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Survey on the Application of a 3D General Purpose Wind-Tunnel Research Model

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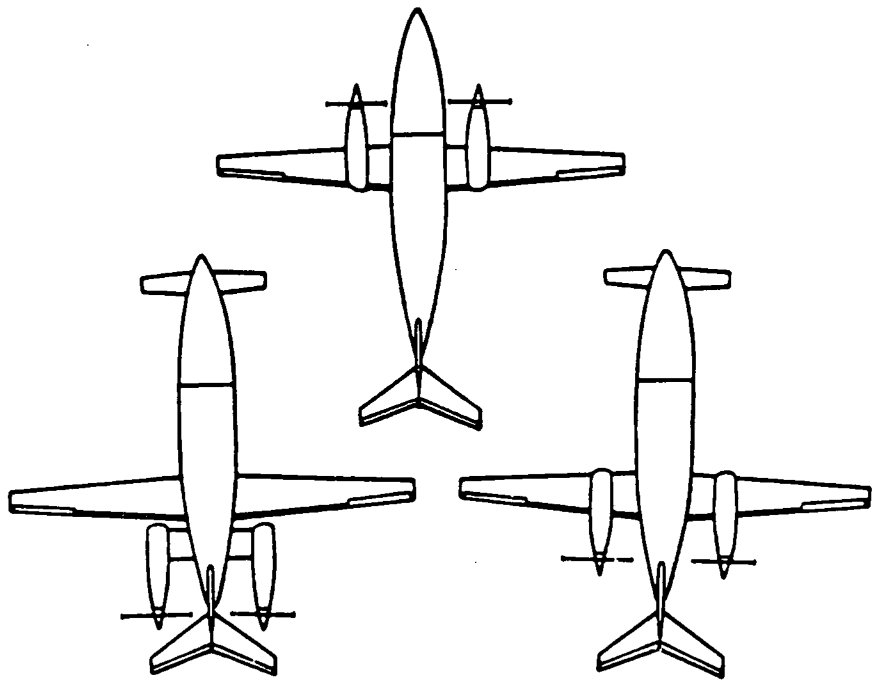
M.J. Pagen



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Summary

Since the introduction of advanced propeller propulsion systems and the appearance of unconventional aircraft configurations the need is felt to enhance the program of configuration studies at the Wind-Tunnel Laboratory for Low-Speed Aerodynamics of the Department of Aerospace Engineering of the Delft University of Technology. A major element in the research program will be a new general purpose wind-tunnel model to be used in parametric studies of various configuration arrangements to evidence the importance of power effects and other significant aerodynamic considerations.

As a first stage in the design of the model a study of literature has been conducted to determine the aspects of interest of aircraft configuration research. This has brought out that attention in configuration aerodynamics is directed to the aerodynamic integration of highly loaded propellers, and the performance evaluation of multi-wings. Overall there is a tremendous development in computational aerodynamics. It has become apparent that the need for conclusive experimental results to validate computational design codes is considerable.

In this report it is proposed to design the model in assembly kit form so that various configurations can be composed, including two- and three-surface arrangements of which the lifting surfaces can have different settings. It will also be possible to mount the propulsion system in various fashions.

As for the research program systematic component build-up tests will be performed starting from a baseline fuselage to identify aerodynamic contributions of individual airframe components, and aerodynamic interference effects. The same configurations will also be used to establish the effects of propeller slipstream on the flow-field around the model. In this way an extensive collection of valuable aerodynamic data will be acquired.

Contents

1. Introduction

As future performance requirements become more stringent, the successful aerodynamic design of complex advanced aircraft configurations will necessitate more accurate and detailed knowledge of the three-dimensional flow field about aircraft and their aerodynamic behavior. Mutual interference effects between the various aircraft components can be detrimental to the performance and handling qualities of the aircraft and must be assessed. As a result, the utilization of both wind-tunnel test data and analytical aerodynamic predictions will be fundamental to the design and development of advanced aircraft.

At the Low Speed Wind-Tunnel Laboratory (LSL) of the Department of Aerospace Engineering of the Delft University of Technology (TUD) a part of the theoretical and experimental research is devoted to aerodynamic problems which directly relate to the performance and handling qualities of aircraft. These studies are confined to configurations equipped with propeller propulsion because of the interests of the national aircraft industry, and the limitations of the wind-tunnel laboratory.

Since the introduction of advanced propeller propulsion systems and the appearance of unconventional aircraft configurations the need is felt to enhance the program of configuration studies. Recent developments in the area of experimental and computational research of flow fields allow such an enhancement. It is intended to come to a better understanding of the aspects dominating three-dimensional flows by means of a balanced program of experimental and theoretical (analytical and computational) investigations. Detailed flow field analyses will therefore be a major part of the program. The results from this program will be used to validate and upgrade current aerodynamic design methods, and to gain better insight in performance and handling problems of aircraft.

A major element in the proposed research program will be a general purpose wind-tunnel research model (variable geometry model, VGM). This model will be used in parametric studies of various configuration arrangements to assess the importance of power effects, and other significant aerodynamic considerations like aerodynamic interference between airframe components. It will be designed to allow for easy variations in aircraft component location and propulsion system installation.

To determine the aspects of interest of aircraft configuration research a literature study has been conducted. In this report the difficulties and uncertainties in the aerodynamic design process are reviewed with reference to some experiments from literature. To ensure sufficient interfaces with existing study programs several authorities of the national aerospace community (TUD subject groups aerospace design/flight mechanics, stability and control; Fokker, National Aerospace Laboratory NLR) have been interviewed to implement any advisable investigations in the program. This report concludes with a proposal for the concept of a VGM, and for its application within the intended research program.

2. Conceptual Aerodynamic Design

At the beginning of the conceptual design process the geometric definition of the airplane is very simple, and almost nothing is known about what the airplane should look like, what type of powerplant it should have and how big the airplane should be. The initial phase is used to define what configuration type is best to accomplish the task specified for the airplane. This phase answers such question about the airplane as: should it be a flying wing, blended wing body, wing-body-tail, wing-body-canard, forward sweep, aft sweep, etc.? Often, this early conceptual design phase is replaced by experience, intuition, or preconceived configuration/propulsion ideas.

During the course of a conceptual design study sensitivity studies are performed to show what airplane parameters are important for the success of a given airplane concept. Various parameters are changed one at the time to see what effect they have on the airplane performance and handling qualities. If the design changes noticeably as a result of this parameter change, then an accurate estimate of the parameter will be necessary to provide confidence in the resulting airplane design.

Conceptual design considers the interaction between aerodynamics, propulsion, weights, structures, etc., and the mission requirements for the airplane, and integrates all of these items into the best arrangement to accomplish that mission. As the conceptual design process reaches its final stages, and the airplane external geometry becomes well defined, the differences between it and what is called the preliminary design become very vague.

In summary, conceptual design requires the analysis of a variety of configuration types in the early design phase and a wide variety of geometry variations within each configuration as the design refinement process continues.

Conceptual aerodynamic estimates are done using a wide variety of different methodologies. It is important that the aerodynamic estimates have sufficient accuracy to discriminate between good configuration concepts and poor ones. The term airplane aerodynamics is rather a general term covering many different parameters such as lift, drag, pitching moment, steady and unsteady derivatives, etc. Unquestionably, the most important aerodynamic parameters in conceptual design are lift and drag. The stability derivatives are needed to assure that the airplane geometry being analyzed can indeed be a real, flyable airplane.

A conceptual design methodology must be able to analyze a large number of airplane geometries in a reasonably short period of time. The fundamental idea is to vary just one parameter at a time, and thereby provide an understanding of the computed results. In a conceptual design study, there are clearly a large number of variables to be considered. The variables used in a conceptual design study are typically such things as airplane thrust to weight ratio, aspect ratio, wing loading, wing sweep, taper ratio, etc. Clearly, there could be many other variables considered in a design study, but the consideration of a large number of variables will require a vast and unrealistic amount of computer time. Since most of the configuration analysis methods cannot handle a large number of variables, the optimization of aerodynamic variables such as camber, twist, leading and trailing edge flaps, control deflections, etc., must, be done by the aerodynamic code used in the design process. The difficult balance between speed and accuracy has been satisfied classically in conceptual design by the use of semi-empirical aerodynamic methods.

In the development of semi-empirical methods, basic aerodynamic theory is used to make a first order estimate of the lift and drag and to define reasonable aerodynamic parameters to be used in the correlations. Then empirical corrections are made to the theory to produce good agreement with wind-tunnel and flight test data.

Semi-empirical methods produce reasonable aerodynamic estimates for most airplane configurations using only gross geometric parameters. The use of only gross geometric parameters is important to conceptual design. In conceptual design it is desired that sufficiently accurate aerodynamic estimates can be obtained using as little geometric definition as possible. This probably sounds strange to those who are involved with computational fluid dynamics, since almost complete geometric fidelity is needed for those codes to function properly. In conceptual design, complete geometric fidelity is provided by the geometries of the experimental models and test aircraft used in the aerodynamic database. Some sub-optimization of the geometry is done by the shapes used in the test database. What this sub-optimization allows, is the reduction of the number of design variables that need consideration in the conceptual design process.

It is well understood that when the geometric parameters used in an airplane design are significantly different than those in the database that was used to develop the semi-empirical aerodynamic methodology, the methodology results are subject to question. One of the obvious ways to be outside of the database is when a single geometric parameter used in the design is clearly less than or greater than what was available in the database. If this parameter was not correlated in a physically significant manner in the semi-empirical methodology, then an extrapolation outside of the database could produce answers that have unacceptable accuracy.

One not so obvious way to be outside of the database is when combinations of parameters are different than those found in the database. This can occur because the parameters in the database are not necessarily independent of one another.If the theory used as the basis of a semi-empirical method cannot clearly separate the effect of one parameter from another, then the semi-empirical method will not be able to do the separation unless the database itself has done it.

Another obvious way that the design can be outside of the database is when the best configuration for the design is not even in the database. This is probably the most serious problem that nearly all semi-empirical methods currently have. The ability of semi-empirical methods to analyze modern configurations is limited for several reasons. It is due largely to the advent of computers, computer developed aerodynamic methods, and the rising costs of wind-tunnel and flight testing.

During the 1940s, 1950s, and early 1960s, a large amount of parametric testing was done because it was the only reliable way to do aerodynamic estimation. A large database was generated and it was used for developing semi-empirical aerodynamic methods. At the time, this was the process for preliminary and detailed aircraft design. The conceptual design phase was very short and simple.

Beginning in the 1960s, computer aerodynamics dramatically changed the way things were done. It was found that computational fluid dynamics (CFD; largely linear aerodynamic methods) could provide valuable design guidance and that it was no longer necessary to do extensive parametric wind-tunnel testing. Wind-tunnel testing was then mainly used to refine the configuration that was developed by computational aerodynamics. As a result, the amount of costly wind-tunnel parametric testing was significantly reduced. As computational aerodynamics improved in capability with time, the parametric database for semi-empirical aerodynamics was shrinking dramatically. The net result of all this is that the database for use in developing semi-empirical aerodynamic methods is still largely populated by geometries that follow the design practice of more than 25 years ago and not current design practice.

The development of new semi-empirical methods to handle modern configurations will be extremely difficult and will require extensive engineering resources. This is due to the shrinking database and the significant increase in the number of geometric parameters that need to be considered in a modern airplane design. Little or no parametric testing is being done, and as a result the prospect of finding data that clearly has independent variation of one geometric variable versus another, is slim. It will also be extremely difficult, if not possible, to find theoretical parameters that are independent of one another.

Since the aerodynamic conceptual design process seems to rely heavily on the use of CFD codes, it raises some concerns about the status of CFD code developments.

The potential of CFD is well known. Owing to improvements in numerical algorithms, geometric modelling, grid generation, and physical parameter modelling, as well as dramatic improvements in computer processing speed and memory, CFD is becoming an increasingly powerful tool in the aerodynamic design process, one that requires a high level of confidence. This is perhaps the most critical concern at this time about the benefits of CFD for the design process. In the context of this discussion, confidence relates to the dependability of the codes to give accurate solutions over the range of design variables. Capability pertains to the usefulness of the code in modelling flow fields about complex geometries over a wide range of flow conditions, such as Mach number, Reynolds number, angle of attack, and yaw, and in producing results in a form meaningful to the designer.

