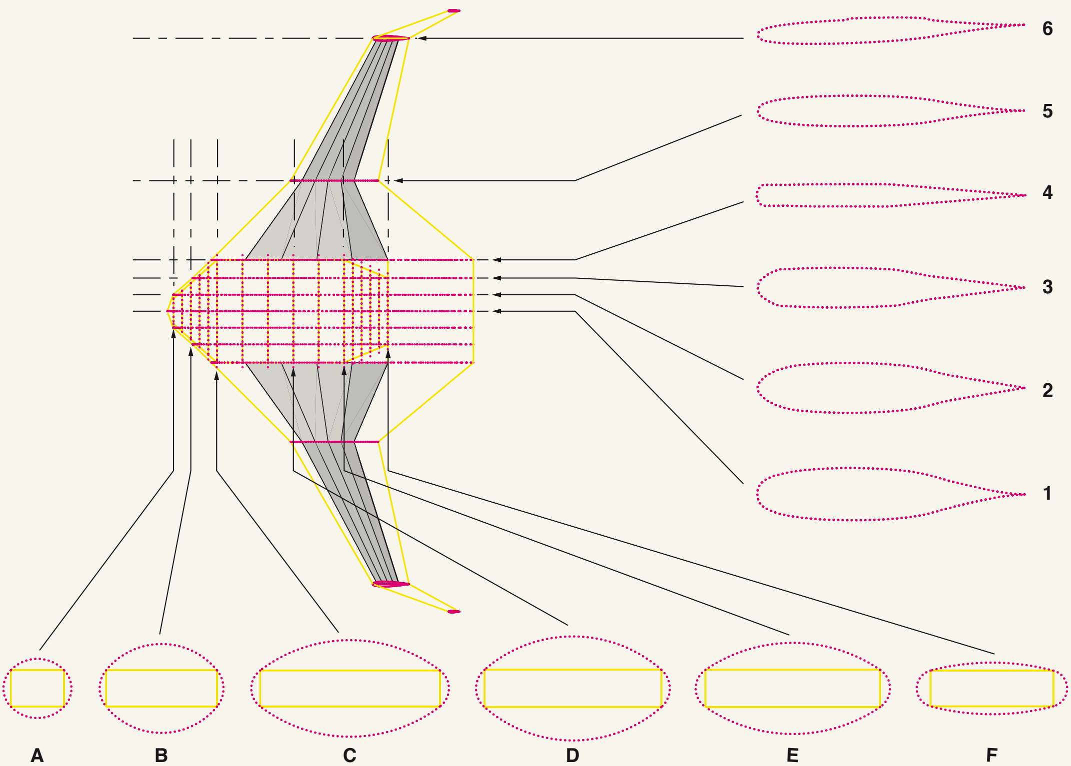


The BWB with Oval Centerbody in 3D-, top- and section-view:

A three-dimensional cabin structure that is built up from two-dimensional oval cross-sections. To investigate whether such a cross section is capable of forming a feasible three-dimensional cabin structure, the oval cross section was tailored to meet specified planform and wing section constraints.

Fig. 65. BWB with Oval Centerbody sections in isometric view.

Fig. 66. (below) The same BWB with Oval Centerbody with its cross sections.



MAKE IT ENJOYABLE

Cabin design is part of the geometrical and structural design of an airplane. Cabin configuration is first of all determined by the size of the BWB. Depending on the diameter of the individual cylindrical-sections of the cabin, the cargo can either be put under the floor or in the outer sections of the pressure cabin. The best place depends on the height of the cabin (for passengers) and thus the size of the aircraft. Three interesting configurations were worked out for the multi-bubble, but also apply to the other structural concepts.

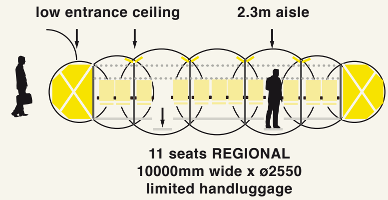
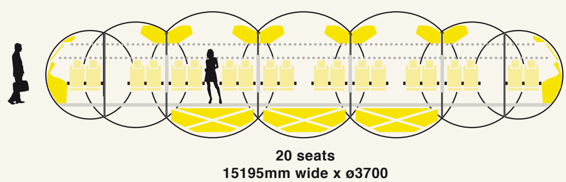
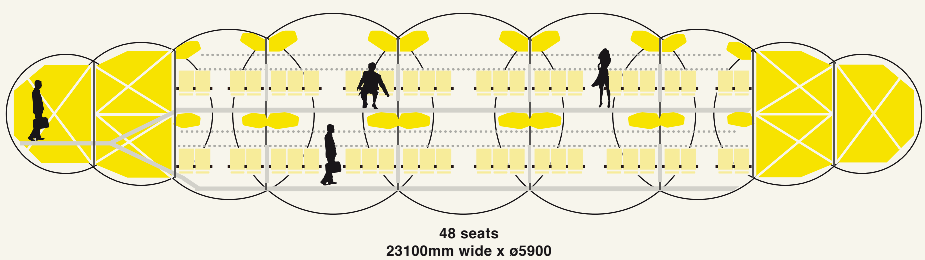


Fig. 67. Three size variants and cross-section lay-outs.

(image: Z. van der Voet)





A traditional cabin configuration cannot be blindly tagged on to a newly shaped aircraft. The topological change of the aircraft pressure cabin therefore requires a fresh approach to the entire passenger transport experience. In the CleanEra project we have applied an experience-driven approach. This means we envision the intended and expected use of the aircraft and tailor the (limitations of the) technological context to human behaviour and preferences.

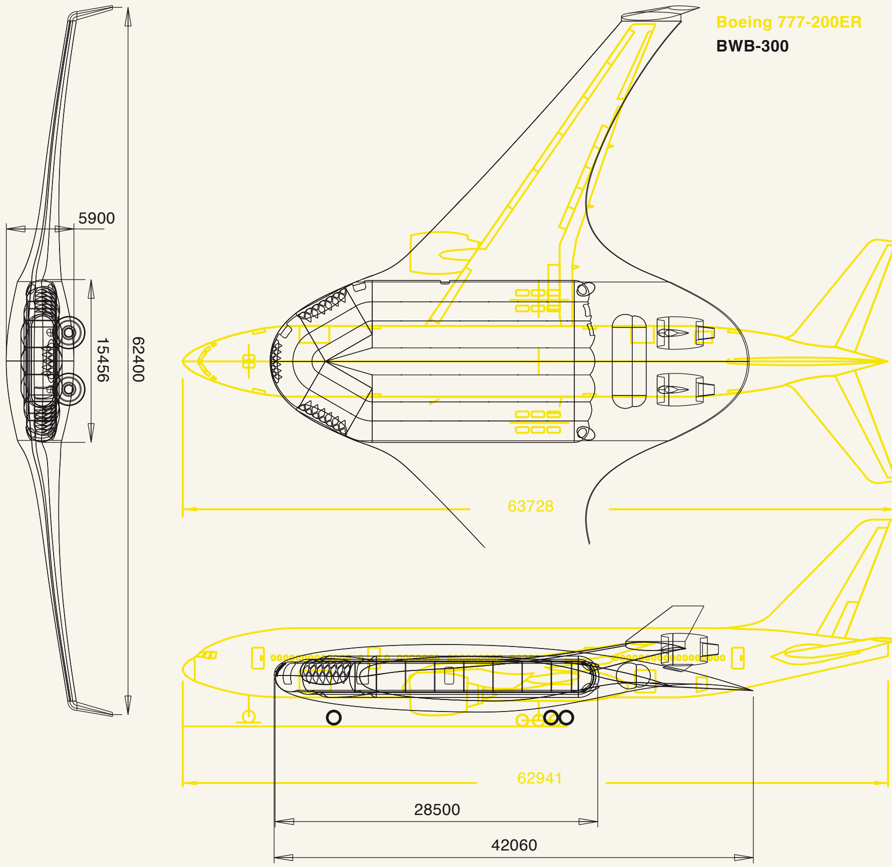


Fig. 68. BWB-300 dimensions in comparison with the Boeing 777-200.

Our research has shown that for most passengers flying in a BWB will be more enjoyable than in a Boeing 777. The passengers' experience changes drastically due to the new topology of the aircraft and the introduction of shared large windows. In fact, that is its biggest selling point. The BWB gives all passengers the same view outside rather than giving just a few lucky passengers a window-view during the entire flight.

Evacuation of BWB aircraft will be somewhat of a challenge. Every new BWB configuration needs to be re-assessed for this purpose. For conventional aircraft evacuation regulations can easily be implemented into guidelines. Also, the orientation possibilities are slightly worse in the Blended Wing Body, as it has considerably less window surface. Nevertheless, the BWB can be made into a comfortable and safe passenger transport in regards to orientation and evacuation. Stories circulating that a BWB is very uncomfortable for the passengers at the sides due to higher roll-rate accelerations are mere rumours. Even in extreme conditions passenger are subjected to less acceleration than when in the tail of a conventional aircraft or even when corner-

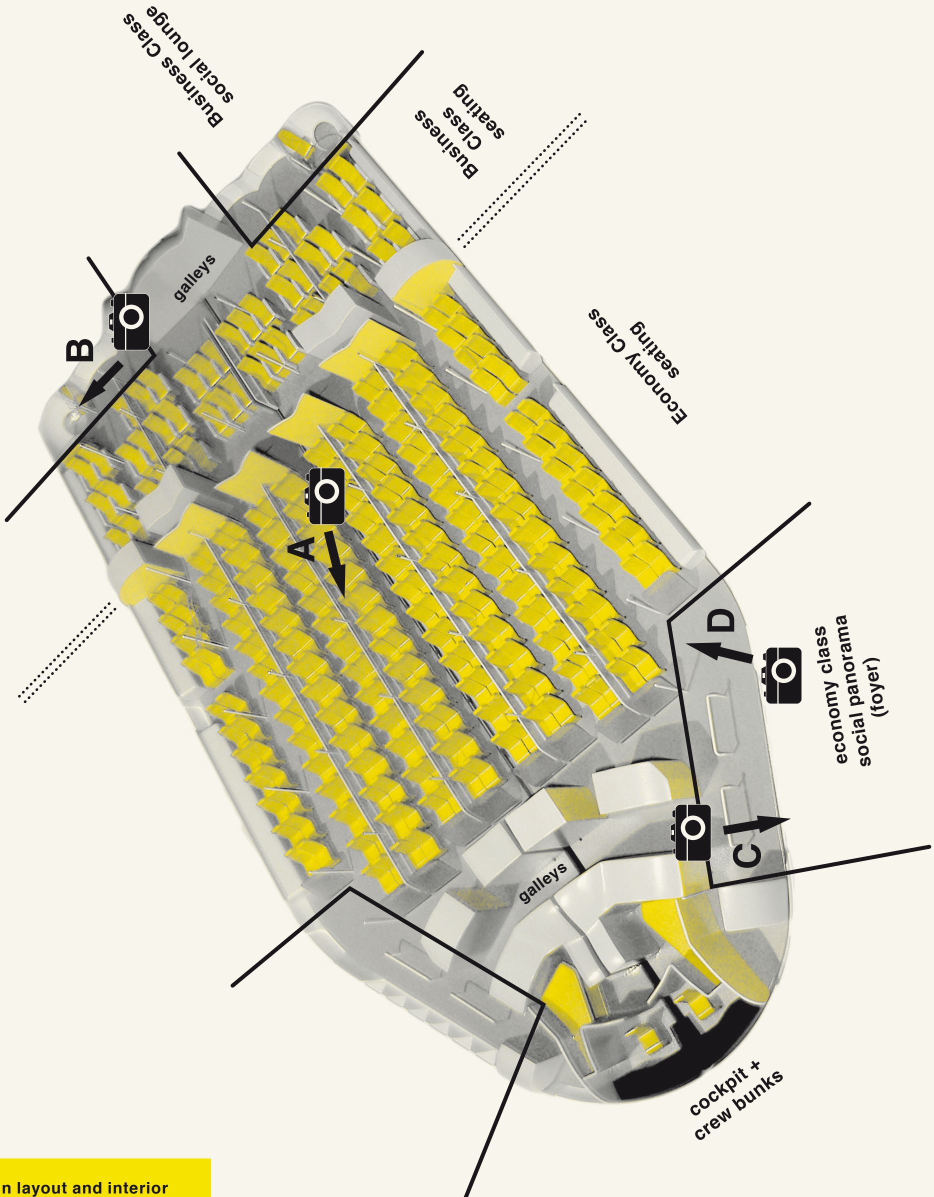
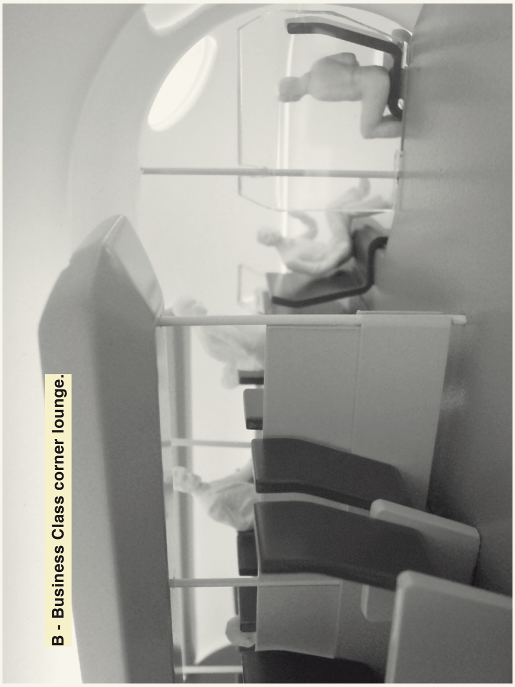
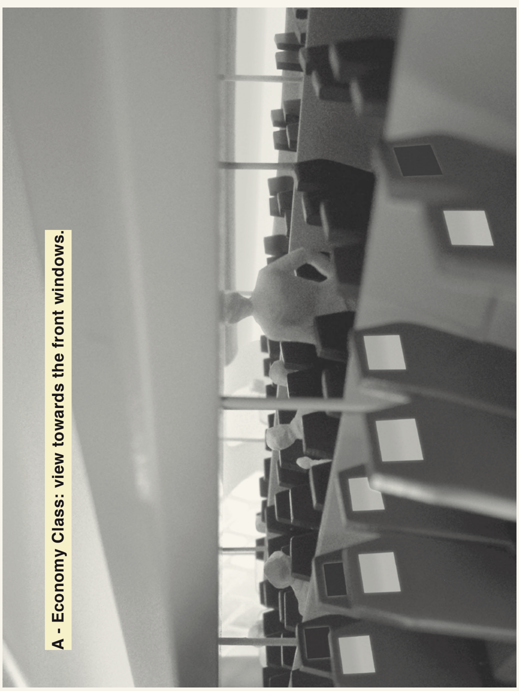


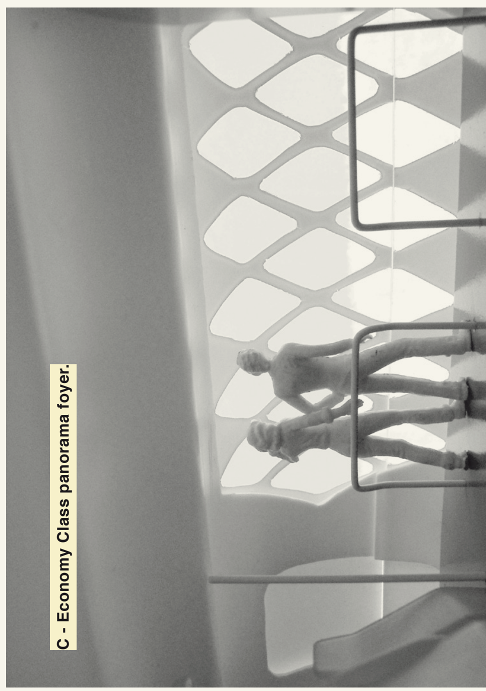
Fig. 69. Cabin layout and interior views of the BWB-300 concept.

(image: Z. van der Voet)


B - Business Class corner lounge.


D - Economy Class view from foyer to seating area.


A - Economy Class: view towards the front windows.


C - Economy Class panorama foyer.

ing in a car. The BWB offers passengers more freedom to move around. They can walk towards the common window areas in the front to enjoy a panoramic view, socialise and stimulate the blood-flow at the same time. Dividers in between the seat rows are installed to improve cabin quietness and make the middle seats more comfortable. These also function as a privacy screen or wall to lean against. This makes middle seats comparable to window seats without the private window.

Overall, we believe the introduction of the Blended Wing Body will be greeted by passengers with the same excitement as the introduction of the first jet aircraft or the Concorde.

Skin and bones

Grid stiffened structures

by Sonell Shroff

"Complex creatures evolve from more simplistic ancestors naturally over time."

The basis of Darwin's Theory of Evolution is the development of life from non-life and it stresses a purely naturalistic and undirected "descent with modification".

Let us assume for a minute that man evolved to his present form over the years from simplistic ancestors. The tough regenerative skeleton – bones to give strength, and joints, cartilages and tendons – to hold it together, and finally a skin – to cover it and give it shape, gives the human body an essential structure. Similarly, the aircraft has achieved its current form over the years, evolving from the simplistic Wright Flyer to the current composite or hybrid structure with a stiffening element acting as the skeleton and the metal-sandwich composite skin providing the much needed support and surface. Engineers and scientists have been on a constant mission to invent and re-invent a structure that is both feasible and highly efficient. After all, evolution does support the survival of the fittest – whether for the living or for the machine.
The following section provides a basic idea of this evolutionary journey of the flying machine and a vision for the skin and bones that hold this machine together.

LET'S START FROM THE VERY BEGINNING

Design has been and will continue to be based upon efficiency, i.e. higher output per unit of input. The only thing that changes over the years is the factors that go into the efficiency equation - safety, cost, minimum weight, emissions, damage tolerance and so on. Learning from past mistakes, the efficiency of an aircraft can be improved by involving not only more factors, but by introducing components that are more efficient. The dependence of the evolution of design upon the material available is visible in the development of structures technology over the years. The basic configuration of the aircraft, though under constant development, has not changed all that much since its conception in the late 1920s. But with the advances in material selection, the structure gained the capability to grow to the limits of the Antonov An-225, B-2, Concorde and the new Airbus A380. Over time, the materials used on aircraft/spacecraft lacked consistency and did not follow a historical pattern per se. While there were early developments of composite sandwich structures in the 1920s, metal stiffened-skin structures were established to be the state of the art with the final development of the DC-3 in 1936. However, because of research and development of better materials, sandwich structures were exploited again in the 1950s and 1960s with the design of such models as the B-58, C5 and Condor. Further, as this constant tug-of-war between design and materials continued, geodesic structures were realised. Independent of material properties, these could be built with a metal (duralumin) lattice, as in the Vickers Wellington Bomber, or with advanced composites as in the interstage for the Proton rocket.

HISTORICAL OVERVIEW OF DEVELOPMENT IN STRUCTURES

Whether the first invention in flying or not, the Wright Flyer is the most well-known aircraft. Fast-forwarding a decade or two, to functional powered flight, we arrive at the first monocoque structure. Wood and fabric were the state of the art at that time and this gave rise to the Deperdussin Monocoque in 1912, which was manufactured out of strips of tulipwood glued together in a concrete mould with the help of a pressurised rubber bag and a plywood skin. This design was later featured in the Lockheed Vega, a 5-seater cabin plane that flew in 1927, with the same monocoque fuselage, but this time with spruce instead of tulipwood.
The late 1920s and early 1930s bore witness to wood-metal hybrid structures. Some of the technologies that saw the light of day during these years, paved the way for most airplane designers. Flush riveted aluminium semi-monocoque, wing boxes made of aluminium stiffened skin, shear webs and other such important inventions made the DC-3 the epitome of design, when it first flew in 1935 with a riveted aluminium stiffened skin stringer frame structure. Although such metal design concepts were gaining importance, wooden structures had not been completely phased out yet. In 1940, the de Havilland Mosquito was developed out of a sandwich structure – a fuselage of balsawood sandwiched between sheets of Canadian birch. When the resistance of this structure to heat, humidity and insect attack was proven incompetent, it was finally time to shift gears as far as materials were concerned.

The invention and manufacturing of glass fibre textiles by the Nitto Boseki Company in Japan in 1938, opened up new possibilities, especially for smooth doubly-curved surfaces facilitating a lower drag. The Japanese soaring plane Todai LBS-3 (1956) was a sandwich-composite hybrid with a fuselage made of balsa core and two-ply fibreglass skin invented by Nitto Boseki. In the United States of America, the Convair B58 Bomber was manufactured with honeycomb sandwich panels and an outer skin made of Al-fibreglass honeycomb core. In-service damages caused by handling, walking and punctures, lead to costly and time-consuming inspections, so the B58 was only in service until 1970. Fibreglass plastics (traditional composites) were developed further and used throughout the 1960s to make fuselages, spars, tails, etc. of aircraft such as the Boeing 707, 727, 737, 747 and Akaflieg Braunschweig SB-6 (Germany).

The low modulus of elasticity and flexibility of fibreglass made the aircraft prone to aeroelastic instability in the form of flutter and divergence; this catalysed the search for stiffer fibres. Thus advanced composites emerged, such as carbon and aramid fibre reinforced plastics. These composites were used to achieve weight savings, fatigue resistance, corrosion prevention and damage tolerance, to name a few advantages. However, they were, and still are, only being used for smaller parts of the aircraft. By 1972, Grumman F-14 and F-15 stabilizers were designed with a boron-epoxy surface layer causing 18% weight savings. The need for lighter aircraft was recognized by NASA soon after the 1973 oil crisis, providing advanced composite research a much needed boost. In the early 1980s, Boeing 757 and 767 were developed with all movable control surfaces made of graphite-epoxy. The Lear Fan 2100 was an all-advanced composite airplane of graphite-epoxy and Kevlar. It claimed to have a mileage (per passenger) equal to that of a family automobile!

In recent structural technology development, composite sandwich (NOMEX) has gained importance with the Airbus A340 and A380, while the filament-wound single composite barrel fuselage for the Boeing 787 Dreamliner is a breakthrough in composite manufacturing techniques.

As can be gleaned from this quick recap of material and structure history, each time the structure demanded an advancement in material technology, efforts were made towards a new development. And each time a new material was developed, structures were readily adapted to test its capabilities. With this rich background spanning over more than 90 years, we have the opportunity to extract the advantages and limitations of each stage of development. Learning from past mistakes and incorporating the successful techniques, we can propose a technology that could become the next state of the art.

THE ELIMINATION ROUNDS

The state-of-the-art structural design concepts are discussed below with a larger focus on their vulnerability in order to learn from their shortcomings. A higher importance is given to Sandwich and Stiffened Skin Structures since their strengths can be combined or individually harnessed in the proposed design later.

Fig. 70. Britannia Bridge, Wales, circa 1852. A sandwich structure in the form of iron compression sheets riveted to both sides of a wood core.

(image: Frederick S. Williams)

Sandwich structures are a common phenomenon in nature; we can see them in bones, for example. An early example of sandwich as we know it today is the 1849 Britannia Tubular Bridge in North Wales. The bridge is made with iron compression sheets riveted to both sides of a wood core. Further, in aviation, Von Karman and Stock first patented a sandwich fuselage for a glider plane in 1924. This was followed by the memorable design of the de Havilland Mosquito fuselage and wing.

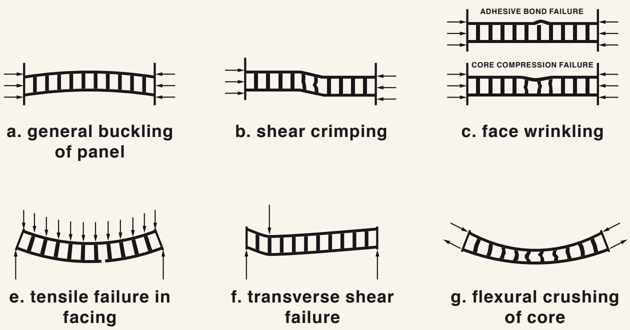


Fig. 71. Failure modes of a sandwich structure.

Sandwich structures are not free from shortcomings; the damage tolerance requirements and failure modes of a sandwich structures enforce limitations on the thickness of the face sheets. Insufficient panel thickness can cause general buckling, intracell buckling and face sheet failure as well as impact damage. And a minimum thickness requirement imposes a weight penalty. Other problem areas are moisture retention in the core, leading to degradation of the skin-to-core bonding and this affects structural integrity.

A practical difficulty during assembly is their attachment to the adjacent structure – composite inserts have proven to be lighter and stronger than aluminium inserts, but that translates into extra costs and additional failure mode analyses. For all these reasons, sandwich structures have not been widely used for high load bearing structures; their application has been limited to tail planes, stabilizers, ailerons, etcetera.

- **Rotor blades from the McDonnell Douglas Apache and the Boeing Chinook helicopter are known to have problems with water accumulation in their honeycomb core cells.**
- **Thermographic inspection of a United Airlines 767 revealed that nose landing gear doors made of a composite honeycomb, could contain liquid water in an area as high as 7500 cm^2 (equivalent to 20 kg of extra weight if the cells were fully filled).**
- **Disbonded areas detected inside the elevator sandwich panel of an Airbus transport aircraft were attributed to moisture ingress, resulting in an FAA airworthiness directive mandating inspection and reprotection for all Airbus A330, A340 stabilizers and elevators.**

STIFFENED SKIN STRUCTURE

Stiffened Skin structure was an evolutionary design, first used in the early 1920s in the Dornier aircraft. Dornier employed a covering made from aluminium alloy sheet, reinforced against buckling with the help of external stringers running in the flight direction. These external stringers had obvious aerodynamic limitations, so the design evolved to internal stiffening by a corrugated sheet. From 1936 onwards, the riveted aluminium skin-stringer frame structure of the DC-3 has been the standard. This structure has been optimized over the years, yet it could be improved further in some areas.

Fig. 72. Detail of the Dornier Do-J - the Flying Boat.

(photo: Jesús Manuel Cuartero)

Regulations state a minimum skin thickness of 1.625 mm, whether metal or composite laminate. This means there is a limitation on the weight reduction of the structure that can be achieved, even though some materials might in fact have higher strength at a lower thickness. The skin accounts for approximately 40% of the weight of the fuselage in most cases.

Further, manufacturing costs are high if skin and stiffeners are assembled separately. But co-curing of stiffened skin is not free of risks for larger or more complex parts. A high level of precision is required in order to accurately place the stiffeners during the cure cycle and to apply uniform pressure overall. Any step that goes wrong in the co-curing process will add to the cost of the product. Additionally, failure modes such as fatigue and skin-stiffener separation prevent the achievement of high post-buckling ratios. Metal stiffened skin has been used predominantly in large structures. It is high time for a further evolutionary step in structures and their design to give composite stiffened-skin structures a breakthrough.

Fig. 73. Fuselage of the DC-3 (1941).

As early as 1910 Graham Bell found that the optimum design for kites was a lattice structure. In its essence, a lattice structure is nothing but a web of ribs arranged at certain angles. These contribute to compression, shear and torsion depending upon their arrangement.

So far, grid stiffened structures have only been used in applications not intended to fly – such as the Shukhov Tower in Moscow (1922) and the Ford Rotunda (1933). Yet their benefits and credibility can be deduced from Vickers Wellington Bomber that had its maiden flight in 1936. Its geodesic structure of Duralumin was covered with fabric. This novel design was succefully developed further for application in spacecraft.
McDonnell Douglas patented the Al-Isogrid in 1964. It was used in interstages, shrouds and tanks for the Delta Vehicle. This structure was machined out of a single piece of Al stock to create skin and stiffeners that formed equilateral triangles, and hence it was termed isogrid. Predictably, it was heavy and expensive.

In the 1970s composite development had been undertaken by the government research groups in both USA and USSR. Along with a reduction in weight, the manufacture of composite grids lead to an increase in the stiffener strength. This can be attributed to the increased material strength in the direction of the ribs.

Fig. 74. Vickers Wellington Bomber with its fuselage exposed.

(source: Imperial War Museum)

WHY A COMPOSITE GRID STIFFENED STRUCTURE?

A state-of-the-art composite skin stiffened structure has a thick load-bearing skin which accounts for 40% of the total weight of the structure. The structure can be designed to be stiffened by a unidirectional CFRP (carbon-fibre-reinforced polymer) grid, so that the majority of the load is carried by the grid while the skin carries the aerodynamic loads. This suppresses global buckling and makes the skin thinner and lighter. Moreover, in comparison to sandwich structures, grid stiffened structures with the same weight are stiffer in-plane.
In addition to weight savings for equivalent load carrying capability, grid stiffened structures exhibit higher damage tolerance. Delaminations as a result of impact damage are contained within a single cell, saving the structure from catastrophic failure. Damage tolerance extends to other damages such as cracked ribs and skin that are caused by the redundancy in load paths inherent to grid stiffened structures.

The open configuration counters the problems of moisture absorption and retention in the structure. This is a significant improvement over sandwich structures which are infamous for retaining water over an entire lifetime.

WEIGHT AND COST

The design of a novel structure is driven necessarily by weight and cost. Using a structure with a load-bearing grid and a thin skin can deliver considerable weight (and hence cost) savings.
In traditional structures, the skin is much heavier than the stringers. In the proposed grid stiffened structures, the grid is the major load-bearing member so the skin can be of minimum thickness as a non-load-bearing part of the structure leading to an average mass reduction of about 30%. Apart from the thinner skin, the stringers also play a role in the final weight saving. More weight can be saved with the reduced use of mechanical fasteners by manufacturing an integrally stiffened panel. And a composite material design will reduce the weight even more as compared to a metal design. The use of lighter materials – glass fibre, thermoplastic, etc. – can lead to further improvements.

To sum up, grid stiffened structures have many advantages over available technology: higher strength for a lower weight, higher damage tolerance, increased reliability, and lower moisture absorption (depending on the lattice design). They are simple to manufacture with automated techniques. They can also be tailored to demand by varying the grid densities and angles. This then, comes at the price of a more complicated manufacturing process. Also, the impact and damage behaviour of such tailor-made structures will be largely unknown.

MODELLING, ANALYSIS AND OPTIMIZATION

Grid stiffened structures are essentially a type of stiffened skin design with the stiffeners laid out in a particular pattern, that is repeated over the entire span of the structure. Like any other stiffened skin design, they can be modelled and analysed using principally two methods: the smeared stiffener method and the discrete method. Most of the models conduct a global and local buckling analysis, yielding the ultimate buckling load. This is then used as the chosen objective function in the optimization process.

The smeared stiffener approach is based on the theory of homogenisation and is most accurate when the grid is dense. In order to simplify the analysis, it is assumed that the material is uniformly distributed over the panel in such a way that an unstiffened panel with smeared or average material properties is analysed instead of a stiffened one. Also, the outcomes can be applied in the finite element method for better results on local effects such as local buckling, local mode of vibration, etc.

The discrete approach treats the stringers or stiffeners and the skin as discrete entities maintaining the compatibility between them. Due to the retained geometric details, the discrete method is more accurate as compared to the smeared stiffener method.

However, it comes at a cost of increased complexity in analysis and computation time. This method is largely coupled to the finite element analysis method in which the stiffened panels are modelled in various ways, keeping the approach of discrete skin and stiffeners intact.

SOME EXAMPLES OF EARLIER ANALYSES AND OPTIMIZATION

Smeared stiffener method:

- An equivalent continuum of a grid structure with or without a laminated skin is modelled, analysed and optimized by Chen and Tsai taking torsion, in-plane bending and shear of ribs and hygrothermal effects into account. The model takes the form of a Mindlin plate that can easily be incorporated using an existing FEM technique and analysed in a commercial code. They compared laminates, sandwich and grid structures with and without skin(s) subjected to hygrothermal and multiple mechanical loads. Under conditions of local buckling of skin and grids and material failure, the optimizer results indicated that a grid stiffened structure without a skin is of optimum weight under all kinds of loading with the grid stiffened structure with a single upper skin coming in a close second.
- The traditional smeared stiffener theory does not take into account the local skin-stiffener interaction and is hence known to wrongly estimate the buckling loads. An approach called the improved smeared stiffener theory incorporating the local skin-stiffener interaction is described by N. Jaunky et al. This theory takes into account the shift in the neutral surface of the stiffened plate from the mid-plane of the plate. Critical eigenvalue analysis using this approach are closer to the finite element approach when compared to the traditional smeared stiffener theory.
- The moment effect of the stiffener was included in the general smeared stiffener theory developed by S. Kidane et al. The results of this study showed that sparse stiffening causes a decrease in buckling load because the skin becomes the main load-carrying member of the structure.

