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On the reduction of the engine and aerodynamic noise of aircraft

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ABSTRACT

Air traffic is growing at a steady rate of to 7% per year in most regions of the world, implying a doubling every 10-25 years. This requires major advances in aircraft noise reduction at airports, just not to increase the noise exposure due to the increased number of aircraft movements. In fact it can be expected, as a consequence of increased opposition to noise by near airport residents, that the overall noise exposure will have to be reduced by bans, curfews, fines, and other means and limitations, unless significantly quieter aircraft operations are achieved. The ultimate solution is aircraft operations inaudible outside the airport perimeter, or noise levels below road traffic and other existing local noise sources. These substantial noise reductions cannot come at the expense of a degradation of cruise efficiency, that would affect not just economics and travel time, but would increase fuel consumption and emission of pollutants on a global scale. The paper reviews the: (i) current knowledge of the aircraft noise sources; (ii) the sound propagation in the atmosphere and ground effects that determine the noise annoyance of near-airport residents; (iii) the noise mitigation measures that can be applied to current and future aircraft; (iv) the prospects of evolutionary and novel aircraft designs towards quieter aircraft in the near term and eventually to operations inaudible outside the airport perimeter.

Keywords: Jet engine, aerodynamic noise, airport noise.

1. INTRODUCTION

The present paper attempts to make a concise but comprehensive review of the problem of aircraft noise near airports, organizing the contents in four chapters. Chapter 2 concerns the physics of sound generation and propagation, that is the noise sources associated with propulsion and aerodynamics that are responsible for aircraft noise. The Chapter 3 addresses the modification of the spectrum and directivity of aircraft noise due to atmospheric and ground effects, that is the difference between emitted aircraft noise and the noise received by the near-airport resident, and its effects as an annoyance to living, working and sleeping habits of near-airport resident. The Chapter 4 lists a number of noise reduction measures that can be applied to aircraft, taking into account the associated penalties in weight, fuel consumption and complexity and how much can be expected in return as an achievable noise reduction. The Chapter 5 considers evolutionary and novel aircraft configurations needed to achieve substantial noise reductions towards the objective of an aircraft inaudible outside the airport perimeter. The conclusion summarizes the gap between this ultimate aim and the current state-of-the-art.

2. NOISE GENERATION AND PROPAGATION

The noise generation mechanisms in an aircraft are related to propulsion, aerodynamics and their interactions. Jet engine noise has been reduced dramatically since the dawn of the jet age due the increased by-pass ratio of jet engines, leading to a win-win situation because the lower average jet velocity has twin benefits: (i) increasing propulsion efficiency and reducing specific fuel consumption; (ii) reducing noise by shielding the hot high-speed core jet by a surrounding colder and slower fan flow. The success in reducing jet engine noise has lead to the current situation where on approach to land with the engine at idle aerodynamic noise can be dominant. At take-off and other flight conditions engine noise is most important, and the prospects for further

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reductions by increasing the by-pass ratio of turbofan engines are reaching their limits somewhere between 10:1 and 20:1. Larger by-pass ratios are achieved by unshrouded propulsions, which do without the weight of an engine nacelle, but also lose the benefits of: (v) noise shielding by inlet and exhaust ducts; (ii) sound absorption by acoustic liners on duct walls. The modern counter-rotating ultra-high by-pass-ratio unducted engine adds to the propeller noise that of the interaction of two rotors, one in the wake of the other. This variety of noise generation mechanisms is considered starting with open rotor noise (section 2.1), proceeding to the noise of ducted engines (section 2.2) and concluding with installation and flight effects (section 2.3) in addition to aerodynamic noise.

