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Aircraft Noise: The major sources, modelling capabilities, and reduction possibilities

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Aircraft Noise: The major sources, modelling capabilities, and reduction possibilities

Übersicht:
In October 2014, the first "Joint DLR & TU Delft Aviation Noise Workshop" was organized. This publication is the executive summary of this event. Overall, 38 invited participants from industry, academia, and research institutions have discussed the specific topic of this first 3 day workshop, i.e "Aircraft Noise Reduction at the Source".
Four specific tasks were formulated in order to address the problem, i.e. (1) identification of main aircraft noise sources on-board of a given reference vehicle, (2) assessment of simulation capabilities for noise prediction, (3) identification and assessment of promising noise reduction concepts for the reference vehicle, and (4) integration of these measures on-board of the reference vehicle. The major noise sources on-board of the reference vehicle as identified by the participants could have been reduced significantly if selected measures are installed on-board. These proposed measures promise to reduce the system noise by 8 dB along a take-off and by 10 dB along an approach flight. Yet, the almost 65% reduction in perceived noise as specified by ACARE's Flight Path 2050 could not be achieved. The most effective measure has been identified as structural shielding of engine noise emission.

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Abstract

In October 2014, the first "Joint DLR & TU Delft Aviation Noise Workshop" was organized. This publication is the executive summary of this event. Overall, 38 invited participants from industry, academia, and research institutions have discussed the specific topic of this first 3 day workshop, i.e. "Aircraft Noise Reduction at the Source". The concept of the workshop was to avoid the usual presentation marathon but enable detailed discussions. The invited participants with their various educational, cultural, and working backgrounds have been assigned into work groups to work on specific and predefined tasks. Four specific tasks were formulated in order to address the problem, i.e. (1) identification of main aircraft noise sources on-board of a given reference vehicle, (2) assessment of simulation capabilities for noise prediction, (3) identification and assessment of promising noise reduction concepts for the reference vehicle, and (4) integration of these measures on-board of the reference vehicle.
The major noise sources on-board of the reference vehicle as identified by the participants could have been reduced significantly if selected measures are installed on-board. These proposed measures promise to reduce the system noise by 8 dB along a take-off and by 10 dB along an approach flight. Yet, the almost 65% reduction in perceived noise as specified by ACARE's Flight Path 2050 could not be achieved. The most effective measure has been identified as structural shielding of engine noise emission.
Overall, the workshop can be understood as the first attempt to establish a new and active network for international cooperation in the field of aircraft noise.

Contents

Nomenclature

ANoPP	Overall aircraft noise simulation tool, NASA
ANOTEC	ANOTEC consulting, aircraft noise technology
ASRI	Aircraft Strength Research Institute, China
ARI	Aerodynamics Research Institute, China
AzB	Overall aircraft noise simulation tool, DLR
CAA	Computational Aeroacoustics
CFD	Computational Fluid Dynamics
DNS	Direct Numerical Simulation
DFS	Deutsche Flugsicherung GmbH, German air navigation service provider
DLR	German Aerospace Center
EPNL	Effective Perceived Noise Level [EPNdB]
EMPA	Swiss Federal Laboratories for Materials Science and Technology
FLULA	Overall aircraft noise simulation tool, EMPA
HEIDI	Engine noise simulation tool, DLR
IESTA	Overall aircraft noise simulation tool, ONERA
INM	Integrated Noise Module, simulation tool, FAA
JAXA	Japan Aerospace Exploration Agency
LES	Large Eddy Simulation
NASA	National Aeronautics and Space Administration, USA
NLR	National Aerospace Laboratory, Netherlands
MTU	MTU Aero Engines, company, Germany
ONERA	French Aerospace Research Agency
OASPL	(Overall) sound pressure level, [dB]
UPACS-LES	CFD/CAA code, JAXA
U-RANS	Unsteady Reynolds Averaged Navier Stokes
PANAM	Overall aircraft noise simulation tool, DLR
PIANO	Computational Aeroacoustics tool, DLR
Profan	Airframe noise simulation tool, DLR
Propnoise	Propeller noise prediction tool, DLR
RWTH	RWTH Aachen University
sonAIR	Overall aircraft noise simulation tool, EMPA
SOPRANO	Overall aircraft noise simulation tool, ANOTEC
STAPES	Airport noise exposure simulation tool, EUROCONTROL
SPL	(non or A-weighted) Sound Pressure Level, [dB] or [dBA]
TAS	True Air Speed [m/s]

1 Introduction

In October 2014 the workshop "Aircraft Noise Reduction at the Source" was held in Meisdorf, Germany. The event was organized jointly by DLR and the Delft University of Technology.

The motivation for this workshop was to investigate the potentials in low-noise aircraft design by bringing together experts from various fields in aircraft noise. Selected participants have been invited from industry, academia, and research institutions around the world.

A crude distinction can be made between engine noise and airframe noise, with many subthemes within these two (fan noise, jet noise, landing gear, flaps, slats). Also, a distinction between model-based and experimentally focused research can be made. Further, industry and research institutes have their own, sometimes distinct, interests.

