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AIRFRAME SELF-NOISE - FOUR YEARS OF RESEARCH.

by

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16. Abstract

This paper presents a critical assessment of the state of the art in airframe self-noise. Full-scale data on the intensity, spectra and directivity of this noise source are evaluated in the light of the comprehensive theory developed by Ffowcs-Williams and Hawkings. Vibration of panels on the aircraft is 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 and areas for further research as well as potential methods for airframe noise reduction are identified. Finally, the various experimental methods which have been developed for airframe noise research are discussed and sample results are presented.

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INTRODUCTION

The importance of airframe self 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[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. The surprisingly high intensity of this hitherto neglected noise source could, if verified, impose a troublesome lower bound on aircraft noise reduction. Thus, significant research efforts toward experimental evaluation of the magnitude and characteristics of airframe self noise were stimulated.

Verification of the existence of these high levels involved ground measurements of noise produced by large aircraft during landing approach flyovers. Such measurements are difficult to make and interpret since, for safety reasons, such aircraft usually cannot be flown without power (deadstick). Thus, there is the necessity for some method of separating the airframe or nonpropulsive noise from the engine noise, as well as for accurate determination of the aircraft position and velocity for correlation with noise data. Nevertheless, the work was pursued with the result that the predicted levels were generally confirmed. For example, the Boeing Company has cited measured airframe noise levels for the 727 and 747 aircraft[2] approximately eight EPNdB below FAR-36 standards.

The significance of this lower bound set by airframe noise lay 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 self 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[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 landing gear/wheel well combination becomes dominant. Attempts are now being made to study these individual component sources in isolation in order to better characterize the physical mechanisms involved.

This paper contains a critical assessment of the present understanding of airframe self noise in order to identify potential methods of noise reduction as well as to highlight areas where further research is needed. A review of full scale data on the magnitude, spectra, and directivity of this type of aircraft noise is presented, followed by a discussion of theory in an attempt to establish a theoretical framework which can explain the observations. Analytical models for noise generation by the individual component sources are reviewed, and the various measurement techniques now being employed in airframe noise research are evaluated.

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. While 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.

Overall airframe noise measurements directly beneath the flight path of the aircraft have been made for a number of years. A table listing 65 data points published prior to 1975 has been compiled by Hardin et al[4]. However, many of these early data were obtained 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.

The first of these studies[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. Some data obtained in this study for the clean configurations are listed in table 1 and are plotted in figure 2. The data in figure 2 were normalized to an altitude of 152 meters by assuming an inverse square dependence on distance but were not corrected for pressure doubling effects due to the flush mounting of the microphones. Data from ref. 5 on the Aerocommander are not included as this aircraft is propeller driven and exhibited significantly higher normalized sound levels which the authors attributed to noise generation by the feathered propellers.

Also presented in table 1 and figure 2 are clean configuration data on the HS125, BAC111 and VC10 obtained by Fethney[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. These data on the figure are also normalized to an altitude of 152 meters and are not corrected for ground augmentation. Reference 6 also contained data on the HP115, a delta winged research aircraft, which is not included herein due to the fact that it had nonretractable landing gear.

The data presented in figure 2 indicate the airframe noise level directly beneath the various clean configured aircraft flying at an altitude of 152 m as a function of airspeed. Also shown on the figure is a line indicating the expected behavior if these levels exhibited fifth power dependence on velocity. By noting the sets of data points for individual aircraft, it can be seen that the velocity dependence is approximately the fifth power. This is a lower velocity dependence than would be observed for a dipole source.

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[6] made some estimates based upon measurements for the VC10. 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. Note that 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.

Based upon early measurements, Healy[7] 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. More recent measurements indicate a much more complex spectrum.

Figure 4 displays the peak one third-octave band spectra normalized to equal overall sound pressure levels (OASPL) for the clean configured Jetstar, CV-990 and 747 aircraft as measured by Putnam et al[5]. Although such measurements are complicated due to the fact that the moving source produces a non-stationary 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, Putnam et al 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 HS125 and BAC111 obtained by Fethney[6] display the same shape and peak location.

The change in spectrum shape for the VC10 in going from the clean to dirty configurations is illustrated by the data of figure 5. The characteristic double peaked clean spectrum is not discernable for this aircraft. The major difference in the dirty configuration spectrum is a broad band increase in level, particularly at the low frequency end. Figure 6 shows a narrow band analysis of the low frequency portion of spectra, similar to those of Figure 5, obtained under somewhat different flight conditions. Note the appearance of narrow peaks in both the clean and dirty configurations.

The directivity of airframe noise has only recently begun to be explored and only a modest amount of data exist in the open literature. Figures 7 and 8 depict spectra directly below and to the side respectively of the HP115 aircraft in the cruise configuration. (Note that this aircraft has a non-retractable landing gear.) Although this is a delta wing craft, it exhibits essentially the same spectral shape below as that observed by Putnam, et al[5] for more conventional configurations. To the side, however, the higher frequency peak shifts from about 1 kHz to 2 kHz. This behavior indicates that different noise sources may dominate at different angles with respect to the aircraft.

Figure 9 portrays the reductions in measured overall noise levels (over those directly below the aircraft) with sideline distance for the four aircraft tested by Fethney[6]. These data are compared with predicted reductions based upon considering 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 clusters about the solid curve indicates a monopole-like fall off to the side. Similar behavior has been observed by Lasagna and Putnam[8] for the Jetstar aircraft in the landing configuration. This result is important in its implications for the source type dominant in airframe noise as well as for the airframe noise "footprint".

Figure 10 shows airframe noise measurements in the flyover plane for a clean configured Douglas DC-10 aircraft[9]. The data have been corrected for an inverse square falloff with distance and are plotted as a function of λ, the angle of the approaching aircraft with respect to the horizontal. (Before normalizing, the airframe noise peaked slightly before the aircraft was directly overhead.)

The above 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[10] who extended the Lighthill-Curle[11,12,13] theory of aerodynamic sound generation to include arbitrary convection motion. For this case, the wave equation governing the generation and propagation of sound admits the general solution

$$4\pi a^2(\rho(\vec{x},t) - \rho_o) = \frac{\partial^2}{\partial x_i \partial x_j} \int_V \left[\frac{T_{ij}\ J}{r|1 - M_r|}\right] d\vec{\eta}$$

$$- \frac{\partial}{\partial x_i} \int_S \left[\frac{p_{ij} n_j A}{r|1 - M_r|}\right] dS(\vec{\eta}) + \frac{\partial}{\partial t} \int_S \left[\frac{\rho_o v_n}{r|1 - M_r|}\right] dS(\vec{\eta}) \qquad (1)$$

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[10] further showed that, for the case of a rigid surface, the monopole distribution degenerates into a distribution of dipoles and quadrupoles throughout the volume contained within the surface.

In the majority of airframe noise research to date, the aircraft has been assumed to be rigid. Application of this assumption in the above theory 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.

First, 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[14] and Powell[15]. They considered the radiation from a volume of turbulence near the edge of a rigid halfplane and found that the sound production of quadrupoles with axes in a plane normal to the edge was enhanced such that the farfield 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. While 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 (See fig. 4) is puzzling. This peak, which was observed by both Putnam, et al.[5] and Fethney[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[16] who investigated sound produced by turbulent boundary layer excited panels. Shown in figure 11 is [illegible]e one third octave band spectrum of acoustic power radiated by a 0.28 m by [illegible] steel panel of 0.08 mm thickness which was mounted in the side of a low turbulence wind tunnel. Davies found that the frequency of this peak was reasonably independent of flow speed.

A similar spectrum has also been observed by Maestrello[17] who reported interior measurements in an unupholstered Boeing 720 aircraft. Shown in Figure 12 are spectra of panel acceleration as well as sound pressure level close to the panel for the aircraft in flight at a Mach number of 0.87 and an altitude of 7700 m. 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.

The above 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[14] and Powell[15] 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 [illegible] equation (1) 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 effectively interfere 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 18. 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[13], who extended Lighthill's[11,12] theory 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[19]. 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 flowfield 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, i.e. noise generation by cylinders, streamlined bodies and cavities. Although the geometry of real aircraft may differ substantially from the models which have been analytically and experimentally studied, it is assumed that the basic noise generation mechanisms remain valid. As a comprehensive review of the literature has been attempted by Hardin et al[4], only the best present understanding of these mechanisms will be discussed.

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 13.

