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# AIRFRAME NOISE

## A DESIGN AND OPERATING PROBLEM

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## SUMMARY

A critical assessment of the state of the art in airframe noise is presented in this paper. Full-scale data on the intensity, spectra, and directivity of this noise source are evaluated in light of the comprehensive theory developed by Ffowcs Williams and Hawkings. Vibration of panels on the aircraft are identified as a possible additional source of airframe noise. The present understanding and methods for prediction of other component sources - airfoils, struts, and cavities - are discussed. Operating problems associated with airframe noise as well as potential design methods for airframe noise reduction are identified.

## INTRODUCTION

The importance of airframe noise as the "ultimate noise barrier" to the reduction of noise levels produced by future commercial aircraft was recognized just 4 years ago as a result of NASA sponsored research on the Advanced Technology Transport. (See ref. 1.) This work included preliminary calculations, based upon sailplane data, which indicated that the nonpropulsive noise produced by a large subsonic aircraft on landing approach lay only approximately 10 EPNdB below the FAR 36 certification levels (ref. 2). The significance of the surprisingly high intensity of this hitherto neglected noise source lies in its impact on future noise regulations. Since it would be counterproductive to require engine noise levels much below those of nonpropulsive sources, the potential for further overall aircraft noise reductions is limited unless nonpropulsive noise generation can be controlled.

For this purpose, airframe noise research was begun, with the goals of understanding the generation and propagation of aircraft nonpropulsive noise as well as its reduction at the source. The first such attempts were empirical in nature, involving correlations of airframe noise measurements with gross aircraft parameters such as weight, velocity, and aspect ratio. (See ref. 3.) Such studies led to useful prediction schemes but did little to identify and rank-order the sources of the noise. Gradually, however, some understanding of the actual sources and their relative importance began to emerge. For the "clean" (cruise-configured) aircraft, it is now generally conceded that the primary sources are associated with the interactions of the wake of the wing with the wing itself, while for the "dirty" (landing-configured) aircraft, noise generated by the flaps and the

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landing-gear–wheel-well combination becomes dominant. This paper presents an appraisal of the state of knowledge of airframe noise in an attempt to assess its impact on aircraft operations as well as to identify potential methods for its reduction. Also, included is an evaluation of full-scale data regarding levels, spectra, and directivity of airframe noise which suggests that airframe noise is more complex than had previously been assumed. Thus, the early empirical airframe noise prediction techniques are giving way to more refined analyses which view the total sound radiation as a summation of noise generation by individual components such as airfoils and flaps, wheel wells, and landing gear. Noise generation mechanisms for these individual component sources are discussed and methods for their reduction identified.

## SYMBOLS

| | |
|---|---|
| A | ratio of area elements |
| EPNdB | effective perceived noise level |
| J | Jacobian of transformation |
| K | wave number |
| $M_r$ | Mach number in observer direction |
| OASPL | overall sound pressure level |
| R | Reynolds number |
| S | surface |
| SPL | one-third octave band sound pressure level |
| $S_w$ | wing area |
| $T_{ij}$ | Lighthill stress tensor |
| U | flow or aircraft speed |
| V | volume |
| $V_{ed}$ | eddy volume |
| a | speed of sound |
| d | cylinder diameter |
| h | aircraft altitude |
| $l_s$ | streamwise correlation length |

| | |
|---|---|
| $n_j$ | components of normal vector |
| $p$ | acoustic pressure |
| $p_{ij}$ | compressive stress tensor |
| $r$ | observer distance |
| $r_{ed}$ | distance of center of eddy from edge |
| $s$ | sideline distance |
| $t$ | time |
| $u$ | turbulent intensity |
| $v_n$ | normal velocity |
| $\vec{x}$ | observer position |
| $x_i, x_j$ | components of position vector |
| $\epsilon$ | observer angle |
| $\vec{\eta}$ | source position |
| $\theta$ | angle between flight path and observer directions |
| $\theta_o$ | angle between mean flow and trailing-edge directions |
| $\lambda$ | directivity angle in flyover plane |
| $\nu$ | kinematic viscosity |
| $\rho_f$ | far-field density |
| $\rho_o$ | ambient density |
| $\phi$ | angle between trailing edge and observer directions |
| $\omega$ | circular frequency |
| ΔOASPL | increment in overall sound pressure level |

A bar over a symbol indicates time average.

## AN OVERVIEW OF AIRFRAME NOISE

There are many potential sources of airframe noise on an aircraft, as shown schematically in figure 1. Each of these sources is believed to have its own characteristic amplitude, spectrum, and directivity. If one measures the overall airframe noise produced by an aircraft, one sees the resultant produced by the summation of these individual sources. Although this may be confusing from the standpoint of defining and evaluating mechanisms, it is nevertheless the noise field of ultimate interest. Thus, it may be useful to review available overall airframe noise measurements.

## Intensity

Overall airframe noise measurements directly beneath the flight path of the aircraft have been made for a number of years. Tables listing 65 data points published prior to 1975 have been compiled by Hardin, Fratello, Hayden, Kadman, and Africk (ref. 4). However, many of these early data were obtained by using less than optimum measurement and analysis techniques. Microphones were often pole mounted in order to compare results with certification levels, determination of the aircraft position and velocity was crude, and only minimal efforts to remove the effects of residual engine noise were made. Recently, however, two studies which attempt to overcome these objections were published. (See refs. 5 and 6.)

The first of these studies (ref. 5) presented measurements of Aero Commander, Jetstar, CV-990, and B-747 aircraft. The microphones were mounted flush with the ground to remove spectral distortion produced by reflection and radar was employed to track the aircraft as it flew a nearly constant airspeed glide slope over the microphone array.

Airframe noise data on the British aircraft H.P. 115, HS. 125, BAC 111, and VC. 10 were obtained by Fethney (ref. 6). This study employed flush-mounted microphones and a kine-theodolite system for precise position tracking, repeat flights to reduce statistical variability in the data, and extensive efforts to determine and remove residual engine noise from the data.

On the basis of these data, Fink (ref. 7) has developed a semiempirical prediction scheme for airframe noise produced by aircraft in the clean (cruise) configuration. The overall sound pressure level directly below the aircraft is given by

$$\mathrm{OASPL} = 10 \log_{10}\left[\left(\frac{U}{100}\right)^{5}\left(\frac{S_w}{h^2}\right)\right] + 108.3 \text{ dB} \tag{1}$$

where

| | |
|---|---|
| $U$ | aircraft speed, meters per second |
| $S_w$ | wing area, meters$^2$ |
| $h$ | altitude, meters |

All sound pressure levels in this paper will be referenced to 20 μPa. Note that this relation implies a dependence of clean airframe noise on velocity to the fifth power. A comparison of this prediction with measured data from a number of cruise-configured aircraft is shown in figure 2.