2.1 Open rotor noise

The open rotor noise is chosen as the starting point for convenience of presentation, since in this case the noise sources are in free space (section 2.1) unaffected by the duct acoustics of turbojet or turbofan engines (section 2.2). In both cases installation and flight effects have to be considered (section 2.3). From the point-of-view of propulsive efficiency the propeller is the best choice, as long as blade tip speeds do not approach sonic conditions leading to shock waves and a sharp increase in drag. The sonic effects are of no concern for slower regional aircraft and can be minimized for modern high-speed rotors with advanced blades using supercritical airfoil sections. The airplane propellers provide thrust in horizontal flight, as helicopter rotors provide lift in vertical flight, and there is a combination of thrust and lift for an helicopter in forward flight. There is one important difference regarding noise: the aircraft propeller leaves a vortical or turbulent wake behind, whereas for as helicopter rotor the wake of one blade can impinge on the next or following blades, creating a characteristic flapping noise. This blade-vortex interaction (BVI) noise applies not only to helicopter rotors but also to contra-rotating propellers since the wake of the upstream blades impinges on the downstream blades.

The modeling of the noise of propellers and rotors applies equally well to turbomachinery, since the fan compressor and turbine consists of the one or more stages of blades. The main component of noise in all cases is discrete noise at (7a) the blade pass frequency (BPF) and its harmonics (7b):

$$\omega_1 = N\,\Omega\,, \quad \omega_n = n\,\omega_1 = n\,N\,\Omega\,; \tag{7a,b}$$

the blade pass frequency (7a) is the product of the angular velocity of rotation Ω by the number N of blades. A fan, compressor or turbine stage has a much larger number of blades N~ 20-35 than a typical propeller or rotor $N\zeta \sim 2 - 6$, and a higher rotation speed as well, leading to a much higher fundamental blade pass frequency, typically $\omega_1 \sim 103 - 104$ Hz versus $\omega_1 \sim 102 - 103$ Hz. The harmonics have usually smaller amplitudes, and in the case of turbomachinery the frequency may exceed the audible range 20 Hz – 20 kHz or become cut-off for evanescent modes rather than cut-on for propagating modes. In the case of counter-rotating propellers with (N_1, N_2) blades rotating at the same angular velocity Ω, the interaction leads to sum and difference frequencies of the harmonics (n_1, n_2) of each propeller:

$$\omega^{\pm}_{n_1 n_2} = \left(n_1\,N_1 \pm n_2\,N_2\right)\Omega\,, \tag{7c}$$

and thus the discrete spectrum can be much denser. The mode cut-off can result from the interaction of sound with vorticity, that can have other far-reaching consequences in the noise of a ducted engine.

2.2 Ducted engine noise

An aircraft propeller operates in a uniform stream unless there are atmospheric disturbances. An helicopter rotor operates in an atmosphere at rest in hover and in a uniform stream in forward flight, but may be ‘locked into’ its own wake in certain dangerous descent conditions. The simplest case of acoustic propagation in a duct is quasi-one-dimensional longitudinal waves with wavelength larger than the cross-section excluding transversal modes; this leads to an extension of the acoustic of horns that is ducts with non-uniform cross-section without mean flow, to nozzles that have an accelerated mean flow in converging sections and a decelerated convection of sound in diverging sections. The quasi-one-dimensional approximation assumes uniform flow and acoustic properties in each cross-section with variations only in the axial direction. For higher frequencies transverse acoustic modes must be considered in horns as well as non-uniform flow over the cross-section of a nozzle. A turbofan engine in a nacelle is never in a uniform flow: (i) there is a shear flow in the air inlet leading to acoustic-shear waves; (ii) downstream of the turbine the flow is swirling leading to acoustic-swirl waves; (iii) the heat exchanges in the combustion process lead to acoustic-vortical-entropy waves.