The exact nature of the wake and, thus, the sound produced is highly dependent upon the Reynolds' number ($Re = \frac{Ud}{\nu}$, 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 $10^5 - 10^6$. 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[20] who studied the fluctuating lift and drag forces on cylinders for the range $3 \times 10^5 < Re < 1.4 \times 10^6$. He found the root mean square fluctuating lift and drag coefficients to be 0.13 and 0.04 respectively, i.e.,

$$C_L = \sqrt{\frac{\overline{F_n^2}}{qA_p}} = 0.13 \tag{2}$$

and

$$C_D = \sqrt{\frac{\overline{F_D^2}}{qA_p}} = 0.04$$

where the overbar indicates a time average, $q = 1/2\ \rho_o U^2$ is the dynamic pressure and $A_p = \ell d$ is the projected area where ℓ and d are the length and diameter of the cylinder respectively. Unfortunately, the correlation of these lift and drag forces was not measured. The manner in which they are correlated could have a significant effect on the noise produced.

In the case of 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[21]. Further, in the absence of any information on the correlation of fluctuating lift and drag and noting that the RMS drag is only a third of the lift, the drag contribution will be neglected entirely. Thus, assuming the aircraft to be flying at the constant airspeed U, the acoustic pressure at the observer location $\vec{x}$ is given by

$$p\ (\vec{x},\ t + \frac{r}{a}) = \frac{\operatorname{Cos} \beta}{4\pi(1 - M_r)^2 ar} \frac{dF_N(t)}{dt} \tag{3}$$

where β is the angle between the force and the observer direction and $M_r = M \cos\theta$ where $M = U/a$ and θ is the angle between the flight path and the observer direction. Thus, taking the aircraft to be far enough from the observer that changes in β, θ and r are negligible over the time for which the fluctuating force is correlated, the spectrum of acoustic pressure at the observer location is related to the spectrum of the fluctuating lift through

$$S_a(\vec{x},\omega) = \frac{\cos^2\beta}{16\pi^2(1 - M_r)^4 a^2 r^2}\,\omega^2\, S_N(\omega) \tag{4}$$

Measurements of the spectrum of the fluctuating lift on a circular cylinder in the appropriate Reynolds' number range have also been obtained by Fung[20]. Figure 14 presents Fung's data on the normalized power spectrum of lift fluctuations at a Reynolds' number of 5.7×10^5 in comparison with the analytical relation

$$S_N(\omega) = \frac{2\,\overline{F_N^2}\,d}{\pi U}\sqrt{\frac{\alpha^3}{\pi}}\left(\frac{\omega d}{2\pi U}\right)^2 e^{-\alpha\left(\frac{\omega d}{2\pi U}\right)^2} \tag{5}$$

where α is a nondimensional parameter taken as 6.94×10^1. This spectrum is defined such that the total power is obtained by integrating over only non-negative frequencies.

Since Fung found that the normalized spectra at other Reynolds' numbers in the range of interest were not appreciably different, Eq. (5) may be employed in Eq. (4) to calculate the mean square acoustic pressure at the observer location, i.e.

$$\overline{p^2(\vec{x})} = \int_0^\infty S_a(\vec{x},\omega)d\omega = \frac{3}{8}\,\frac{\overline{F_N^2}\,M^2 \cos^2\beta}{(1 - M_r)^4 r^2 d^2 \alpha} \tag{6}$$

with the resulting overall sound pressure level

$$\mathrm{OASPL}(r,\beta,\theta) = 10 \log_{10} \left(\frac{\overline{p^2(\vec{x})}}{p_o^2}\right) \tag{7}$$

where p_o is a reference pressure usually taken as 2×10^{-5} N/m^2. Equations (4) and (7) may be employed to estimate the spectra and overall sound pressure levels produced by moving cylinders.

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[22] 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. 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[23] 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 the case in airframe noise - except near the edges. This "edge noise" source will be discussed below.

In reference to the panel vibration source proposed earlier in this paper, it might be mentioned that Laufer et al[24] 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 15 which is taken from a report by Siddon[25]. 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 inducing a fluctuating force concentration 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[4]. Again, the generation process is highly dependent upon Reynolds' number. Much recent work[26,27] 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 length of less than about 2×10^6 while 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[28] 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[14] and Powell[15]. 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

$$\overline{p^2}(r,\theta,\phi) \simeq \frac{\rho_o^2\, U^5\, \gamma^2\, V_o^2 \sin\phi \sin^2\theta_o \cos^2\theta/2}{\pi^2\, a\, \delta\, r_o^3\, r^2} \tag{8}$$

where γ is the turbulent intensity, V_o is the eddy volume, δ is the streamwise correlation length of the eddy, θ is the angle between the streamwise and observer directions, θ_o is the angle that the mean flow makes with the trailing edge and ϕ is the angle between the 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 turbulence intensity squared. It also gives rise to a directivity pattern in a plane normal to the edge dependent upon $\cos^2 \theta/2$. This directivity pattern, which Hayden[29] has associated with a "baffled dipole", is shown in Figure 16. 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.

It should be noted here that summation of equation (8) over all eddies to produce the total mean square pressure at an observer location must be approached with extreme caution. The primary trailing edge source on an aircraft is the wing. Thus, the source dimension is of the order of the span. Since airframe noise is typically of interest at distance of only a few spans from the aircraft, the geometric far field of the source distribution has not been reached and a simple summation employing average values of distances and angles could be in considerable error. For this case, a "stripwise" summation as suggested by Hayden et al.[18] is undoubtedly superior. Further, the fact that these sources are in motion should, of course, be taken into account.

The variables which appear in equation (8) are fairly straightforward to obtain with the exception of those which characterize the eddy. Clark[30] has made measurements in the wake behind an airfoil placed in the potential core of a low turbulence jet. These measurements suggest that the controlling parameter in the eddy size is actually the width of the wake, Δ, and that the number of eddies across a span b should be $\simeq b/\Delta$. The eddies are apparently ellipsoidal with $\delta = \frac{3}{2}\Delta$ and $V_o \simeq \frac{3}{4}\Delta^3$. Thus, if the eddy distance r_o is taken as $\frac{3}{2}\Delta$, equation (9) becomes

$$\overline{p^2}\,(r,\theta,\phi) \simeq \frac{\rho_o^2\, U^5\, \gamma^2\, \Delta^2 \sin\phi\, \sin^2\theta_o}{9\pi^2 a r^2} \cos^2\frac{\theta}{2} \qquad (9)$$

This relation indicates that sound generation by an aerodynamic surface is highly dependent upon the width of its wake. The drag of the body is also related to the wake width, a result which has led Revell[31] to attempt to predict airframe noise from steady state drag.

Unfortunately, very few measurements of the amplitude and spectra of this trailing edge source exist due to the difficulty in making the required measurements in present day flow facilities. Some data at very small scale were obtained by Clark[30]. These have been employed by Clark et al[32] in a recent attempt to develop an expression for the power spectrum of sound radiation by isolated airfoils. Their theory, however, requires a knowledge of the spectra of wake velocity components. It can be noted that this study also showed a low (-0.2) power dependence of the eddy correlation lengths on Reynolds' number.

In the absence of precise information, practical estimation of the frequency content of trailing edge noise might well employ the nondimensional spectrum obtained by Healy[7]. This spectrum, shown in Figure 17, is a composite of spectra measured directly below several small aircraft with pecularities removed. As the aircraft were all in the "clean" or cruise configuration, the primary source of noise directly below the craft should have been trailing edge noise. For the peak frequency, Healy suggests

$$f_{max} = 1.3 \frac{U}{t_w} \tag{10}$$

where t_w is a representative wing thickness. At positions other than directly below the aircraft, this relation should be modified to account for the Doppler shift, i.e.

$$f_{max} = \frac{1.3U}{t_w(1 - M_r)} \tag{11}$$

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(4), it is useful to observe that, since Ffowcs-Williams and Hall's(14) work 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 (9) 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.

When the observer is far enough away to be in the geometric far field of the entire leading edge source (which probably is not the case for normal airframe noise measurements) an analysis of this problem has recently been formulated by Amiet(33). This theory decomposes the incoming turbulence into Fourier components and then employs the Sears function to calculate the airfoil response. It yields an expression for the (one-sided) power spectral density of the radiated sound at a distance z directly above (or below) the airfoil as

$$S_a(0,0,z;\omega) = \frac{b}{\pi a}\left(\frac{2\mathcal{L}}{3\pi z}\right)^2 \gamma^2(\rho_o U)^2 \left[\frac{\Gamma(1/3)}{\Gamma(5/6)}\right]^2 \frac{\tilde{K}_x^2}{(1+\tilde{K}_x^2)^{7/3}} \tag{12}$$

where the Von Karman spectrum has been used to describe the turbulence, b is the span of the airfoil, $\Gamma(\cdot)$ is the Gamma function, $\mathcal{L}$ is the integral scale of the turbulence and

$$\tilde{K}_x = \frac{K_x \ell \Gamma(1/3)}{\sqrt{\pi}\, \Gamma(5/6)}$$

where $K_x = \omega/U$. This relation holds as long as $MK_x b > 2$. The corresponding third octave band sound pressure level is given by

$$SPL = 10 \log_{10} \left[\frac{\ell b}{2z^2} M^5 \gamma^2 \frac{\tilde{K}_x^3}{(1 + \tilde{K}_x^2)^{7/3}} \right] + 181.3 \qquad (13)$$

Figure 18 shows a comparison of this relation with data on sound generation by an airfoil in an acoustic tunnel. A grid was placed in the tunnel in order to generate the incident turbulence.