The airframe noise levels generated in the landing configuration are believed to be more dependent upon the detailed design of the aircraft than those of the cruise configuration. Several additional components such as leading-edge slats, trailing-edge flaps, landing gear, and wheel wells are deployed during landing whose relative contributions to the overall noise may vary considerably from aircraft to aircraft. Further, these sources are not necessarily independent, but may interact with each other due to changes in the total flow field. Although it is difficult to directly measure the effects of the individual components on the airframe noise, Fethney made some estimates based upon measurements for the VC. 10 in reference 6. The data shown in figure 3 for comparison are decibel increases over the clean-configuration overall sound pressure level as produced by several different flight conditions. The total change in airframe noise level from the cruise to approach configurations for this aircraft was 11 dB. Either flap deployment or landing-gear deployment with open wheel well is estimated to account for about 9 dB individually. The difference in noise level between open and shut undercarriage doors is estimated to be about 4 dB; this seems to indicate that substantial noise may be generated by large open cavities which suggests a method for noise reduction on those aircraft whose undercarriage doors normally remain open after gear deployment.

In reference 7, Fink has also developed a prediction scheme for airframe noise produced by aircraft in the dirty (or approach) configuration. The overall sound pressure level below the aircraft is given by

$$\mathrm{OASPL} = 10 \log_{10} \left[ \left( \frac{U}{100} \right)^6 \left( \frac{S_w}{h^2} \right) \right] + 116.7 \text{ dB} \qquad (2)$$

A comparison of the prediction by this relation with data from several aircraft in the approach configuration is shown in figure 4. Although most of the data appear to be well predicted by this relation, two of the aircraft, the H.P. 115 and the BAC 111, exhibit substantially lower levels corresponding better to the clean airframe prediction of equation (1) because of design peculiarities of these aircraft which, when better understood, should yield design methods applicable to other aircraft.

Fink's relations have been employed to predict cruise and approach noise levels for modern aircraft comprising most of the current commercial fleet. The results are shown in figure 5. The approach airframe noise lies at approximately the FAR 36 - 10 dB level.

## Spectra

Based upon early measurements, Healy suggested that airframe noise directly below an aircraft produced a "haystack" type spectrum which peaked at a constant Strouhal number based on airspeed and a characteristic wing thickness. (See ref. 8.) More recent measurements indicate a much more complex spectrum. Figure 6 displays the peak one-third octave band spectra normalized to equal overall sound pressure levels for the clean Jetstar, CV-990, and B-747 aircraft as measured by Putnam, Lasagna, and White (ref. 5). Although such measurements are complicated because the moving source produces a nonstationary signal, third-octave analyses are generally reliable as long as short averaging times are employed. Note that the spectra exhibit two peaks, a lower one in the vicinity of 200 Hz, which corresponds roughly to the frequency predicted by Healy's Strouhal relation, and a higher one near 1250 Hz. However, reference 5 stated the surprising result that the shape of these spectra and the position of the peaks showed no consistent change with airspeed. Spectra for the H.P. 115, HS. 125, and BAC 111 obtained by Fethney (ref. 6) display the same shape and peak location.

The change in spectrum shape for the VC. 10 in going from the clean configuration to the dirty configuration is illustrated by the data of figure 7. The characteristic double-peaked spectrum for the clean configuration is not discernible for this aircraft. The major difference in the spectrum for the dirty configuration is a broadband increase in level, particularly at the low-frequency end.

## Directivity

The directivity of airframe noise has only recently begun to be explored and only a modest amount of data exists in the open literature. Figure 8 portrays the reductions in measured overall noise levels (over those directly below the aircraft) with sideline distance for the four aircraft tested by Fethney (ref. 6). These data are compared with predicted reductions based upon consideration of the total aircraft either as a point monopole (solid curve) or as a point dipole (dashed curve) oriented in the lift direction. The fact that the data cluster about the solid curve indicates a monopolelike falloff to the side. Similar behavior has been observed by Lasagna and Putnam for the Jetstar aircraft in the landing configuration. (See ref. 9.) This result is important in its implications for the source type dominant in airframe noise as well as for the airframe noise "footprint" and will tend to make airframe noise more important on the sideline then had previously been assumed.

Figure 9 shows airframe noise measurements in the flyover plane for a clean DC-10 aircraft (ref. 10). The data have been corrected for an inverse square falloff with distance and are plotted as a function of $\lambda$, the angle of the approaching aircraft with respect to the horizontal. (Before normalizing, the airframe noise peaked slightly before the aircraft was directly overhead.) These measured data are compared with calculated values of the sum of two dipoles oriented, respectively, in the lift and drag directions. Note that the main directivity features of the measurements are supported by the calculations.

The best agreement between the measured data and this theoretical approach is obtained when the dipoles are negatively correlated.

## A THEORETICAL BASIS FOR AIRFRAME NOISE

The most inclusive theoretical basis for the study of sound production by the airframe is that developed by Ffowcs Williams and Hawkings (ref. 11) who extended the Lighthill-Curle theory of aerodynamic sound generation (refs. 12, 13, and 14) to include arbitrary convection motion. For this case, the wave equation governing the generation and propagation of sound admits the general solution

$$\begin{aligned} 4\pi a^2\left(\rho_f(\vec{x},t) - \rho_o\right) &= \frac{\partial^2}{\partial x_i\,\partial x_j} \int_V \left[\frac{T_{ij}\ J}{r\,|1 - M_r|}\right] d\vec{\eta} \\ &\quad - \frac{\partial}{\partial x_i} \int_S \left[\frac{p_{ij}n_j A}{r\,|1 - M_r|}\right] dS(\vec{\eta}) + \frac{\partial}{\partial t} \int_S \left[\frac{\rho_o v_n}{r\,|1 - M_r|}\right] dS(\vec{\eta}) \end{aligned} \qquad (3)$$

This solution implies that the sound sources may be represented by a quadrupole distribution related to the Lighthill stress tensor $T_{ij}$ within the volume of turbulence, a surface distribution of dipoles dependent upon the compressive stress tensor $p_{ij}$, and a surface distribution of monopoles produced by the normal velocity of the surface $v_n$. Ffowcs Williams and Hawkings further showed that, for a rigid surface, the monopole distribution degenerates into a distribution of dipoles and quadrupoles throughout the volume contained within the surface. (See ref. 11.)

