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INSTALLATION NOISE EFFECTS OF PROPULSION-AIRFRAME INTEGRATION: AN OVERVIEW

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Abstract. *Installation effects in aircraft external noise is the name given for some acoustic changes produced when the propulsion system is integrated to the rest of the airframe. They can be grouped into those issues having to do with flow-to-flow or flow-to-structure interactions and those having to do with wave propagation, although they are not entirely unrelated. Further studying those effects is nowadays being considered as a key element for achieving industry's future goals of noise reduction. This paper presents an overview of some approaches and analytical tools for quantifying these effects. Experimental data and community noise final numbers are also investigated.*

Keywords: Installation Noise, Engine-Airframe Integration, Aircraft Noise

1. INTRODUCTION

One of the most important decisions during preliminary design phase of jet aircraft is to determine the location of the engines around the airframe body. Many configurations have been historically tested but the most selected ones are still the under-wing mounting, followed by the rear fuselage mounting concept (Figure 1). The choice for one configuration instead of another is usually driven by maintainability, safety assessment or performance issues. Only rarely is aero-acoustics or sound propagation included among them. However, further studying those installation effects is being considered nowadays as a key strategy for achieving the industry's goals for noise reduction in near future (Thomas, 2003).

Figure 1. Examples of propulsion-airframe integration solutions. Source: (www.airliners.net)

1.1 Background

Installation effects in aircraft external noise is the name given for some acoustic changes produced when the propulsion system is integrated to the rest of the airframe. They can be grouped into those issues having to do with flow-to-flow or flow-to-structure interactions and those having to do with wave propagation, although they are not entirely unrelated (Thomas, 2003). They can appear in many degrees of intensity for different aircraft configurations and seem to depend on a large variety of design parameters in a quite complex way. The most affected region, according to Elkoby (2005), seems to be the forward angles of emission in all parts of the frequency spectrum.

Flow interaction effects, also known as Propulsion-Airframe Aero-acoustic (PAA) effects, are caused by the flow field of one component interacting with another. They can create new acoustic sources or just modify existing ones already associated with each component (Thomas, 2003). Studies based on experimental investigations (SAE/ARP-876E), (Elkoby, 2005), (Senzig et al, 2001) have suggested strong correlation between those effects and some aircraft

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parameters such as location and orientation of the installed components, as well as flight Mach number and angle of attack. Other experimental evidences (Clark et al, 1973), (Shivashankara and Blackner, 1997) point towards a flap deflection dependence. An example of PAA effect is the influence of the engine mounting pylon on exhaust jet. The influence of the pylon creates flow features in the jet that are not present in an isolated jet. Another example is the interaction of the exhaust flow with an extended flap particularly for the engine-under-the-wing configuration.

Other important effects brought on by propulsion-airframe integration would be some pure acoustic propagation phenomena such as reflection, diffraction or refraction of sound waves off airframe surfaces and/or jet plume. Reflections are usually applicable to higher frequencies while low frequency noise is more suitable to diffraction (Elkoby, 2005). Therefore aircraft with rear mounted engines tend to have fan/inlet noise shielded by the wing, (Lieber, 2000) while under-the-wing configurations, in the other hand, can be affected by wing reflection (Lieber and Brown, 2000).

2 ANALYSIS AND EVALUATION OF SOME INSTALLATION EFFECTS

The following sections present results obtained from analytical and experimental investigations with the goal of better understanding the aero-acoustics of installed jets. The topics are separated into effects generated by flow field interactions and pure acoustical propagation effects.

2.1 Engine Position Effects

A simple empirical method is proposed at SAE/ARP-876E an Aerospace Recommended Practice for under-wing-mounted configuration where the engine positioning is modeled by a few geometric parameters, shown in Figure 2.

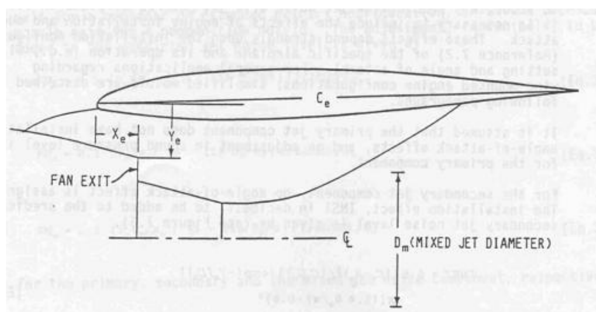

Figure 2. Engine Positioning parameters. Source: (SAE/ARP-876E)

Those parameters are then related to the correction INST, in dB which is added to the Overall Sound Pressure Level accounted for the engine noise, as follows:

$$INST = 0.5 \cdot \left[\frac{(Ce - Xe)^2}{Ce \cdot Dm} \right] \cdot \left[\frac{1.8 \cdot \theta_s}{\pi} - 0.6 \right]^2 \cdot EXP\left(\frac{-Ye}{Dm} \right) \qquad \textbf{(1)}$$

Where, θs is the angle of emission, of the sound radiated from the secondary jet or fan exhaust flow considered in SAE's model as a single point acoustic source contributing to the total engine exhaust noise.