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[6] (See Fig. 3) 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. 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 due to 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[34]. 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. A reasonably accurate expression for the frequencies of the shear layer instability modes in simple rectangular cavities has been developed by Rossiter[35] i.e.

$$f_m = \frac{U}{L} \frac{(m - 0.25)}{1/k_v + M} \quad m = 1,2,\ldots \tag{14}$$

where L is the length of the cavity in the flow direction and k_v is the ratio of eddy convection speed to the flow speed. 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[36]. Figure 19 displays a typical spectrum measured directly above the cavity in comparison with a spectrum of the fluctuating pressures inside the cavity for a length to depth ratio (L/D) of unity. The directivity of this noise source was determined to be nearly that of a monopole although small deviations do occur. On the basis of this work, Bliss and Hayden[37] have developed a prediction relation for the mean square pressure radiated by the cavity, i.e.

$$\overline{p^2}(r) = [.015(m - 1/4)q \frac{w}{r}]^2 \qquad (15)$$

where q is the dynamic pressure and w is the width of the cavity. This equation assumes good coupling between the forcing frequency and the fundamental acoustic mode. Thus, predictions on the basis of this relation often tend to be high. Further, such coupling is usually only seen for the modes $m = 2$, 3 or 4.

This "basic" cavity noise mechanism is primarily a low frequency phenomenon, occurring for Strouhal numbers $St = \frac{fL}{U}$ less than about 2.5. Further, it is also critically dependent upon the cavity shape. Recent tests of a circular cavity conducted at NASA Langley 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[37]. 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 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 of these sources may be analyzed by the theories developed earlier and both will produce a more broadband noise. The analysis is simplified by the fact that these sources will appear compact.

An alternate theory, tailored to the case of the cavity, has recently been developed by Hardin and Mason[38] which allows the sound generation to be calculated on the basis of the vorticity present in the cavity flow. This theory identifies monopole, dipole and quadrupole type sources inherent in the flow field over the cavity and has been applied in a two dimensional model of cavity flow in order to better understand the broadband noise generation mechanisms. Figure 20 presents the spectrum of this noise source as calculated directly above a cavity with length to depth ratio of 2.0. Note that the broadband spectrum peaks near the Strouhal number of 4.0, which is considerably above the value of 2.5 below which tones are observed. Figure 21 displays the directivity of the sound in a plane parallel to the streamwise direction. Note that the peak intensity occurs slightly upstream of the cavity. This effect has also been observed in full scale airframe noise tests.

EXPERIMENTAL RESEARCH TECHNIQUES

A common problem encountered in airframe noise research is the fact that the self noise sources are not very intense compared either to propulsive noise sources or to background noise levels in typical test facilities. Overcoming this obstacle has required considerable innovation of new techniques and refinement of old ones.

FULL SCALE FLIGHT TESTING

The first airframe noise testing was done utilizing full-scale aircraft. However, it is expensive, requires extensive instrumentation and can be dangerous. Ordinarily such tests must be accomplished with the aircraft's engines inoperative or at flight idle. Such operating conditions may not be possible with all aircraft. Furthermore, unless the engines are extremely quiet, it is necessary to look for a "window" between the low frequency jet and ambient noise and the high frequency compressor noise through which the airframe noise may be observed. Such windows do not exist for all aircraft.

There are numerous problems and subleties connected with obtaining valid full scale airframe noise measurements. The fact that the source is moving past a fixed observer makes the design of an optimum experiment difficult. Not surprisingly, the various groups which have attempted such measurements have utilized different approaches to the acquisition and analysis of the data. However, this makes comparison of data obtained in different tests a tenuous undertaking. Thus, one of the urgent needs in this field is some standardization of testing techniques. For this reason and at the risk of sounding didactic, this paper will discuss many of these problems and offer approaches to them.

The primary quantity of interest in airframe noise research is its impact on the community, or airframe noise "footprint". Thus, the objective of airframe noise testing should be to obtain the directivity of the total airframe noise produced by the aircraft. Since accurate positioning of an aircraft with respect to a microphone is difficult, and repeat flights are expensive, a good (practical) way to obtain such data is with an array of microphones in the shape of a tee. The flight path of the aircraft is along the cross of the tee. Of course, each microphone will measure a sound pressure time history which increases in intensity and then dies away as the aircraft flies past. However, by properly picking short segments of these records for analysis, such records can be employed to obtain the directivity of the airframe noise in the flyover plane as well as to increase the statistical reliability of the data. Similar analysis of the sideline microphones will allow the rest of the footprint to be obtained, although with increased variability.

One question which arises at this point is: How should the microphones be mounted? Early testing employed pole mounted mics as those are required for aircraft certification. However, this leads to ground induced cancellation which may occur in the frequency range of interest. Perhaps a better technique is to mount the microphones flush with a hard reflecting surface which produces a pressure doubling effect over the entire spectrum that is well understood and easily corrected. This technique has been employed in two recent studies[5,6] with Fethney[6] even cutting away the lower half of the microphone windscreen so that the mic would lie flat on the concrete runway.

A second question which arises is how the aircraft should be flown over the microphone array. As the aircraft's speed and distance from the observer are important parameters in airframe noise, ideally one would like to fly the aircraft at constant speed and altitude. However, to do so requires more than flight idle power, which increases the engine noise level, and risks introducing unwanted sources through aircraft acceleration as can be seen in the last term of equation (1). Thus, it appears better to fly the aircraft at constant airspeed down a glide slope over the array. The pressure signals recorded by the microphones can later be corrected for the altitude variation utilizing an inverse square dependence of overall sound pressure level on observer distance as long as the observer was truly in the acoustic and geometric far fields of the aircraft.

The necessary corrections certainly require an accurate determination of the aircraft's position as a function of time. The best way of accomplishing this seems to be one of the radar tracking schemes which are usually available at suitable test sites. However, the problem is a little more complex. Typical aircraft of interest have spans and fuselage lengths of the order of thirty meters, while the altitude may be only a hundred meters or so. Thus, there is a nonnegligible difference depending upon what reference point on the aircraft is used to determine the observer distance. One should like to use the "center of gravity" of the source distribution. However, this is not known. Thus, this author might suggest the center of gravity of the aircraft as being as reasonable as any other. Once a point is chosen, a simple way of measuring the correct distance is to mount a radar target reflector on the aircraft and then translate the data to the chosen point on the aircraft.

Another problem crops up when one tries to relate the aircraft position information to the measured pressure time histories. The signal arriving at the observer location at time t was transmitted by the source at the earlier time $t - r_e/a$ where r_e was the source-to-observer distance at the time of emission. These considerations lead to a complex relation between the known aircraft position at time t and the actual acoustic propagation distance which should be employed in correcting the pressure time histories.

A further consideration in such testing is the variability of the data. The statistical variability of any spectral analysis is inversely proportional to the product of the bandwidth and the analysis time. Thus, for fixed bandwidth, one should like for the analysis time to be as long as possible. However, in this case where both the source/observer distance and the directivity angle are changing with time, the process is nonstationary and too long an analysis time can lead to aberrations in the data. Thus, there must be a trade off between statistical variability and nonstationarity. This problem is not critical for third-octave analysis where analysis times of a few tenths of a second yield adequate estimates. However, for narrow band analyses, severe problems arise. These may be overcome by averaging analyses of several microphones on a single flight or a few microphones on nominally identical repeat flights.

A final problem deals with calculation of overall sound pressure levels when the spectra are contaminated with engine noise. Some studies have merely calculated the OASPL value as if the engine noise were not there, others have integrated only up to some maximum frequency implying that all higher frequency power was engine noise while still others have attempted to subtract out the engine noise on the basis of static test data. Two problems with this last technique are that the static data are not measured at the same angles with respect to the aircraft as the airframe noise data and that no consideration of the known flight effects on jet noise has been given.

MODEL TESTING

There are considerable incentives toward the use of models in airframe noise testing. Among these are the possibility of eliminating engine noise and reducing the cost and danger of testing of any changes prompted by the application of noise reduction techniques. However, certain disadvantages due to reduced source intensity and the necessity of developing scaling relations (particularly since airframe noise is known to be Reynolds' number dependent) are introduced.