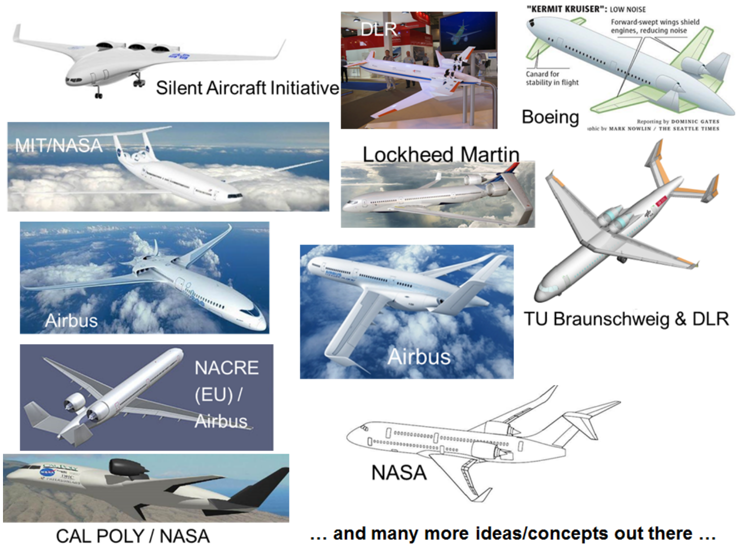


Figure 1.1: Exemplary low-noise aircraft concepts (please note picture copyrights).

Both existing and new aircraft concepts were discussed, see Fig. 1.1 for some examples, although in the workshop only tube-and-wing configurations were considered.

Today new aircraft concepts are designed with noise assessment incorporated in the design process, including installation effects. However, even such a state-of-the-art approach will not guarantee that the optimum or best design is identified. In general, concepts and new ideas are driven by individual experts or dedicated groups with limited experience in other fields than their main expertise. This can result in only component wise optimization and only little or no improvement at a system level will be achieved. In addition, the various simulation tools that are applied have different fidelity, limitations, and accuracy.

Therefore, the relevant questions and problems for the workshop participants were identified as the following.

- Are individual technologies still "low-noise" if installed on-board of the aircraft? (e.g. are leading edge devices as tested in a wind-tunnel really low-noise on-board?)
- How good are our predictions? (e.g. is neglecting mean flow for shielding problems allowed?)
- Have we considered all relevant noise sources and major interactions? (e.g. is flap side edge noise important?)
- What about the influence of "realistic" flight operation? (e.g. what is the effect of engine thrust correction and/or speed increase?)
- What about counteracting effects? (e.g. what is the effect of additional drag and weight of a new low-noise high-lift system?)
- What about the overall vehicle noise at a system level? (e.g. is flying at higher altitudes always better?)

In order to be able to answer these questions, a broad ("holistic") assessment methodology and active exchange with various experts become essential. Involvement of experts from different disciplines with various backgrounds (e.g. academia vs. industry, cultural and educational differences) is mandatory.

In order to answer the above mentioned questions, the workshop attendants were assigned to work on the four tasks as listed in Tab. 1.1.

Task	Description
1	Identification of main aircraft noise sources on-board of reference vehicle
2	Assessment of simulation capabilities
3	Identification and assessment of promising noise reduction concepts
4	Integration into a new low-noise vehicle concept

Table 1.1: Short description of the four workshop tasks

The following scenario and limitations were predefined: the reference aircraft is an existing vehicle, i.e. a conventional, single-aisle, tube-and-wing, medium-range transport aircraft as depicted in Fig. 1.2 (predicted market share of 70% by 2030, see Refs. [2, 3]). Also, the developed new low-noise technology should be available in 2030 at Technical Readiness Level of 5-6. The overall goal for this 2030 scenario is a reduction in perceived noise level (with respect to the reference aircraft) of 65% per flight operation as proposed by the Advisory Council for Aviation Research and Innovation in Europe (ACARE) in their "Flightpath 2050"[1]. This corresponds to approximately 12 dB reduction in overall sound pressure level (OASPL) or a level 35 EPNdB cumulative below Chapter 4[2].
In the subsequent chapters of this paper, the four tasks are described in more detail, including the major results of the workshop per task.

The workshop was not a traditional conference, i.e. fully filled with presentations. Basically, such a presentation marathon was avoided by dedicating most of the time to active participation in groups working on the four tasks above. Five groups were formed, based on background and research interest (e.g. focus more on airframe noise or engine noise) and mixed members from academia, research institutions, and industry, where we tried to separate direct colleagues. The five groups worked in parallel on the four tasks. In plenary sessions the results of the five groups were discussed per task. In the plenary sessions, individual ideas and concepts of each group were discussed with the aim to find common ground, and to identify the best ideas and most promising concepts. To ensure maximum uniformity in the outcomes of the individual groups, the participants were provided with templates for documenting their discussion results.
In total, there were 38 participants out of 10 countries (China, France, Germany, Italy, Japan, Netherlands, Spain, Switzerland, UK and US). In Tab. 1.2 the participating institutions are listed.

Industry	University	Research institutions
ANOTEC Consulting	Georgia Institute of Technology	ASRI
Airbus	Peking University	ARI
DFS	Roma Tre University	Bauhaus Luftfahrt
MTU	RWTH	EMPA
Rolls-Royce	Southampton	DLR
	University of Tokyo	JAXA
	TU Braunschweig	NASA
	TU Delft	NLR
	TU Muenchen	ONERA
	TU Stuttgart	

Table 1.2: The workshop participants' institutions

[1] For more information, visit http://www.acare4europe.com/sria/flightpath-2050-goals
[2] According to ICAO Annex 16.