If one groups parameters from Eq. (1) into non-dimensional quantities in order to make a reduction on the number of variables, it gets possible to come up with a few interesting insights. At first it is necessary to introduce the description and mathematical definition of each new quantity, which are found on Table 1.

Table 1: Synthesis of ARP876 inputs for installation noise effects

Synthesized parameter	Description	Unit	Formula
S_{ref}	Normalized gap area	none	$\left[\frac{(Ce-Xe)^2}{Ce \cdot Dm}\right]$
h_{ref}	Normalized height	none	$\left(\frac{Ye}{Dm}\right)$
a	constant	rad	0.6
b	constant	none	1.8/π

Equation (1) is then turned into Eq. (2), as follows:

$$INST = 0.5 \cdot S_{ref} \cdot (a \cdot \theta_s + b)^2 \cdot EXP(-h_{ref}) \quad \textbf{(2)}$$

Now it is possible to compare different size aircraft in a common basis, as long as the dimensions listed on **Table 1** are known. The color map from Figure 3 makes it clear weather an aircraft has an advantage of installation or not. Although the differences may seem small (less than 1 dB) they can have a great role in certified noise levels. The angle θs is fixed in 120° which can be considered as an average value for the maximum lateral noise point.

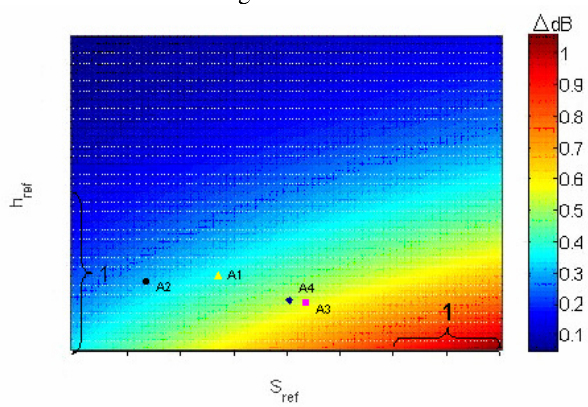

Figure 3. Engine position contribution map for θ_s fixed in 120°

The points marked in Figure 3 represent real dimensions from representative commercial airplanes with under wing mounting configuration.

2.1.1 Evidences of Engine Installation Effects in Real Certified Noise Levels

The importance of installation effects in aircraft noise gets once again clear when one looks at the certified noise levels from two engine aircraft which is public information available at official websites (http://noisedb.stac.aviation-civile.gouv.fr). Figure 4 reveals the margin to Stage 3 noise limit for lateral measurements of some similar aircraft. All values represent average levels normalized to a common reference thrust more suitable to each weight class. Some basic data from the selected aircraft can be checked on Table 2 for comparison.

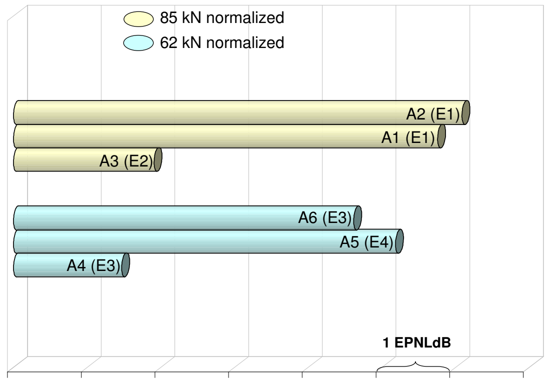

Figure 4. Normalized Stage 3 margin for certified for lateral noise of two engine aircraft

Table 2: Similar aircraft basic data

Aircraft	Engine	MTOW (tons)	Nominal TO thrust per engine (kN)	Engine installation
A1	2x E1	56.0-77.0	96.1-120.1	Under wing
A2	2x E1	52.6-79.0	82.9-120.1	Under wing
A3	2x E2	47.8-51.8	77.4-83.7	Under wing
A4	2x E3	35.9-38.7	59.7-62.5	Under wing
A5	2x E4	41.0-45.8	61.6-65.5	Rear fuselage
A6	2x E3	32.9-38.3	61.3-64.5	Rear fuselage

It is interesting to observe that even though when they correspond to the same engine, thrust class and basic configuration, the margins do not agree. Furthermore it is possible to confirm some trends already expected. For instance, the disadvantage of installing the engines under the wing (see A4 values and its thrust class counterparts A5 and A6) can be clearly observed. The advantage of A2 against A1, A3 and A4 in the color map from Figure 3 is also preserved for the certified levels.

2.2 Angle of Attack Effects

It seems quite intuitive that flight effects may also affect the resultant engine noise during real operation. Although the aero-thermodynamics of the isolated engines merged in a moving air is carefully simulated and experimentally tested before installation there are still a lot of technological challenges on predicting the behavior of installed jets.

Experimental evidences show that this scenario is even more critical for wing mounted configurations. Aerodynamic effects such as the downwash imparted by the wing and flaps, for example, can lead to distortions of the jet plume together with turbulence increase (Elkoby, 2005). Additionally, the deceleration imposed by the flow field under the wing usually increases the relative velocity between jet and ambient and hence increasing shear layer noise.

