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THE PREDICTION OF AIRFRAME NOISE AND COMPARISON WITH EXPERIMENT

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The success of the high bypass ratio turbofan engine in reducing the external noise of civil transport aircraft at take-off and landing, while improving the economics of air travel, has opened up the debate as to how much further it will be possible to reduce aircraft noise by the introduction of new aircraft or existing aircraft retrofitted with new engines. Irrespective of what new technology can offer in respect of further engine noise reduction for no loss of performance, it is now clear that all future aircraft will require airframe noise to be reduced on the approach, since today it is comparable with engine noise. This paper discusses the major components of airframe noise and reviews the present state of airframe noise prediction. Finally, a comparison is made between prediction and experimental data and the prospects for airframe noise reduction.

1. INTRODUCTION

Since the beginning of the jet transport age in the early 1950s, Civil Transport Aircraft have produced, at take-off and landing, an unwanted noise nuisance, annoying all populations living close to both major and minor airports throughout the world. Land-use planning has in a few cases enabled new airports to be built far from the centres of population. But even in such cases soon after the airport was built, housing developments began to encroach on the airport and it became inevitable that the new residents made claims that the noise from aircraft plus the noise from road traffic approaching the airport were intolerable. The control of aircraft noise in the vicinity of airports from the late 1960s to the present day has been by monitoring the aircraft noise at every take-off and setting statutory limits which could not be exceeded. In addition, the noise from all new aircraft have to meet stringent levels set by FAA in FAR Part 36, and ICAO Annex 16. Currently, all Civil Transport Aircraft have to meet the limits set by FAR Part 36 Stage 3 and the possibility exists of a further requirement to meet a new Stage 4 limit in the near future. Naturally, the concerns of the people exposed to aircraft noise are central to all Noise Certification but the noise limits have to be carefully selected within the bounds of the available technology and the economic viability of the aircraft. Continuing research and development is making new technology available for the design of quieter aircraft. Due to the great success in noise reduction methods during the past 40 years the further noise reduction although desirable is more difficult to achieve. The main source of aircraft noise in the past has been that of engine noise. However, the changeover from the straight-jet engine to the high-bypass ratio

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front-fan engine has not only produced a large reduction in its radiated noise, but at the same time has resulted in a reduction in the fuel burn and a consequent economic benefit to civil aviation. It is not often a solution to noise reduction is paid for by a gain in economic benefit. However, today on the approach it is found that the noise from the airframe is only marginally lower than the engine noise and in some modern transport aircraft the engine noise is less than the airframe noise as a result of noise arising from the high-lift system, the flaps and slats, and the undercarriage. Further reduction in Aircraft Noise can therefore only be achieved by the joint reduction of both airframe and engine noise.

Research into airframe noise prediction and reduction had already started in the early 1970s. This research was reviewed by Crighton [1]. Crighton defined airframe noise as the non-propulsive noise of an aircraft in flight and includes the noise of a glider. However, an analysis of the results of this theoretical and experimental programme showed that the peak values of airframe noise were of the order of 10 dB below those of the engine at the three check points used in Noise Certification, namely at take-off 6500 m from the start of roll, sideline at 450 m, and during the approach at 2000 m from touchdown on a three-degree glide-slope. The experimental data recorded on aircraft noise assisted in the formulation of an empirical airframe noise prediction method published by Fink [2]. Current aircraft design technology, in regard to high-lift devices, renders sections of this manual obsolete, so that as a prediction tool it is not reliable. One outstanding feature of airframe noise is its scaling with aircraft speed. If we take as a baseline case the noise on the ground below the aircraft in straight and level flight at some nominal flyover speed without flaps, slats and undercarriage deployed, and with the engine cut back, we find that for a wide range of civil aircraft, as well as for gliders and birds, the noise intensity at ground level varies approximately as V^5 where V is the aircraft flyover speed. This law, originally derived by Ffowcs Williams and Hall [3], Howe [4], and confirmed in the experiments of Brooks and Hodgson [5], shows that the dominant noise source on the airframe arises from scattering of the noise generated due to the passage of the wing turbulent boundary layers over the wing trailing edge. Thus, the source of noise lies in the turbulent pressure fluctuations in the wing boundary layers within an acoustic wavelength of the trailing edge. The spectrum of the noise ranges from 100 Hz to over 10 kHz. It is also found that the noise intensity is a function of aircraft size and mass.