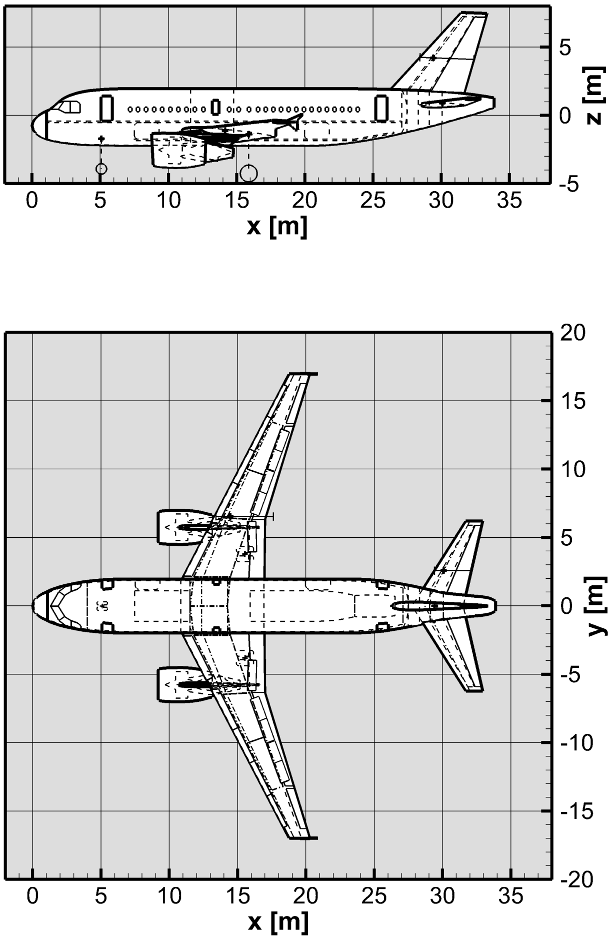


Figure 1.2: Reference vehicle layout for the workshop tasks (see Ref. [1]).

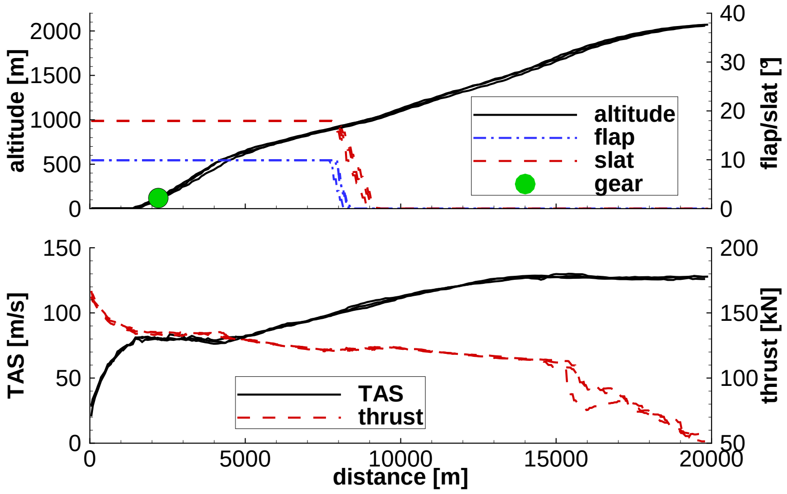
2 Identification of main aircraft noise sources (Task 1)

2.1 Detailed description of task

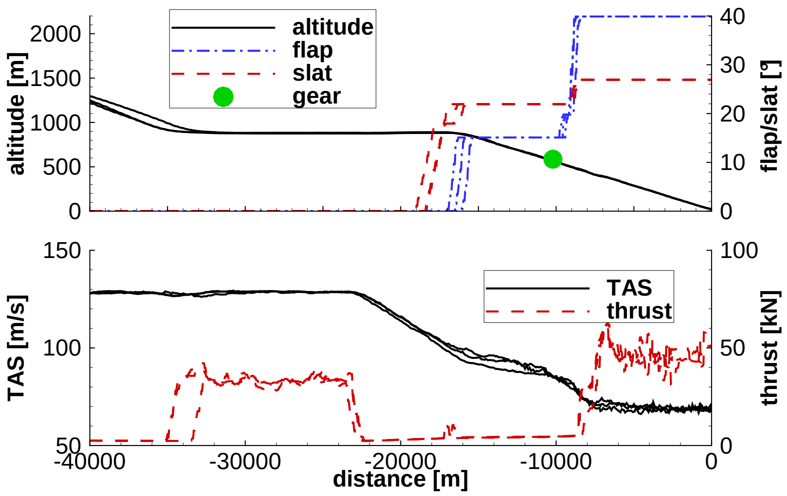
Task 1 comprises the identification of the main noise sources on-board existing aircraft, i.e. the reference vehicle as depicted in Fig. 1.2, was used as an example case. Participants were asked to identify the main sources (airframe or engine noise) along typical flight segments (approach / departure / cruise), taking into account whether sources are classical, parasitic, or due to installation effects. Also the spectral (tonal or broadband contribution, low or high frequency) and directional characteristics had to be indicated. For each source, the relevant parameters, both operational (flight condition) and geometrical, had to be specified. If possible, the importance of each parameter had to be ranked.

2.2 Summary of results

The workshop participants identified the following classical aircraft noise sources, see Tabs. 2.1 and 2.2. Also the noise generating mechanism (including the relevant parameters in descending order of importance) and the departure and approach conditions under which these noise sources are important are also indicated, see Fig. 2.1. Finally, the level of theoretical understanding was estimated. A distinction is made between noise sources due to the airframe, see Fig. 2.2(a), and engine noise sources, see Fig. 2.2(b).



(a) Standard departure flights.



(b) Standard approach flights.

Figure 2.1: Typical and representative operating conditions along departure and approach flights; flight data was recorded during a 2006 fly-over noise campaign by DLR [4].