Once again the most widely known attempt to include a few of those aero-acoustic effects in predictions of in-flight jet noise is another semi-empirical model from (SAE/ARP-876E). Designated as the “Angle of Attack Correction”, it suggests a correction of the predicted OASPL for coaxial jets as a function of the Aircraft Mach number (*Ma*) and the angle of attack (α). Similarly to the engine installation correction it is also a function of the angle of emission of the most contributing acoustical source (θ_m), which is considered here as the completely mixed jet. The mathematical expression for computing this correction is presented in Eq. (3), bellow:

$$ATK = 0.5 \cdot \alpha \cdot M_a \cdot \left[\frac{1.8 \cdot \theta_m}{\pi} - 0.6 \right]^2 \tag{3}$$

At first glance this method as it is presented is unlikely to provide any feasible opportunity of improvement. That is because it is solely function of flight parameters which are too complex to modify from design without compromising performance. In order to seek for design solutions to minimize installation effects, the following adaptation is here proposed:

It is assumed that the effective angle of attack experienced by the engine would be the sum of the thrust angle (α_F) and the aircraft in-flight angle of attack (α_a), as shown in Figure 5:

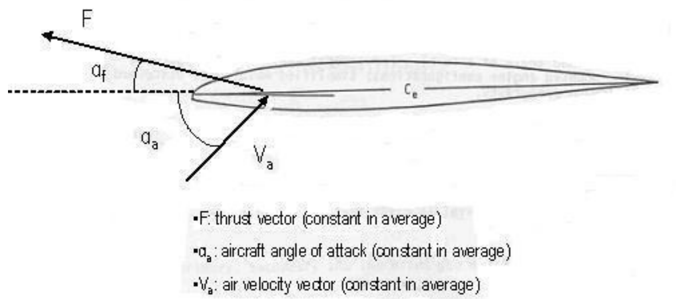

Figure 5. Thrust angle illustration

Equation (3) then turns into Eq. (4):

$$ATK = 0.5 \cdot (\alpha_a + \alpha_f) \cdot M_a \cdot (a \cdot \theta_m + b)^2 \tag{4}$$

Now it is possible to run a sensitivity analysis of the "Effective Angle of Attack Correction" to a concrete design parameter. The results plotted in Figure 6 were obtained for a hypothetical aircraft during a typical take off trajectory. The flight conditions (height, Mach and α) were selected such as to simulate the maximum sideline noise point during fly-by. It is observed that a 6o variation in α_f can only produce more than a 0.1 dB increase for emission angles greater than 95°. That direction is coincidentally around the average director angle correspondent to the maximum sideline noise measured during noise certification procedures.

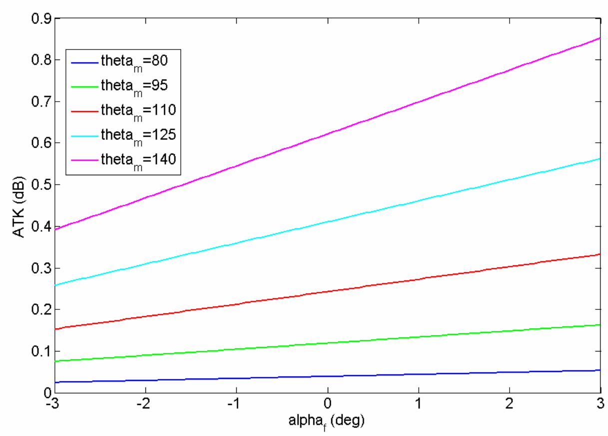

Figure 6. Parametric analysis of angle of attack correction

2.3 Jet-Flap Interaction

The interaction between engine exhaust gases at high velocities with the flaps located just downstream, is an important contributor to total noise levels from engine under wing configurations. The design of the flaps and the engine installation must observe this interaction or the aircraft will be penalized with high noise levels for some flap settings (Embraer Internal Report, a). Some experimental evidences can clearly show the influence of flap setting on the noise from installed engines.

Figure 7 present some results from ground static tests, when there is no aerodynamic airframe noise. It can be observed that the most affected regions are the forward and lateral angles, what is probably (Elkoby, 2005) a consequence of the exhaust jet noise diffraction off the flap trailing edge. This can be confirmed by the correspondent spectra at the 90° direction which shows a significant increase at low frequencies, typically dominated by jet noise.