This early work, referred to above, included a definitive study by Kroeger *et al.* [6] on the silent flight of the owl, which is the only known flying object which can fly silently, at least within a specified range of frequencies. The study of the owl is important, in spite of its small size, mass and low flight speed compared with the aeroplane, since it is found that the owl flies at a large angle of attack and its noise sources are produced by the turbulent pressure fluctuations in the wing boundary layers and from its legs, or undercarriage. As such it should be a very noisy flying object but it has evolved changes to its feathers on its wings and legs such that in the frequency range of greatest resolution in the prey's hearing, it flies silently and stably at a high angle of attack without flow separation on its wings. Its prey are unaware of its approach until they are captured in its claws. Thus any study of airframe noise, including methods of noise reduction, needs to be aware of the physical principles of what can loosely be called "owl technology". A recent review of this subject has been given by Lilley [7].

The present paper discusses the several sources of airframe noise and their major characteristics on both the "clean" and the "dirty" aircraft, when the aircraft high-lift system is employed in the final approach to landing.

2. DEFINITIONS

NOISE
=
AIRCRAFT NOISE – ENGINE NOISE
– ENGINE/AIRFRAME INTERFERENCE NOISE

The subdivision of airframe noise used in this paper is as follows:

(i) *Wings* including tail surfaces and fuselage:
(ii) *High-lift devices* including trailing-edge flaps, leading-edge slats and brackets:
(iii) *Undercarriage* including main and nose wheels, axles, oleo legs and struts, fairings, brake cables and hydraulic pipes, wheel wells and doors.

Airframe noise is defined as the noise intensity, $I(W/m^2)$, as measured by an observer at ground level directly below the aircraft, which corresponds to $\theta = 90^\circ$, where θ is the angle measured in the longitudinal flight plane from downstream.

The typical flight speed on the approach speed is 1·3 times the aircraft stalling speed with the aircraft at its all-up-weight as required under Noise Certification. Typically, the flyover speed will be taken at 132 knots = 68 m/s with the aircraft flying at an altitude of 120 m about 2–3 min before landing. Thus, for an aircraft having a maximum wing loading of 4500 N/m^2 the overall lift coefficients based on wing area are $C_L = 1{\cdot}59$ with $C_{Lmax} = 2{\cdot}69$.

The aircraft in the "clean" condition has flaps, slat and undercarriage stowed. The aircraft in the "dirty" condition has flaps, slats and undercarriage deployed. The overall sound pressure level, (OASPL), is measured relative to (20 μPa) as N (dB):

$$N(\text{dB}) = 10\log_{10}\frac{I(W/m^2)}{I_{ref}} = 120 + 10\log_{10} I(W/m^2)$$

since $I_{ref} = 10^{-12}(W/m^2)$ and $I = \langle p^2\rangle/\rho_\infty c_\infty$. Suffix '$\infty$' refers to atmospheric conditions.

Airframe noise has its highest levels on the approach to landing with the full high-lift devices operational and the undercarriage down with engines at approach settings. In the older aircraft, the high-lift flap system deployed single, double, or triple slotted Fowler flaps and leading-edge slats. The typical Mach number varies between $M = 0{\cdot}2$ and 0·3.