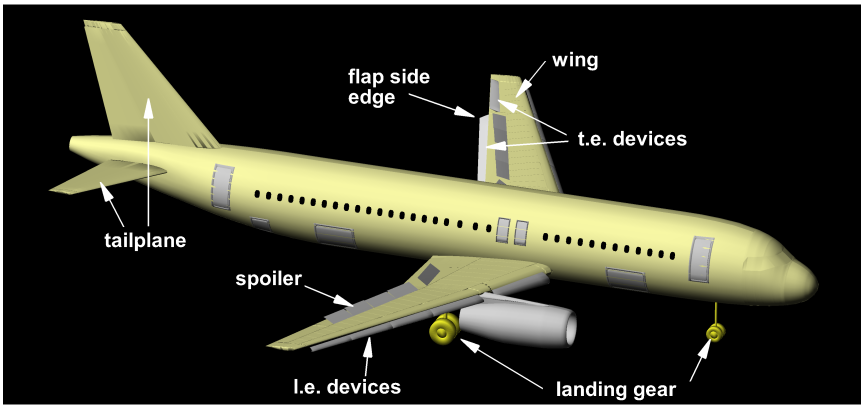
Noise source	Noise generating mechanism	Relevant parameters	Conditions under which important	Comments	Level of theoretical understanding
Landing gear	Broadband noise due to turbulent flow on various elements of landing gear and tonal noise due to cavities	- Length of strut - Diameter of wheels - Number of gears - Gear doors - Number of axles - Number of wheels - Inflow speed	Low engine setting (final approach)	- Heavy aircraft deploy landing gear 15 km before touchdown - The noise of the main landing gear is directly influenced by circulation around the wing	Medium
Flaps	Broadband noise due to turbulence around side edges and gaps	- Flap deflection angle - Local inflow velocity - Chord length - Angle of attack - Slat deflection angle - Sweep angle	Low or idle engine setting (approach)	- Flap tracks are of importance and produce excess noise - Flap side edge noise is dominant compared to flap noise itself	Good
Slats	Broadband noise due to turbulence in gaps	- Local inflow velocity - Chord length - Sweep angle - Geometry between slat and wing, e.g. gap height and overlap	Low or idle engine setting (approach)	- Laminar flow does not allow slats (therefore future aircraft might have no slats) - Slat tracks are of importance and produce excess noise	Medium
Lift and control surfaces (e.g. wing)	Broadband noise due to turbulence at the trailing edge	- Turbulent intensity at the trailing edge - Sweep angle of the wing - geometry/shape of the trailing edge, e.g. bluntness of trailing edge	Low engine setting, clean configuration (far approach)	- Limited acoustical data available (difficult to measure because of low noise intensity) - Might not be relevant for current vehicles but for future designs (e.g. without slats)	Medium
Spoilers and speed brakes	Detached flow	- Spoiler geometry - Flight velocity	Low engine setting (complete approach)	Spoiler noise can be shielded if the gap behind the spoiler and between wing and high-lift system is closed, e.g. with a splitter blade	Low
Krueger (leading edge device)	Not understood	- Geometry - Inflow velocity - Sweep angle	Heavy use of spoilers during standard approaches, dominant during low or idle engine setting	Track system might dominate Krueger itself	Low

Table 2.1: Overview of airframe noise sources.

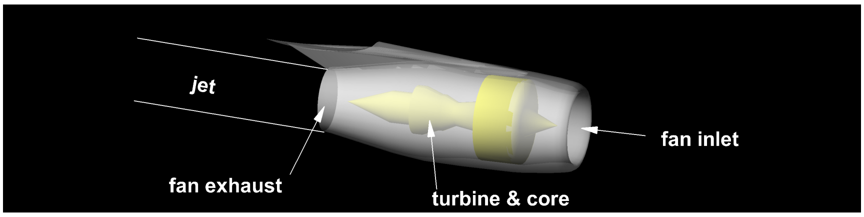
Noise source	Noise generating mechanism	Relevant parameters	Conditions under which important	Comments	Level of theoretical understanding
Fan	-Thickness and loading noise - Interaction rotor-stator - Stator vane - Struts - Fan-intake interaction, e.g. engine inlet or pylons - Tonal noise due to shock cells on blades (harmonic) - Shock cell interaction with nacelle (not a harmonic sequence)	- Inlet geometry - Number of blades - Number of vanes - Fan pressure ratio - Relative Tip Mach number - Inlet flow distortion, e.g. due to an angle of attack or due to a pylon in front of the engine inlet	Always	- For current engines both tones and broadband noise important. The broadband contribution becomes more important for future designs - Buzzsaw (tonal) is relevant - Fan noise increases due to increased inflow distortion by engine installation - Fan noise is reduced due to lining - Fan noise can be subject to significant noise shielding due to structural elements	- Medium for tones - Low for broadband contribution
Jet	- Turbulent mixing - Shock noise (only in cruise condition)	- Velocity differences between the streams, i.e. free, core, and bypass stream - Temperature - Nozzle diameter - Nozzle type	Take-off	Jet noise is a distributed source behind engine	- Good (under subsonic conditions) - Medium (under sonic conditions)
Combustion	- Mainly broadband noise - Direct contribution due to the expansion of the gas mixture in the combustion chamber - Indirect noise contribution due to the convection of non-uniformities through pressure gradients in the turbine	- Temperature - Pressure ratio - Combustor type (lean, rich)	- Approach - Departure after thrust cutback - Side-line	Becomes more important since all other sources are being reduced	Low
Turbine	Tonal and broadband noise (due to same mechanism as fan noise generation)	- Number of blades - Number of vanes - Mach number - Shaft speed - axial stage spacing - Number of stages - Exit area - Shaft power	Mainly approach and then departure after thrust cutback	- Becomes more complex due to multi-stage design - Haystacking might be of importance, i.e. a characteristic spectral broadening effect of turbine tones due to the jet shear layer	Low-Medium
Compressor	Tonal and broadband noise similar to fan	Same as fan	Departure after thrust cutback and approach		Medium

Table 2.2: Overview of engine noise sources.