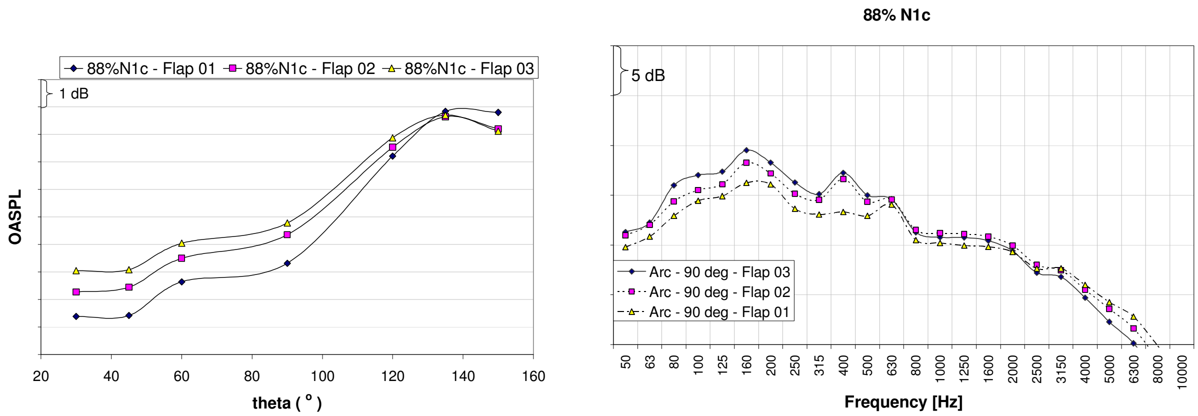

Figure 7. Engine OASPL directivity (left) and 90^o 1/3 octave spectra (right) for several flap settings at TO thrust

Another expected result (Shivashankara and Blackner, 1997) confirmed in most cases is that noise levels tend to increase monotonically with flap deflection. Figure 8 shows an attempt of correlating the flap angle with the OASPL. This is not a simple task, though, as the amplitudes of the increases are about the same order of the associated errors. Another important issue to keep in mind is that each thrust rating and direction angle may be differently correlated with flap angle due to flow changes and asymmetry of the boundary conditions.

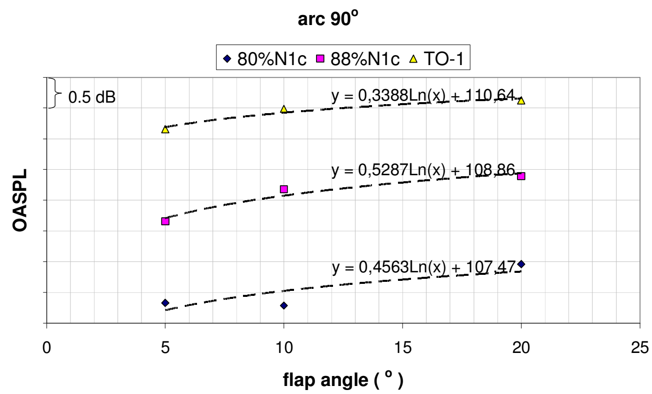

Figure 8. Engine noise correlation with flap angle for typical take off thrusts at the 90o arc

Similarly from what is suggested in Figure 8, earlier studies (Clark et al, 1973) propose a simpler linear correlation between OASPL and flap angle. His model gets even further with a complete prediction of noise levels including corrections for distance to receiver, direction and exhaust nozzle size. The influence of the individual flap aerodynamic noise is modeled by the 6th power of an average velocity incident on the high lift devices leading edges. Equation (5) is the basis for the model.

$$OASPL_{ref} = K + 10 \cdot Log\left[\left(\frac{A}{A_0}\right)\cdot\left(\frac{R_0}{R}\right)^2\right] + 60 \cdot Log\left(\frac{V_{eff}}{V_0}\right) \qquad \textbf{(5)}$$

Where, K is the correction associated with the flap angle (ψ) by means of a linear model, written in Eq. (6).

$$K = 865 + 0.14 \cdot \psi \qquad \textbf{(6)}$$

The effective velocity V_{eff} incident on the flaps is calculated based on the assumption that flap noise is basically a dipole associated acoustical source. So an averaging is made between the 6th power of the individual exhaust velocities coming from both the core and fan exits, as follows:

$$V_{eff} = \left(\frac{A_c \cdot V_c^6 + A_f \cdot V_f^{\,6}}{A_c + A_f} \right)^{1/6} \tag{7}$$

As mentioned before the reference noise level $OASPL_{ref}$ should additionally suffer corrections for direction changes which are usually empirical. For complete predictions it is also desirable to build an empirical shape function for the general spectral behavior of the jet noise in order to model frequency domain characteristics. The model assumes that the spectral characteristics from pure exhaust jet noise are preserved after jet flap interactions.

2.4 Airframe surfaces reflection

It is quite intuitive that the sound produced by engines may reflect on airframe surfaces. This can increase noise towards community whenever the engines are mounted under the wing of airplane. Most models developed for predicting sound waves reflections are based in a combination of direct application of ray-tracing theory and simple sound propagation models. It is also interesting to comment that the assumption of a simple doubling of the acoustic energy when a reflection is identified after a pure geometric analysis turns out not to be very accurate. In general the following acoustic effects are expected to contribute to final far-field noise levels:

- Emission angles can differ from direct and reflected rays changing the associated directivity correction
- Higher frequencies are more susceptible to reflection
- Lower frequencies are more susceptible to diffraction and absorption
- Path differences between direct and reflected ray may cause phase cancellation effects, as both are physically caused by the same source
- Too curved surfaces may produce much more complex reflection patterns
- Steps and gaps in real airplane structures may cause additional losses and deviations which are difficult to simulate

2.4.1 Wing and flaps reflection

In the model proposed by Lieber and Brown (2000), the wing and flaps are considered as flat reflecting panels and a so called image source approach is used calculation of reflection points. Because of their small contribution to far field noise enhancement, multiple reflections are not accounted in the model. The schematic drawing of Figure 9 shows the path of reflected sound rays off wing and flap panels for consecutive wing orientations (left) in simulated leveled trajectories (right). The calculations were made for 3 flat panels and a single ground observer.