3. THE HALF-PLANE PROBLEM

The noise from turbulent boundary layer pressure fluctuations over an infinite plane surface was shown by Powell [8] to be quadrupole and therefore proportional to V_∞^8 at low Mach numbers, where V_∞ is the freestream or flight velocity. This was explained on the basis that the normal force fluctuations on the surface, which were dipole, were exactly cancelled by image dipoles in the infinite plane wall case, when viscous forces were neglected. However, for a wing of finite area it was found that in the acoustic compact case the noise radiation was dipole and hence proportional to V_∞^6. But in the non-compact case, where a wing of moderate to high aspect ratio had its chord large compared with the acoustic wavelength, it was found that the acceleration of the turbulent flow around the trailing edge caused a scattering of the resultant sound field with the result that the noise was amplified by scattering from the trailing edge. The farfield radiated noise was thereby increased from proportionality with V_∞^6 to V_∞^5 for a sharp trailing edge. The index was shown by Crighton [9] to be a function of the trailing-edge geometry.

Let us now consider the noise radiated from the unsteady flow past a semi-infinite plate of zero thickness and at zero incidence which was first introduced by Ffowcs Williams and Hall [3]. They found that the solution to the farfield noise problem was dominated by the singularity in the Green function at the sharp trailing edge. At low Mach number the sources within an acoustic wavelength of the trailing-edge emit noise which scatters at the trailing edge, and the intensity of the radiated noise is proportional to $V_\infty^5 \sin^2(\theta/2)$. We find for the "flyover" case with $\theta = 90^\circ$ that the farfield noise intensity per unit volume of acoustic sources is

$$I(W/m^2) = \frac{c_\infty^3}{\rho_\infty} \frac{\omega_0}{2\pi^3 H^2} \frac{\rho_0^2 u_0^4}{c_\infty^5} \tag{1}$$

which is a form of the Ffowcs Williams–Hall equation given by Goldstein [10], and is similar to that given by Howe [4, 11], and Crighton [1, 9], where the characteristic source frequency, ω_0 is given by the Strouhal relation for the turbulent flow $\omega_0 \ell_0 / u_0 \approx 1.7$, with the characteristic length and velocity scale for the turbulence being, respectively, ℓ_0 and u_0. H is the height of the aircraft. Equation (1) is for low Mach numbers and omits the Doppler factors which would be required at higher Mach numbers for directivity angles different from 90°, and the term $\cos^3\beta$ where β is the sweep angle of the trailing edge. The latter term is important, for with highly swept edges it suggests that the radiated noise from scattering may be reduced to a small value. It was suggested by Howe [12] that a serrated trailing edge would reduce the radiated noise and recent experiments have confirmed this result.

This is an idealized problem but it is found to represent to a "good" approximation the baseline problem for the airframe noise of a "clean" aircraft. Simulations of turbulence crossing a wing trailing edge have been performed by Singer *et al.* [13], where the radiated noise has been evaluated from a time-accurate flow solver coupled to the Lighthill acoustic analogy in the form presented by Ffowcs Williams and Hawkings [14]. Agreement was obtained with the formulation given in equation (1). In addition, measurements of the trailing-edge scattering noise have been made by Brooks and Hodgson [5] and more recently by Ostertag *et al.* [15], confirming the result given in equation (1).

4. AIRFRAME NOISE OF "CLEAN" AIRCRAFT

We assume that equation (1) is applicable for the derivation of the radiated noise from the wing of an aircraft flying straight and level in the "clean" configuration. Thus when we integrate over the span, b, of a wing of mean chord, $\bar{c}$, we find in the far field at a distance H from the aircraft for the upper surface only,

$$I(W/m) = \frac{1{\cdot}7}{2\pi^3} \frac{S V_\infty^3 M_\infty^2}{H^2} \left(\frac{u_o}{V_\infty}\right)^5 \left(\frac{\delta}{\delta_1}\right)_{TE}, \tag{2}$$

where the wing area is $S = b\bar{c}$, and δ_{TE} is the boundary layer thickness at the trailing edge. The characteristic length scale of the turbulence in the proximity of the wing trailing edge, ℓ_0 has been put equal to the boundary layer displacement thickness $(\delta_1)_{TE}$. Here we ignore the presence of the engines and the fuselage as well as the noise from the tail surfaces.†

† Corrections for these components can easily be made by summing just those contributions that include a "scattering" trailing edge.

