JOURNAL OF AIRCRAFT
Vol. 47, No. 2, March–April 2010

Almost 40 Years of Airframe Noise Research: What Did We Achieve?

Werner Dobrzynski*
DLR, German Aerospace Center, 38108 Braunschweig, Germany

DOI: 10.2514/1.44457

I. Introduction

IN THE early 1970s the first twin cycle bypass turbofan engines came into service. The development of such engines was triggered by the need to reduce fuel consumption but also had a beneficial side effect on aircraft noise impact through the corresponding reduction in jet noise. In the last decades the bypass ratio of the following generations of turbofan engines was continuously increased. As a result, aircraft engine noise now has come down to a level comparable to that of noise originating from the turbulent flow around the airframe for approach and landing conditions, that is, with deployed landing gears and high-lift devices. Efforts in aircraft noise reduction, therefore, must also focus on the airframe as relevant noise contributor.

This problem was already perceived in the 1970s, when airframe noise was first identified as a potential lower (aircraft) noise barrier. At that early stage extensive studies were initiated to both quantify airframe noise levels and identify the major noise sources. Since then almost 40 years passed by, but the efforts in airframe noise research were not always as intense as in the beginning. The reason was two fuel crises around 1980, which caused a redirection of national government funding toward research for fuel saving in public transport.

Yet, since 1995 aircraft noise impact again became an issue of public interest, last but not least due to the ongoing growth in air traffic and the corresponding needs for new airports or the expansion of current ones. The political consequence was the publication of the European Visions 2020 [1] with the requirement, among others, to “reduce subjective noise impact by half” (i.e., minus 10 dB per operation by 2020 relative to the year 2000 technology). Almost at the same time a still more stringent requirement had been spelled out in the U.S. through the national AST (Advanced Subsonic Transport) and Quiet Aircraft Technology research programs.

This paper is an attempt to subsume the most important findings from experimental and applied research in airframe noise worldwide without claiming to be complete, and the cited references only represent selected examples out of the bulk of relevant publications. The paper starts with a very brief review of airframe noise research in the last 40 years in Sec. II, and then focuses on the description of the major airframe noise sources in Sec. III. Noise from landing gears and high-lift devices is covered in successive subsections, again partitioned in the description of respective noise source mechanisms, noise prediction capabilities, and reduction technologies.

II. Brief Review of Airframe Noise Research

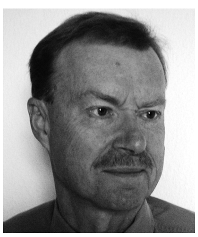
When airframe noise was identified as the potential lower aircraft noise barrier in approach, efforts were undertaken to first quantify airframe noise through dedicated flyover noise measurements [2–6]. Such test campaigns encompassed a variety of different aircraft types ranging from gliders to the Galaxy aircraft. Based on this dataset Fink [7] developed the first semiempirical airframe noise prediction method, which occasionally is still in use today. Both landing gears and high-lift devices were identified as the two major airframe noise contributors.

Parallel to such flight tests, laboratory-type aeroacoustic source studies were launched, for example, noise testing of scale model lifting surfaces or of small-scale generic landing gears [8] in quiet freejet facilities. Building on the understanding of noise source mechanisms from earlier theoretical work in aeroacoustics [9–11], from 1975 on many of the basic noise reduction technologies were invented, which are still relevant today. The primary technology is porous [12] and perforated or serrated edge extensions [13,14] to reduce trailing-edge noise. Porous edge inserts were tested [14] to mitigate interaction noise from turbulent inflow to flap leading edges. Also, flap side edge noise reduction was achieved through porous edge replacements [14,15].

More recent research efforts in airframe noise source description and noise reduction are essentially based on these early experimental results, but now have available high-quality and large-scale aeroacoustic wind-tunnel facilities combined with sophisticated measurement techniques such as microphone arrays for source location and, for example, particle image velocimetry (PIV) for nonintrusive and accurate local aerodynamic data monitoring. Moreover, advanced numerical tools such as computational fluid dynamics (CFD) and computational aeroacoustic (CAA) methods can be used to support the experimental work, and vice versa.

III. Major Sources of Airframe Noise

For current commercial aircraft the major sources of airframe noise can be listed in a typical rank order of priority as follows



Werner Dobrzynski received his diploma in engineering from Technical University Berlin in Germany in 1971 and started his professional career in the German Aerospace Center (DLR). He first worked in the area of flame stabilization in aeroengine combustion chambers. With the expansion of aircraft noise activities at DLR he then joined the Division of Technical Acoustics in 1974 and focused on airframe noise research. He received a Ph.D. on wind rush noise prediction in passenger cars under M. Heckl in 1983. In 1984 he changed to the DLR Institute of Aerodynamics and Flow Technology and focused on propeller and propfan noise. From 1995 on he revisited airframe noise problems and performed the first full-scale noise tests on landing gears and high-lift configurations in acoustic wind tunnels. In the continuation of this work he held leading positions in numerous European research projects on airframe noise.

Received 19 March 2009; revision received 15 December 2009; accepted for publication 15 December 2009.

*Research Engineer, Institute of Aerodynamics and Flow Technology, Lilienthalplatz 7.

(Fig. 1): landing gears, slotted slats, flap and slat side edges, flap and slat tracks, spoilers, and component interaction noise sources, for example, gear-wake/flap interaction. However, the rank order of these noise contributors may change depending on the specific design of an aircraft under consideration. It should be noted that for single aisle or regional aircraft the noise from high-lift devices is quite close to that from landing gears, whereas landing gear noise is the far dominating airframe noise component for current wide-body aircraft.

There are still other potential sources of airframe noise which, based on current knowledge, need only be considered after a drastic reduction of the previously listed major noise contributors. This is noise originating from wing tips, turbulent surface boundary layers (including surface roughness and vibration), and free wake turbulence downstream of airframe components, the latter for low Mach number flows (say <0.3).

There are still other types of noise sources, which were detected lately when the first full-scale original airframe component tests were possible with the availability of large acoustic wind tunnels. Such noise tests were performed on original landing gears and an aircraft wing in high-lift configuration. Excess noise sources were detected to originate from flow around construction details, which are unique to a particular aircraft. Unfortunately such parasitic noise sources could be that strong to mask noise as is radiated from classical sources, for example, side edges or trailing edges of lifting surfaces. Because such noise-producing construction details are never reproduced at model scale, it is obvious that there is an inherent problem with the comparison of results from full-scale flight tests and those obtained from scale model wind-tunnel experiments. Analytical or semiempirical airframe noise prediction models that are calibrated with scale model wind-tunnel test data are, therefore, endangered to underestimate airframe noise levels to be expected for the corresponding full-scale aircraft.

It is due to the importance of this problem that in the following, selected examples of parasitic noise sources are discussed first.

A. Parasitic Noise Sources

Parasitic noise can have either tonal or broadband characteristics. Landing gear structures are composed of a variety of struts, which are connected through joints with hollow pins. Flow-induced cavity resonances in these pin holes can cause prominent tone noise, which may govern the overall A-weighted landing gear noise level. An example derived from full-scale gear tests in the wind tunnel is shown in Fig. 2 [16]. Whether or not such resonances are excited depends on both the orifice geometry and the local flow conditions, the latter in turn being affected by the position of the pin within the gear structure and the actual aircraft operational conditions (e.g., cross wind). Accordingly, it is extremely difficult to predict the potential of cavity resonance related tone noise generation. Therefore, pin-hole caps should be used to solve this problem. Manufacturers, however, hesitate to adopt this cheap solution, referring to corrosion problems.

Quite similar tone noise effects were observed for aircraft wings with small regular cutouts in the wing surface. Examples are antiice vents or fuel pressure vents. The latter feature circular cutouts in the lower wing surface with a backing cavity. Flow-induced cavity resonances can generate excessive tone noise as is depicted in Fig. 3

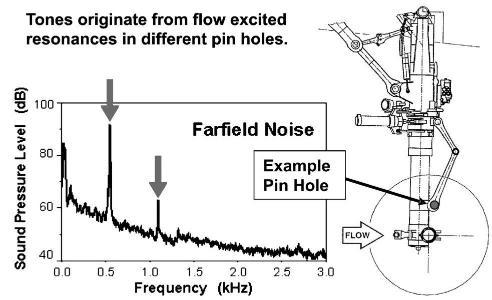


Fig. 2 Example of flow-induced tone noise from open pin holes in landing gear structures.

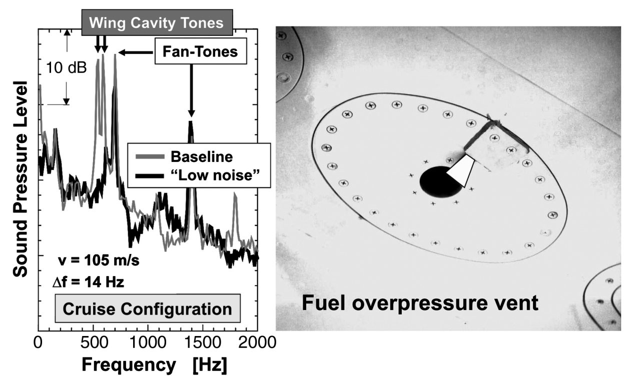


Fig. 3 Example of flow-induced tone noise from fuel vent opening in the lower wing surface from aircraft flyover noise measurements.

based on noise data taken from aircraft flyover measurements [17]. A systematic investigation of this phenomenon revealed that the excitation mechanism, that is, the unsteady shear layer in the cavity orifice, can easily be suppressed through an upstream installed vortex generator (see Fig. 3).

Also, broadband parasitic noise sources were detected from wind-tunnel tests on a full scale A320 wing. Such sources of aerodynamic noise are 1) the cutouts in the wing leading edge to accommodate the slat tracks, and 2) cavities in flap side edges (Fig. 4) [17]. Although the side-edge design could easily be improved, sealing of the slat track cutouts is difficult because in-flight wing bending causes the tracks to move relative to the wing structure and thus, requires some clearance between tracks and wing.

It should be emphasized again that parasitic noise levels can be dominating or at least contribute significantly to the overall airframe noise signature. Because such sources of noise are never reproduced at model scale, it is doubtful how noise prediction tools based on scale model data (or analytical methods) can compare or be validated through aircraft flyover noise test data, unless the test aircraft was subject to dedicated component modifications to suppress parasitic noise contributions.

B. Landing Gear Noise

When airframe noise was identified as a major aircraft noise component in approach scale model wind-tunnel experiments were

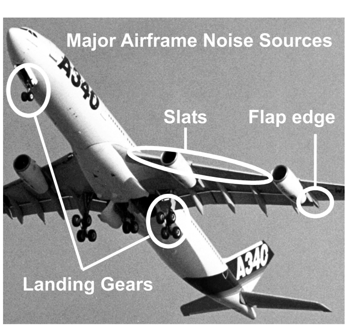


Fig. 1 Major classical airframe noise sources.

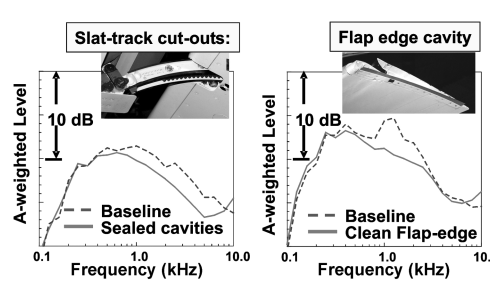


Fig. 4 Parasitic broadband noise sources on high-lift devices.

conducted to quantify landing gear noise characteristics. The generic landing gear models used in these experiments, however, provided misleading results due to the lack of design details. As a consequence, landing gear noise was erroneously considered a low-frequency phenomenon. Only in the 1990s, when large high-quality acoustic wind-tunnel facilities were available, was this error realized, when full-scale landing gears (i.e., original gears) were noise tested in such wind-tunnel facilities [18,19]. It turned out that the spectral maximum of A-weighted noise levels occur in the range between 0.5 to 3 kHz, which corresponds to the most sensitive range of human noise perception. More recently, high-fidelity scale model gears were also wind-tunnel tested and provided good results [20,21] (Fig. 5).