2.3 Installation and flight effects

The sound generation by open (section 2.1) and ducted (section 2.2) propulsors has been discussed using: (i) the first theory of aerodynamic sound [1-2], known as the Lighthill-Proudman theory, leading to the Ffowls-Williams-Hawkins (FWH) equation, that is most appropriate for moving bodies in a uniform stream, e.g. aircraft propeller, helicopter rotor and fan/compressor/turbine noise; (ii) the second theory of aerodynamic noise [3-4] that is less widely known, and is most appropriate for sound sources convected in a flow, such as ‘entropy noise’ in jets, vortex or BVI noise of helicopters, and also installation effects and aerodynamic noise that relate to jet noise and scattering.

3. AIRPORT NOISE ENVIRONMENT

The noise emitted by an aircraft in flight differs from that received on the ground at an airport due to atmospheric effects and the possible influence of ground composition and nearby buildings (section 3.1). The noise annoyance caused to the near airport resident depends on the objective physical outdoor-to-indoor sound transmission and also on psycho-acoustic effects related to the situation at the time, be it sleep, work or leisure (section 3.2). The mitigation of the noise annoyance to near airport residents is an objective of the planning of flight operations within the limits of flight safety and certification standards (section 3.3).

3.1 Atmospheric and ground effects

The aircraft noise recorded in flight by microphones mounted on a nearby aircraft does not coincide with that which reaches a similar set of microphones on the ground at an airport for two reasons. First atmospheric wind and turbulence modify the directivity and spectrum of sound as it propagates from the sources in the flying aircraft to the observer on the ground. Second the nature of the ground and the position relative to buildings do affect noise reception at the microphone. There is a vast literature on atmospheric and ground effects on noise.

3.2 Noise annoyance to the near airport resident

Unless the near airport resident is outside the house in the garden or elsewhere the noise annoyance will depend on outdoor-to-indoor sound transmission. The same indoor noise exposure may be more or less annoying during sleep, when doing intellectual work demanding mental concentration or when occupied with house hold tasks like cleaning and refurbishing that are noisy by themselves. At last but not least: is the noise annoyance determined solely by noise level in whatever dB scale it used, or is there a subjective discrimination of less annoying noise signatures?

3.3 Certification, regulations and limitations

The ICAO noise certification standards to provide a worldwide standard for acceptable aircraft noise. Like most bodies of the United Nations, ICAO has no authority over individual countries, and indeed local rather than central governments and airport operators can set stricter noise standards. The airport operators may have limited room for choice between local claims and court orders that limit airport operations and aircraft manufacturers can hardly ignore the requirements of major airports and hubs.

4. NOISE REDUCTION MEASURES

The simplest through not the most effective approach to noise reduction is the ‘piecemeal’ method of dealing with a specific problems at a time, often as an ‘afterthought’, trying to remedy a noise problem with weight, complexity, cost, fuel consumption and efficiency penalties. The ‘piecemeal’ approach can be applied to existing and future aircraft and can be quite effective at providing local noise reduction (Section 4.1) without affecting much overall design (Chapter 5). Generic noise reduction technologies can also be applied at design stage (Section 4.2) although some of the benefits may be partially lost in the absence of an overall design integration. Further noise reduction without hardware modifications may be result from noise abatement flight procedures (Section 4.3) consistent with safety and certification standards, air traffic management and local conditions.

4.1 Retrofittable acoustic silencing devices

While making no attempt to exhaust the list of noise reduction measures that can be fitted to an existing aircraft as an afterthought, or designed for new aircraft, some examples are mentioned starting with the ubiquitous acoustic liner. Another example is the evolution is nozzle design from lobed to chevron nozzles. The steady decrease in engine noise has made it necessary to address aerodynamic noise that may require other solutions.

4.2 Noise mitigation technologies

The generic noise mitigation technologies, like passive sound absorption and active noise and vibration reduction can be applied to aircraft, and can be complementary since the former is more effective at higher frequencies and the latter at low frequencies. Both techniques have limitations and penalties associated with extra weight or equipment and cost. The noise reduction at the source would be the preferred alternative when feasible.