In general, CFD methods of today can simulate flows about complex geometries with simplified flow physics, or flows about simple geometries with complex flow physics, however, they cannot simulate both in many cases. These simple methods usually involve solutions of the potential flow or Euler equations and typically require assumptions about the structure of the flow field to make the solutions more tractable. Flow phenomena on complex three-dimensional configurations such as flow separation and vortex generation, are still very difficult to model accurately. For instance, effects of propulsion from propeller slipstream or turbofan exhaust flow can be accounted for in only a limited way. The future use of CFD methods will depend on their ability to accurately model these critical physics of the flow.

In the light of known limitations inherent to CFD codes, validation must entail a thorough understanding of how those limitations affect the ultimate accuracy of a solution in a given application. Thus, validation is seen to include the bounds of accuracy in terms of a range of numerical and physical parameters for which an acceptable error band may be achieved. This level of confidence, then, must be related to experimental evidence that is subject to its own band of uncertainties. In order to meet the required confidence level, the CFD codes must be verified with the best available experimental data. Because of the complexity of the aerodynamic flows that will be routinely computed, the experimental database must be expanded to include not only surface-measurable quantities, but also detailed measurements of flow parameters throughout the flow region of interest.

It is, of course, important to note that CFD codes can be used in analysis and design applications long before the codes are considered to be mature. Engineers have always been able to use less than perfect tools to provide design guidance by using them in conjunction with experience and calibration to know physical quantities. In the past, the terms "validation" and "calibration" have been used loosely to describe any comparison with experiment. A definition of calibration as it applies to CFD is suggested by Bradley (Ref. 1) in order to distinguish the process from validation: "The comparison of CFD code results with experimental data for realistic geometries that are similar to the ones of design interest, made in order to provide a measure of the capability of the code capability to predict specific parameters that are of importance to the design objectives without verifying that **all** the features of the flow are correctly modeled."

So, considering the status of CFD developments, does CFD have a place in conceptual design ? CFD could be used to check the aerodynamics of airplane geometries that are outside the database when these particular geometries make the semi-empirical aerodynamic estimates suspicious. By using systematic parametric variations of the geometry, CFD methods could be used to develop a parametric database in which the geometric variables could truly be independent of one another. This would allow the development of a dependable semi-empirical method for aerodynamic prediction in which the geometric parameters could be varied independently.

In order to provide the basis for the necessary CFD code validation, experiments must provide measurements, with adequate accuracy and resolution, under flow conditions that are representative of those for which CFD will be used. So, like in the days before the existence of CFD, parametric testing has to be done, for CFD code validation purposes, and with that, for the development of semi-empirical design methods for modern configurations.

3. Subsonic Configuration Aerodynamics

In this chapter a review is presented of the developments in aerodynamic research on three-dimensional aircraft configurations. In this review attention is focused on new developments in civil aviation such as the introduction of the propfan and the appearance of canard configurations. The reason for this is that, judging from literature, for conventional aircraft little can be gained from configuration investigations. A 'conventional' configuration is defined here as one with which the designer and user community have some degree of familiarity and confidence. The improvement of the performance and handling qualities of conventional aircraft is the result of an evolutionary process of refining of the aerodynamic characteristics of the aircraft, a process usually started within the existing aerodynamic database. Based on years of experience the overall performance and handling characteristics of conventional aircraft are thus reasonably well-understood and predictable. The emphasis in research lays on details which generally cannot be studied with configuration models. For aircraft with either unconventional propulsion systems, or unconventional configurations, or both, this overall insight is lacking and the need for basic three-dimensional configuration research is still existing. In fact, this is a clear indication for the shrinking database for semi-empirical design methods, as described in chapter 2. Unconventional configurations obviously transgress the limits of the existing aerodynamic database. Thus, in any research program on aircraft configuration aerodynamics unconventional configurations will play a major role. Of course, the need for code validation and database expansion remains for conventional configurations, but is finding less expression in literature. All attention is focused on the obvious problems unconventional configurations constitute.

3.1 Propeller Propulsion Aerodynamics

3.1.1 Open Rotors... Back to the Future

In an effort to alleviate the problem of rising fuel costs, aircraft designers are again considering open rotors as a viable propulsion alternative for the future. As a result, recent efforts have been directed toward an attempt to make open rotors even more fuel efficient over wider operating conditions. Open rotor is used here as a generic term, defined by Blythe (Ref. 9), to cover unswept propellers, propfan and unducted-fan propulsors, tractors or pushers, single or contra-rotation.

Today open rotors have the potential to improve specific fuel consumption without sacrificing speed. Figure 1 plots the speed and altitude requirements for subsonic civil transport aircraft.

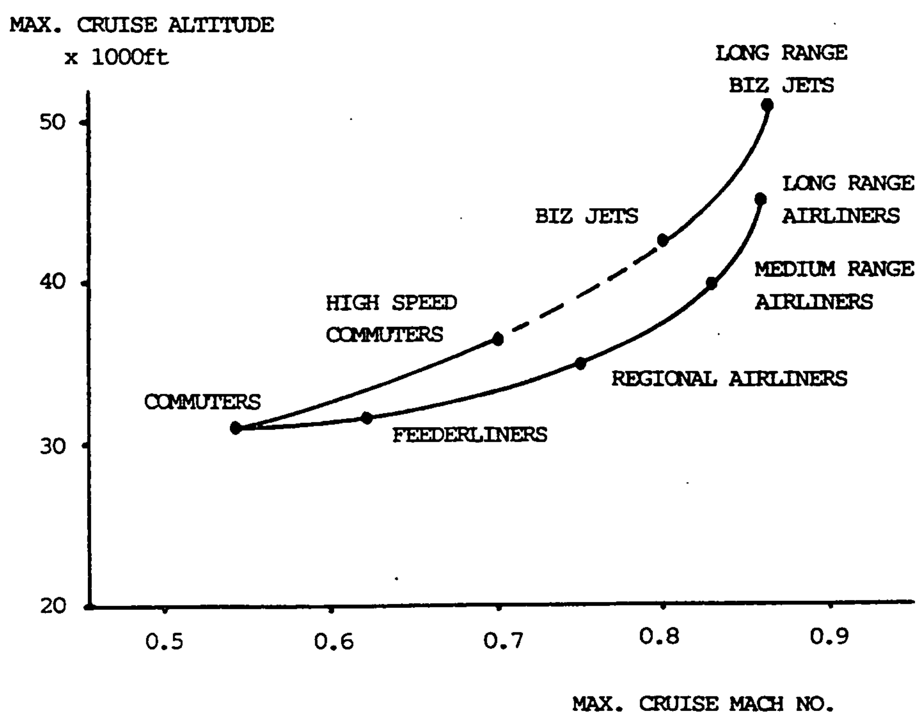


Fig. 1 Speed and Altitudes Regimes (Ref. 9)

Down at the relatively low speed, low level commuter end of the spectrum of subsonic civil transport aircraft, twin-engine aircraft with single-rotation unswept propellers will continue to remain the most effective solution because of their propulsion efficiency at low speeds. As speed increases through the feederliners up to the regional airliners the improved efficiency of contra-rotation leads to the introduction of contra-props at the higher speed end. Business jets which are being developed to operate above the scheduled traffic require a combination of high Mach number and high altitude thus pushing the open rotor up to the top end of its operational spectrum.

Since conventional propellers are unable to compete economically at higher speeds associated with modern commercial jets, and the turbojets and turbofans presently used are most efficient when operating at higher speeds than used presently, an intermediate propulsion concept is needed to properly fill the speed range between that of the propeller and the turbofan. Studies conducted by Hamilton Standard, NASA, Pratt & Whitney and other companies in the aircraft industry have shown that a new high speed propeller, the transonic propfan, when coupled with an advanced turboprop engine, can play a significant role in reducing fuel consumption and operating costs. The evolution of the propfan with its highly swept and tapered blades enables the increased propulsive efficiency of the open rotor to be maintained up into the high subsonic speed region previously confined to ducted propulsors (Fig. 2).

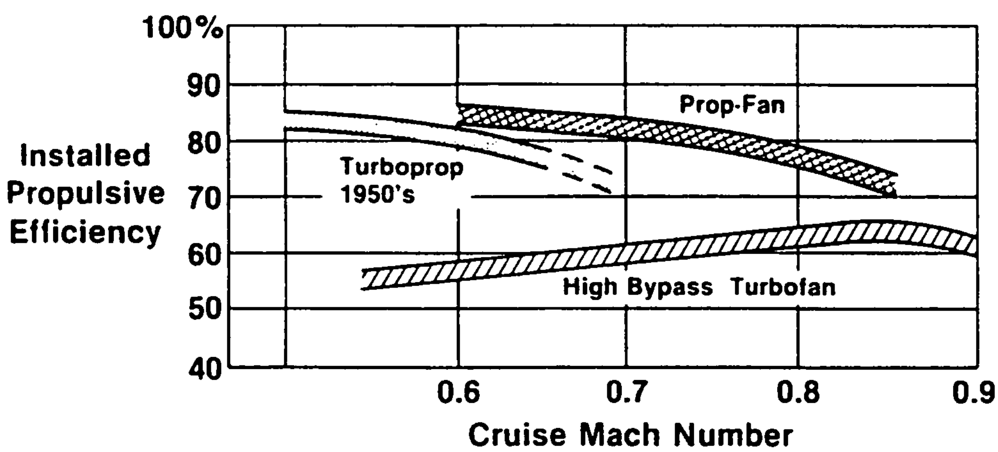


Fig. 2 Installed Propulsive Efficiency at Cruise (Ref. 11)

The early enthusiasm for the fuel-efficient propfan has become noticeably dampened. Propfan protagonists in industry and the airline business such as Boeing, General Electric, Pratt & Whitney, Allison and McDonnell Douglas appear to have not been able to forecast the future trend in the world price for oil. The underlying problem is that the development and production costs of new or even derivative propfan transports would make the aircraft too expensive for the airlines to support while the price of aviation fuel remains at its present modest level. The ultimate result for the civil operator must be reduction in operating costs.

As Fulton (Ref. 13) points out, there had also been a view, especially within the European industry, that the propfan should first be funded for, and prove itself via, military projects. The fading of the cold war and associated moves to cut or keep down national defence budgets have at best delayed if not completely eliminated any such prospect.

There are considerable design and environmental concerns about the excessive noise levels produced by propfans compared to the noise of turbofans. This is chiefly due to the presence of local supersonic flow and shock waves in the tip region of the propfan blades. In order to meet the stringent noise regulations of the aviation authorities the far field noise produced at take-off and landing must be minimized. Acceptably low cabin noise levels can only be maintained with severe weight penalties due to the extensive soundproofing. Over a period of time excessive near field noise may cause acoustic structure fatigue. Knowledge of the flow field and the acoustic field produced by the propfan is necessary to effectively address these problems.

As long as fuel prices remain low the derivative aircraft approach may well be the only viable route for launching an advanced open rotor civil transport aircraft because of the large effect of aircraft price on operating costs. The derivative approach places geometric and engineering constraints upon the application of advanced open rotors if development costs are to be minimized. In the absence of any all-out development of an advanced-open-rotor-powered airliner, moves can be detected towards taking incremental advantage of the performance and operational benefits of advanced open rotors. On the one hand there are indications of turbofan developments to achieve higher by-pass-ratios, and on the other there is the proposed use of advanced propellers with varying degrees of blade sweepback for forthcoming high-cruise-speed turboprop airliners.

3.1.2 Propulsive Efficiency

Consideration of fuel efficient propulsion systems includes the turboprop as an alternative to the high-bypass-ratio turbofan. It is well known that the turboprop exhibits significantly better propulsion efficiency than the turbofan at low cruise speeds, Mach 0.6 to 0.7. At turbofan cruise speeds, Mach 0.8, currently available turboprop engine installations could possibly equal the high-bypass turbofans in terms of propulsive efficiency (Fig. 3).