In fact, landing gears feature a vast number of small components attached to the gear main structural components (last but not least the dressings), which in turn are responsible for noise contributions at high frequencies. In contrast, low-frequency noise levels are related to the more bulky gear components, such as tires and large struts. Therefore, a landing gear can be considered a cluster of aerodynamic noise sources due to flow separation from the variety of struts, joints, and dressings exposed to and interacting with the incoming flow.

1. *Noise Source Mechanisms*

Aerodynamic noise from landing gears is essentially broadband in nature, although occasionally distinct narrow band noise components are observed due to coherent periodic vortex shedding off extended struts with smooth circular cross sections for Reynolds numbers below a value of about $5 \cdot 10^5$ (based on strut diameter d), that is, when laminar flow separation prevails. At a typical landing speed of 160 kt ($\approx$82 m/s) this would correspond to strut diameters of less than 100 mm and thus apply to small struts only and hydraulic lines (dressings) in particular. Vortex shedding tones would correspond to a Strouhal number value of $St = f \cdot d/v$ close to 0.2. It should be noted, however, that there is very little experimental evidence that vortex shedding-related tone noise is a major problem for current landing gear architectures.

Broadband noise from flow around landing gear structures is generated by 1) turbulent flow separation off the variety of bluff-body structural components, and 2) the interaction of such turbulent wake flows with downstream located gear elements. The respective underlying noise source mechanisms are essentially identical. The interaction of turbulent flow pressures with solid boundaries cause a small fraction of the turbulence energy to be transformed into propagating sound pressure waves. In the acoustic analogy this noise source mechanism is modeled by acoustic dipoles (compact source). The major parameters that govern this noise generation process are the flow turbulence intensity and the average turbulence eddy length scale, as well as the local mean flow velocity. Regarding the latter, sound intensity increases with flow velocity to the power of 6 (compact source). Also, low-frequency noise components predominantly originate from large gear components (e.g., the tires) and vice versa.

Interaction noise is primarily governed by the velocity of the impinging flow and its turbulence characteristics. Systematic investigation of interaction noise phenomena revealed that the beneficial effect of reduced local inflow velocity, for example, in the turbulent wake of an upstream located component, is more substantial than the adverse effect on noise of increased turbulence intensity. As a result it might be beneficial in certain conditions to deliberately arrange components in line of flow to minimize aerodynamic noise generation [22].

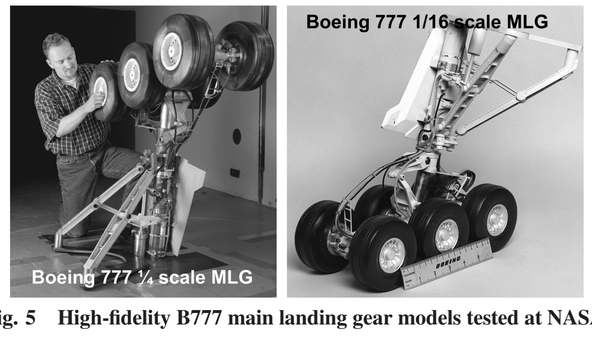


Fig. 5 High-fidelity B777 main landing gear models tested at NASA.

In a complex gear structure both the local turbulence characteristics and the corresponding mean flow velocities are different at each individual gear element. Moreover, the dipole-type radiation directivity, to be associated with each gear element, depends on its geometry and orientation relative to a common and fixed coordinate system. Accordingly, the resulting overall broadband landing gear noise characteristic is very complex and not in reach for an accurate noise prediction based on only global design and operational parameters. It should also be noted that once one gear component is redesigned with regard to its outer shape and/ or position in the gears' structure, the local flow conditions at adjacent gear components, and thus their noise contribution, will change.

Landing gear noise is affected by installation effects. Although the inflow velocity to a nose landing gear (NLG) is almost equal to the flight speed, an under-the-wing installed main landing gear (MLG) experiences a reduced local inflow velocity due to the circulation flow as induced by the wings' lift [23–25]. Because of the strong effect of flow velocity on the noise level, it is imperative to account for this installation effect when comparing test results obtained from an isolated gear attached to a flat plate (zero lift) supporting structure in a wind tunnel with test data from installed gears in-flight. The corresponding level difference can be up to about 5 dB depending on the source distance below the wing and the local lift coefficient of the aircraft wing. Therefore, the transposition of noise data from wind tunnel to flight conditions must account for this installation effect.

The lower wing surface also acts as acoustic reflector. For medium to high frequencies in particular (i.e., wavelength smaller than wing chord), sound reflections cause distortions in the noise level spectra due to acoustic interference effects. Fortunately, however, these distortions are not extremely pronounced because the gear structure represents a geometrically extended cluster of sound sources (with, respectively, different distances to the reflecting wing) such that interferences at correspondingly different frequencies partially smear out [26].

Full-scale landing gear broadband noise spectra and directivities can be derived from far-field noise measurements in aeroacoustic open jet wind tunnels [16,18]. After correction of the test data for both wind-tunnel and moving source effects, noise characteristics are obtained for a stationary landing gear at rest. The reason for this latter procedure is that in this way corrected data can be projected to any flight speed (different from the wind-tunnel test speed) through inversely applying moving source effects to this set of stationary data.

Maximum A-weighted one-third octave band noise levels roughly occur between 0.5 and 3 kHz at typical landing speeds for different sized landing gears of current technology. To allow for an extrapolation of available test results to both different gear sizes and operational conditions beyond the test window, a nondimensional data representation is required. In the first place, this concerns the effect of flow velocity on noise level spectra. The assumption of aeroacoustic dipoles as the dominant noise sources predefines the squared sound pressure p to be proportional to the sixth power of flow velocity v (i.e., $p^2 \propto v^6$). Similarly, the sound frequency f should scale with velocity on a Strouhal number basis, that is, $St = f \cdot s/v$. Herein s stands for a typical source dimension, which, however, cannot easily be defined, because a variety of differently sized gear components contribute to the overall noise signature. The nondimensional representation of landing gear noise data therefore often refers to a unit scale of $s = 1$ m as reference source dimension. A typical result of this data normalization is depicted in Fig. 6 for three different polar radiation angles φ (66 deg: forward arc; 90 deg: overhead; 133 deg: rear arc). For the example test data it turns out that the chosen data normalization (with one-third octave band levels L_m) provides good results for both low and high Strouhal numbers (corresponding to, respectively, low and high one-third octave band frequencies f_m). For the intermediate Strouhal number range some data scatter is observed due to noise level peaks, which occur at constant frequencies independent of the test flow velocity. Similar effects were also observed for other gears tested in the wind tunnel.

The radiation directivity is another important noise characteristic that must be known to predict the corresponding flyover noise impact on the ground. Current wind-tunnel tests were essentially limited to the determination of the polar noise level directivity, that is, in flight direction. Typical radiation directivities for different bands of Strouhal numbers are depicted in Fig. 7 (the ranges of Strouhal numbers within which the levels were integrated, L_{Band}, are indicated in the graphs). Accordingly, for low Strouhal numbers a slight level maximum occurs in the rear arc, and for higher Strouhal numbers a successively pronounced level minimum is obtained for a $\varphi = 90$ deg radiation direction (overhead). This same characteristic was found to be true for all tested gear types with one exception: once a gear is cleaned up from all small-scale add-on structures, which results in a significant high-frequency noise reduction, then an almost omnidirectional characteristic is achieved, independent of Strouhal number.

2. *Prediction Models*

The first empirical landing gear noise prediction model as developed by Fink [7] was based on both flight-test data and simplified generic scale model wind-tunnel test data and turned out to significantly underestimate high-frequency noise levels. Recent efforts in the development of noise prediction schemes, therefore, are based on full-scale noise test results and aim to incorporate maximum knowledge in basic physics, while being acceptable as an engineering tool with limited access to detailed local flowfield information.

The model of Smith and Chow [27] was the first to break down the gear into its major components, compute sound intensities according to the components' dimensions and orientation with respect to an observer location, and at the end sum up the noise intensities from all components to provide the overall sound level spectrum. The estimation of the sound intensity originating from flow around individual components is based on Curle's theory [10], thus assuming dipole-type noise sources, which scale to the sixth power of flow velocity and the square of the source characteristic dimension.

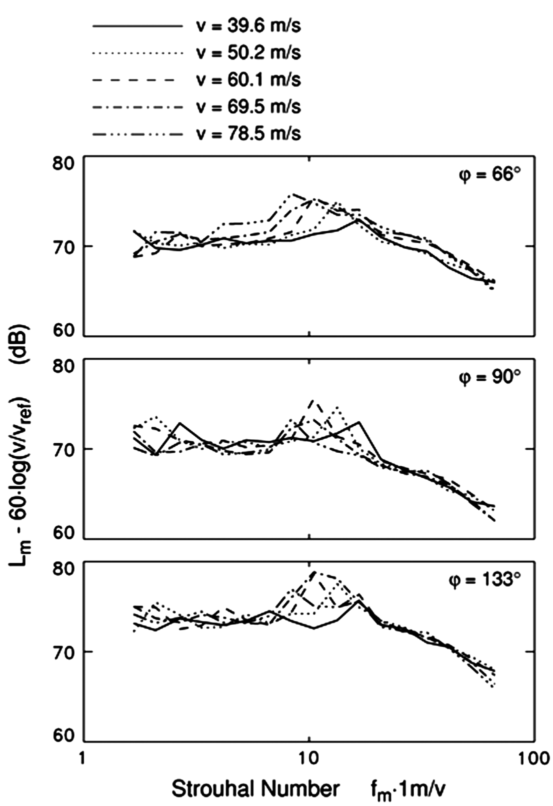


Fig. 6 Nondimensional representation of landing gear noise spectra for different radiation angles.

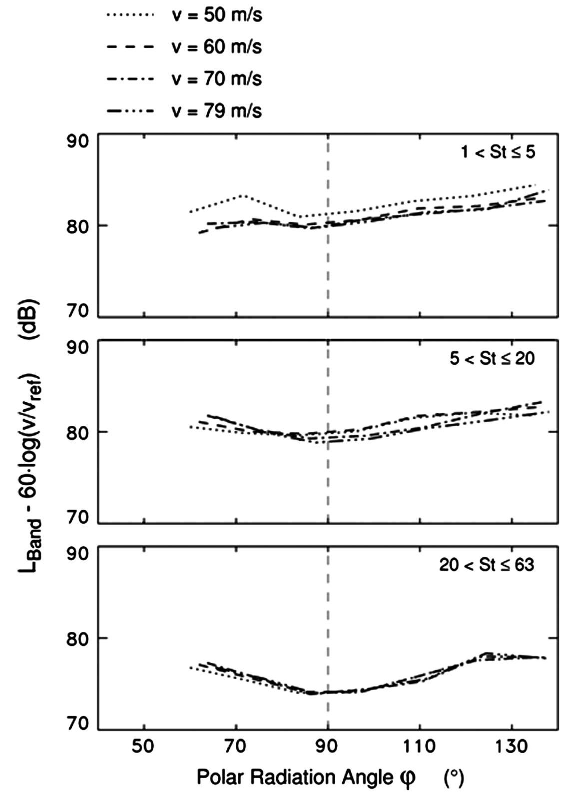


Fig. 7 Nondimensional representation of landing gear noise level directivities for different ranges of Strouhal number.

Of course, this procedure can only consider components of reasonable size (primary structure). The variety of small-scale add-on parts and voids in structural components (secondary structure), which are likely to produce small-scale turbulence and thus high-frequency noise, is accounted for in this prediction scheme in a somewhat cumulative way through a so-called dressing factor to be set by an educated user. Still, this procedure needs to be calibrated against existing test data and thus has no full potential to predict noise for novel unconventional gear architectures. Nevertheless, this tool proved its capability to predict reasonably well the noise reduction potential to be expected from a low-noise redesign of selected gear components [28].