For an aircraft, of all-up-weight, W, flying straight and level before the approach the aircraft speed V_∞ and lift coefficient, $\bar{C}_L$ are given by

$$W = 1/2\rho_\infty V_\infty^2 S\bar{C}_L \tag{3}$$

from equations (2) and (3) we find for the radiated farfield noise

$$I(W/m^2) = \frac{17}{\pi^3} V_\infty M_\infty^2 \left(\frac{u_0}{V_\infty}\right)^5 \frac{W}{\bar{C}_L H^2}, \tag{4}$$

where we have assumed for the case of a typical civil aircraft flying at the high Reynolds number that $(\delta/\delta_1)_{TE} \approx 10$, which includes the effect of the adverse pressure gradient on the wing upper surface boundary layer towards the trailing edge. It is assumed that only the wing upper surface boundary layer contributes to the farfield radiated airframe noise.

On substituting suitable values for the typical turbulent intensity we find

$$I(W/m^2) = K\left(\frac{W V_\infty M_\infty^2}{\bar{C}_L H^2}\right), \tag{5}$$

where $K \approx 7 \times 10^{-7}$. Although the coefficient K will vary with the Reynolds number of the aircraft ranging from gliders, light aircraft, to large jumbo-jets, we find that this simple formula fits remarkably well the experimental data collected from ground noise measurements over the past 25 years. For constant height and speed, and an average flight $\bar{C}_L = 0{\cdot}5$, we see that the farfield noise intensity is a function of aircraft all-up-weight only. For other angles in the longitudinal flight plane we find that the noise directivity follows the $\sin^2(\theta/2)$ law. This law fits the measured data for aircraft flying straight and level in the "clean" state, as well as gliders and birds, with the exception of the owl, over a weight ranging from about 10 to 4×10^6 N. As an example when $W = 2 \times 10^6$ N, $\bar{C}_L = 0{\cdot}5$, $V_\infty = 125$ m/s, $H = 120$ m, we find N(dB) = 95·4 dB.

The spectrum of noise is important especially for calculating the high-frequency weighting required for calculations involving perceived noise levels. In this simplified formulation, we will find only a measure of the peak in the frequency spectrum for complete aircraft. If we define the Strouhal number for the frequency of the peak,

$$S_T = \frac{f_{peak}\bar{c}}{V_\infty} = \frac{1{\cdot}7}{2\pi}\frac{u_0}{V_\infty}\frac{\bar{c}}{\delta_{TE}}\left(\frac{\delta}{\delta_1}\right)_{TE}, \tag{6}$$

we find, using the same values of u_0/V_∞ and $(\delta_1)_{TE}/\bar{c}$, that $S_T \approx 13{\cdot}5$. As an example for a large civil transport aircraft with a mean chord of $\bar{c} = 7$ m, flying at a speed of $V_\infty = 68$ m/s we find $f_{peak} = 132$ Hz. The decay law for the spectrum beyond its peak is not universal and is a function of aircraft geometry. In addition, the spectrum has a "broad" peak before the decay occurs. As is the case for many shear layers the frequency spectrum beyond the "broad" peak falls as f^n where $n = 1{\cdot}5$–2.

5. AIRFRAME NOISE IN APPROACH (FLAPS)

For the aircraft on the approach, with part-span "Fowler" flaps deployed, and the aircraft $\bar{C}_L = 1{\cdot}5$–$1{\cdot}7$ based on the wing area, the spanwise loading suffers a "strong" discontinuity at the inboard and outboard flap extremities. The result is that strong trailing vortices develop along the flap side-edges as found by Crowder [16] and shown in Figure 1. The