Remotely Piloted Vehicles

One such technique, involving the use of a remotely piloted vehicle (RPV) as the airframe noise source, has been investigated by Fratello and Shearin[39]. This testing is quite similar to that used in full scale flight research. In preliminary work employing powered RPV's whose engines were stopped before crossing the microphone array, they were able to obtain a 10 dB signal-to-noise ratio in the clean configuration with an RPV whose wingspan was 1.5 m flying at an altitude of 3 m with a speed of 25 m/sec as shown in Figure 22.

The data acquisition and analysis procedures are more critical in this type of testing than in full scale flight testing. The RPV must fly quite low over the array in order to produce a sufficient sound level at the microphone. Thus, the change in observer angle per unit time is large. However, acceptable methods for data collection have been devised. These utilize arrays of microphones and photodiodes as shown in Figure 23.

A more recent test program is employing an unpowered model of a Boeing 747 aircraft with a wingspan of approximately 2 m. Grit is glued onto the leading edges of the model surfaces to trip the boundary layer in an attempt to simulate full scale Reynolds numbers. The model is dropped from a helicopter and allowed to seek its natural (known) glide slope until it is pulled up into nearly level flight over the microphone array. Figure 24 is a photo of the model mounted on the drop helicopter. A rather sophisticated control system for this RPV has been designed and installed.

Anechoic Flow Facilities

A second technique for whole model testing which has been investigated is the use of anechoic wind tunnels. Such testing is hampered by the fact that a tunnel produces its own surface interaction noise which is difficult to separate from the model noise. Thus, the tunnel must have a very low background noise level. Further, at present, the test section must be open such that the microphones may be placed outside the flow in order to avoid swamping the airframe noise signal by microphone wind noise. NASA Langley engineers have been successful in such testing at the NSRDC Quiet Flow Facility in Carderock, Maryland[40]. Figure 25 is a photo of a 0.03 scale model of a Boeing 747 aircraft mounted in this tunnel. This model was carefully constructed to properly represent insofar as possible full-scale geometric and aerodynamic properties. Note that the mounting sting is airfoil shaped in order to minimize the generation of aeolian tones. These tests determined that model airframe noise can be geometrically scaled to that of the full scale aircraft with the exception of cavity generated sound[41]. The simple scaling relations for one-third octave sound pressure levels and frequency are

$$SPL_F = SPL_M + 10 \log_{10}[(SF)^{-2} \left(\frac{U_F}{U_M}\right)^5 \left(\frac{r_M}{r_F}\right)^2] \tag{16}$$

and

$$f_F = (SF)\, f_M \left(\frac{U_F}{U_M}\right) \tag{17}$$

where the subscripts F and M designate the full scale and model respectively and SF is the scale factor. Figure 26 shows a comparison of model and full scale data for a 747 aircraft with leading edge flaps deployed. The full scale data were obtained by the Boeing Aircraft Company directly below the aircraft during flyover tests. This measurement position is geometrically similar to that employed in the model tests. When scaled by means of equations (16) and (17), the model and full scale data agreed within 3 dB. During the model tests, measurements of sideline noise levels with and without the vertical tail on the model were made. No difference in noise level could be observed.

Anechoic wind tunnels are also useful for testing of component sources of airframe noise. The data on airfoil sound generation shown in figure 18 were obtained in the UTRC acoustic tunnel[33]. Another such tunnel[42] exists at Bolt, Beranek and Newman, Inc. in Cambridge, Mass. This tunnel was utilized to obtain the cavity noise data shown in figure 19.

One of the problems with all types of testing in acoustic wind tunnels is the fact that the sound must propagate through the shear layer of the tunnel flow. It is known that propagation through such a shear layer can alter the directivity and reduce the high frequency intensity of such sound. Although corrections for such changes are known for point sources at moderate frequencies[43], those required for a distributed source such as an airframe model are still a matter for research.

A conceptually different, yet very similar, type of facility which is useful in airframe noise research is an anechoic chamber with quiet flow capability. Such facilities exist in many research organizations. A constraint for airframe noise testing, however, is that the flow must be large enough that a reasonable sized model may be tested. Such testing has been successfully accomplished in the chamber in the new Aircraft Noise

Reduction Laboratory at NASA Langley Research Center. The air supply has a capability of 41 m^3/sec which will allow a 52 m/sec velocity through a 1 m diameter nozzle. Figure 27 is a photo of a recent experiment in this chamber to investigate cavity noise and the interaction of cavity/strut generated turbulence with downstream flaps. Figure 28 shows noise directivity patterns of the cavity alone in the plane normal to the flow for two different frequencies obtained during these tests in the Facility of Figure 27. The flow speed was 119 m/sec and the cavity length and depth were 4 cm and 5 cm respectively. Note that distinct lobes appear in the directivity pattern. Thus, the directivity pattern of the cavity tonal noise is not strictly monopole.

Moving Source Apparatus

A final type of facility which could be useful in airframe noise reserach is a moving source apparatus. This apparatus can be envisioned as some sort of tracked vehicle with a quiet propulsive system which would carry a model through an anechoic test section. Such an apparatus would accurately simulate an actual flyover in the sense that the model would move past a stationary observer and would eliminate some of the problems of anechoic wind tunnel testing. However, development of a quiet propulsive system is a nontrivial undertaking. Although such devices have been discussed, the author knows of no instance of their actual use in airframe noise testing.

CONCLUDING REMARKS

This paper has presented a critical assessment of the state of the art in airframe self noise. Full scale data on the intensity, spectra, and directivity of this noise source were evaluated in the 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 and areas for further research as well as potential methods for airframe noise reduction were identified. Finally, the various experimental methods which have been developed for airframe noise research was discussed and sample results were presented.

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Table 1: Clean Airframe Noise Data

Aircraft	U(m/sec)	h(m)	W(kg)	b(m)	OASPL
Jetstar	128.8	152.0	16682	16.6	84.6
Jetstar	154.5		16454		88.0
Jetstar	175.1		15909		90.5
Jetstar	182.8		15454		91.4
Jetstar	185.4		15136		91.6
CV-990	96.3		71364	36.5	85.0
CV-990	162.2		82273		94.1
747	133.9		228,182	59.4	95.3
747	114.3		227,727		92.5
HS125	74.1	45.7	6800	14.3	81.1
HS125	82.4				83.4
HS125	106				86.3
BAC111	90.6		30000	27.0	87.6
BAC111	111				90.2
BAC111	123				91.4
BAC111	133				92.9
VC10	82.9	182.9	90000	44.5	83.4
VC10	98.3				87.1
VC10	108				88.9

SYMBOL LIST

A	ratio of area elements
A_p	projected area
C_D	fluctuating drag coefficient
C_L	fluctuating lift coefficient
D	cavity depth
EPNdB	effective perceived noise level
F_D	streamwise force fluctuation
F_N	normal force fluctuation
J	Jacobian of transformation
K	wavenumber
K_x	wavenumber in x-direction
$\tilde{K}_x$	nondimensional wave number in x-direction
L	cavity length
M	Mach number
M_r	Mach number in observer direction
OASPL	overall sound pressure level
Re	Reynolds' number
S	surface
S_a	one-sided acoustic pressure spectral density
SF	scale factor
S_N	one-sided normal force spectral density
SPL	one-third octave band sound pressure level
St	Strouhal number
T_{ij}	Lighthill stress tensor

U	flow or aircraft speed
V	volume
V_o	eddy volume
W	aircraft weight
a	speed of sound
b	wing span
c	distance between microphones and diodes in RPV testing
d	cylinder diameter
f	frequency
f_m	modal frequency
f_{max}	frequency of spectral peak
h	aircraft altitude
k_v	ratio of eddy convection speed to flow speed
ℓ	cylinder length
m	mode number
n_j	components of normal vector
p	acoustic pressure
p_{ij}	compressive stress tensor
p_o	reference pressure
q	dynamic pressure
r	observer distance
r_e	observer distance at time of emission for moving source
r_o	distance of center of eddy from edge
s	sideline distance
t	time
t_w	wing thickness

v_n	normal velocity
w	cavity width
$\vec{x}$	observer position
x_i	components of position vector
z	$= x_3$
α	spectral parameter
β	angle between force and observer directions
γ	turbulent intensity
δ	streamwise correlation length
ε	observer angle
$\vec{\eta}$	source position
θ	angle between flight path and observer directions
θ_o	angle between mean flow and trailing edge directions
λ	directivity angle in flyover plane
ν	kinematic viscosity
ρ	farfield density
ρ_o	ambient density
ϕ	angle between trailing edge and observer directions
ω	circular frequency
Δ	width of wake
ΔOASPL	increment in overall sound pressure level
$\Gamma(\cdot)$	Gamma function
$\mathcal{L}$	integral scale of turbulence