4.3 Noise abatement procedures

The aircraft noise disturbance can be reduced by suitable operating procedures, like approach to land with the engine at idle and thrust cut-back as soon as possible after take-off without compromising flight safety. The aim is to reduce the noise footprint, that is the area on the ground subject to noise levels higher than the threshold deemed acceptable. Depending on the local housing distribution around the airport relative to the runways, it may be possible to reduce the noise footprint by modified flight paths again within safety, certification and air traffic management (ATM) procedures.

5. NOVEL AIRCRAFT CONFIGURATIONS

Starting with the conventional Cayley-style tube-and-wing aircraft configuration and using all the available noise reduction technology is expected to lead to an overall noise reduction of about 10 dB as an average of the three certification measuring points. Making the aircraft inaudible outside the airport perimeter would require a noise reduction of about 30-40 dB. A noise reduction well in excess of 10 dB, even well short of 30 dB is most likely to be unachievable with a conventional aircraft configuration. This suggests the consideration of radical new aircraft configurations, such as a flying wing, buried engines or distributed propulsion (section 5.1). The risks and maturation time may relegate these to longer term prospects, prompting the consideration of improvements to the current conventional aircraft (section 5.2). A compromise proposal is an evolutionary low-risk design optimized differently for ducted and unducted propulsions (section 5.3).

5.1 Radical new designs

Among the many alternatives for radical new designs, the flying wing is chosen since it provides better noise shielding than say a joined wing. Further noise reduction may achieved replacing the engine nacelles with buried engines or using a distributed propulsion system. The consideration of these more radical novel aircraft configurations cannot ignore the technological challenges and maturation that may defer these concepts to longer term prospects beyond the next generation.

5.2 Evolutions of the conventional configuration

In order to make feasible the application in the next generation of aircraft, that must be based on available data bases and consolidated certification experience, it is more prudent to consider evolutions of the current conventional tube-and-wing aircraft configuration with greater noise reduction potential. Two examples are: (i) the U-tail with engines in between to achieve better noise shielding; (ii) engine nacelles joining the trailing-edge of a low wing to the leading-edge of a low tailplan. Besides evolution of airframe configurations, that affect aerodynamic noise and shielding of engine noise, the role of the engine as noise source implies considering the evolution of propulsion systems ranging from the contrarrotating open propulsors to the variable-cycle turbofan.

5.3 Low-noise cruise-efficient aircraft

At the beginning of the jet age aircraft noise was an afterthought: hence the multi-lobe nozzle used to reduce jet noise at the expense of drag, thrust and fuel consumption. The remarkable technical achievement of Concorde and the noise issues that it raised, contributed to the consideration of noise earlier in the aircraft and engine design process, as is nowadays the case. The next grand step of conceiving low-noise aircraft configurations poses greater challenges since there are many other objectives to be met, and not all are easily compatible. A simple demonstration is to conceive an aircraft optimized for low take-off and landing noise: it would resemble a glider, with an unwept wing of high aspect ratio for low stall, take-off and landing speeds, hence low aerodynamic noise, and an engine with low jet exhaust speed from relatively slow rotating turbomachinery. The implications for cruise efficiency would be dire: low thrust, high drag, high fuel consumption, high emissions, low speed and long duration flights. The design targets for low noise at the airport can be at odds with high cruise efficiency, and the main challenge is to achieve the former without compromising the latter. Thus high-cruise efficiency is one of the multiple requirements to be considered for a low-noise aircraft configuration, that may differ for ducted engines in nacelles and open rotors since they pose different challenges. An additional issue is combining low noise with low emissions, that would justily a separate disunion.