In Tab. 2.3 we list possible interaction and installation effects, including the relevant driving parameters. In general, the theoretical understanding of the corresponding noise generating and/or the noise shielding effects is low.



(a) Airframe contribution.



(b) Engine contribution.

Figure 2.2: The various noise generating components on-board of the aircraft, i.e. the "classical" noise sources [1].

"Noise source"	Relevant parameters
Jet with flap	- Flap-jet vertical distance - Mach numbers (of jet and flight speed) - Pylon design and position
Engine pylon with wing	- pylon design - location of engine installation
Spoiler on flap and slat	- flow conditions around flap and slat due to spoiler deflection
Landing gear with flap	- influence on flow conditions around the flap due to the extracted main landing gear
Shielding effect of engine noise	- location of engine installation

Table 2.3: Interaction and installation effects.

3 Assessment of simulation capabilities (Task 2)

3.1 Detailed description of task

Concerning the state-of-the-art modelling capabilities of aircraft noise, in task 2 the following questions were addressed:

- What are the modelling techniques for the various noise sources obtained from task 1?
- What are the available simulation capabilities?
- What tools have been developed and applied already?
- What are the main applications of these tools?

In addition, task 2 should have also addressed the most urgent gaps in simulation capabilities:

- Can industry provide a wish-list for future simulation developments?
- What accuracy is required?

However, this second topic was hardly covered during the workshop. For this specific task, the discussion groups were formed based on the participants' expertise, i.e. model developers and software users.

3.1.1 Summary of results

It was proposed to distinguish four different approaches within the current full range of modelling capabilities. A well-known distinction is that of Farassat [5], by which the following 4 different approaches are distinguished (specifically derived for airframe noise but in principal applicable to engine noise as well):

- *Fully numerical*, where the source and propagation are simulated simultaneously in one time-dependent Computational Fluid Dynamics (CFD) and Computational Aeroacoustics (CAA) run. These type of simulations require the computational domain to be large enough for both capturing the sound source regions and the propagation of the sound to the receiver.

- A *CFD step combined with application of the acoustic analogy*, i.e. the source and propagation are simulated in two different steps. The aerodynamic flow is calculated first for the region where the origins of the sound are expected to be located. Based on post processing the aerodynamic field results, the sound sources are calculated, e.g. using Lighthill's acoustic analogy [6, 7]. The term analogy refers here to the method of capturing processes in the flow that are capable to generate sound by a sound source term that can then be used for calculating the acoustic propagation. This second type is based on the assumption that there is no feedback from the acoustic field on the turbulence.

- *Fully analytical*. This group comprises all approaches where both the flow and acoustic field are derived analytically. The source model is some combination of monopoles, dipoles and quadrupoles, based on the flow characteristics and object geometry. The sound at the receiver location is typically calculated from the Green's function.

- *Semi-empirical*. Methods in this class are based on databases containing measured acoustic data, either from component wind-tunnel tests or from full-scale aircraft and for varying operational conditions.

This classification was discussed during the workshop. The outcome was to retain classes 1 and 2 conform Farassat [5], but to redefine class 3 as *semi-analytical*, as the known models that are based on analytical approaches are often combined with some other approach. Class 4 was split in two, i.e. 4a, which was denoted as the class of *fully empirical methods*, and 4b, containing the fast (semi-empirical) *scientific approaches*. Class 4a is solely based on measurements, whereas for class 4b a combination is made between acoustic data for those elements in the calculation for which no analytical or numerical tools are available, and analytical or numerical methods for the remaining steps, i.e. a physics-based approach[1].

The various exiting methodologies and tools as developed or applied by the workshop participants are summarised in Fig. 3.1. The tools listed in Fig. 3.1 are explained in more detail in Tab. 3.1.

[1] This is according to the classification as specified in Ref. [16].