Essentially based on the same theoretical background, similar noise prediction approaches were developed by Guo et al. [29] and Guo [30], validated by both full-scale wind-tunnel and flight-test data. Guo's tool distinguishes between three sets of gear components, i.e., large, medium and small scale elements, responsible for correspondingly low-, medium-, and high-frequency noise contributions, respectively. To account for the effects on noise of small construction details he defines a complexity factor (similar to Smith's dressing factor) that determines the high-frequency noise level spectrum. The Aircraft Noise Prediction Program (ANOPP) of NASA, which originally relied on the Fink method only, now is in an upgrade process by combining the methods from both Fink and Guo to improve the prediction accuracy for sideline radiation directions in particular [31].

Computational methods for landing gear noise prediction could in principle be general, meaning that such methods could be applied to any novel landing gear architecture because they do not need to be calibrated against existing test results. Currently, however, such tools have not yet been applied to complex landing gears with all structural details and results for more generic gear geometries have not yet been validated [32].

3. *Noise Reduction Technologies*

From the knowledge gained through various wind-tunnel experiments, noise reduction concepts either aimed at a reduction of the number and complexity of components exposed to the flow or the reduction of flow separation off bluff-body components and, thus, the ensuing wake/solid body interaction with downstream components. A straightforward noise reduction approach, therefore, would be to cover the whole gear structure with streamlined fairings. This was done in a wind-tunnel study and revealed a basically achievable noise reduction potential of more than 10 dB (Fig. 8). However, such a solution is not practical because there are numerous constraints to be considered ranging from operational and safety aspects to cost issues.

A low-noise gear design, therefore, has to account for the following major constraints. Regarding operation, 1) limitation of runway loads defines number and spacing of wheels, 2) gear locations are defined by lateral aircraft stability and rotation before liftoff, and 3) brake cooling must not be disturbed to minimize the turn around time in the airport. Regarding safety, 1) freefall requirement (main landing gear leg door can not be used as spoiler, 2) mechanical gear downlock (affects main landing gear side-stay design, and 3) tire burst (affects location of dressings and enforces redundancy). Regarding cost (weight and maintenance), 1) effects on airframe (minimum bay size for stowing, 2) potential add-on fairings may not obstruct quick routine inspection, and 3) systems complexity must be as low as possible (avoid articulated components).

The development of noise reduction concepts distinguishes between the application to an existing landing gear or for a future new gear design. In the first case, only add-on fairings could be used to cover complex gear structures, whereas in the latter case the overall gear architecture and the detailed component design could be optimized for low aerodynamic noise generation including the local application of flow control devices.

Streamlined add-on fairings for current gears to protect complex gear structure elements from high-speed inflow have extensively been tested in numerous wind-tunnel experiments [33]. In Fig. 9 examples of such add-on fairings designed for Airbus A340-type landing gears are depicted. An undertray fairing was designed to completely cover the bogie area, including the brakes, from the flow. Wind-tunnel tests indicated a noise reduction potential in the order of 3 dBA for such kinds of fairings. In subsequent flight tests Airbus documented a landing gear source noise reduction of 2 EPNdB (effective perceived noise level).

A similar approach was followed by NASA and Boeing with the toboggan for the six wheel main landing gear of the B777 aircraft. This device was successfully tested both in the wind tunnel and in-flight (see Fig. 9) [20,34,35].

All these tests revealed that add-on fairings can also have an adverse effect, that is, a noise increase due to the flow displacement enforced by a fairing and the corresponding increase in local velocity and, thus, noise from adjacent gear components. Therefore, a partially flow transparent fairing design was considered. The flow resistance should be selected as low as possible (to reduce the displacement effect) but high enough to limit the wake flow velocity.

Accordingly, the next generation of fairings was manufactured from flow transparent materials, such as meshes or elastic cloth

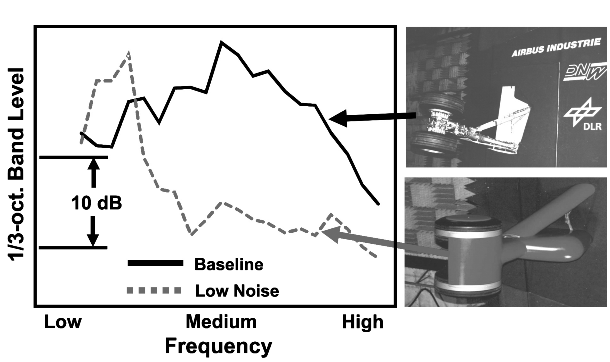


Fig. 8 Basic noise reduction potential from initial full-scale landing gear noise tests.

Fig. 9 Examples of landing gear add-on noise reduction fairings.

[21,36,37]. An example for the latter is depicted in Fig. 10, showing elastic cloth membranes covering the bogie area of this gear, which provided a local (component-based) average noise reduction in the order of 2 dB. Most recently, mesh type fairings were also investigated and provided good noise reduction, though coupled with a high-frequency noise increase. Because this excess noise is generated by the interaction of the flow with the mesh wires, only fine meshes should be applied so that mesh self noise occurs at correspondingly high frequencies that are subject to rapid damping in the atmosphere or even far off the audible frequency range.

The strategy for the development of advanced low-noise landing gears can be based on knowledge gained throughout extensive noise testing of different gear architectures. This process can be supported by the use of semiempirical noise source models and CFD computations with the primary focus on the modification of the noisiest components.

Three-dimensional flowfield calculations help to identify and potentially avoid local flow separations and the impingement of high-speed flow onto critical gear structure elements. The evaluation of such CFD results with respect to the expected effects on aerodynamic noise currently can only be performed on the basis of common understanding of flow noise generation and related experimental experience. Both low-noise NLG and MLG designs were developed by means of such a procedure. For the NLG the major improvements (compared with add-on fairing solutions studied in the European Reduction of Airframe and Installation Noise (RAIN) project [33]) are related to a deployable ramp-type spoiler to protect the upper gear leg area from high-speed inflow and the inverted steering mechanism, that is, locating this complex structure in the bay out of the flow. Such a low-noise design was studied in the European project Significantly Lower Community Exposure to Aircraft Noise (SILENCER) [38] and is depicted in Fig. 11. Also depicted is the corresponding static pressure distribution on the gears' surface and the achieved noise reduction relative to the baseline A340 gear and that achieved with add-on fairings as in RAIN. The SILENCER low-noise MLG design is marked by a telescopic side-stay to replace the original folding side-stay (including the downlock mechanism) and the retraction actuator, and to realize a much smaller and aerodynamically shaped leg door design and avoid the necessity for an additional hinged door. The brakes are protected from high-speed inflow by means of a closure half and the articulation link is eliminated, because the bogie is aligned with the inflow direction. Subsequent noise testing on full-scale gear mockups in the wind tunnel revealed a noise reduction potential in the order of up to 7 dB (A) in the midfrequency range for these advanced gear designs (see Fig. 11) relative to the original A340 gear architectures. The noise reduction was accompanied, however, by some increase in gear weight [21,38].

It is worth noting that a low-noise gear design through an almost complete elimination of structure details provides lower noise levels in the mid and high-frequency range, whereas low-frequency levels occasionally tend to increase and the radiation directivity approaches an almost omnidirectional characteristic.

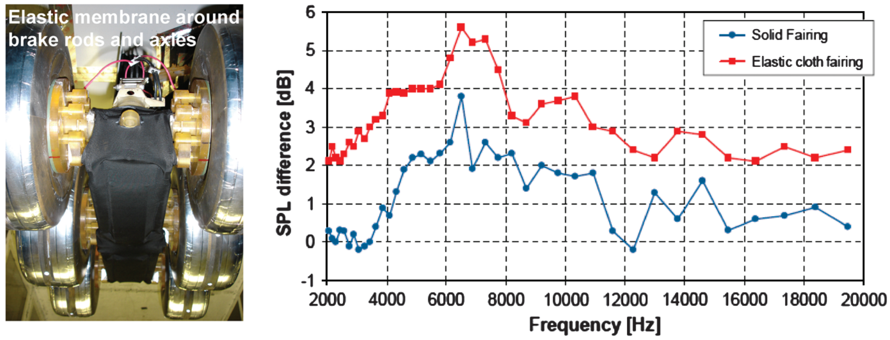


Fig. 10 Example of an elastic cloth-type landing gear fairing [36].

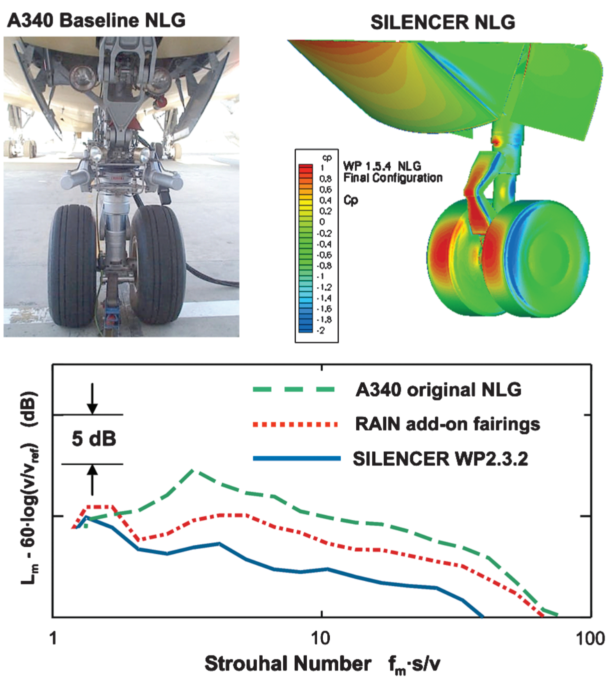


Fig. 11 Advanced low-noise nose landing gear design and achieved noise reduction (with 1/3-octave band level L_m at frequency f_m).

Different from add-on fairings, to more or less completely cover complex structures, flow control might serve in the future to locally reduce flow separation and related unsteady wake shedding off single struts. The application of such means focuses on struts with smooth contours, that is, beams with circular or elliptic rather than H-shaped (inherently noisy) cross sections. Accordingly, flow control is the last member in the development chain toward low-noise landing gears. There are both passive control means (e.g., splitter plates, truncation of cylinders) [39,40] and active means such as blowing and plasma actuation [41,42]. The practical application of such means, however, requires still more basic research and development.

In contrast to simple passive means, active control technologies inherently increase the systems complexity. Therefore, significant noise benefits from such means must be verified before a practical application on an aircraft.

C. High-Lift Device Noise

The high-lift devices, that is, leading-edge slats and trailing-edge flaps, represent the next important sources of aerodynamic noise. Different from landing gears, however, systematic experimental research for high-lift device noise source description and noise reduction on complete wing systems with accurate flow simulation cannot be performed at full scale due to the unavailability of sufficiently large acoustic wind tunnels. In contrast, scale model aircraft or wing configurations (i.e., of scale 1/4 down to 1/11) must be applied. Figure 12 depicts examples of full or semispan aircraft model test setups as realized in the 8 by 6 m open test section of the German–Dutch Wind Tunnel and in the NASA Ames Research Center 40 by 80 ft closed test section wind tunnel. As a result such scale model data suffer from inadequate Reynolds number similarity and not always accurately scaled components (e.g., slat/flap track shape and trailing-edge thickness), which might cause unrealistic tone noise effects.

The development of high-lift device noise reduction technologies still faces another complication. This is the wind-tunnel flow deflection (downwash) inherently coupled to the wing systems' lift. For an accurate aerodynamic simulation, therefore, preference is given to closed test section wind tunnels, whereas acoustic far-field noise directivities can only be acquired in open test section wind tunnels. This dilemma could only be solved by future advanced microphone array techniques (both hardware and software), which would allow to determine quantitatively accurate noise level spectra and directivities in closed hard-wall wind tunnels. Alternatively, advanced CFD methods can be applied to compute the complete open jet wind-tunnel flow with the model installed and, thus, also obtain accurate local flow conditions for correlation with the noise radiation from the high-lift component under consideration.

From complete scale model wind-tunnel tests [43–47] a rank order of different high-lift wing noise sources was derived, that is, slotted slats, slat tracks, slat horn (inboard slat side edge), flap side edges, and flap tracks (Fig. 13). In contrast to flap side edges, slats feature less noise source power per unit area. In terms of their respective total noise contribution, however, flap side-edge noise is less important compared with slat noise because the latter represents an extended line source, the power of which integrates to finally dominate over more intense point sources.