In the majority of airframe noise research to date, the aircraft has been assumed to be rigid. Application of this assumption in the theory discussed in the preceding paragraph implies that airframe noise consists of a distribution of dipoles and quadrupoles. Further, at the low Mach numbers of interest (approximately 0.3 for landing approach), the quadrupole distribution has been neglected. Thus, airframe noise sources have been considered as dipole in nature. These dipole sources have also been assumed to be compact and, often, replaced by equivalent point dipoles acting at the center of the distribution.

Several aspects of experimental data regarding airframe noise are difficult, if not impossible, to explain in terms of such a theory.

Firstly, the velocity dependence of airframe noise has consistently been found to be less than the sixth power which would be expected of an aerodynamic dipole. This result has led to considerable interest in the theories of Ffowcs Williams and Hall (ref. 15) and Powell (ref. 16). They considered the radiation from a volume of turbulence near the edge of a rigid half-plane and found that the sound production of quadrupoles with axes in a plane normal to the edge was enhanced such that the far-field sound intensity varied as the fifth power of the typical fluid velocity. However, there was no enhancement of quadrupoles with axes parallel to the edge.

Secondly, the definite monopolelike sideline directivity of airframe noise, which has been observed by independent research groups, is hard to understand on the basis of a purely dipole theory. Certainly it is possible for three mutually perpendicular dipoles to masquerade as a monopole. However, this requires them to be statistically independent and of equal amplitude. Although it is not hard to imagine the overall fluctuating lift and drag forces on an aircraft to be the same order of magnitude, a fluctuating side force of equal strength is more difficult to visualize. About the only place where such a force could exist in the clean configuration is on the vertical tail. However, since it is much smaller in area than the wing surface, much higher fluctuating pressures on its surface would be required.

Finally, the source of the high frequency peak in the airframe noise spectrum (fig. 6) is puzzling. This peak, which was observed by the authors of both references 5 and 6, is higher in frequency than that expected from known wing noise mechanisms and seems to be relatively insensitive to airspeed. Since the frequency of an aeroacoustic source ordinarily scales on airspeed, the presence of this peak suggests the possibility of radiation from fundamental vibratory modes of the aircraft structure. Although such vibration has not previously been considered as a source of airframe noise, just such a spectral peak has been observed by Davies in reference 17, who investigated sound produced by turbulent-boundary-layer excited panels. Davies found that the frequency of this peak was reasonably independent of flow speed.

A similar spectrum has also been observed by Maestrello (ref. 18) who reported interior measurements in an unupholstered Boeing 720 airplane. Shown in figure 10 are spectra of panel acceleration as well as sound pressure level close to the panel for the airplane in flight at a Mach number of 0.87 and an altitude of 7700 meters. Also shown are the changes in these spectra with cabin pressure. Maestrello notes that the sound pressure level varies as the fifth power of velocity. He further observes that most sound radiation comes from the edges of the panels and demonstrates methods for noise reduction by stiffening the panel boundaries. If panel vibration is truly responsible for the high frequency peak observed in airframe noise radiation, Maestrello's techniques offer a direct method of noise reduction.

More recently, Wilby and Gloyna (ref. 19) made similar measurements on a Boeing 737 airplane. Again the 1-kHz peak was observed which was taken as evidence that the panel structure acts as a filter with that center frequency. Correlation of the vibration data was high in the longitudinal direction but low in the circumferential. Adjacent panels were essentially uncorrelated.

These phenomena emphasize the necessity of a closer look at the assumptions employed in the theory of airframe noise. While it is wise to recall that there are many absolutely equivalent formulations of aeroacoustic sources, the enhancement of quadrupole sources in the vicinity of an edge as predicted by Ffowcs Williams and Hall (ref. 15) and Powell (ref. 16) suggests that quadrupole terms in any theoretical formulation should not be dismissed lightly. Further, the evidence cited previously which indicates that vibration may be a source of airframe noise brings into question the assumption of rigidity. If the surface vibrates, the monopole source term in equation (3) may dominate which would explain the monopolelike sideline directivity that has been observed. Of course, there is still no mass addition to the flow but, due to the size of the body, each point on the surface may be acting as a baffled piston unable to interfere effectively with its mate of opposite phase elsewhere. The large size of the body also sheds doubt on the assumption of compactness. The spatial extent of the source region is of the order of the span of the aircraft while a typical frequency of interest has a wavelength of 0.5 m. It is possible to take into account the correlation length of the source distribution and replace each correlated region by a point source as suggested in reference 20. However, even the correlation length may be of the order of, or larger than, the wavelength. Thus, the assumption of compact sources cannot be rigorously justified. Further, this "component source technique" neglects diffraction of the sources by the fuselage which may be important in airframe noise and could be partially responsible for the observed directivity pattern.

## COMPONENT SOURCES OF AIRFRAME NOISE

As noted earlier in this paper, airframe noise is the resultant of many different noise generating mechanisms. Thus, in order to render the research problem more manageable, it is prudent to identify and evaluate these individual sources.

The work of Curle (ref. 14), who extended Lighthill's theory (refs. 12 and 13) to include the case where rigid bodies are present within the field of interest, showed that the sound generation in the presence of a body could be expressed by a distribution of dipoles over its surface in addition to the usual volume integral. The strength of these dipoles is related to the fluctuating pressure experienced by the surface. This theory is exact and highly useful for computational purposes. However, it has led to a certain amount of confusion about the roles of surfaces in sound generation. Actually, a rigid surface can produce no sound, as can be seen by noting that the acoustic energy flux must approach zero close to a rigid surface (ref. 21). Thus, the true sources of sound are disturbances within the flow field itself and the surface can act only in changing the strengths of these volume sources and in reflecting and diffracting the sound they produce. The fact that the flow disturbances generate the fluctuating pressures on the surface is responsible for the alternate description of the sound production. The importance of this result is that it emphasizes the vital role played by the local flow field about the airframe components. Little is known about such flows.

The many different noise-generating mechanisms which comprise airframe noise can be crudely classed in terms of three simple models, that is, noise generation by cylinders, streamlined bodies, and cavities.

## Cylinders

Perhaps the simplest and best understood of all examples of sound generation by flow-surface interaction is that of a cylinder in a flow. Fortunately, this is also a useful example as the entire undercarriages of aircraft are constructed essentially of cylinders of various lengths and orientations. As the flow attempts to negotiate the cylindrical contour, it separates from the surface creating a turbulent wake. This wake is highly vortical which results in a solenoidal velocity field that induces fluctuating forces on the cylinder in the streamwise and normal directions. The situation is shown schematically in figure 11.