Discrete method:

- Results from an investigation carried out by M-W. Guo et al indicate that the use of a 3D beam element for the stiffener is particularly useful for capturing the stiffener's true buckling behaviour due to the inclusion of lateral, flexural and torsional degrees of freedom.
- In a discrete analysis carried out by Wang et al. the skin and the stiffeners are coupled through unknown interacting normal and shear loads which are computed by satisfying the continuity conditions in the displacements at the interfaces for both isotropic and orthotropic cylindrical shells. Their work helps obtain stresses, strains and displacement at any point in the shell.
- Yap et al. use shell elements to model both skin and stiffeners to analyse the skin-rib debonding failure mode based on fracture mechanics. The skin and ribs or stiffeners are constrained at all six degrees of freedom at nodal interfaces with rigid bar elements (RBAR). The simulations predict the global buckling mode and local buckling mode in the debonded region successfully, however, these models require the number of degrees of freedom of the skin and stiffeners to be equal, and an accurate study of the skin-stiffener interaction comes at a high cost for time and processing power due to the high mesh refinement necessary in these areas.

At CleanEra we aim to develop an optimization technique that incorporates the best of the existing mathematical and numerical schemes. With this, we want to be able to produce a complete fuselage with the right grid pattern across its entire length. The weight savings that can be achieved by using the right optimization parameters and constraints, are much greater if we first do a topology optimization. With the results we can then figure out where exactly in the fuselage high stiffness is required. The aircraft fuselage is more heavily loaded at certain areas than at others, therefore the fuselage barrel should not be designed with a uniform grid pattern throughout its entire length. That is where a combination of analytical and finite element analysis comes into play. A global analysis of the barrel can then be followed up with a local effect analysis.

We are therefore working on a program that enforces displacement continuity between the skin and the grid and takes into account the grid height offset, moment and force at skin and grid interface. This program is capable of creating a model of a grid stiffened panel of any desired grid pattern that can be used as an input to a commercially available finite element analysis package in order to study its global and local response.
The analysis of joints and attachments between the skin and other parts of the aircraft is vital to the future of the grid stiffened structure. Examples are the fuselage barrel to floor interfaces, adjacent fuselage barrel interfaces and windows and other cut-outs. Keeping weight and cost of these attachments should be their prime design criteria. A finite element analysis of strength and buckling of the various structural interfaces will pave the way for their sizing and detailed design. A finite element analysis of such a joint will help determine areas of stress concentration in the grid structure and a parametric model of the joint with varied grid dimensions can help optimize the design of the interface.

"..grid stiffened structure without a skin is the optimum under all kinds of loading.."

Chen and Tsai

Flying inside an open grid?
- **What about pressurization?**
- **Aerodynamics?**

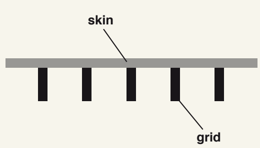
We cannot do without a skin.
- **Material - composite, metal, hybrid or sandwich?**
- **Thickness - minimize to prevent moisture ingression.**

Conceptualization:

concept A

Skin handles aerodynamic loads, pressure loads and shear loads

Grid handles the rest

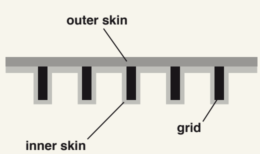


concept B

Inner skin supports the grid and takes up impact

Grids handle pressure-, shear- and axial loads

Outer skin handles the aerodynamic loads



concept C

Concerns:
weight, materials, moisture retention, damage detection and repairs

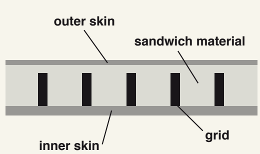
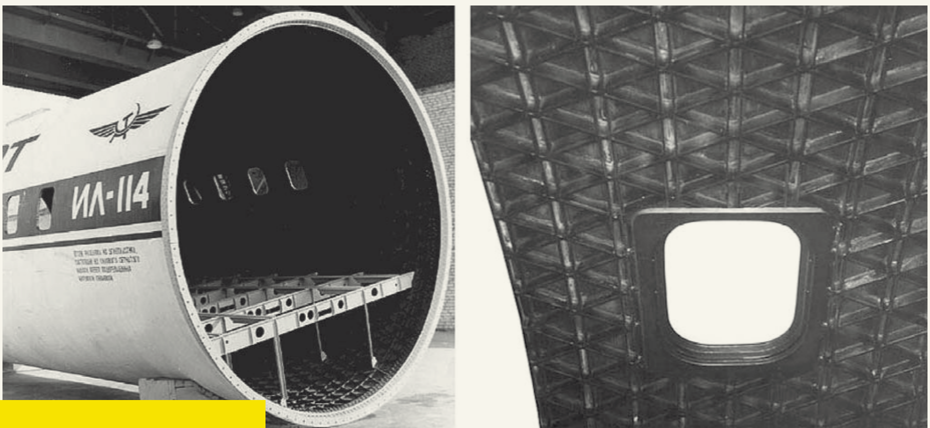


Fig. 75. Concepts for grid stiffened structures.

MANUFACTURING

In the 1930s early grids were manufactured in the form of metallic geodesic structures. Stiffened structures made of composites are a recent development. Both isogrid and anisogrid structures have been successfully tested in the USA, Russia, Japan, China and recently in India. The most-used techniques of grid structure manufacturing are winding, hand or automatic lay-up, and moulding. It is unknown whether these manufacturing techniques were developed with the grid stiffened structure in mind or whether the manufacturing technique determined the application of the final manufactured product. However, some manufacturing methods can be adapted to the type of material used to create such a structure while others can be used as it is for several types of materials; fibres and resins.

The oldest and most commonly used technology is the winding method. Several types of winding techniques have been established to create e.g. interstage and payload shrouds for rockets.



- Grooved Foam tool
- Carbon tows wound into grooves
- Grooves can be metal lined for hybrid structure
- Dry winding possible w.r.t material used

Fig. 76. Carbon-epoxy lattice fuselage section and window frame of the IL-114. (source: Vasiliev + Razin, 2006)

Fig. 77. Spectrum S-33 with a single-section fuselage. (source: Spectrum)

MANUFACTURING METHODS IN PRACTICE

1. Winding:

- **The Central Research Institute for Special Machinery or CRISM, Russia manufactured a Grid Stiffened fuselage for the Ilyushin IL-114 in 1986. This carbon-epoxy fuselage was manufactured with a filament winding technique. Phillips Laboratory, in the early 1990s, developed a rubber tooling for the winding process. Solid moulded silicon rubber sheets, preferred due to its high Coefficient of Thermal Expansion, were wrapped around metallic mandrels. The material buildup at the rib intersections lead to lower fibre volume fraction and hence, poor part consolidation.**
- **To counter the lower fibre-volume fraction at rib intersections, Airforce Research Lab, USA developed two methods in 1997: the Hybrid Tooling Method and the Expansion Tooling method. The former is a winding technique in which the tool is made of two different materials as the base tool and the expansion tool.**

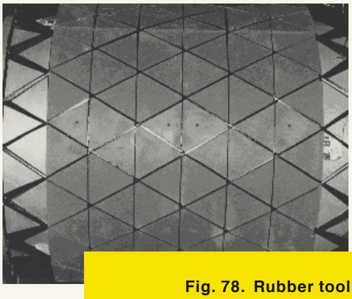


Fig. 78. Rubber tooling for Isogrid lattice winding.

(source: Huybrechts + Meink)

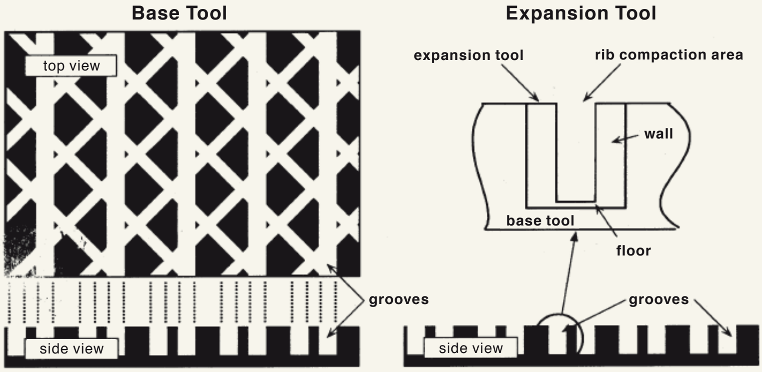
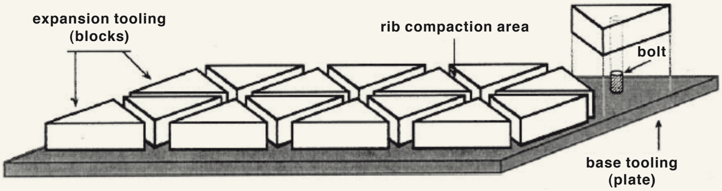


Fig. 79. Schematic of Hybrid tooling consisting of base and expansion tool.

Fig. 80. Schematic of Expansion block tooling consisting of a stable base tool with expansion blocks.



- **Scaled Composite LLC. tested the Visionaire Vantage demonstrator light business jet in 1996 with a wet filament wound CFRP grid stiffened fuselage. The exact details are unfortunately not public. The fuselage of 1.71 m. diameter and 11 m. length was manufactured as a single shell.**
- **A similar proprietary winding technique was used in 2006 to manufacture a complete 4m long, 1.5m wide fuselage in five hours followed by curing in a low-temperature oven. This method provides for the fuselage to be built in a single section and is extremely time-efficient. This method is used to manufacture the complete fuselage of the VLJ Spectrum 33 Independence.**

2. Lay-up:

- **In 1994 Composite Optics Inc. manufactured flat laminates by lay-up technique that were cut precisely using a CNC controlled water jet cutter, assembled together using edge-bonded, tongue and groove joints. This method was called SnapSat™ - Short Notice Accelerated Production Satellite. This technology was used in a number of space applications including frames, most noticeably in the payload deck of the Mighty I Satellite launched in 1998.**
- **Around the same time, Stanford University was working on TRIG (Tooling Reinforced Interlaced Grid). In this process, the tool becomes an integral part of the product. The Expansion Tooling method, developed by the Airforce Research Lab mentioned above, is an example of the lay-up method. It is based upon the Hybrid tooling method, but with an advantage of producing wider range of rib geometry.**
- **Isogrid Composites Canada Inc., in collaboration with Canadian National Research Centre and Aerospace Manufacturing Technology Centre, Montreal, has patented an automated lay-up system and produced the first large surface isogrid panel in 2011. A 0.61 x 1.2 panel weighs 2.1 kg and is 16 mm thick.**

3. Other techniques:

- **Han and Tsai introduced a new type of grid joint, a Cap Reinforced Slotted Joint and the resulting grid structure was called the Interlocked Composite Grid (ICG). This structure takes advantage of pultruded carbon grids of unidirectional fibres with a property of being one of the most efficient forms of composite structure.**

FILAMENT WINDING

Aircraft parts manufacturing is ever progressing towards using composite lightweight single shells for the various sections of the aircraft. The advantages of manufacturing a single-barrel fuselage from fibre-reinforced composites are known to the industry. Some of the filament winding techniques are particularly suitable for manufacturing grid stiffened fuselage structures. A fuselage thus manufactured is not only lightweight, due to a reduced number of joints and optimized grid patterns, it also has a lower assembly cost owing to the lower part count. Further weight savings can be achieved with localised grid patterns for different parts of the fuselage. For this, the filament winding technique has to be controlled appropriately. We also must not overlook the difficulties that arise during repair of damage to a single continuous barrel, or the complexity of the problems around introducing cut-outs for windows.

The winding techniques have also shown to have limitations as far as double curved structures are concerned. The extension of these manufacturing methods to wings and - in the far future - to blended wing body aircrafts, will pose even bigger challenges.

BUILDING BLOCKS

Grid stiffened structures have been used succesfully in spacecraft structure for the past few decades. However, in contrast with spacecraft, aircraft applications demand a severe limit load. The use of composite materials comes with reductions in impact characteristics. Composite materials, so far, are no match to metal where impact is concerned. Joining and attaching of composite parts is a challenge in itself because of their low bearing strength. Hence, bolts cannot be used easily to join these structures. Innovative composite laminate skins have to be developed so that impact capabilities are increased.

The development of grid stiffened structures has been a process of repeated setbacks. Optimization and modelling of such structures was a challenge a quarter of a century ago, and still is. Some modelling difficulties prevail in spite of a clear understanding of FE Analysis of composite structures.

When it comes to defining conditions and element types for the intersection points where several ribs cross each other, the question of incorporating physical changes in modulus and strength properties arises. We do not yet completely understand the behaviour of the intersection where several composite plies cross each other and cause a resin buildup. Comprehensive tests that are currently being carried out on rib intersections under various loads and boundary conditions, should bring us answers to these questions.

Thus, the design of advanced structures to be used in severe limit load conditions poses challenges not only in the field of material selection and analysis type, but in the realms of a design methodology as well. Whether we can use the traditional safety factor for a grid stiffened shell, for example, is unclear. The behaviour of grid stiffened structures under tension and compression is completely different from well-established aluminium skin-stringer structures, for which this traditional safety factor was originally defined. Moreover, studies show that the safety factors for grid stiffened structures vary for different types of loads applied.

Besides all that, the proposal of an extremely light and damage tolerant structure is not the complete solution to a cleaner and greener aircraft. The various parts of the aircraft have to be designed in such a way that weight addition in the form of repair patches can be minimised. And manufacturing processes have to be modified in such a way that waste due to tooling is minimised or recyclable. This implies that structural design is much more than the need of light weight alone. Nonetheless, the potential cost and weight benefits that the grid stiffened structures technology offer, make its further development very worthwhile.

Painting it green

Coatings in aerospace

by Gustavo Guerriero

Coatings used in aeronautical structures have to withstand a lot. Wide temperature variations on both the structure and the coatings cause dimensional changes. Water condensation collects inside unpressurised or unheated areas and exposes the coatings to high humidity. With increasing altitude, lower pressures make residual liquid in the coating much more volatile, and the less dense and polluted atmosphere increases UV radiation. Moreover, the humidity and salt concentrations of the atmosphere promote weathering and corrosion. In addition, the fluids used in the aircraft, such as aggressive phosphate-ester based hydraulic fluids, also attack coatings at the surface or at the metal-coating interface.

PROBLEMS WITH CURRENT COATINGS

Coatings need to be both flexible and adhesive, and they also have to meet all the requirements for temperature, UV resistance, and water and fluid resistance. Currently, several layers of coating are used to get all the required specialized functions, such as adhesion, protection against environment and corrosion, and visual aesthetics. The use of different layers makes coating a complex business. A single chemistry that covers all functions is therefore a long-desired goal in the coating industry.

There are more reasons to reinvent coatings. The organic materials used to protect metal surfaces, such as latex paints and polymers cannot fully protect an underlying substrate from corrosion. The coating layers contain micro-pores, areas of low cross-link density, or high pigment volume concentration – and these leave room for corrosive agents such as water, oxygen and chloride ions to get in between the metal and the coating. This makes it necessary to mix inorganic or organic inhibitors into a paint system. The most effective inhibitors are hexavalent chromium compounds (Cr6+); these have been in use for decades. But hexavalent chromium compounds are genotoxic carcinogens. If they are breathed in, they can cause irreversible genetic damage or mutations by binding to human DNA.

Typical coating systems consist of three individual layers:

1. **a product of substrate anodization**
   - **a very thin (<10 μm) inorganic layer**
   - **provides corrosion protection and improved adhesion between substrate and primer**
2. **primer, a pigmented organic resin matrix**
   - **usually a two component epoxy with a thickness of around 25 μm**
   - **provides protection against corrosion**
3. **top-coat**
   - **usually a polyurethane resin with a thickness of 50 to 200 μm**
   - **main barrier against environmental influences and ultraviolet rays**
   - **also used for decoration**

Another problem are solvents. These are used in large amounts in the spray application of two-component coatings. High volumes of solvents are also involved in the paint stripping process prior to repainting. This is necessary to reduce weight buildup and to allow inspection of the structure. Historically, a wide variety of solvents have been used, such as methyl-ethyl-ketone (MEK), toluene, xylene, and methyl-iso-butyl-ketone (MIBK).

In the USA, the Clean Air Act, which addresses volatile organic compounds (VOCs) that contribute to the formation of ground-level ozone, has a significant impact on solvent users. The Air Resources Board (ARB) developed a reactivity-based aerosol coatings rule that was approved by the Environmental Protection Agency (EPA) in 2005. This rule encourages reductions in the use of higher reactivity VOCs, instead of regulations based on mass. High photochemically reactive VOCs, such as alkenes (olefins), have greater potential to contribute to ozone levels. In addition to being regulated as VOCs, some aviation coatings (e.g. chromium compounds) are also regulated as "hazardous air pollutants" (HAPs). In 1995, the EPA developed regulations that apply to "major sources" of HAP emissions. HAPs are air toxic pollutants known to, or suspected of, causing cancer or other serious health effects.

In Europe, the 2003 Solvents Directive from the European Commission Environment regulates industrial emissions of VOCs. European regulations on Registration, Evaluation and Authorization of chemicals and their safe use, known as the REACH regulations, came into force in 2007. REACH calls for the progressive substitution of the most dangerous chemicals, when suitable alternatives have been identified. Chromates used as corrosion inhibitors for treatment and coating of metals in aerospace are included as Substances of Very High Concern (SVHC) according to the Article 57 of REACH Regulations. SVHC may have serious and often irreversible effects on human health or the environment.

ENVIRONMENTAL REGULATIONS

Current regulations demand two things from the aerospace industry: elimination or reduction of VOCs, and elimination of chromates. These regulations will evidently impact suppliers and customers of these substances.

Options for complying with regulations are to switch to an alternative technology or to reformulate coatings composition. The aircraft industry tends to move cautiously, so reformulation is the preferred option. Magnesium and cerium compounds, molybdates, vanadates and phosphates, are the most promising candidates for reformulation of active inhibitors. The reduction of resin viscosity is an alternative to reduce solvent usage and improve performance. But this comes at the expense of increasing paint cycles, as surface drying is slower and paint remains sticky until chemical curing starts. It also reduces pot life - the amount of time between the moment you open the paint and it gets hard inside the pot.

REDUCING SOLVENTS

Other approaches are based on alternative technologies. High-solids systems (i.e. paints formulated with solid particles to improve coating properties) have been developed, but they increase weight and do not eliminate solvents. Water-based paints have better application properties and lower VOC levels, but they also have higher curing temperatures and require more energy for drying. The ultimate improvement in VOC level would be to completely eliminate solvent use. This can be achieved with alternative technologies such as powder coatings or radiation cured materials. Powder coatings are the choice of the automotive industry and other industries. But, for high performance coatings, the powder usually has to be stoved at temperatures detrimental to aerospace aluminum alloys. Moreover, non-solvent coating technologies can only be used with certain types and shapes of substrates, and the materials used in non-solvent technologies can have relatively high toxicity compared to the solvents they replace. In addition, the up-front capital costs required for new equipment can be high.

REPLACING CHROMATES

Research groups around the world, e.g. at TU Delft, CSIRO, and Ohio State University, are looking for alternative systems to chromates. Deft Inc., Sherwin-Williams, and AkzoNobel Aerospace Coatings have already commercialized several chrome-free systems, and the military sector has taken the lead in the qualification of chrome-free primers and pre-treatments. But the elimination of chrome from primers and pre-treatments for aerospace continues to be the challenge that keeps researchers developing new products.

SMALL PARTS

Most of the aircraft coatings are applied by thin-film spray cured at ambient temperature, mainly in exterior painting. On small parts, sprayed paints can not meet requirements such as resistance to specific fluids or wear, so other methods have to be used. For some landing gear parts, door handles, and struts currently polyphenylene-sulfide (PPS), polyether-ether-ketone (PEEK), and epoxy powder coatings are used. Ongoing research at TU Delft aims at the development of a single chemistry that covers all functionalities in these highly demanding areas: scratch/wear and environmental resistance. The CleanEra research focuses on novel liquid crystalline thermosets (LCTs) that have shown clear advantages over other thermoplastic LCPs, such as improved adhesion and processability.

POLYMERS

When polymer molecules are aligned and extended they tend to have higher module and tensile strengths, so this is what we are looking for in our single-chemistry solution.

Conventional polymers consist of long backbones that in the melt form a random coil configuration. Under tensile and shear fields during extrusion, injection molding, and fiber spinning operations these long molecules tend to align under the influence of tensile and shear fields. But the continuity of the alignment is low and the chains remain partially coiled. Moreover, once the stress is removed, the molecules partially lose their orientation and tend to recoil completely.

In semi-crystalline polymers, crystalline regions are surrounded by amorphous regions. This crystallinity makes them stiffer, so they can be used above the glass transition temperature (Tg). But the crystallization shrinkage during the cooling produces high internal stresses and this makes thick parts difficult to produce.

LIQUID CRYSTALLINE POLYMERS

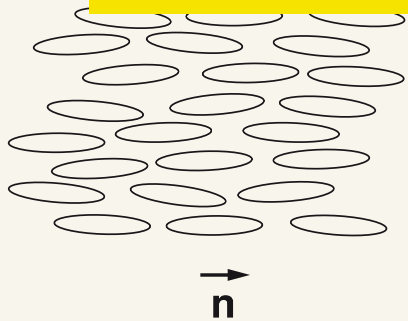
Liquid crystalline polymers (LCP) can form regions of highly ordered structure during the liquid phase. This liquid crystalline phase, also known as mesophase, has a degree of order intermediate between a crystalline solid and an isotropic liquid.

It is this chemistry that tells us how to attain the extended chain conformation we are looking for. In LCPs, the molecules are subject to long range and short range order and may be arranged in domains. Within these domains, the molecules are aligned and the average direction of the molecules is referred to as the director n. There is generally no relationship between the directors in adjacent domains. However, all the directors may be aligned by shear stresses during processing.

Fig. 81. Schematic representation of a semicrystalline thermoplastic polymer, indicating crystalline and amorphous regions.

The polymer molecules in LCPs have been likened to cut logs in log jams on a river. If the groups of logs are orientated in the direction of the stream they readily flow away. This orientation also aligns all the logs in all the groups, giving an extended alignment which is what we need to get high modulus in LCPs. This analogy suggests that the good mechanical properties of LCPs should be accompanied by low melt viscosity and hence an unusual ease of processing. This is, in fact, the case.

Fig. 82. Schematic representation of a nematic liquid crystalline phase. The average direction is refered to as the director 'n'.

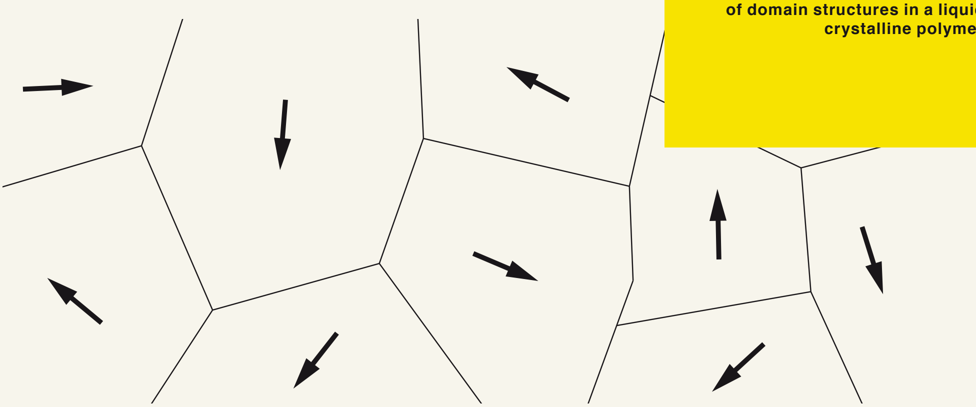


The willingness of LCP molecules to remain in alignment gives granules of these materials a wood-like appearance and a fibrous fracture. Moreover, the mechanical properties of LCPs are similar to those of fiber reinforced thermoplastics. For these reasons, LCPs are often referred to as self-reinforcing polymers.

In LCPs, the rigid portions, which are responsible for the mesophase state, can be either connected head-to-tail in the polymer main chain or linked to the polymer backbone as side chains. Liquid crystal polymers can also be divided into lyotropics and thermotropics. Lyotropic liquid crystal polymers (LLCPs) form mesophases in solution at a certain temperature and concentration. Thermotropic liquid crystal polymers (TLCPs), on the other hand, are compounds that exhibit liquid crystallinity upon melting. This phase behavior can be reversible (enantiotropic) or can show up only upon heating or cooling (monotropic).

The superior properties of these materials are very interesting for surface protection. Low coefficients of thermal expansion (CTE) will lower internal stresses. This makes it a promising material for thin film applications. TLCPs also possess excellent solvent resistance, very low permeability, retention of properties at cryogenic and high temperatures, and flame-retardant

Fig. 83. Schematic representation of domain structures in a liquid crystalline polymer.



properties. And their aromatic structure ensures high melting points and thermal stabilities. TLCPs are commercially used in applications such as fibers and injection moldable structures with high modulus, strength and thermal stability, and electrical connectors.

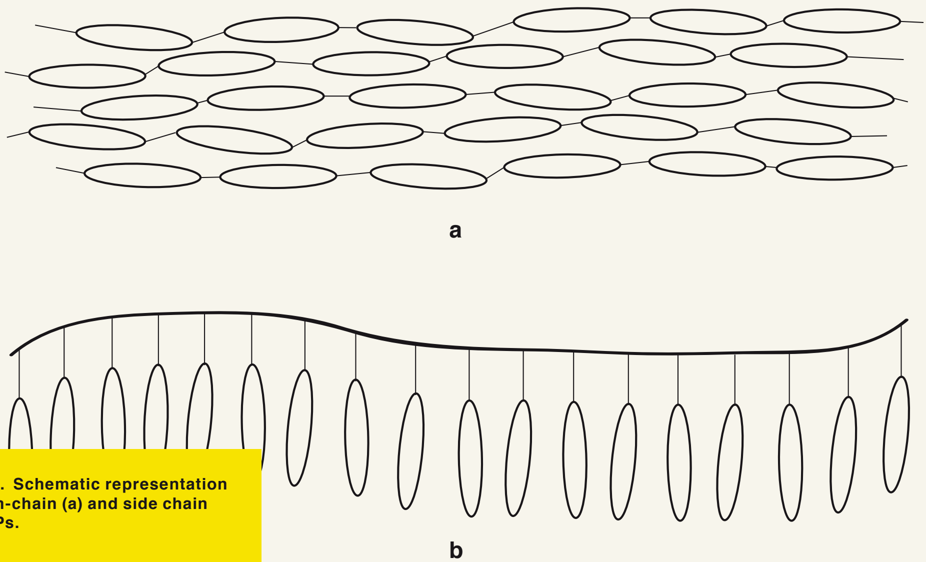
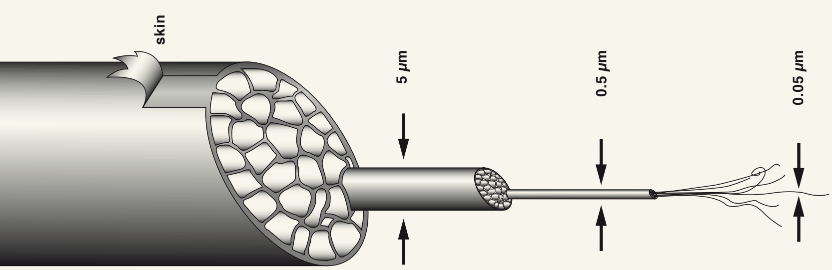


Fig. 84. Schematic representation of main-chain (a) and side chain (b) LCPs.

Fig. 85. (bottom) LCP fracture model proposed by Sawyer.

LIQUID CRYSTALLINE THERMOSETS (LCTs)

The most widely know LCPs are thermoplastics; however, thermosetting LCPs or liquid crystalline therosets (LCTs) have been known for some fifteen years. LCTs were developed to replace polymers such as epoxies and aryletherketones. LCTs crosslink and retain their ordered structure, forming a tridimentional organized network. Different kinds of these materials have been synthesized and investigated, with various backbones and reactive end-groups. Examples are acrylate, epoxy, rigid-rod, and elastomeric LCTs.



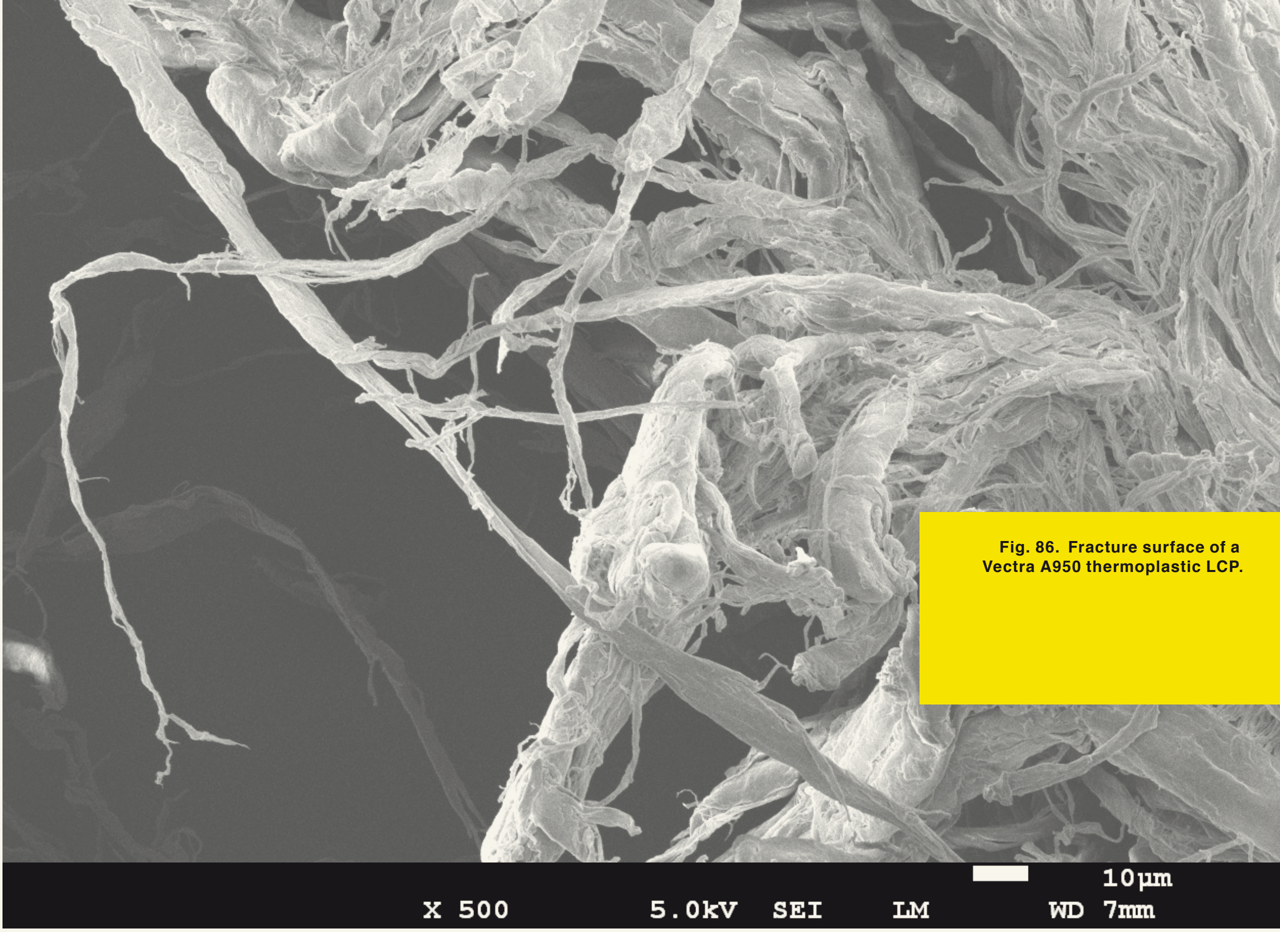


Fig. 86. Fracture surface of a Vectra A950 thermoplastic LCP.

PHENYLETHYNYL-TERMINATED LIQUID CRYSTALLINE OLIGOMERS

These thermotropic LCTs are formed by aromatic rings, with the liquid crystalline segments along the main backbone of the polymer. The backbone is that of the commercial liquid crystalline thermoplastic, Vectra-A, which consists of 73 mol % HBA and 27 mol % of HNA.

Curing of these resins requires heating from 350° to 400° C for 60-90 min and yields a thermally stable, insoluble, and intractable material. The 4-(phenyl-ethynyl)-phthalic anhydride (PEPA) end-group is preferred because of its facile synthesis and low toxicity. PEPA-terminated oligomers consistently display excellent thermal and mechanical properties and a narrow cure temperature, affording a large processing window. True crosslinks, chain extensions, and branchlike structures were observed. These LCTs have been studied as matrix materials for composite structures, but what about coating applications?

