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Control strategies for aircraft airframe noise reduction

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Abstract With the development of low-noise aircraft engine, airframe noise now represents a major noise source during the commercial aircraft's approach to landing phase. Noise control efforts have therefore been extensively focused on the airframe noise problems in order to further reduce aircraft overall noise. In this review, various control methods explored in the last decades for noise reduction on airframe components including high-lift devices and landing gears are summarized. We introduce recent major achievements in airframe noise reduction with passive control methods such as fairings, deceleration plates, splitter plates, acoustic liners, slat cove cover and side-edge replacements, and then discuss the potential and control mechanism of some promising active flow control strategies for airframe noise reduction, such as plasma technique and air blowing/suction devices. Based on the knowledge gained throughout the extensively noise control testing, a few design concepts on the landing gear, high-lift devices and whole aircraft are provided for advanced aircraft low-noise design. Finally, discussions and suggestions are given for future research on airframe noise reduction.

1. Introduction

The popularity of air travel has increased dramatically in the last few decades. With the ongoing growth of air traffic around the world, the annoyance of aircraft noise, especially where near airports, is rapidly increasing. The resultant environmental concern makes the attenuation of the aircraft noise a very important topic. The aircraft noise attenuation has now witnessed steady progress in two directions, that is, aero-engine noise and airframe noise. Since the 1970s, the introduction of the turbofan engine and the application of the high bypass ducts and serrated nozzle have seen that the main contributor of aircraft noise gradually move from the engines to the airframe during landing phase when the engines operate at low power setting with the high-lift devices and landing gears fully deployed. Therefore, in order to further reduce aircraft noise, noise control efforts had also been extensively focused on the airframe noise problems in the last decade.

The airframe noise problem was first identified as a potential noise barrier in the 1970s and efforts were initially focused on the noise level and identifying the noise sources through the early aircraft flyover noise measurements.[1–3] The airframe noise sources generally include flap and wing trailing edges, flap and slat side edges, landing gears, cavities, spoilers, component interaction noise and sources associated with the fuselage and wing turbulent boundary layers (see the review by Crighton[4] summarising the early airframe noise research).

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Among these noise sources, landing gears and high-lift devices including slat and flap were identified as the two major airframe noise contributors.

Further investigations[5] on scaled models of these two major-noise-source airframe components give the understanding of noise source mechanism that the airframe aerodynamic noise is normally caused by flow separation off bluff body and unsteady interactions between aerodynamic surface and turbulent flows, as shown in Fig. 1. Due to the complexity of airframe components and vastly different noise mechanisms, and the increasing strict noise reduction target set by the ICAO (International Civil Aviation Organisation), airframe noise reduction has been facing a lot of challenges, as mentioned by Lockard and Lilley.[6] At the quite early stage, some basic control methods were introduced to reduce high-lift devices. Examples include porous, perforated, serrated edge extensions[7–9] and porous edge replacements.[9,10] These control methods are classified as passive control in the sense that there is no power input. Such passive noise control methods have been recently further developed due to their straight realizations in practical flight applications. On the other hand, many attempts have recently been tried to further improve the noise control efficiency and effectiveness using active flow control methods, such as plasma actuation, air blowing and suction. Such active control strategies have shown significant impacts on aerodynamic characteristics of the flow around the airframe components and thus their potential in airframe noise reduction are promising. It is worthwhile to notice that investigations of active flow control are still at primitive stage. Taking aviation safety into consideration, at the present stage these active flow control methods are mainly applied to the scaled model of airframe components.

This paper is mainly focused on the control strategies explored in the last decade for aircraft airframe noise reduction. Details of the airframe noise mechanism and the noise numerical predictions can be found in the review by Dobrzynski[11] summarising the airframe noise research achievements worldwide in the last 40 years. We first briefly summarise the noise mechanisms of landing gear and high-lift devices in Section 2 and introduce in Section 3 the development of recent passive noise control methods and their main achievements in landing gear and high-lift devices noise attenuation. The effectiveness and mechanism of active flow controls on generic models of airframe components are described in Section 4. Section 5 provides the advanced low-noise aircraft design based on the knowledge gained from the extensively noise control tests. In the end, Section 6 gives further discussions and suggestions for future research on airframe noise reduction.

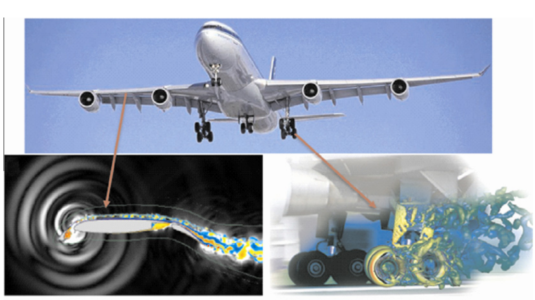


Fig. 1 Flow separation and fluid-structure unsteady interaction on high-lift devices and landing gear of an aircraft causing the airframe aerodynamic noise.

2. Airframe noise generation mechanism

One of the major airframe noise sources is landing gears. The noise generated by a landing gear is normally broadband in nature. Several noise sources have been identified on a typical landing gear configuration. The wheels and main struts are responsible for low frequency noise whilst the smaller details, such as the hoses and dressings, are responsible for the high frequency noise. This wide frequency spectrum makes testing of detailed scale models important as the high frequencies are an important factor to the overall noise level.[12] Some studies have shown tonal noise due to cavity resonances from tube-type pins in various joints linking gear components,[13] tire treads[14] and hinge-leg door configurations.[15] It seems that this tonal noise is dependent on inflow velocity, turbulence and flow direction, so it is impossible to predict whether these will manifest themselves during the approach of an aircraft. It should be noted, however, that there is little experimental evidence that vortex shedding-related tone noise is a major problem for current landing gear architectures.

On the other hand, the landing gear broadband noise is normally generated by the turbulence flow separation off the bluff-body components and the subsequent interaction of such turbulent wake flows with downstream located gear elements. The turbulence-related noise and interaction noise are normally governed by the flow turbulence characteristics and the local impinging flow velocity. Since sound intensity increases with flow velocity to the power of 6, it can reveal that the beneficial effect of reduced local inflow velocity is more substantial than the adverse effect on noise of increased turbulence intensity, as mentioned by Dobrzynski.[11]

Another major source of airframe noise is high-lift devices, including leading-edge slats and trailing-edge flaps. Other high-lift-related noise generating devices include spoilers if deployed during a steep approach operation. Although the spoiler noise may be subjectively important, it has little impacts for airworthiness and thus does not receive much attention for the noise research community by now, and will not be addressed in this article. To gain physical insight, the local steady and unsteady flow conditions of both slats and flaps have been carefully investigated through numerical simulations and fluid experiments. Choudhari and Khorrami[16] sketched a diagram to summarize potential noise sources of a slat, including the vortex flow developing in the slat cove, the unstable shear layer between the vortex and the undisturbed slot flow, the impingement of the vertical shear flow on the downstream cove surfaces and the unsteady flow shedding off the trailing edge (see Fig. 2(a)). On the other hand, it is believed that vortices developing on the side edge of the flap and its interaction with the flap surface are major noise sources of the trailing-edge flap[17,18] (see Fig. 2(b)).