Subscripts

F	full scale

M model

Superscripts

Overbar - Time-average

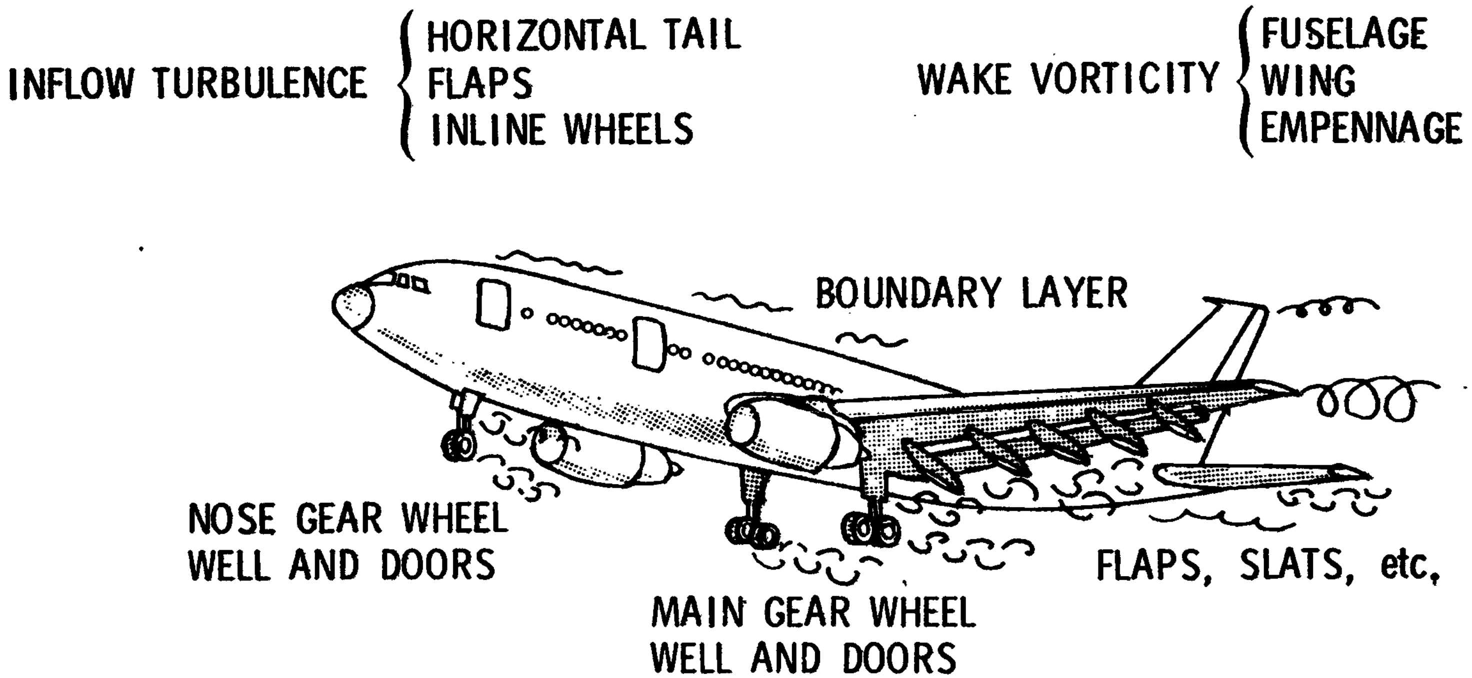

Figure 1. Schematic diagram illustrating potential sources of airframe noise.

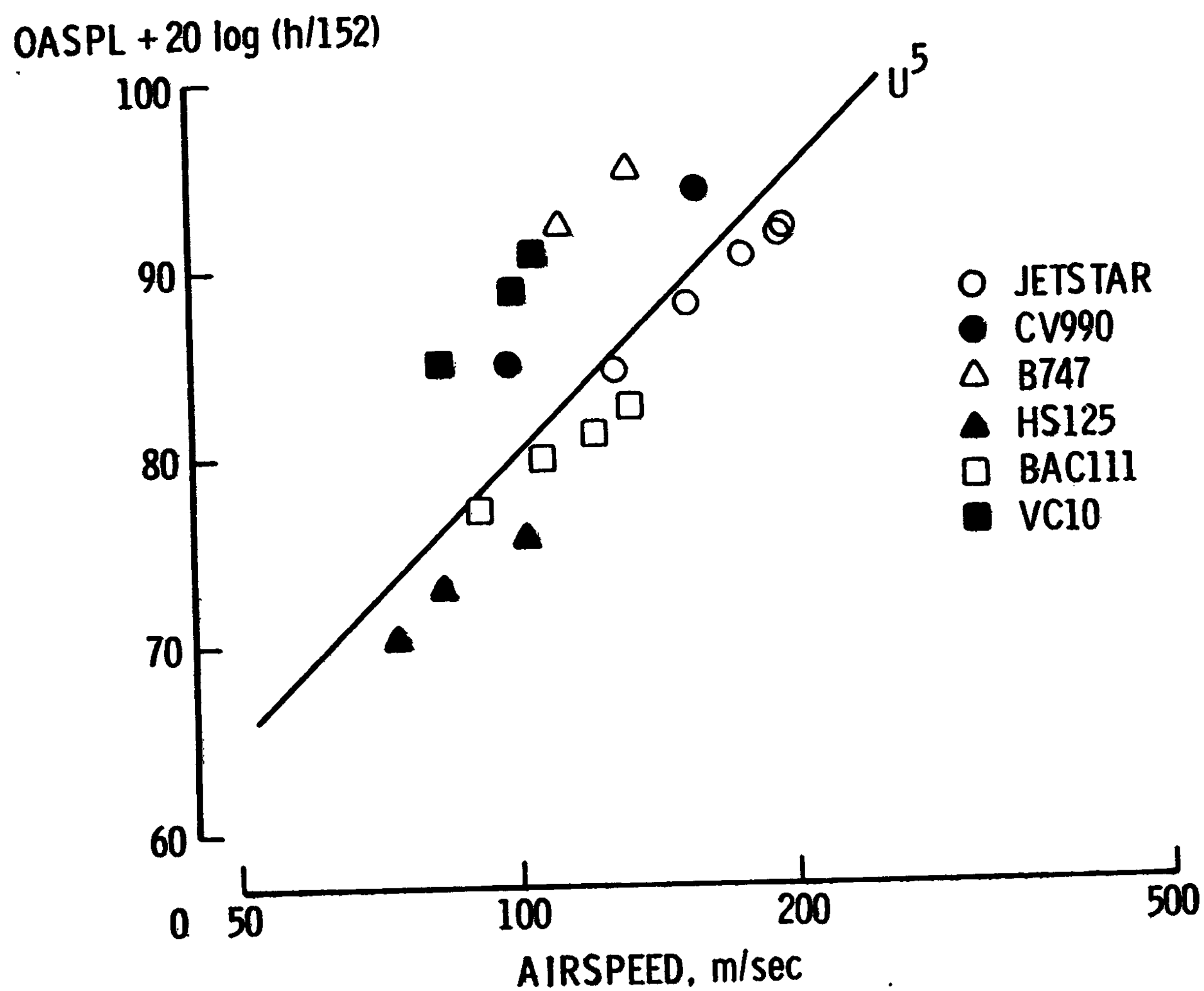

Figure 2. Clean airframe noise levels directly below aircraft normalized to an altitude of 152 m.