LCTs AS PROTECTIVE COATINGS

Thermosetting oligomers require no additional curing agent prior to application or curing. Moreover, the reactive oligomer is easily processable for powder coating techniques. Powder coating processes are gaining great importance in recent years. With zero volatile organic compound (VOC) emission, they are very environmentally friendly.

Fig. 87. Surface topography of a 1000 g.mol-1 LCT coating cured for 45 min at 370°C.

Thermal spray powder coating is not limited by the melt viscosity and/or thermal conductivity of the substrate material. It is an effective method to produce coatings with a large range of thicknesses on a variety of substrate materials. Coating applications are not restricted by the size of the part being coated and coatings can be readily applied in the field, which is an important consideration for industrial use. However, coating performance is strongly influenced by processing parameters and the subsequent coating microstructure that develops. Carefully designed processing conditions are necessary to obtain optimal heat input into the powder and to prevent polymer degradation. Sufficient heat input, optimal substrate preparation, and material changes during deposition must be carefully balanced so that the polymer deforms and adheres well to the substrate.

Highly ordered polymers applied as primer or adhesive can hinder the permeation of water to the interface. For instance, the use of linear liquid crystalline polyurethane (LC-PU) as a primer increases the wet adhesion stability of a polymeric coating on steel as substrate. The perme-

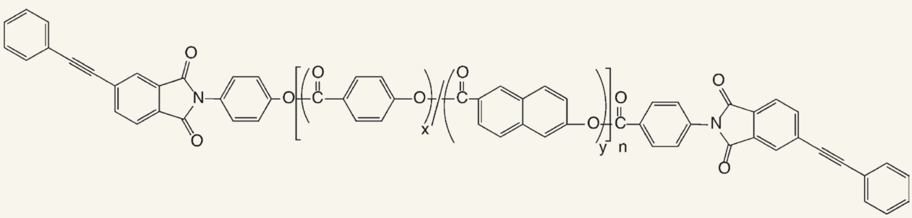


Fig. 88. Molecular structure and melt polymerization route towards the synthesis of phenylethynyl terminated Vectra based reactive oligomer.

ation of water through the polyurethane layer correlates with the degree of order of the polyurethane. Hence, the interfacial bonds are not weakened as is often the case when water penetrates to the interface. This means that ordered structures provide protection against corrosion. In this respect, LCPs are superior to surfactant- or polyacid-based primers.

LCTs AND THE AEROSPACE INDUSTRY

The replacement of Cr6+, elimination of VOCs, and compliance with HAP regulating laws are not the only concerns for the aerospace industry. Other goals are to reduce waste, extend component life, and reduce weight and maintenance costs. Several barrier coatings have been developed or modified to follow environmental regulations and increase performance. New barrier systems include plasma-deposited coatings, sol-gel systems, electro-deposition, and powder coating.

The potential of TLCPs for coating applications lies in their outstanding combination of fracture toughness, chemical resistance, and barrier properties over a wide temperature range. One of the most studied TLCPs is the thermoplastic Vectra® (Ticona GmbH), which exhibits an exceptionally low coefficient of thermal expansion (CTE), high temperature stability and chemical resistance.

Thermoplastic TLCPs have two main problems: they require a complex coating manufacturing process, and their adhesion properties are poor. This has restricted the use of TLCPs in coating applications and co-extruded films. They have high melt processing temperatures and a hierarchical fracture behavior, which makes it inherently difficult to grind TLCPs and obtain a powder suitable for powder-coating techniques.

Liquid crystalline thermosets can overcome these disadvantages. Recently, a new family of phenylethynyl end-capped Vectra-based oligomers was introduced. The end-group polarity of these LCTs should give them increased surface activity. This means the new LCTs have all the properties of LCPs, with greatly improved adhesion. Another advantage is that they can be easily milled into fine powders suitable for powder-coating applications, because of the lower mechanical properties of their reactive oligomer intermediate. We expect these new LCTs to overcome commercial TLCP drawbacks and to become successful as protective, environmentally compliant coatings. They are especially suited to aggressive environments such as hydraulic fluids or de-icing agents used in aerospace.

CONCLUSION

Although currently several chromium free coating systems have been developed, chromate-containing coatings are still in use. High demanding areas are particularly challenging for the replacement of chromium-containing coatings. The LCT coatings studied at TU Delft are chromium and solvent free, and can provide both high levels of wear protection and corrosion resistance. Typical applications are the protection against aggressive fluids in pressurized piping and the protection of surfaces exposed to wear damage. Moreover, several steps during surface preparation would be eliminated, simplifying the process and further reducing costs. And last but not least, these materials have the potential to achieve all that in a completely environmentally friendly way. Nevertheless, additional research and product certification are still needed to bring these systems on board.

No smoking

Towards a hybrid engine

by Arvind Gangoli Rao

"The flight of a strong man by great muscular exertion, though a curious and interesting circumstance, in as much as it will probably be the first means of ascertaining this power, and supplying the basis whereon to improve it, would be of little use. I feel perfectly confident, however, that this noble art will soon be brought home to man's general convenience, and that we shall be able to transport ourselves and families, and their goods and chattels, more securely by air than by water, and with a velocity of from 20 to 100 miles per hour. To produce this effect, it is only necessary to have a first mover, which will generate more power in a given time, in proportion to its weight, than the animal system of muscles."

Sir George Cayley

It took a chain of visionaries, engineers and inventors, each of them solving a piece of the puzzle, almost another 100 years before the first manned, powered flight in 1903. Yet in his series of articles "On Aerial Navigation", Sir George Cayley effectively predicted the propulsion system as we know it today.

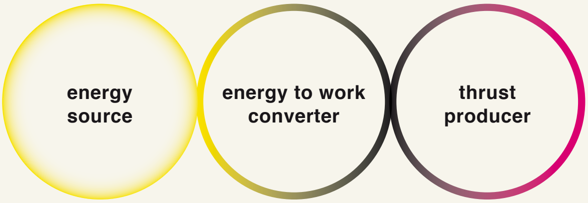


Fig. 89. The three elements of a propulsion system.

A modern propulsion system comprises of three synergistically working elements: the energy source, the energy-to-work converter and the thrust producer.
Batteries, kerosene, diesel, petrol, LNG (liquefied natural gas), hydrogen or even nuclear energy are all options for the energy source. Criteria to be taken into account when selecting an energy source are:

- Energy density (both in terms of mass and volume)
- Ease of storage
- Availability
- Safety

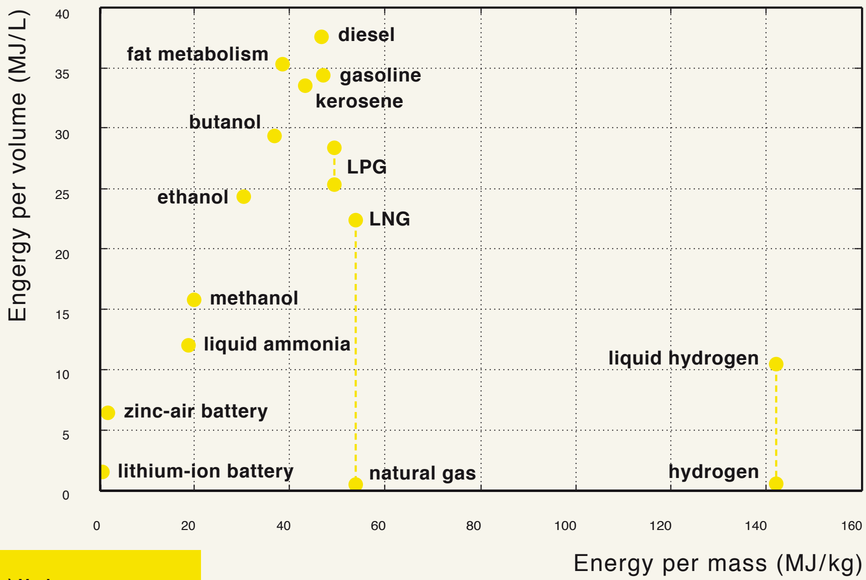


Fig. 90. (above) Various energy sources and their stored energy.

The energy carried on board must be converted into work by way of a heat engine or an electric motor. Such energy-to-work converters can be characterized by power range, power-to-weight ratio and efficiency. Military jet engines have the highest power-to-weight ratio, whereas electric motors have a very high efficiency, but are limited in their maximum power and have a lower power-to-weight ratio.

Type	Power to Weight (kW/kg)	Power range (kW)	Efficiency approx. (%)	Speed range (Mach N°)
Military engines	15	< 25000	30	< 2
Large turbofans	10	< 50000	40	< 1
Micro gas turbines	6	< 50	7	< 1
Turbo props	6	< 10000	42	< 0.7
Electric motors	5	< 250	95	< 0.5
Wankel engine	2.5	< 200	30	< 0.5
Radial engines	1.8	< 3000	30	< 0.5

Table: Comparison of energy-to-work converters.

Finally, the work has to be converted to thrust, either by expanding gases in a nozzle, as in a jet engine or by using a propeller, as in a turboprop engine. Both methods involve increasing the momentum of incoming air, thereby imparting a force / thrust.

Key drivers in the design and development of aircraft engines were the constant need for more power, a higher power-to-weight ratio and greater reliability. Military planners and strategists soon saw the potential of aircraft as a weapon of war. World Wars I and II saw many new developments in aircraft engines, such as rotary engines and radial engines. By the end of World War II, designers started to realise the limitations of the internal combustion engine with a propeller as a propulsion system in terms of limited speed and flight altitude.

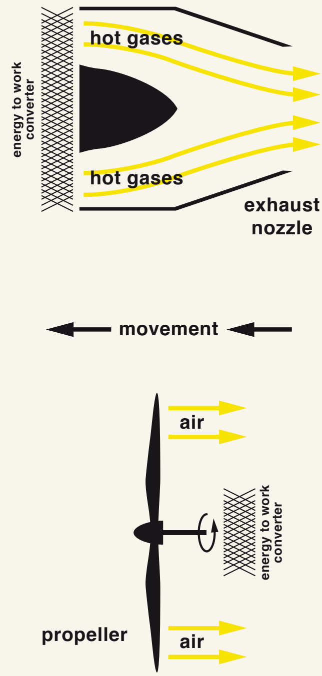


Fig. 91. Two types of thrust producers: exhaust nozzle (top) and propeller (bottom)

Energy source	Energy to work converter	Thrust producer
Li-ion battery 0.7 MJ/kg	**Piston engine** 1.7 kW/kg	**Propeller / Fan**
Li-sulphur 2.0 MJ/kg	**Wankel engine** 2.5 kW/kg	**Nozzle**
Gasoline / Kerosene 43 MJ/kg	**Electric engine** 3.5 kW/kg	
Hydrogen 120 MJ/kg	**Gas turbine engine** 7.0 kW/kg	
Uranium 85 TJ/kg		

Table: Various elements of a propulsion system.

THE JET AGE

The jet engine ushered in a new era in aviation. Around 1939, Sir Frank Whittle, a British engineer, and Hans von Ohain, a German scientist, independently developed a totally different propulsion system. Based on the Brayton cycle, it was referred to as the "Gas Turbine Engine" or the "Jet Engine". Sir Frank Whittle designed an aircraft engine capable of operating at high altitudes and speeds of up to 900 km/h, far beyond the operating limits of contemporary piston engines and propellers.

The first purpose-built jet airliner was the de Havilland Comet which entered into service in 1952. The coming of the jet engine redefined aviation. Early jet engines were driven by hot exhaust from the nozzle, but they were noisy and not very fuel-efficient. Engine designers solved this by using a large part of the energy to drive a fan that produced thrust with a cold low-velocity jet, rather than using the entire energy in the jet to produce thrust. This new engine architecture, called the turbofan engine, had higher fuel efficiency and was much less noisy.

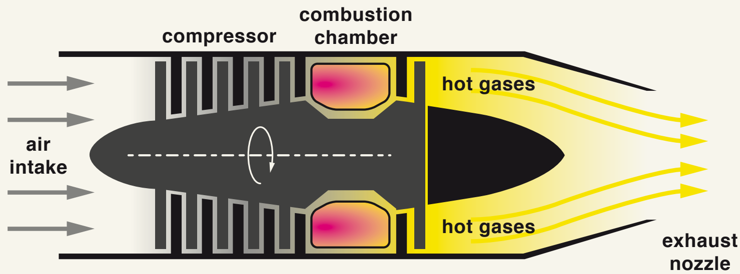


Fig. 92. Schematic of a Gas Turbine Engine (Jet Engine).

A gas turbine engine uses a rotary compressor and turbine to achieve the required compression and work extraction process. Unlike a piston engine, it does not have any reciprocating elements, and thus produces power on a continuous basis. Also, the mass flow intake of gas turbines is orders of magnitude higher than that of a reciprocating engine. Hence, their power/thrust output is also much higher.

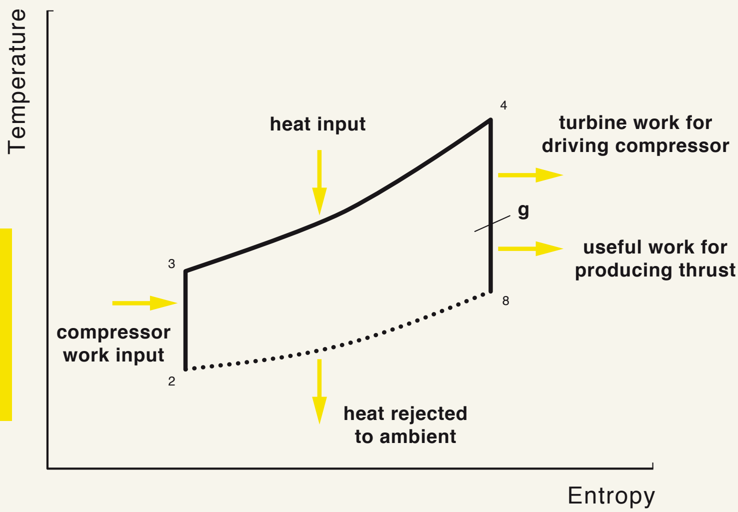
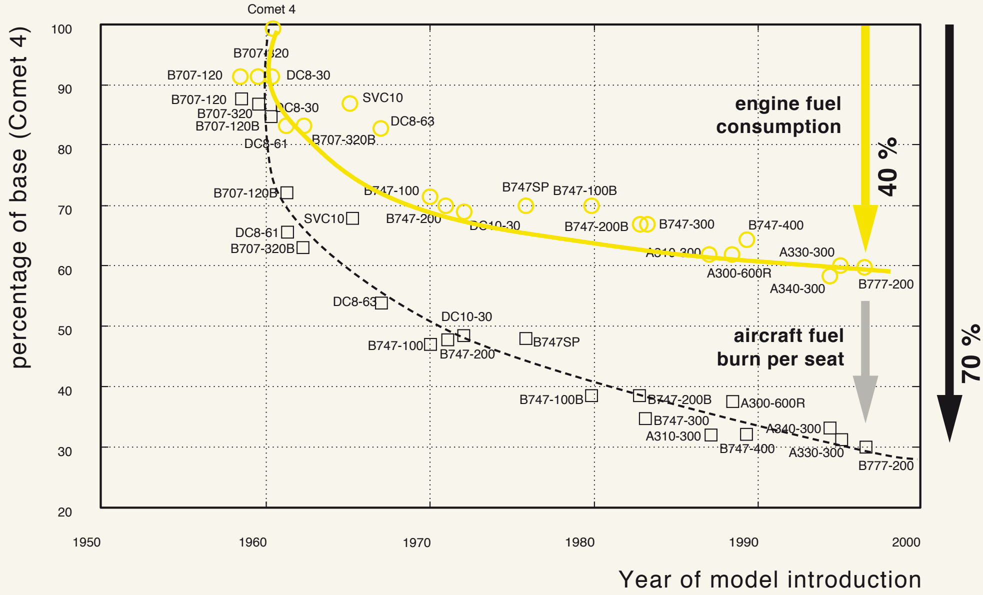


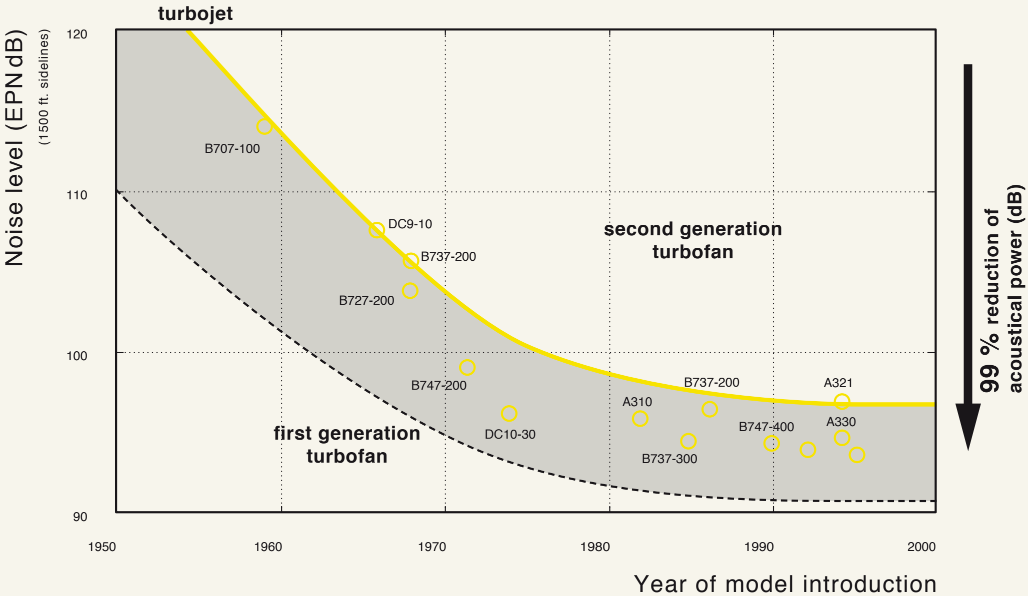
Fig. 93. The ideal Jet Engine thermodynamic cycle (Brayton cycle) depicted on a temperature-entropy diagram.

Modern aero engines operate at a high-pressure ratio of up to 50, and a high turbine inlet temperature of around 2000K to achieve high thermal efficiency. To enhance their propulsive efficiency, their by-pass ratio has been increased to around 10. The GE 90, which was put into service in the mid-90s, holds the world record for being the highest thrust-producing engine. It produces a thrust of over 500 KN (the Wright flyer produced a thrust of around 300N) and has a thrust-to-weight ratio of 5.6. The reliability of modern turbofan engines has also increased a lot, making air travel one of the safest modes of transportation.

NEW ENGINE ARCHITECTURES

Engine technology has improved drastically over the years. Aircraft fuel consumption has been reduced by over 70% in the last five decades; more than 40% out of this was due to engine development. The remaining 30% are due to developments in aerodynamics, structural materials, controls, avionics and better fleet utilization. The reduction in noise levels has also been dramatic. In terms of acoustic power, the noise radiated by modern turbofans is 100 times less than that of the early turbojets.





(Normalized to 100 000lb thrust. Noise levels are for configurations at time of initial service.)

Fig. 94. (top) Decrease in aircraft fuel consumption over the years. (source: IPCC, J.E. Penner et al.)

Fig. 95. (bottom) Decrease in noise emitted by aircraft over the years.

Modern turbofan engines combine a high bypass ratio (BPR) with reduced fan tip speeds. This leads to a reduction of the LP (low pressure) shaft speed and a subsequent increase in the number of stages for the LP compressor and the LP turbine (LPT), in order to retain satisfactory efficiency and pressure ratios for these components. In addition, reduced speed also imposes higher torque requirements on the LP shaft, resulting in larger shaft diameters. The Geared Turbo Fan (GTF) engine concept addresses these problems by introducing a reduction gear system to de-couple the fan from the rest of the LP Systems, namely booster, shaft and LPT. The GTF system allows the fan to operate at a slower, optimum speed while letting the booster and the LPT to operate at their higher optimum speeds. However, the additional weight and complexity of the gear system can reduce some of these benefits.

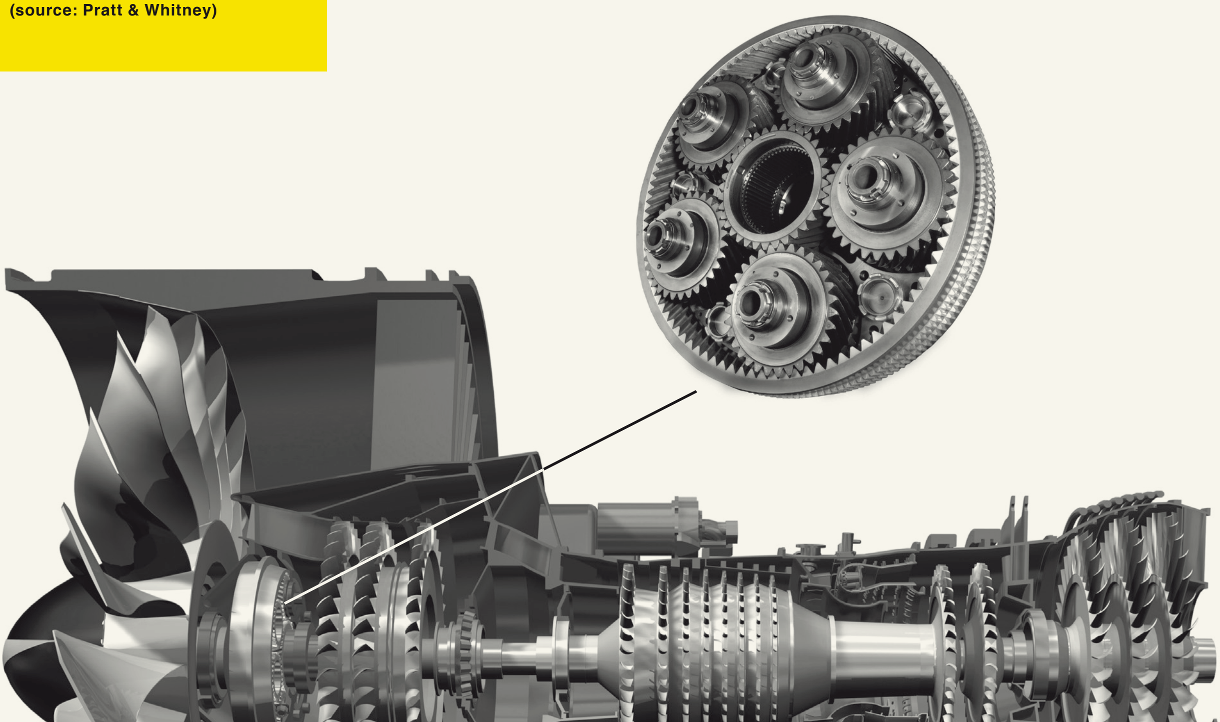
The GTF concept has a number of advantages over a direct drive high BPR engines:

- Slow fan speed, hence lower fan noise
- Improvement in booster efficiency
- Higher LPT loading, hence reduction in the number of LPT stages
- Increased propulsive efficiency, hence reduction in specific fuel consumption

Pratt and Whitney first demonstrated a GTF engine for a commercial aircraft. Their Pure Power PW1500G (shown in the following figure) is to be brought into service for the Bombardier C series by 2015.

Fig. 96. The Pratt & Whitney geared turbo fan engine PW1000G showing the sun and planetary gear system.

(source: Pratt & Whitney)



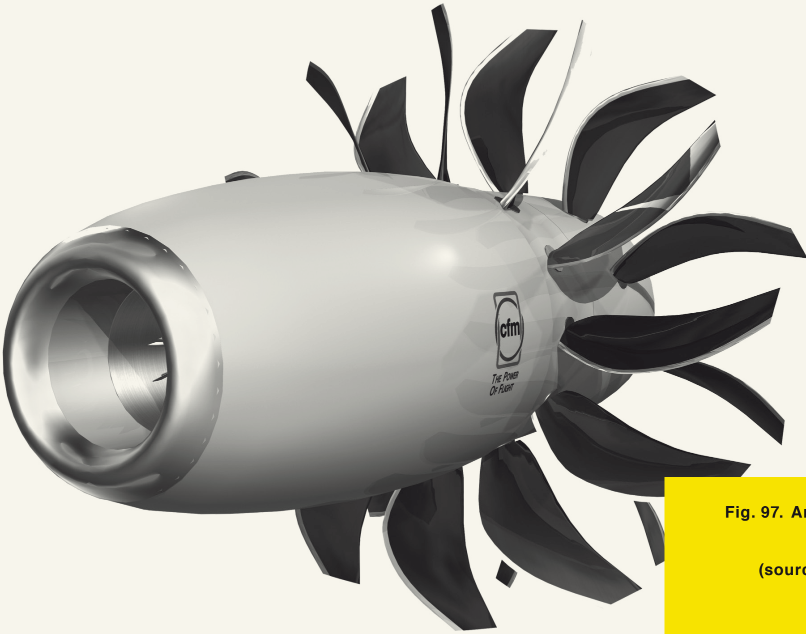


Fig. 97. An open rotor turbo fan engine by CFM.

(source: CFM International)

OPEN ROTOR TURBOFAN ENGINE

An unducted fan or open rotor engine is a modified turbofan engine, with the fan placed outside of the engine nacelle on the same axis as the compressor. Open rotor engines are also known as ultra-high bypass (UHB) engines or unducted fan (UDF) engines. This design aims to offer the speed and performance of a turbofan with the fuel economy of a turboprop.

This concept is not new; it was investigated by GE and NASA in the late 1970s and was recently revived by CFM. CFM's open rotor vision with two sets of contra-rotating blades is slated to have a bypass ratio of 35:1. To ensure maximum efficiency during every stage of the flight, each blade will have its own pitch change mechanism. However, the main concern with this concept is its high noise intensity, especially during take-off. Moreover, installing these large diameter engines on conventional aircraft is challenging and can reduce the benefits substantially. Also, due to the unshielded blades, blade containment is a major safety issue.

So far, the increase in fuel efficiency was primarily due to the increase in the bypass ratio (BPR) and the increase in the core thermal efficiency. Unfortunately, increasing the BPR even further is not an option. For the GP7000 engine designed for the A380, for example, the BPR had to be reduced in order to comply with noise emission restrictions. Therefore, to continue on the path of decreasing fuel consumption and noise further, we need a paradigm shift in propulsion technology for airplanes.

FUTURE PROPULSION SYSTEMS

An important difference between aviation and other industries is the timescale. While most sectors of industry are used to market changes every few years, the timescale in aviation spans decades. It takes around 15-20 years before a new technology can be incorporated in an aircraft or engine. As the life of an aircraft is around 30 years, technology developed in the 1990s will still be in use in 2030 and beyond. What we do today affects the industry for many years, hence we must plan for the far future.

> **"The best airplanes can only be designed around the best engines."**
>
> **Frederick Rentschler**

The propulsion system spearheaded developments in aviation. Improvements in the propulsion system were for a large part behind the 70% decrease in fuel consumption over the last five decades. However, with 4.5% annual growth predicted over the next decades, the sector is faced with new challenges, most notably the environmental impact of aviation. Efficiency, emissions, energy sources and noise are now aviation's main areas of focus.

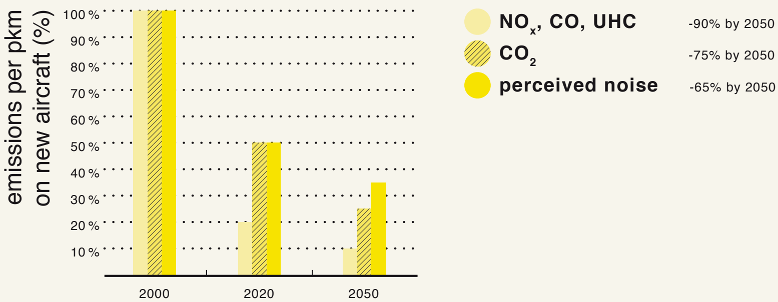


Fig. 98. The ACARE goals.

The Advisory Committee for Aeronautics Research in Europe (ACARE) has set the aviation sector some very ambitious goals. Complying with ACARE goals will not require evolution but rather, revolution. Current aircraft technologies have reached a technological plateau. The classical aircraft configuration – a cylindrical fuselage with wings – is bound to change after serving aviation for over seventy years.
The most important reason is that a cylindrical fuselage creates drag and does not contribute to the aerodynamic efficiency of the aircraft. The novel configuration of a blended wing body, or BWB, would solve these problems, but what would that mean for the propulsion system?

Apart from fuel efficiency, the engine can play an important role in meeting the other major challenges to aviation. Future propulsion systems, such as for a BWB, should incorporate:

- *Low Emissions*: The contribution from aviation to the global warming is widely debated, with estimates ranging from 3-5%. With an expected annual growth in aviation of around 4.5%, this number is set to increase further. The ACARE has set ambitious goals for aviation in 2050; these are known as Flight Path 2050. The target reduction in CO_2 emission is 75%, and for NO_x

and CO even 90%, compared to a baseline aircraft from 2000.

- *Low Noise*: Since most airports are located in close proximity to residential areas, restrictions on noise emission are stricter than ever before. ACARE targets a reduction in cumulative and perceived noise levels from engines and airframes of around 65%.
- *A Lower Installation Penalty*: The current trend in aero engines is to increase the engine's BPR, making for larger engines. Even though the Specific Fuel Consumption (SFC) of such engines is lower, the resulting aerodynamic drag and weight is large, thus increasing their installation penalty. This penalty will become more prominent when looking into new aircraft configurations such as the BWB aircraft.
- *Boundary Layer Ingestion (BLI)*: Future aircraft designs would have stringent requirements on engines in terms of aircraft-engine integration. BLI refers to the technology where the engine is partly embedded within the aircraft fuselage, so that it ingests part of the boundary layer that develops over the aircraft. The potential advantages of BLI are that it:
    1. reduces the aerodynamic drag of the aircraft,
    2. increases the propulsive efficiency of the engines, and
    3. enables embedded engine installation to reduce noise significantly.

The aircraft-engine integration for such configurations requires that the engine is buried within the nacelle and that the engines (and fans) are smaller in diameter. Large fans

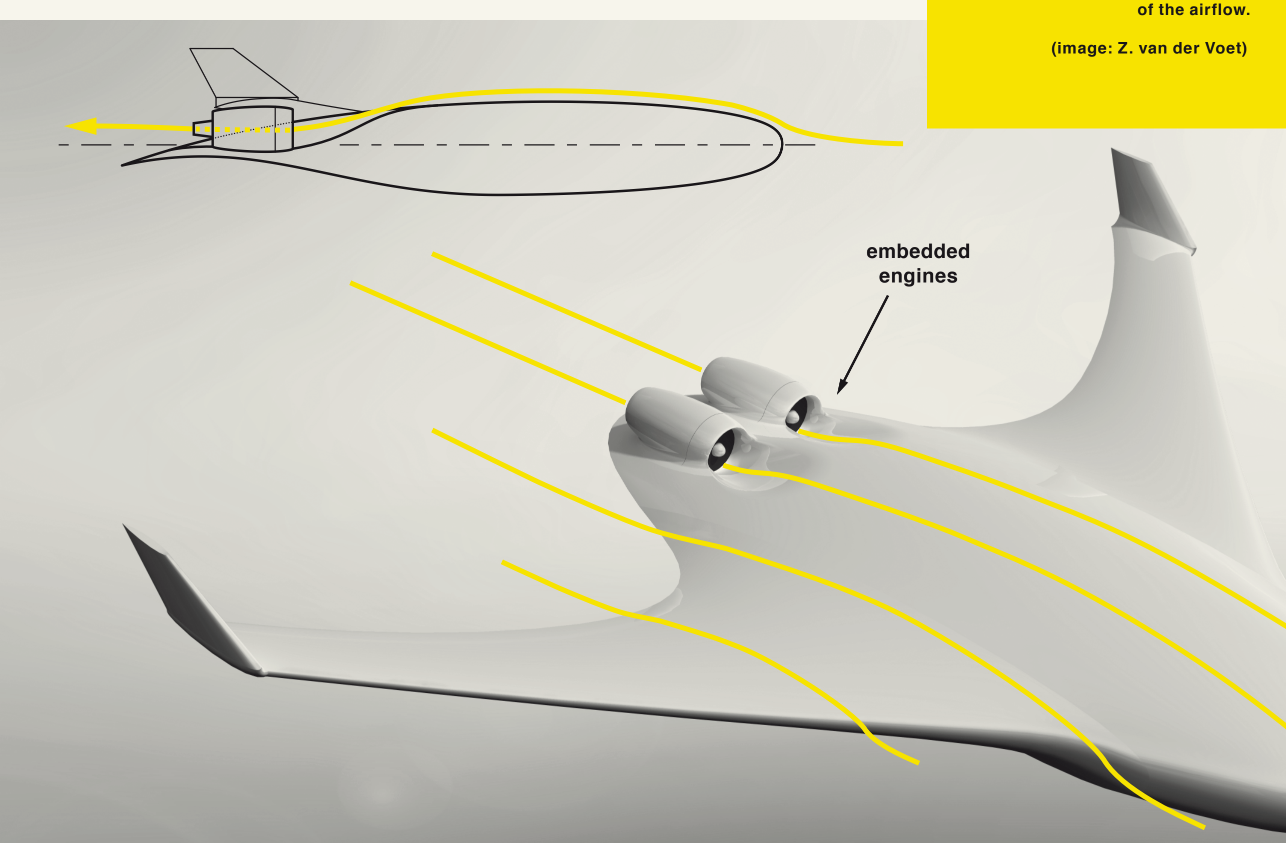


Fig. 99. Embedded engines can ingest part of the boundary layer of the airflow.