3. Main achievements from recent passive noise control

Recent successful control methods developed for airframe noise reduction are presented for landing gears and high-lift devices, respectively. They are normally passive controls such

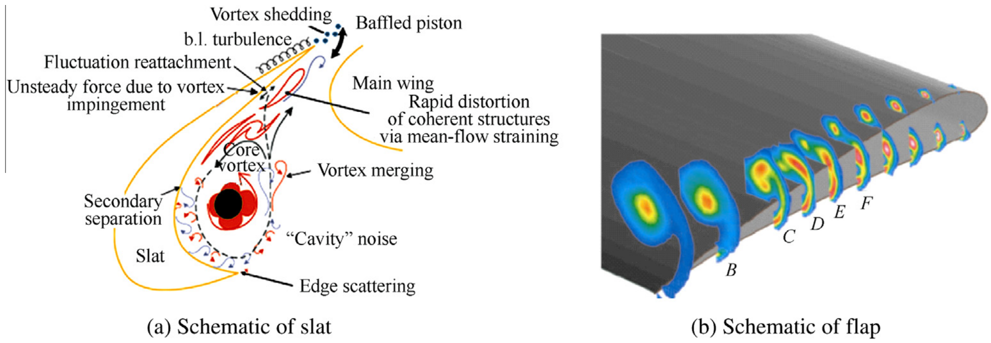


Fig. 2 Schematic of slat and flap noise source mechanisms.

as fairings, deceleration/splitter plates, acoustic liners, slat cove cover and side-edge replacements.

3.1. Landing gear noise control

Based on the knowledge of landing gear noise source mechanism, an effective way to reduce landing gear noise is to cover most of the gear components behind a fairing. It was demonstrated that a total noise reduction of 10 dB could be achieved if the entire gear structure was covered by one fairing to appear as a streamlined body.[11] Such fairing design, however, prevents the retractability of the landing gear and is thus impractical. Nevertheless, the work elucidates the potentially optimal noise control outcomes that can be possibly achieved.

Individually customized fairings covering different gear components should be adopted taking account of practical design needs. Dobrzynski et al.[13] demonstrated several noise reduction improvements by installing individual fairings on the full scale tow bar and axle, covering the steering column and the upper leg and applying a cap to the wheels and the steering actuator (see Fig. 3). The installation of all these fairings showed a potential noise reduction of −2 dB to −3 dB and −3.5 dB, in terms of overall sound pressure level (OASPL), for nose landing gear and main landing gear respectively when compared to the landing gear baseline configuration. For the test of individual fairings, the bogie beam undertray fairing turned out to represent the most efficient noise reduction device. In order to investigate the effect of scaling and test environment on landing gear noise, Li et al.[19] applied the same type of fairings on a detailed 1/4 scale A340 main landing gear and obtained similar results in both conventional wind tunnel and anechoic jet facility, after projecting the scaled model test results to full scale structure. This result demonstrated that testing of detailed scale models is very important as the high frequencies associated with the smaller parts are an important factor to the overall noise level.

In flight tests, such add-on fairings designed for A340-type landing gear presented a landing gear noise reduction of 2EPNdB[20,21] (Effective Perceived Noise in Decibels). Similar approach using such fairings was also successfully applied to

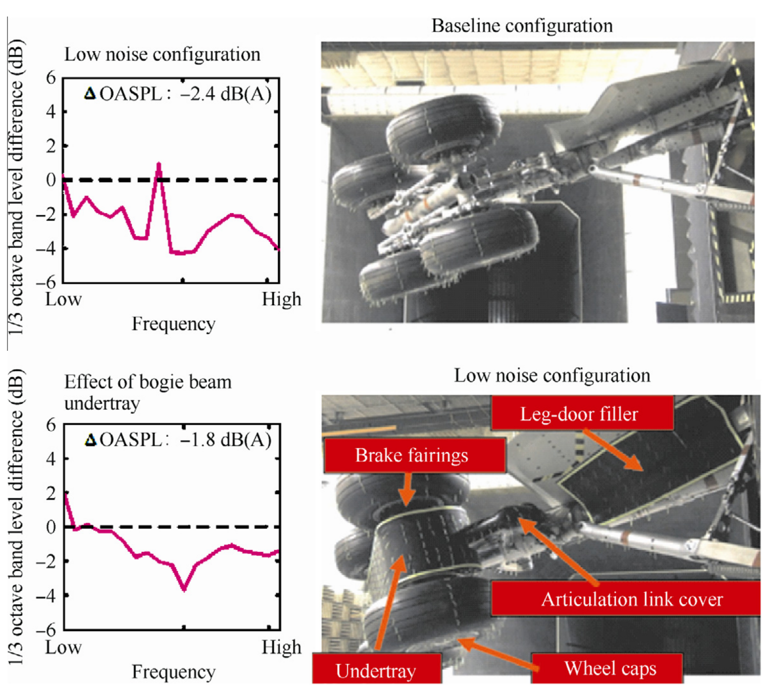


Fig. 3 Example of noise reduction potential of A340 full-scale main landing gear fairings.[13]

reducing airframe noise of B777 aircraft by NASA and Boeing in both wind tunnel and flight tests.[22–24]

The solid fairing mentioned above, however, can cause high-speed flow to be deflected onto adjacent uncovered gear components. As noise levels of landing gear components increase with the 6th power of the locally incident flow speed, it is likely that the total sound power output of the landing gear noise is proportional to the spatially averaged 6th power of flow velocity U, that is, U^6.[25] As a result, the gain of noise reduction achieved by the fairings could be lost if the add-on fairings cause noise increase from other uncovered components. Another disadvantage of the solid fairings is the low-frequency noise associated with the vortex shedding from the relatively large size of the fairings. To further minimize the deflected flow speed and eliminate vortex shedding caused by add-on fairings, partially flow transparent fairing design should be considered to allow for a limited amount of air to penetrate through the fairing. Li et al.[19] studied the noise control effects of different undertray fairings, including solid fairing, perforated undertray with edge brushes and slotted undertray with cloth on the landing gear noise reduction (see Fig. 4), in both closed and open jet wind tunnels. The comparison of sound level difference (ΔL) measured at position of ($\Phi = 90°$) relative to that the slotted fairing covered with cloth was the most effective replacement to the solid fairing. This design produced a reasonable reduction at low frequencies compared with the baseline and solid fairing. Furthermore, a significant noise reduction in the mid-frequency and high-frequency range can still be observed. The perforated fairing also significantly reduced the noise level in the broadband frequency range except at the very high frequencies where the noise level was increased due to the interaction of the oncoming flow with the fairing orifices, producing fairing self-noise. The orifice should thus be carefully designed so that the fairing self-noise damps rapidly at high frequencies in the atmosphere or beyond the audible capability of human beings.