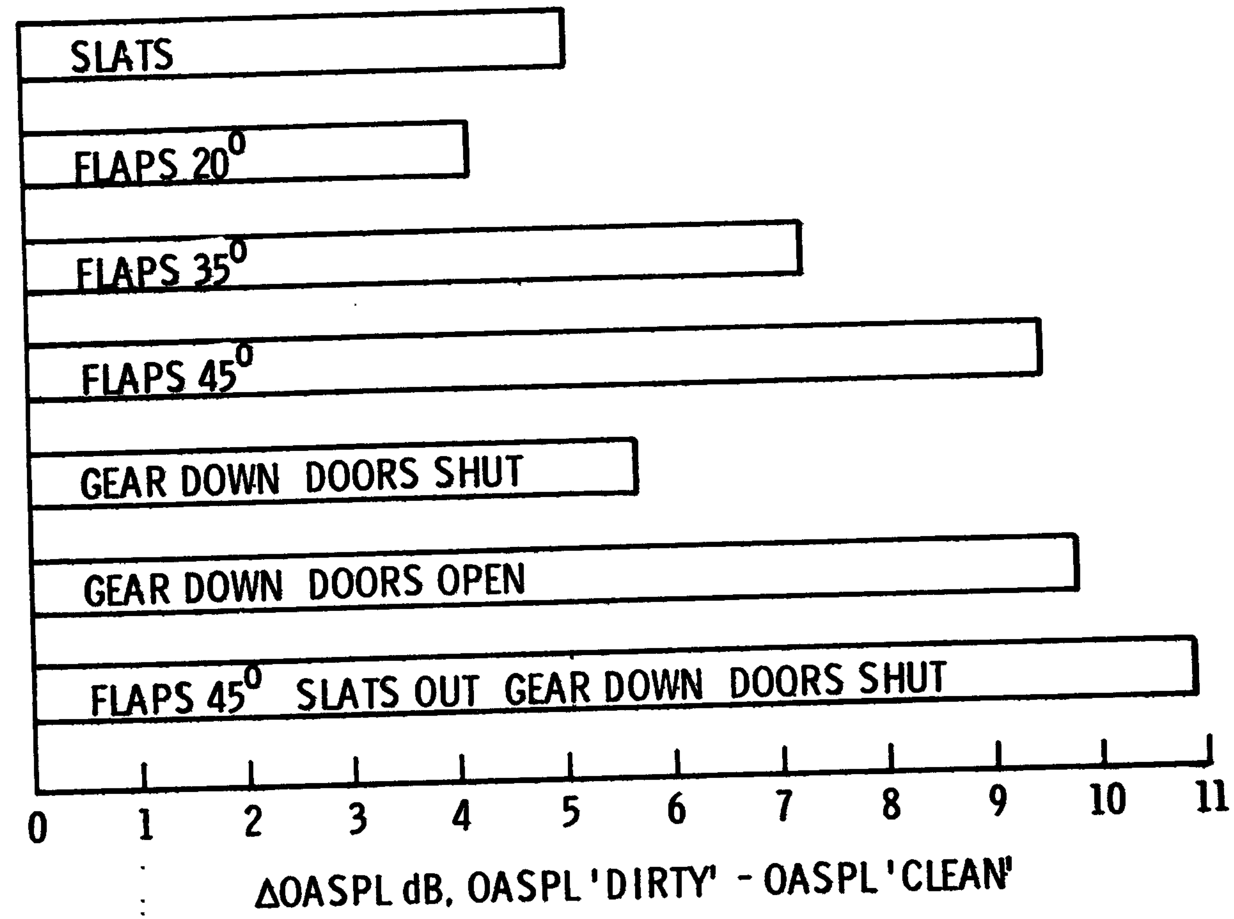

Figure 3. Estimated nonpropulsive noise increase due to changes from the cruise configuration for the VC10 airplane.

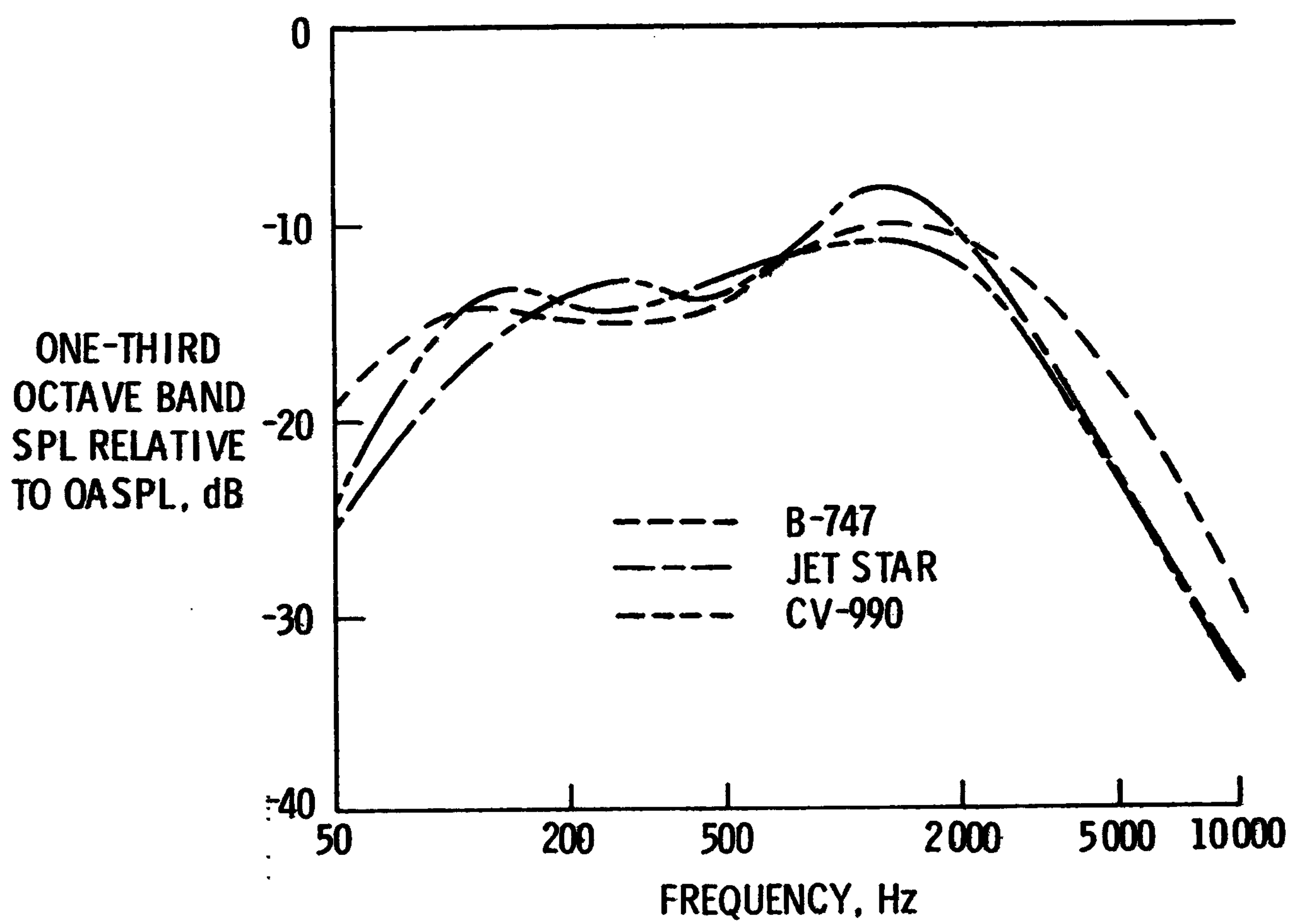

Figure 4. Clean configuration airframe noise spectra directly below aircraft normalized to equal overall sound pressure level.