(image: Z. van der Voet)

cannot withstand the distortions in the inlet, therefore smaller, more robust and lightly loaded fans would be needed. Contra-rotating fans with a smaller diameter might be a solution.

- *Alternative Fuels*: Right since the beginning of aviation kerosene has been used as the fuel of choice. However, in the future this will change because of dwindling fossil fuel resources. If aviation has to sustain itself economically, then alternative fuels must be investigated. The following figure depicts the expected trend for future aviation fuels. In the later part of this century, hydrogen-rich fuels (such as LNG) will become more popular due to their availability, cost, ease of use and lower CO_2 footprint.

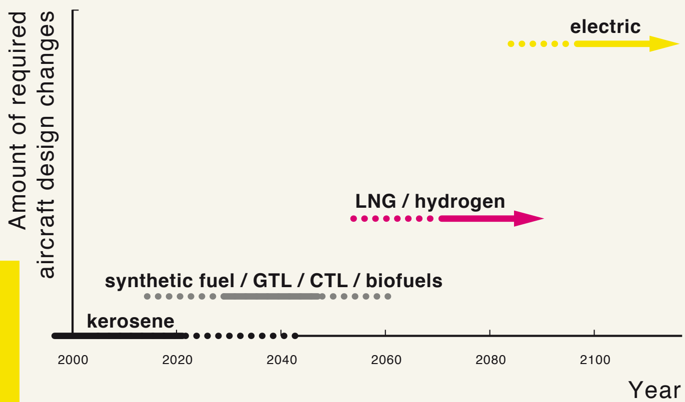


Fig. 100. The expected trends for future aviation fuels set out against the necessary design changes for their implementation in aircraft.

THE MULTI-FUEL BLENDED WING BODY AIRCRAFT

One of the main challenges for aviation in the future is the energy source. The amount of fuel needed by the aviation industry has exceeded a billion liters per day and this is set to double over the next twenty years. Moreover, kerosene is on the verge of depletion and CO_2 emissions are increasing. Several alternatives are being investigated, such as biofuels and gas to liquid (GTL) fuels.

The introduction of biofuels is far from straightforward. The problems surrounding the availability of biomass, the variation in fuel properties depending on the feed stock, the competition with the food chain, and the scaling up of the production process will all have to be solved for biofuels to become a successful alternative to kerosene. It is therefore to be expected that biofuels will only be used as a drop-in fuel. If we want to reduce the CO_2 footprint of aviation significantly, we will have to switch to hydrogen or hydrogen-rich fuels such LNG. However, these fuels have to be stored at low temperatures in pressurized cylinders. Current wing volumes are not sufficient for storing such pressurized cylindrical vessels. The use of hydrogen-rich fuels calls for an innovative new aircraft concept.

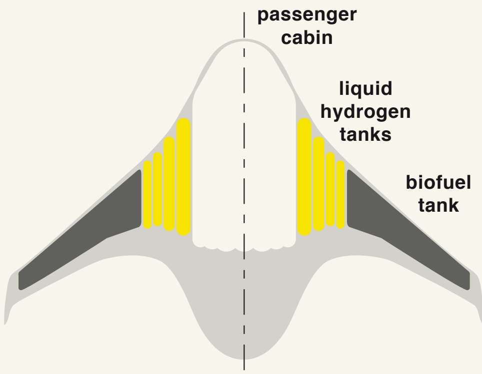
Research has been done into the feasibility of carrying LH_2 or LNG in conventional aircraft. The benefits of LH_2 are its positive effects on the environment. Several EU sponsored research projects are looking into the production of hydrogen: GreenAir and the FCH JTI. EU project ALFA-BIRD looked into the development of alternative fuels and biofuels for aviation.

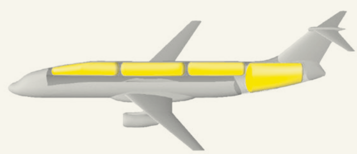
Another EU project studied the Cryoplane concept and showed the advantages of using hydrogen for aviation. However, storing the cryogenic fuel tanks within the aircraft proved to be a problem. In conventional aircraft fuel is stored in the wings, but this is not possible for cryogenic fuel. Cryogenic fuel has to be stored in pressurized cylinders and the wings of a conventional passenger aircraft are too thin to accommodate cylindrical tanks. The LH_2 storage scheme envisaged in the Cryoplane project was a bubble fuselage: a large cylindrical tank placed above the cabin. Because of the lower volume density of LH_2 and LNG, the body of the aircraft has to be enlarged to be able to carry the necessary fuel, resulting in an aerodynamic penalty.

The Blended Wing Body (BWB) is a promising concept for the use of alternative fuels. Instead of a separate fuselage with wings, a BWB integrates body and wing. Thus, more space becomes available within the aircraft, making it possible to carry cylindrical fuel tanks. The cryogenic fuel tanks can be stored without interfering with the passenger section. The wing root sections of a BWB have sufficient room for storing LH_2 tanks. Liquid biofuel can be stored further away from the centerline, where wing thickness is reduced. That way, a combination of biofuel and cryogenic fuel becomes a viable energy alternative for future aircraft configurations.

Fig. 101. (left) A BWB concept showing the layout of multiple fuel tanks within the body.

Fig. 102. (below) LH_2 tanks storage scheme for the Cryoplane project.





THE HYBRID ENGINE

In order to make aviation sustainable, both in terms of reducing the fuel consumption and emitting less CO_2 at higher altitudes, new engine configurations have to be explored. A novel engine configuration can meet all these requirements: the hybrid engine. This proposed engine is a rigorous departure from the conventional turbofan and includes a number of breakthrough technologies. This engine was investigated in the EU-sponsored AHEAD project within the FP7 framework program.

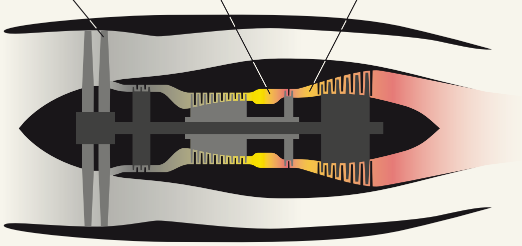


Fig. 103. Schematic of the proposed hybrid engine layout.

Salient features of a hybrid engine:

- A contra-rotating fan
- Two combustion chambers:
    1. a main combustion chamber on cryogenic fuel (LNG or LH_2)
    2. a secondary inter-turbine flameless combustion chamber on liquid fuel (kerosene or biofuel)
- Bleed cooling by the cryogenic fuel (LNG or LH_2)

Contra-Rotating Fans (CRF) - The BWB class of aircraft presents unique aircraft engine integration challenges which require the engines to be buried within the nacelle. The current trend of increasing bypass ratio and diameter of engines is not going to meet the requirements of future BWB class of aircraft. The proposed hybrid engine with contra-rotating fans will have a smaller diameter and higher propulsive efficiency for the same bypass ratio. Also, since each stage of the fan is less loaded than single stage fan architecture, a CRF can sustain more non-uniformities in the flow generated due to BLI than a conventional architecture.

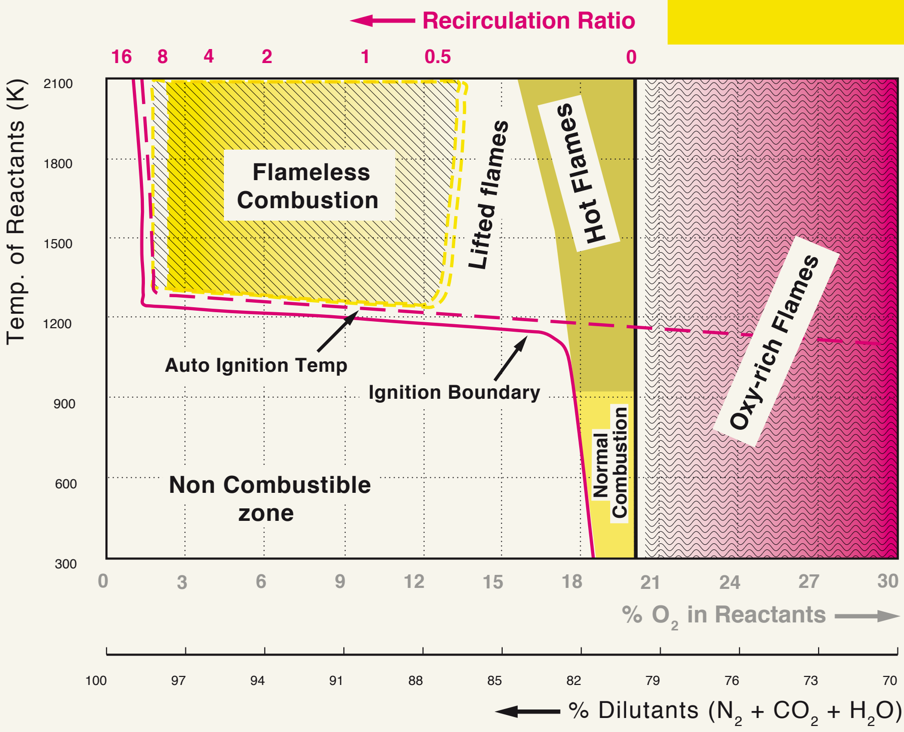
Dual Combustion System - The proposed hybrid engine uses two combustion chambers. The main combustor operates on the cryogenic fuel (LNG or LH_2). The second combustor between HPT and LPT, uses liquid fuel (biofuel or kerosene) in the flameless combustion mode. Such a combustion system has never before been used in aero engines.

The advantages of this unique design are:

- Since the flammability limit for CH_4 (methane, which is the largest component of LNG) is wider than for kerosene, combustion can take place at lean conditions, potentially reducing NO_x emissions in comparison with a conventional kerosene combustor. Lean direct injection (LDI) combustion technique (as discussed in chapter 10) is an ideal candidate for burning gaseous fuel such as CH_4 or H_2. The LDI combustion technique produces very low levels of NO_x emissions and has several other advantages over conventional combustors.

- The length of the LDI combustor would be less than that of a conventional combustor, thus reducing the distance between the high-pressure compressor (HPC) and the high-pressure turbine (HPT). This reduces the HP spool shaft weight and may also enhance its rotodynamic behavior of the engine.
- Before being used in the first combustor, the cryogenic fuel will be used for cooling the bleed air (tapped from the HPC for cooling the turbine vanes and blades). This reduces the amount of bleed air required for turbine cooling and thereby increases the overall efficiency of the engine.
- Using fuel from the first combustion chamber will increase the concentration of water vapour and reduce the concentration of O_2, thus creating a vitiated environment for the inter-turbine flameless combustor in which Flameless Combustion can be sustained using biofuel / synthetic fuel such as GTL/CTL or any other liquid fuel.
- The use of flameless combustion technology for the second combustor will reduce the emission of CO, NO_x, UHC and soot to a minimum.
- The reduced emission of soot and UHC will reduce the amount of nucleation centers available for condensation of water vapor in the plume, thus reducing the contrail formation.

Fig. 104. Various combustion regimes.



Bleed Cooling - The thermal efficiency of a gas turbine engine increases with increasing pressure and temperature. However, this also results in the temperature increase of the bleed air (the air that is used for cooling the hot section components like the turbine blades and vanes), thus increasing the amount of bleed airflow required to cool the hot components. This increase in bleed air has an adverse effect on the thermodynamics of the gas turbine engine, reducing the efficiency of the cycle substantially.

The proposed hybrid engine uses both cryogenic fuel and biofuels. The cryogenic fuel is an excellent heat sink and can be used for cooling the bleed air (via a heat exchanger) prior to being used in the first combustion chamber, thus significantly reducing the amount of bleed air required. Also, by using this novel technique, the amount of heat released by the fuel in the combustion chamber increases slightly, therefore reducing the fuel requirement even further. Studies have shown that using this novel technique can reduce the engine fuel consumption by more than 6%.

ADVANTAGES OF THE HYBRID ENGINE

- **Multiple fuel capability (cryogenic fuel and biofuel)**
- **Dual Combustion chamber (LH_2 / LNG Combustor & Biofuel / Kerosene Flameless combustor)**
- **Contra-rotating shrouded fans for enhanced propulsive efficiency and boundary layer ingestion**
- **Smaller engine diameter**
- **Turbine bleed air cooling by the cryogenic fuel**
- **Low installation penalty**
- **Significant reduction in CO_2 emission (30% with LNG and 90% with LH_2) as compared with a baseline engine of PW4056**
- **Significant reduction in NO_x (around 60%)**
- **Lower noise emission on the ground due to BLI**

Most major breakthroughs in aviation stem from advances in propulsion technology. Propulsion technologies are set to play an even greater role in shaping the future of aviation.

Hushing jet-engines

Noise suppression

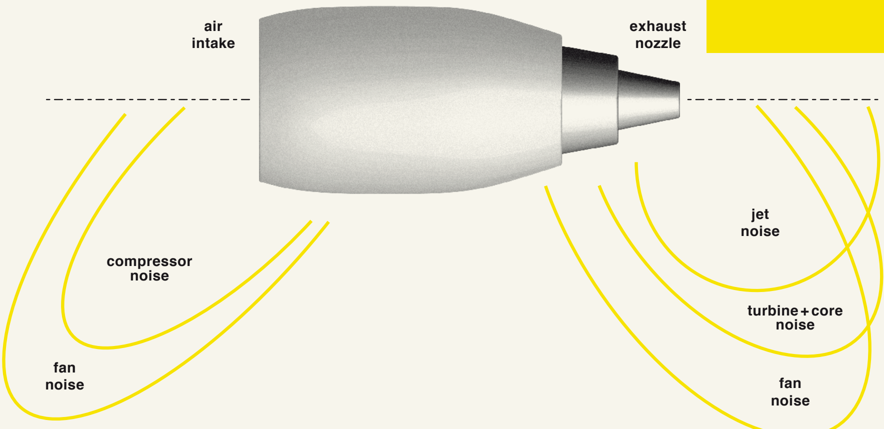
by Chara Lada

The air transport industry has to reckon with growing environmental concerns. Those related to noise have already been acknowledged by POST (the Parliamentary Office of Science and Technology) as "one of the most objectionable impacts of airport development".

Jet engine noise reduction has become a challenge that requires serious attention from industry as well as academia, because a limit has been reached where further noise reductions cannot be achieved without using extra fuel, causing additional emissions. Hence, new technologies have to be developed, since aviation can only continue to grow as long as noise nuisance is further reduced.

This chapter deals with the noise emissions associated with the jet engine, specifically those that are caused by the fan and the high speed propulsive gas.

Fig. 105. Noise sources of a jet engine.



NOISE OF THE JET ENGINE

Shortly after the introduction of the jet engine for commercial applications, it became clear that jet noise was going to be a problem, especially in the vicinity of airports. Jet engine noise is very different from the sound produced by a propellor-driven aircraft, both in amplitude and in sound character. It is a low frequency rumble that transmits over long distances. - So what exactly causes the noise of a jet engine?

FAN AND COMPRESSOR NOISE

Like all rotating machines, the fan and compressor emit both tones with a narrow-band frequency (screech) and broadband noise. The tonal mechanism has been studied extensively over the years.

Tonal or periodic noise is a discrete frequency noise and is perceived as irritating and repetitive. Some examples of tonal noise sources are fans, saws, motors and pumps. Broadband noise is the type of noise that has components over a wide range of frequencies.

The aerodynamic phenomena described below occur on all engineering applications with blades, like wind turbines or helicopters.

TONAL OR PERIODIC NOISE

Tonal noise is a discrete frequency noise and is characterized as irritating and repetitive. Some examples of tonal noise sources could be fans, saws, motors and pumps.

Rotational Noise - Rotational noise is caused by air-volume displacement effects; each passing blade disturbs the air and produces a regular pulse observed by a stationary observer. This type of noise simply results from the regular parting of the air; it is called thickness noise and becomes important at high speeds. Rotational noise is also emitted due to the unsteady pressure on the blade surface, for example on a helicopter rotor. Since there is a difference in relative speed during forward and backward motion of the blade, a cyclic incidence variation is required to provide a uniform lift over the disc. When observed from a steady point in the air next to the disc, the force appears constant under these conditions, but from a fixed point on the disc the rotating field appears as an oscillating force. The frequency of the oscillation is the blade passage frequency (BPF), the frequency with which the blade passes a fixed point.

This type of noise is generally referred to as loading noise and dominates at low speeds. The localised effects in the fluid around the blade, when the Mach number of the blade relative to the local airflow approaches or exceeds unity causes Mach or shock waves to form and can be a source of intense noise.

Interaction and Distortion Effects - Blade slap occurs due to three mechanisms:

1. **Blade vortex interaction,**
2. **Blade stalling and un-stalling,**
3. **Shock wave formation and collapse at the tip of the blade.**

Blades often pass through or near a tip vortex, or through the unsteady wake field of preceding blades and these unsteady flow fields cause strong fluctuating forces on the blade. Blade slap is generally unavoidable, especially in applications such as fan rotors where the blades are very close to each other. Most current fans and compressors have about twenty to fifty blades and even more stators. Shock waves result from the rotation of blades with high tip speeds. In propeller applications, modern designs have very thin blades and they are swept back at the tip so that the component of velocity at the leading edge remains subsonic. This mechanism of noise emission is also known as buzz saw noise.

BROADBAND NOISE

Broadband noise is the type of noise that has components over a wide range of frequencies.

Vortex noise - The formation and shedding of vortices behind a blade is a source of broadband noise called vortex noise. The process of vortex shedding in a rotating airfoil is similar to that of an infinitely long cylinder you find in a laminar flow. An orderly vortex street is shed; this is a function of the cylinder diameter and the flow velocity. The different velocities that are associated with different chordwise locations of the blade along the span result in broadband shedding frequencies and a dipole form of acoustic radiation results, in which the strength of the source is proportional to the 6th power of the section velocity. The noise produced by this mechanism combines with vortex noise caused by the lift force on the blade. Additional tip and spanwise vortices are formed, proportional in strength to the force gradients. Their dipole acoustic radiation is combined with that of the trailing edge vortices to make up the vortex noise.

Narrow band vortex shedding - Occasionally a laminar boundary layer exists on one or both sides of the airfoil and does not develop to fully turbulent prior to the trailing edge. If the trailing edge of the blade is within an instability region where Tollmien-Schlichting (T-S) waves are present, a closed loop phenomenon is formed that emits noise. The T-S waves propagate downstream from an instability point on the blade towards the trailing edge, where scattering occurs and acoustic waves are generated. These acoustic waves then travel upstream, past the origin of the boundary layer instability. The point of instability needs to be far enough upstream of the blade trailing edge to allow sufficient time for the natural amplification of the waves.

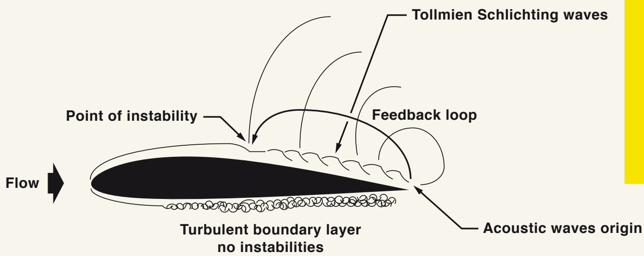


Fig. 106. Schematic feedback loop of the narrow band vortex shedding noise.

TURBINE NOISE

Turbines produce noise through the same mechanisms as the compressor, since both consist of several stages of stationary and rotating blades. However, there are some vital differences:

- a turbine has many more blades,
- the spacing between adjacent rotor and stator is generally much less, and
- the flow ahead of the turbine is choked.

The higher number of blades causes tones of much higher frequency than in a compressor. Compressors cause tones in the order of 40 Hz or less, but their noise nuisance is similar. Other problems need to be taken into account, such as the vibration of lightweight structures, or the effect vibration might have on high precision equipment.

The spacing between rotor stages and stator stages causes tonal noise to dominate and the choked flow upstream prevents the tones to propagate in that direction. Instead, all the energy is radiated through the exhaust nozzle. Because of the shear layer of the jet mixing with the atmosphere, the tones refract and become more diffused and are sometimes mistaken for broadband noise.

With the ultra-high bypass ratio engines, sources of noise that were thought insignificant in the past start to attract the attention of scientists. One of these is turbine noise.

JET NOISE

Jet noise is broadband, meaning it has components over a wide range of frequencies. It has been studied the most and appears to be the hardest to reduce by either mechanical or aerodynamic means.

Jet mixing noise is caused by the violent mixing of the turbulent hot exhaust plume with the cold air of the atmosphere. The small eddies of the turbulent plume near the nozzle lip cause high frequency noise and as the plume propagates the eddies get bigger and cause low frequency noise.
In the 1950s British mathematician Sir James Lighthill published a research study about the 8th power law. According to this law, the acoustic power radiated by the fluctuating shear stress in the mixing region behind the nozzle, creates broadband noise proportional to the 8th power of the jet speed. Lighthill's work also showed that jet noise was dependent on temperature. If the temperature of the plume rises, jet noise also increases. However, core jet temperature stays more or less constant, so the velocity of the jet is still the most important factor.

All in all, for zero or low bypass ratio engines with jet velocities up to 600 m/s, jet noise is the aircraft's dominant noise component throughout all missions.

CONE OF SILENCE

An interesting feature of this noise is called the 'cone of silence'. This is a region within 10° to 15° of the jet exhaust axis, viewed along the exhaust axis and into the back of the engines, where jet noise becomes almost inaudible due to refraction effects. This image shows a numerical simulation performed by GE in order to fully understand and reduce such noise sources. This phenomenon though is highly dependent on turbulence and hence difficult to predict.

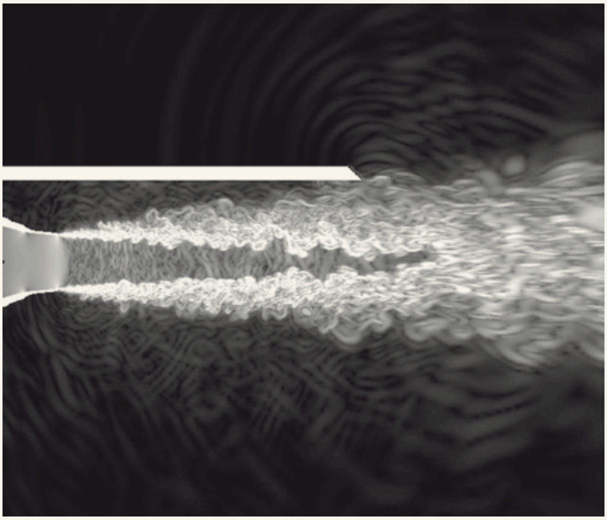


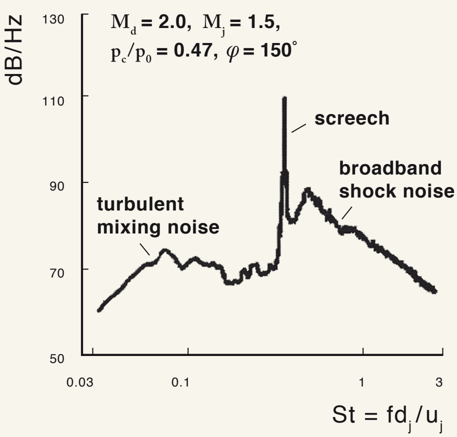
Fig. 107. Noise Generation from a low speed jet. Argonne Leadership Computing Facility at Argonne National Laboratory.

(Visualization: Joe Insley, ANL; Simulation: Umesh Paliath, GE.)

The expansion diamond shocks that are generated aft of the exit nozzle are part of a noise mechanism that has both tonal and broadband components. The broadband component is emitted through the quasi-static shock cell structures in a narrow frequency band compared with turbulent mixing. The tonal component originates through a feedback mechanism between the shocks and the nozzle lip.

DIAMOND SHOCK WAVES AND THE FEEDBACK LOOP
The vertical structures that are created and shed periodically from the nozzle lip propagate downstream in the mixing layer by the mean flow. When these vortices traverse the shock cells in the plume they set the entire shock structure in motion. Pressure disturbances are developed due to the shock motion and acoustic waves propagate upstream to excite the thin shear layer of the jet near the nozzle lip. This leads to continuous shedding of vortices and closes the loop.

The figure below shows a typical far field supersonic jet noise spectrum, where all three noise components are presentl: turbulent mixing, broadband associated shock noise and screech in the 1-Hz bandwidth. The figure on the right shows the feedback loop as captured in a Schlieren image with the feedback shock originating at the third shock-cell during intense screech at Mach n° 1.4.



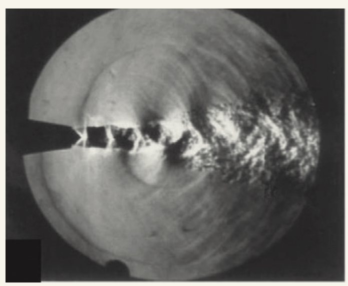


Fig. 108. (left) Supersonic jet noise spectrum showing all three components of jet noise. (source: J.M.Seiner, 1984)

Fig. 109. Schlieren photograph of a feedback shock.

COMBUSTION NOISE

The total noise resulting from combustion in a jet engine is called core noise. For many years this type of noise was loosely attributed to the jet mixing noise. It was not until the mechanisms of jet mixing were fully understood that the two different components were distinguished, but even then core noise research was mainly directed towards rocket engines and afterburners. A few years ago, a new premixing process was tried out, where fuel and air are premixed at higher temperatures, prior to combustion. It was an attempt to reduce emissions, but as a side-effect it did increase noise oscillations. By now most of the jet engine's other noise sources could be suppressed, so research attention was finally drawn to combustion noise.

The mechanisms generating noise in combustors are:

Direct noise - This is caused by the combustion process itself. It is emitted when a volume of gas is heated at constant pressure. The expansion of the gas forces the surrounding gas to expand as well, and this produces a sound wave that propagates outside the flame. The pressure inside the sound wave, hence the intensity of the sound, depends on the rate of volume generation by the source. The source can be described as a monopole. Two parameters are important for the description of the direct combustion noise: the sound radiated power and the thermo-acoustic efficiency, which is the ratio of the sound emitted power to heat released during the combustion. Of course, only a small fraction of the total thermal power transverses into acoustics.

Indirect combustion noise, or entropy noise - This is caused by the flow of hot combustion products through the turbine and exhaust nozzle. It is generated when a fluid with a non-uniform entropy distribution is accelerated in or convected through the nozzle located at the downstream end of the combustion chamber.

The most important factor that controls combustion noise is engine power, because as engine power increases, the mass flow rate through the combustor increases as well as the temperature level. Other factors that can make a difference are the fuel type, the operating conditions (inlet air temperature), the fuel injector instabilities and the pressure fluctuations in the air supply from the compressor.

NOISE SUPPRESSION

A number of noise control methods have been successfully applied over the past decades.

Turbines and compressors:
- Increasing the distance between rows: to minimise blade wake interactions.

Propellers:
- Increasing the number of blades. This places the harmonic tone energy above the audible range or into the range above 3-4 Hz where it is less annoying to human ear and is absorbed by the atmosphere much faster. This method has been applied for many years now, and most four-bladed designs have been replaced with six-bladed designs.
- Differentially selecting blade numbers. When blade numbers are equal in all rows, noise is excited at the same frequency bands with higher energy.
- Reducing tip speed so that blade Mach numbers are reduced.

Other methods to reduce fan and compressor noise have not been put into practice yet. These include shielding the noise by placing the jet engine on the frame of the aircraft to redirect the noise upwards instead of downwards.9 Another one is boundary layer ingestion (BLI), where the turbulent boundary layer of the fuselage is directed to the propulsor. This is expected to improve fuel efficiency because it reduces drag, but noise reduction is also probable as the curved geometry of the S inlet duct could increase the attenuation of inlet radiated noise. However, the increase in fan noise resulting from the flow distortion could offset these potential benefits. An analytical or an experimental assessment of the technology has not yet been made.

So far, some common ways to suppress jet noise involve the use of different nozzle shapes and linings. Nozzle shapes with deep corrugations, lobes or multi-lobes, give the largest noise reduction, but it is important to maintain the same overall area as the basic nozzle, because the bigger and heavier the nozzle, the higher the performance penalties. Noise absorbing lining materials convert acoustic energy into heat. Their porous skin is supported by a honeycomb backing. They slightly increase the weight and the surface drag, but they are a powerful suppression method.

The most successful method to suppress jet noise is to mix the hot and cold exhaust streams within the engine and use a single nozzle to expel the gases that have cooled down. Combined with a recently developed nozzle shape called a chevrons, this method was a breakthrough in engine jet noise. Chevrons are the saw-tooth pattern at the trailing edge of the jet engine nozzle. As hot air from the engine core mixes with cooler air blowing through the engine fan, these edges serve to smooth the mixing, which reduces turbulence, and therefore, noise.

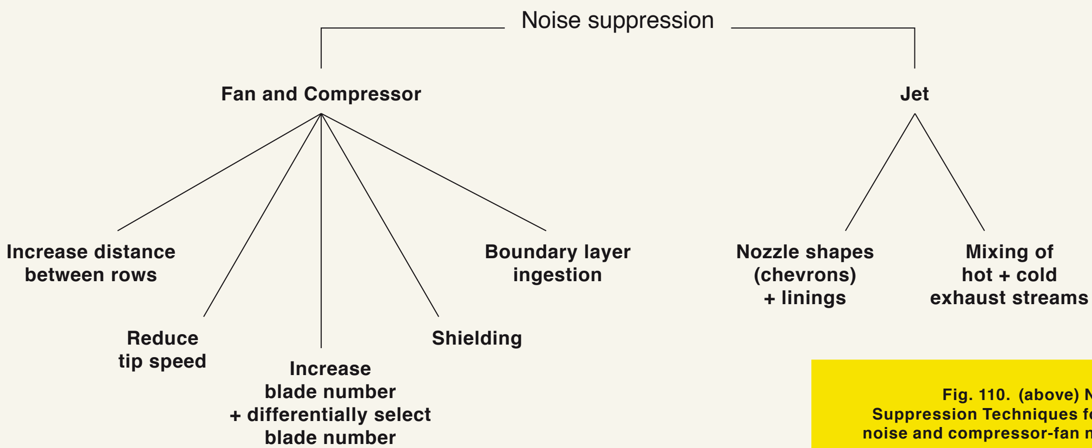


Fig. 110. (above) Noise Suppression Techniques for jet noise and compressor-fan noise.

Fig. 111. Chevrons on a jet engine. (photo: Olivier Cleynen)

SOME INTERESTING NOISE REDUCTION RESEARCH PROJECTS

The Silent Aircraft Initiative was a project funded by the Cambridge MIT Institute. The main aim of the project was to design an aircraft that would not be heard outside the vicinity of the airport. This project did not concentrate only on reducing engine noise but on the total noise emission of the aircraft. A blended wing body configuration was considered the most promising. The study of noise reduction regarding the engines resulted in some interesting concepts:

- Embedding the engines into the airframe of a blended wing body to shield the noise.
- Making a variable geometry exhaust system allowing a smaller, low-weight engine that can be quiet at low altitude and efficient at cruise.
- Using several smaller engines as opposed to a single engine.
- Using extended exhaust ducts that minimise rearward propagating noise using advanced acoustic liner technology.

Propulsion Noise Reduction Concepts and Progress is a NASA project supported by the Subsonic Fixed Wing Project and the Environmentally Responsible Aviation Project. The project is looking at three ways to reduce engine noise:

- To change the engine cycle by increasing the engine bypass ratio even further
- To apply noise reduction technology, such as next generation liners and soft vanes. These are vanes with internal chambers that are tuned to various frequencies for various noise cancellation issues.
- To shield the noise by using the body of the aircraft to shield the engine, mainly for open rotor engines.