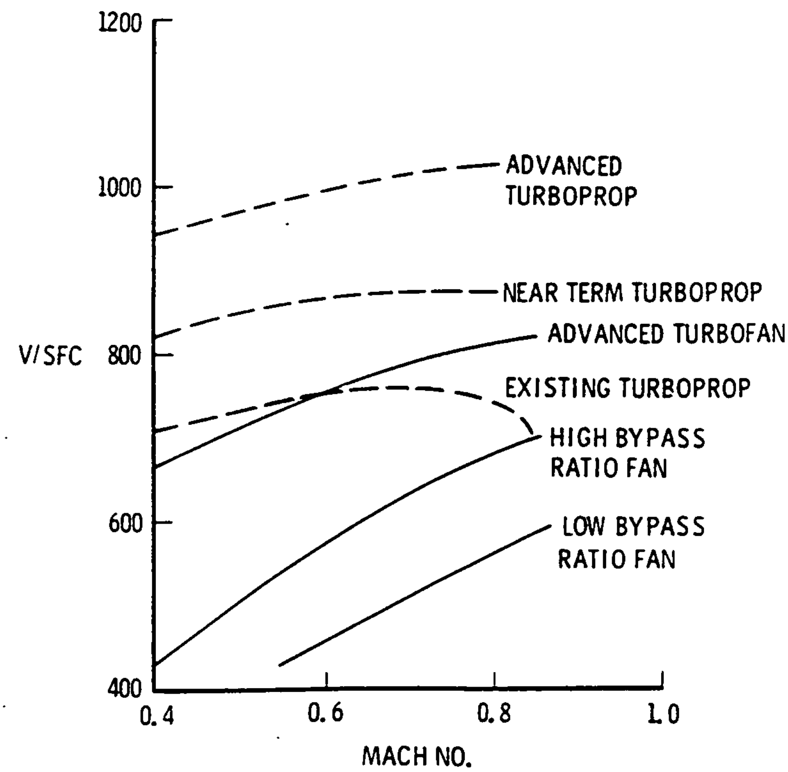


Fig. 3 Propulsive Efficiency (Ref. 12)

The sharp reduction in propulsive efficiency shown is caused by the sharp fall-off in propeller efficiency exhibited by conventional propellers as compressibility effects on the blades become significant. The new turboprop propulsion concept incorporating a high speed propeller, denoted the propfan, which delays the compressibility effects to higher Mach numbers, would be able to operate at Mach numbers competitive with the turbofan. The potential improvements expected with these advanced technology propellers are indicated by the upper lines in Fig. 3.

Although attention is focused on the advanced high speed propeller several improvements have been accomplished for the conventional propeller. Examples of such innovations on the propeller propulsive system include advanced blade airfoil sections, blade sweep, spinner area ruling, and counter rotation.

As most important is considered the development of new propeller blade airfoil sections (de Wolf, Ref. 22). Figure 4 shows a comparison between conventional (left) and advanced (right) propeller blade airfoils.

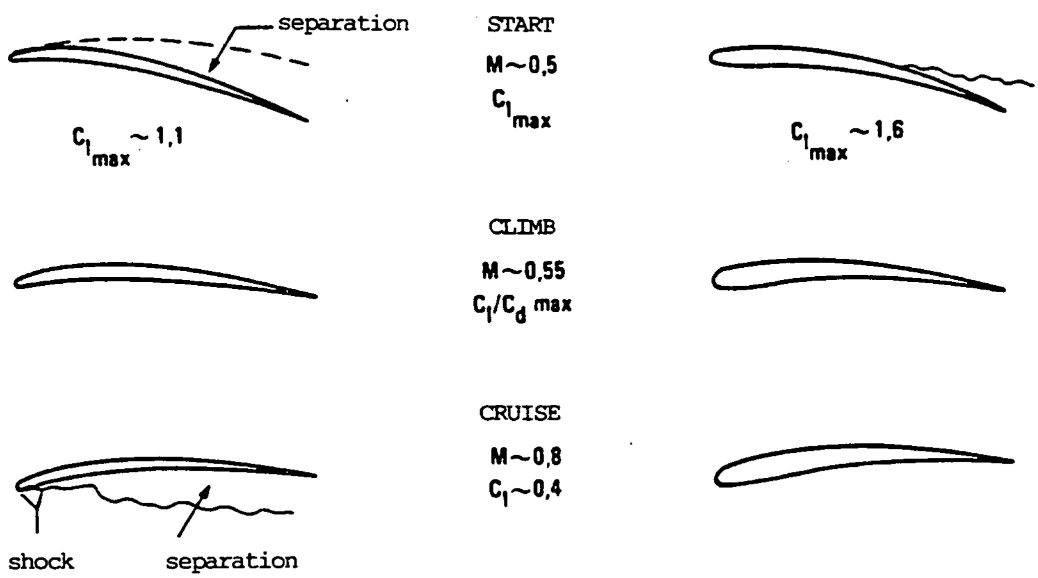


Fig. 4 Propeller Airfoil Performance (Ref. 22)

By implementation of a more blunt nose a much higher maximum lift coefficient is achieved. Leading edge separation is replaced by gradually progressing trailing edge separation. In cruise advanced blade section performance differs little from conventional. Design lift coefficient for maximum lift to drag ratio is higher, however. In cruise shock waves at the underside of the blade section are being avoided by enlarging the airfoil nose radius and drooping the leading edge, thus reducing local Mach numbers.

Inherent to the consideration of open rotors as an aircraft propulsion system is the problem of interaction between the highly loaded propellers and other aerodynamic surfaces of the aircraft. This interaction can affect aircraft stability and aerodynamic performance as well as generate noise and vibrations. As a result, engineers must investigate methods of integrating the propeller and aircraft for optimum installed efficiency in addition to improving the performance of isolated propeller systems. For wing mounted configurations the integration aspect that will have the greatest impact on the overall aerodynamic performance of the aircraft is the interaction between the propeller slipstream, the nacelle, and the wing.

It has long been known that a substantial part of the power consumed by a single-rotation propeller is wasted on the generation of a tangential or swirl velocity which in no way contributes to the thrust. This is not too penalizing at low speed but above Mach 0.6 the loss of efficiency begins to become significant. Counter-rotating propellers and stationary guide vanes or stators have been employed successfully as methods of improving propeller efficiency since they divert the swirl component of velocity into the streamwise direction, thus augmenting the thrust or diminishing the drag of the combination. By the same logic, it should be feasible to achieve some performance benefit from a propeller and wing combination.

Wing mounted tractor propeller aircraft can be designed to have relatively uniform inflow to the propeller disk for a range of conditions including cruise and climb. There may be local variations close to the nacelle but a major portion of the disk will have near constant velocity magnitude and direction. As cruise speed rises above Mach 0.75, however, it is doubtful whether open rotors can be mounted ahead of wings. The supervelocity over the wing caused by the slipstream from the highly loaded open rotor will cause shocks and push the wing up the drag rise. This leads to a requirement for pusher installations. This propeller position, however, has its inherent problems with the propeller blades crossing the wing wake, an interference that is usually responsible for elevated propeller noise levels and vibrations.

Propeller source noise needs to be minimized. This is particularly important on wing mounted installations where cabin noise must be constrained to levels comparable to those of a ducted engine. Propeller tip speed is a major parameter concerning near field noise. Reduction in tip speed on a single-rotation propeller, however, can result in a significant reduction in efficiency. For reasons of maintaining propeller efficiency and reducing passenger cabin noise levels, it might be argued that a rear engine and propeller position, tractor or pusher arrangement, would be feasible from a technical point of view.

By removing the propulsion system from the wing and installing it aft on the fuselage an aerodynamically clean wing would be obtained. Figure 5 shows a typical aft fuselage mounted propfan configuration.

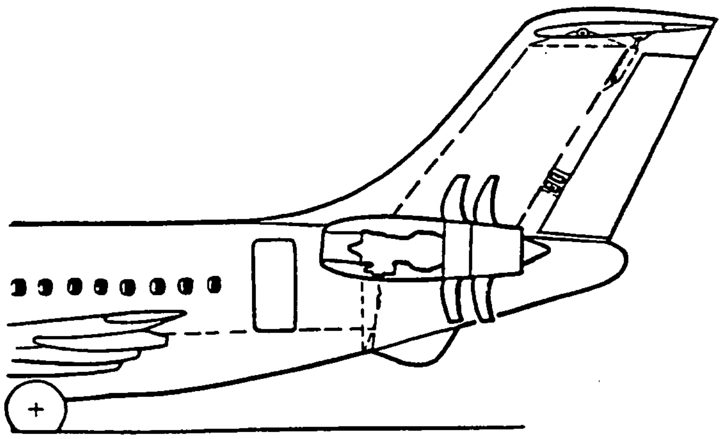


Fig. 5 Aft Mount Propfan Installation

Rear fuselage located propellers, however, pose a problem for the designer. In close proximity to the fuselage tractor or pusher propellers can have very non-uniform inflow velocity fields due to the disturbances from the aircraft surfaces upstream. Wing, flap, canard, tail, and pylon wakes, boundary layers from the fuselage, nacelle, or other bodies upstream can all affect the inflow. Engine exhaust through the propeller disk plane also adds to the non-uniformity. All this means that propellers are located in positions which can cause unacceptable vibrations and loss of performance. On the other hand location of the propellers at the aft end of the fuselage might reduce momentum drag and provide a fin effect. Ground clearance on rotation dictates a high thrust line resulting in a trim drag penalty unless the thrust offset can be countered by an opposing nose-up moment from the aircraft lift system. The prospect of a more forward location of lift, however, is limited by the need to maintain the correct lift centre/undercarriage relationship. This might lead to the use of a lifting foreplane.

3.1.3 Effects on Stability & Control

Although decades of experience exist with propeller-driven aircraft, this experience has been for configurations having significantly lower power loadings than those presently considered. A major uncertainty associated with the aerodynamic characteristics of advanced turboprop aircraft configurations is the lack of information regarding the effect of the highly-loaded turboprop installation on aircraft stability and control during the take-off, climb, and landing phases of flight.

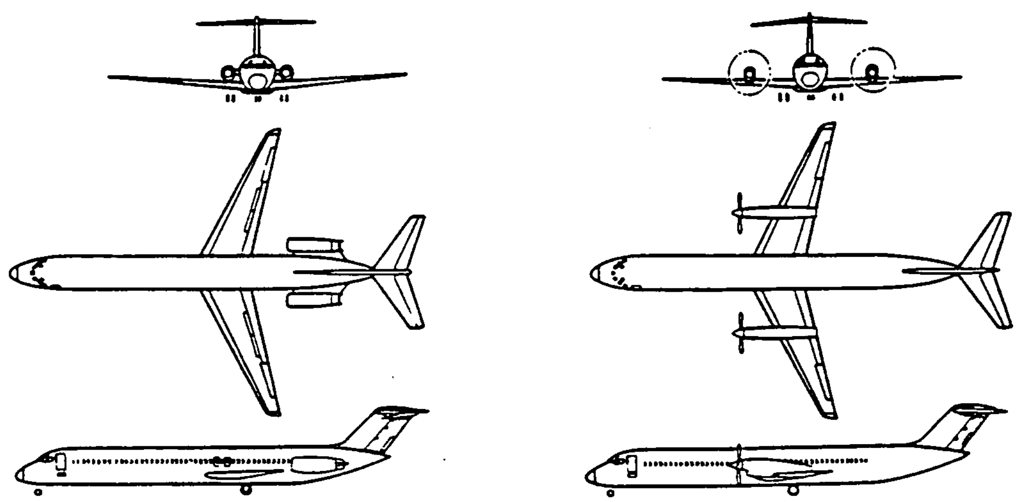
The effects of propulsion on the stability and control characteristics can be separated in two categories: direct and indirect. The direct effects are due to the isolated aerodynamic behavior and the location of each component relative to the centre of gravity of the aircraft. The indirect effects are due to the aerodynamic interaction of the components, such as propeller slipstream disturbances on a horizontal tail.