Different from slats and flaps, noise originating from tracks has not yet been accurately quantified. The reason is that both slat and flap track geometries were never accurately reproduced in scale model aircraft. Nevertheless, initial comparative testing of different slat track shapes proved that track noise is an issue for future low-airframe-noise aircraft (Fig. 14).

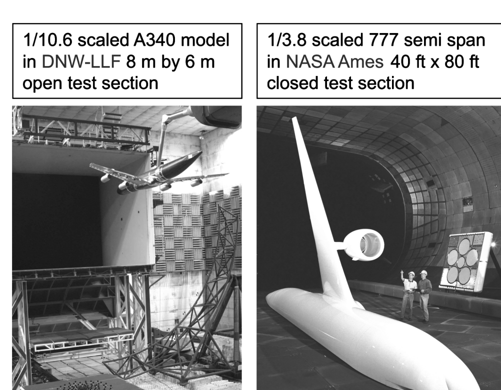


Fig. 12 Examples of scale model aircraft acoustic wind-tunnel tests.

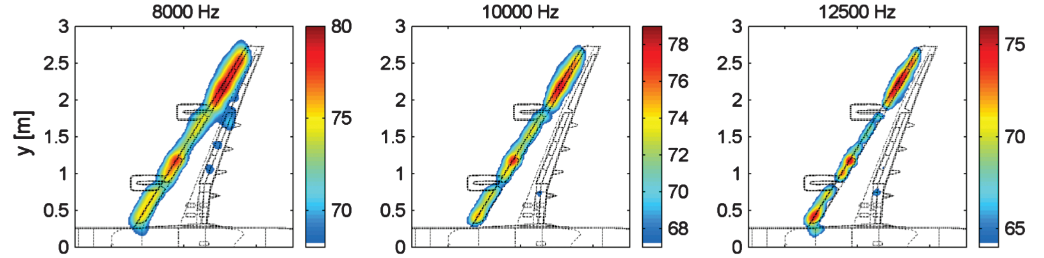


Fig. 13 Typical noise source distribution (dB) on a scale model high-lift wing (unpublished data from the National Aerospace Laboratory (NLR).

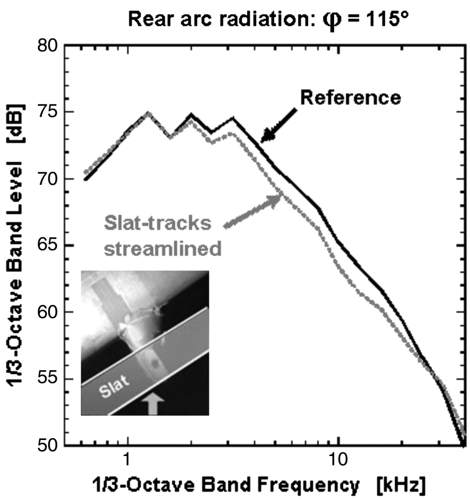


Fig. 14 Ad-hoc slat track modification to prove importance of track noise as tested on a scaled aircraft model.

It is interesting to note that for the same speed a high-lift wing is about 10 dB noisier compared with the same wing in cruise configuration. However, for typical flight operations this level difference is much lower because the typical speed of an aircraft in cruise configuration is higher compared with the speed of an aircraft in high-lift configuration during approach.

The two major noise sources, best accessible to a physical modeling of source mechanisms with support by CFD computations, are slotted slats and flap side edges, which will be looked at in more detail.

1. Noise Source Mechanisms

Tests on complete models in large wind tunnels (as is shown in Fig. 12) are too expensive to be suited for time-consuming basic research into complex noise source mechanisms. Therefore, this type of research is typically conducted on two-dimensional unswept scale model wing sections in smaller acoustic wind-tunnel facilities. This again, however, is associated with another inevitable drawback: unrealistic local flow conditions due to missing crossflow effects for unswept high-lift wings.

The approach to gain insight into the local steady and unsteady slat slot flow conditions was through both CFD computations and corresponding flow measurement techniques (hot-wire and particle image velocimetry, or PIV). Figure 15 depicts a schematic source description and test result from dedicated work at NASA [48]. Accordingly, and this is current understanding, a vortex flow develops in the slat cove driven by the flow through the slat slot. Between this vortex and the undisturbed slot flow a free and, therefore, unstable shear layer develops. It is assumed that the impingement of the vortical shear flow on the downstream cove surface represents one of the slat noise sources, followed by noise that is generated when this unsteady flow is shed off the slat trailing edge. Because the wing leading edge is located in the acoustic nearfield of this trailing-edge noise source it can also be assumed that the wing leading edge reacts as a sound source. The vortex position in the slat cove is not stationary but is slightly oscillating and could, thus, contribute to the low-frequency part of the slat noise spectrum.

Coherent vortex shedding off a blunt slat trailing edge (see Fig. 15) is often observed in two-dimensional scale model experiments and thus was the subject of numerous CFD studies [49]. It should be noted, however, that such tone noise phenomena are not likely to occur (and was never observed) at a real full scale slat because its relative trailing-edge thickness is smaller compared with that realized for most scale model slats. As an example, for a 1/10 scaled slat model a trailing-edge thickness of about 0.1 mm would be required, whereas due to manufacturing and handling constraints the trailing-edge thickness of slat models typically is between 0.2 and 0.5 mm. Therefore, the occurrence of slat trailing-edge bluntness noise in scale model experiments is considered a model artefact.

Still two more model effects were identified from two-dimensional scale model slat experiments in particular, both being a consequence

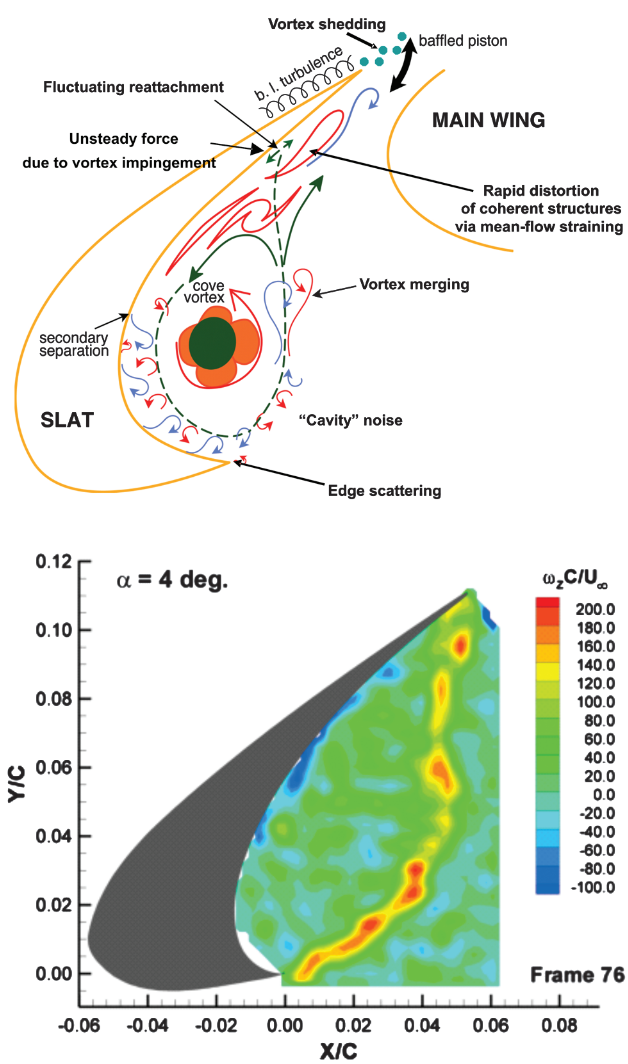


Fig. 15 Schematic of potential slat noise source mechanisms [48].

of too low Reynolds numbers. This is 1) low-frequency tone noise due to coherent laminar flow separation at the slat hook (Fig. 16), and 2) high-frequency tone noise due to Tollmien–Schlichting boundary-layer instabilities on the slat suction side (Fig. 17). For about a 1/10 scaled high-lift model low frequency means between about 1–4 kHz and high frequency between about 10–20 kHz. Experiments with different tripping devices showed that low-frequency tone effects (occurring in a limited range of angles of attack) could be attenuated or even eliminated through massive tripping at the slat hook (see Fig. 16) [44]. This low-frequency tone mechanism is considered to represent a kind of cavity resonance in the slat cove in combination with the adjacent wing leading edge, but it is not yet fully understood. Some researchers found a correlation with Rossiter modes, and others speculate about open cavity resonances (Parker modes) and a potential excitation through trailing-edge vortex shedding. In this context it is interesting to note that no such tone phenomena are reported from comparable studies in the United States. It seems that potential resonance effects are extremely sensitive with respect to slight differences in the slat gap/overlap geometry, which are known to exist between typical high-lift profiles developed in Europe or in the United States, respectively.

In contrast to the low-frequency phenomena, high-frequency tone effects occasionally also occur in three-dimensional models (see Fig. 17), that is, with sweep, and can easily be eliminated through tripping on the slat suction side to enforce transition to turbulent boundary-layer conditions and avoid the formation of a laminar separation bubble.

Yet, the application of any slat tripping is a matter of ongoing debate between aerodynamicists and acousticians. Whereas the acousticians aim at the determination of broadband slat noise without a deterioration of the result through unrealistic tone contributions, the aerodynamicists fear a corruption of flow conditions and thus the related high-lift performance.

With the exception of these tone noise artifacts, slat noise is broadband in nature with highest levels at Strouhal numbers around 2, when the slat chord is taken as the relevant source dimension in default of a value representing the physics of the complex combination of different noise-generating mechanisms. Figure 18 depicts correspondingly normalized slat noise spectra from test results obtained for a 1/7.5 scaled A320 model and a full-scale A320 wing (with all construction irregularities covered from the flow) partially immersed in the wind-tunnel core flow [50]. Respective measured noise data provide the best fit when scaled on the 4.5th power of flow velocity, which is close to the theoretically obtained fifth power law for trailing-edge noise and also accounting for the source dimension, that is, the wetted slat span (SF in Fig. 18). The slat noise directivity shows maximum levels in rear arc direction and levels decrease slightly with increasing aircraft angle of attack. This latter finding, however, is only valid for low and moderate values of angle of attack (typical for landing conditions), whereas for higher angles a rapid and massive level increase is observed (Fig. 19).

Flap side-edge noise represents the next important contribution to airframe noise from high-lift systems and is of particular interest for aircraft without slotted slats (e.g., some regional aircraft). Numerous investigators have performed CFD computations and detailed experimental flow surveys to characterize the complex three-dimensional vortex structure that develops at flap sides edges [51,52]. One example is depicted in Fig. 20 showing a primary vortex developing from the flap pressure side close to the flap leading edge. A secondary vortex then evolves from the edge toward the flap

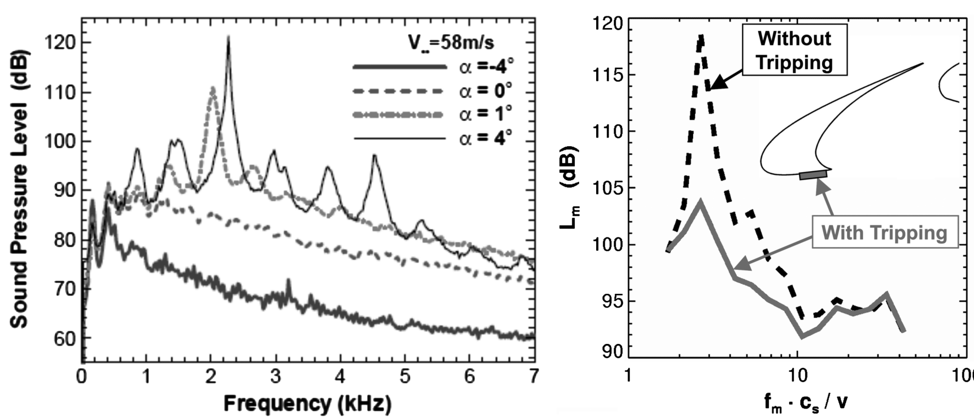


Fig. 16 Application of slat hook tripping on two-dimensional scale model high-lift wings to attenuate low-frequency tone noise phenomena (with 1/3-octave band noise level L_m, corresponding frequency f_m, and slat chord c_s).