CLEEN Engine Program - In June 2009, the FAA awarded a total of 125 million dollars to Boeing, General Electric, Honeywell, Pratt and Whitney and Rolls Royce North America to participate in the Continuous Lower Energy, Emissions and Noise (CLEEN) program. This is a very demanding program that targets 2015 for these technologies to enter into service. Some of the main goals are a 33% cut in fuel burn, a reduction of NO_x emissions by 60%, and cut in cumulative aircraft noise levels by 32 dB.

HUSHING JET ENGINES?

The aviation noise issue will probably not be solved by a single technology, but by a combination of noise reduction techniques on all the components of the engine. With the help of improved computer power, new predictive tools are emerging that enable us to make a more accurate assessment of jet engine noise reduction approaches. New research should start now with design studies to define realistic noise requirements for the next generation aircraft. All these solutions combined, especially including noise shielding, could add up to an almost imperceptible aircraft noisewise.

Lean machine

Reducing NO_x emissions

by Dipanjay Dewanji

The 21st century aviation gas turbine industry is facing a fundamental challenge: how to increase cycle efficiency and at the same time keep emissions at the lowest possible levels? The emission goals set by the NASA – especially the mid- and long-term goals – demand a step change in gas turbine technologies. Unlike other problem areas – noise pollution, carbon emissions, and fuel consumption – the emission of nitrogen oxides (NO_x) is mostly governed by the combustion process.

Combustion technologies have improved steadily, but there is limited potential to further decrease NO_x production with present combustion systems. Therefore, CleanEra investigated an ultra-low NO_x combustion technology for the future.

	N+1= 2015 Technology Benefits Relative to a Single Aisle Reference Configuration	**N+2 = 2020** Technology Benefits Relative to a Large Twin Aisle Ref. Configuration	**N+3 = 2030-35** Technology Benefits
LTO NO_x (below CAEP-6)	- 60%	- 75%	> - 75%
Aircraft Fuel Burn (below B777/GE90 Baseline)	- 33%	- 50%	> - 70%
Noise (below Stage 4)	- 32 dB	- 42 dB	- 71 dB

Table: Subsonic Fixed Wing Goals (Source: NASA)

In recent years, major aero-engine companies have come up with potential ultra-low NO_x combustion concepts.

A promising one is Lean Direct Injection (LDI) developed by NASA. Experiments with LDI combustors showed low NO_x and CO emissions without combustion instability. Encouraging results, but these experiments were limited to an observation of exhaust emissions. The dynamics of the mixing and combustion process that resulted in the low emissions have not yet been investigated. For this reason, CleanEra set out to gain insight into the underlying unsteady physics of the LDI combustor.

NITROGEN OXIDE FORMATION AND ITS CONSEQUENCES

NO_x emissions in the lower atmosphere cause the formation of ozone (O_3) and smog. When captured by moisture, NO_x produces acid rain, which affects ecosystems.

Nitrogen dioxide (NO_2) reacts with air and ultraviolet light in sunlight (UW) to form ozone and nitric oxide (NO):

$$NO_2\,(g) + O_2\,(g) + hv \text{ (in sunlight)} \longrightarrow O_3\,(g) + NO\,(g)$$

[g = gas, hv = emitted photon]

The UV light also reacts with volatile organic compounds (VOC) in the atmosphere to create free radicals:

$$hv + VOC \longrightarrow \text{Free radicals}$$

[Free radicals = atoms, molecules, or ions with un-paired electrons]

NO then reacts with the free radicals present in the atmosphere to form NO_2. Therefore, NO_2 is recycled and each molecule of NO can produces ozone multiple times:

$$NO + \text{Free radicals} \longrightarrow NO_2$$

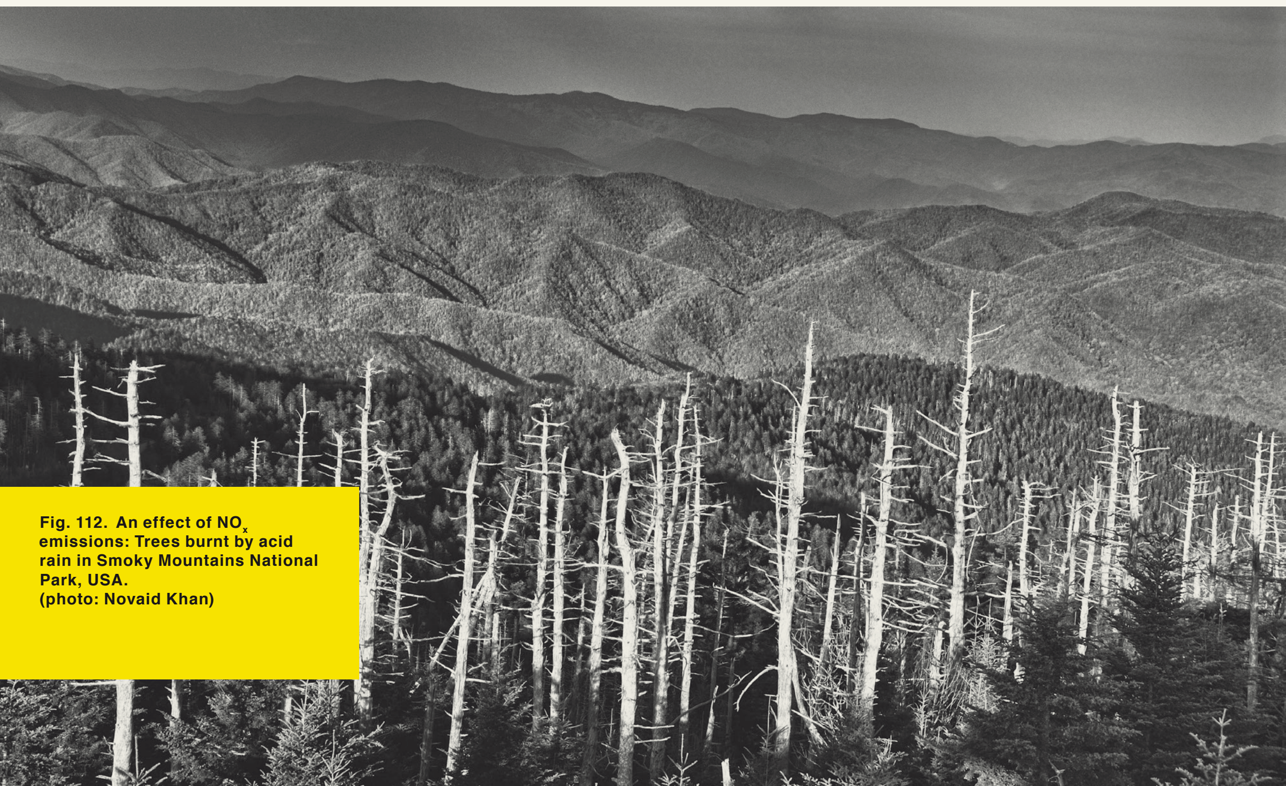


Fig. 112. An effect of NO_x emissions: Trees burnt by acid rain in Smoky Mountains National Park, USA. (photo: Novaid Khan)

NITROGEN OXIDE PRODUCTION IN GAS TURBINES

To reduce NO_x emissions we must first understand the detailed mechanisms of NO_x generation and control. Two distinct mechanisms are responsible for the production of NO_x in gas turbine combustors:

1. The oxidation of atmospheric nitrogen present in the air for combustion (thermal NO_x and prompt NO_x)
2. The conversion of nitrogen that is chemically bound in the fuel (fuel NO_x)

THERMAL NO_x

Thermal NO_x is formed by a series of chemical reactions in which oxygen and nitrogen present in the combustion air dissociate and subsequently react to form NO_x. The chemical mechanisms, representing the major pathways for NO_x formation, are as follows.

Extended Zeldovich Mechanism:

Nitric Oxide

1. $O + N_2 \longleftrightarrow NO + N$
2. $N + O_2 \longleftrightarrow NO + O$
3. $N + OH \longleftrightarrow NO + H$

Nitrous Oxide

4. $N_2 + O + M \longleftrightarrow N_2O + M$
5. $N_2O + O \longleftrightarrow NO + NO$
6. $N_2O + H \longleftrightarrow NO + NH$

[M = inert substance]

PROMPT NO_x

Prompt NO_x is a form of thermal NO_x , which is formed close to the flame front when intermediate combustion products (e.g. HCN) are oxidized.

1. $N_2 + CH \longleftrightarrow HCN + N$
2. $N + O_2 \longleftrightarrow NO + O$
3. $HCN + OH \longleftrightarrow CN + H_2O$
4. $CN + O_2 \longleftrightarrow NO + CO$

FUEL NO_x

Fuel NO_x is produced when fuel containing nitrogen is burned. Typical examples are some types of natural gas that contain molecular nitrogen and some synthetic fuels that contain nitrogen in the form of ammonia. When these fuels are burned, the nitrogen bonds break and some of the resulting free nitrogen oxides form NO_x.

NO_x production in gas turbines mostly occurs during fuel injection. The NO_x formation rate depends on the local flame temperature and the residence time of the gas mixture. Non-uniform fuel-air mixtures cause local hot spots that contribute to NO_x production.

NO_x production in gas turbines can be minimized significantly if combustion is performed in either fuel-rich or fuel-lean conditions. Also, the gas mixture residence time must be reduced to near stoichiometric conditions. Burning rich in combustion chambers causes NO_x reduction, but it also has adverse effects. Lean combustion schemes however, hold the promise to reduce emissions and fuel consumption significantly.

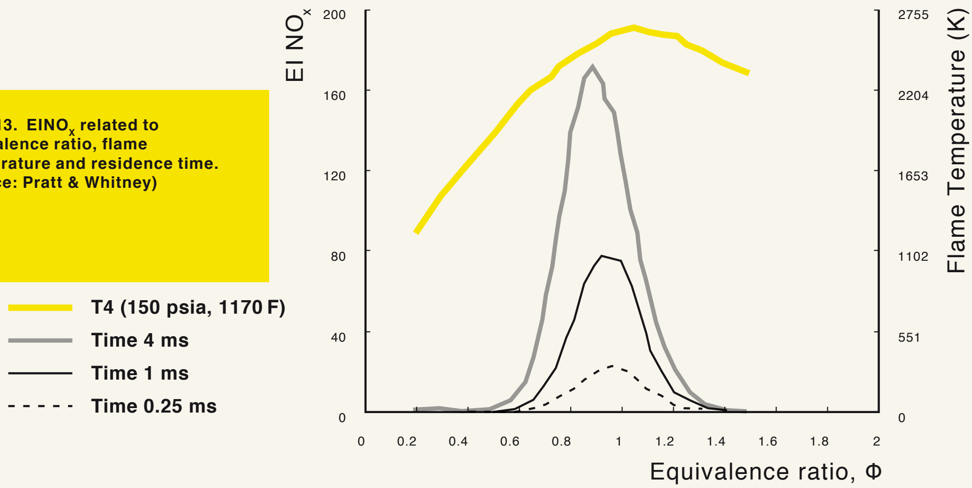


Fig. 113. $EINO_x$ related to equivalence ratio, flame temperature and residence time. (source: Pratt & Whitney)

BURNING LEAN: THE MOST PROMISING LOW-NO_X METHOD

The Lean-Premixed (LPM) concept is a method to achieve Low-NOx levels in gas turbines. LPM is already being used successfully in industrial gas turbines. In this type of system, gaseous fuel and air can be mixed uniformly at a very low equivalence ratio to lower the flame temperature, which reduces $EINO_x$.

Aircraft combustion does not use gaseous fuel, but the LPM method can be adapted into the Lean-premixed-prevaporized (LPP) concept: a premixed-prevaporized fuel injection system mixes the liquid fuel with the air in the premixed section and turns it into vapor that is burned in the main combustion chamber. But the high-pressure environment of an aircraft engines proves to be a problem for LPP. The high compression ratio increases the chamber inlet temperature. This leads to an increase in the fuel-air temperature, resulting in a short ignition delay of the fuel-air mixture. This delay makes the combustor more susceptible to auto-ignition. Auto-ignition in the premix duct leads to almost instant destruction of the fuel-air preparation and should be avoided. Furthermore, LPP burners are prone to flashback or upstream propagation of the flame in the premixing tube.
The main challenge for lean combustion technology lies in the mixing of fuel and air in the combustion chamber and achieving a stable performance over a wide range of operating conditions. Furthermore, inherent problems with lean combustion, such as auto-ignition and flashback, need to be overcome.

LEAN DIRECT INJECTION (LDI) SCHEME: A STEP FORWARD

The LDI scheme avoids the short ignition delay of the LPP method. The mixing process is expedited, so that the fuel and air are mixed before they can burn. The simplest way is to increase the pressure drop across the injector, which will generate more turbulence to rip apart the liquid fuel injection. But an increase in pressure loss means a loss of system efficiency.

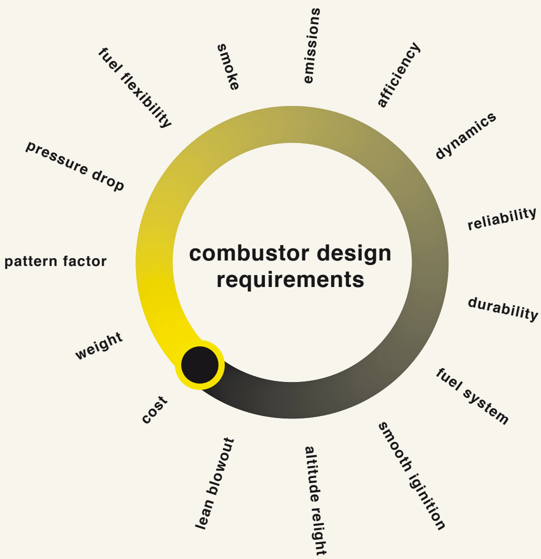


Fig. 114. Detailed analyses and component-testing are required to balance the system design.

Enter the Multi-Point Lean Direct Injection (MPLDI). By replacing large fuel injectors with many small fuel injectors the mixing will be improved, because the distance that the fuel and air stream need to traverse is reduced. Testing by NASA-GRC has found that some MPLDI systems can approach the performance of LPP combustors.

MPLDI VERSUS CONVENTIONAL

How different is an LDI combustion system from a conventional combustion system? In a conventional combustor, one third of the total air is mixed in the front end with the fuel. As the spray comes out in the conical shape, some hot gas circulates backwards in the center and ignites the incoming fresh mixture. The vortex formed in this region stabilizes the flame and acts as a primary flame holding mechanism. This is where a lot of NO_x is produced, because the mixture here is close to stoichiometric and has a very high temperature.

The rest of the air enters through the dilution holes to bring the gas temperature down to a level acceptable to the first stage of turbine, and on through the cooling systems. The fuel-rich region in the frontal section produces a lot of CO. Therefore, a long combustor length is required to burn off the CO. Consequently, the long residence time of the gas mixture at warm temperatures results in additional NO_x.
The MPLDI combustor takes almost all of its air in the front, except for a small percentage of air that is required for liner cooling. Therefore, the mixture is essentially lean. It burns at a lower temperature and produces less NO_x to start with. An efficient mixing process in the MPLDI combustor also produces less CO. Therefore, the combustor length can be made shorter, which means the mixture residence time shortens. This reduces NO_x production further. Consequently, a more compact combustor needs less liner cooling and a shorter engine shaft.

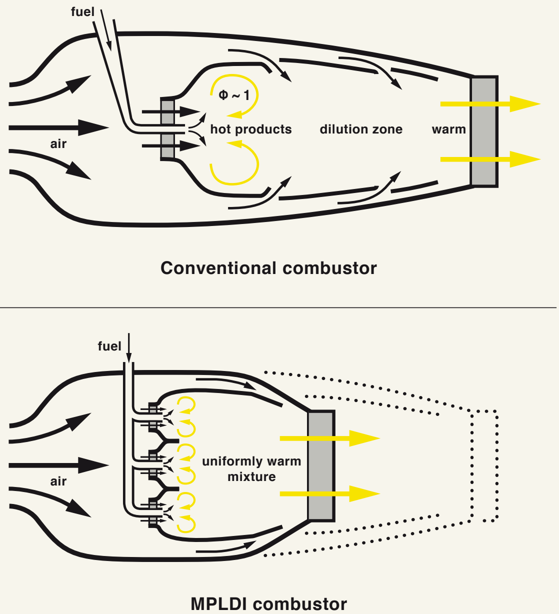


Fig. 115. Schematic of a conventional combustor (top) and an MPLDI combustor (bottom).

The design of the MPLDI combustor allows control over the individual fuel injectors so fuel can be modulated in time and space and local hot streaks inside the chamber can be reduced. This combustor design can also be used for injecting alternative fuels, such as bio-fuels and gaseous hydrogen, without the need for major system modifications.

THE ADVANTAGES OF MPLDI AT A GLANCE

- **Low thermal NO_x**
- **Shorter combustor and reduced shaft**
- **Low-power piloting**
- **Hot streak elimination**
- **Fuel modulation flexibility**

CLEANERA RESEARCH ON LDI COMBUSTORS

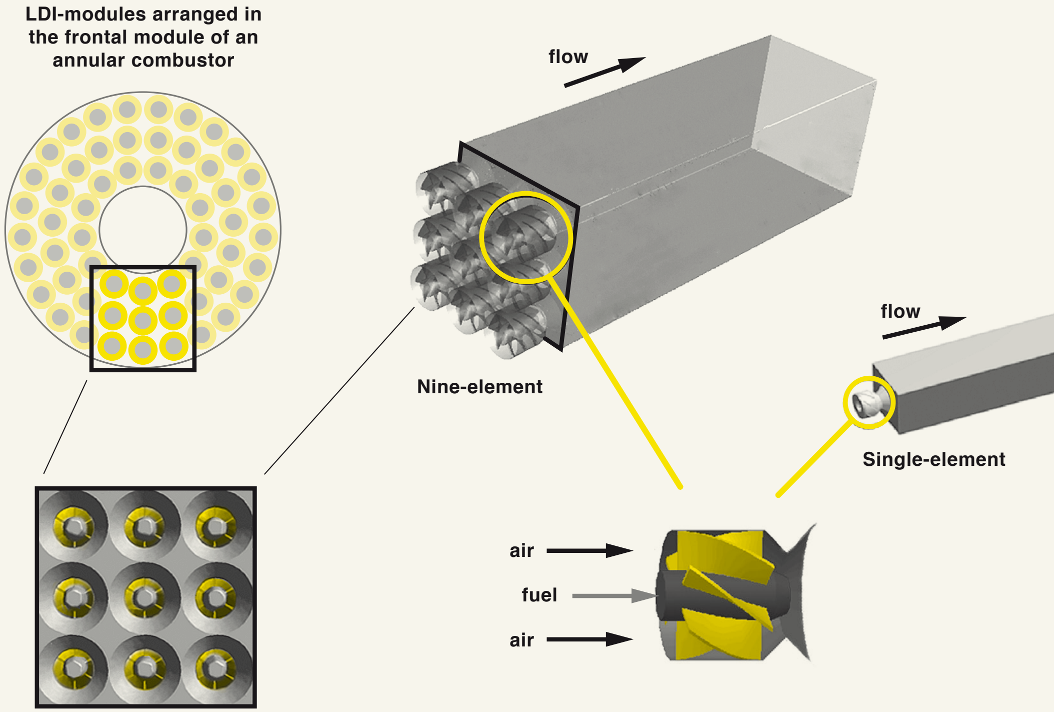
CleanEra has researched LDI combustors using computational fluid dynamics (CFD). The main objective of the project was to understand the unsteady dynamics of the mixing and combustion process in the LDI combustor. These dynamics are thought to be behind the low NO_x emissions.

As a first step, the flow field in a single-element LDI geometry has been numerically investigated. Next, the same geometry of the single-element LDI is used in the MPLDI with a 3x3 array of injectors to perform a spray combustion simulation. The results are validated with the available measurement data.

GEOMETRICAL CONFIGURATIONS

The geometry of the single-element LDI combustor is illustrated below on the right. It comprises a 60°, six helicoidal swirled-vaned inlet, followed by a short converging-diverging venturi that ends at the dump plane of a square combustion chamber. The inner and outer diameters of the swirler are 8.8 mm and 22.5 mm, respectively. The calculated swirl number is 1.0. Both the converging and diverging angles of the venturi are 45°. The helicoidal axial vanes of high swirl number create a high degree of swirling air flows, which facilitates fuel atomization and rapid mixing of fuel and air inside the combustion chamber. A simplex type fuel injector is inserted through the center of the swirler with its tip being at the throat of the venturi.

Fig. 116. Schematic of the Single-element and Nine-element LDI combustor.



The MPLDI geometry consists of an array of nine single-element swirler fuel injector modules that are designed to fit within a 76.2 mm square section. All the nine individual swirlers are co-rotating. The design of the MPLDI also allows fuel staging. In an aircraft engine several such swirler-injector modules will be arranged at the frontal section of an annular to create several small burning zones in the combustion chamber.

INITIAL CONDITIONS AND NUMERICAL METHODS

The initial conditions applied in the calculation of the single-element LDI are taken from the NASA measurements. The computation for the single-element LDI is performed at the atmospheric flow condition. To study the influence of these parameters on spray combustion, the simulation for the MPLDI is conducted at elevated air inlet temperature, inlet velocity, and fuel injection pressure. The fuel injector is a hollow-cone simplex type nozzle with an initial spray half-cone angle of 45°. Equivalence ratio, Φ, which is a measure of fuel to air ratio, is varied to study its effect on combustion.

The reacting spray simulation in the LDI combustor includes all the essential mathematical spray sub-models to characterize the liquid spray. The mixture-fraction/PDF modeling approach is used to model the non-premixed turbulent combustion. The Euler-Lagrange approach is applied to treat the multi-phase flow. In other words, the gas-phase is considered as a continuum by solving the Navier-Stokes equations, while the dispersed phase is resolved by tracking the liquid particles through the calculated flow field.

MODELS APPLIED FOR SPRAY COMBUSTION

	- Process -	- Numerical Model -
1.	Atomization	Linearized Instability Sheet Atomization (LISA)
2.	Droplet breakup	Kelvin-Helmholtz breakup / Wave model
3.	Droplet drag	Dynamic Drag model
4.	Turbulence dispersion	Discrete random walk model
5.	Collision / Coalescence	O'Rourke's collision model
6.	Combustion	Mixture-fraction / ß-PDF

THE SINGLE-ELEMENT LDI COMBUSTOR FLOW FIELD

From the discussions above, it is evident that the geometry of the LDI essentially provides a high degree of swirling flow inside the combustion chamber. Therefore, one of the important aspects observed in the flow field is the gas-phase tangential velocity profile. This velocity component essentially represents the swirl of the flow and speeds up the mixing of fuel and oxidizer.
The main motive behind the LDI combustion concept is to create a lean mixture, which in combination with an efficient mixing process, essentially reduces peak flame temperature and NO_x production. The lean mixture can be attained by mixing fuel and air at a low equivalence ratio. In this research, combustion in the LDI system is studied by varying equivalence ratio.

The following figure compares the centerline instantaneous temperature distribution between the 0.75 and 0.45 equivalence ratio (Φ) mixtures along the axial direction. From the plots, it is evident that by lowering equivalence ratio, both peak flame temperature and chamber exit temperature can be reduced.

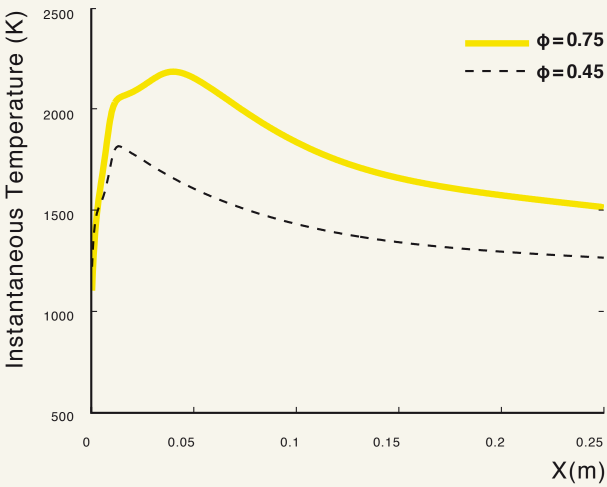


Fig. 117. Centerline instantaneous temperature comparison between two mixtures in a single-element LDI combustor.

THE MPLDI COMBUSTOR FLOW FIELD

Our main aim is to investigate the flow characteristics in the MPLDI combustor. The insights obtained from the simulation of the single-element LDI geometry are useful to understand the flow behavior of the swirler-fuel injector module. However, the flow calculation for the MPLDI is far more complex with several injectors at close proximity to each other. Therefore, the flow field is expected to be highly instationary.

The reacting spray simulation of the MPLDI combustor gives an insight into the fuel and air mixing process, which holds the key to keeping the NO_x emission level down. Similar to the single-element combustor, the simulation for the MPLDI predicts high tangential velocities at all computed locations, indicating the presence of a high degree of swirl.

The temperature profiles (see Fig. 118) at different axial locations in the combustor exhibit a uniform temperature distribution in most of the downstream regions and a good pattern factor at the chamber exit, indicating an efficient fuel atomization and fuel-air mixing at upstream.

The strain-rates are found to be quite high at the interface of the fuel and air stream mixing in the divergent nozzles and in the regions where the flows from the adjacent swirlers interact among themselves (see Fig. 119). The net result is a low peak flame temperature of a highly strained flame, which in turn reduces thermal NO_x production.

In addition to high strain rate and fluid shear, OH mass fraction distribution is plotted in the mid-plane (see Fig. 120-left), which suggests a short flame emanating from each injector.
Figure 120-right shows the existence of gas-phase vaporized fuel in the mid-plane, indicating the fuel-rich portion of the flame, where the vaporized fuel rapidly mixes with the oxidizer before undergoing chemical reactions.

Figure 121-left shows the interactions among swirling gas flow, reacting spray drops, VBBs, and PVCs inside the MPLDI combustor, implying the presence of a highly complex and unsteady flow field, especially in the regions of injector exits and chamber inlet. The precessing motion of the gas entrains the drops (except for large Stokes-number drops), thus playing a pivotal role in their dispersion. The Q-criterion vortices near the chamber inlet (see Fig. 121-right) also influence the spray drop distribution and further make the flow field complex and unsteady.

The mean diameter profiles for the MPLDI have significant differences from that of the single-element combustor, which are as follows.

MPLDI	Single-element LDI
Smaller drops. D10 distribution ranges between 10-21 µm, while D32 distribution ranges between 14-25 µm	Relatively bigger drops. D10 distribution ranges between 10-60 µm, while D32 distribution ranges between 20-100µm
D10 and D32 profiles are nearly uniform both in radial and axial directions	Diameter profiles widely vary in both directions
No clear diameter peak is observed	Distinct diameter peak is observed in the radial direction and the peak value varies along the axial planes

Table: Comparison of drop diameter distribution between the MPLDI and single-element LDI

The differences in the drop distribution profiles between the two cases arise mainly due to the complex arrangement of the swirler-injector modules in the MPLDI system. Increasing swirling flow velocity reduces the drop size, while the complex arrangement of the swirler-injector modules influences both size and distribution of drops in the combustor.

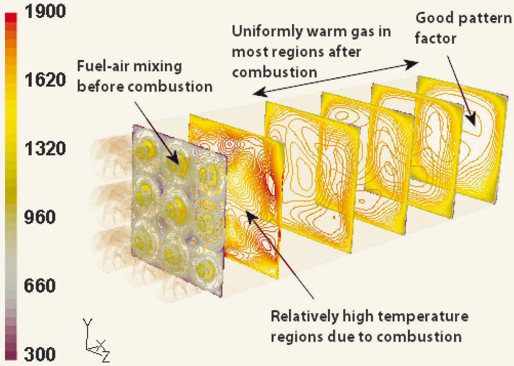
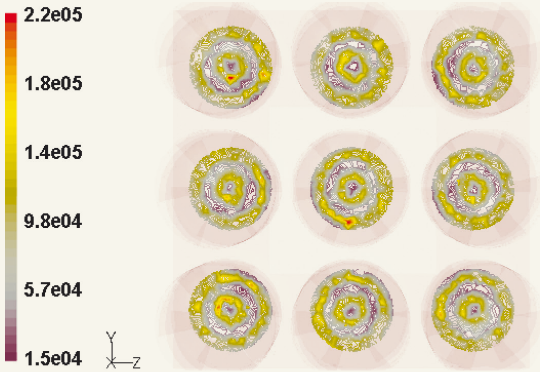


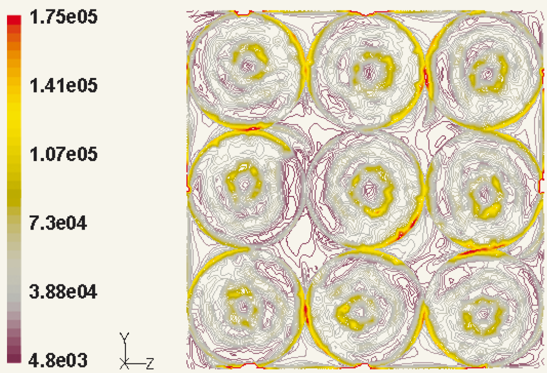
Fig. 118. (left) Instantaneous temperature contours (in Kelvin) in the MPLDI combustor.

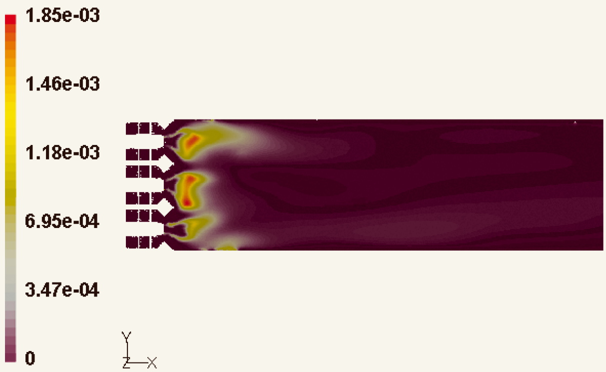
Fig. 119. (2nd row) Strain rate contours (in 1/s) at 4mm inside the venturi (left) and the chamber inlet (right) in the Y-Z plane.

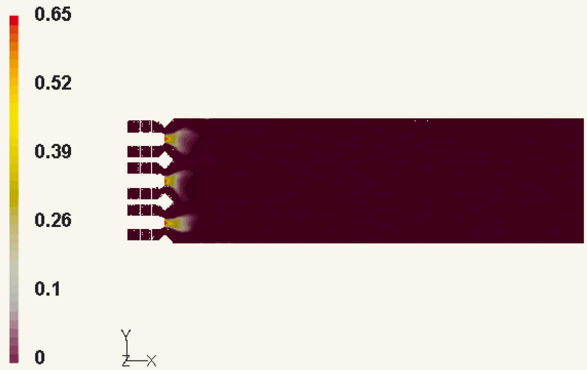
Fig. 120. (3rd row) Fraction distributions of the OH mass (left) indicating shorter flames and the Mixture (right) depicting the presence of fuel vapor.

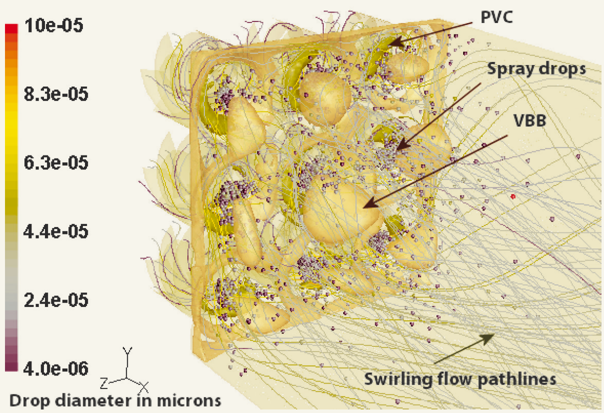
Fig. 121. (bottom) Interactions among swirling flows, PVC, VBB, and spray drops (left) and Interactions between Q-vortex and spray drops (right).

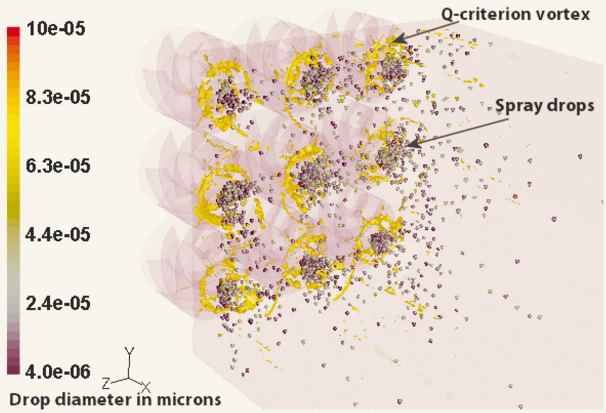












CONCLUDING

CleanEra's ambition to develop a green concept for future aviation includes a wide range of system level studies. Reducing NO_x emissions significantly from the present allowable limit is one of the main targets that motivate our combustion research to identify an ultra-low NO_x concept. The following are the main conclusions from this research.