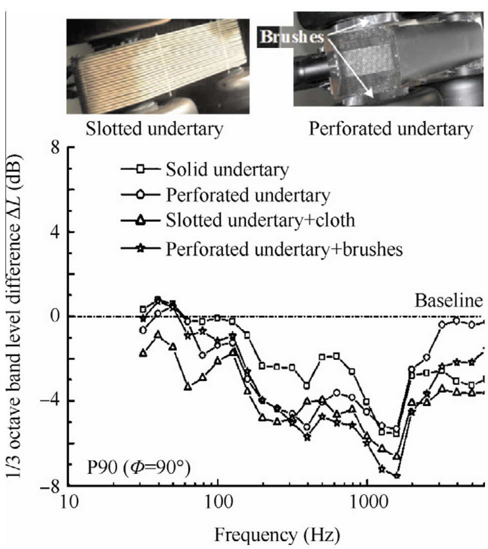


Fig. 4 Add-on undertray fairings installed on a landing gear and their noise reduction potential.[19]

Similar tests with elastic clothes or meshes were also conducted by other researchers.[26–30] Ravetta et al.[26] covered the landing gear bogie area with elastic cloth membranes and provided a local average noise reduction in the order of 2 dB. Boorsma et al.[27,28] investigated the effects of different porosities of the perforated fairing (mesh) on both generic bluff body and landing gear respectively, and indicated that the large vortex behind the fairing vanished, resulting in a reduction of the broadband noise level.

Although the fairings covering complex structures work well, in some areas it is difficult to install such fairings, e.g. on the steering system of the nose landing gear or upstream of the rear brake system of a four-wheel main landing gear. It was demonstrated in the European SILENCER (Significantly Lower Community Exposure to Aircraft Noise) project that a plate placed in a wake of an upstream component (gear structure) generates less noise due to the reduced mean flow velocity impinging on the structure (see Fig. 5(a)), even if it is exposed to an increased turbulence level. As a consequence of this finding, Pott-Pollenske[31] conducted a wind tunnel aeroacoustic study by applying wheel and main leg decelerating plates (DP) on a 1/10 scale high fidelity landing gear (see Fig. 5(b)). The decelerating plates were positioned behind the rear brake system and the lower part of the main leg. The results indicated that by reducing the impinging speed on the tow bar and the main leg, the decelerating plate tended to reduce the radiated farfield noise by up to 4 dB.

Another kind of plate applied by Pott-Pollenske[31] to control the landing gear noise was the splitter plate. By applying splitter plates behind various gear components including main leg, sidestay, dragstay, torque link and wheels, some reason-

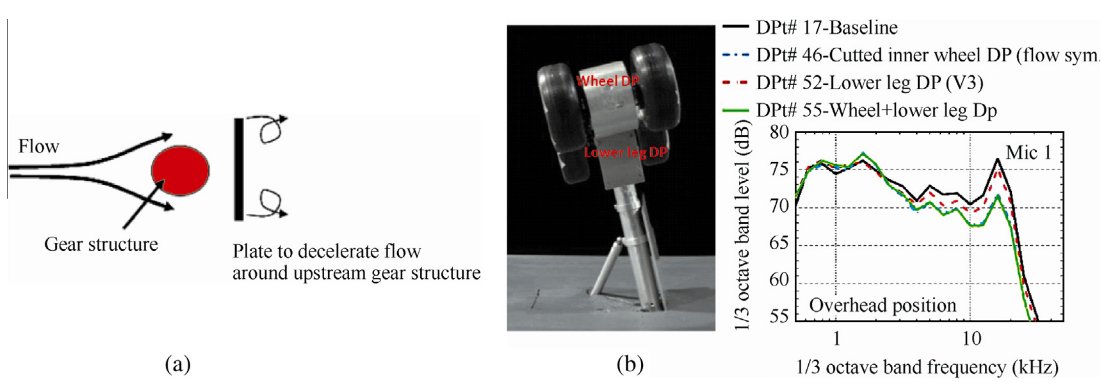


Fig. 5 Noise control concept of deceleration plate and noise reduction potential of wheel and leg deceleration plates[31] on a 1/10 scale landing gear.

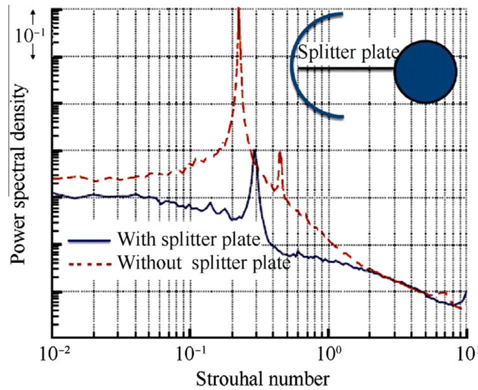


Fig. 6 Schematic of simplified model in splitter plate configuration and power spectra density comparison at Strouhal number with and without splitter plate.[33]

able noise reduction of 1–2 dB could be obtained. This control concept is based on the findings by You et al.[32] who indicated that drag and lift fluctuations on a body in flow generated a dipole characteristic noise and an unsteady wake generated a quadruple characteristic noise, and demonstrated that an attached splitter plate could reduce the flow unsteadiness in the wake and the on-surface force fluctuations, leading to a desired noise reduction. Instead of attaching splitter at the rear side of a cylinder, Spiteri et al.[33] placed splitter plates between an upstream fairing and a downstream landing gear main strut to reduce the fairing-induced low-frequency noise (see Fig. 6). The splitter plate prevented the interactions between two opposing shear layers of the fairing's trailing edge, and thus attenuated the flow-induced noise from the downstream strut.