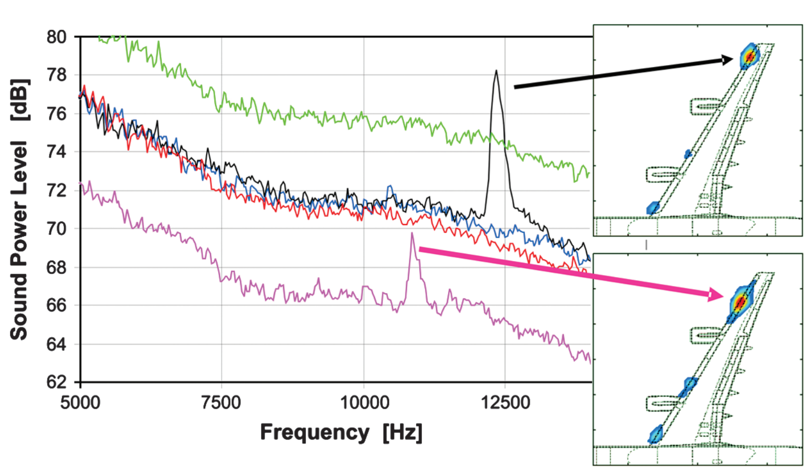


Fig. 17 Application of slat suction side tripping on scale model high-lift wings to avoid high-frequency tone noise from boundary-layer flow instabilities (unpublished data from NLR).

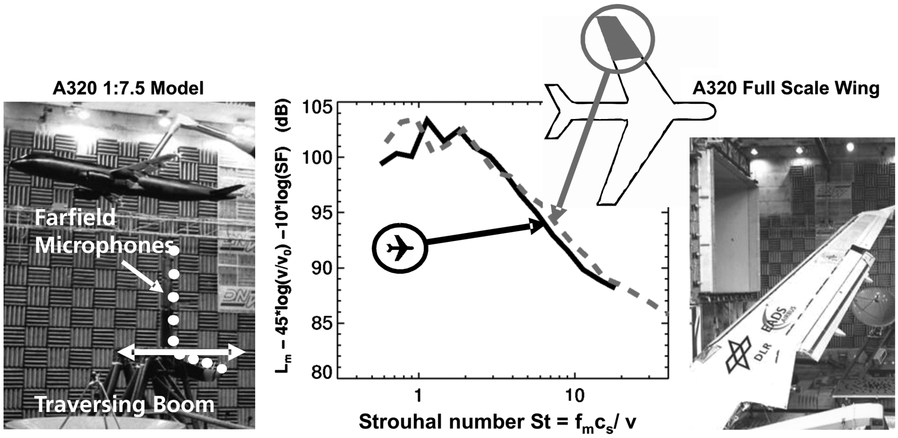


Fig. 18 Nondimensional representation of slat noise spectra (with 1/3-octave band noise level L_m, corresponding frequency f_m, and slat chord c_s).

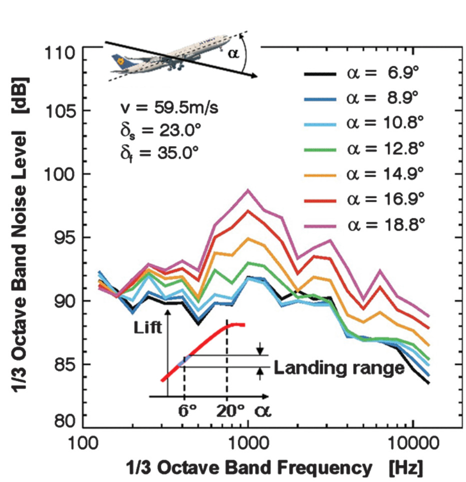


Fig. 19 Effect of angle of attack on noise from high-lift wings (scale model test results).

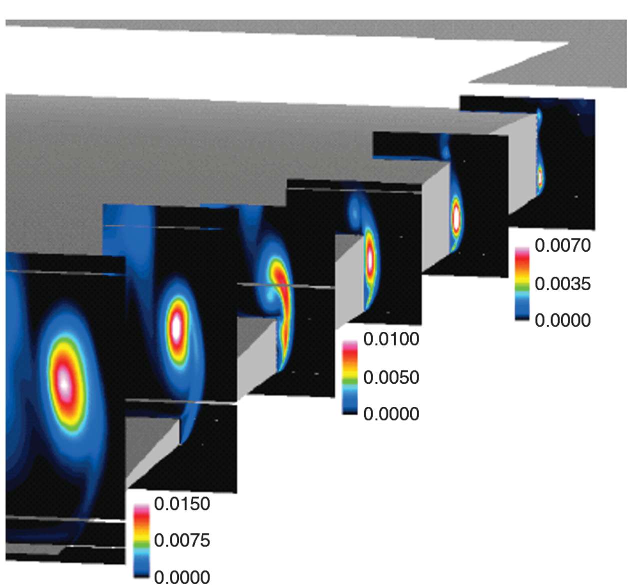


Fig. 20 Three-dimensional flap side-edge vortex flow structure from CFD computations [51].

suction side. Both vortices merge and finally separate from the flap suction side surface. The location of this separation process depends on the flap deflection angle (among other parameters) but can typically be detected around a 70% flap chord position. Flap side-edge noise, therefore, is assumed to be a composition of the classical trailing-edge noise source mechanism, noise from the interaction of the vortex flow with the flap upper surface and noise originating from accelerated free turbulence in the vortex flow. Broadband flap side-edge noise scales on a Strouhal number basis and levels increase with flow velocity corresponding to a fifth power law. The radiation directivity is found to be quite complex and frequency dependent [53]. According to [54], one of the major noise parameters is the edge directed crossflow velocity on the flap pressure side.

2. *Prediction Models*

Again, the first empirical high-lift noise prediction model was that developed by Fink [7] based on flight test data from a variety of different aircraft. Accordingly, the somewhat statistical analysis of this data could only aim at a correlation of noise levels with global wing design parameters. One major pitfall was that slat noise could only be accounted for by a broadening of the spectrum toward higher frequencies combined with a level increase by 3 dB relative to clean wing trailing-edge noise.

Although some aircraft manufacturers still apply this model with reasonable success, the major aircraft manufacturers developed their own prediction codes based on more detailed physical knowledge obtained over the years. Typically such codes are company confidential or the distribution is limited to partners in dedicated research projects, and only general descriptions are published in the open literature [23,55–57].

It should be mentioned that the need for high-lift device noise prediction codes is twofold. For the development of noise abatement flight procedures, noise source models are needed that do not require excessive computer power. Therefore, semiempirical tools are needed to describe the noise characteristics of the engine and, preferentially, all airframe noise components individually, depending on the aircraft configuration (e.g., high-lift devices setting) and operational conditions [58]. For this application a high-prediction accuracy is not required, because either only level differences are of interest or integral noise levels are computed to assess the overall noise impact in the vicinity of an airport.

In contrast, high-fidelity methods are needed for a high-lift components' design for noise approach. Such capabilities are offered by advanced CFD tools (e.g., large eddy simulation, or LES) in combination with computational aeroacoustics' tools (CAA), the latter being in the process of development since the late 1990s. Such tools must incorporate the description of the noise source terms, that is, local turbulence spectra and length scales, and the sound propagation through inhomogeneous flowfields in the presence of complex three-dimensional solid boundaries. Various codes are under development and validation worldwide, for example for two-dimensional high-lift device applications. One essential feature of such methods is the adopted philosophy for source description. Through a LES the turbulence source terms can accurately be determined, but the computations are excessively time-consuming and thus not applicable for a low-noise development in an industrial development process. A more convenient approach is the random particle mesh (RPM) method [59], to just cite one example. This method (Fig. 21) is based on a Reynolds-averaged Navier–Stokes (RANS) flow solution to obtain the local mean flow features in the noise source area under consideration including the integral turbulence kinetic energy and the corresponding turbulence length scales. Based on this input the turbulence spectrum is reanimated through a stochastic model, thus providing the turbulence source terms to be fed into a CAA code to compute the far-field noise signature. This method proved to be accurate enough for the determination of (at least) noise level differences, for example, variations in component geometry, and is several orders of magnitude faster compared with a LES computation.

3. *Noise Reduction Technologies*

As for landing gears, the development of low-noise high-lift devices must account for a variety of constraints with the additional and mandatory requirement to not degrade the devices' aerodynamic performance. The latter, in fact, turned out to be a show stopper for many ideas brought forward for slat noise reduction. The major problem is a certification requirement that links the maximum lift coefficient to the minimum landing speed (linearly related to the stall speed). As an example, if the maximum lift coefficient is reduced by 10% through a noise reduction modification, the landing speed must increase by about 5.4%, which results in a 1.4 dB increase in overall airframe noise and thus can compromise a previously achieved benefit in source noise reduction.

In summary, the following constraints must be considered within a low-noise high-lift device design. Regarding operation: 1) maintenance of maximum lift, and 2) provision of sufficient lift for moderate angles of attack (prevent tail-strike for takeoff). Regarding safety: 1) reliability (malfunctioning of low-noise treatments must not affect the aircraft performance), and 2) handling quality (no sudden changes in lift/moments with activation of control devices). Finally, regarding cost: 1) weight, 2) structural constraints (e.g., slat tracks should not affect front spar design), and 3) system complexity and maintenance.

When detailed research into noise reduction for slotted slats, as one major noise contributor, started around 1995, the first ideas focused on add-on devices and were based on the current knowledge of unsteady flow characteristics in the slat cove/slot area. Consistently a slat cove cover was designed to attenuate the strength of the vorticity in the free shear layer between the cove vortex and the slot flow [47], that is, a reduction of the actual source quantity. Such a device was tested on a three-dimensional scale model aircraft in the wind tunnel and indeed showed a promising broadband noise reduction (Fig. 22). However, the application of a rigid cover is not easily implemented on an aircraft, because a fixed cover shape is only optimal for one selected angle of attack, and the cover must not prevent the retraction of the slat for cruise flight. A similar but more realistic approach is an extended seal attached to the slat hook [60] as is shown in Fig. 23. Again, a meaningful noise reduction potential was detected and finally triggered the idea to completely fill the slat cove through a streamlined body. Such slat cove fillers were designed and tested at NASA, European Aeronautic Defense and Space Company, and the Japan Aerospace Exploration Agency [61–63], and provided a significant noise reduction potential for the design point (Fig. 24). It should be emphasized that the noise reduction result shown in Fig. 22 (for the slat cove cover) pertains to the complete aircraft far-field high-lift noise signature, and the more pronounced noise reductions shown in Figs. 23 and 24 were acquired through microphone arrays, thus providing the reduction on slat source noise level.

Regarding the application of a slat cove filler, it was noted that the filler's outer contour is an extremely sensitive parameter and a cove filler can as well cause a noise increase for angles of attack, which only slightly deviate from the design point. This behavior makes such devices not the first choice for practical aircraft applications.

Other noise reduction means aimed to alleviate the transformation of boundary-layer flow turbulence into propagating sound waves at the slat trailing edge through flow transparent edge replacements, for example, perforated/foam material or brushes. The latter, in fact, turned out to represent an extremely effective device for trailing-edge noise reduction (Fig. 25) [64,65]. However, the appropriate brush design and installation must be carefully chosen to not degrade the high-lift performance, and the airworthiness of such materials must be proven through dedicated studies.

Slat cove and wing leading-edge liners were also considered [66]. In contrast to cove fillers and trailing-edge modifications, liners do not affect the source mechanisms in the first place but aim at the attenuation of sound waves on their propagation path between the slat cove and the wing leading edge. Recent experimental studies on wing leading-edge liners indeed provided some meaningful noise reduction.