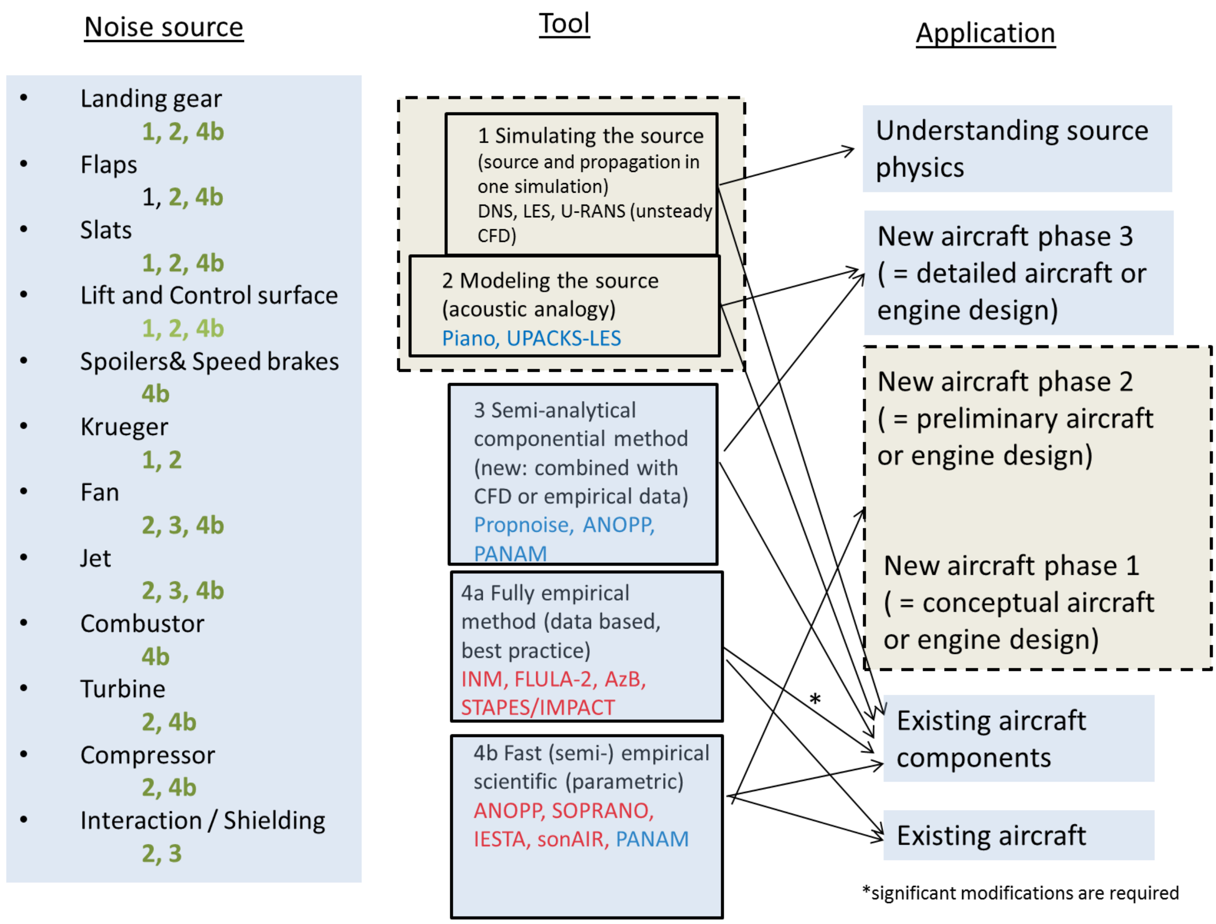


Figure 3.1: The existing methodologies and tools (middle column). For the direct numerical simulation (DNS), Large Eddy Simulation (LES) and unsteady RANS approaches (U-RANS) various tools are used which are not further specified. In the left column one finds the noise sources identified in task 1 (under each noise source the current available modelling methodologies from the middle column are indicated). The right column indicates the applications that are possible with each tool.

Tool	Type	Description	Origin	Reference
INM	4a	Integrated Noise Model	Federal Aviation Administration	Olmstead et al. [8]
FLULA	4a	Fluglaerm, acoustic investigation of complex scenarios such as yearly air traffic	Swiss Federal Laboratories for Materials Testing and Research	Pietrzko and Buetikofer [9]
ANoPP	3, 4b	Aircraft Noise Prediction Program	NASA	Gillian [10]
ANoPP 2	3, 4b	Aircraft Noise Prediction Program, new version	NASA	Burley [11]
SOPRANO	4b	Silencer Common Platform for Aircraft Noise calculations	ANOTEC consulting	Van Oosten [12]
IESTA	4b	Infrastructure for Evaluating Air Transport Systems	ONERA	Rozenberg and Bulté [13]; Brunet et al. [14]
SonAIR	4b	Model for predicting single flight events to investigate and optimize noise abatement procedures by using either generic data, e.g. from a full flight simulator, or cockpit data from real flights	Empa, Swiss Federal Laboratories for Materials Science and Technology, and Swiss Laboratory for Acoustics/Noise Control	Zellmann, Wunderli and Schaeffer [15]
PANAM	3, 4b	Aircraft system noise modeling Airframe noise model: Profan Engine noise model: HEIDI	DLR	Bertsch [1] and Bertsch & Isermann [16] (PANAM); Rossignol, Lummer, and Delfs [18] (Profan); Bassetti and Guérin [17] (HEIDI)
AzB	4a	German calculation standard (e.g. implemented in commercial codes Soundplan, Cadna, and IMMI)	DLR	Isermann and Vogelsang [19]; Bertsch and Isermann [16]
STAPES	4a	SysTem for AirPort noise Exposure Studies (in IMPACT: An Integrated Aircraft Noise and Emissions Modelling Platform)	EUROCONTROL	ECAC Doc. 29 / ICAO Doc. 9911
Propnoise	3	Propulsion Noise	DLR	Moreau and Guérin [20]
Piano	2	Computational Aeroacoustics code	DLR	Caro [21]
UPACS-LES	2	Computational Fluid Dynamics / Aeroacoustics code	JAXA	Imamura [22]

Table 3.1: Existing aircraft noise modeling tools.

4 Identification and assessment of promising noise reduction concepts (Task 3)

4.1 Detailed description of task

This task concerned the identification and assessment of promising noise reduction concepts. The following issues were addressed:

- Which new technologies or systems are known to result in noise reduction (the noise sources obtained from task 1 are considered)?
- What are the implications when installed on-board of the aircraft?
- What is the operational impact, e.g. is it effective only in slow flight when the engines are idle?

4.2 Summary of results

Tab. 4.1 gives the overview of all discussed noise reducing measures and the implication for the aircraft.