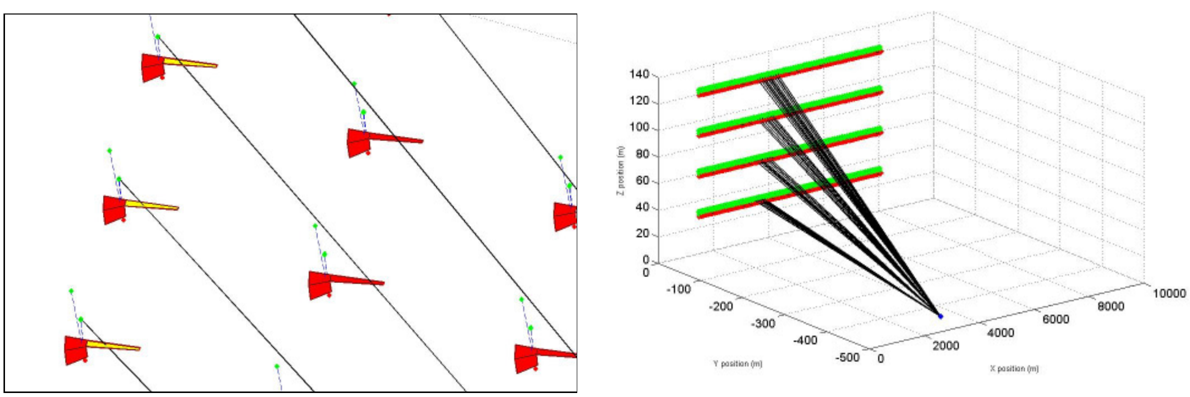

Figure 9. Reflected ray paths from each panel's imaginary source (left) to one single ground observer (right)

The effects of such reflections on calculated PNLT histories are found in Figure 10. The blue curves correspond to direct incident sound only, while the red ones include the wing/flaps reflections. The results show that, for this geometry model, reflections affect low emission angles for flyover and the reflection surface hit is the deflected flap panel. For lateral pass-by or sideline, in the other hand, is the outer board wing panel the surface responsible for reflection which is only observed at very high emission angles.

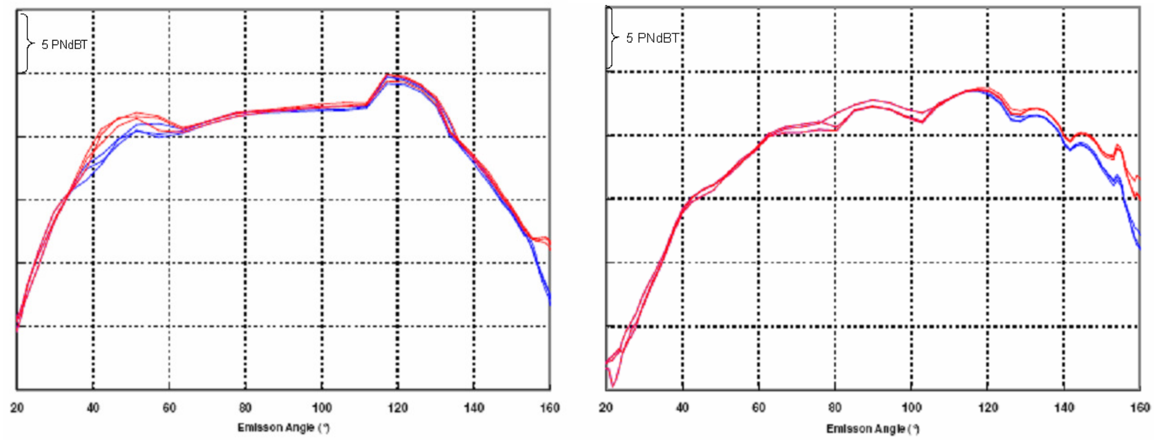

Figure 10. Wing/flaps reflection effects on calculated PNLT history for flyover (left) and sideline (right) trajectories

Further considerations, such as adding different absorptive properties, spectrally uniform or not, to each surface can contribute to more sophisticated models. Reflections are usually applicable to higher frequencies while low frequency noise is more suitable to diffraction or transmission to inner structures (Lieber and Brown, 2000).

2.5 Noise Shielding by Airframe

A few discussions may often rise during preliminary design phases regarding the benefits of some engine mounting configurations on engine noise shielding by airframe body. One claim that seems to be pretty much logical at first glance is that: if the receptor does not see one or more of the engines, the experienced noise associated may be lower. A more careful analysis, though, shows that there are some tricky aspects involving this issue.