3.2. High-lift device noise control

Based on the current understanding of the noise source mechanism in the slat cove/slot area, add-on devices have been developed to reduce the broadband noise. Such devices are slat cove cover,[34] slat hook extensions[35] and slat cove filler.[36] Dobrzynski et al.[34] applied a slat cove cover to attenuate the strength of the vorticity in the free shear layer between the cove and the slot flow, and the comparison of A-weighted 1/3 Octave sound pressure level (SPL) in the farfield showed a promising broadband noise reduction using the cove cover (see Fig. 7(a)). Khorrami and Lockard[35] extended this concept by attaching an extended blade seal to the slat hook and documented a further noise reduction potential compared to the cases of no blade seal and baseline blade seal (see Fig. 7(b)). Furthermore, Horne et al.[36] designed a slat cove filler to completely fill the slat cove through a streamlined body and their microphone array measurements presented a significant noise reduction potential of 4–5 dB in a broadband frequency range (see Fig. 7(c)). Other similar tests on slat cove filler had also been conducted by Kolb et al.[37] and Imamura et al.[38] The effects of slat hook tripping and slat hook serrations were also studied by Dobrzynski et al.[39] and Kopiev et al.[40] respectively.

For the slat trailing-edge noise control, transparent edge replacements, such as porous material or edge brushes,[41,42] were used to alleviate the transformation of boundary layer flow turbulence into propagating sound waves. All of them were shown to be very effective in trailing-edge noise reduction.

Other than the above mentioned control methods that directly affect the noise source mechanisms in the slat cove and trailing edge, acoustic liner is aimed at the attenuation of sound waves on their propagation path between the slat

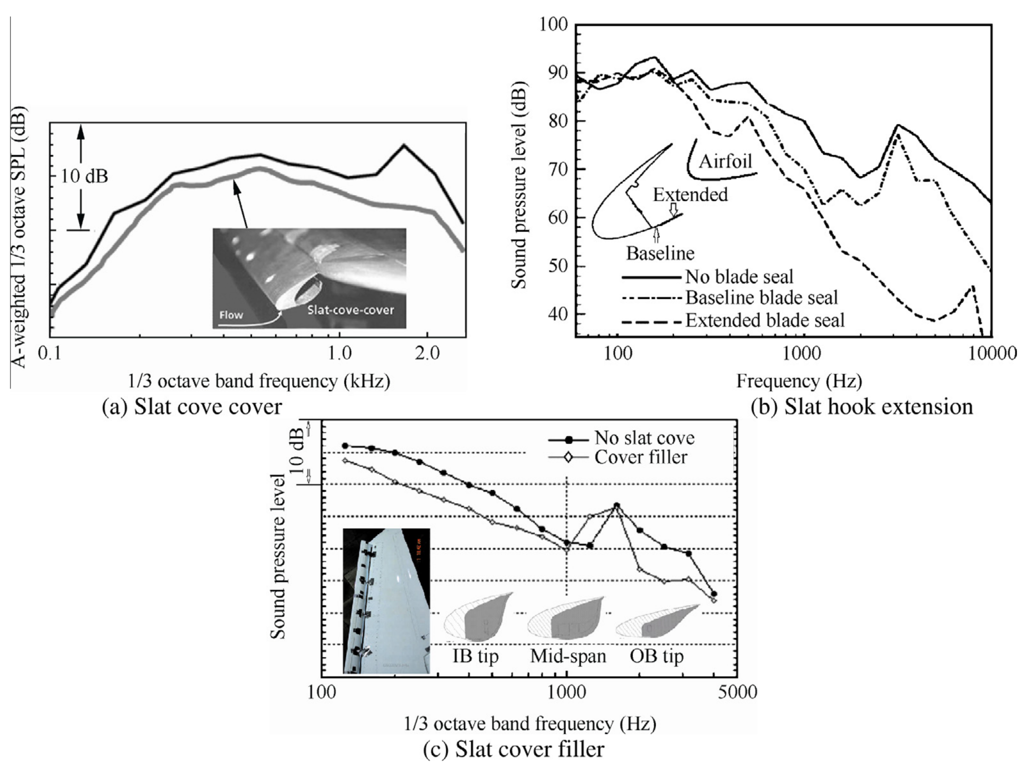


Fig. 7 Noise reduction potential of a slat cove cover[34], slat hook extension[35] and slat cover filler.[36]

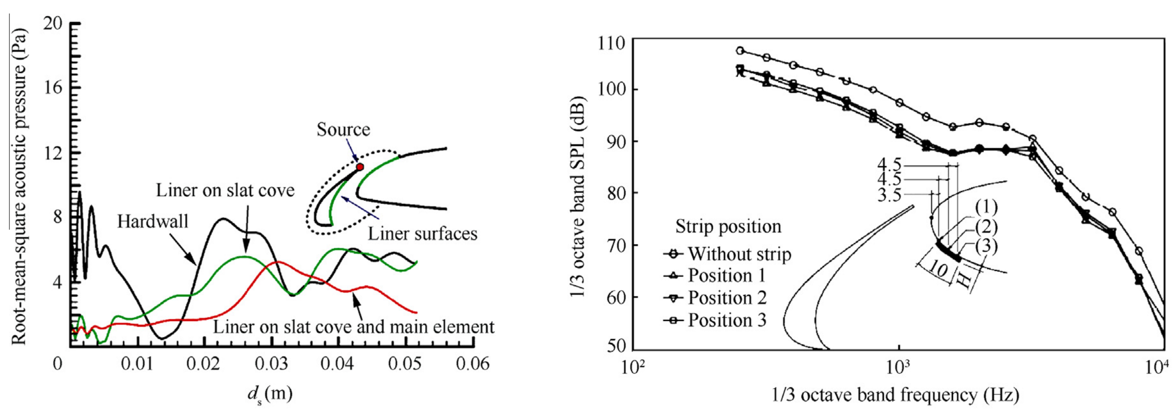
cove and the wing leading edge, i.e. to alleviate the fluid-structure interaction to reduce noise. Ma et al.[43,44] utilised acoustic liners on the slat cove surface and the upper surface of the airfoil leading edge. Compared with the hard wall of the slat, the acoustic liner on slat cove surface and main element provided a meaningful acoustic pressure reduction along the slat gap (see Fig. 8(a)). In a similar way, Chen et al.[45] applied strips with sufficient thickness on the pressure-side surface of the airfoil leading edge and showed that noises in the near and far-field were attenuated significantly (see Fig. 8(b)).