For multi-engine propeller transport aircraft the arrangement with wing mounted engines and the propellers in a tractor position has become the accepted standard solution. The principal merit of this configuration is that the weight of the propulsive system is disposed in such a way that is favourable for a low weight of the airframe and for the centre of gravity problem of the aircraft. A principal disadvantage associated with wing mounted engines are the high yawing and rolling moments in the critical engine-out condition. Also the reduction in pitch stability due to the propeller slipstream effects on control surfaces poses problems.

An aft propulsion system location with the thrust line above the aircraft moment centre produces stabilizing power effects. At angle of attack the normal forces generated by the aft propeller result in a nose-down or stabilizing pitching moment. This effect is particularly powerful at higher angles of attack when the wing and/or control surfaces are stalled and their effect on pitching moment has stabilized. A major unknown in the aft fuselage installation of highly loaded advanced propellers is the stability and control of the aircraft with one engine out and the impact of reverse thrust. The large propeller diameter of advanced turboprops require considerable fuselage clearance and large pylons. Thus the aircraft centre of gravity range is affected because of the aft located increased structural weight.

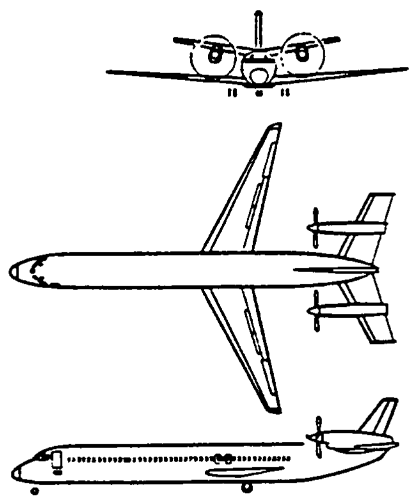
A striking example of the last mentioned problem can be found in one of the early preliminary design studies of propfan-powered aircraft, conducted by Goldsmith of the Douglas Aircraft Company (Ref. 16). Using the DC-9 Super 80 as the baseline airframe, the design and performance characteristics of one wing-mounted and two aft-mounted derivative propfan aircraft configurations in tractor arrangement were analyzed and compared to the baseline turbofan design. The three propfan configurations were: conventional horizontal tail aft mount, wing mount, aft fuselage pylon mount (Fig. 6). The table of group weights statements (Table 1) shows that the aft fuselage pylon mounting of the propfans causes an considerable increase of structural weight of the mounting structure. The horizontal tail mount benefits from an efficient integration of the mounting structure with the horizontal tail structure, so the weight penalty from this mounting concept is almost nonexistent. It was stated that for the aft fuselage pylon mount configuration the air-conditioning system and a fuel tank had to be relocated in the forward cargo compartment to obtain a balanced aircraft.

It's interesting to notice that McDonnell Douglas, with greater and more varied propfan flight experience than any other company, gained by aft fuselage mounted pusher configurations, no longer talks enthusiastically about its DC-9 Super 80 based MD-90 series of mid-size mid-range airliners with propfan power. Instead, October 1989, the company announced that it had switched to turbofans.

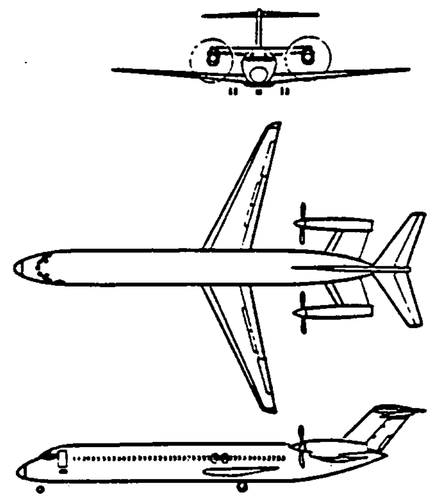


Baseline Config. Config.1 Wing Mount

Fig. 6 Preliminary Design Configurations of Goldsmith (Ref. 16)



Config. 2 Horizontal Tail Mount



Config. 3 Pylon Mount

Fig. 6 Continued

	DC-9-80	TURBOPROP		
	BASE	CONFIG NO. 1	CONFIG NO. 3	CONFIG NO. 2
GEOMETRY	AFT FUS	WING	HORIZ TAIL	AFT FUS
TAKEOFF GROSS WEIGHT (LB)	140 000	140 000	140 000	140 000
MAX PAYLOAD WEIGHT (LB)	39,334	34,800	35,010	31,732
PAYLOAD WEIGHT – 155 PASSENGERS (LB)	31,775	31 775	31 775	31 775
WING AREA (FT2)	1,209	1 209	1 209	1 209
HORIZ TAIL AREA/VERTICAL TAIL AREA (FT2)	313/161	380/198	505/225	390/213
HORIZ TAIL ARM/VERTICAL TAIL ARM (IN)	734/615	852/710	562/543	712.577
RATED SHAFT HORSEPOWER/ENGINE		16 520	18 275	16 515
NO OF BLADES/TIP SPEED (FPS)	0	8/800	8/800	8/800
PROPELLER DIAMETER (FT)	0	14 47	14 36	14 47
WEIGHT DATA:				
WING	15,318	15,490	15 397	15 373
HORIZONTAL TAIL	1 918	1 941	2 868	2,460
VERTICAL TAIL	1,197	1 546	1 249	1 533
FUSELAGE	18,273	18 483	16 757	18 700
LANDING GEAR	5,345	5 488	5 445	5 445
NACELLE AND MOUNTING STRUCTURE	2,129	2 525	2 276	4 596
PROPULSION AND ENGINE SYSTEM	10,441	12,402	12,175	12,397
FUEL SYSTEM	727	685	788	1 364
FLIGHT CONTROLS AND HYDRAULICS	2,298	2,502	2 947	2,745
AUX POWER UNIT	839	839	839	839
INSTRUMENTS	922	922	922	922
AIR-CONDITIONING AND PNEUMATICS	1 938	2,211	2 186	2 498
ELECTRICAL AND LIGHTING SYSTEM	2,535	2,555	2 550	2,545
AVIONICS AND AUTO FLIGHT CONTROLS	1,349	1 349	1 349	1 349
FURNISHINGS	11,113	11 928	11,113	11 213
ANTI ICE	594	604	619	598
AUX GEAR	88	88	88	88
MANUFACTURE EMPTY WEIGHT	75,024	79,558	79,568	82,566
OPERATOR ITEMS WEIGHT	3 642	3 642	3 642	3 642
OPERATIONAL EMPTY WEIGHT	78,666	83,200	83,210	86,208

Table 1 Group Weight Statements (Ref. 16)

3.1.4 Experiments

Aljabri (Ref. 7) presents an analytical technique which predicts the influence of a propeller slipstream on a nacelle/wing combination. This is achieved by coupling a slipstream code with a complex configuration potential flow analysis code. The slipstream code is based on the vortex theory of propellers and predicts the slipstream in terms of its shape induced velocities and swirl angles. To verify the slipstream code two experiments with different model propellers were carried out. The first was a test of a four-blade 11.2-inch diameter model propeller. The second experiment was a test of a 1/10-scale Lockheed C-130 Hercules propeller complete with a 1/10-scale wing and nacelle (Fig. 7). The wake immediately behind these propellers was surveyed using a 7-probe, 5-holes-per-probe rake. The test data were reduced to give the three components of wake velocity from which circulation, kinetic energy, and total pressure within the wake were computed. Maps of these aerodynamic parameters were made to give a visual demonstration of the nature of the propeller wake.

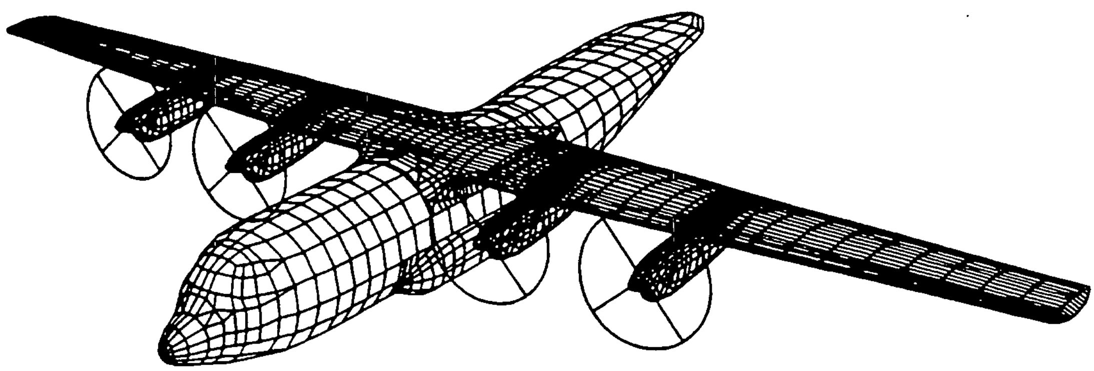


Fig. 7 Panelling Scheme of a C-130 Aircraft (Ref. 7)

The analytical technique used here is strictly applicable to propellers with axisymmetric nacelles at zero angle of attack and has therefore very limited design application. This is probably the result of the pre-imposed wake trajectory used here. Corrections need to be incorporated within the program to reflect azimuthal variation of slipstream properties due to thrust axis inclination or nacelle/wing presence.

Panel method analysis techniques for calculating propeller flow fields may be reasonably valid for tractor installations but do not fully handle pusher configurations in which wakes pass through the propeller disk. A development study was undertaken by Pfeiffer (Ref. 19) to determine the inflow for a pusher propeller installation, in this case of the Beechcraft Starship (Fig. 8).

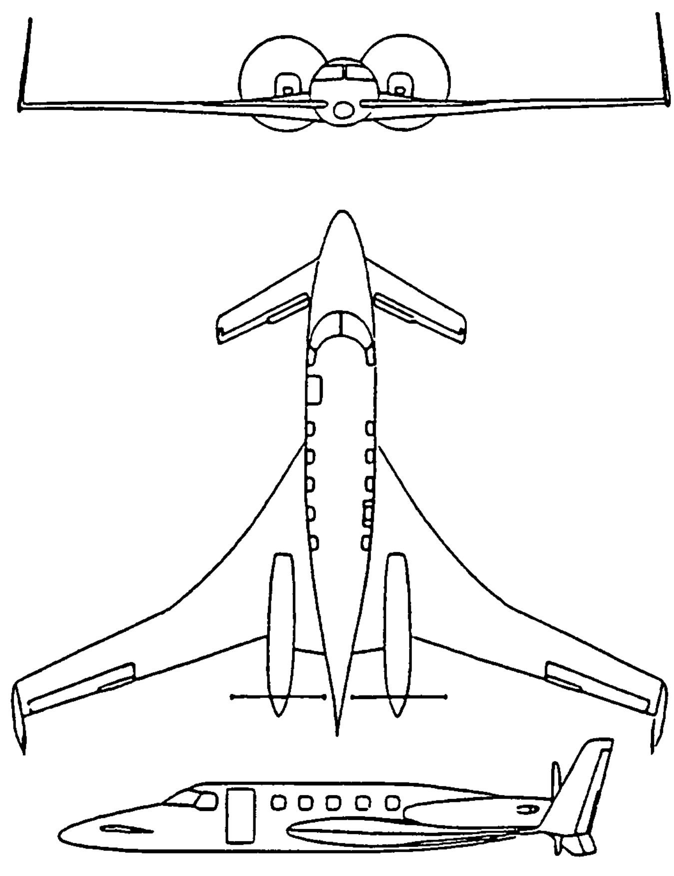


Fig. 8 Beechcraft Starship Arrangement (Ref. 19)

The study does not model the details of the propeller itself or the flow field created by a propeller but instead is focused on the non-uniform flow field that a pusher propeller is subjected to by the configuration upstream. The effects of wing trailing edge shape and nacelle orientation on the propeller inflow were evaluated. Potential flow computer analysis was used initially to examine the problem. This analysis showed that there is a possibility of highly non-uniform flow fields occurring near pusher propellers. Potential flow does not give the complete picture, however, since it neglects the effects of viscosity. These viscous effects are significant when wing and/or canard wakes and fuselage and nacelle boundary layers pass through or near to a propeller disk. With a 1/7-scale model wind-tunnel testing was done, using a 5-hole pressure probe, to map the flow field velocity at the disk location to determine the viscous effects. Wind-tunnel inflow measurements like these are an effective tool for evaluating the effects of configuration changes to the flow into the propeller disk. These measurements are also valuable for the detailed design of a propeller.