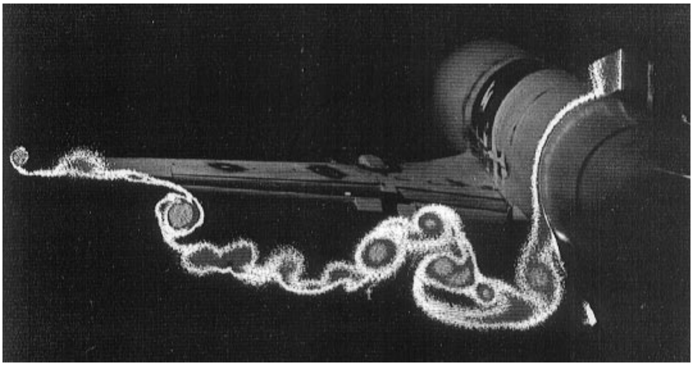

Figure 1. The structure of the wake downstream of high-lift extended flaps. (Photograph using the Wake Imaging System) (from J.P. Crowder [16])

resultant flow field has been found experimentally by Radeztsky *et al.* [17], and computationally by Khorrami et al. [18]. The flap side-edge vortex forms close to the leading edge of the extended flap in the cove region between the flap and the main element. The side-edge vortex is fed from the spanwise flow from the lower boundary layers and the vortex grows in strength as it develops along the side-edge between the leading and trailing edges of the flap. The flap side-edge vortex remains close to the flap except at large flap deflections when flow separation occurs. The experimental and computational data show the side-edge vortex has a large curved feeding sheet and a near-circular core.

Now the combined side-edge vortex and its curved feeding sheet are turbulent and close to the flap side-edge during its evolution and close to the flap trailing edge when the vortex is cast off into the wake. We can therefore make the assumption that the noise radiated to the far field arises from turbulence generated in the vortex and its feeding sheet and the noise scattered at the flap edges. The calculation is made complex when both inner and outer flaps are deployed and when each flap has either a single, double, or triple element. A complete calculation involves the aerodynamic loading on each element of each flap as well as the growth of the vortex along the edge. Further, the spiral velocity on the surface of the vortex being a combination of the axial, V_0, and swirl velocity, V_s, components must be known together with the distribution of the turbulent intensity u_0/V, where $V = \sqrt{V_0^2 + V_s^2}$. We assume similarity properties for the flow along the side edge of each flap and hence the overall radiated scattered noise is a function of the properties of the vortex as it crosses the flap trailing edge, where the radius of the side-edge vortex is R_F. Apart from the overall lift coefficient, $\bar{C}_L$ we have to evaluate the component lift coefficients for each flap and the main wing, for the given wing incidence and flap deflection. The resultant integrated formula for the farfield-radiated noise is a modified form of equation (5) and is given by

$$I(W/m) = \sum_{flaps+wing} \frac{1}{\pi} \frac{f_p c_F}{V_\infty} \frac{W}{A\bar{C}_L} \frac{V_\infty M_\infty^2}{H^2} \left(\frac{u_0}{V_\infty}\right)^4 \left(\frac{R_F}{\bar{c}}\right)^2, \tag{7}$$

where A is the unflapped wing aspect ratio and c_F is the individual flap chord.

It is found that the increase in noise from the wing tip vortices in the high-lift configuration over that of the noise from the “clean” aeroplane at the lower lift coefficient is relatively unimportant. The formulation discussed here is found to give broad agreement with measured flight data provided the flap side-edge vortex can be modelled as a single conical vortex. Clearly, this is a poor approximation for a high-lift system when the slotted Fowler flaps have double- or triple-slotted elements. Measurements show that the latter are less noisy than the single-element flap.

A major source of noise is that from the large brackets which support the flap during its deflection. The estimation of their noise is almost impossible due to their complex shapes and the complexity of the unsteady flow they generate as well as the non-uniform flow they operate in. Bracket noise is part of flap noise and is difficult to make meaningful calculations for their radiated noise in isolation and *in situ*. Experience and experiment are the only methods available to find an empirical correction to allow for bracket noise. The problem is that it is not a small correction especially as it affects not only the total noise intensity but also the noise spectrum.