The exact nature of the wake and, thus, the sound produced is highly dependent upon the Reynolds number ($R = \frac{Ud}{\nu}$, where U is the flow speed and d is the cylinder diameter) of the flow. Typical Reynolds numbers for aircraft undercarriage components during landing approach are in the range of $10^5$ to $10^6$. In this range, the classical periodic Von Karman vortex street breaks down and the wake becomes random. The most relevant work in this area is that by Fung (ref. 22) who studied the fluctuating lift and drag forces on cylinders for the range $3 \times 10^5 < R < 1.4 \times 10^6$. He found the spectrum of the fluctuating lift to peak at a Strouhal number based on strut diameter near 0.1. The spectrum of the fluctuating drag peaks at twice this frequency.

For a cylindrical component of an aircraft, if it is assumed that wavelengths of the sound produced are large compared with the dimensions of the cylinder, retarded time differences in the source region may be neglected and the sound calculated as if from a moving point dipole through the theory of Lowson (ref. 23). However, if the principal landing-gear struts are oriented such that their lift and drag dipoles yield a null below the aircraft, the strut-generated sound is not a tremendously important source of community noise. Nevertheless, the struts may be significant in generating turbulence which impinges on other surfaces of the aircraft to create substantial noise.

## Streamlined Bodies

The most fundamental (in the sense of being omnipresent) component source of airframe noise is produced by the flow over the streamlined surfaces of the aircraft. Taking such surfaces to be rigid (i.e., neglecting any radiation due to panel vibration which was indicated as a possible source earlier in the paper), a dipolelike sound generation may still be observed which can be related to the fluctuating forces experienced by the surface. There are three mechanisms by which such forces may be developed: The pressure field arising in the turbulent boundary layer over the surface, force fluctuations induced by vorticity shed from the surface, and the action of any turbulence present in the incident stream. (See ref. 24.) However, these phenomena are not equally efficient in noise generation and, of course, their relative contributions vary with the characteristics of the flow field in which the surface is placed.

Boundary-layer turbulence.- The question of sound generation by boundary-layer turbulence has been effectively resolved by Powell (ref. 25) who used the "reflection principle" to show that the major surface dipoles vanish on an infinite, flat, rigid surface leaving only the viscous dipoles with axes lying in the surface itself. Since such viscous stresses can only become significant at Reynolds numbers much smaller than those developed on commercial aircraft, direct radiation from the turbulent-boundary layer is a much less efficient source of direct radiation than others present even for moderately curved surfaces (as long as no separation occurs). This result remains valid for finite surfaces when the surface is larger than the sound wavelength - which is usually true of airframe noise - except near the edges. This "edge-noise" source is discussed later.

In reference to the panel vibration source proposed earlier in this paper, it might be mentioned that Laufer, Ffowcs Williams, and Childress (ref. 26) have considered the case where the surface is flexible and able to respond to the boundary-layer excitation. They remark that for surfaces of limited extent, wall motion becomes equivalent to a simple source system of high acoustic efficiency and can quickly become the most important feature of the practical boundary-layer noise problem. Thus, it appears that the boundary-layer pressure fluctuations are not major sources of noise, but the aircraft surface may generate sound through vibration and may reflect sound produced by other sources. Both of these roles require further research for better understanding.

Wake vorticity.- Sound generation by force fluctuations induced by vorticity shed from the surface is probably the primary cause for the experimentally observed fact that aerodynamic surfaces radiate predominantly from slender strips along their edges. At the edge of an aerodynamic surface, the flow must separate shedding vorticity into a wake. This vorticity will induce fluctuating surface pressures which fall off with distance from the vortex. Thus, the largest pressures will occur close to the edge. In addition, non-cancellation of boundary-layer fluctuations also occurs in this region. Which of these effects is dominant is not known at this time, although wake-induced pressures normally should be more intense. However, both point to edge noise as a primary source of airframe sound generation.

The present understanding of this source is well depicted by figure 12 which is taken from a report by Siddon (ref. 27). Siddon suggests that alternate vortex shedding, with a fairly narrow band of preferred frequencies, leads to a time-dependent relaxation of the Kutta condition at the trailing edge. The "stagnation streamline" switches cyclically from the upper to the lower surface; thus, a fluctuating-force concentration is induced near the edge. Note that this is exactly the same mechanism responsible for the production of strut noise as discussed earlier.

There has been extensive work on the prediction of this edge-noise source and numerous, sometimes conflicting, theories have been produced. (See ref. 4.) Again, the generation process is highly dependent upon Reynolds number. Much recent work (e.g., refs. 28 and 29) has dealt with the intense tones which can be produced by isolated airfoils with laminar boundary layers. However, such tones require Reynolds numbers based on airfoil chord of less than about $2 \times 10^6$ whereas commercial aircraft ordinarily exhibit Reynolds numbers of many millions. At these higher Reynolds numbers, a transition similar to the collapse of the classical Von Karman street behind a cylinder apparently occurs and a more broadband radiation results.

Fink, in reference 30, has experimentally evaluated the various theories for trailing-edge noise generation. He concludes that the best present theories are those by Ffowcs Williams and Hall (ref. 15) and Powell (ref. 16). The first of these papers considers the scattering of sound generation by Lighthill-type quadrupoles due to the presence of a half-plane in the flow. The results show that sound output of quadrupoles associated with fluid motion in a plane normal to the edge is increased by a factor $(Kr_o)^{-3}$ where $K = \omega/a$ is the acoustic wave number and $r_o$ is the distance of the center of the eddy from the edge. There is no enhancement of sound from longitudinal quadrupoles with axes parallel to the edge. According to this theory, the mean square pressure produced by a single eddy near the trailing edge is

$$\overline{p^2}(r,\theta,\phi) \approx \frac{\rho_o^2 U^5 u^2 V_{ed}^2 \sin\phi \sin^2\theta_o \cos^2\theta/2}{\pi^2 a l_s r_{ed}^3 r^2} \tag{4}$$

where

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| $u$ | turbulent intensity |
| $V_{ed}$ | eddy volume |
| $l_s$ | streamwise correlation length of eddy |
| $\theta$ | angle between streamwise and observer directions |
| $\theta_o$ | angle that mean flow makes with trailing edge |
| $\phi$ | angle between trailing edge and observer directions |

This expression can then be summed at the observer location over all the (independent) eddies near the trailing edge. Note that this theory implies a dependence on the fifth power of velocity and the square of turbulence intensity. It also gives rise to a directivity pattern in a plane normal to the edge dependent upon $\cos^2\theta/2$. Finally, the theory predicts that a "swept" trailing edge (relative to the mean flow direction) would produce less noise due to the $\sin^2\theta_o$ dependence.