6. CONCLUSION

The present paper has addressed some of the issues relating to aircraft noise at airports across the full ‘cradle to grave’ spectrum of aeroacoustics research (chapter 2), through environmental (chapter 3) and operational (chapter 4) aspects to aircraft design (chapter 5). The review of aeroacoustics research (chapter 2) has focused on some aspects not widely known but that could have considerable impact such as: (i) the existence of two alternative theories of aerodynamic noise [1-2] and [3-4]; (ii) the coupling of sound with vortical and entropy modes in jet engines [5-6]. The account on sound transmission from the aircraft noise sources to the interior of the near aircraft residence (chapter 3) has included: (i) the spectral and directional broadening of noise [7-8]; (ii) the psychoacoustic distinctions between noise components. The noise mitigation measures (chapter 4) mentioned include: (i) optimization of non-uniform acoustic liners [9-10] and use of partial chevron nozzle [11]; (ii) low noise operating procedures consistent with flight safety and air traffic management rules. The proposed low-noise aircraft designs (chapter 5) differ for ducted engines in nacelles and open rotors to: (i) retain uncompromised cruise efficiency; (ii) rely only on mature technology certifiable for the next generation of aircraft.

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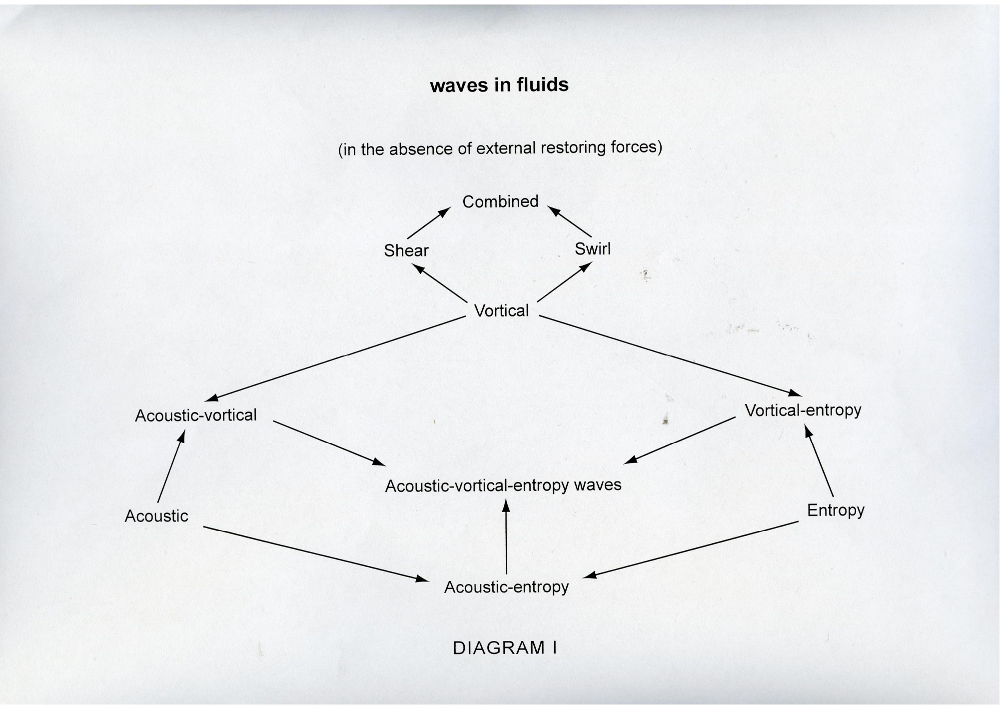

Diagram 1. There are three types of waves in a fluid (in the absence of external restoring forces): (i) sound waves associated with compressions and rarefactions; (ii) vortical waves due to shear and/or swirl; (iii) entropy waves associated with heat exchanges. There is the possibility of two or three wave couplings.