There are two major methods that need to be explored when considering noise reduction schemes for trailing-edge flaps. As discussed above, the noise of all aircraft in both the "clean" and "dirty" configurations follows the V_∞^5 law, or at least an exponent close to 5. If trailing-edge scattering were absent the law would be V_∞^6 . We have noted above that a wing with a saw-toothed or serrated edge has a reduced noise provided the effective periodic trailing-edge angles of sweepback are suitably large. A further method is in the hands of the wing designer of the high-lift system. The strong trailing vortices from the flap extremities were shown above to be the result of the design of the flap system generating strong discontinuities in the wing spanwise loading. Changes in spanwise loading and wing/flap geometry could probably reduce the impact of the flap trailing vortices and hence reduce the farfield radiated noise.

We have briefly discussed above the silent flight of the owl. The owl flies at low speeds and hence its lift coefficient is high approaching unity. Of course, its flight Reynolds number is small and it would be expected that the laminar boundary layer flow past the wing leading edge would separate on the wing upper surface close to the wing leading edge long before the owl could achieve a flying speed corresponding to a high $\bar{C}_L$. In fact, the owl achieves highly stable flight at low speed by using a passive boundary layer control mechanism which prevents separation near the wing leading edge. This is the result of the owl's leading-edge primary feathers forming a comb of vortex generators which cover the entire upper surface with streamwise vortices similar to the effect of a turbulent flow over an aircraft wing in the presence of a strong adverse pressure gradient. But such a boundary layer flow over the upper surface of an owl should be noisy and the formulation given in sections 2 and 3 above for the calculation of the resultant radiated noise should apply and the radiated noise should be proportional to V_∞^5. The owl avoids this relatively large radiated noise level by having a fringe formed by its trailing-edge feathers, which in effect reduce the scattering to zero, since the angle of trailing-edge sweep, β, is now equal to 90°. Of course with these two devices alone the owl would be relatively less noisy than any other flying object of similar size, weight and speed, but not silent with respect to its prey, which have acute hearing at frequencies greater than 2 kHz. Thus, the owl not only needs to reduce its noise generation at all frequencies but it needs to make no noise above 2 kHz. This the owl does by having "down" feathers on its wing upper surface, which form a compliant layer preventing the pseudo-turbulent boundary layer from generating any noise above 2 kHz.

Thus we find two of the owl's devices of passive flow control are already familiar in aircraft technology. The third, involving a special compliant boundary, is already creating interest in aeroacoustic investigations.

6. AIRFRAME NOISE IN APPROACH (SLATS)

The high-lift system for a modern civil transport involves, as discussed above, a large increase in wing lift coefficient. This is obtained by the trailing-edge flap system but this can only operate efficiently if the flow remains unseparated over the wing leading edge. To avoid leading edge separation it is a common practice to employ a leading edge slat. The geometry of the slat is determined by the condition that when retracted it must form the correct aerofoil geometry for the wing in cruising flight. Consequently, the slat has a highly curved under surface, referred to as the cove, and when the slat is deflected downwards the flow in the slat cove region is separated. The slat when deployed experiences a large lift coefficient when operated at certain slat deflections, gaps, and overhangs with respect to the main wing. Even when the aircraft is flying at a low flight speed the flow around the slat and in the gap between the slat and the main wing, is at a high speed and any unsteadiness in the flow will result in the generation of significant noise.

Experiment and computation [19] show that the main source of slat noise arises from the region close to the slat trailing edge. The three regions where unsteady flow is likely are (i) the slat cove, (ii) the slat trailing edge, involving its geometry and in particular its thickness relative to the boundary layer thicknesses on the upper and lower surfaces of the slat, and (iii) the unsteady flow in the gap arising from the near-wake flow from the slat trailing edge and from the unsteady flow between the slat cove and the main wing. It is found that depending on the finite thickness of the slat trailing edge vortex shedding is generated which excites a strong flow oscillation. The unsteady flow appears to be strongly two dimensional. The dominant frequency is associated with the Strouhal shedding and is given by