One way of avoiding wing wake/propeller blade interference and lack of ground clearance is mounting the propellers in a tractor arrangement at the tips of the horizontal tail (Fig. 10).

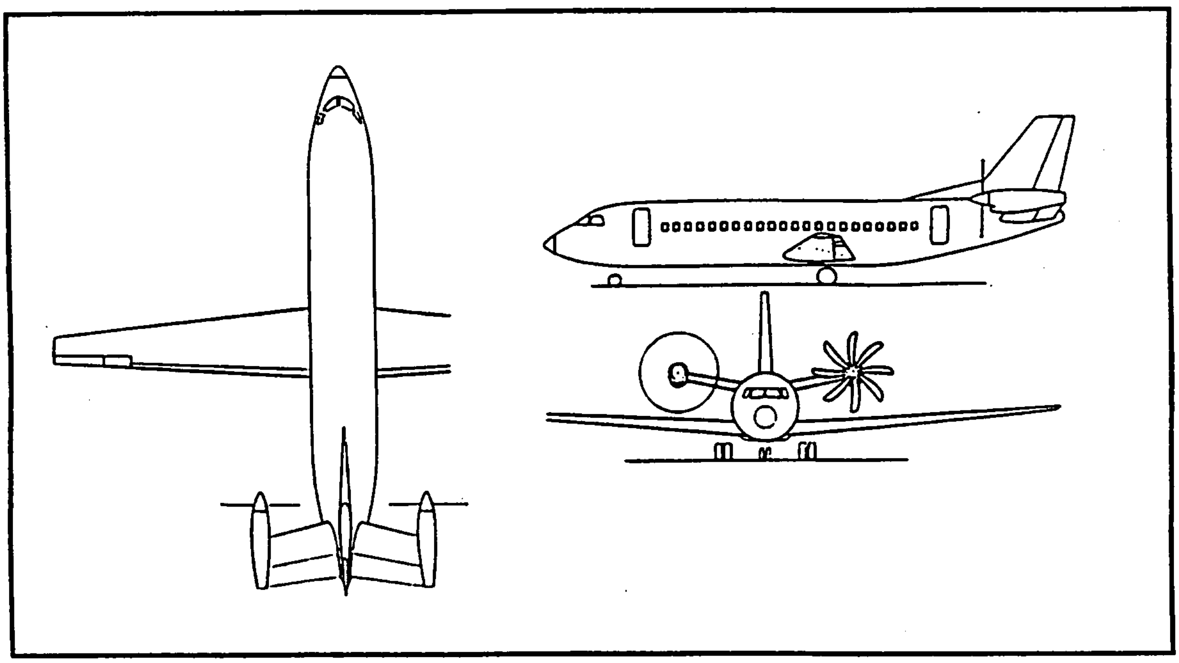


Fig. 10 Horizontal Tail Mount Configuration of Ridder (Ref. 20)

In this configuration the 'wetted' surface immersed in the propeller slipstream is minimized. With the wing in a low position on the fuselage the horizontal tail is mounted high on the rear fuselage in order to get the propeller disk plane above the wing wake. The object of the experimental study carried out by Ridder (Ref. 20) was to establish the effects of propulsion on the aerodynamic characteristics of this type of aircraft configuration. In order to clearly sort out these effects it was desirable that the basic aerodynamics of the model in the wind-tunnel would reasonably well correlate with a hypothetical full-scale aircraft. With a test section wind speed of 40 m/s the tip section Reynolds number was about 0.16 million. The wing was fitted with a single slotted trailing edge flap set at 10 and 30 degrees to represent take-off and landing configurations respectively. The propellers used were six-blade model aircraft propellers with a hub that permitted setting of the desired blade angle. The effects of propulsion were investigated for several conditions including one engine out. The forces and moments measurements were supplemented by various flow field surveys.

From this study it was concluded that the interference of the slipstream from the co-rotating propellers with the horizontal tail was responsible for considerable rolling and yawing moments, and also a marked change in pitching moment from the stopping of either engine, all without elevator deflection. Missing from this experiment, but a major concern, are investigations of these effects of slipstream rotation on the stability and control of this aircraft at rotation during take-off or landing, when the elevator is deflected.

Most short-take-off-and-landing airplanes (STOL) use large flaps to deflect the propeller slipstream to achieve the high-lift coefficients required for flight at low speed. Propulsion effects on stability and control characteristics of this type of configuration can be expected to be considerable. In order to provide some badly needed data Margason (Ref. 17, 18) conducted a static wind-tunnel investigation of a powered model of a twin-propeller, deflected-slipstream, STOL aircraft configuration (Fig. 11). The wing was fitted with a double-slotted high-lift flap system with a maximum flap deflection of 45 degrees. The three-blade propellers were driven by electric motors. For the powered tests the Reynolds number based on the wing chord was about 0.65 million. During the experiment horizontal tail area and position was varied.

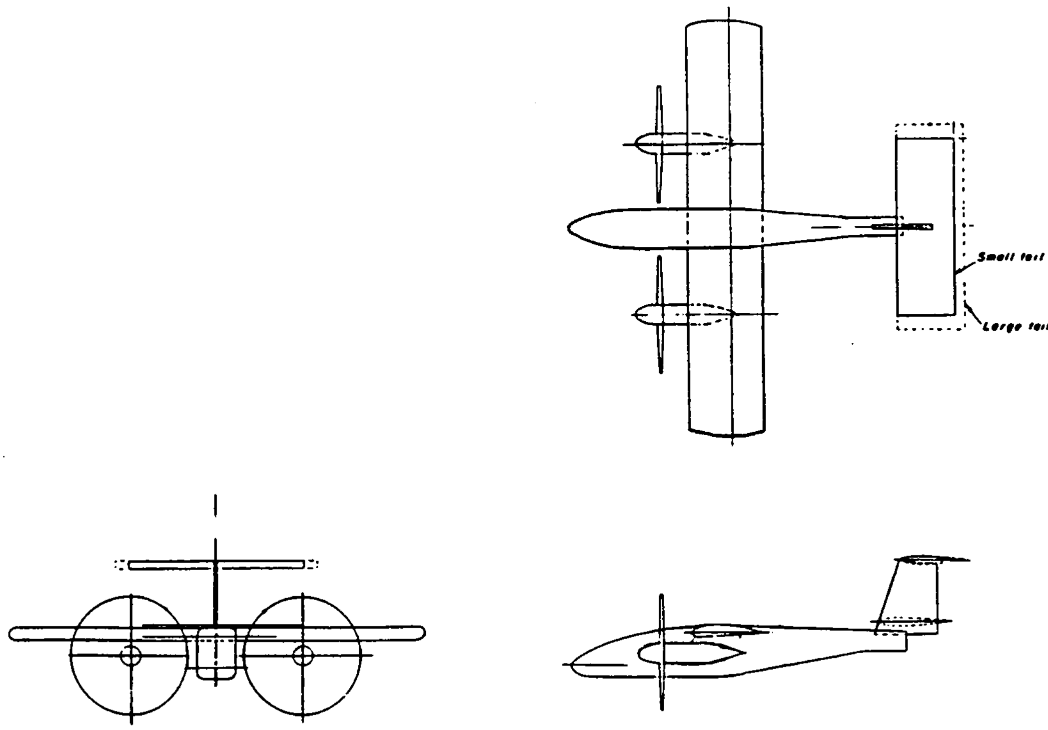


Fig. 11 STOL Configuration used by Margason (Ref. 17, 18)

The wing-body combination for the flaps-deflected configuration had a large tail requirement for longitudinal trim, particularly for high power settings. At these high power conditions the small tail in the high position stalled before trim was achieved. The large tail in either position had the capability of trimming the airplane up to the angle of attack corresponding to the maximum lift coefficient, but for the highest power setting it also stalled. No directional stability tests were included in the investigation but it can be assumed that these high propeller loadings will considerably affect rudder effectiveness and produce unfavourable rolling and yawing moments in the engine-out condition.

A limited experimental investigation was conducted by Applin (Ref. 8) to explore the effects of aft-fuselage-mounted advanced turboprop installations on the low-speed stability and control characteristics. This test examined a single-rotation (SR) tractor configuration and a counter-rotation (CR) pusher configuration (Fig. 12), with the aircraft model in a part-span-flap landing condition. Both the propeller systems were powered by electric motors. Because the wind-tunnel velocity is a variable properly matching the propeller characteristics in coefficient form enables the tests to simulate the aerodynamics of higher-power-loading advanced turboprop concepts.

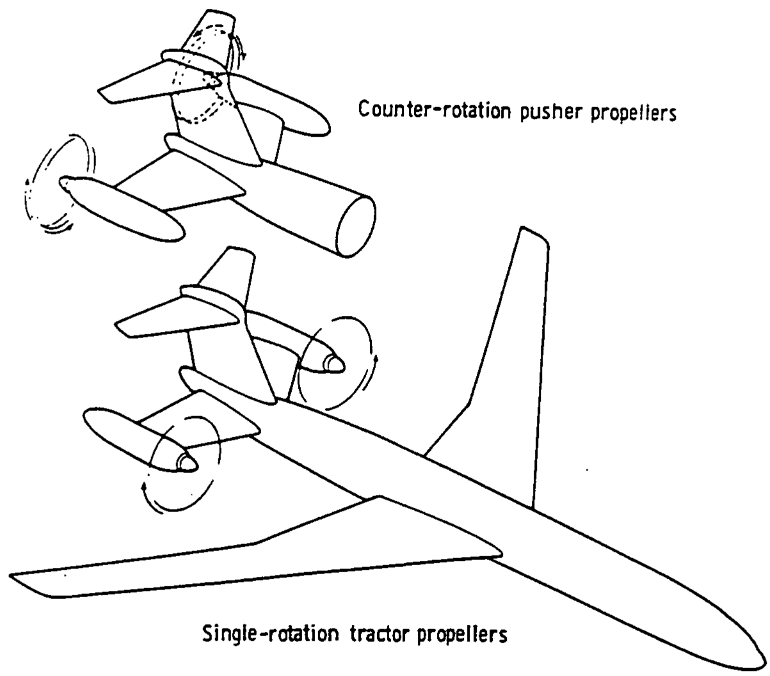


Fig. 12 Propeller Installations (Ref. 8)

Thrust effects on pitching moment are different for the two propeller configurations. For the SR tractor propeller the principal effect of thrust is a nose-up, or positive, increment in pitching moment. The primary reason for this is probably related to the direction of propeller rotation. During the tests the SR propellers rotated downward inboard. This would result in an effective downwash acting on the pylon surfaces; this downwash results in a positive increment in pitching moment. By contrast the pitching-moment characteristics for the configuration with the CR pusher installation show a marked increase in longitudinal stability with increasing thrust and angle of attack. The effect of the loss of one engine was not investigated. For the SR configuration the rudder effectiveness is increased with the addition of thrust. The slipstream generated by the tractor propeller increased the dynamic pressure on the rudder, and the slipstream deflection caused by the rudder increased its effectiveness. An opposite effect was noted for the CR pusher configuration. For this configuration rudder effectiveness was reduced with increasing thrust. It is possible that the sidewash generated by rudder deflection produced an effective flow angularity at the propeller plane. This effective propeller yaw angle would produce propeller forces causing an aircraft yawing moment opposing that produced by rudder deflection. In comparison with the tractor configuration the rudder has no opportunity to deflect the propeller slipstream of the pusher configuration. Especially in this case it would be worthwhile to investigate the effect of asymmetric thrust.