Because all these technologies did not really provide a breakthrough in terms of noise reduction, but rather were accompanied by either some degradation in high-lift performance or were not

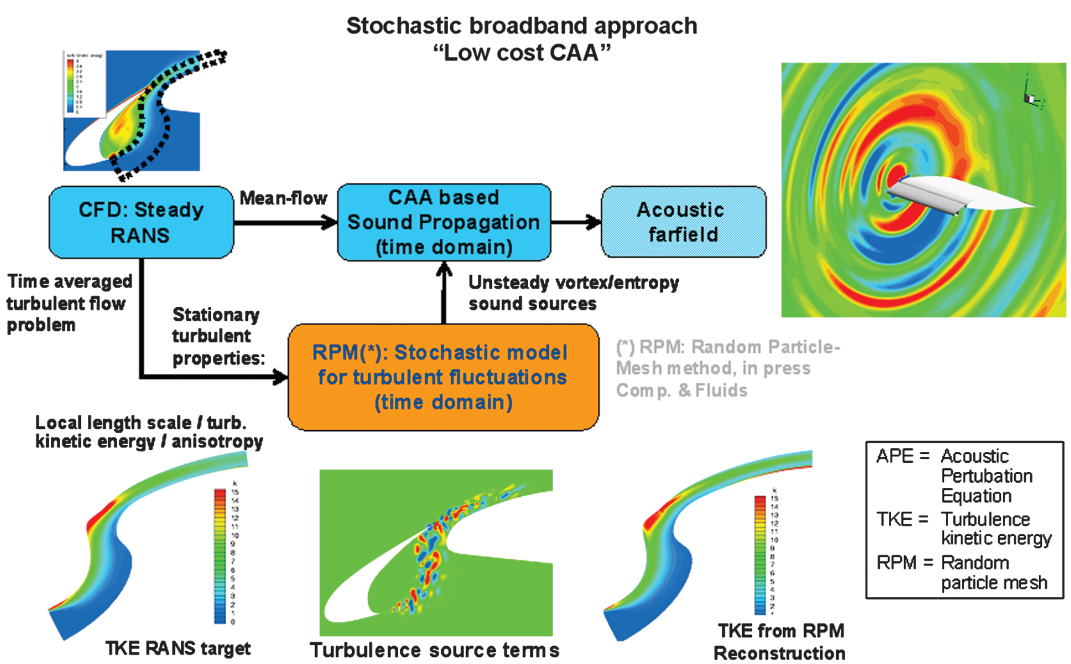


Fig. 21 Low-cost CAA using a stochastic approach for turbulence simulation.

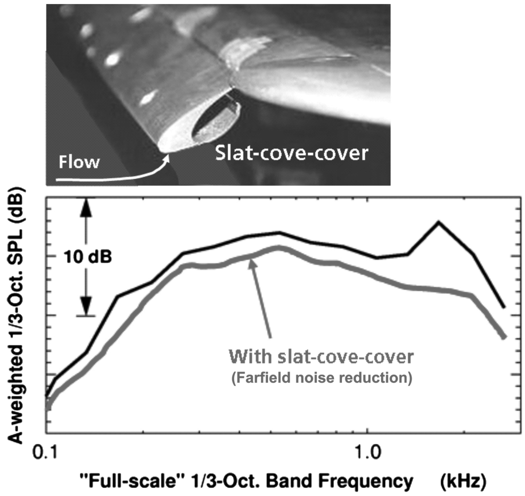


Fig. 22 Far-field high-lift noise reduction potential of a slat cover from tests on a scale model aircraft (transposed to full-scale conditions).

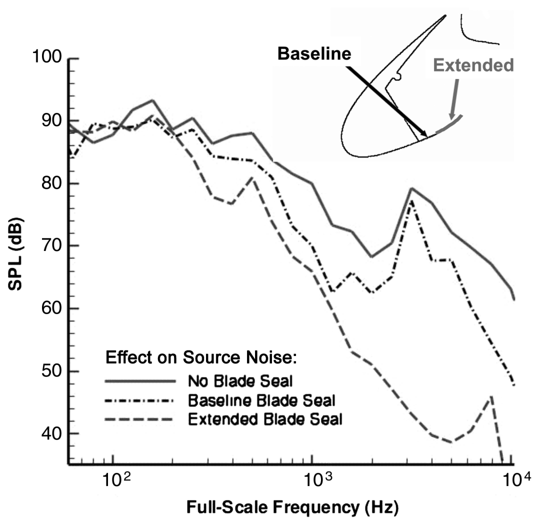


Fig. 23 Slat source noise reduction potential of an extended slat hook seal from wind-tunnel tests on a scaled aircraft half-model [60].

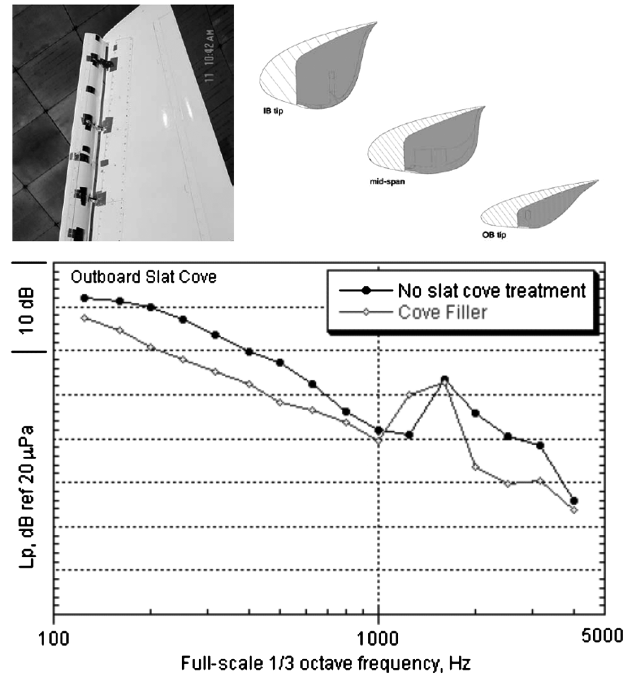


Fig. 24 Slat source noise reduction potential of a slat cove filler from wind-tunnel tests on a scaled aircraft half-model [61].

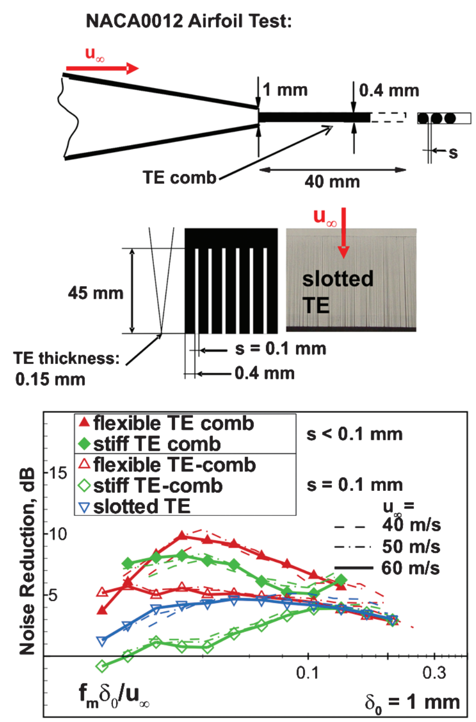


Fig. 25 Trailing-edge noise reduction through brush-type edge extensions.

practical for aircraft application, the noise reduction potential of a balanced aerodynamic and acoustic design of both slat shape and setting was envisaged and indeed showed a marked noise reduction potential. As one example, Fig. 26 depicts the lift polars for a conventional three-element high-lift system (denoted reference in the figure) in comparison with the polar measured for an advanced three-element system with a so-called very long chord slat (VLCS) [67]. According to Fig. 26 the VLCS device achieves a higher maximum lift coefficient. At the same time slat noise is reduced be about 4 dB for the VLCS for the identical lift force (Fig. 27), achieved at a slightly different angle of attack. It should be emphasized that such solutions can only be developed with reasonable effort through the application of validated CFD and CAA tools, and corresponding experimental investigations would be both extremely time-consuming and costly.

Because flap side edges represent the next important sources of high-lift devices' noise, almost in parallel to research into slat noise reduction technologies efforts were undertaken to develop means for side-edge noise reduction. Corresponding edge modifications comprised both add-on side-edge fences and flow transparent edge replacements, for example, porous metal foam or brushes (Fig. 28) [47,64,68–70]. The latter proved to be very effective but still suffer from the practical problem that no such material has yet been approved for aircraft applications. Aerodynamic tests with either side-edge fences or a flow transparent edge design showed that the side-edge vortex diameter is increased and shifted outboard (for constant overall vortex strength), which is assumed to be the reason for the observed noise reduction. A still more drastic approach is the elimination of the edge through the so-called moldline technology (Fig. 29) [71,72], providing a significant noise reduction potential. Here the former single edge vortex breaks up into a spanwise distribution of weaker vortices due to a more continuous spanwise variation of the wings' circulation. The practical application of this solution, however, would require quite complex flap structures and articulation mechanisms.

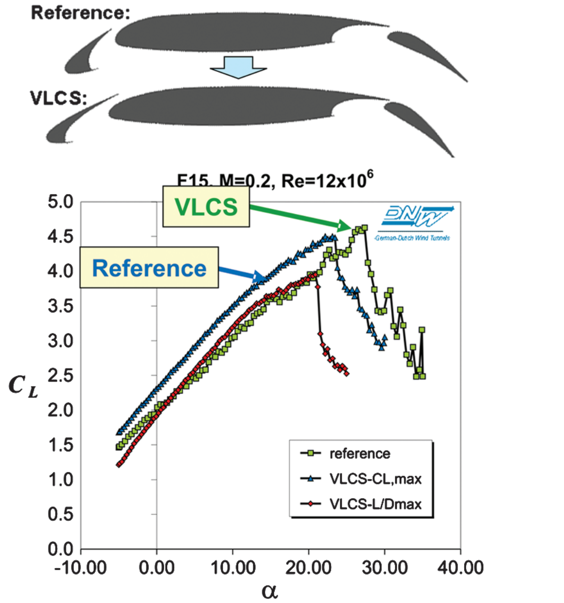


Fig. 26 Comparison of lift polars for a conventional three-element high-lift system (reference) and one with a very long chord slat (VLCS-CL, max). Note that the VLCS-L/Dmax polar is valid for reduced takeoff slat and flap setting.

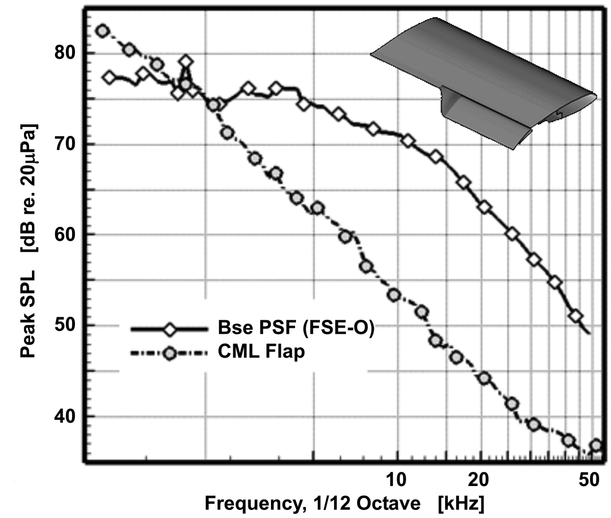


Fig. 29 Outboard flap side-edge (FSE-O) source noise reduction through moldline technology (continuous moldline flap) from scale model experiments [71].

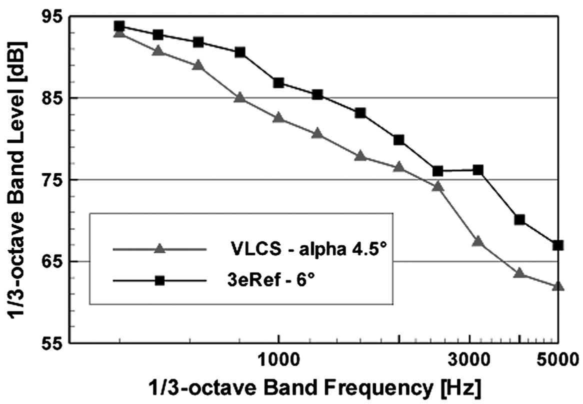


Fig. 27 Slat noise reduction as achieved with the advanced VLCS high-lift system relative to a conventional three-element device for the same lift force.