As for the flap noise reduction, edge flow modifications using side-edge treatments, such as added-on side-edge fences,[46–48] porous flap edge[49] and edge brushes[11,41] (see Fig. 9(a)) proved to be very effective. Aerodynamic tests showed that these treatments led to the formation of significantly weaker side-edge vortex system and the elimination of the bursting of the side-edge vortex. Both effects resulted in a decrease in the radiated noise.

Another drastic approach to control flap side edge noise is the elimination of the edge by the so-called continuous moldline link (CML) technology.[50–52] The CML is to prevent the formation of the strong and concentrated shear-layer/vortex system that is present at the blunt flap side edge, and break up the single vortex into a spanwise distribution of weaker vortices by imposing a more continuous spanwise variation of the wing's circulation. Streett et al.[50] tested the CML concept (see Fig. 9(b)) on a high-lift system configuration. The test model consisted of a swept wing with a full-span leading-edge slat and a part-span fowler flap. They indicated that a large reduction of the noise radiating from the flap side-edge region was achieved when compared to that obtained from a baseline flap configuration.

4. Active flow control for airframe noise reduction

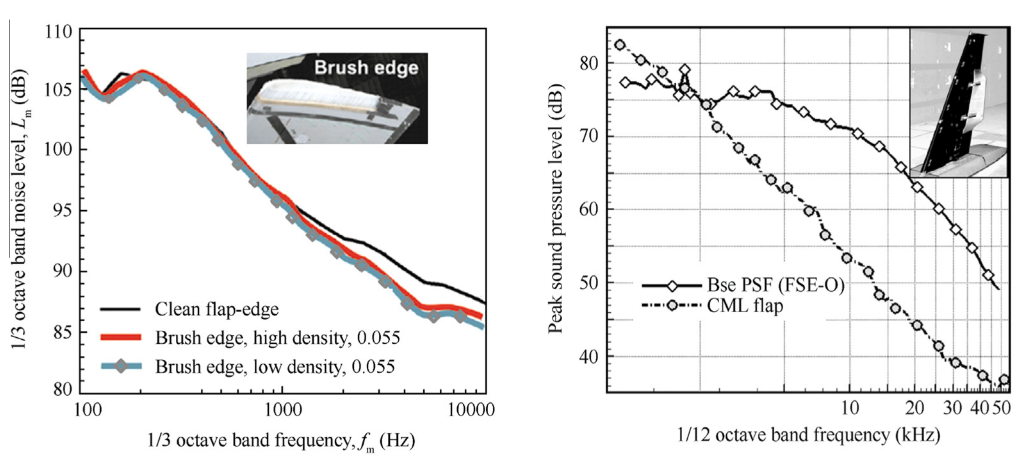
The past trends in aircraft noise reduction have shown a steady rate of decline, obtained through the conventional circle of research and development, as briefly introduced in Section 2. However, it is clear that the 'asymptotic' improvements in noise performance adopted by industry at the moment will not achieve the noise reduction target of 10 dB relative to the year 2000 technology set by the "European Visions 2020" and NASA QAT (Quiet Aircraft Technology) program. It is evident that these targets call for new research into alternative approaches. Based on the understanding of the above passive flow controls, this section discusses the recent advance-



(a) Slat acoustic liner on slat cove and main element

(b) Airfoil leading - edge strips

Fig. 8 Noise reduction potential of a slat acoustic liner on slat cove and main element[43] and airfoil leading-edge strips.[45]



(a) Using brush-type edge replacements

(b) Using continuous moldline link

Fig. 9 Side-edge noise reduction using brush-type edge replacements[11] and continuous moldline link.[50]

ments in active flow control activities, such us plasma and air blowing/suction.

4.1. Noise control by plasma actuator

Plasma technique has been widely demonstrated to be able to modify the local flow by introducing extra momentum.[53] Dielectric barrier discharge (DBD) plasma actuators (see Fig. 10) are now the most widely used discharge actuators for airflow control. An DBD plasma actuator generally consists of two electrodes which are flush mounted on both sides of a dielectric plate. One of the electrodes is exposed to the ambient air, and the other is insulated by a dielectric material. A high AC voltage of a particular waveform applied to the exposed electrode weakly ionizes the atmospheric air adjacent to the exposed electrode. The ionized air (plasma) in the presence of the electric field gradient produced by the electrodes results in a body force that acts on the external air to induce airflow (synthetic jet) along the actuator surface. Some recent works have demonstrated the potential of the plasma actuators on the attenuation of the flow-induced noise. The testing models used were generally the generic models of airframe components.

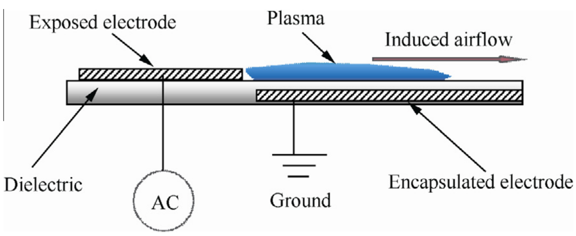


Fig. 10 Schematic of DBD plasma actuator.

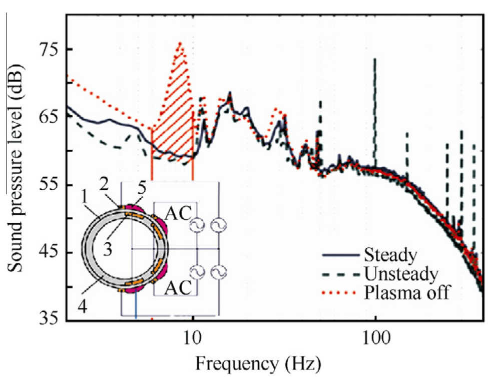


Fig. 11 Bluff body near-field noise reduction as achieved with plasma reducing turbulence level and eliminating vortex shedding.[54]

For noise reduction of a bluff body consisting of a single circular cylinder, which represents the generic model of landing gear main leg, Thomas et al.[54] performed steady and unsteady actuation using DBD plasma actuators on both sides of the cylinder and generated Coanda effects on surfaces (see Fig. 11). They found that at Reynolds number (Re_D) of 3.3×10^4 based on the diameter of the cylinder, Karman vortex shedding was totally eliminated, turbulence levels in the wake decreased significantly, and near-field sound pressure levels with shedding were reduced by 13.3 dB. They claimed that although the unsteady actuation had the advantage of total suppressing of shedding at lower power, it produced a tone at the actuation frequency, and steady actuation was more suitable for noise-control applications. Kozlov and Thomas[55] then compared the effects of spanwise and streamwise oriented plasma actuators and showed almost the same noise reduction level. However, due to the complexity of landing gear (not a single strut) and high Reynolds number in real flight, the dominant noise is most likely the interaction broadband noise between the upstream turbulence wake and the downstream gear elements. Li et al.[56] and Huang et al.[57] then applied a generic model of main strut consisting of a upstream circular cylinder and a downstream oblique strut in their plasma control experiments respectively. In contrast to the Thomas's idea of reducing the degree of flow separation and eliminating the associated Karman vortex shedding, Li et al.[56] introduced the upstream plasma forcing on the cylinder surface at ±90°