2.5.1 Wing Shielding for Rear Mounted Engines

The first aspect to keep in mind is that sound is a traveling mechanical wave and so it is submitted to all wave properties. Diffraction property, for instance, enables a source hidden by a perfectly reflective barrier to be heard at the other side depending on wave length and barrier size. So a complete shielding is never achieved and it is mandatory for any shielding model to include frequency dependence features.

A model proposed by Lieber (2000) employs the Fresnel diffraction theory for a semi-infinite barrier. One of the key parameters for the model is the difference between the direct path from source to observer and the paths passing through the nearest point W of each wing edge, as shown in the schematic drawing of Figure 11.

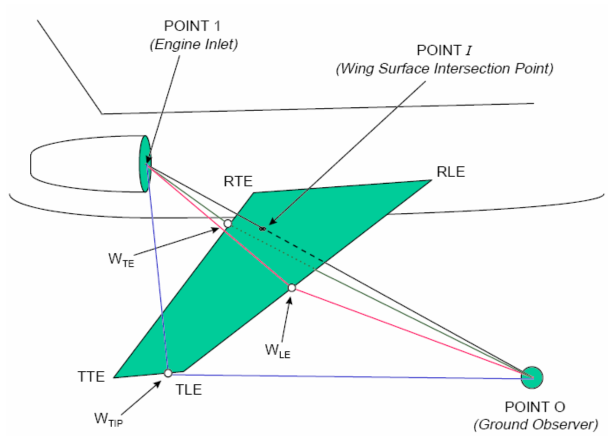

Figure 11. Wing shielding – ray paths. Source: (Lieber, 2000)

The accuracy of this method is strongly related to the model adopted for the acoustic source. Number and location of the sources as well as frequency domain characteristics and directivity may produce quite different results. Simulations for take off and approach conditions are presented in Figure 12. It can be observed that shielding is more effective for the approach configuration when inlet noise is dominant. The simulations also confirm the low influence of wing shielding at aft emission angles where generally exhaust noise is dominant.

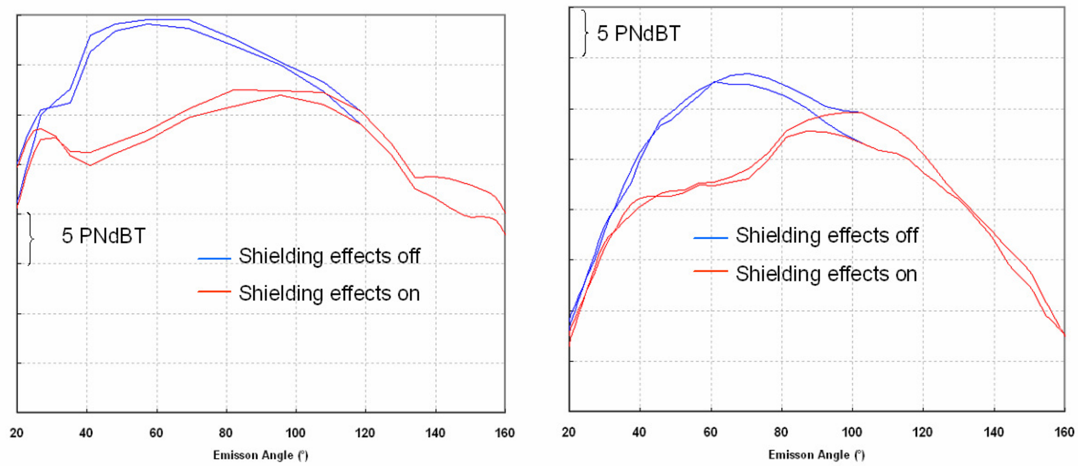

Figure 12. Wing shielding for approach (left) and TO (right) configuration

2.5.2 Fuselage Shielding for Under Wing Mounted Engines

The majority of commercial aircrafts have the wing mounted on bottom region of the fuselage with engines just under them. Suchlike configurations not only tend to increase installation effects but also enable lateral observers to receive direct sound rays from both engines for almost all fly-by trajectories. This last effect could be attenuated in upper wing configuration design, as some shielding of the opposite side engine noise is expected.

A few interesting insights then may arise after a simple geometric analysis of this case. The schematic drawing of Figure 13 shows the two possible ways (excluding wing reflection) in which a lateral observer could be exposed by sound rays coming from the engines.

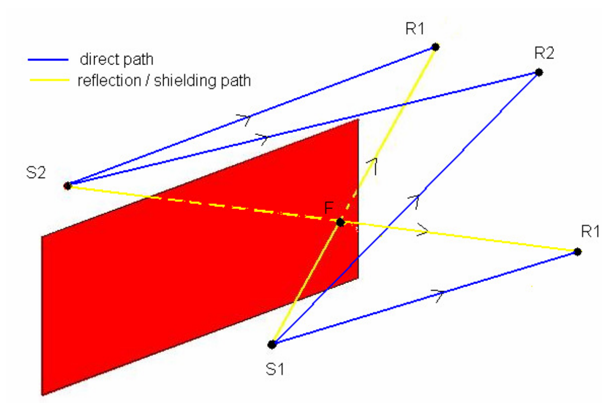

Figure 13. Fuselage shielding – ray paths

It turns out that due to the symmetry of the engine location a receptor exposed to fuselage shielding (R1) is also necessarily affected by fuselage reflections. Receptors located in positions such as R2 would only experience direct sound rays coming from both sources.