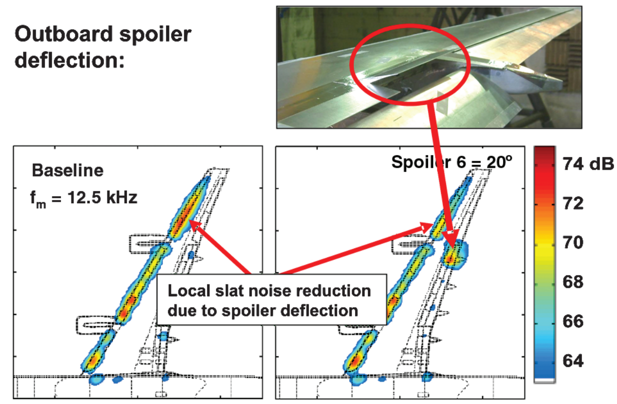


Fig. 30 Example of the effect of spoiler deflection on the noise source distribution on a scale model high-lift wing (unpublished data from NLR).

Somewhat similar to the flap side-edge noise problem is that to be associated with spoilers (airbrakes). The potential application of airbrakes to enable or enhance the aircrafts' capability to perform low-noise steep continuous descent approaches (and also contribute to alleviate the wake vortex problem) requires a low-noise design of airbrakes. However, there is very little data available to date to quantify and characterize spoiler noise, and the knowledge in the relevant noise mechanisms is also quite limited. The latter might be extremely complex regarding the effect of a deflected spoiler on the wing aerodynamics and thus on slat noise. This interdependence was revealed from a dedicated experiment on a scaled aircraft model in the wind tunnel [73]. It turned out that excess spoiler self noise is primarily a low-frequency phenomenon. But it was also observed that a deflected spoiler can reduce slat noise through its local effect on the corresponding wing sections' lift (Fig. 30).

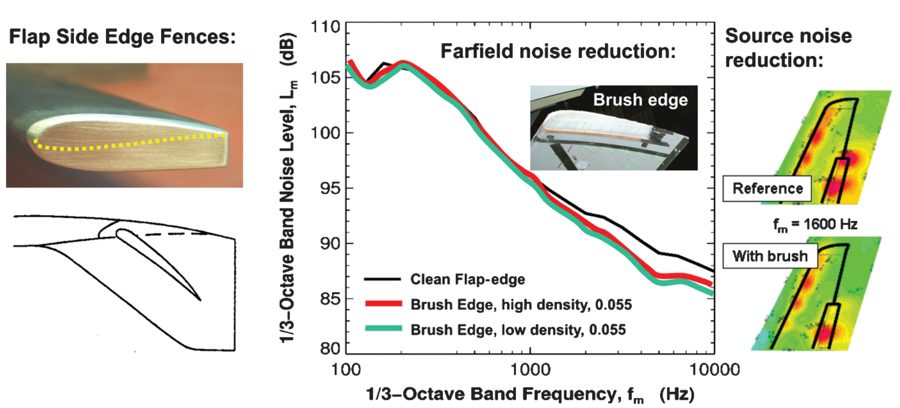


Fig. 28 Flap side-edge fences and porous-edge or brush-type edge replacements for side-edge noise reduction.

Last but not least, interaction noise originating from a deployed flap when exposed to the turbulent wake of an upstream installed landing gear must be considered. An experimental investigation of this phenomenon [74] revealed the generation of low-frequency excess noise at the flap leading edge, which could be reduced by locally applied inserts of absorbing porous material in the leading-edge area.

IV. Conclusions

Low-noise levels of modern high-bypass ratio aeroengines cause airframe noise to now represent one of the dominating aircraft noise components during approach and landing. Therefore, efforts were directed toward a significant reduction of airframe noise to cope with the challenging aircraft noise reduction visions of minus 10 dB for the year 2020. Landing gears represent the dominating sources of airframe noise for large commercial aircraft, and noise from landing gears and high-lift devices are of almost equal importance for single-aisle and regional aircraft.

Much progress was made in the last decades regarding enhanced capabilities of both aeroacoustic measurement techniques and computational tools (CFD and CAA), which led to a more detailed insight in a variety of airframe noise source mechanisms without, however, providing final answers on the relevant dependences of noise on local three-dimensional steady and unsteady flow and geometrical parameters. Such information would be needed by engineers to develop low-noise airframe components. Because noise originating from most of the relevant airframe components can be considered to represent a composition of different and interacting source mechanisms, it seems unlikely that one could pick individual local geometric and flow parameters and combine them in an engineering design tool. Therefore, it is inevitable to make all efforts to further the development and validation of three-dimensional CAA tools applicable in an industrial design process.

Experimental work dedicated to the development of landing gear noise reduction technologies has been quite successful thus far. Essentially based on long-standing experience in aeroacoustics, engineers came up with add-on noise reduction solutions and a low-noise gear component design, which finally provided a noise reduction potential of up to about 5 EPNdB on landing gear source noise level (i.e., ignoring the contribution of all other aircraft noise sources) relative to the year 2000 technology. Such low-noise landing gears typically are equipped with numerous fairings to protect complex gear structures from high-speed inflow and thus, obstruct maintenance procedures and increase the gears' weight and system complexity. Therefore, further efforts are necessary to eliminate these drawbacks and still increase the currently achieved noise reduction potential.

Similar research endeavors were undertaken to reduce noise originating from high-lift devices. However, most of the developed noise reduction technologies either led to a degradation of the high-lift performance or can not readily be applied to aircraft structures. The latter is true for flow transparent, porous material trailing- or side-edge replacements, whereas adverse effects on lift performance were observed for various slat modifications. Still, a significant noise reduction potential was identified for a balanced aerodynamic and acoustic optimization of slat shape and setting without major lift penalties for new high-lift devices' designs. The current achievements for add-on noise reduction technologies is still limited to about 1 EPNdB on high-lift device source noise level relative to the year 2000 technology. Therefore, further efforts must aim at the airworthiness certification of flow transparent materials for both flap side-edge and slat trailing-edge add-on solutions.

To cope with the −10dB noise reduction goals for the year 2020, efforts in landing gear noise reduction must be directed toward the development of fuselage-mounted short, and thus quieter, landing gears, which of course necessitates engine installations either at the rear fuselage or over the wing and corresponding changes of the airframe structure. Low-noise high-lift devices might benefit from flow control technologies to avoid slotted slat configurations. At that stage it will be imperative to also develop low-noise slat and flap tracks as well as low-noise airbrakes. The latter might be necessary to produce low-noise drag for noise abatement steep continuous descent approaches.

Accurate noise prediction tools are a prerequisite to design and assess the potential noise benefits as expected from new aircraft configurations. The aircraft design should aim at a reduced approach speed, and the gear's drag should be minimized. The latter would allow for a lower engine thrust setting on the final glide slope and in turn would also contribute to engine noise reduction.

References

[1] Busquin, M. A., "European Aeronautics: A Vision for 2020, Meeting Society's Needs and Winning Global Leadership," Rept. of the Group of Personalities, KI-34-01-827-EN-C, Advisory Council for Aeronautics Research in Europe, Office for Official Publications of the European Communities, Luxembourg, Jan. 2001.

[2] Gibson, J. S., "The Ultimate Noise Barrier: Far Field Radiated Aerodynamic Noise," *Inter-Noise 72 Proceedings*, Washington, D.C., 1972, pp 332–337.

[3] Healy, G. J., "Measurement and Analysis of Aircraft Far Field Aerodynamic Noise," NASA CR-2377, 1974.

[4] Gibson, J. S., "Non-Engine Aerodynamic Noise Investigation of a Large Aircraft," NASA CR-2378, 1974.

[5] Revell, J. D., "The Calculation of Aerodynamic Noise generated by Large Aircraft at Landing Approach," *Journal of the Acoustical Society of America*, Vol. 55, 1974, p. 73.

[6] Fethney, P., "An Experimental Study of Airframe Self-Noise," Royal Aircraft Establishment, Rept. AERO1623, 1975.

[7] Fink, M. R., "Airframe Noise Prediction Method," Federal Aviation Administration RD-77-29, 1977.

[8] Heller, H., and Dobrzynski, W., "Sound Radiation from Aircraft Wheel-Well/Landing-Gear Configurations," *Journal of Aircraft*, Vol. 14, No. 8, 1977, pp. 768–774.
doi:10.2514/3.58851

[9] Lighthill, M. J., "On Sound Generated Aerodynamically. I. General Theory," *Proceedings of the Royal Society of London, Series A: Mathematical and Physical Sciences*, Vol. 211, No 1107, 1952, pp. 564–587.

[10] Curle, N., "The Influence of Solid Boundaries Upon Aerodynamic Sound," *Proceedings of the Royal Society of London, Series A: Mathematical and Physical Sciences*, Vol. 231, No 1187, 1955, pp. 505–514.

[11] Ffowcs Williams, J. E., and Hall, L. H., "Aerodynamic Sound Generation by Turbulent Flow in the Vicinity of a Scattering Half-Plane," *Journal of Fluid Mechanics*, Vol. 40, No. 4, 1970, pp. 657–670.
doi:10.1017/S0022112070000368

[12] Bohn, A., "Edge Noise Attenuation by Porous-Edge Extensions," AIAA Paper 1976-80, Jan. 1976.

[13] Grosche, F., "A Body for Location in a Fluid," United Kingdom Patent No. 1541108, June 1975.

[14] Fink, M. R., and Bailey, D. A., "Model Tests of Airframe Noise Reduction Concepts," AIAA Paper 1980-0979, June 1980.

[15] Revell, J. D., Kuntz, H. L., Balena, F. J., Horne, C., Storms, B. L., and Dougherty, R. P., "Trailing-Edge Flap Noise Reduction by Porous Acoustic Treatment," AIAA/Confederation of European Aerospace Societies Paper 1997-1646, May 1997.

[16] Dobrzynski, W., Chow, L. C., Guion, P., and Shiells, D., "A European Study on Landing Gear Airframe Noise Sources," AIAA/Confederation of European Aerospace Societies Paper 2000-1971, June 2000.

[17] Pott-Pollenske, M., Dobrzynski, W., Buchholz, H., Gehlhar, B., and Walle, F., "Validation of a Semiempirical Airframe Noise Prediction Method Through Dedicated A319 Flyover Noise Measurements," AIAA Paper 2002-2470, June 2002.

[18] Dobrzynski, W., and Buchholz, H., "Full-Scale Noise Testing on Airbus Landing Gears in the German–Dutch Wind Tunnel," AIAA/Confederation of European Aerospace Societies Paper 1997-1597, May 1997.

[19] Stoker, R. W., "Landing Gear Noise Test Report," NASA Rept. NAS1-97040, 1997.

[20] Ravetta, P. A., Burdisso, R. A., and Ng, W. F., "Wind Tunnel Aeroacoustic Measurements of a 26% Scale 777 Main Landing Gear Model," AIAA/Confederation of European Aerospace Societies Paper 2004-2885, May 2004.

[21] Smith, M. G., Fenech, B., Chow, L. C., Molin, N., Dobrzynski, W., and Seror, C., "Control of Noise Sources on Aircraft Landing Gear Bogies," AIAA/Confederation of European Aerospace Societies

Paper 2006-2626, May 2006.

[22] Dobrzynski, W., Pott-Pollenske, M., Schöning, B., and Foot, D., "Landing Gears Aerodynamic Interaction Noise," ECCOMAS Conference Proceedings on CD-ROM, July 2004.

[23] Pott-Pollenske, M., Dobrzynski, W., Buchholz, H., Guérin, S., Saueressig, G., and Finke, U., "Airframe Noise Characteristics from Flyover Measurements and Predictions,"AIAA/Confederation of European Aerospace Societies Paper 2006-2567, May 2006.

[24] Smith, M. G., Chow, L. C., Molin, N., Piet, J. F., and Carrilho, J., "Landing Gear Noise with Installation Effects," AIAA/Confederation of European Aerospace Societies Paper 2007-3472, May 2007.