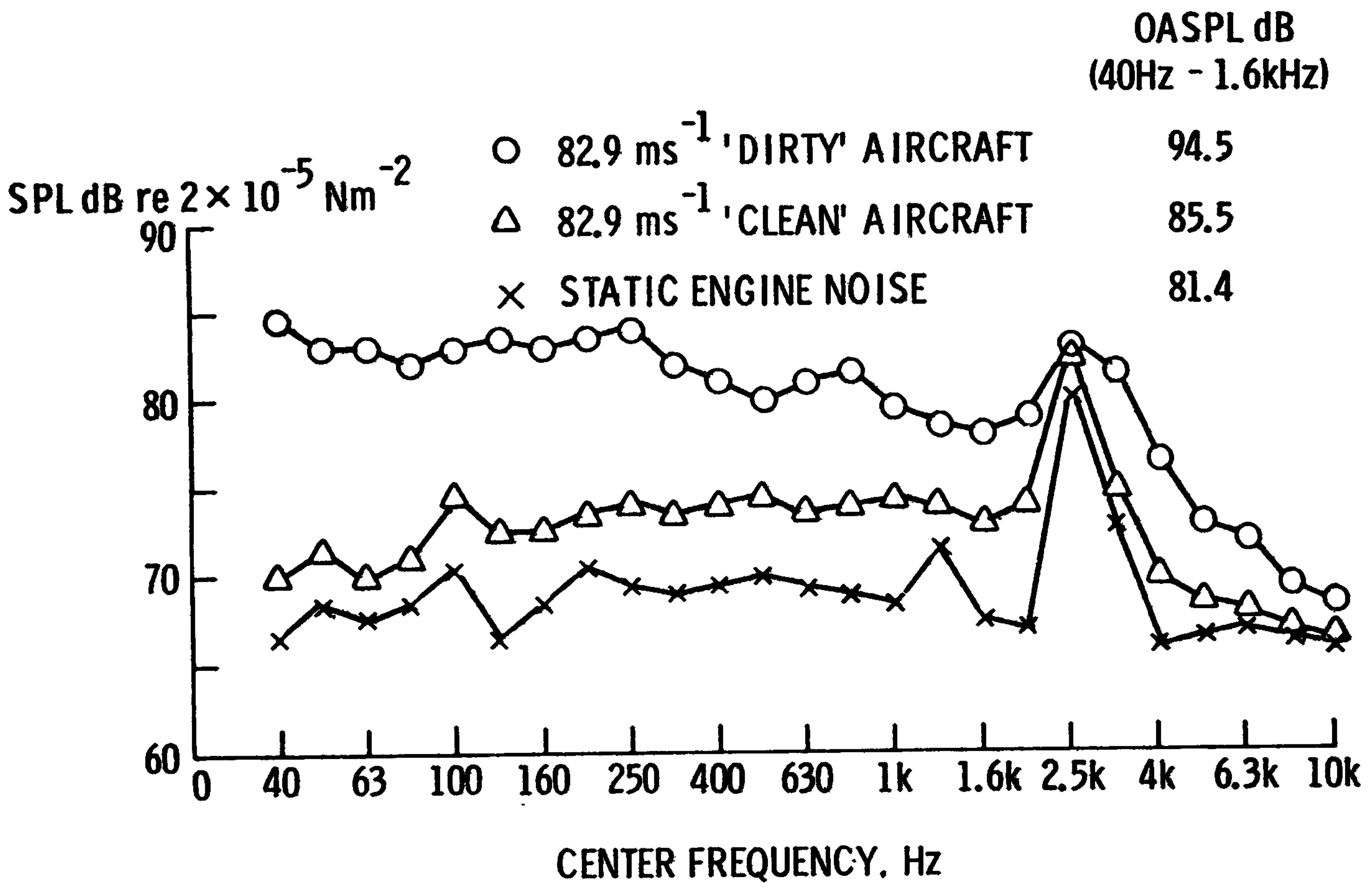

Figure 5. Comparison of one-third-octave band airframe noise spectra for dirty and clean configurations of VC10 aircraft flying overhead at 183 m altitude.

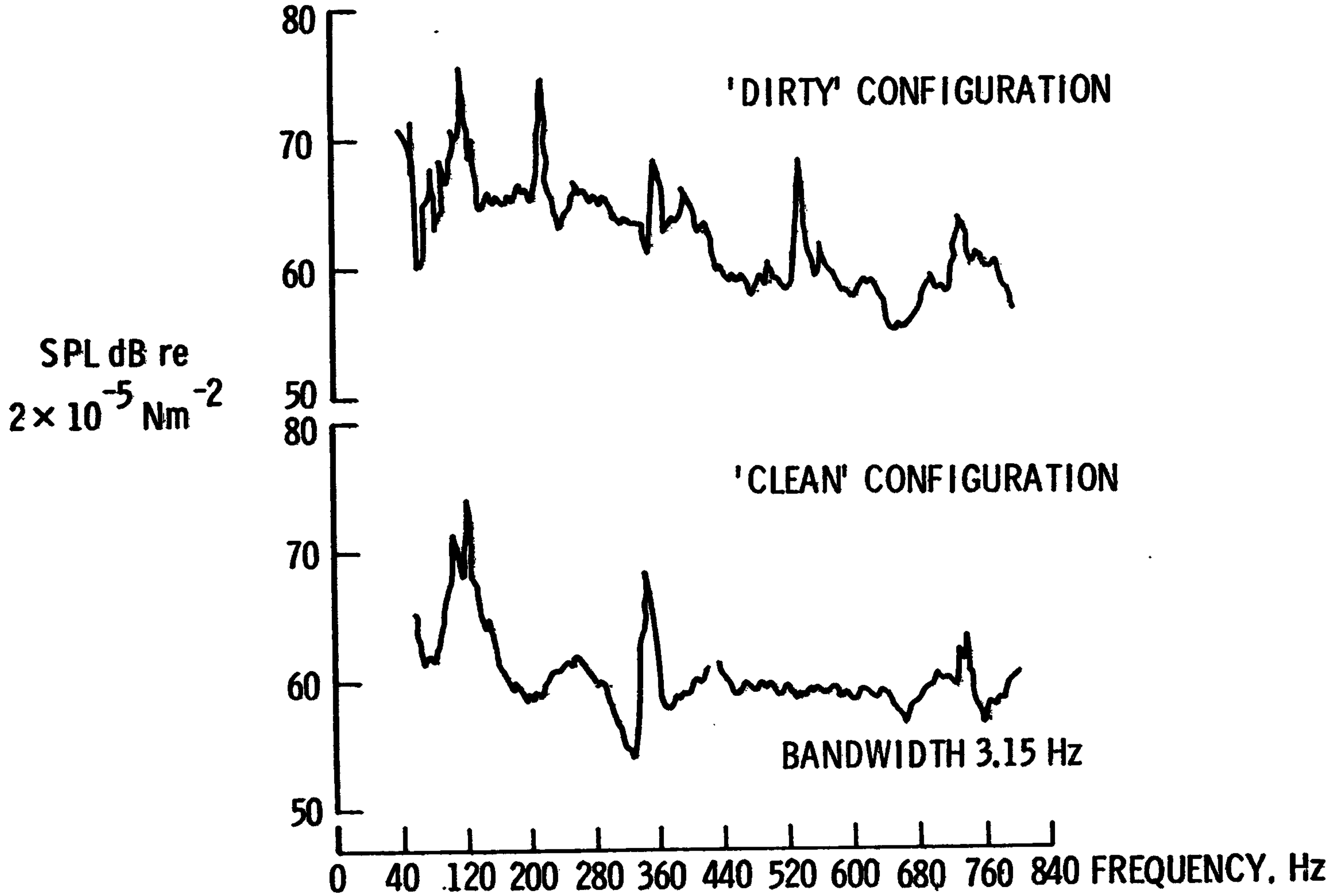

Figure 6. Comparison of narrow-band airframe noise spectra for VC10 aircraft in clean and dirty configurations at an airspeed of 104 m/sec and an altitude of 183 m.

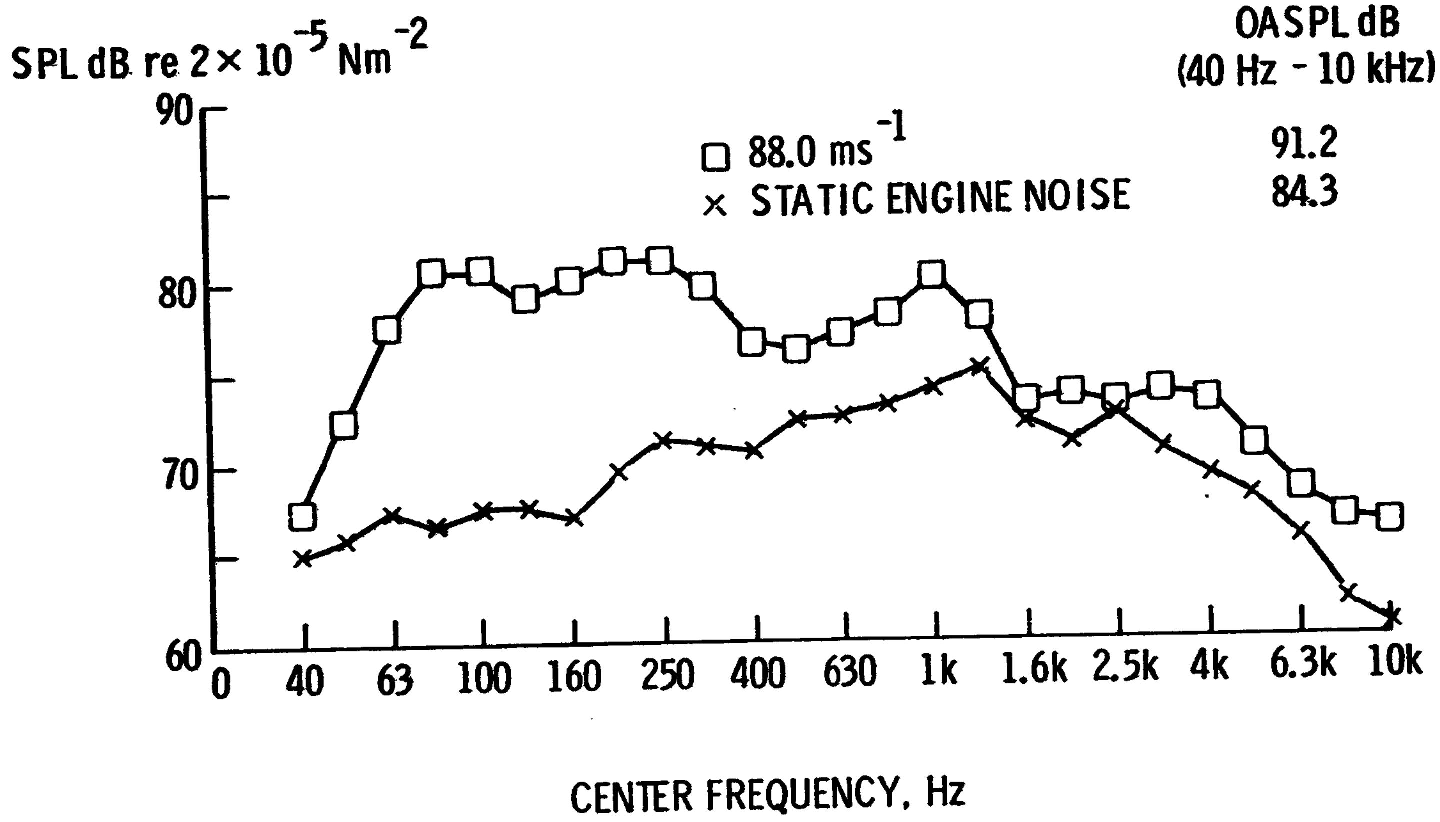

Figure 7. Airframe noise spectra for the HP115 aircraft overhead at 45.7 m altitude.