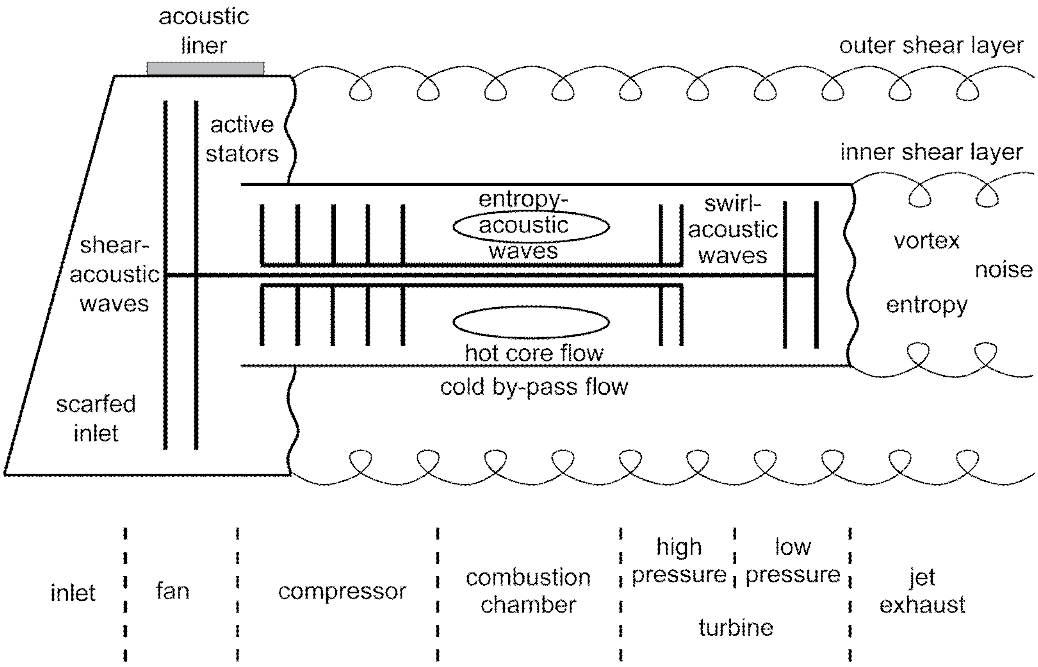

Diagram 2. Schematic of a turbofan engine indicating wave sources and types of waves.

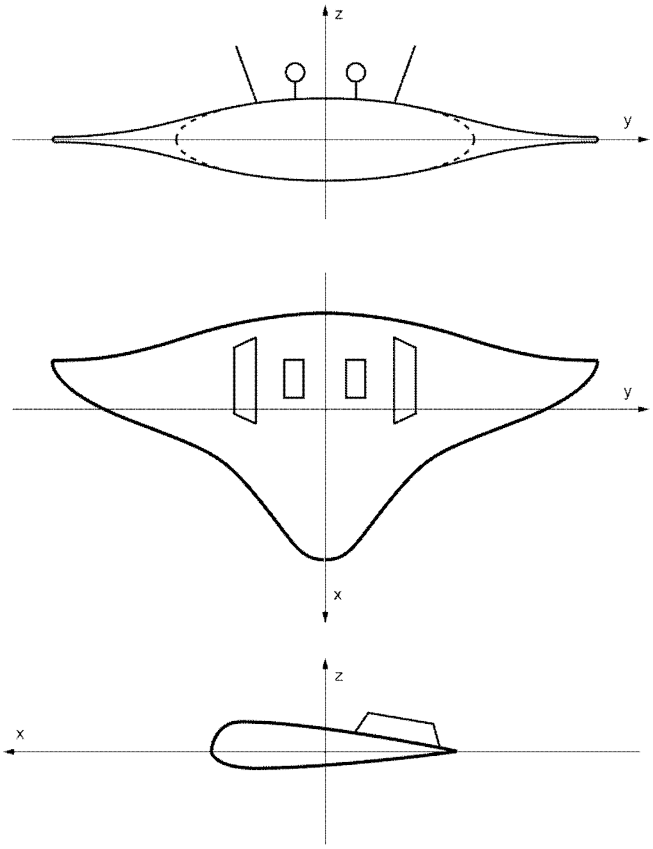

Figure 1. The blended wing body (BWB) with overwing nacelles is a favourable configuration for noise shielding.