- The highly swirling flows in the LDI combustor strongly influence fuel atomization, fuel-air mixing, and liquid drop evaporation, thereby producing a uniform temperature distribution inside the combustor. A good pattern factor is obtained at the chamber exit.

- In addition to the highly swirling flows, the complex arrangement of the swirler-injector modules in the MPLDI combustor enhances the liquid drop breakup process, resulting in the formation of smaller drops and rapid evaporation of sprays. The mean diameter profiles become uniform in both axial and radial directions, suggesting a homogeneous dispersion of spray drops.

- The highly strained flows at the injector exits and the interfaces of adjacent swirlers at the chamber entrance speed up the mixing of fuel and oxidizer before combustion and reduces peak flame temperature and flame residence time, which in turn reduce thermal NO_x production. Shorter flames are noticed in the MPLDI combustor, which further reduce the residence time within the flame, leading to thermal NO_x reduction.

- In the regions near the MPLDI chamber inlet and nozzle exit, the presence of dynamic rotating vortex structures and their interactions with the vortex breakdown bubbles make the flow highly unsteady. Precessing motion of these vortices entrains the drops, resulting in the dispersion of drops into the gas-phase.

Overall, our numerical research on LDI combustion has explained some of its fundamental features, which are primarily responsible to producing low NO_x. The computed data for both gas and liquid phases agreed with the available measurement data. All in all, we believe the MPLDI concept can become the low NO_x combustion scheme for the future.

Free flight

Making aircraft see for themselves

by Ronald van Gent

The way aircraft operations are organized today is primarily based on the fact that they cannot 'see' each other. The reason for that is historical. When the first aviators started flying, they quickly realized that flying in low or no visibility – like at night or in clouds – was extremely dangerous. During flight, humans are confronted with varying gravitational fields and they cannot orientate themselves under these circumstances without visibility of reference points. Many pilots – and their passengers – have lost their lives due to vertigo or other forms of disorientation.

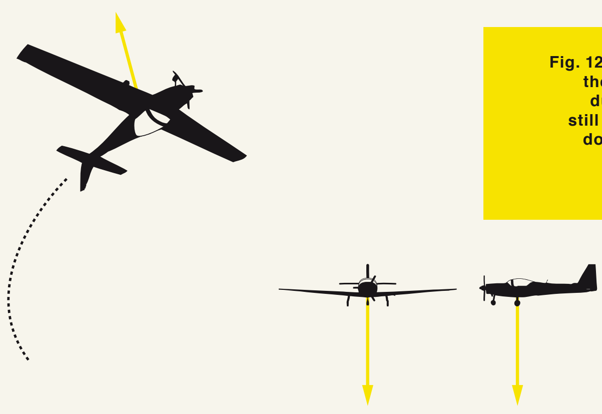


Fig. 122. Vertigo.. even though the aircraft is upside down during a looping, the pilot still feels a gravitational pull downwards because of the centrifugal forces.

The hazards of disorientation led to attempts to equip the cockpit with instruments to give the pilot enough information to fly the aircraft safely without visual reference.

On 24 September 1929, pilot Jimmy Doolittle undertook the first documented flight solely on instruments. He was unable to look outside, as he performed this feat from the backseat of a biplane, covered under a hood. He used various instruments to determine his altitude, airspeed and heading and navigated with the help of radio signals to line up for the runway. A safety pilot was present in the front seat, but the need to intervene did not arise. This flight laid the basis for present Instrument Flight Rules (IFR). The same principles to determine altitude (by ambient pressure), airspeed (by accumulated air pressure in a pitot tube), heading (by means of a compass) and radio navigation to determine the location are still in use in cockpits today.

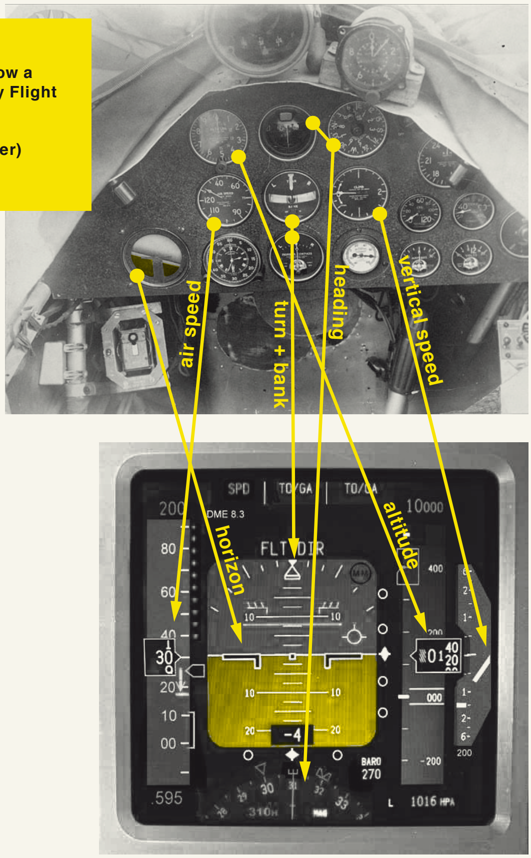


Fig. 123. Jimmy Doolittle's instruments (right) and below a modern Boeing 777 Primary Flight Display.

(image below: J. Meriweather)

Having determined his position and altitude, a pilot would then have to check on a map whether any mountains or other obstacles were in the aircraft's flight path. Because of this, flight planning became an important part of the flight itself. An instrument telling pilots the location of other aircraft was neither thought-of nor possible at the time. It was hardly necessary, because very few aircraft were airborne at the same time in the same location.

As air traffic increased steadily over the years, the need for such an instrument became apparent on one catastrophic occasion. In 1956 two airliners collided over the Grand Canyon, killing all 128 people on board. This accident urged the authorities to quickly solve the problem with the means available at the time, and Air Traffic Control (ATC) as we know it today was born.

Ground-based radar systems had been used for detecting enemy air attacks during the Second World War and radar installations to facilitate low weather operations were in use at a number of civilian airports. Expanding this idea lead to a system whereby an air traffic controller on the ground used a ground-based radar to separate aircraft in the air.

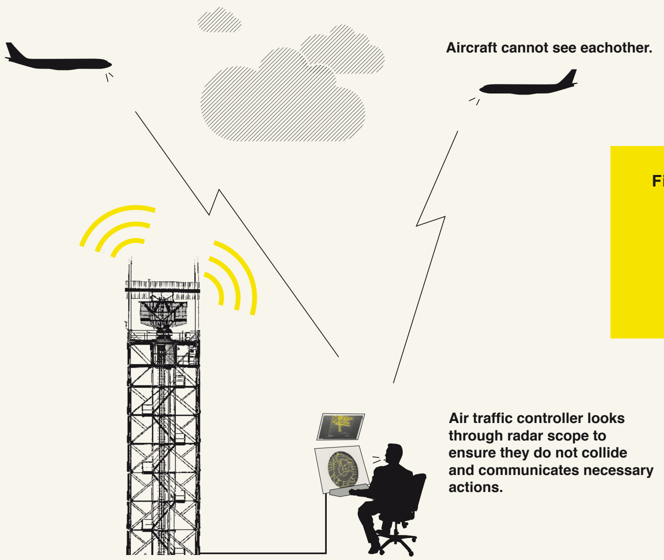


Fig. 124. Air Traffic Control with a ground based radar system.

An air traffic controller today has two main responsibilities:

- Separating aircraft to ensure safety
- Expediting and maintaining an orderly flow of traffic

Naturally, providing safety comes first, so preventing collisions has priority over expediting and maintaining an orderly flow of traffic.

AIR TRAFFIC SERVICES AND CONFLICT PREVENTION

In the current ATM system, Air Traffic Services (ATS) provide, with safety as their first priority:

1. **Flight information service**
2. **Alerting service**
3. **Air traffic advisory service**
4. **Air traffic control service**

The need for air traffic services is determined by a number of factors, such as type of air traffic involved, the density of air traffic, and the meteorological conditions.

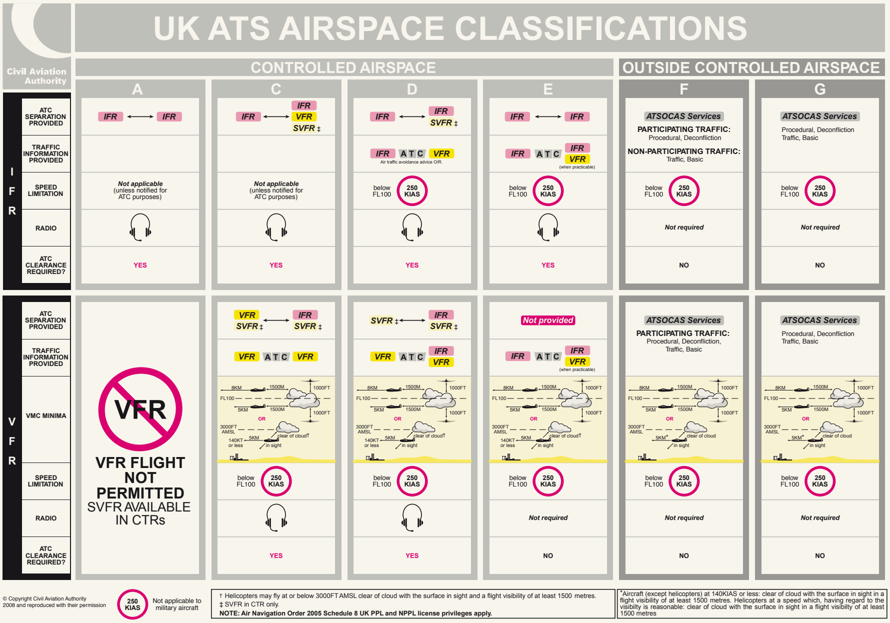


Fig. 125. Example of an ATS Airspace Classification Chart.

(source: ©NATS + UK CAA)

Airspace is divided into classes (Classes A to G) for which air traffic services and rules of operations are specified:

- Controlled airspace corresponds to Classes, A, B, C, D and E.
- Advisory airspace corresponds to Class F.
- Flight information is the only service provided in Class G.

Under the current ATM system, flight crews are responsible for the safe and efficient control and navigation of their individual aircraft in all airspace and on the airport surface.

1. Flight Information Service

Flight information service provides advice and information useful for the safe and efficient conduct of flights (ICAO Annex - Rules of the Air).

2. Alerting Service

Alerting service provides notification to appropriate organizations regarding aircraft in need of search and rescue aid, and assists such organizations as required (ICAO Annex - Rules of the Air).

3. Air Traffic Advisory Service

Air traffic advisory service is provided within advisory airspace to ensure separation, in so far as practical, between aircraft that are operating in IFR flight plans (ICAO Annex - Rules of the Air).

4. Air Traffic Control Service

The purpose today of the Air Traffic Control Service (ATC) is to:

- Prevent collisions;
- Expedite and maintain the orderly flow of traffic.

To prevent collisions, air traffic control units issue clearances and information (ICAO Annex - Air Traffic Services - section 3.3.):

Traffic information alerts the flight crew to (known or observed) air traffic that is in the proximity to the position or intended route of flight, and helps the flight crew avoid collision.
Depending on the type of flight (IFR/VFR) and the class of airspace, clearances and instructions are issued to provide separation. The separation minima to be applied are established by the regulatory authority taking into account factors such as the communication, navigation and surveillance capabilities and the operational procedures.

Because of the international character of this mode of transport authorities urged for the international standardization of systems and procedures. For a global system, globally accepted rules and standards were necessary to ensure uniformity among aircraft, but even more so for uniformity within the various airspaces.

INTERNATIONAL CIVIL AVIATION ORGANIZATION

The International Civil Aviation Organization (ICAO) is a specialized agency of the United Nations. It codifies the principles and techniques of international air navigation and fosters the planning and development of international air transport to ensure safe and orderly growth. Its headquarters are located in the Quartier International of Montreal, Quebec, Canada.
The ICAO Council adopts standards and recommended practices concerning air navigation, its infrastructure, flight inspection, prevention of unlawful interference, and facilitation of border-crossing procedures for international civil aviation. In addition, the ICAO defines the protocols for air accident investigation followed by transport safety authorities in countries signatory to the Convention on International Civil Aviation, commonly known as the Chicago Convention (established in April 1947).

Once in place, this global system proved very resilient to change. In order to amend any of the rules, regulations or procedures, all members of the ICAO need to agree. This takes a lot of time, and there is also an attitude of “let’s not change a winning team”, mainly based on safety records. Any big change to the system creates a number of unknowns, which could lead to incidents during the introduction phase.

Thus, we fly today according to the same principles as in the 1950s. As a result, aircraft are still virtually blind in low or no visibility conditions. This creates a number of significant operational problems with flight today:

- Controlled Flight into Terrain (CFIT)
- Difficult Instrument Flight Rule operations
- Limited and suboptimal Air Traffic Control

Controlled Flight into Terrain and Difficult Instrument Flight Rule operations are the result of limited or no visibility operations. As explained before, a pilot has to determine the aircraft’s position and check on a map whether or not any obstacles are in the aircraft’s flight path. When an error occurs in the positioning, the altitude determination or the map checking, controlled flight into terrain can be the result. It also increases workload, especially with older types of aircraft, where the positioning and map checking has to be done by the pilot.

Limited and suboptimal Air Traffic Control: An Air Traffic Controller has to control the flight path of up to 30 aircraft at the same time, often resulting in suboptimal flight paths for the individual aircraft. A controller bases his decisions on radar information, whose accuracy deteriorates with its range to the receiver and has an update rate of several seconds. Furthermore, aircraft are controlled by voice radio communications, which introduce their own delay time. On top of that, only one aircraft at a time can be instructed - unless generally applicable instructions are given. It is therefore logical to organize traffic in such a way that control becomes simple, e.g. via predefined routes and altitudes and comparable speeds.

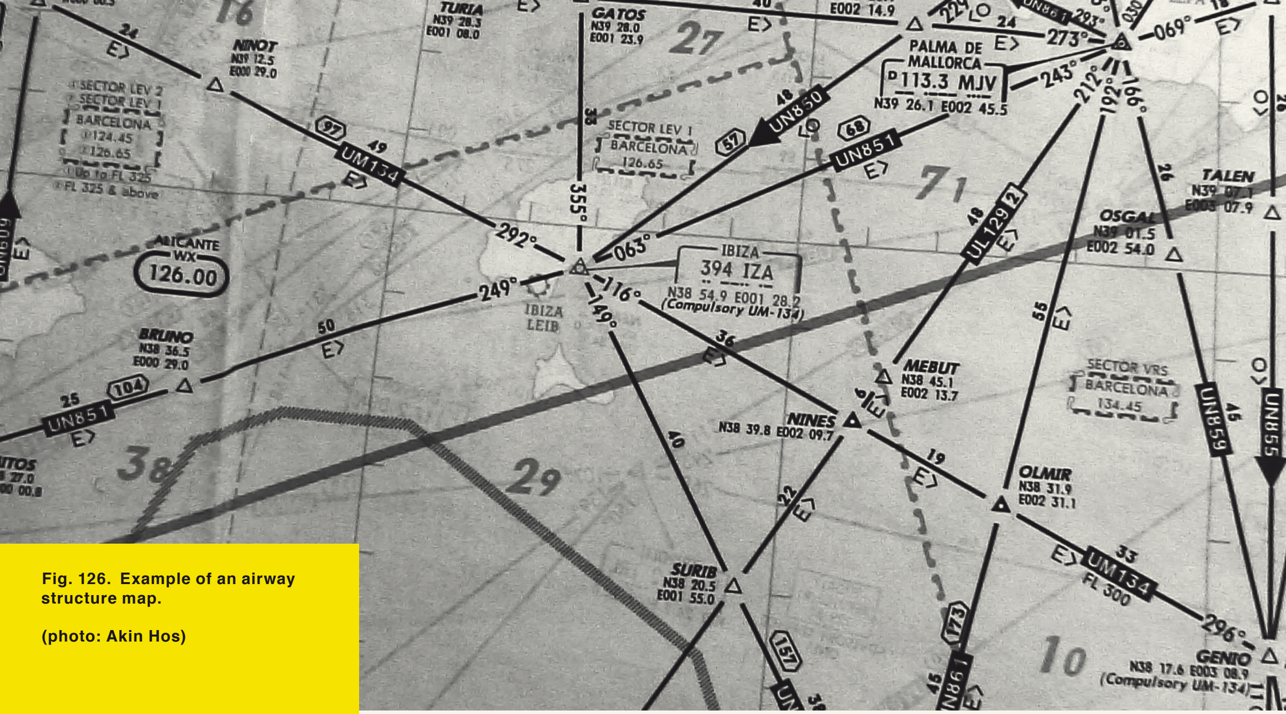


Fig. 126. Example of an airway structure map.

(photo: Akin Hos)

Hence, the efficiency of individual flight operations is sometimes hampered. Aircraft often cannot fly on their optimal routes or at their optimal altitudes. With ever-increasing traffic the present system is regularly overloaded, which leads to delays and fuel-consuming procedures.

FREE FLIGHT

'Free Flight' is an alternative air traffic management concept, based on the assumption that aircraft can see each other. It was first studied during the 1990s.
Assurance systems (ASAS) were developed and tested based on systems such as Automatic dependent surveillance-broadcast (ADS-B). These can transmit position, velocity, airborne separation and other data with update rates that are superior to those achieved by radar. Simulations and studies were performed based on the premise that all IFR aircraft are equipped with ASAS systems and the performance, reliability and robustness of the ASAS equipment is superior to present systems for collision prevention. In such a situation, restrictions based on ground separation systems are no longer necessary, making a clean sheet approach possible.

However, as a result from traffic density and the specifications of airborne surveillance systems, certain restrictions would still exist. In order to fulfil the function of expediting and maintaining an orderly flow of traffic, the ATS provider would have to establish operational constraints (flow targets and airspace restrictions) that accomplish the flow management goals. The aircraft were required to choose trajectories that meet these constraints.

The ATS provider's prime responsibility thus shifted from tactical separation provision to strategic conflict management.

Strategic conflict management is the first layer of conflict management and is determined by the airspace organization and management, demand and capacity balancing and traffic synchronization components.
The term 'strategic' is used to mean in advance of 'tactical'. This recognizes that a continuum exists from early planning to the user activity through to the latest avoidance of the traffic hazard. Strategic actions presently only occur prior to departure, but in the free flight concept these continue through the entire flight. Any changes to the trajectory by the user should be in accordance to the restrictions imposed by strategic conflict management.

The flight deck would become responsible for the provision of 'tactical' separation. 'Tactical' separation provision is the second layer of conflict management and is the tactical process of keeping aircraft away from traffic hazards by at least the appropriate separation minima. Separation provision will only be used when strategic conflict management — i.e. airspace organization and management, demand and capacity balancing and traffic synchronization — fails to ensure separation.

If the air traffic service providers no longer have to perform collision prevention and separation provision, this will free their resources for expediting and maintaining traffic flow and thus allow more aircraft to fly more optimal flight paths.

Strategic conflict management can impose restrictions on autonomous flight management trajectories. Aircraft are responsible for meeting these, but they are free to choose how to do so. These restrictions are to prevent:

- Exceeding airport or airspace capacity
- Unauthorized flight through special use airspace
- Unsafe flight (e.g. weather)

Such restrictions will be based, among others, on data provided by operators. These data comprise (airborne) surveillance data, flight plans and estimated times of arrival (ETAs), weather predictions, planned military operations, airport information etc. The data are updated continuously.

With the Free Flight concept a pilot would need to ensure safe separation from other aircraft. This initially provoked the thought that pilot workload would increase to unsafe levels during certain phases of flight. However, research showed that pilot workloads did not increase; in fact after training it was less than in standard IFR operations.

An ASAS system including a human-machine interface has been tested in several flight simulator trials by the Dutch National Aerospace Laboratory (NLR). Airline pilots have been exposed to scenarios replicating current densities ('single') up to three times the Western European ('triple') density. It is worth noting that both density and conflicts were tripled resulting in a 9-fold increase in conflict rate. Training only lasted a few hours. No significant increase in workload has been found during the cruise phase. The acceptance was surprisingly high and, further, the subjective safety was equal to or better than today's situation. (See following figures.)

Fig. 127. Rating of safety by subject pilots in comparison with ATC for each set (1,2 or 3) of 6 runs in the experiment.

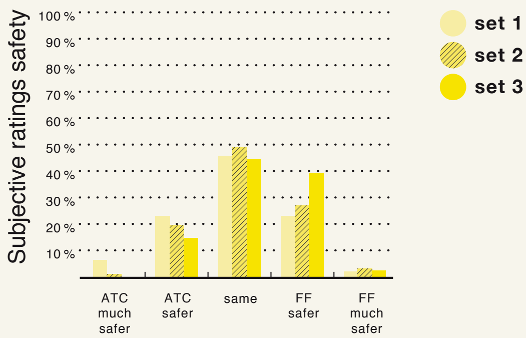
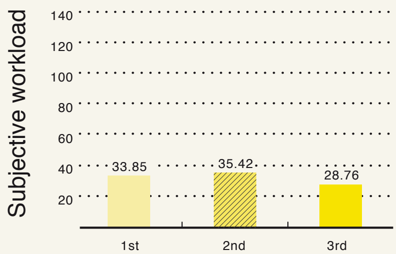


Fig. 128. Rating of workload on scale 0-130. The third sesion shows a workload rating very close to the ‘27’ found for a comparable ATC situation.



These results were obtained using a resolution method based on position and velocity information only. No flight plan information, co-ordination procedures, priority rules or ground-based systems were used. An extra system called Predictive ASAS has been developed alleviating the need for exchanging flight plan information. Because of the simplicity of the architecture and the resolution method, the system was transparent to the crew, allowing a display design as shown in the figure. The display shows both a horizontal and vertical resolution advisory to the pilot, who is free to choose one.

In summary, none of the sub-studies could refute the feasibility of airborne separation, even under extremely dense and constrained traffic situations.

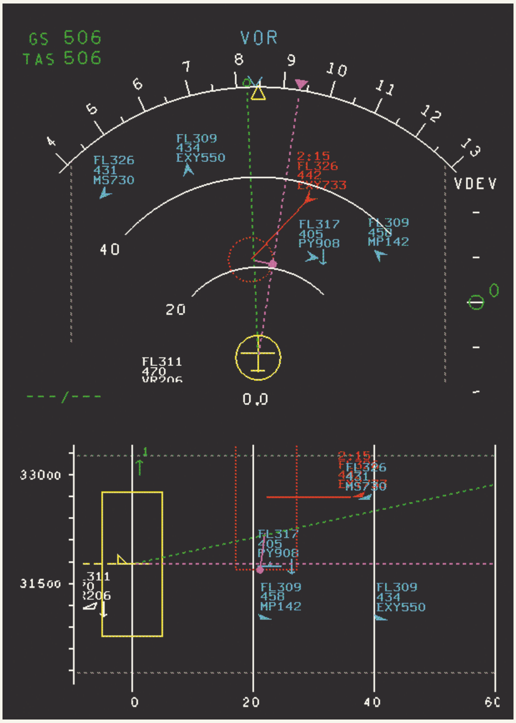


Fig. 129. Co-planar traffic display as used in the study. The symbology indicates a conflict (in red) and the resolution advisory (in magenta).

It was also shown that with increasing traffic load the workload of an air traffic controller increased exponentially, whereas the workload of a pilot with ASAS increased linearly.

EFFECTIVE CONFLICT RATE FOR AIR AND GROUND

When looking at a direct routing scenario, the higher capacity of Free Flight compared to the current en-route ATC system can be shown. Suppose the probability of two aircraft having a conflict when flying a direct route in a sector is p_2. This is independent of traffic density and whether the separation task is on the ground or in the air. The global conflict probability as a function of the number of aircraft N in a sector can be calculated assuming p_2 is known. It is the product of the number of combinations of two aircraft times the probability of conflict between two aircraft:

$$p_{c_{ground}} = \binom{N}{2} p_2 = \frac{N!}{(N-2)!\,2!} p_2 = \tfrac{1}{2} N(N-1) p_2 = \tfrac{1}{2} N^2 p_2 - \tfrac{1}{2} N p_2$$

When N increases as traffic grows, the probability, and therefore the effective conflict rate as experienced by the controller, increases quadratically with the number of aircraft in the sector.

For the airborne conflict probability this is different: it is simply the product of the number of aircraft with the probability of meeting that aircraft. The number of other aircraft is ($N-1$) so the formula becomes:

$$p_{c_{air}} = (N-1)p_2 = Np_2 - p_2$$

This probability and the perceived conflict rate increase linearly. The probabilities are equal for $N = 2$, in this case any conflict is also perceived by all (both) aircraft.

For the European airspace the conflict rate for single density ($N = 13$, see table) proved to be once per 50 minutes per aircraft. This yields an example p_2:

$$p_{c_{air}} = (13-1)p_2 = \tfrac{1}{50}\ {}^{1}\!/\!_{\text{min}} \Rightarrow p_2 = \tfrac{1}{600}\ {}^{1}\!/\!_{\text{min}} = 0.1\ {}^{1}\!/\!_{hour}$$

The difference between the curves is shown in the figure below. Compare the number on the x-axis with the table of the traffic growth to see the effect of time.

From this figure the effect of the traffic increase on the central and the distributed system can be observed. Traffic growth will probably make Free Flight more acceptable over time. Other measures, such as improving the ATC user interface or decreasing sector size, will only change the slope of the curve but not the quadratic nature.

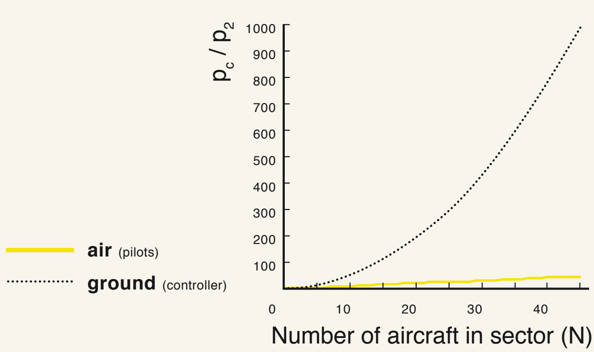


Fig. 130. Relationship between the number of aircraft N in a sector and perceived conflict rate for air (pilots) and ground (controller)

ADS-B

As mentioned before, the Free Flight concept relied heavily on the ADS-B system responsible for providing the aircraft position and velocity data among all airspace users. Right now ADS-B is being rolled out within US, Europe and other airspaces, but not for ASAS functionalities.

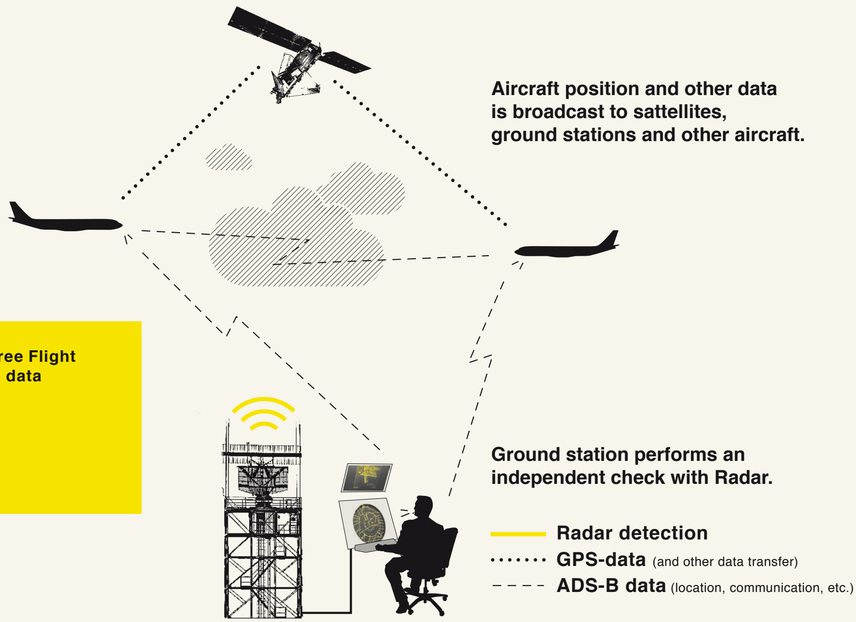


Fig. 131. The initial Free Flight concept using ADS-B data transfer.

An ADS-B system is basically a data link, which broadcasts position and other information (such as identification, altitude, velocity or flight plan) of the aircraft into its environment (ADS-B Out) or receives such information from other aircraft (ADS-B In). Although the data link can operate in several ways, most often a frequency of 1090 MHz is used, based on a modified Mode S transponder.

ADS-B In can be used to receive Flight Information Service Broadcast (FIS-B) and Traffic Information Service Broadcast (TIS-B) data and other ADS-B data from aircraft in the vicinity.

ADS-B can make radar-based ATC obsolete by using much higher-accuracy data, except for the fact that it is a dependent system, meaning the accuracy depends on the on-board navigation system. Many Air Traffic Service providers believe that an independent system as a check (radar) will therefore always be needed.

It is important to note that although the air traffic service providers are relying on ADS-B to enhance their radar-based operations, they do not foresee airborne separation assurance in the near future. In other words: they want to keep the responsibility for aircraft separation, even though there are a number of obvious advantages for delegating this responsibility to aircrew, as we have shown. A number of reasons can be thought of why airborne separation assurance systems have not taken off. One of the main objections is that ADS-B is a dependent system, as the definition implies. You will only receive information if the transponder of the other aircraft works. This is potentially a huge problem, because it touches on one of the fundamental issues of safety. There is no guarantee that the systems of the other aircraft will work.

Thus a true step forward would be if we could device a Free Flight system that can operate independently or has an independent checking mechanism to ensure that systems are operating. One way is to take radar on board of the aircraft. That sounds expensive, heavy and needing a lot of power. But just as other electronics technologies have developed immensely over the past years, radar technology has now developed to the extent where radars can be relied on as aids for both navigation and collision avoidance. What was impossible or very expensive to achieve in the past, is very achievable now. Low-weight, low-power continuous wave radars have been developed in the past years. In combination with the availability of high performance computing, this makes airborne radar very feasible.

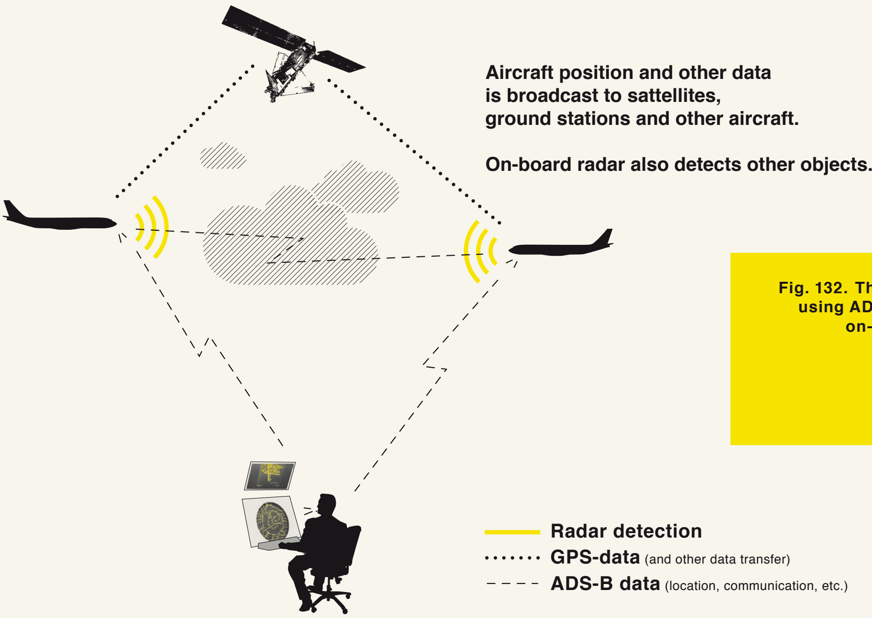


Fig. 132. The Free Flight concept using ADS-B data transfer and on-board Radar systems.

A future system could rely on ADS-B for almost all of the ASAS functionality, but could employ a low cost radar system to verify the ADS-B functionality and scan for imminent collisions. This modified Free Flight concept would make the air traffic management system safer and at the same time provide more capacity and more optimal routes for aircraft. This in turn will result in more efficient flying all together.