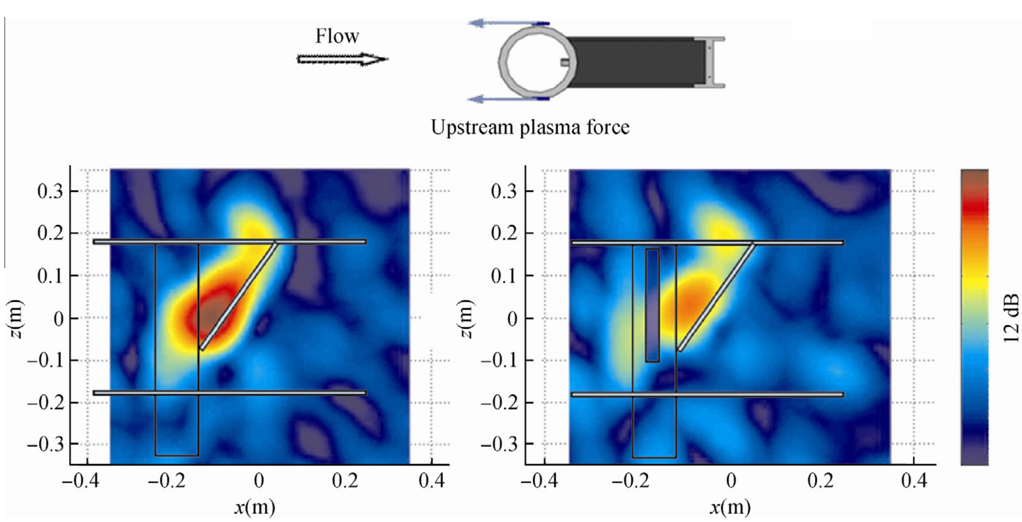


Fig. 12 Bluff body near-field noise reduction as achieved with upstream plasma force (virtual fairing) on both sides of the cylinder.[56] Noise source maps were taken by phased microphone array.

with respect to the approaching flow (see Fig. 12) to simulate the application of the solid fairings on the landing gear, and showed that the major broadband noise was effectively attenuated at Re_D below 2.4×10^5 The induced upstream plasma forcing, acting as a "virtual fairing", pushed away the main stream flow from the downstream oblique strut, thus reducing the flow impingements and resulting in noise reduction. Furthermore, Li et al. compared the effectiveness of the DBD and the sliding plasma discharge (combining DBD and DC discharge), and demonstrated that the sliding discharge plasma actuator had better performance due to its elongated plasma sheet and more momentum introduced into the boundary layer.

To the authors' best knowledge, the effectiveness of the plasma on the high-lift device noise reduction has yet been published. However, several control concepts have already been considered by some research groups in the US and UK, such as the Centre for Flow Physics and Control (CFPC) at University of Notre Dame and the Airbus Noise Technology Centre (ANTC) at University of Southampton. For flap side-edge noise reduction, combination of passive side-edge shaping in conjunction with plasma induced blowing could weaken and guide side-edge vortices away from flap edge, resulting in an edge noise reduction (see Fig. 13). The plasma applied on the surface of the slat cove and on the leading edge of the airfoil could provide an on-demand "virtual" acoustic liner to minimize reflection of sound toward the ground, whereas the chordwise oriented plasma actuators at the trailing edge can produce streamwise vorticity to form a "virtual" serrated slat trailing edge, reducing trailing edge noise (see Fig. 14). The ANTC group (private communication) has also been utilizing plasma on slat hook to reduce the shear layer instability and intend to reduce the corresponding noise.

A cavity driven by a low-speed flow is a generic model of aircraft's landing gear bay, wing cavity or other pin holes. Several attempts have been applied to controlling the dominate cavity tones using plasma.[58–60] Chan et al.[58] applied plasma actuators on the approaching surface to the cavity aligned with the direction of the oncoming flow (see Fig. 15), and demonstrated that the plasma actuators lead to a significant attenuation of the dominate cavity tone. The flow visualization showed that plasma actuators produced vertical structures which were convected downstream with the mean flow and produced disturbances similar to that of vortex generator. This affects the convection of the discrete vortices in the cavity shear layer, disrupting the mechanisms that allow the cavity to produce tones. Huang et al.[59] conducted similar work on cavity tonal noise reduction using plasma actuators with different duty-cycle AC voltage supply and showed that both the duty cycle of the driving signal and the period of the control signal affected the performance of the plasma actuator. With plasma fully applied on, the tonal noise was totally suppressed. In order to increase the control efficiency of the plasma, Huang et al.[60] proposed a variable control structure models and designed a close-loop control scheme accordingly to reduce the required input power consumption.

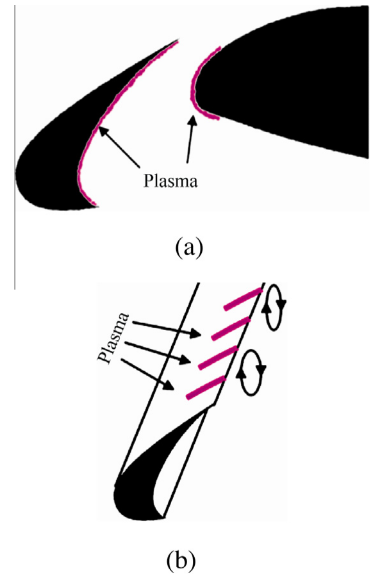


Fig. 14 Plasma acoustic liner on slat cove/leading edge of airfoil and plasma generated virtual serrated slat trailing edge. Ideas are from CFPC.