Inflow turbulence.- The final mechanism by which fluctuating forces may be developed on an aerodynamic surface is through the action of incoming turbulence. Although atmospheric turbulence is ordinarily of too large scale and too low intensity to be important in this regard, airframe components, such as flaps, which lie in the wake of other portions of the aircraft, may generate noise through this mechanism.

Although several different approaches to the analysis of this noise source have been devised (ref. 4), it is useful to observe that, since the work of Ffowcs Williams and Hall (ref. 15) is purely concerned with scattering of sound near an edge, it is equally applicable to this case as well. In other words, their theory makes no distinction between incoming turbulence impinging on a leading edge and turbulence being shed from a trailing edge. Thus, equation (4) can be employed to calculate the level and directivity of this leading-edge source as well. The same concerns about source distribution apply, with the only change being, perhaps, the characteristics of the eddies themselves.

One possible means of reducing both the incident turbulence and trailing-edge noise on streamlined bodies is through use of porous surface treatment such as has been developed for high lift configurations. This application has recently been considered by Hayden in reference 31. Figure 13 shows the noise reduction produced by porous trailing-edge treatment on an NACA 0012 airfoil at $4^0$ angle of attack. This airfoil was in the Reynolds number range where a narrow band tone can be generated which is not the case for commercial aircraft. However, it can be seen that the lower frequency trailing-edge noise is also significantly reduced. Such treatment may also be utilized on the leading edge although maintainance of aerodynamic performance is difficult.

## Cavities

The final component source of airframe noise to be discussed in this section is sound generation by cavities in the surface of the aircraft. Recent data (ref. 6) indicate that one of the most intense sources of airframe noise on landing approach is produced by the wheel cavities of the aircraft since a significant increase in the broadband noise spectrum is observed when the wheel wells are opened. (See fig. 3.) This phenomenon is shown in figure 14 which is a compendium of cavity noise data from actual aircraft produced by Heller and Dobrzynski (ref. 32). It can be seen that the larger the cavity, the higher in intensity and lower in frequency is the sound produced. Of course, the larger cavities generally contain more landing-gear assemblies which may also be a factor. Although it is not yet clear whether this noise increase is due to the cavity itself or to a change in the flow field around the wing-flap system, considerable research into noise generation mechanisms of cavity flow has been stimulated.

The flow field within cavities has been of interest for several years because of fatigue and buffeting problems. Thus, extensive data on cavity flow fields have been obtained and methods for the reduction of internal pressure oscillations have been developed. (See ref. 33.) Unfortunately, however, few measurements of far-field sound generation by cavities exist due to the difficulty of making such measurements in present day flow facilities.

The "basic" (this author's terminology) cavity noise mechanism is a fairly complex interaction between the shear layer over the cavity and the volume within it. The shear layer apparently has fundamental modes of instability which act as a forcing function to produce oscillation of the air within the cavity. However, the efficiency of this forcing function in producing sound depends upon how well it couples with the fundamental acoustic modes of the cavity. If the coupling is strong, very intense tones can be produced. These tones have been studied by Block and Heller (ref. 34).

This basic cavity noise mechanism is primarily a low frequency phenomenon, occurring for Strouhal numbers less than about 2.5. Further, it is also critically dependent upon the cavity shape. Recent tests of a circular cavity conducted at the Langley Research Center produced much less tonal noise radiation than a square cavity of side length equal to the diameter of the circular cavity. This is important as the cavities on real aircraft are much different in shape from the simple rectangular model. (See ref. 35.) Finally, of course, this tonal mechanism cannot be responsible for the observed broadband radiation of real aircraft cavities. Thus, it is necessary to consider other potential cavity noise mechanisms.

There are at least two other possible sources of cavity noise. The shear layer shed from the leading edge of the cavity will induce fluctuating pressures on the edge resulting in an edge-noise source as discussed previously. Further, the turbulence in the shear layer will impinge on the back wall of the cavity resulting in an incident turbulence source similar to that mentioned earlier. Thus, there is the potential for a "trailing-edge" source at the leading edge of the cavity and a "leading-edge" source at the trailing edge of the cavity. Both these sources may be analyzed by the theory previously developed and both will produce a more broadband noise. The analysis is simplified by the fact that these sources will appear compact.

A potential design and operating problem might be pointed out here. The noise generation by these component sources is intimately related to the flow around them which also determines their drag. In fact, Revell (ref. 36) is attempting to predict airframe noise from steady drag measurements. If it turns out that there exists a one-to-one relation between airframe noise and drag, a general drag cleanup of the aircraft in landing approach would be necessary. This might well imply higher landing speeds, perhaps requiring longer runways, and cause consternation among pilots who prefer high drag on approach.

## CONCLUDING REMARKS

This paper has presented a critical assessment of the state of the art in airframe noise. Full-scale data on the intensity, spectra, and directivity of this noise source were evaluated in light of the comprehensive theory developed by Ffowcs Williams and Hawkings. Vibration of panels on the aircraft was identified as a possible additional source of airframe noise. The present understanding and methods for prediction of other component sources - airfoils, struts, and cavities - were discussed. Operating problems associated with airframe noise as well as potential design methods for airframe noise reduction were identified.

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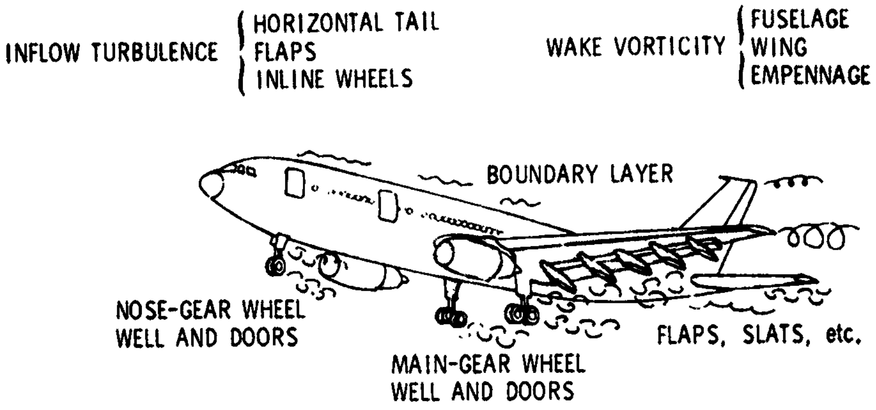