$$f_t t/V = 0{\cdot}3, \tag{8}$$

where t is the trailing-edge thickness and V is the velocity at the slat trailing edge. However, there are also harmonics and broadband excitation plus the effect of the unsteadiness present in the cove region. The dominant frequency from the vortex shedding is sufficiently high that the acoustic wavelength is comparable with the gap thickness, and hence the generation of resonances is likely to occur. By changing the gap and overlap, it is possible to detune the system to avoid resonances at the expense of reducing the aerodynamic efficiency of the high-lift system. The geometry of the wing leading edge and the slat cove region make it possible for the presence of multipole reflections to occur. In experiments, a broad range of high-frequency and high-intensity noise is normally obtained unless special care is taken to find gaps and overlaps which avoid all resonances.

A possible flow model is to consider the gap flow as an unsteady wall jet with strong excitation arising from slat trailing-edge vortex shedding. Such calculations can be used to find the noise intensity when resonance is and is not present. From a practical viewpoint slat noise has to be eliminated at source either by changing the slat/main wing leading-edge geometry or preventing the multipass reflections by fixing acoustic liners in the slat/wing passage.

A major problem in considering the noise of the slat is the noise from the relatively large brackets which are associated with the actuation mechanism controlling the slat deflection. The noise radiated from these brackets is difficult to estimate due to their complex geometry and the unsteady flow fields they generate. The problem is that they are part of the slat operation and isolated measurements are difficult or impossible to make.

7. AIRFRAME NOISE IN APPROACH (UNDERCARRIAGE)

Both the main and nose undercarriages comprise a series of circular cylinders of different aspect ratios and inclinations relative to the flow direction. The resultant unsteady forces generate noise in all three directions: vertically, horizontally, and sideways or spanwise. The fluctuating forces are all Reynolds number dependent and their wake flows strongly interact with each other. The wakes from the undercarriages are strongly dependent on the number of bogies, the number of tyres and the axle spacings. The peak frequency appears to be related to the tyre diameter with

$$f_p D/V_\infty = 0{\cdot}3, \tag{9}$$

where D is the tyre diameter. The estimation of undercarriage noise in isolation can be obtained from Fink [2], Crighton [1], Heller and Dobrzynski [20], and Dobrzynski [21].

A further noise source occurs from open wheel wells after the undercarriage has been lowered. This noise is known as cavity noise and is avoided by closing at least part of the opening when the undercarriage is down. In some cases, doors are attached to the undercarriage and their noise is estimated using the formula given in equations (1) and (2).

However, in isolation all components of the undercarriages, with the exception of doors and cavities, generate noise which is dipole and hence proportional to V_∞^6 . If this were true for the undercarriage mounted on the aeroplane the deployment of the undercarriage would not change the noise radiated to the far field from that when the undercarriage was stowed. Experience tells us this is untrue and indeed the radiated noise from both the aircraft with and without undercarriages deployed show proportionality nearer to V_∞^5 than V_∞^6. This confirms that the unsteady flow generated by the undercarriage suffers interference with the airframe and the noise is scattered at doors in the vicinity of the undercarriage legs and the wing trailing edge. Thus, experiments to determine undercarriage noise in isolation may prove incomplete unless repeated with the undercarriage mounted on the airframe in its true flight configuration.

8. COMPARISON WITH FULL-SCALE FLIGHT MEASUREMENTS

The simple formulae for airframe noise given above may not be sufficiently accurate for prediction purposes and the requirements of Noise Certification. However, they give some insight into the dominant noise characteristics generated by the complete aircraft and its components. Comparison of flight data for the “clean” aircraft with the trailing-edge noise scattering formula shows that all aircraft obey the law $I \sim W V_\infty^3$, and the inverse square law H^{-2}. Such a law provides information on the lower bound of airframe noise for the present-day types of aircraft if it were possible to eliminate entirely all extra noise arising from the “dirty”, or high-lift, plus landing, noisy configurations, and utilizing current technology. (We have ignored the effect of atmospheric sound absorption at the higher frequencies due to the relatively short distances involved when the aircraft is on the final approach.)