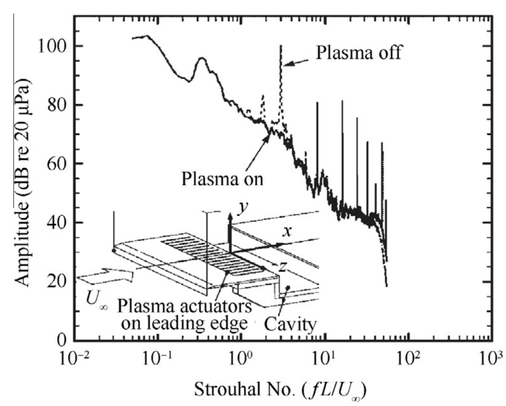


Fig. 15 Application of plasma at the leading edge of a cavity to attenuate the dominant cavity tone.[58]

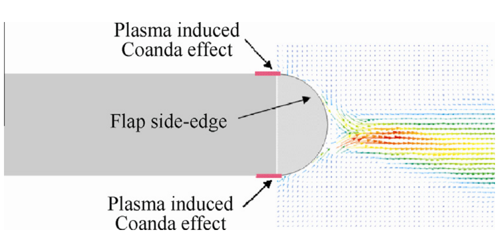


Fig. 13 Flap side-edge vortices eliminated by plasma actuators. Idea is from CFPC.

4.2. Noise control by air blowing and suction

The concept of utilizing air blowing on landing gear is to deflect the flow from downstream airframe components, just as a fairing does, reducing the local flow speeds and thus the aerodynamically generated noise. From this point of view, the air blowing forms an air curtain (visual fairing) before the components. In Fig. 16, Oerlemans and Bruin[61] applied the air blowing through a slot upstream of a simplified landing gear main strut model. Tests were done at different wind tunnel speeds, blowing speeds, slot geometries and model geometries. Broadband noise reductions of 3–5 dB were obtained using an air curtain with normal blowing (i.e., perpendicular to the main flow). They also found that the noise reductions could be in-

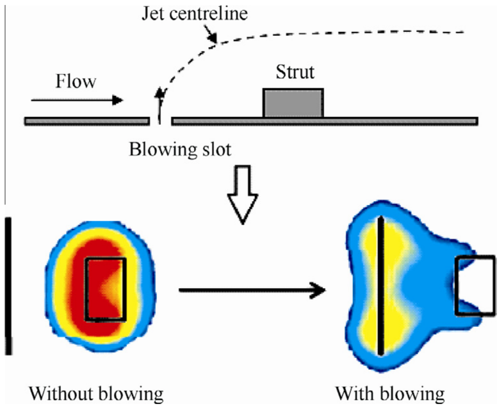


Fig. 16 Air blowing setup model and the corresponding noise source maps at the frequency of 4 kHz with and without air blowing control at 70 m/s wind speed.[61]

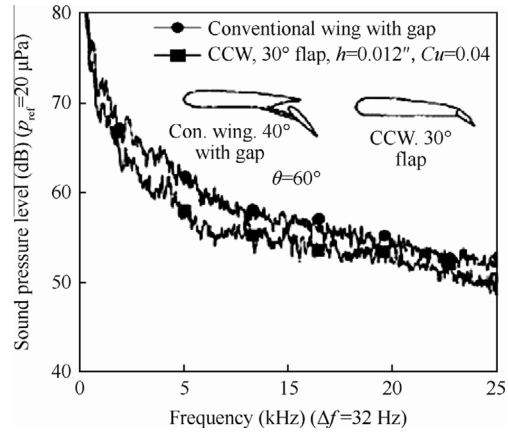


Fig. 18 Example of noise reduction using circulation control wing with air blowing.[64]

creased to 5–10 dB by oblique blowing (30° upstream) or by applying a small flow deflector directly before the blowing slot. In order to reduce the interaction noise, Angland et al.[62] utilized a tandem component of a cylinder and an H-beam. Air blowing applied through the perforated surface of the cylinder was demonstrated to be effective at reducing the broadband fluid–structure interaction noise. Only relatively small blowing coefficients were required to achieve large reductions in the free-field acoustics.

Koop et al.[63] demonstrated air blowing for flap side-edge noise reduction, as shown in Fig. 17. Air was blown into the flap side-edge vortex system through a series of small round orifices located along the flap suction and pressure side edges between 13% and 35% chord. The blowing caused the vorticity in the flap side-edge shear layer to be concentrated in small vortices. As a result, noise reduction of 3–4 dB was achieved.

Another innovative control concept based on air blowing is the circulation control of a wing (CCW). Circulation control is a means to eliminate both the flaps and the slats. In particular, CCW using tangential air blowing has been normally applied to improving aerodynamic performances. Munro et al.[64] demonstrated that this technology had a substantial advantage in the acoustic realm as well (see Fig. 18). They showed that after carefully designing the air blowing configurations a lower noise spectrum for a CCW system could be obtained when compared to a conventional flap system for the same lifting condition.

The control effect of air suction on slat noise was numerically studied by Knacke and Thiele.[65] By using steady suction at the inner slat surface, they demonstrated that the dominant noise was from the slat cove and this dominance was massively reduced by the air suction.

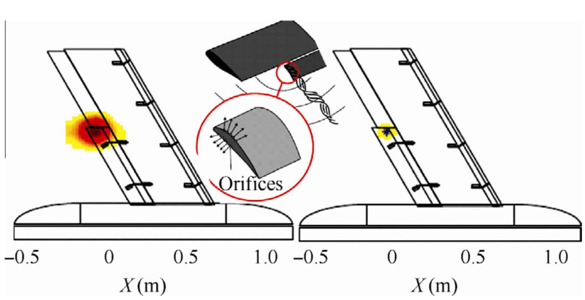


Fig. 17 Example of noise source map comparison between baseline and air blowing on flap side edge.[63]

5. Advanced low-noise airframe design

The add-on noise reduction devices, such as fairings, to conventional landing gears and high-lift devices have shown a limited potential of the order of −3 dB and the active flow control methods have not been in practical process, therefore more drastic approach is needed in the design of future low noise aircraft airframe components. The strategies for the development of low-noise aircraft design can be based on the knowledge gained throughout the extensively noise control testing of different airframe configurations, as aforementioned control methods, with the primary focus on the modification of the noisiest components.

In European SILENCER Project[66], both low-noise nose landing gear (NLG) component and main landing gear (MLG) component designs were developed by the support of semi-empirical noise source models and CFD computations. For the NLG design, the complicated upper gear leg area was located in the bay out of the flow. For the MLG design, as shown in Fig. 19, the original folding side-stay was replaced by a telescopic one. The articulation link and hinge door were both eliminated and the brakes were protected from high speed inflow by a closure half. Tests revealed a noise reduction potential of up to 7 dB(A) for the advanced low noise NLG and a reduction potential of about 5 dB(A) for the quietest advanced MLG configuration compared to the baseline configuration. However, one of the drawbacks of the SILENCER landing gear design was the excessive weight of the telescopic sidestay. In European TIMPAN[67] (Technologies to IMProve Airframe Noise) project, a new landing gear combined with porous fairings and new sidestay without weight penalty was designed and tested under different configurations, such as wheel spacing and bogie angle. The TIMPAN low noise MLG configuration provides more than 7EPNdB noise reduction, which results in a total aircraft noise reduction of 1.5EPNdB for otherwise unchanged high-lift devices and engine noise levels.