Noise reduction measure	Estimated reduction	Implications for the aircraft
Landing gear mesh fairings (add-on device)	3 - 5 dB	Landing gear design, weight, maintenance
Flap-side-edge noise: Porous device at the edge	5 dB	Maintenance
Slats: Setting optimization (overlap, gap)	3-5 dB	Additional complexity/weight with respect to kinematics and tracks
Fan: Optimized fan speed, improved liner design for wide-band noise reduction, design for by-pass-ratio (bpr) 15, pressure ratio 1.2 (reference is 1.6)	5 dB (mainly attributed to fan rpm); higher reduction possible with increasing bpr	Engine weight, nacelle design, drag increase
Jet: Increase bpr, add chevrons	1-2 dB (chevrons); higher reduction possible with increasing bpr	Bigger nacelle, weight
Engine noise shielding (especially fan noise)	10 dB and more	Aerodynamic disadvantages due to location of engine installation

Table 4.1: Noise reduction measures identified during the workshop.

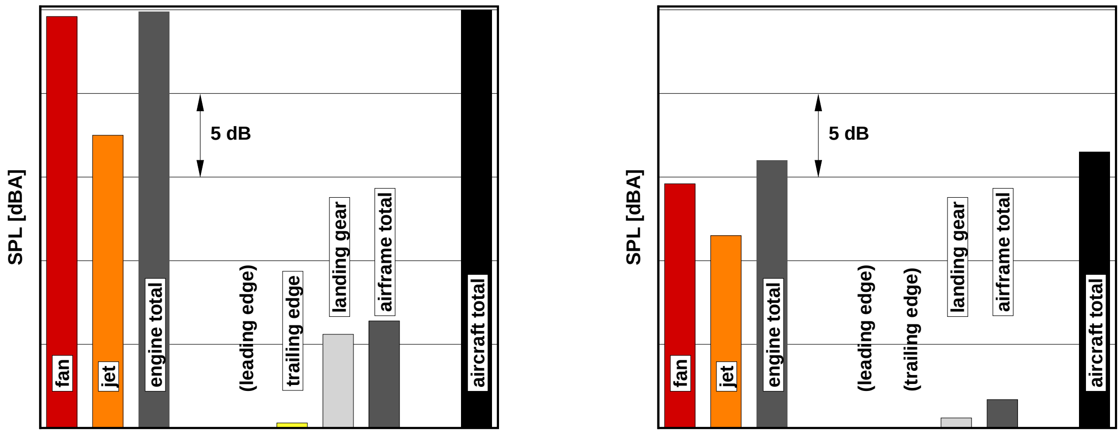
5 Integration of reduction concepts into new low-noise vehicle (Task 4)

The objective of this task was to identify the most promising low-noise technologies and concepts and how to integrate these on-board of the reference aircraft.

The noise source contributions for the reference vehicle are depicted in Fig. 5.1 for approach and in Fig. 5.2 departure. The noise source contributions on the ground are evaluated for two typical and representative observer locations. Depicted are PANAM simulation results [1]. The vehicle is simulated under typical operating conditions along approach and departure, respectively. Along the simulated flight path, observer locations that are typically subject to increased community noise annoyance have been selected. The approach observer is approx. 7 km prior touch-down whereas the departure observer is located approx. 3 km after take-off.
Applying the selected noise measures as identified in Tab. 4.1, the ground noise impact can be significantly reduced. It is assumed, that airframe noise contributions can be reduced by the maximum as identified by the experts. This is a 5 dB level reduction for each source, i.e. landing gear, flap-side edge, and leading edge noise contribution. Furthermore, jet noise can be reduced by 6 dB[1] and modifications to the fan can yield noise level reductions in the order of 10 dB[2]. Obviously, the reduction of one individual noise source contribution will yield another dominating noise source so that all measures have to be implemented simultaneously. Finally, for the selected operating conditions and at the corresponding representative observer location, an overall level reduction of 8.5 dB along the take-off and 6.2 dB along the approach can be achieved. Yet, it has to be mentioned, that the landing gear remains as the dominating noise source for the approach case. If the gear is not deployed, a level reduction of almost 10 dB is predicted along the approach case. Take-off noise is still dominated by fan noise contribution even after application of the measures as identified in Tab. 4.1. Exploitation of noise shielding effects promises further significant noise reduction to the fan noise impact on the ground. So overall, it can be concluded, that the technology as identified by the work-

[1] Here it is assumed, that a 2 dB reduction is achieved due to nozzle modification and additional 4 dB reduction due to an increase in BPR.

[2] It is assumed, that 10 dB reduction are achievable due to increased BPR, a reduced fan rpm, and advanced fan design.



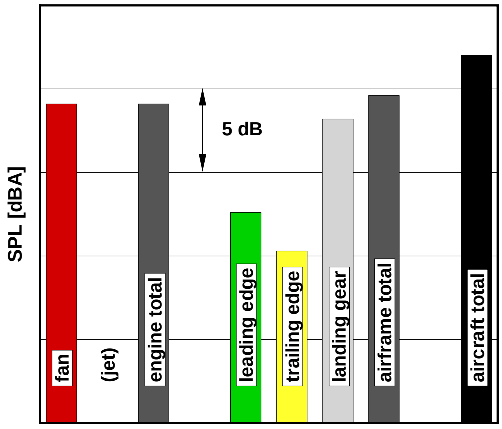
(a) Reference vehicle. (b) Ref. with installed measures.

Figure 5.1: Typical take-off noise source ranking.