This scenario does not mean that the noise resultant in receivers of type R1 would be the same as if the airplane configuration had wing mounted at the bottom, plus the diffractions from the shielded engine. Other acoustic effects such as directivity changes between direct and reflected rays, as well as phase cancellation may produce special features at the final noise levels. So a deeper analysis should come up with more solid conclusions.

An adaptation of the “Wing Reflection Code” (Lieber and Brown, 2000) for fuselage reflection/shielding case was developed so that the fuselage surface is modeled as a rectangular flat, perfectly reflective panel. Point sources and panel locations are modified values of a real commercial jet coordinates in order to approximate for a cargo type aircraft with similar weight and size, such as in Figure 14. Constant height passages were then simulated with receivers located at a lateral position. Changes in aircraft attitude other than leveled flight conditions were neglected. The reflection paths identified for this case are plotted in Figure 15.

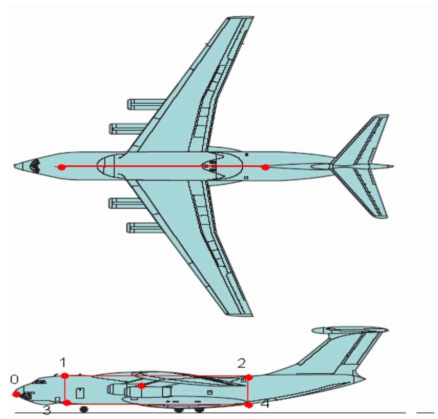

Figure 14. Modeling the fuselage surface of an upper wing type cargo by flat panels

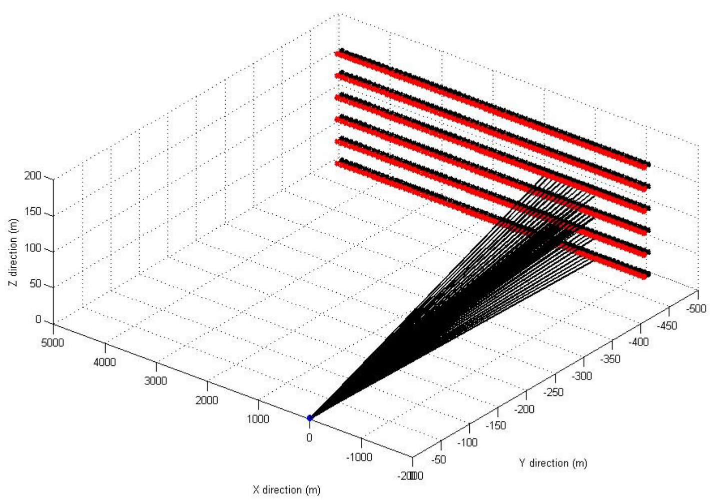

Figure 15. Calculated fuselage reflected rays for a hypothetical upper wing airplane during constant height passages

In the present case it is important to comment that although the fuselage may interfere on the noise at the observer point, it would hardly affect certification levels for example. The reason is that the reflections occur only for too low altitudes (less than 200 m) where other phenomena such as lateral attenuation and ground absorption are dominant.

2.6 Lateral Attenuation

Lateral Attenuation is a name given for a difference observed between one microphone under the flight path and another one, equidistant to the aircraft in a lateral position. Despite of being two apparently equivalent measures there seem to be additional effects related with ground absorption of grazing sound waves (specially for low altitudes) as well as some directivity in the aero-acoustics of engine/airframe integration. The attempts of modeling such phenomena in separate from the other installation effects are a bit misleading though. So what is usually made is a quite empirical approach in which the difference in noise measured by a receiver right under the flight path and another one shifted side wards is mapped into common geometrical parameters during flight.

The first widely known model for Lateral Attenuation was the SAE/AIR-1751. Other improvements were later proposed in SAE/AIR1906 and SAE/AIR-5662. In summary they basically propose an exponentially decaying rule which is a function of the elevation angle between ground and the direct receiver-to-source distance, and the ground distance between receiver and source (see Figure 16). Sometimes the aircraft bank angle is also taken into account SAE/AIR-5662.