**Figure 1.- Schematic diagram illustrating potential sources of airframe noise.**

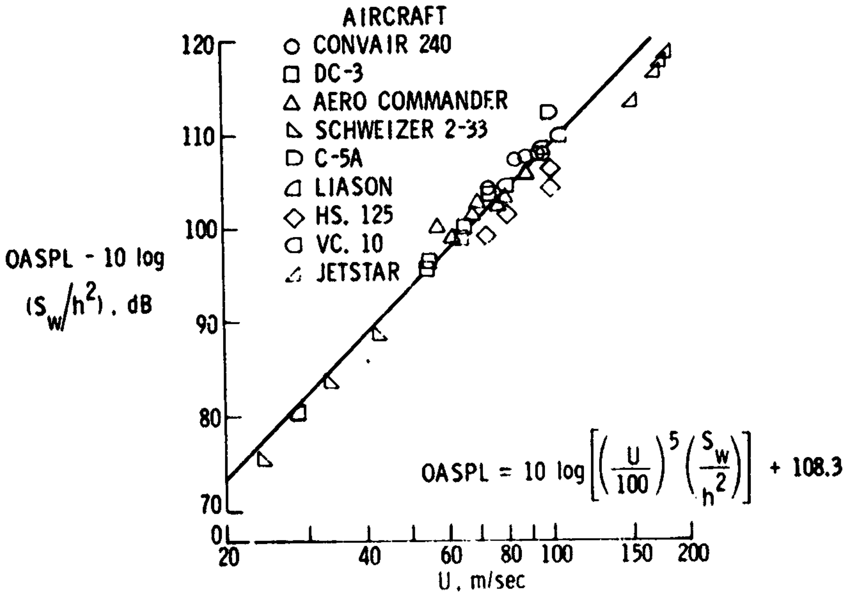

**Figure 2.- Measured and calculated maximum OASPL for conventional airframes with retracted gear and flaps.**

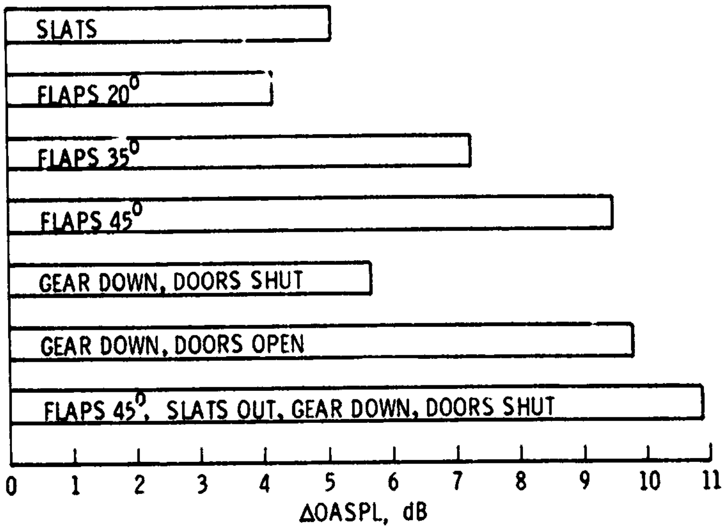

Figure 3.- Estimated nonpropulsive noise increase due to changes from the cruise configuration for the VC. 10 airplane.

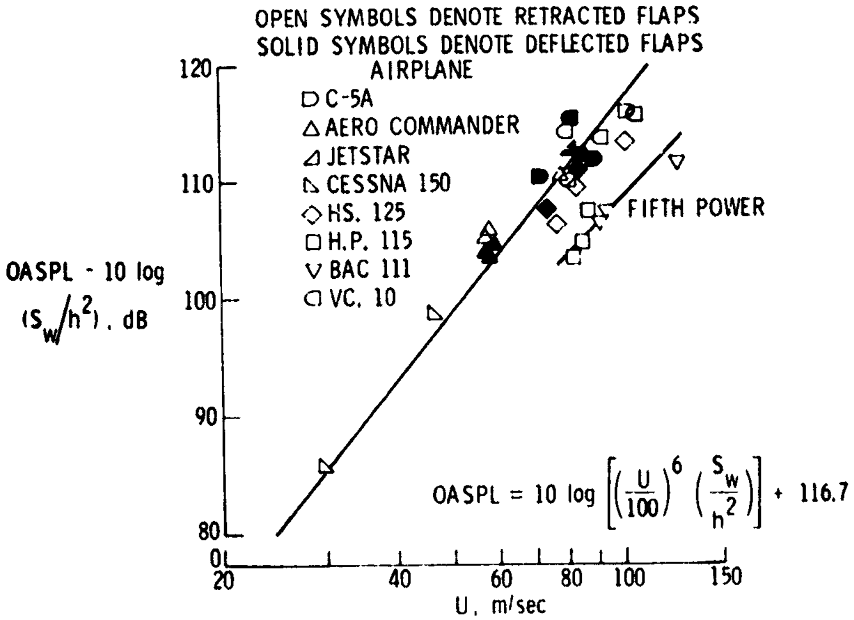

Figure 4.- Measured and calculated maximum OASPL for airframes with extended landing gear.

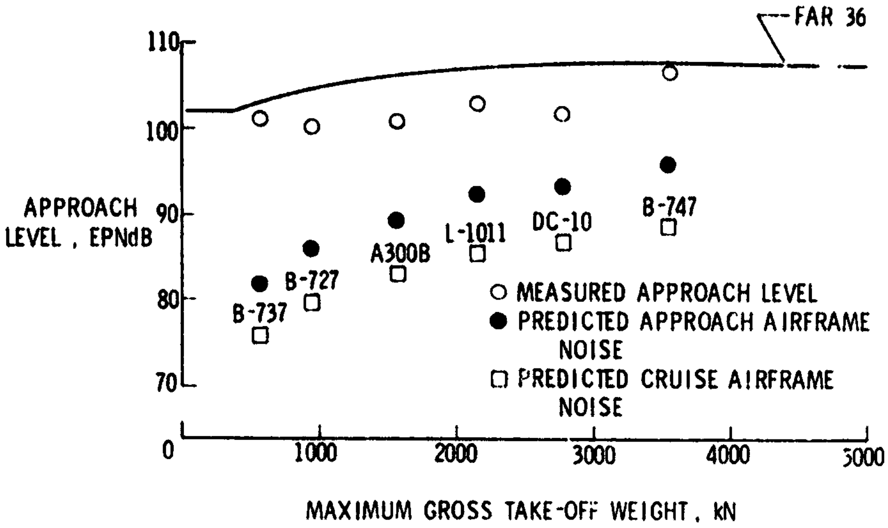

Figure 5.- Comparison of predicted approach and cruise airframe noise levels with FAR 36 certification standard (ref. 2).