3.1.5 Conclusion

The benefits in fuel consumption and the propulsion efficiency of propellers have been a decisive factor of the renewed interest in the use of these systems. The increasing cruise speed of current passenger flight has stimulated efforts of aerodynamicists in the conception and design of modern highly loaded propellers. As a counterpart, this has accentuated the need to optimize the integration of the propulsion system in connection with the reciprocal influence of the propeller slipstream and other aircraft components. In this process the concept of propeller driven aircraft might be fundamentally changed through relocating the propulsion system. Consequently this concept has to be redefined in all its aspects resulting in a considerable need for research in configuration aerodynamics.

3.2 Airframe Aerodynamics

3.2.1 Deviation from Convention

Recent technological advances offer considerable opportunities for improving the performance, efficiency, and passenger acceptance of future aircraft. Aerodynamic design methods, for example, permit shaping the aircraft to obtain and maintain significant amounts of natural laminar flow which provide substantial reductions in drag over the entire flight profile. Propulsion system improvements allow lighter, more efficient engines that can be combined with lighter, quieter, and more efficient propellers. In addition, advanced flight control systems can provide reliable active control for stability and control augmentation. Advanced unconventional aircraft configurations may allow the designer to capture more of the benefits from individual technology advances.

Unconventional aircraft configurations have always captured the imagination of aircraft designers. Over the years a wide variety of concepts have been proposed and flown with varying degrees of success. In addition to tail-aft configurations canard, tandem wing, three-surface, tailless (flying wing), and lifting-body configurations are examples of aircraft which were conceived with the thought to have specific advantages in performance or control. The great variation in these designs contrasts sharply with the relative standardization of tail-aft configurations and suggests that some aspects of their design may be less well-understood. For unconventional designs, to a greater extent than for conventional, 'optimal' solutions show great sensitivity to the choice of goal function and imposed constraints. Variations in mission requirements are likely to produce greater variations in 'optimal' geometry for these unconventional aircraft.

Future airplane concepts may range from conventional designs, with stabilizer aft, to tandem wings, with wings of equal or nearly equal span; to canard designs, with stabilizer forward; to three-surface designs. With aircraft operating costs bound to increase in the next decades, it is desirable to compare the performance of these various configurations in order to determine the more efficient ones. Developments affecting the concept of airplanes are only of interest when by application improvement in operational costs can be achieved and technological risks are limited. In order to explore the potential advantages, disadvantages, and uncertainties associated with unconventional configurations, system studies and wind-tunnel investigations have to be conducted.

3.2.2 Drag Efficiency

Since the energy crisis in the early seventies, there has been an emphasis in airplane design towards minimizing the drag due to trim. The theories and modifications to Prandtl's biplane theory and Munk's stagger theorem have been used by a number of researchers to explore the minimum induced drag of multi-planes (aircraft with multiple lifting surfaces). These studies have yielded comparative predictions of the induced drag and static longitudinal stability of conventional aircraft, canard, and three-surface configurations. The effect of variations of gap and stagger are also an integral portion of these studies. Kendall (Ref. 34, 35, 36) has summarized these analytical results, theorizing that minimum induced drag should be attainable at any c.g. location so long as equal and opposite vertical loads are applied by the forward and aft lifting (or trimming) surfaces. Furthermore, these minimum-induced-drag loads should be achievable at any usable c.g. location, within the practical limits set by the size and shape of the lifting surfaces.

An important and pragmatic concern about these theoretical studies is that idealizing assumptions have been made, usually closely allied to Prandtl's and Munk's assumption of an elliptic spanwise lift distribution. Both Butler (Ref. 25) and Kroo (Ref. 38, 39) have suggested that for non-elliptical lift distributions with pure canards the effects are significantly different from idealized theory. Butler predicts that the three-surface-induced drag at both typical cruise and high lift conditions is lower than the induced drag of either a conventional or a canard-wing type. However, an analytical study by Selberg and Rokhsaz (Ref. 50) of the aerodynamic trade-off between the three configurations shows that the three-surface is superior to the canard only at the lower stabilisator aspect ratios and that the overall induced drag penalty is not sufficiently different to be of primary concern in the configuration selection process. McLaughlin (Ref. 40), Keith and Selberg (Ref. 33) have compared canard and conventional configurations analytically and found that canard configurations have lower flight efficiencies than tail-aft configurations when trimmed for similar static margins. This is caused by the high canard loadings required for trim in the canard aircraft. Although these studies are useful, conclusions regarding 'optimal' configurations are valid only in a very restricted sense. Further work is required to determine the magnitude of the benefits under more practical design conditions.

An important consideration is the effect of propeller slipstream. By correct location of the propellers relative to the wing favourable interaction effects larger than those due to trim surface interactions are attainable. Clearly, aerodynamic interference studies and wind-tunnel tests on complete aircraft are required to determine whether the ideal trim drag advantages can be sustained under practical design conditions. Also handling and ride qualities must be evaluated and found to be acceptable for any unconventional design which is arranged to exploit favourable aerodynamic interference effects.

It is becoming increasingly apparent that natural laminar flow (NLF) is a technology whose time has come to the general aviation industry. This is reflected by the European Laminar Flow INvestigation (ELFIN) presently conducted. Laminar flow, which had been the exclusive province of high-performance sailplanes, is now commonplace in sport aviation and is appearing on high-performance, advanced-technology prototype business aircraft. The adoption of NLF methodology brings numerous design problems in the general area of aerodynamic cleanliness. An important design problem is where to put the propeller, or more to the point, what to do about the apparent adverse effects of the propeller slipstream. Tractor propeller installations offer many advantages. A generally accepted disadvantage, however, is that the propeller slipstream can eliminate the beneficial effects of laminar flows. The commonly applied solution is to adopt pusher installation designs to remove the slipstream from contact with the airframe. Investigations of pusher configurations have revealed that NLF is practical for aircraft constructed with modern smooth aluminum or composite manufacturing methods. It represents a significant improvement in aerodynamic performance and efficiency. In order to avoid significant changes in aircraft flight characteristics with boundary-layer behavior the selection of airfoils that have good low-drag characteristics with large amounts of NLF must also include consideration of the aerodynamics of these airfoils with a turbulent boundary layer. Advanced NLF-airfoils have been designed to insure that the maximum lift coefficient will not decrease with transition fixed near the airfoil leading edge. Careful airfoil selection and experimental verification with transition fixed is particularly important for canard airfoils.

It is well known that aft-swept wings (ASW) tend to stall at the wing tips. This can cause serious roll-off problems unless significant wing twist is employed or stall protection devices are used. Either way, the end result is that the actual lifting capability of an ASW can only be partially employed. A forward-swept wing (FSW) behaves in just the opposite manner: the root tends to stall first. Since the roll-off associated with root stall is usually insignificant, a FSW can use more of its high-lift potential than an ASW. However, careful consideration must be given to tailoring of the FSW-design to minimize pitch-up tendencies associated with early wing root stall and lateral instability (loss of effective dihedral) inherent with forward sweep. Because twist in a FSW is not needed for good stall behavior, FSW-configurations tend to have slightly lower induced drag. By combining the FSW with both a canard and a horizontal tail, configurations emerge with interesting possibilities (Fig. 13).

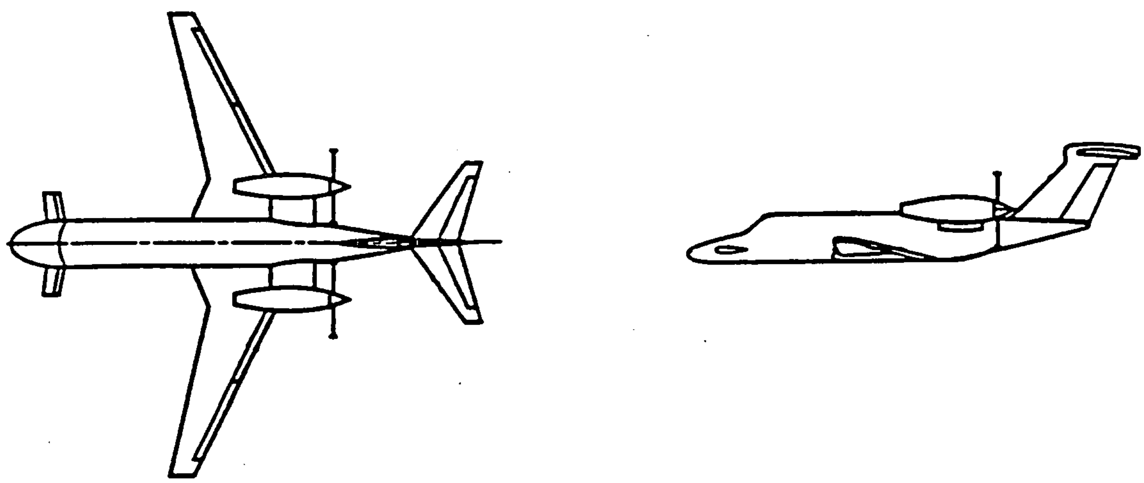


Fig. 13 FSW Three-Surface Pusher Configuration

Studies by Roskam (Ref. 46) have shown that a three-surface design coupled with a FSW and aft-mounted propellers has potential weight savings which may be realized from structural synergism, i.e. a design that ties the wing spar, engine nacelle/pylon attachment point, landing gear structure, aft pressure bulkhead, and tail empennage into one structural member. It has been claimed that a three-surface FSW configuration has significantly better cruise performance, better low-speed handling qualities, better c.g. envelope flexibility, and easier fuselage stretching ability compared to conventional, unswept-wing aircraft. A full exploitation of these benefits has been prevented in the past by the lack of adequate structural technology to cope with the FSW aero-elastic divergence problem. With the recent advances, notably in composite material structures and improved understanding of flight dynamics and control, the idea of using a FSW is being explored on several military and civil-transport aircraft.

3.2.3 Canards... Kitty Hawk Revisited

From the earliest attempts at flight, stability and control characteristics have influenced the success or failure of virtually all types of aircraft. Historic aircraft that exemplify the importance of stability and control are the Lilienthal gliders and the Wright biplane. The Lilienthal gliders were designed to have positive pitch stability, but were seriously lacking in pitch control power (obtained by movement of the body of the pilot, which was suspended from arm holds). Lilienthal made many successful flights before he was fatally injured when his glider was upset by a strong gust. Powered flight began with the Wright Flyer, which was a canard-configured aircraft in an attempt to provide more powerful control capability. Unfortunately, however, that aircraft was longitudinally unstable, resulting in the pilot overcontrolling pitch attitude during most of the flight. From that the misconception arose that all canard aircraft would be unstable at pitch, irrespective of the placement of the centre of gravity. In the early years of aircraft development the canard concept was dropped in favour of tail-aft designs.

Since the energy crisis in the early seventies, the quest for energy-efficient aircraft has led to a recent resurgence of interest in canard configurations, evidenced by the appearance of a variety of such designs in general aviation, business aircraft, and some proposed commuters. Such designs have been recommended as being efficient, easily controllable at high angles of attack, and highly stall resistant. Although flights of aircraft using this type of configuration appear to be successful, adequate experimental flight and wind-tunnel data are hardly available to evaluate the aerodynamics of this type of airplane configuration.

For a conventional configuration with an aft-mounted tail location, the tail must be designed to operate in the downwash of the wing. For a canard configuration, however, the canard operates with a slight benefit due to the upwash of the wing, and the wing must accommodate the nonuniform canard downwash flow field. The effect of this canard downwash on the wing aerodynamics is evidenced in the wing span loading. The loading is reduced on the inboard part of the wing by the canard downwash, and the loading outboard of the canard span is increased by the upwash associated with the canard tip vortices. This canard/wing flow field interaction also delays stall on the inboard part of the wing, and can cause premature or early stall outboard because of the increased angle of attack experienced in the canard upwash region. In order to maximize the wing aerodynamic efficiency and insure desirable stall progression, these canard flow field influences must be considered in the selection of the wing airfoils, planform, and twist distribution. One excellent means of correcting for the effect of the canard upwash causing earlier stall on the outboard wing is the addition of a drooped wing leading edge over this portion of the span, thus increasing the airfoil stall angle of attack.