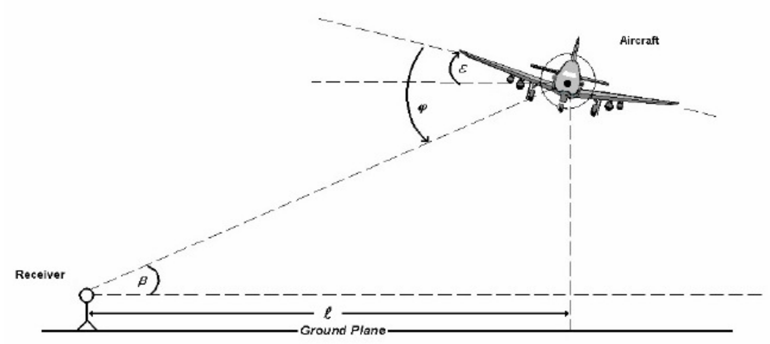

Figure 16. Relevant parameters for Lateral Attenuation. Source: SAE/AIR-5662

One interesting insight about these methodologies is that, for the same distances and elevation angles, any measured difference in noise between two distinct aircraft could be accredited to “pure” installation effects. Thus, models that consider a wide variety of aircraft configurations in there experimental database are able to track installation effects due to different engine positions. That is the case in SAE/AIR1906 and SAE/AIR-5662. To illustrate this tracking capability two studies are shown next, one experimental and the other analytic.

Some studies sponsored by NASA (Senzig et al, 2001) have put in confront experimental flight data from tail mounted and under wing engine aircrafts with SAE/AIR-1751 predictions. From Figure 17 it can be observed that SAE/AIR-1751 generally agrees more with the tail-mounted case which is the configuration of the database used for building that model.

The second study illustrated in Figure 18 refers to analytically built PNLT histories (as a function of angle of emission) for a hypothetical flight passage from two distinct configuration aircraft over a lateral ground observer. This is a direct implementation of AIR’s 1751, 1906 and 5662 on an isolated engine noise model extrapolated to flight conditions. The plots also show the engine self noise as a reference and an additional installation effect extracted from the analytical models in prior the sections of this article. Indeed the tail mounted configuration presents more Lateral Attenuation for almost all angles of emission while the under wing mounted seem to have its potential cancelled by noise increase from wing reflection.

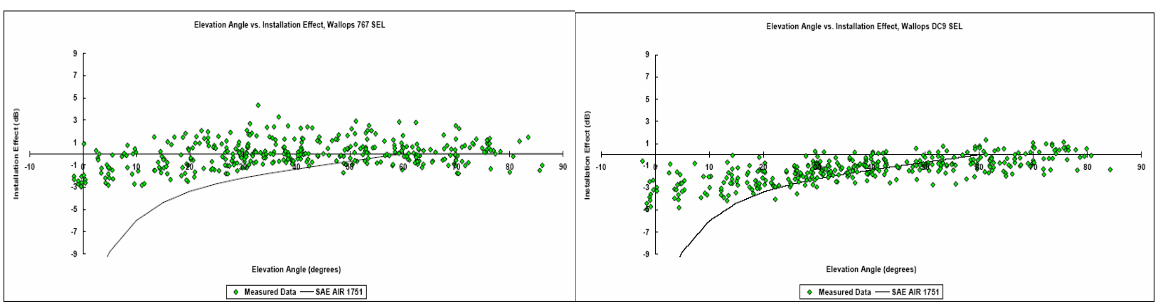

Figure 17. Predicted and measured Lateral Attenuation for a wing-mounted engine (left) and tail-mounted (right). Source: (Senzig et al, 2001)

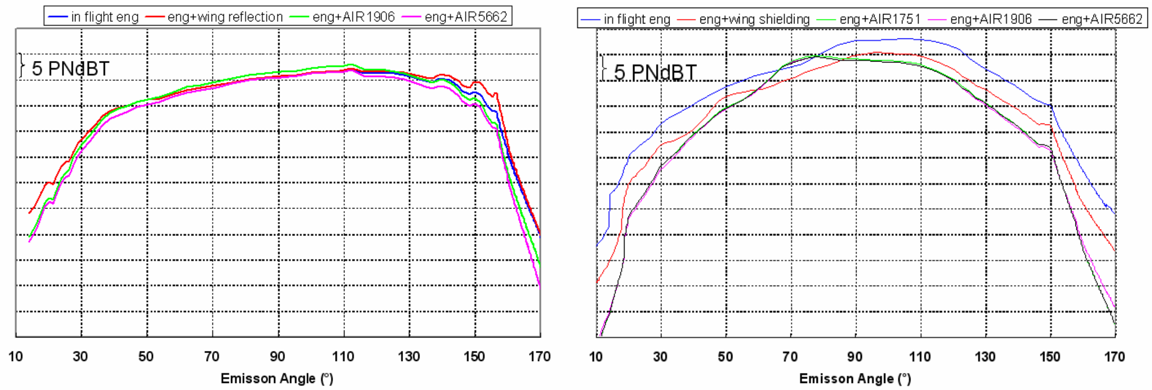

Figure 18. Lateral Attenuation models results for a simulated tail-mounted (left) and under wing (right) configuration

2.7 Conclusions

This paper has presented a collection of results from studies related to acoustical effects of engine installation in jet aircraft. The information presented is an overview of the topic which is being considered as a key element that challenges the industry's goals for noise reduction in the near future. Current limitations of computational aero-acoustics are pushing engineers into the adoption of semi-empirical models and expensive test. The reliability of such model is a major concern for their results impact directly preliminary design phase.

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