Having radar-based avionics system has a number of additional advantages based on the fact that aircraft can 'see' during low and no visibility conditions. The aircraft cannot only see moving obstacles such as aircraft, but also terrain, making controlled flight into terrain perhaps a thing of the past. Having an on-board sensor actively scanning the surroundings can also provide data to ensure attitude information, ground velocity information, height information etc. can be checked independently. This in turn would raise the robustness of the avionics in a very significant way. Thus we would have made a blind aircraft resembling a bat, but better.

New low cost RADAR technologies have been developed in the last decades based on Frequency Modulated Continuous Wave (FMCW) principles, which could be put on board of an aircraft in a cost effective way. These require extensive post processing, which in the early days made the use prohibitively expensive, but the increase of low cost computer power has changed this paradigm.

Such a radar can now be developed such that full 3D 360 degree coverage can be achieved whereby the following functions can be fulfilled:

- Detection of the ground below and in front of the aircraft
- Accurate mapping of the ground underneath of the aircraft
- Simple 3D imagery of all obstacles all around the aircraft

This in turn results in the aircraft having an electronic continuous full view of its surrounding. With this system collisions with any obstacles can be avoided without any dependency on outside systems. Presently TCAS (Traffic Collision Avoidance System) depends on working transponders of other aircraft and GPWS (Ground Proximity Warning System) depends on accurate navigation and up to date earth elevation databases.

Three problems were mentioned earlier:

- Controlled Flight into Terrain
- Difficult IFR operations
- Limited and suboptimal Air Traffic Control

These problems are thus solved.

Fig. 133. A radar system that collects and maps terrain information can help avoid collisions.

A quiet approach

Reducing noise at take-off and landing

by Hui Yu

Over a century ago, the Wright Brothers changed the concept of travel by making man airborne in a controlled and powered heavier-than-air machine. However, it was only after World War I that people started to realize the chances for profit from air transportation. Nowadays, there are some 54,000 routes scheduled all around the world. Commercial airlines deliver billions of passengers to their destinations for business, holidays, or other important events each year. Air transportation is also the fastest way of shipping certain categories of cargo over long distances.

People benefit from air transportation, yet they are also affected by its downsides, mainly its negative impact on the environment. Public complaints usually centre on local airports and are mostly aimed at air pollution and aircraft noise. Such issues can impact the health, quality of life and socio-economic characteristics of residential communities in the vicinities of airports. This, in turn, can lead to conflicts between the public and the air transport industry.

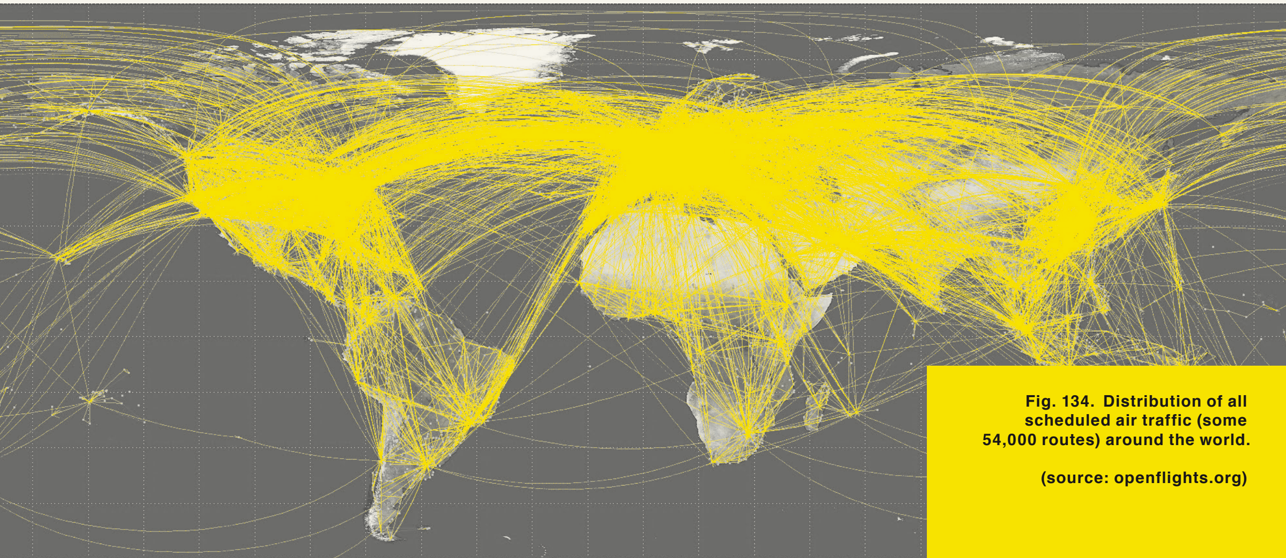


Fig. 134. Distribution of all scheduled air traffic (some 54,000 routes) around the world.

(source: openflights.org)

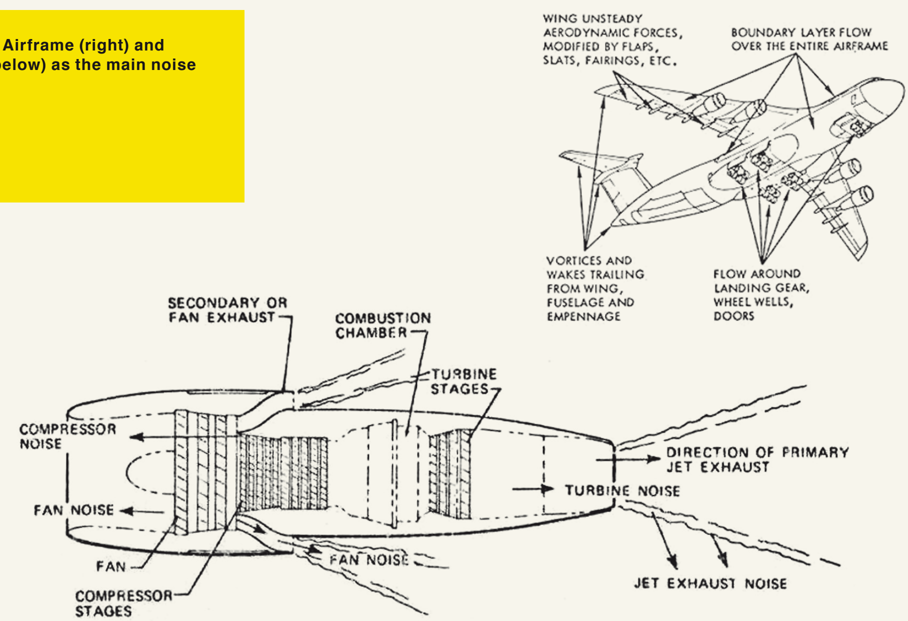
Therefore, both air pollution and aircraft noise need to be integrated in the strategy-making process of the industry in order to make the air transport industry sustainable. In this chapter, the latter one is discussed and corresponding measures are developed in order to minimize the nuisance generated by aircraft noise around airports.

NOISE

Noise is defined as unwanted sound. Sound is actually a form of energy transmitted by pressure variations which can be detected by human ears. This is a subjective matter: a sound defined as noise by one person may be acceptable to another. This is because a number of factors affect the receiver's personal impression, such as the characteristics of the pressure variations, the moment of occurrence, the receiver's preferences, etc. However, there is a simple but effective standard: whether or not the receivers are disturbed. Applying this standard, in most cases, the sound generated by aircraft is recognized as noise by the receivers.

There are two main sources for aircraft noise: airframe and engines. Then, it is reasonable to believe that aircraft noise can be restricted below a certain level by improving the acoustic performance of these two components. Before entering service, aircraft have to be assessed for compliance with the technical standards set by the International Civil Aviation Organization (ICAO) in order to get certified. Aircraft violating these standards must be phased out from operations. However, overall aircraft noise is still expected to rise because the reduction gained by these standards is outweighed by the increase caused by the growth of aircraft operations.

Fig. 135. Airframe (right) and engine (below) as the main noise sources.



NOISE ABATEMENT PROCEDURES AND TRAJECTORY OPTIMIZATION

In order to address the aircraft noise in an environmentally responsive and economically responsible way, the ICAO Assembly endorsed a concept called "Balanced Approach" in 2001. Following are four elements included in the concept:

- Reduction of noise at the source
- Land-use planning and management
- Noise abatement operational procedures
- Operating restrictions on the aircraft

Acknowledged by most ICAO-countries, the last element should only be applied after evaluating the benefits which might be gained from the others. Moreover, considering a given aircraft departing from or approaching to a certain airport, the acoustic performance of the aircraft and the land-use situation around the airport are assumed to be known and also unchangeable. In this case, the first and second elements can also be cancelled from the list. Therefore, the only remaining direction is noise abatement operational procedures.

After taking off from the runway, the aircraft usually needs to go through a number of flight phases to reengage with the ground, including departure, en route, arrival, and approach. Once the aircraft is in the en route structure, there is usually no need to achieve noise abatement. The aircraft is far away from the airport and so high to be barely audible on the ground. When the aircraft is in the flight phases of departure, arrival, and approach, it will be flying at relatively low altitudes so that the noise significantly impacts the residential areas under the flight trajectory. Therefore, procedures in these three flight phases play a key role in the reduction of aircraft noise nuisance. On the one hand, by following pre-defined procedures, the air traffic flow can be very well structured, both laterally and vertically. On the other hand, these procedures are defined for different types of aircraft with different aerodynamic and acoustic performances. Therefore, in terms of noise abatement, they may not have the best performance for particular scenarios.

If an aircraft is operating under Instrument Flight Rules (IFRs), it is often required to follow certain procedures with the assistance of navigation equipment and instruments. Below are the procedures that are usually implemented in the phases of departure, arrival and approach:

- **STANDARD INSTRUMENT DEPARTURES (SIDs) are pre-published procedures to simplify clearance deliveries for departing aircraft from the runway to the en route structure. They increase the capacity of the terminal airspace, control the traffic flow with minimum amount of pilot-controller communication, and reduce environmental impacts via implementing noise abatement procedures, etc. SIDs start from the runway and end at en route.**
- **STANDARD TERMINAL ARRIVING ROUTES (STARs) are pre-published procedures for arriving aircraft to strike a balance between safe separations and airspace management considerations. In certain cases, STARs are designed to achieve some other goals at the same time, such as reducing fuel consumption or noise impact. STARs start from the en route structure but don't make it all the way to the runway.**
- **An INSTRUMENT APPROACH PROCEDURE (IAP) consists of a series of pre-determined manoeuvres that connect the end of a STAR and the scheduled runway if no missed approach was initiated. There can be as many as four segments in an instrument approach: the initial, intermediate, final, and missed approach segments. If the aircraft is under radar control, air traffic controllers may modify some or all of the segments by radar-vectoring to lead the aircraft to the final approach course.**

At the present time, various noise abatement procedures are under development. Some of these are aimed at using noise preferential routes to avoid noise-sensitive areas on the ground. The focal point of this kind of methods is to modify the projections of the aircraft's trajectories in the horizontal plane to direct the aircraft away from noise-sensitive places. In addition, the vertical profiles of the aircraft can also be adjusted in certain ways to reduce their noise nuisance even more, such as escalating the interception altitude with the Instrument Landing System (ILS), increasing the ILS glide-slope angle, using displaced landing threshold, implementing low-drag low-power approaches and continuous descent approaches. As yet, all are knowledge-based methods. In other words, they are designed based on previous experiences, experimental data, etc. Although they have shown promising benefits in terms of noise nuisance reduction in practical applications, more is still expected.

It is believed by the author that more noise nuisance reduction can be achieved by using model-based methods. One such method is the optimization of the aircraft's trajectory in the 3-D airspace. In the optimization process, actions in both horizontal and vertical planes are available to be taken. Decisions are made by optimization algorithms and the only criterion is whether the noise nuisance would be minimized or not. This chapter presents an optimization tool which is capable of carrying out trajectory optimization for a single-event flight. This tool handles different scenarios specified by the aerodynamic performance of the aircraft, the acoustic performance of the aircraft, and the population distribution situation in the vicinities of the scheduled airport. Therefore, the resulted optimal trajectory is not standard, but specially designed for a particular scenario.

AN OPTIMAL CONTROL PROBLEM

Mathematically, trajectory optimization is usually formulated as an optimal control problem. Since the coming of high speed computing systems, optimal control problems have led to major research activities in a number of fields, including various applications in aerospace engineering.

An optimal control problem generally consists of:

- a mathematical model of the system,
- a statement of the physical constraints, and
- a specification of the performance index.

The objective of solving an optimal control problem is to decide the controls that cause the system to satisfy all physical constraints and minimize (or maximize) the performance index at the same time.

MATHEMATICAL MODEL: EQUATIONS OF MOTION

For trajectory optimization problems, the aircraft is assumed to be a point-mass object and all the external forces are assumed to be acting on the centre-of-mass of the aircraft. Moreover, the Earth is considered to be flat and non-rotational since the required airspace for around the airports is rather small, so that it is reasonable to ignore the spherical and rotational effects on the movements of the aircraft. Under such

assumptions, the equations of motion can be derived to govern the movements of the aircraft. In practice, there are quite a number of different ways of selecting states and controls.
In the work presented in this chapter, the (1) states include the position (three dimension), the velocity, the flight-path angle, and the heading angle while the (2) controls include the angle-of-attack, the bank angle, and the propulsive force from engines. Note that all variables are functions of the flight time in this conventional representation of equations of motion. Herein, if we use x to include all states and u to include all controls after the reformulation, the state-space equations of motion would have a general form of $\dot{x} = f(x, u)$, where both x and u are functions of the flight time and f is a vector including all state equations.

Aerodynamic lift and drag forces are part of the equations of motion. These two forces relate to the angle-of-attack and the relations vary when the configuration of the aircraft changes. For example:

- during departure, the pilots retract the landing gear and flaps step by step while the aircraft accelerates and climbs, and
- during approach, the pilots gradually extend flaps and landing gears to establish the landing configuration while the aircraft is decelerating and descending.

The transition from one configuration to another is performed according to a schedule of the indicated airspeed rather than the flight time. Therefore, a conversion from the true airspeed to the indicated airspeed is required.

PHYSICAL CONSTRAINTS: FLIGHT PERFORMANCE

In order to make the resulted optimal trajectory feasible and acceptable, physical constraints need to be taken into account when defining the optimization problem. As for a single-event flight, instead of being shared by multiple aircraft, the entire terminal airspace is available for a single aircraft. That is, no interventions from other aircraft or air traffic controllers are involved.
First, the conditions at the initial point and the final point need to be satisfied since the trajectory connects these two end-points. Additionally, constraints on the histories of the states and controls should be satisfied in order to restrict the behaviour of the aircraft throughout the entire flight. Last but not the least, certain parameters other than the states and controls also need to be restricted, such as the vertical speed, the overall flight time, etc. Due to the fact that all constraints are (in)directly related with the states and controls, they can be given by $c(x, u) \leq 0$, where c is a vector including all constraint functions.

PERFORMANCE INDEX: SLEEP DISTURBANCE

In an optimal control problem, an index needs to be selected to evaluate the performance of the system quantitatively. Conventionally, noise footprints are usually used to evaluate the noise nuisance of a single-event flight. This performance index works in most cases, but it runs the risk that the resulting optimal trajectory generates a small noise footprint that happens to enclose densely populated areas. In that case, although the noise footprint is minimized, the noise nuisance and then the public complaints can still be relatively great. In order to avoid this risk, sleep disturbance is recognized as a better option for the performance index.

With sleep disturbance as the performance index in the optimization process, the resulted trajectory is optimal at night since the population distribution situation is different at daytime. As for day-time cases, sleep disturbance needs to be replaced by other indexes since people usually don't sleep at daytime. Most difficultly, the real-time population distribution situation at daytime is not easy to model in practice and indexes that reflect the noise nuisance at daytime are still under research. At present, the solution is that the population distribution model is built in such a way that it can be replaced by others in future work when different performance indexes are selected.

Sleep is so essential for both physical and emotional health that sleep disturbance is a major concern of residential communities near airports. Another reason for selecting sleep disturbance is the likelihood that residents return home for sleep during the night. Thus the population distribution can be easily obtained from censuses. However, the extent of sleep disturbance varies from individual to individual. This subjective nature makes it difficult to decide the relation between the sleep disturbance and the level of the perceived noise. In 1997 the Federal Interagency Committee on Aviation Noise (FICAN) predicted a conservative relationship between the percentage of awakenings and the indoor A-weighted Sound Exposure Level (A-weighted SEL) at receivers. Their findings are based on a number of experimental datasets.

Quite a number of metrics are available to describe the noise levels of a single-event flight at certain receivers, such as sound exposure level, maximum noise level, effective tone-corrected perceived noise level, maximum tone-corrected perceived noise level, etc. In addition, noise weighting is also involved to emphasis the parts of the spectrum that are most important, mainly including A-weighted, B-weighted, C-weighted and D-weighted noise levels. In practice, the most commonly used metric is A-weighted Sound Exposure Level (A-weighted SEL), because this indicator best describes the noise generated within the entire flight.

Now, the only problem is the gap between the A-weighted SEL and the single-event flight. We can bridge this gap by a method presented in the Integrated Noise Model (INM) by the Federal Aviation Administration (FAA). Knowing the engine thrust of the aircraft and the relative position of the aircraft to the receiver, it is easy to calculate the outdoor A-weighted SEL at the receiver. The indoor A-weighted SEL can then be obtained depending on the sound-isolation situation of the house. With the assistance of the FICAN-relationship and the INM-method, it is possible to calculate the number of people awakened by a single-event flight. This number is (in)directly associated with the state and control variables and it thus can be given by $J(x, u)$, where J is a scalar function to be minimized.

Methods for aircraft noise modelling can be categorised into two groups: simulation methods and integrated methods. Each of these two groups has its own strengths and weaknesses. However, it is in general agreed that integrated methods represent the best current practice, especially for trajectory optimization problems. The methodology presented in the INM by the FAA is employed by most researchers. The core of this method is the Noise-Power-Distance (NPD) tables derived from empirical measurements for different types of aircraft under specified situations.

A PARAMETER OPTIMIZATION PROBLEM

This optimal control problem involves a nonlinear dynamical system so that there is no analytical solution. That is, it has to be solved using numerical methods. The central idea is that the indefinite-dimensional optimal control problem can be converted into a finite-dimensional optimization problem by certain parameterization methods. Unknowns introduced in the parameterization process become the variables in the resulted parameter optimization problem. In this work, the conversion is achieved through the following steps:

1. Split the entire flight trajectory into a certain number of segments which are assumed to be straight lines and of finite lengths.
2. Approximate the history of the true airspeed with certain polynomials.
3. Approximate the flight-path angle and the heading angle of the aircraft in each of the resulted segments and it is assumed that both angles are constant within individual segments.
4. Achieve the history of the position of the aircraft via integration based on the equations of motion.
5. Rewrite the constraint functions and the cost function into functions of the introduced unknowns.

Then differently, the goal of the optimization problem after conversion is to minimize

$$J\left(x\left(\mathrm{p}\right), u\left(\mathrm{p}\right)\right)$$

subject to

$$c\left(x\left(\mathrm{p}\right), u\left(\mathrm{p}\right)\right) \leq 0$$

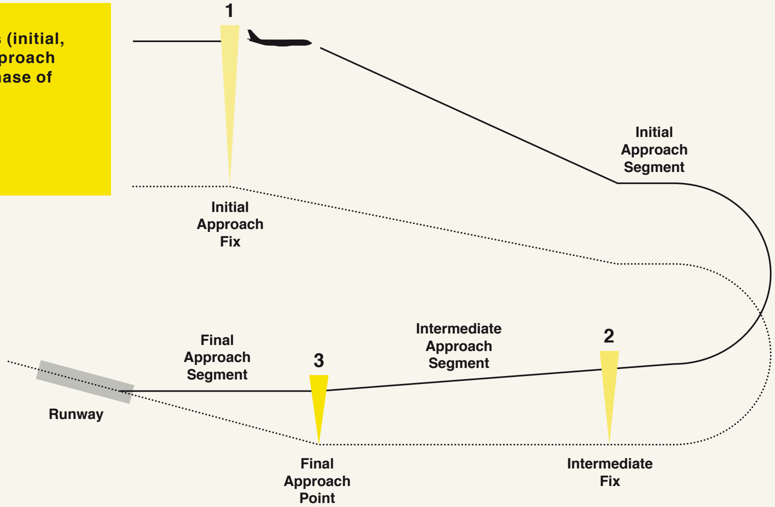
where $\mathbf{p}$ is a vector including all introduced unknowns.

> **In general, numerical methods that are able to solve optimal control problems can be categorized into two groups: indirect methods and direct methods. Indirect methods, originating back to the 1950s, use calculus of variations to obtain the first-order optimality conditions, forming a two-point boundary value problem. Since the 1980s, direct methods started dominating the field of numerical optimal control. By approximating some or all of the state and/or control variables, direct methods convert optimal control problems into parametric optimization problems. By doing so, the dimension of the problem is reduced from infinite to finite and hence the complexity is greatly reduced. The state parameterization method used in this work is one of those direct methods.**

A QUIETER APPROACHING AIRCRAFT

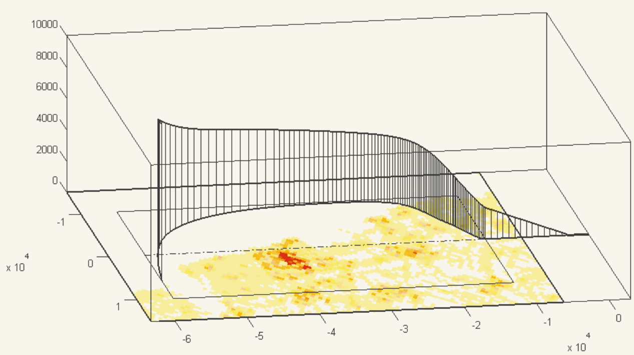
Trajectory optimization for an aircraft within the phase of approach is presented as an example to demonstrate the principles of the optimization tool. Although there may be as many as four approach segments in the phase of approach, we ignore the last one and only plot the others. The trajectory under optimization connects the Initial Approach Fix and the Final Approach Point. At the Final Approach Point, the aircraft intercepts with the ILS and then approaches the runway along a three-degree glide slope. An example is given here for the sake of demonstration. A Boeing 747-400 aircraft enters the terminal airspace of Amsterdam Airport Schiphol from one of the Initial Approach Fixes, at which the altitude is 10,000ft and the indicated airspeed is 250kts. From there, the aircraft starts to decelerate and descend until it reaches the Final Approach Point (FAP) of the scheduled runway at an altitude of 2,000ft and an indicated airspeed of 147kts. The flaps are extended gradually according to the flap extension speed schedule, while the landing gears are engaged exactly at the FAP.

Fig. 136. Three segments (initial, intermediate and final approach segments) in the flight phase of approach.



The population distribution and the resulted optimal trajectory are given in the figure below. As shown, the aircraft flies to the left-hand side of the centreline of the runway from the very beginning, to avoid the first densely populated area in the front and then maintains the same heading of the runway till it passes the second densely populated area. In the end, the aircraft makes a right turn to reach the FAP to intercept with the ILS. Inevitably, a number of people will be awakened by the approaching aircraft, especially at the late stage when the aircraft is relatively close to the ground. However, with the optimization tool we presented in this chapter, the number is able to be minimized. Note that the final approach segment can also be a part of the optimization, then there will be more freedom and it is expected more noise nuisance reduction can be achieved.

Fig. 137. An aircraft approaching from one of the Initial Approach Fixes at Amsterdam Airport Schiphol toward Runway 06. Population density on the ground is plotted in colors.



IMPLEMENTATION

Although noise nuisance reduction can be achieved by optimizing trajectories, effective implementation may be difficult. Different from knowledge-based methods, such type of model-based method is highly dependent on the actual situation of a specific scenario. If it was only a single-event flight, the resulting optimal trajectory would be relatively easy to implement since the entire terminal airspace is available. However, if there are more than one aircraft in the sky, the flexible nature of such optimal trajectories becomes the biggest obstacle on the way to actual implementation.

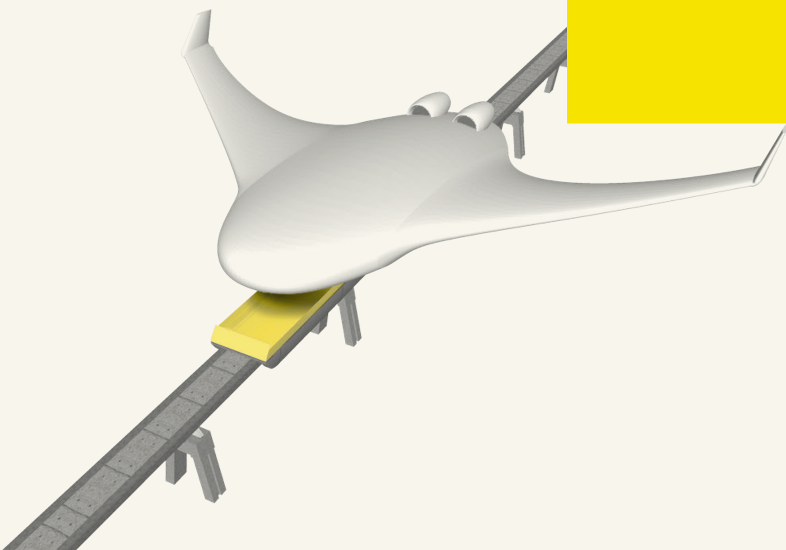
AN APPROACH ON TAKE-OFFS

by Jochem Kuiper and Ronald van Gent

Indeed, the structure of the air traffic will definitely be more flexible and there may not be one stream of air traffic in the sky. However, air traffic would not be completely random since the same types of aircraft have the same or very similar dynamic and acoustic performance. Therefore, it is possible for them to follow the same or very similar noise-optimal trajectories while taking off from or approaching to airports. Would this significantly reduce the capacity of the airspace around commercial airports? It is a question that remains unanswered in this chapter.

Research described in the "Free Flight" chapter discusses the different concepts of air traffic management. It is based on the assumption that aircraft can "see" each other while in the sky. This aids the development of the optimization tool presented in this chapter. The optimization can be extended to handle multiple aircraft in the air. Then the capacity of the airspace around airports can be explored.

Fig. 138. Artist impression of a MagLev take-off and landing system.



So far we have dealt with the approach and landing phase. This is the noisiest phase because of the strict altitude and speed regimes imposed by air traffic control. Although much more engine power is used, the take-off phase is generally less noisy than the approach and landing phase, because altitude is gained quickly, and the aircraft is more maneuverable due to the excess power compared to the approach and landing phase, allowing it to avoid busy areas. Nevertheless, reducing noise on take-off and climb-out is very important, therefore an alternate technology to reduce the noise footprint was also investigated within CleanEra by MSc student Jochem Kuiper. A study was performed to determine the feasibility of a MagLev take-off and landing (MTOL) system. The development of MagLev technology is thus far advanced that passenger transport is possible, and indeed certified in some projects. Several options are available, and there seem to be no large obstacles that could hamper the further development of MagLev technology.

The use of an MTOL system originates from the wish to remove the aircraft's landing gear, or at least to reduce its size and weight. The landing gear weight of large aircraft is approximately 4% of the Maximum Take-Off Weight (MTOW). For a Boeing 777-300 with a MTOW of 300,000 kg, this amounts to roughly 12,000 kg (comparable to 120 passengers of 80 kg carrying a 20 kg suitcase). This landing gear is carried the entire flight, while it is only used during taxiing, take-off run and landing.

In addition to weight reduction, significant noise reduction can also be achieved by using a MagLev system to perform a high-speed take-off, combined with a thrust cutback procedure. Thus, kinetic energy is exchanged for potential energy, which allows for a lower thrust setting during initial climb. The accelerations provided by Linear Synchronous Motors (LSM) can be sufficient to launch an aircraft at a high velocity, within the current length of a runway.

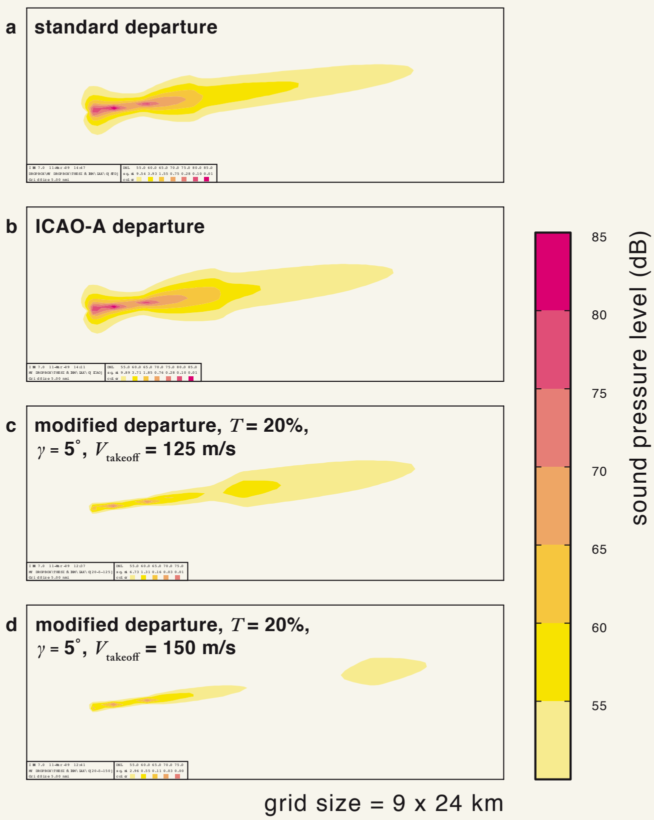


Fig. 139. Plotted noise profiles for a 777-300 taking off at LAX airport using a MTOLS. Changing settings for thrust (T) and launch speed ($V_{takeoff}$) during release and the flight path angle (γ) can influence noise emissions.

Using the MTOL system, an aircraft (for instance a Prantdl-plane or Blended Wing Body aircraft) is positioned at the start of the runway with its engines optimized for cruise, and running at a low thrust setting. Slotless flaps are deployed to increase lift at lower velocities. The aircraft takes off, assisted by the LSMs and low friction from the MagLev system.

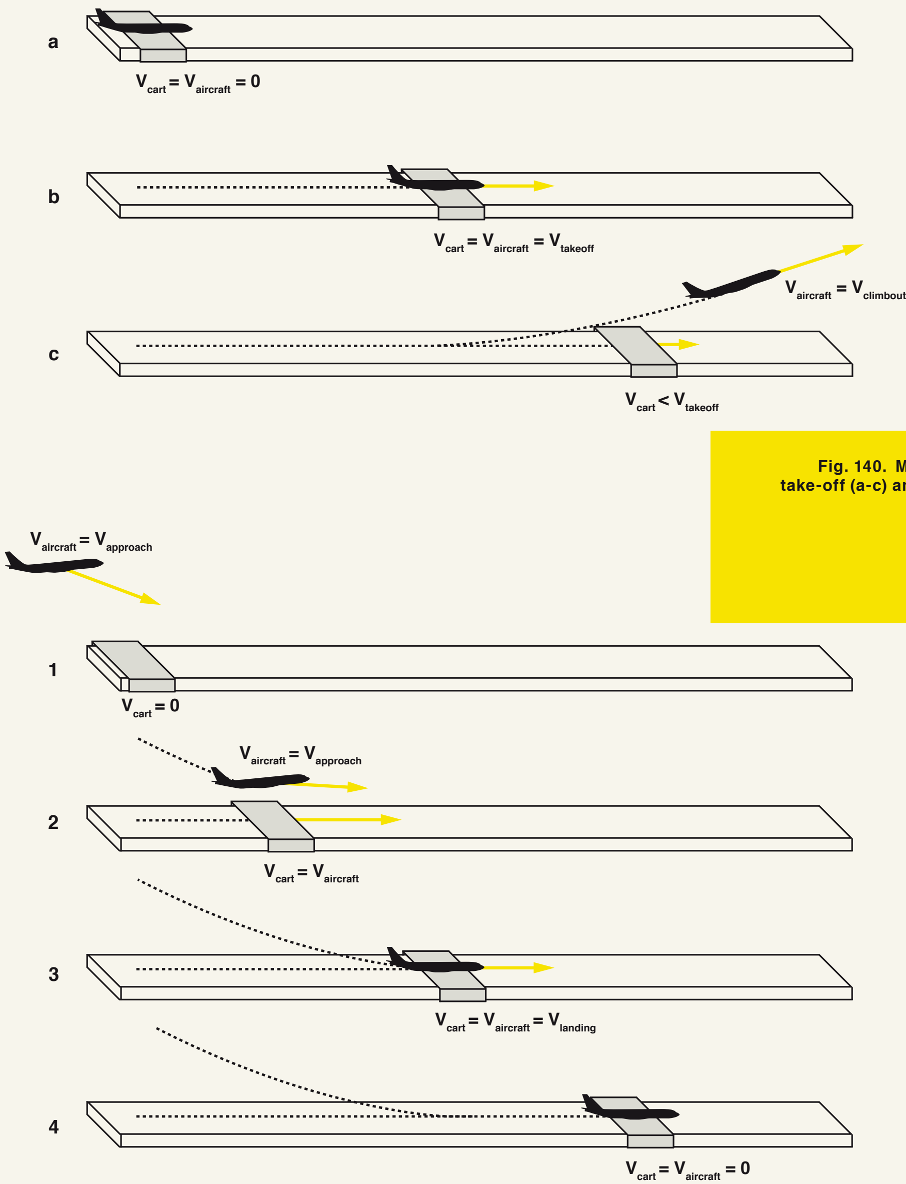


Fig. 140. MagLev concept take-off (a-c) and landing (1-4) procedures.