Important considerations in canard design include the airfoil selection, incidence, vertical position relative to the wing-chord plane, and fore and aft position (Williams, Ref. 51). A primary objective is that the canard should lose nose-up trim capability by a favourable stall progression before any degrading wing stall characteristics occur. In addition, linear pitch control effectiveness is required throughout the stall manoeuvre to assure good stall recovery. Nonlinear pitch control effectiveness at the stall could possibly lead to a 'locked-in' or 'deep-stall' condition and cause the pilot to apply improper stall recovery techniques. Factors which aggravate this condition include a rearward c.g. location and canard airfoil characteristics which promote a flat lift-curve top. In comparison with conventional designs, the c.g. position must be accurately controlled and must be relatively far forward, not only to provide positive pitch static stability, but also to assure that canard nose-up effectiveness drops off before main wing stall occurs. In summary, current canard designs can obtain inherently save flight behavior provided the wing is kept stall-free. The natural tendency of the canard to lose lift before the main wing stalls and low cross-coupling makes the possibility of entering a spin extremely remote. In addition, pitch damping is inherently strong and low pitch gust sensitivity results by virtue of a low lift coefficient of the swept wing. There are trade-offs in achieving this design goal, however, including higher approach speeds since full lift of the main wing is not usable, and flightpath control limitations due to the inability to vary the lift-to-drag ratio appreciably since most of the concepts do not employ flaps on the main wing. Also directional damping is inherently low at high angle-of-attack, resulting in a tendency for a lightly dampened Dutch roll mode. In addition, low directional control power may limit crosswind landing performance. Limited forward visibility due to the canard hampers lookout for air traffic in the climb and makes landings less precise.

Because of the configuration layout, canard configurations tend to have reduced directional control due to the short moment arm from the aircraft centre of gravity to the vertical tail, often placed on the tips of the aft-swept wing. Obtaining increased rudder control power requires an increase in rudder area or the use of drag producing flared rudders to improve the effectiveness.

In flight the power effects on the stability and control characteristics of a canard, single-engine tractor configuration (Fig. 14) are de-stabilizing because of the normal forces produced by the propeller at angle of attack, the propeller slipstream which increases the de-stabilizing lift generated by the canard, and the increased downwash from the canard which reduces the stabilizing contribution of the wing (Chambers, Ref. 26). Propeller slipstream swirl may cause asymmetry effects by decreasing the local angle of attack on one side of the aircraft. Also the pitch trim changes with each engine power variation. The unstable slope of the pitching moment curve at post-stall angles of attack offers the potential for pitch-up and entry into a deep stall trim condition with very little control power available for recovery. The de-stabilizing effects of power present the pilot with the unusual characteristic that the application of power inhibits recovery.

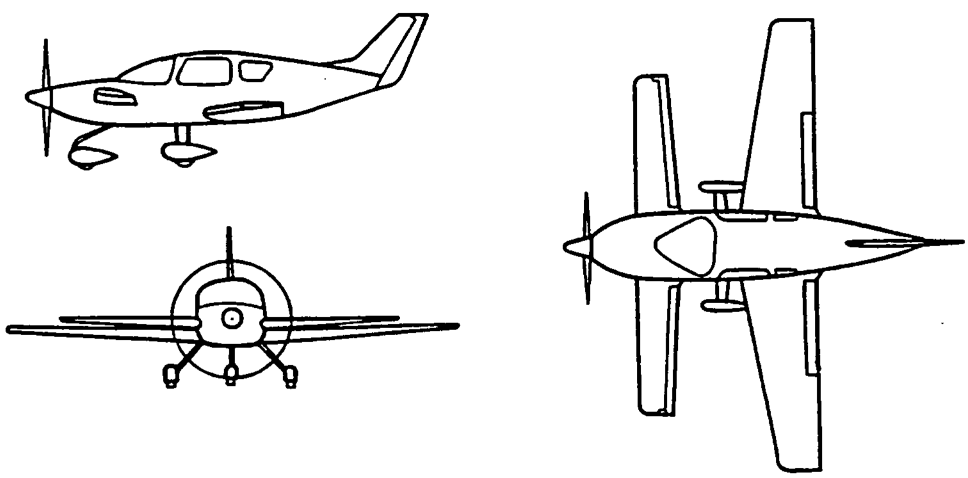


Fig. 14 Canard, Single-Engine Tractor Configuration used by Chambers (Ref. 26)

In contrast to these results, the aft propulsion system location on a pusher configuration (Fig. 15) produces stabilizing power effects in flight (Yip, Ref. 52). The normal forces generated by the propeller at angle of attack result in a nose-down or stabilizing pitching moment. This effect is particularly powerful at higher angles of attack where the wing and control surfaces are stalled and their effect on pitching moment has stabilized.

In examining pitch control requirements, a common problem to all pusher designs is the need for adequate nose-up control power during the take-off run to overcome not only the normal ground-reaction moment, but also to overcome the thrust moment (nose-down), since the thrust line is usually considerably above the wheels. Here a tractor arrangement has a benefit.

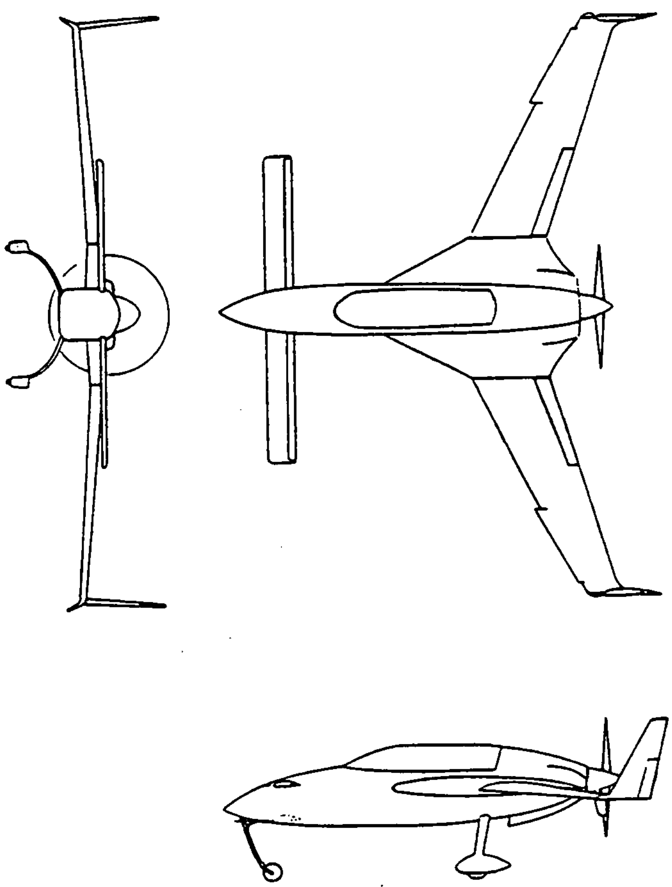


Fig. 15 Canard, Single-Engine Pusher Configuration of Yip (Ref. 52)

While the canard configuration has many advantages, it also has some distinct disadvantages. To make use of the advantages of the canard without the disadvantages, the three-surface concept is utilized. Interest has been shown in three-surface (canard, wing, aft tail) commuter turboprop designs due to potential advantages of improved cabin layout, increased cruise performance, more efficient structural design, increased control power, and greater centre-of-gravity range relative to two-surface (wing, canard or aft tail) designs (Ostowari, Ref. 43). By having a conventional tail aft of the wing, the three-surface configuration can lower landing speeds by allowing the wing to trim up to its maximum lift coefficient. Results of wind-tunnel investigations of the stability and control characteristics of three-surface transport configurations (Owens, Ref. 44) show that a T-tail empennage can cause a severe pitch-up at the stall which is aggravated by the far aft wing location typical of three-surface designs. Power effects were found to improve the static stability about all three axis.

3.2.4 Experiments

Most experimental studies that have been performed on multi-wing systems concerned finite span wings which therefore include the effect of tip vortices on the performance of each of the wings. In order to reduce wing tip effects, and subject the downstream airfoil to only the canard wake, Scharpf (Ref. 49) conducted an experimental study of a closely coupled tandem wing configuration at low Reynolds number, where both airfoils were mounted between one set of endplates (Fig. 16). The models used were two identical 6"chord Wortmann FX63-137 airfoils. The objective was to determine if any benefits could be gained from using a tandem-wing configuration over a single-wing configuration, so the combined lift and drag of the canard and wing are compared to the results from the single-airfoil measurements.

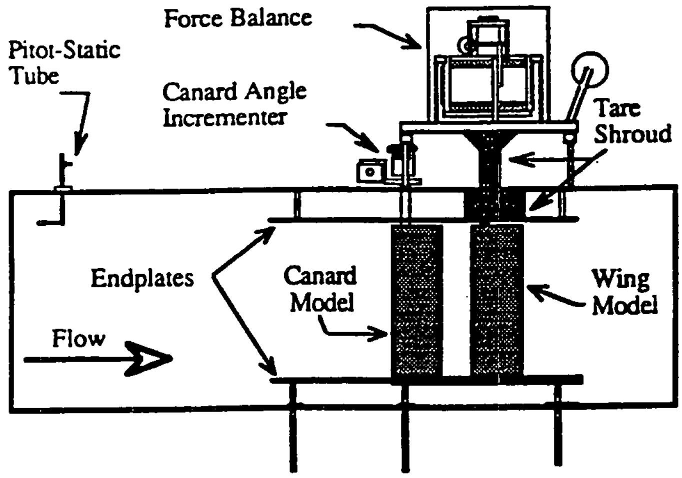


Fig. 16 Testing Arrangement of Scharpf (Ref. 49)

Force data were acquired for one of the airfoils while the other was held at a constant angle of attack. This resulted in a series of force coefficient curves for the measured airfoil for constant angles of attack of the second airfoil. From this data the complementary force coefficients from the canard and wing were added to give the combined effect of the tandem wings. These combined and individual results were compared to a baseline case consisting of a single airfoil under the same conditions as the tandem-wing configuration. This was performed for Reynolds numbers of 85,000 and 200,000, based on the wing chord.

For a Reynolds number of 85,000 the combined lift-to-drag ratios varied, while the combined lift and drag coefficients were greater than the single-wing coefficients. For a Reynolds number of 200,000 the lift and drag on the tandem wing decreased and increased, respectively, for all configurations, resulting in a loss of performance for all configurations. Therefore, one cannot simply say that one configuration is better than another, except when a specific requirement is identified.

It must be noted, however, that some difficulties with modelling flows at low Reynolds numbers, can arise from the fact that in this flow regime a laminar separation bubble can form on the airfoil thus having a dramatic effect on the aerodynamics of the airfoil. In this experiment this was recognized and for all data presented an attached flow condition existed.

The effects of the vortical wake shed by a finite span canard on a low Reynolds airfoil were examined by Khan (Ref. 37). Using the same models and procedures as Scharpf, with only the downstream airfoil situated between two endplates (Fig. 17), the experiments were conducted at a Reynolds number of 150,000.