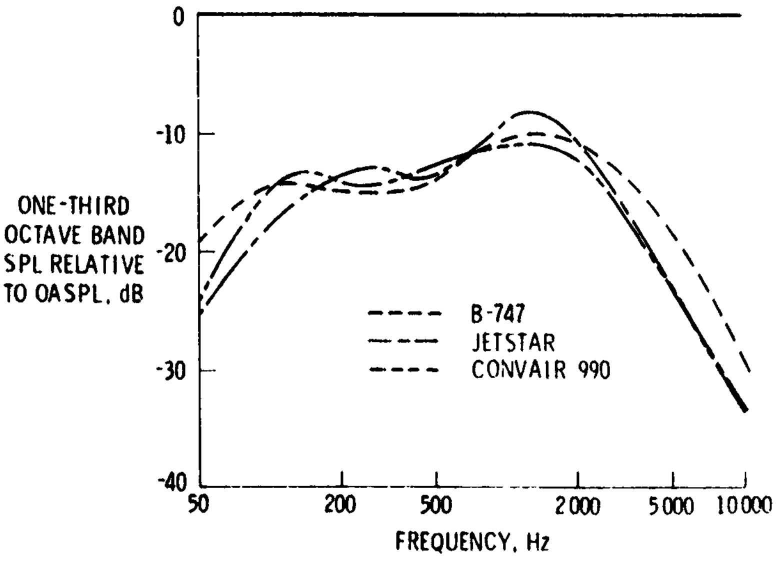

Figure 6.- Clean configuration airframe noise spectra directly below aircraft normalized to equal overall sound pressure level.

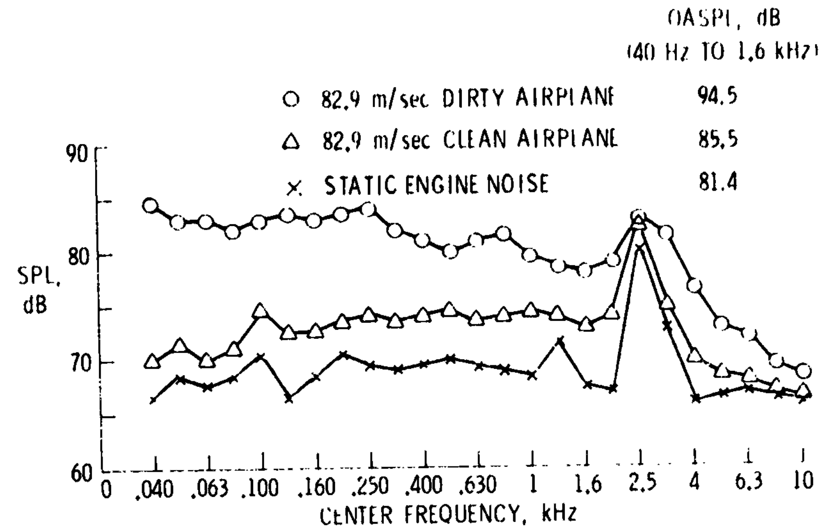

Figure 7.- Comparison of one-third octave band airframe noise spectra for dirty and clean configurations of VC. 10 airplane flying overhead at 183 m.

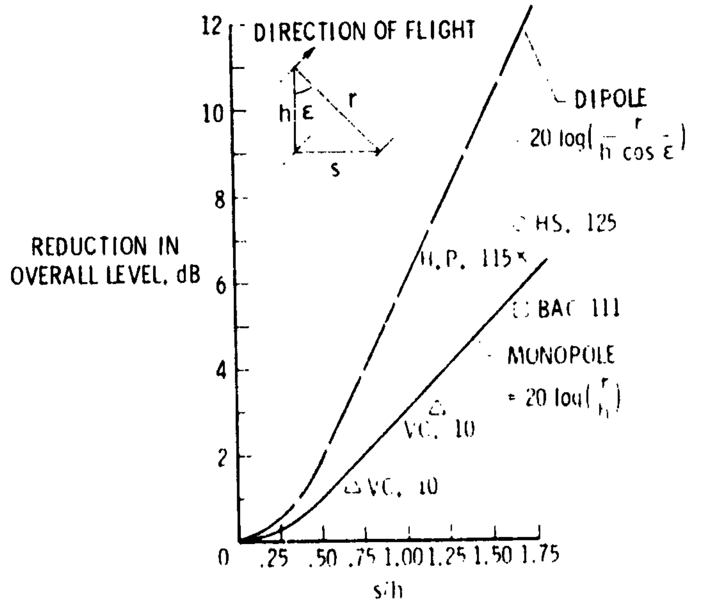

Figure 8.- Measured and predicted reduction in sideline OASPL for four aircraft in clean configuration.

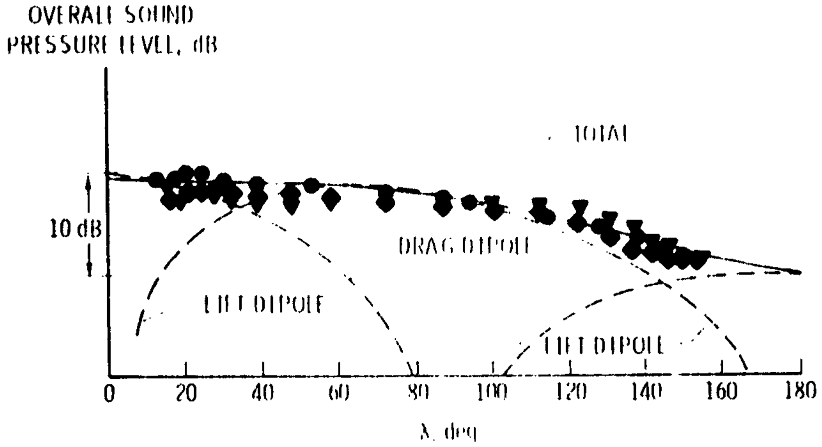

Figure 9.- Directivity pattern of DC-10 airframe noise in flyover plane compared with that calculated for dipoles oriented in lift and drag directions.