Since a MagLev system is capabable of large accelerations, the aircraft can take of at a higher velocity than in a regular take-off procedure. After disconnecting from the MagLev system, and using a reduced engine thrust setting, the aircraft starts its initial climb, resulting in a significantly reduced noise footprint. As kinetic energy is converted into potential energy, the engines then take over after the airspeed is reduced below a pre-determined value. The climb is continued, until the aircraft arrives at cruising altitudes.

In addition to the reduction in noise during take-off, a reduction of emissions can also be achieved. The take-off thrust setting for an engine is only used briefly during regular flight operations, and aircraft engines are optimized for performance at lower thrust settings since an aircraft spends most of its time during cruise. Operation outside of the optimal thrust setting range leads to an increase of unburnt hydrocarbons (UHC), carbon monoxide (CO) and nitrous oxides (NO_x). Also, the fuel which is usually carried for take-off only is not needed on board anymore since the MagLev system provides all the energy needed for acceleration.

The power needed for a MagLev system can be generated by several power sources, a number of which are renewable. A large amount of energy is required, but this can be generated by a fairly small power plant. Yearly power consumption is in the order of 0.7% of the capacity of a 4000 GWh power plant for a low speed- and 2.2% for high-speed take-off.

In summary, a Maglev take-off system can be made to reduce an aircraft's noise footprint by giving an aircraft an additional take-off velocity and allowing it to 'glide' to a predefined altitude at a lower thrust setting. The emission of UHC's, CO and NO_x is also reduced since the engines are running at a more efficient power setting. A lot of additional research is needed in order to successfully implement a MagLev take-off system, but the potential benefits are very promising.

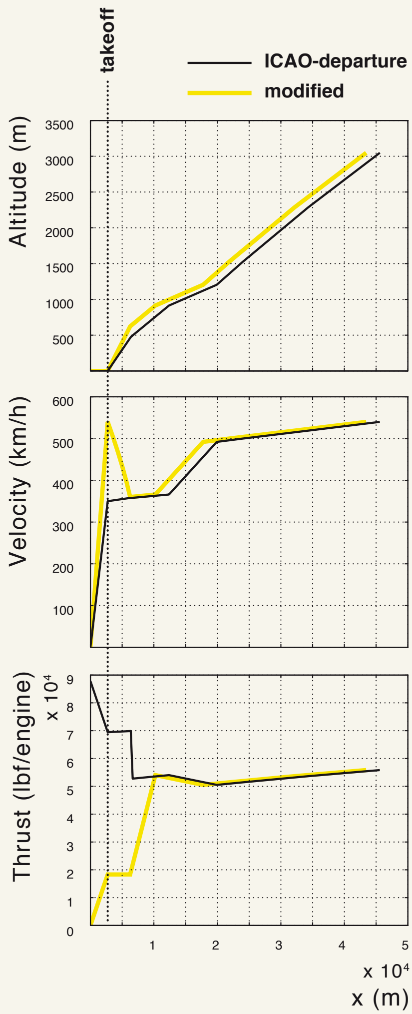


Fig. 141. ICAO-A departure and custom departure.
Custom departure settings:
thrust (T = 20%),
launch speed ($V_{takeoff}$ = 150 m/s),
flight path angle (γ = 10˚).

Design for sustainability

A system approach

by Marcel Schroijen

In response to the increasing anthropogenic environmental impact, regulations are becoming ever stricter. In order to meet these new regulations, the industry and ground transport sectors are changing their paradigms. Industry is quickly reducing its impact on the environment in response to the carbon dioxide trading scheme. Road transportation is reducing its impact in response to the increasing fossil fuel price, for example by introducing hybrid cars. The limited improvements achieved in aviation, combined with the significant reductions in other industries, put aviation at a disadvantage. If aviation cannot adapt to meet the demands of reduced environmental impact, it will become the main pollution contributor. Aviation has defined goals to reduce its environmental impact and become sustainable, but whether the means to reach these goals are sufficient remains to be seen.

LIMITATIONS TO THE ACARE GOALS

In order to realize a sustainable future for aviation ACARE has proposed technological solutions in order to reduce the impact of aviation.

These goals can be summarized as:

- 50% reduction of carbon dioxides
- 80% reduction of nitrous oxides
- Limitation of noise nuisance to the boundaries of the airports
- Remain competitive

As has been discussed in the previous chapters, the focus is on the technological side of aviation to achieve these goals. However, the impact of aviation is for a large part dependent on the number of passengers, i.e. on the growth of the aviation industry.

PROJECTED CARBON DIOXIDE IMPROVEMENT

For example, let's assume that the ACARE goals of technology efficiency and system efficiency are achieved in 2050. This means that every aircraft flying in 2050 has reduced its carbon emission with 50% compared to the aircraft flying in 2000. Furthermore, the overall system efficiency has improved with 50% compared to 2000, for instance through more efficient landing and approach routes, more efficient routes, minimum pollution by on-ground taxiing and so on. In addition to this, aviation is considered to have switched to biofuels which make up 40% (EU target) of the consumed fuel quantities in 2050. Since the carbon dioxide overhead on these biofuels is 20%, the 60/40 mixture of fuels still produces 60% + 40% * 0.2 = 68% of the carbon dioxide emissions compared to a 100/0 mixture.

PROJECTED PASSENGER GROWTH

When based on the passenger growth from 2000 to 2010, the projected growth in traffic over the period 2000 to 2050 will mean an increase of 43% every 10 years. If we assume growth will be slightly less due to the increasing resistance towards flying (caused by increasing costs and / or awareness of the impact of flying), the projected growth is still 41.4% every 10 years. For the period 2000 to 2050 this results in: $1.414^{(50/10)}$ = 5.65 or an increase of 465% compared to passenger numbers in 2000.

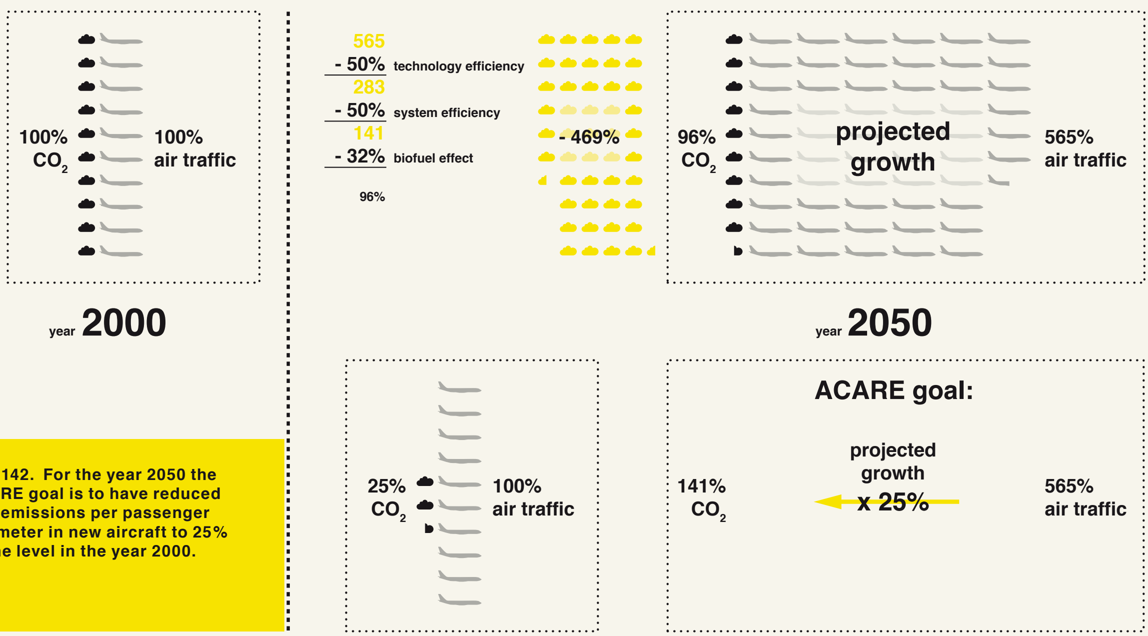


Fig. 142. For the year 2050 the ACARE goal is to have reduced CO_2 emissions per passenger kilometer in new aircraft to 25% of the level in the year 2000.

DESIRED CARBONDIOXIDE LEVELS

The target for 2050 by ACARE is to achieve a 25% impact compared to the impact in 2000. If we combine the passenger growth prediction with the projected reductions on carbon dioxide, we find a decrease of around 5% compared to carbon dioxide levels in 2000. This 95% is still 70% above the 2050 target of 25% and this includes all foreseen improvements to the system. Even replacing the 60/40 mixture with a full biofuel content would only achieve 28% of the carbon dioxide emissions in 2000 which is still 3% above the target. If we leave the carbon dioxide reduction due to the use of biofuels out of the equation, the system impact even increases by 41% due to the passenger growth.

	Year 2000	Year 2050	2050 target
n° of Passengers	100 %	565 %	
Technology efficiency	100 %	50 %	
System efficiency	100 %	50 %	
Biofuel effect	100 %	68 %	
Overall	100 %	96 %	25 %

Table : Comparison of relative CO_2 emissions as a result of technological improvements versus the ACARE goal.

All of the above is based on the assumption that all aircraft are replaced at a certain time, which in reality is not the case, so the outcome is even worse than shown above. Consequently, if we focus solely on technological solutions we will not solve the sustainability problem. As a side note, increasing the efficiency beyond the 2050 ACARE targets will require increasingly more resources.

STAKEHOLDER REQUIREMENTS

The demands on aviation change over time. Since the early days, when air travel was limited to the elite, aviation has become a means of transportation for the masses. Nowadays, people want to fly to new and distant destinations, preferably at decreasing costs. The downside to aviation is the negative impact it has on the environment. This impact should be reduced according to the goals of ACARE. The desired rate of reduction of the environmental impact stems from the number of people negatively affected by aviation. In economics these effects are called 'externalities'. Externalities are effects beyond the parties involved in the transaction itself.

Consider for example the traveller and the airline. The traveller wants to be somewhere at a certain time and needs transportation to get there. The airline can provide this product at a certain cost. If there is agreement on the product and the traveller decides to travel, a mutually agreed transaction occurs. However, the effects of this transaction go beyond these two parties. The traveller uses two airports, customs, passes through multiple air spaces and the pilots of the aircraft use multiple air traffic control services along the route and during take-off and landing. These are the stakeholders usually taken into consideration with regard to the aviation system. Nevertheless, other parties are also affected by the choice of the traveller, often negatively. Consider for example the people living in the vicinity of the airport who experience the nuisance of the aircraft taking–off or landing, or those affected by the land use of the airport or the degradation in air quality.

It appears that the effects of these externalities are growing more rapidly than the benefits, i.e. the ability to travel to any location on earth within reasonable time. The demands of stakeholders negatively affected by aviation are changing at a pace that aviation technology cannot keep up with.

FLEXIBLE TECHNOLOGY REQUIREMENT

Every technological improvement has an impact. However, limiting the adverse effects is possible. Though adverse effects at a far-off point in the future may not seem urgent now, the tolerance towards the adverse effects of a growing aviation system is decreasing. Hence, a system that is capable of continuously adapting itself to the changing requirements of stakeholders will become a requirement of the system in its own right. This will pose challenges for future aircraft design and for the aviation system as a whole. Challenges we have to meet if we want to keep up with the demands of increasing usage, as well as with changing perceptions of what constitutes nuisance.

The main limitation of the ACARE goals is not that they are not strict enough or that they primarily focus on technology. It is the development time needed to meet the demands on the aviation system. The development time of the required technological improvements to achieve the environmental impact reductions as represented by the ACARE goals is estimated to take up to 20 years. This conflicts with the rapidly increasing demands from stakeholders to address the adverse impact of aviation. Hence, to achieve further reductions in environmental impact, a change in aviation paradigm is mandatory. This new paradigm should focus on continuously improving the technology and adapting it to the requirements of all stakeholders.

AVIATION SYSTEM

The flexibility required to transform the system is not part of the current aviation system. To ascertain this we only have to look at the complexity of the system both on the technology and the aviation side:

- On the technology side, the complexity of the aircraft and the associated risks of developing a revolutionary aircraft can be seen as the main contributors to the inflexibility of the system.
- On the aviation level, we are confronted with a consolidated industry, reluctant to quickly adapt to new requirements. This is exacerbated by the dominance of shareholders, rather than stakeholders, and by strict regulations.

TECHNOLOGICAL LIMITATIONS

Rigidity in technological improvements can be traced to the complexity of the aircraft and the associated risks in developing a novel technology.

Let's try to estimate how much more difficult it will become to design an aircraft if we use the new technologies proposed to reduce the environmental impact of aviation. A variety of measures have been defined to describe the difficulty of a product. These measures are dependent on the field of use and can vary from difficulty of achieving a preset goal to the number of items one has to consider. Furthermore, complexity appears to be dependent on the individual. What is considered complex by one person can become less complex with the gaining of new insights or achievements.
For the purpose of this chapter we do not aim for an exhaustive definition of the concept of complexity, but we introduce three complementary indicators to define it more easily:

1. complexity as size,
2. complexity as coupling and
3. complexity as solvability.

NUMBER OF COMPONENTS (1)

The complexity of an aircraft based on the components can be illustrated by comparing the number of components in an aircraft to that in other transport vehicles. Although these numbers are only an estimate of the number of unique components composing each of these systems, they give a good indication of the difficulty of designing it.

	Unique parts
Bicycle	1,000
Car	30,000
Aircraft	100,000 - 300,000
Spaceshuttle	1,000,000

Table : Estimated number of unique parts.

As can be seen, aircraft are complex in relation to most other means of transportation. Moreover, when in use, every aircraft is part of the larger aviation system. When we also include the number of unique stakeholders, the number of parts of the aviation system is a multiple of that of the aircraft.
Then, there is an additional difference between the aircraft system and aviation: an aircraft is designed for a defined purpose and can be controlled by a single entity, whereas aviation consists of many independently deciding and interacting systems.

NUMBER OF INTERACTIONS (2)

The limited capacity of both computers and the human mind forces designers to decompose the design problem into smaller pieces. This has its consequences.

Consider for example the wing of an aircraft. The wing cannot be seen as an independent system and can therefore not be designed in isolation. Although the wing's primary function is to generate lift, this lift is needed to transport passengers, which directly links it to the fuselage in which the passengers are housed. These interactions between the various systems directly affect the complexity of the design. If the system can be considered in isolation, i.e. the boundaries are well defined and include all (important) influences, then the design will be less complex than if the system boundaries are ill-defined. Furthermore, the number of boundary interactions to be taken in to consideration are another measure of complexity. The coupling complexity is based on how far the design problem can be decomposed.

UNCERTAINTY IN THE BEHAVIOUR (3)

Finally, the solvability complexity measures the effort required to solve the problem at hand. Summers and Shah (2009) consider the degrees of freedom of design as a measure for the solvability complexity, where the variables are - as previously discussed – size and coupling. The solvability is determined by the availability of an appropriate means to predict the behaviour of the final product.

These combined measures of complexity indicate the level of difficulty involved in designing an aircraft. This complexity is expected to increase for novel designs. The reluctance of established aircraft manufacturers to develop a new aircraft based on novel technologies can be explained by looking a the financial risk of such an undertaking. The Airbus A380 is in essence a conventional concept aircraft with new and improved technology. Development costs were estimated at 8.8 billion euro at the start of the project in 2000, but grew to 11 billion euro for the production of the first airliner. In addition to this, problems with the wiring harnesses caused a delay of twenty months to the delivery of the first airliners, amounting to an estimated 5 billion euro of lost revenues over the first four years.

The uncertainties and impacts (i.e. risks) for the development of novel aircraft concepts are even larger than for conventional airliners, as the development of the cost of the novel technology has to be factored in. Consequently, total costs are much more difficult to predict and the financial risks are even more significant than for the A380.

AVIATION LIMITATIONS

Aviation has grown from an elite mode of transportation to a transport medium for the masses. Growth was always a focal point of the industry and technological development was focussed on increasing the capacity of the system to accommodate the increasing number of passengers.
The growth limitations of the system were increased by technological improvements; e.g. improved navigational aids, increased capacity in aircraft, larger airports to accommodate the increasing traffic flows of both passengers and aircraft.
Changes and improvements in technology were rapid and radical in the early days of aviation as the system was limited in complexity and size. Currently the changes in

technology are evolutionary and require a long time from conception, through design and validation, to introduction. This might be caused by the fact that aviation itself is consolidated, and that introduction of novel technologies and new concept technology is not an integral part of the system. The achieved constant improvement in technology appears to be externally driven by legislation and competition is limited (oligopoly) to two major aircraft manufacturers, Boeing and Airbus.

A good example is the Concorde. This aircraft is seen as a marvel of technology, with its cruising speed of Mach 2, fly-by-wire system, delta shaped wings, fuel balancing trim system, and advanced materials to withstand the thermodynamic load during supersonic operations. With the introduction of Concorde, the conventional eight-hour transatlantic trip could be made in under four hours. However, commercial supersonic flight did not, so to speak, take off. This despite a pioneering technology that was the result of cooperation between numerous nations. Concorde was hampered by the impact of its sonic boom and the resulting noise issues on the ground. Furthermore, the increase in fuel prices during the oil crisis of the 1970s made flying with Concorde only available to the wealthy. Hence, Concorde is an example of a technological breakthrough which was overtaken by the times and the aviation system it had to operate in. At the time of introduction the aviation system had changed to such an extent that the original requirements were no longer valid.

The legislation surrounding the application of new materials is another example. Early aircraft were manufactured from wood covered in cloth. In the 1930s this concept was replaced with aircraft made from metal. The number of accidents with aircraft made from wood and cloth may have played a part in this. Examples of metal aircraft from that era are the Boeing 247, DC-2 and its more famous sibling the DC-3. With these models, air travel became a commercial means of travel. A similar development is currently in progress with the change from metal to composites. Composites have benefits over conventional metals such as high specific strength. They can be tailored to enhance weight saving and good fatigue resistance. However, the legislation for certification of such structures is still incomplete as methodologies for design and certification are necessarily different to those for metal.
What is required, among others, are:

- increased understanding of the crashworthiness
- large scale impact tests
- definition of appropriate failure scenarios
- advance consideration of repairs
- reliability of detection of damage

Addressing these certification issues consumes resources which add to the development costs of any design programme. As a result, the introduction of these materials is highly evolutionary. Their use starts from the secondary structure and they will be slowly introduced into primary structures when more experience is gained. Thus, the full potential of these materials remains unexplored. Commercial aviation relies heavily on general aviation developments. Novel materials are at a disadvantage, both in cost and time, compared to conventional technologies.

Both examples show a mismatch between the technology and the aviation system it has to operate in. With Concorde, its development was overtaken by external factors. The complexity of the project did not allow for quick adaptation of the technology to new requirements. These new requirements arose from the fact that the complete impact of a new technology is not known beforehand. This has the tendency to create unforeseen or unknown effects, as was the case with the noise nuisance of supersonic overland flight.
The second example represents the inflexibility of the aviation system to accommodate and adapt to new developments. The mismatch in the first example needs to be addressed if we are to bring together new technologies and the increasing need for sustainability. The inflexibility in the second example needs to be addressed for aviation to be able to incorporate the revolutionary technologies needed to meet future requirements.

For both examples a distinct beneficiary can be identified in one of the shareholders of aviation:

- Concorde as a technology for fast travel without competition, which could be used by airlines.
- The transition from metals to composites for the reduced weight and hence operating costs for the airlines.

Although these developments were initiated externally, by government or technological developments outside of aviation, they were carried by one of the shareholders. The need for environmental impact reduction is mainly stakeholder-driven and not shareholder-driven, therefore this will not result from a natural evolution of the system. This needs external incentives if it is to be implemented and carried by the system. This will pose a further challenge to aviation in the near future. New technologies often create unforeseen or unknown effects. Combined with aviation's slow response to changing requirements, this results in a aviation constantly lagging behind events.

IMPLICATIONS

In conclusion, the set of goals for aviation, as ambitious as they appear, are insufficient to counter the effects of the increasing nuisance of aviation, even if the complexities of developing a revolutionary technology are met.

Three additional challenges have been identified that have to be met for aviation to become sustainable:

1. The ability to adequately adapt the requirements of the technology to the needs for a sustainable aviation.
2. The ability of the system to incorporate and cope with the revolutionary technologies required for the sustainable aviation.
3. A method of integrating the sustainability requirements stemming from stakeholders into aviation to make sustainability an integral part of aviation and address the externalities.

If aviation is not able to adapt to changing requirements, the externalities, e.g. the increasing nuisance of aviation, are likely to grow faster than technological improvements can address. If this were the case, the special status of aviation as a flexible, affordable means of transportation might be at risk.

Conclusion

by Jacco Hoekstra

As the dean of the faculty in the CleanEra years, it is my privilege to write the conclusion to this book which presents a range of technologies for greener air transport. I'm enthusiastic about the future of aeronautics, when I read about improvements in so many fields.

In aerodynamics, the parameterizing of aircraft shapes in 2-D and 3-D opens the way toward new aircraft shapes with drastically improved lift-to-weight ratios. Technologies to bend / morph aircraft shapes for high lift devices enable ultra-smooth, ultra-efficient wings and a resulting reduction in both emissions and noise. Technologies capable of interacting with the boundary layer itself - such as new, low power plasma actuators - open the door to active flow control and hence to reductions in parasite drag and noise or even to control aircraft without any moving parts.

In the structures area, new ways of designing and producing composite aircraft structures lead to even lower weight aircraft, while increasing the damage tolerance. Pressure vessels for non-cylindrical aircraft such as Blended Wing Bodies are another exciting possibility, as these would also enhance passenger comfort, an area mostly left out of the equation in current aviation practice. New coating technology offers high levels of wear protection and corrosion resistance without the use of toxic substances.

On the topic of engines, new hybrid concepts and lean burning techniques lead to significant reductions of CO_2 and NO_x. Our increased understanding of what constitutes noise pollution and what causes it, can lead to further noise reduction, e.g. through new noise suppression techniques. Combined with novel aircraft configurations, today's whispering aircraft could fall completely silent. Imagine the effect that would have politically and socially.

Stepping outside the boundaries of aircraft design, airspace restrictions could be vastly improved by means of airborne separation assurance systems. This will increase the flexibility, efficiency and capacity of the airspace system, while improving safety. By optimizing aircraft trajectories during descent, noise reductions can be achieved. This in turn leads to minimal thrust usage while it leaves enough manoeuvrability for air traffic control operations. A highly imaginative take-off system, that more or less catapults aircraft into the air, also promises dramatic noise reduction.

These technologies promise energy-efficient, low-emission aircraft that are less dependent on infrastructure restrictions. It is a bit of a no-brainer, you would think, but it is not happening. Unfortunately, we have seen many more technological promises over the past decades, yet few of these make it into operational service. Supersonic flight, hypersonic flight, the use of airships for luxury flight, and lately, promises for green flight as in the case of CleanEra. However, since the deregulation act came into being, aviation has focused on consolidation and few radical changes have found their way into the system. Efficiency improvement is now the credo, leaving no room for revolutionary steps.

You could say that the success of today's the air transport system is its own biggest threat. Why change a system, which is capable of transporting people so fast, so cheap and so safe as it is today? Yet the world is changing and it is changing fast. What is acceptable today could no longer be acceptable tomorrow. Attitudes change fast and people are increasingly intolerant towards the antisocial aspects of aviation. This is partly due to the fact that world population is growing fast, leading to a reduction of resources available, especially available per person.

As the chapter on system design explains, the ability of aviation to adapt to the rapidly changing requirements of its stakeholders is becoming a requirement in itself. If aviation cannot adapt to these flexible requirements, the externalities - e.g. the growing nuisance of aviation - will increase at a rate that outpaces technological improvements. If this were to happen, aviation will lose its special status as a flexible, affordable means of transportation. It might then be replaced by an alternative as soon as it occurs.

Already a number of shadows are looming:

- The ever-increasing population and its inherent transportation demand, effectively nullifying any evolutionary technology improvement for the environment;
- The increasing scarcity of global resources; and,
- Long and often inflexible certification processes, prohibiting the air transport system to adapt in step with our fast-changing society.

It is extremely difficult to change a system as complex and as costly as our present civil aviation system in a meaningful way. What is causing this slow take-up of innovation? It seems the sector has become afraid of changing a system which has been proven to work. On the one hand, we do not accept any new technology unless it has been proven to be absolutely flawless and fits all the rules. On the other hand, we keep systems which are flawed by present standards. Imagine that today you would invent an instrument landing system, which would not only guide you to the correct glideslope of three degrees, but also has the risk of guiding you to a false glideslope of six degrees. I would not be surprised if authorities, based on the advise of expert committees, would not approve of this system. However, today we are using an instrument landing system or ILS, which has this 'feature'. And this is a good thing, as without ILS we would not be as safe as we are today.

Let's take a different example: the information available in the cockpit. Pilots have to rely on a map display which is largely black and shows the beacons and waypoints by codes varying from 1 to 5 characters. This limited amount of information contributed to the crash of American Airlines 965. This flight crashed in 1995 due to flying to a beacon listed as 'R', which turned out to be in a completely different location from the Rozo beacon that air traffic had instructed. Similarly, when a TCAS (Traffic Alert and Collision Avoidance System) alert is given, traffic information is only shown to pilots at the very last moment. This practice contributed to the 2002 mid-air collision of a cargo aircraft with a passenger jet over Überlingen.

For information on the weather on the ground we still rely on METAR messages with five-character codes. In contrast, as a flight passenger with internet you can see geographical moving map displays based on your GPS position, you can see traffic around and you can see moving satellite images for the weather. Why have these technologies not made it into the cockpit yet? The electronics required are cheap. It is the cost of certification that inhibits innovation here. The certification regime was aimed at improving safety but now hinders improvements which could increase that same safety. This, in a nutshell, is the infamous aeronautical innovation-safety paradox: certification requirements aimed at ensuring safety prevent the introduction of improvements which could contribute to the safety. We've seen the same problem in chapter 11: Certification costs also prevent innovation in other areas, and as such hinders the introduction of sustainability improvements.

How can we change this in a responsible way? The certification requirements are beneficial to safety and we certainly want to keep that benefit. On the other hand, we also create a risk when the advances which could improve safety, are impaired by the lengthy and expensive certification process. The only way to improve this is a society-driven urge for change. But such an urgency has then to be dealt with via the economic route as well as the societal. Societal challenges have to be translated into a system which improves the cost-benefit case for technological advances. Regulation of fuel prices, taxing systems, and state funding of radical innovations, are methods in which this can be achieved. To maintain a level-playing field in the internationally oriented aviation sector, such measures should be introduced globally.

Alternatively, step-changes in technology could create a huge demand and a corresponding urgency. A few decades ago, nobody would have foreseen the current demand for cell phones and tablets. Moreover, nobody would have deemed them technologically possible or economically feasible.

There are two fields that could spur a similar revolution in air transport. One is already taking shape and the other one is still very much in the pioneering phase.

In the field of Unmanned Aerial Vehicles (UAV), or Remotely Piloted Airborne Systems (RPAS) innovations are happening fast. CleanEra research also expanded into the UAV area with ZESAR, its zero-emission unmanned vehicle. The goal of the ZESAR was to develop a flying demonstrator of zero-emission unmanned aerial vehicle (UAV) with high cruise speeds of over 300 km/h and a range of more than 800 km. Furthermore, to develop an aircraft that is inaudible to the human ear at low altitudes. New applications are constantly being developed. Both small and large UAVs are emerging, with corresponding new technologies. UAVs offer all the opportunities of the blank-sheet approach, meaning they could include sustainability from the start. Such a bottom-up development is not lumbered by the constraints that hamper innovation in the traditional aviation sector. In fact, it could really take off, especially if backed by the favourable wind of societal demand. It is clear by the huge number of different UAV concepts currently available that this sector is still in the experimental stage.

Still beyond the horizon is personal air transport, or as a Popular Mechanics magazine cover once put it: “Where is my flying car?” Despite the huge potential demand, aviation-type vehicles as a general means of transport are still a way off. A new generation of aviation pioneers worldwide are attempting to develop these vehicles that are safe, efficient, affordable, practical and sustainable. Not to mention fun. It is also easier to make smaller, slower vehicles sustainable than large fast ones, while door-to-door times for aviation will improve dramatically. Such ‘flying cars’ could now be controlled in a semi-automatic and de-centralised way, relieving the workload of air traffic control. Such a system could be the next revolution in air transport. The USA have taken the first steps already with the Small Aircraft Transportation System (SATS) project, and Europe is also studying Small Aircraft concepts within their Framework programs.

Fig. 143. The ZESAR, Zero Emission Silent AiRcraft, an advanced UAV.

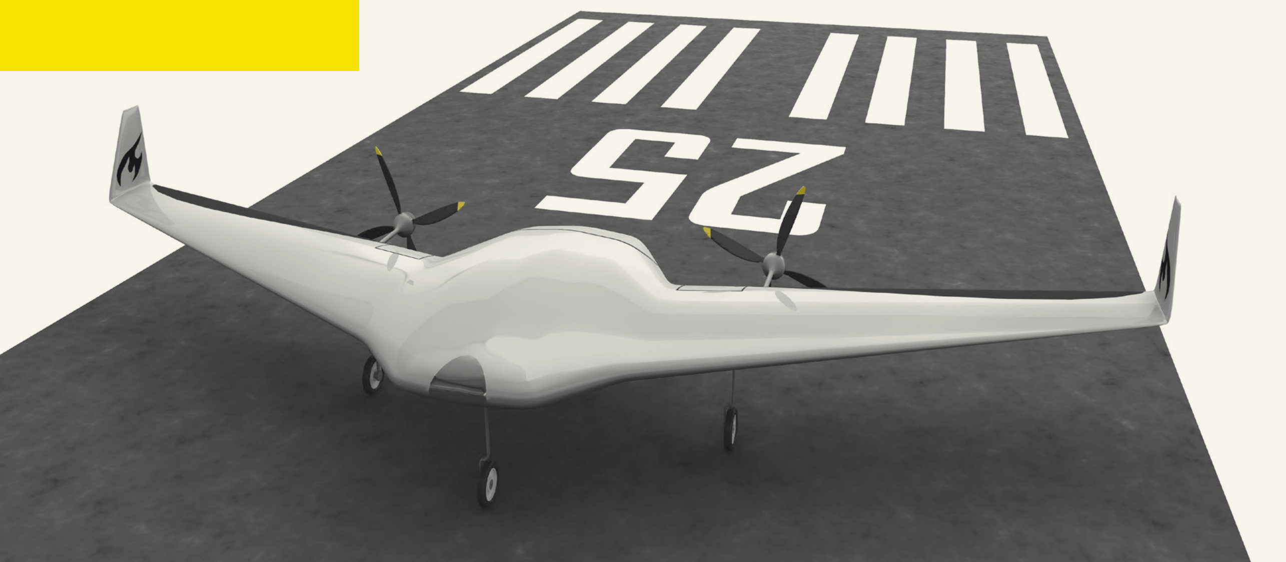


Fig. 144. The CleanEra X-3, a manned version of an emission free testbed.

As we have seen in the introducing chapter, the product lifecycle theory means the aviation industry will have to innovate or risk being overtaken by alternative modes of transport. A similar development can be seen in personal electronics business, where smart mobile devices have largely overtaken PCs and ‘dumb’ mobile phones, leaving behind some of the industrial behemoths that could not adapt in time.

The self-imposed restrictions to change in the industry are being challenged by a growing demand for greener aviation and more adaptable solutions. To survive, the aviation needs a new paradigm that focuses on continuously improving the technology and adapting it to the requirements of all stakeholders. Having said that, the many promising technologies and ideas on offer are set to make the second century of flight as exciting as the first.

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