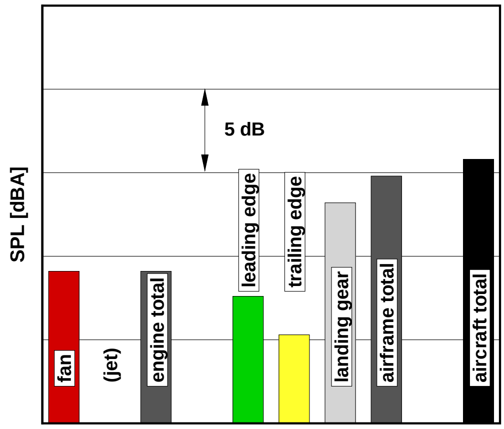
shop participants would not fully meet the first workshop goal, which is a 12-13 dB reduction of the maximum A-weighted sound pressure level for each flight operation, i.e. along approach and departure.

The certification noise in EPNdB is usually dominated by tonal fan noise contribution. Applying the identified measures to the fan noise contribution, i.e. including shielding, promises significant reduction of the tonal fan noise. It can be concluded, that the EPNL at the certification points could be significantly reduced. The selected level reductions for each measure might not yet reach the order of 35 EPNdB cummulative below Chapter 4[3] as specified as another workshop goal, but it gets close. In conclusion, the identified measures promise to reduce the underlying noise sources significantly but do not reach the ACARE goals.

[3]According to ICAO Annex 16.



(a) Reference vehicle.



(b) Ref. with installed measures.

Figure 5.2: Typical approach noise source ranking.

6 Summary & Conclusion

A workshop was organized by DLR and TU Delft in order to bring together experts from industry, academia, and research institutions. The participants were organized into working groups in order to allow for detailed discussions and avoid a presentation marathon. Within the working group, the experts had to work on predefined tasks in order to (1) identify the existing noise sources on-board of a given reference vehicle, (2) identify available and still missing simulation capabilities, (3) identify possible measures to reduce these noise contributions, and finally (4) evaluate the impact of the reduction measures if applied to the reference vehicle.

Classical dominating noise sources have been assessed and parameters identified, that dominate their inherent noise generation. For the airframe noise sources, it can be concluded, that good to medium understanding and data is available for most sources. Yet, spoilers and speed brakes as well as Krueger leading edge devices are not yet fully understood. These sources require more detailed investigation in the near future. Especially, because spoilers are heavily used along so-called "low-noise" or steep approach procedures while their impact on the overall ground noise is still unknown. Krueger devices on the other hand might become very important if laminar-flow wings are still of interest for future aircraft[1].

With respect to the engine noise sources, it should be noted, that more emphasis should be put on the so-called core noise sources, i.e. combuster and turbine. Since significant level reductions seem achievable for the jet and fan noise, the core noise sources will remain as dominating noise sources in the future. Therefore, detailed research on these sources will become essential in the future.
Another very interesting noise source has been identified by the participants. The counter-rotating open rotor concept (CROR) is very promising with respect to a reduction in fuel consumption compared to a conventional 2015 turbofan engine[2]. The noise generation is very complex and not yet fully understood. The CROR concept would easily fill up a separate and dedicated workshop, hence was not in the scope of this

[1]Krueger flaps are very promising high-lift devices for laminar wings because they keep the wing surface protected from insect and dirt impact, therefore keep them clean.

[2]A reduction in fuel consumption in the order of 10% seems possible.

event. Yet, the industry participants indicated confindence that the noise levels of an advanced CROR design will meet the restrictions of Chapter 4[3].

The importance of advanced simulation capabilities for overall noise prediction is accentuated by the fact that most organizations and institutions run their own software developments in that area. An important step to further improve the overall noise prediction is the combination of methods with different fidelity. Interfaces between overall system noise prediction tools and measured data or high-fidelity simulation approaches, e.g. CAA, promises to be an essential step towards more reliable simulation results.

The identified measures to reduce known noise sources are listed in Tab. 4.1. Application of these measures on-board of the reference vehicle promises a significant noise reduction of 6.2 dB and 8.5 dB along approach and departure, respectively. The reduction along the approach can be futher improved to $\approx$ 10 dB without the gear deployed. Yet, the identified measures to the reference vehicle do not reach the order of 12 dB OASPL reduction which corresponds to 35 EPNdB cummulative below Stage 4 as specified in the ACARE goals. Advanced vehicle concepts with engine noise shielding promise even higher level reductions for the specific noise source subject to shielding, therefore might help to finally come close to the ACARE goals, see Ref. [23].

Another problem that has been identified during the workshop is the lack of an appropriate noise metric. Available metrics, e.g. EPNL at the certification points, will not always do the job. By simply considering the certification points, other significant flight segments are not accounted for. For example, it is a known fact that community noise annoyance is dominating along the common approach path towards any major airport. Yet, this situation is still far away from any certification point, hence not even considered for a "conventional" noise assessment.

The workshop participants have filled out an anonymous survey about the workshop after the event. For this survey, special attention was put on the concept of the workshop, i.e. avoid presentation marathon but enable detailed discussions. All of the participants gave the concept 8-10 points with 10 being the highest grade. Furthermore, the participants indicated that they would not have been able to draw such an "holistic" overview on aircraft noise, i.e. the major sources, modelling capabilities, and reduction possibilities, by themselves. The presented event was the first "Joint DLR & TU Delft Aviation Noise Workshop". For more information on follow-up events, the interested reader is referred to directly contact the editors.

[3] According to ICAO Annex 16.

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