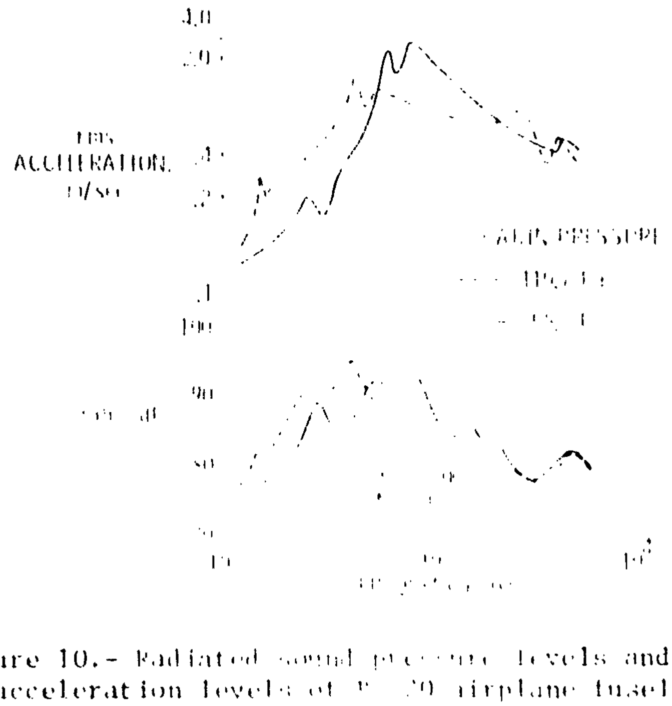

Figure 10.- Radiated sound pressure levels and skin acceleration levels of [illegible] 20 airplane fuselage panel for two different values of cabin pressure.

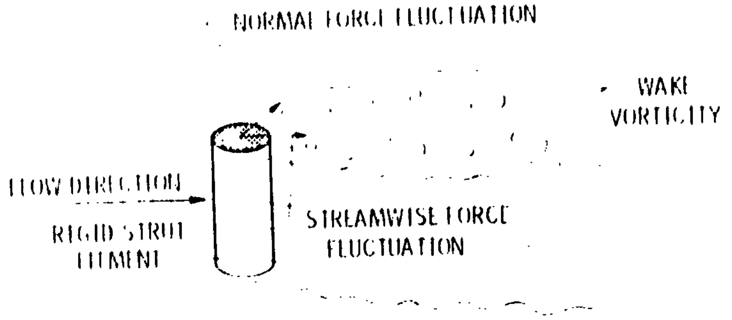

Figure 11.- Schematic diagram of wake-generated forces on a cylindrical segment in an airstream.

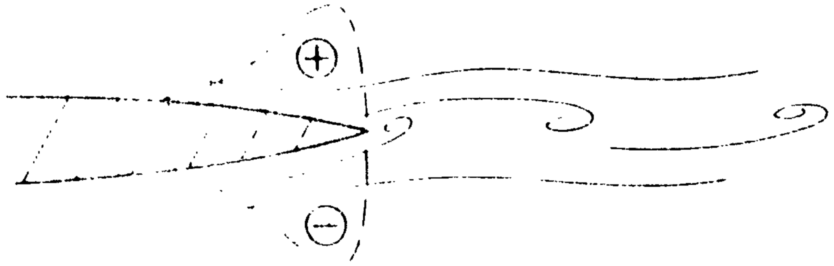

Figure 12.- Schematic diagram of flow field near a trailing edge and vortex induced instantaneous pressure loading.

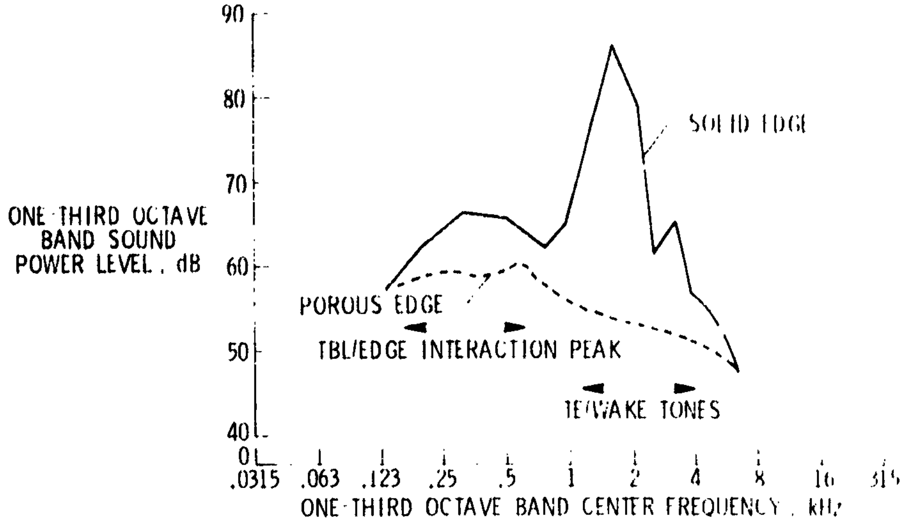

Figure 13.- Airfoil edge source reduction. NACA 0012 airfoil; chord, 0.15 m; span, 0.5 m; α = 4°; U = 30 m/sec.

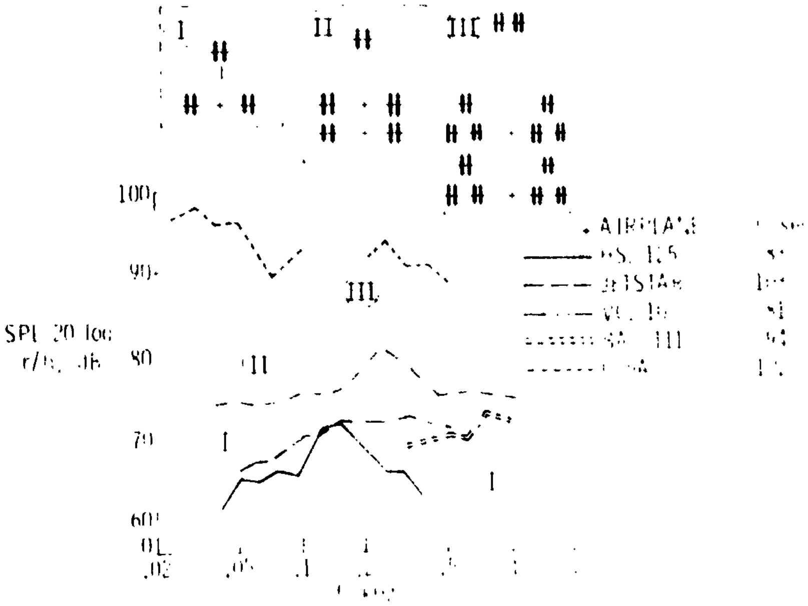

Figure 14.- Maximum landing-gear noise at flight altitude of 100 m.