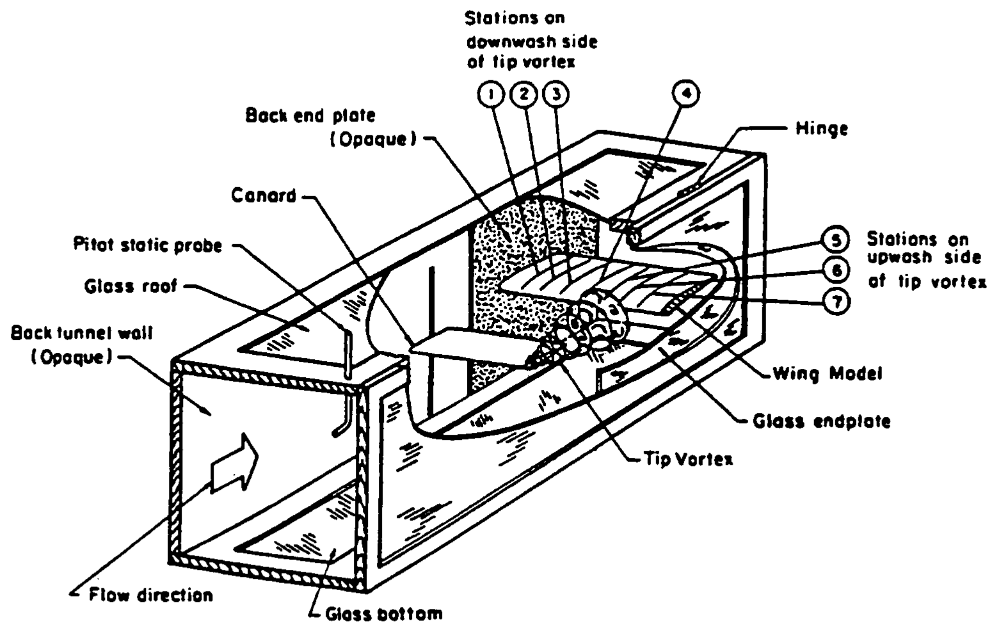


Fig. 17 Test Setup of Khan (Ref. 37)

The position of the tip vortex and wake shed by the canard profoundly influences the performance of the wing. The magnitude of the aerodynamic loads is reduced when the momentum deficient wake impinges directly on the wing. The non-dimensional force and moment coefficients, based on the undisturbed freestream dynamic pressure, are also lowered as a consequence. The net downwash imposed by the canard acts to further reduce the magnitude of the coefficients.

For all wing angles of incidence studied, drag is below the corresponding single airfoil value. Further, the reduction in drag is much more drastic than in lift. As a consequence, the lift-to-drag ratio of the tandem wing is higher than that of the single airfoil. The reduction in the magnitude of pitching moment promises savings in trim drag since smaller canard deflections will be needed to offset the nose-down moment due to the wing. It was noted that the reductions in drag and the increase in lift-to-drag ratio is not as significant at the higher wing angles of incidence.

Several experiments on finite span, multi-wing systems were conducted by Chevalier (Ref. 27), Feistel (Ref. 28), and Muchmore (Ref. 41) using similar generic wing-canard interference models. Figure 18 shows the model used by Feistel. The surfaces are separately instrumented for force and moment data, and were tested separately and combined over a wide range of longitudinal and vertical spacings, and incidence angles, to determine the effects of the presence of each surface on the net forces and moments acting on the other, and to show general aerodynamic characteristics of the various wing-canard combinations. The Reynolds numbers based on wing chords varied from 1 to 2 million.

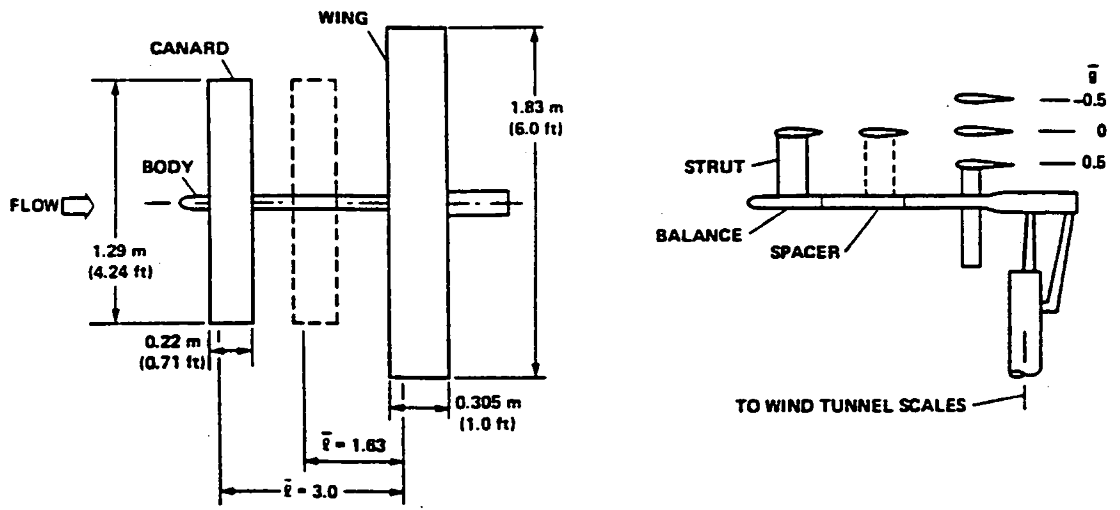


Fig. 18 Generic Wing-Canard Interference Model (Ref. 28)

While Feistel found good agreement with current analytical and theoretical techniques for moderate lift conditions, Chevalier indicated that nonlinear effects, viscous flow effects, play an important role in determining the aerodynamic characteristics of canard configurations, and that it would be extremely difficult to generalize for all canard configurations. As was also stated by Muchmore, especially when separated flow is present on either surface, even many degrees below stall, the linear attached flow trends may not accurately model the interference effects of the canard on the wing. The results to date indicate that each configuration would have to be considered on its own merit and that more wind-tunnel tests, at the appropriate Reynolds number, are needed.

In recent years the NASA Flight Research Centre has been conducting a program to evaluate the flying qualities of a number of general aviation aircraft. As a part of the continuing investigation a number of typical light, twin-engine configurations (Fig. 19) have been tested in the Langley full-scale wind-tunnel. The investigations were made to document the aerodynamic characteristics of the airplanes in their basic configurations. Within a period of a few years Fink (Ref. 29, 30, 31) conducted several of these experiments. The investigations included measurements of forces and moments of the complete configurations and hinge moments on all control surfaces. Downwash surveys were sometimes made at the horizontal tail. The tests were made to determine the static longitudinal and lateral stability of the aircraft over a wide range of flight conditions including engine-out conditions. Most of the tests were made at a tunnel speed of about 28 m/s giving a Reynolds number of approximately 3 million based on the mean aerodynamic chord. The analysis of the general static stability and control characteristics is based on summary plots prepared from some of the basic data obtained during the wind-tunnel investigations, and is highly descriptive. Little or no effort is made to explore the effects of configuration differences. Even in the investigation made specifically to study the effects of configuration changes some significant results were not explained. In that investigation it is stated that the aerodynamic characteristics of a configuration are mainly a function of mode of propeller rotation, slipstream energy, and flap deflection. It would be very useful to have this statement, based on the results of the force balance measurements, confirmed by a thorough flow field analysis.

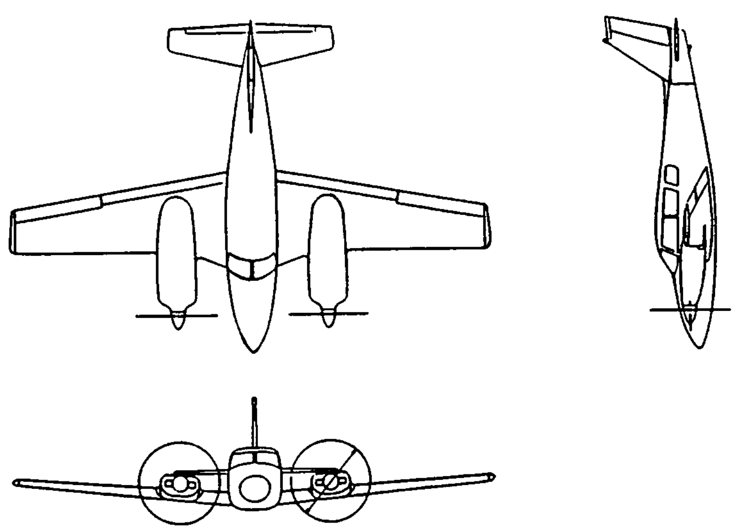


Fig. 19 Typical Twin-Engine Configuration

Some examples of inconclusive results:

"In the investigation of the longitudinal stability characteristics of one airplane the pitching moment variation with angle of attack was not greatly affected by the loss of one engine, left or right, while with another almost identical aircraft with the right engine out a reduction in pitching moment coefficient over most of the angle of attack range was established, especially with flaps down, while left-engine-out condition was essentially the same as that for symmetrical power."

"In the one case rudder effectiveness was relatively unaffected by changes in power or flap setting while in the other case deflecting the flaps resulted in some increase in rudder effectiveness."

"The investigated effects of the modes of propeller rotation on the pitching moment characteristics show that with power on, the mode of propeller rotation has a significant effect on the longitudinal stability, particularly with flaps down. In general, outboard down rotation is the most stable and inboard down rotation is the least stable."

It is obvious that there is still a large field of unexplored aerodynamic research, especially flow field analysis.

3.2.5 Conclusion

Apart from the impact of the application of modern highly loaded propellers on aircraft performance and handling qualities, a main issue in configuration aerodynamics is the demonstration of the claimed greater flight efficiencies of multi-wing aircraft relative to conventional aircraft. After all, if an unconventional aircraft configuration is opted for because of propulsion system considerations, the improvement in flight efficiency expected from the use of advanced propellers must not be counteracted by a drag penalty or handling problem caused by an ill-conceived airframe configuration. So for an unconventional configuration the gain in propulsion efficiency must be matched by a similar improvement in airframe performance. Since the current analytical and experimental investigations of unconventional aircraft performance are clearly inconclusive, the need for further research is apparent.

4. General Purpose Wind-Tunnel Model

As was stated in the introduction, at the LSL the need was felt to enhance the present program of configuration studies because of the introduction of advanced propulsion systems and the appearance of unconventional aircraft configurations. In chapter 2 the deeper background of the necessity for, in particular, experimental parametric research is clarified. It amounts to the conclusion that this kind of research is very advisable, for both the validation of CFD codes, and the development of semi-empirical design methods. In chapter 3 the main bottlenecks in configuration aerodynamics at this moment are established. They appear to be the aerodynamic integration of highly loaded propellers, and the performance evaluation of multi-wing configurations. In order to cover all of these areas of interest, the development is considered of a variable geometry model (VGM), as was also stated in the introduction. A series of different research models without any geometry variation capability, was considered, but it was assumed that, with the available financial resources, a VGM could represent a greater variety of configurations.

It is proposed to design the model in assembly kit form so that various configurations can be composed from a large number of separate elements. Included will be multi-wing arrangements of which the lifting surfaces can have different geometries, positions, and settings. The propulsion system will also be mounted in various fashions, e.g. as single-engine tractor or as twin-engine pylon-mounted pusher. The propellers will be driven by small water-cooled electric motors contained in the nacelles. Capable of independent geometric parameter variation, the desired program of parametric studies can be implemented with this model.

A problem regarding experiments with the VGM in a modest-sized conventional low-speed wind-tunnel like the one in the Laboratory, is the limited Reynolds and Mach number capacity of the wind-tunnel. However, a possible restriction to low-speed research does not have to cause a problem for the program of configuration studies. For especially those low-speed flight conditions like take-off and landing, the modelling of flow characteristics corresponding with high angles-of-attack and the use of flaps, is still very difficult, and the differences between calculation and experiment are still considerable and less well-understood. It is therefore possible and desirable to conduct experiments in this wind-tunnel for these flow conditions.

Concerning the external geometry, the VGM has to be able to represent existing single- and twin-engine propeller aircraft. A certain margin must be present for incorporating future developments in aircraft configurations.

An additional constraint is set by the Department research aircraft. Over a period of several years studies have been made comparing wind-tunnel test results of a powered scale model with actual flight tests on the Department research airplane, a DHC-2 Beaver. These are examples of configuration studies proven to be successful. In 1993 the Beaver will be replaced by a Cessna Citation, bought and to be operated in co-operation with the National Aerospace Laboratory (NLR). There is no intention to build a scale model of the Cessna. In order to preserve this kind of studies at the Laboratory, it is regarded desirable for one VGM configuration to be as similar as possible to the Cessna research aircraft, i.e. an unswept low-wing monoplane with conventional tail.

For further analysis of the various aircraft configurations to be represented, and their subsequent integration into the VGM, the reader is referred to the forthcoming design report.

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