The application of noise control strategies on the high-lift devices is a matter of ongoing debate between aerodynamicists

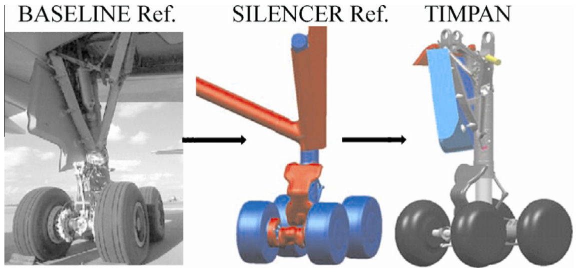


Fig. 19 Comparison of BASELINE, SILENCER and TIMPAN main landing gear.

and acousticians. The latter is aimed at the reduction of the noise whereas the former fears a corruption of flow conditions and thus the related high-lift performance. In order to balance aerodynamic performance and acoustics, some noise control efforts had been tried on designing new slat and leading edge of the main airfoil, as shown in Fig. 20. Pott-Pollenske et al.[68] designed an advanced three-element system with a so-called very long chord slat (VLCS). Compared to the conventional high-lift system (Ref. slat), this new design achieved a higher maximum lift coefficient with additional noise reduction of 4 dB. Other than designing the slat, Andreou et al.[69] and Shmilovich et al.[70] investigated the drooped leading edge (LE) of the main airfoil on the acoustic and aerodynamic characteristics of the high-lift devices, and their results showed that the carefully designed drooped LE was advantageous in an acoustics perspective without imposing aerodynamic penalty. The implementation of practical low noise LE devices will depend on technological advances in the areas of improved mechanical systems or morphing structures.

To cope with the aggressive noise reduction target of −10 dB at 2020, efforts must also be directed toward the whole airframe low-noise design. Fig. 21 shows the Cambridge-MIT SAX-40 conceptual low-noise aircraft design with hybrid wind body. The embedded/podded engine is installed over the wind body to prevent the engine noise radiating to the forward and ground direction which is the most concerned direction at the phase of aircraft approach and landing. The drooped LE and continuous moldline (CML) trailing edge (TE) can provide high lift and lower noise compared to the conventional high-lift devices. The faired low noise main landing gear and the advanced centrebody design enable a low approach speed, thereby reducing the airframe noise sources on approach. The whole aircraft design concepts are aimed at a reduced approach speed by producing lift on the centre-body as well as

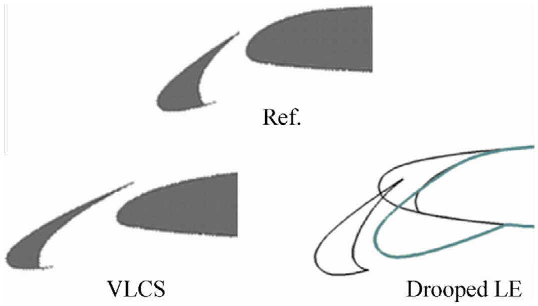


Fig. 20 Comparison of Ref. slat, very long chord slat (VLCS) and main airfoil drooped leading edge (LE) concepts.

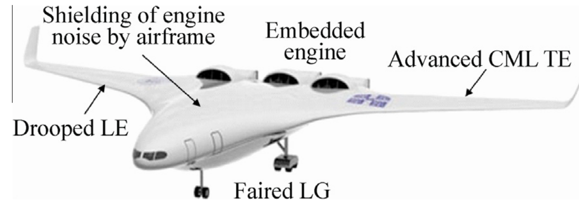


Fig. 21 Cambridge-MIT SAX-40 aircraft low noise conceptual design.

the wings and minimizing the aircraft drag, which allows for a lower engine thrust setting on the aircraft final glide slope and in turn would also contribute to engine noise reduction.

6. Discussion and suggestions

In this review, we present recent major achievements in the control of airframe noise, namely passive control methods such as fairings, deceleration/splitter plates, acoustic liners, slat cove cover and edge replacements etc. Some other important promising active control methods include plasma technique and air blowing and suction. Advanced low-noise aircraft design concept is also provided based on the knowledge of the noise mechanism gained from the extensively noise control researches.

This review attempts to subsume the most import findings from the experimental and applied research in airframe noise control worldwide. However, the cited control strategies are far from completed and the noise mechanisms are not fully understood. In addition, individual noise control method also has its own disadvantages. For example, the streamline fairings covering the landing gear can provide significant noise reduction, but they also add additional weight to the aircraft and may obstruct quick routine inspection. The high-lift device noise control methods such as acoustic liners, slat cove cover and transparent edge replacements are normally accompanied by either some degradation in high-lift performance or are not practical for aircraft application. The promising active flow controls in airframe noise reduction require more basic research and development before practical application on real aircraft. The plasma technique gradually loses its effectiveness for noise control when the wind speed increases, indicating that the plasma actuation authority must undergo a commensurate increase for a practical application in the flight of much higher speeds and Reynolds number. How to contain the strong self-noise is the facing challenge of air blowing/suction technology.

It is worth noting that in practical implementation low-noise landing gear and high-lift device design must account for the following three elements: easy operation, safety and low costs. In addition, the landing gear's drag should be minimized and high-lift devices design should not degrade the device's aerodynamic performance. Best of all, the high lift should yield an increase in the maximum lift to allow for a reduction in approach speed which in turn would lead to a significant reduction in airframe noise. Both aerodynamic and acoustic characteristics, therefore, should be considered together when designing airframe components.

The geometrical complexity of airframe components means that much of the noise control development work and low-noise design must be based on testing rather than modelling. The design of experiments is a compromise between a number of criteria including the scale and physical reality of the airframe components and the Reynolds number of the flow, the accessibility for instrumentation and build changes as well as the cost of the gear and the experimental facility.

In China, research efforts on airframe noise reduction have only been performed recently. The commercial aircraft (C919) will hopefully take off in 2014 and we hope this review on noise control strategies with other related reviews will benefit those engineers of C919 when designing low-noise airframe components.

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