Figure 2 shows a comparison between OASPL and the parameter $W V_\infty M_\infty^2/\bar{C}_L$ covering an enormous range of aircraft weights. For the “clean” aircraft the agreement is very good.

As already stated above, the aircraft in the “dirty” configuration is very geometry dependent when comparing their respective farfield noise intensities. The flap side-edge noise critically depends on the presence of either a single conical-like vortex, or double or triple vortices associated with different number of flap elements. The “dirty” aircraft are in many cases 10 dB noisier than the equivalent “clean” aircraft when extrapolated to the same speed.

The undercarriage, when deployed, generates an increase of about 4 dB over flap noise.

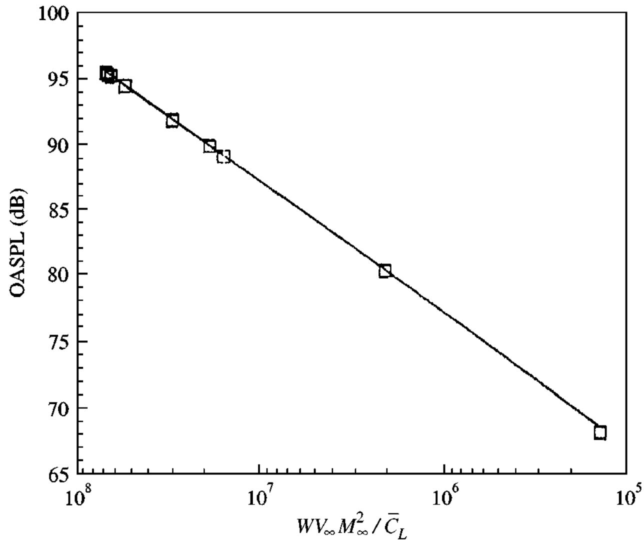

Figure 2. Comparison between theory and flight measurements of "clean" aircraft: □ flight measurements; —— "clean" aircraft theory.

9. CONCLUSIONS

It has been shown that the prediction of airframe noise depends on the availability of a space/time accurate unsteady flow database for the flow over the complete aircraft and its components. The interactions between the component flows cannot be ignored. Measurement and theory strongly point to the flow over the upper surface of the wing approaching the wing trailing edge as a dominant source of noise when the aircraft is flying in its "clean" configuration with flaps, slats and undercarriage stowed. In this configuration, the estimation of airframe noise and its variation with aircraft all-up-weight and speed is well predicted by the simple formula for the turbulent boundary layer noise scattered by the wing trailing edge. The noise radiated varies with flight speed according to V_∞^5.

For aircraft flying in the "dirty" configuration the radiated noise is highly geometry dependent but remains proportional to about V_∞^5. The extra noise is due to the deployment of the trailing-edge flaps, the leading-edge slats and the undercarriage. For the trailing-edge flaps the same generic formula for edge scattering can be used although the scattering now takes place at both the flap side edges as well as at the trailing edge. In the case of the slat it appears that its geometry is critical and "good" aerodynamic performance does not necessarily lead to acceptable noise performance. The avoidance of slat tones and resonances is essential within the operational range of the slat. The undercarriage is probably the most important contributor to airframe noise in the "dirty" configuration and possibly the most difficult component to lower its noise level.

The possibility of reducing the noise of the "clean" aircraft and that of the flaps has been discussed. Reference has been made to the techniques perfected by the owl in producing silent flight at least over the range of frequencies above 2 kHz. It is in such a range of frequencies that aircraft are most annoying when flying over people in the final approach to an airport, and where the important high-frequency weighting is generated in calculating perceived noise levels. Already interest is being shown in developing schemes for application to aircraft based on the same principles as used in "owl technology".

This paper is a contribution to the 80th birthday celebrations for Professor P. E. Doak, a distinguished friend and colleague of the author over many years.

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