[25] Guo, Y. P., "A Study on Local Flow Variations for Landing Gear Noise Research," AIAA/Confederation of European Aerospace Societies Paper 2008-2915, May 2008.

[26] Carrilho, J. A. D., and Smith, M. G., "Scattering of Landing Gear Noise by a Wing," AIAA/Confederation of European Aerospace Societies Paper 2008-2965, May 2008.

[27] Smith, M. G., and Chow, L. C., "Validation of a Prediction Model for Aerodynamic Noise from Aircraft Landing Gears," AIAA/Confederation of European Aerospace Societies Paper 2002-2581, June 2002.

[28] Molin, N., Piet, J. F., Chow, L. C., Smith, M. G., Dobrzynski, W., and Seror, C., "Prediction of Low Noise Aircraft Landing Gears and Comparison with Test Results," AIAA/Confederation of European Aerospace Societies Paper 2006-2623, May 2006.

[29] Guo, Y. P., Yamamoto, K. J., and Stocker, R. W., "An Empirical Model for Landing Gear Noise Prediction," AIAA/Confederation of European Aerospace Societies Paper 2004-2888, May 2004.

[30] Guo, Y. P., "A Semi-Empirical Model for Aircraft Landing Gear Noise Prediction," AIAA/Confederation of European Aerospace Societies Paper 2006-2627, May 2006.

[31] Burley, C. L., Brooks, T. F., Humphreys, W. M., Jr., and Rawls, J. W., Jr., "ANOPP Landing Gear Noise Prediction Comparisons to Model-Scale Data," AIAA/Confederation of European Aerospace Societies Paper 2007-3459, May 2007.

[32] Lockard, D. P., Khorrami, M. R., and Li, F., "Aeroacoustic Analysis of a Simplified Landing Gear," AIAA/Confederation of European Aerospace Societies Paper 2004-2887, May 2004.

[33] Dobrzynski, W., Chow, L. C., Guion, P., and Shiells, D., "Research into Landing Gear Airframe Noise Reduction," AIAA/Confederation of European Aerospace Societies Paper 2002-2409, June 2002.

[34] Abeysinghe, A., Whitmire, J., Nesthus, D., Moe, J., Vista, C., and Stuczynski, G., "QTD 2 (Quiet Technology Demonstrator) Main Landing Gear Noise Reduction Fairing Design and Analysis," AIAA/Confederation of European Aerospace Societies Paper 2007-3456, May 2007.

[35] Remillieux, M. C., Camargo, H. E., Ravetta, P. A., Burdisso, R. A., and Ng, W. F., "Noise Reduction of a Model-Scale Landing Gear Measured in the Virginia Tech Aeroacoustic Wind Tunnel," AIAA/Confederation of European Aerospace Societies Paper 2008-2818, May 2008.

[36] Ravetta, P. A., Burdisso, R. A., and Ng, W. F., "Noise Control of Landing Gears Using Elastic Membrane-Based Fairings," AIAA/Confederation of European Aerospace Societies Paper 2007-3466, May 2007.

[37] Boorsma, K., Zhang, X., and Molin, N., "Perforated Fairings for Landing Gear Noise," AIAA/Confederation of European Aerospace Societies Paper 2008-2961, May 2008.

[38] Dobrzynski, W., Schöning, B., Chow, L. C., Wood, C., Smith, M., and Seror, C., "Design and Testing of Low Noise Landing Gears," *International Journal of Aeroacoustics*, Vol. 5, No. 3, 2006, pp. 233–262.

[39] Spiteri, M., Zhang, X., Molin, N., and Chow, L. C., "The Use of a Fairing and Split Plate for Bluff Body Noise Control," AIAA/Confederation of European Aerospace Societies Paper 2008-2817, May 2008.

[40] Kopiev, V. F., Zaitsev, M. Y., and Ostrikov, N. N., "New Noise Source Mechanism of Flow/Surface Interaction as Applied to Airframe Noise Reduction," AIAA/Confederation of European Aerospace Societies Paper 2006-2717, May 2006.

[41] Thomas, F. O., Kozlov, A., and Corke, T. C., "Plasma Actuators for Landing Gear Noise Reduction," AIAA/Confederation of European Aerospace Societies Paper 2005-3010, May 2005.

[42] Huang, X., Zhang, X., and Gabriel, S., "Bluff Body Noise and Flow Control with Atmospheric Plasma Actuators," AIAA/Confederation of European Aerospace Societies Paper 2008-3044, May 2008.

[43] Hayes, J. A., Horne, W. C., Soderman, P. T., and Brent, P. H., "Airframe Noise Characteristics of a 4.7% Scale DC-10 Model," AIAA/Confederation of European Aerospace Societies Paper 1997-1594, May 1997.

[44] Dobrzynski, W., Nagakura, K., Gehlhar, B., and Buschbaum, A., "Airframe Noise Studies on Wings with Deployed High-Lift Devices," AIAA/Confederation of European Aerospace Societies Paper 1998-2337, June 1998.

[45] Herkes, W. H., and Stoker, R. W., "Wind Tunnel Measurements of the Airframe Noise of a High-Speed Civil Transport," AIAA Paper 1998-0472, Jan. 1998.

[46] Davy, R. and Remy, H., "Airframe Noise Characteristics of a 1/11 Scale Airbus Model," AIAA/Confederation of European Aerospace Societies Paper 1998-2335, June 1998.

[47] Dobrzynski, W., Gehlhar, B., and Buchholz, H., "Model- and Full Scale High-lift Wing Wind Tunnel Experiments Dedicated to Airframe Noise Reduction," *Aerospace Science Technology*, Vol. 5, 2001, pp. 27–33.

[48] Choudhari, M. M., and Khorrami, M., "Slat Cove Unsteadiness: Effect of 3D Flow Structures," AIAA Paper 2006-0211, Jan. 2006.

[49] Khorrami, M., Berkman, M. E., and Choudhari, M. M., "Unsteady Flow Computations of a Slat with a Blunt Trailing Edge," *AIAA Journal*, Vol. 38, No. 11, Nov. 2000, pp. 2050–2058.

[50] Dobrzynski, W., and Pott-Pollenske, M., "Slat Noise Source Studies for Farfield Noise Prediction," AIAA/Confederation of European Aerospace Societies Paper 2001-2158, May 2001.

[51] Streett, C. L., "Numerical Simulation of Fluctuations Leading to Noise in a Flap-Edge Flowfield," AIAA Paper 1998-0628, Jan. 1998.

[52] Radezrsky, R. H., Singer, B. A., and Khorrami, M. R., "Detailed Measurements of a Flap Side-Edge Flow Field," AIAA Paper 1998-0700, Jan. 1998.

[53] Brooks, T. F., and Humphreys, W. M., Jr., "Flap Edge Aeroacoustic Measurements and Predictions," AIAA/Confederation of European Aerospace Societies Paper 2000-1975, June 2000.

[54] Guo, Y., "Empirical Prediction of Aircraft Flap Side Edge Noise," INTER-NOISE Proceedings on CD-ROM, Inst. of Noise Control and Engineering, Indianapolis, IN, Dec. 2006.

[55] Molin, N., Roger, M., and Barre, S., "Prediction of Aircraft High-Lift Device Noise Using Dedicated Analytical Models," AIAA/CEAS Paper 2003-3225, May 2003.

[56] Guo, Y. P., Yamamoto, K. J., and Stoker, R. W., "Component-Based Empirical Model for High-Lift System Noise Prediction," *Journal of Aircraft*, Vol. 40, No. 5, 2003, pp. 914–922. doi:10.2514/2.6867

[57] Dahl, M., "A Process for Assessing NASA's Capability in Aircraft Noise Prediction Technology," AIAA/Confederation of European Aerospace Societies Paper 2008-2813, May 2008.

[58] Bertsch, L., Dobrzynski, W., and Guerin, S., "Tool Development for Low-Noise Aircraft Design," AIAA/Confederation of European Aerospace Societies Paper 2008-2995, May 2008.

[59] Ewert, R., "Broadband Slat Noise Prediction Based on CAA and Stochastic Sound Sources from a Fast Random Particle-Mesh (RPM) Method," *Computer and Fluids Journal*, No. 37, 2008, pp. 369–387.

[60] Khorrami, M. R., and Lockard, D. P., "Effects of Geometrical Details on Slat Noise Generation and Propagation," AIAA/Confederation of European Aerospace Societies Paper 2006-2664, May 2006.

[61] Horne, W. C., James, K. D., Arledge, T. K., Soderman, P. T., Burnside, N., and Jaeger, S. M., "Measurements of 26% Scale 777 Airframe Noise in the NASA Ames 40 by 80 Foot Wind Tunnel," AIAA/Confederation of European Aerospace Societies Paper 2005-2810, May 2005.

[62] Kolb, A., Faulhaber, R., Drobietz, R., and Grünewald, M., "Aeroacoustic Wind Tunnel Study on a Two-Dimensional High-Lift Configuration," AIAA/Confederation of European Aerospace Societies Paper 2007-3447, May 2007.

[63] Imamura, T., Ura, H., Yokokawa, Y., Enomoto, S., Yamamoto, K., and Hirai, T., "Designing of Slat Cove Filler as a Noise Reduction Device for Leading-Edge Slat," AIAA/Confederation of European Aerospace Societies Paper 2007-3473, May 2007.

[64] Dobrzynski, W., Bieler, H., Chow, L. C., and Remy, H., "The Airframe Noise Reduction Challenge: Lessons Learned from the European SILENCER Project," *Deutscher Luft- und Raumfahrt Kongress*, Braunschweig, Nov. 2006.

[65] Herr, M., "A Noise Reduction Study on Flow-Permeable Trailing Edges," *Conference Proceedings of the 8th ONERA-DLR Aerospace Symposium (ODAS)*, H. P. Kreplin, Göttingen, Germany, Oct. 2007.

[66] Ma, Z., and Zhang, X., "Broadband Slat Noise Attenuation with Acoustic Liner Treatment," AIAA/Confederation of European Aerospace Societies Paper 2008-2964, May 2008.

[67] Pott-Pollenske, M., Wild, J., Nagel, B., and König, R., "Multidisciplinary Design Approach Toward Low Noise High-Lift Devices," *Conference Proceedings of the 8th ONERA-DLR Aerospace Symposium (ODAS)*, H. P. Kreplin, Göttingen, Germany, Oct. 2007.

[68] Slooff, J. W., de Wolf, W. B., van der Wal, H. M. M., and Maseland, J. E. J., "Aerodynamic and Aeroacoustic Effects of Flap Tip Fences," AIAA Paper 2002-0848, Jan. 2000.

[69] Choudhari, M. M., and Khorrami, M., "Computational Study of Porous Treatment for Altering Flap Side-Edge Flow Field," AIAA/Confederation of European Aerospace Societies Paper 2003-3113, May 2003.

[70] Angland, D., Zhang, X., Chow, L. C., and Molin, N., "Measurements of Flow Around a Flap Side-Edge with Porous Edge Treatment," AIAA Paper 2006-0213, Jan. 2006.

[71] Streett, C. L., Casper, J. H., Lockard, D. P., Khorrami, M. R., Stoker, R. W., Elkoby, R., Wenneman, W. F., and Underbrink, J. R., "Aerodynamic Noise Reduction for High-Lift Devices on a Swept Wing Model," AIAA Paper 2006-0212, Jan. 2006.

[72] Hutcheson, F. V., Brooks, T. F., and Humphreys, W. M., Jr., "Noise Radiation from a Continuous Moldline Link Flap Configuration," AIAA/Confederation of European Aerospace Societies Paper 2008-2966, May 2008.

[73] Oerlemans, S., Broersma, L., and Sijtsma, P., "Quantification of Airframe Noise Using Microphone Arrays in Open and Closed Wind Tunnels," *International Journal of Aeroacoustics*, Vol. 6, No. 4, 2007, pp. 309–333.
doi:10.1260/147547207783359440

[74] Oerlemans, S., and Pott-Pollenske, M., "An Experimental Study of Gear Wake/Flap Interaction Noise," AIAA/Confederation of European Aerospace Societies Paper 2004-2886, May 2004.