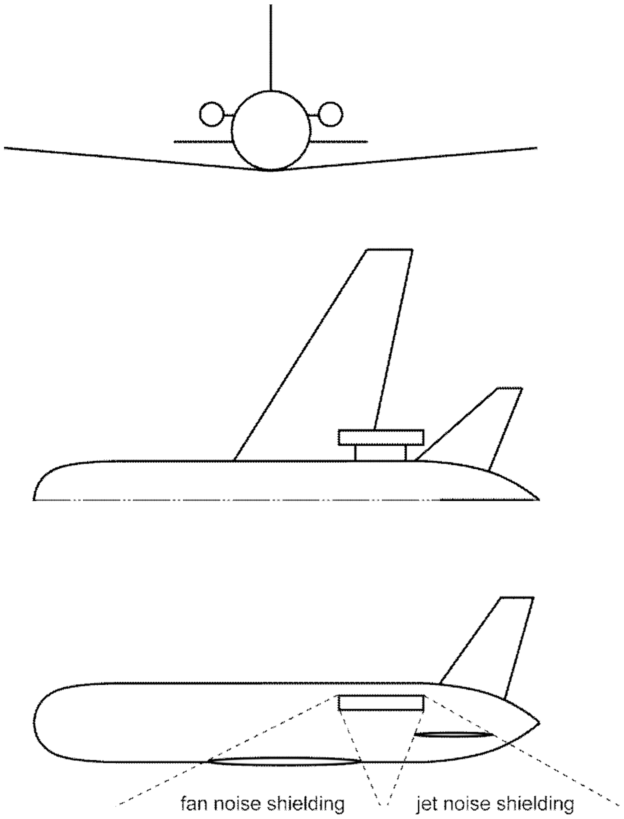

Figure 2. Noise shielding can also be achieved with conventional tube-and-wing aircraft configurations.

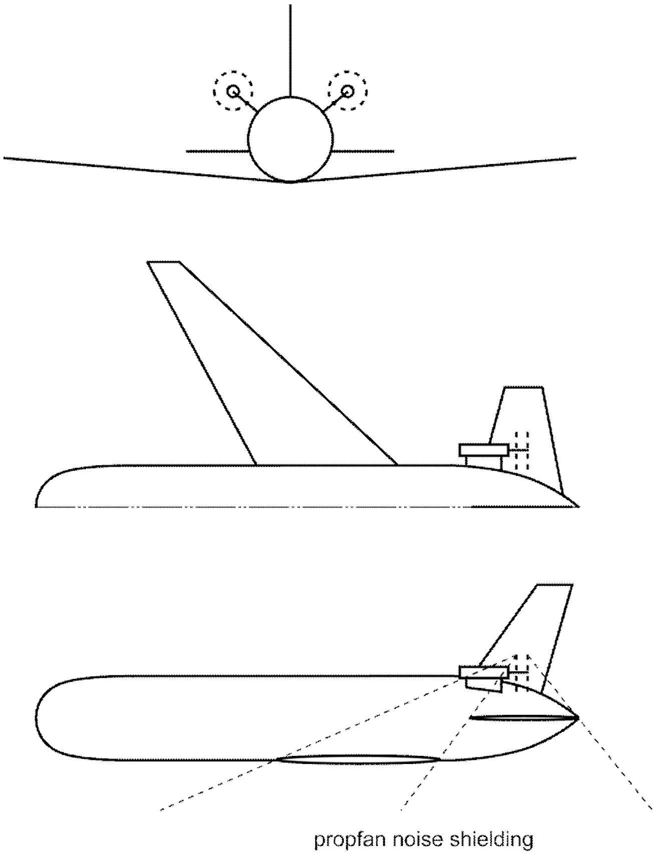

Figure 3. If certification requires that the prop-fan has to be located behind the pressurized fuselage section, then noise shielding may require a forward swept or joined wing configuration.