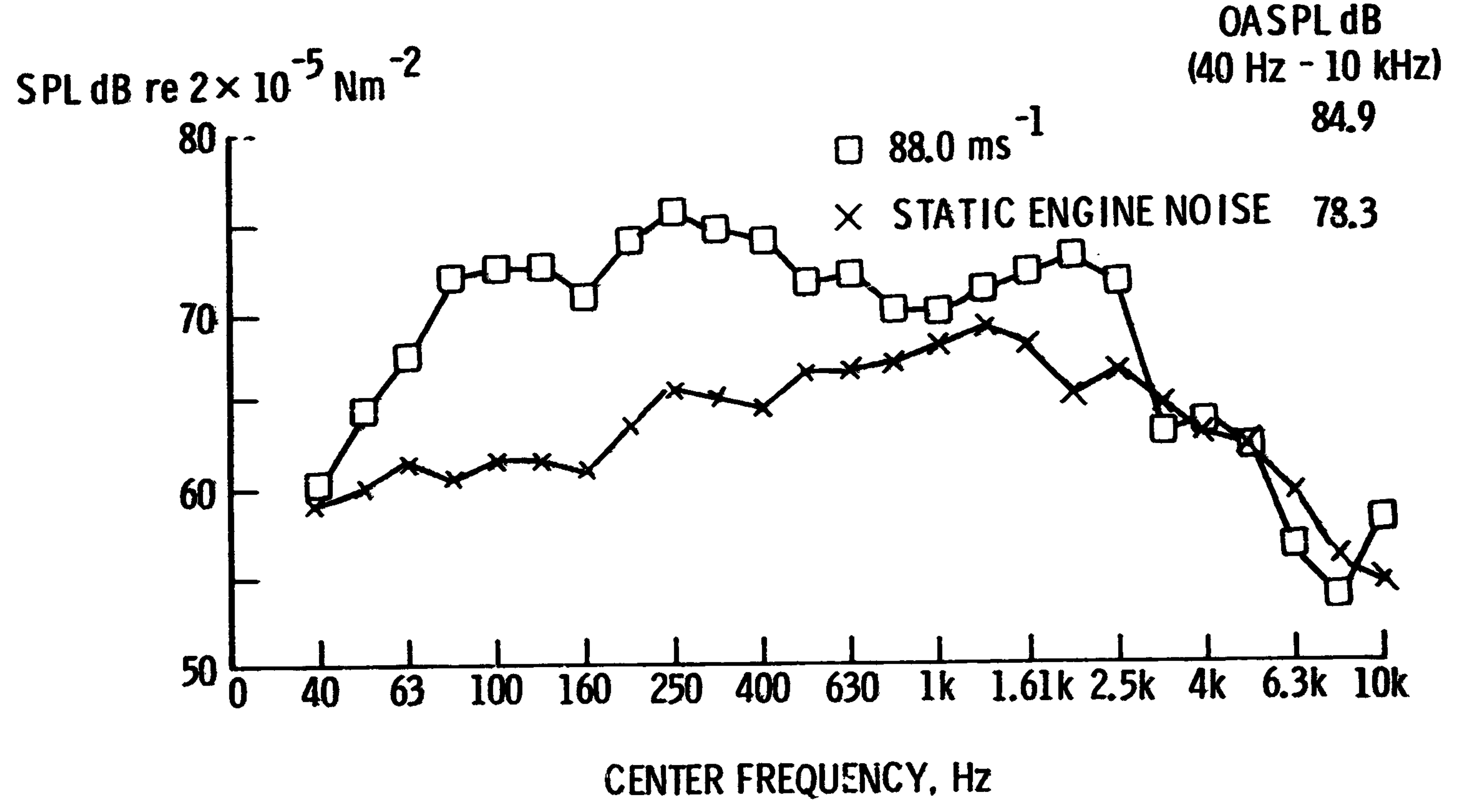

Figure 8. Airframe noise spectra of HPT15 aircraft at a sideline distance of 76.2 m for an altitude of 45.7 m.

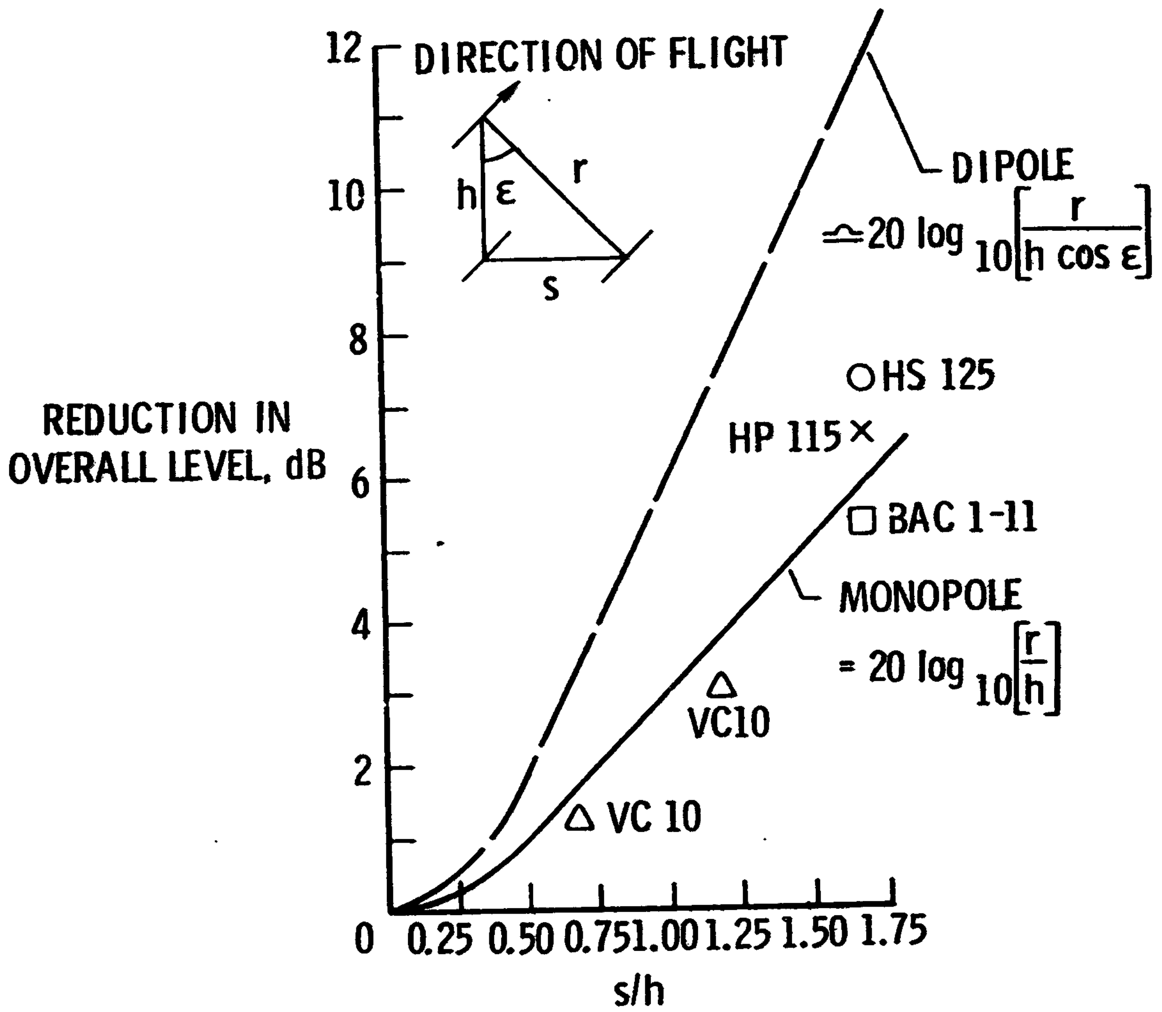

Figure 9. Measured and predicted reduction in sideline OASPLs for four aircraft in clean configurations.

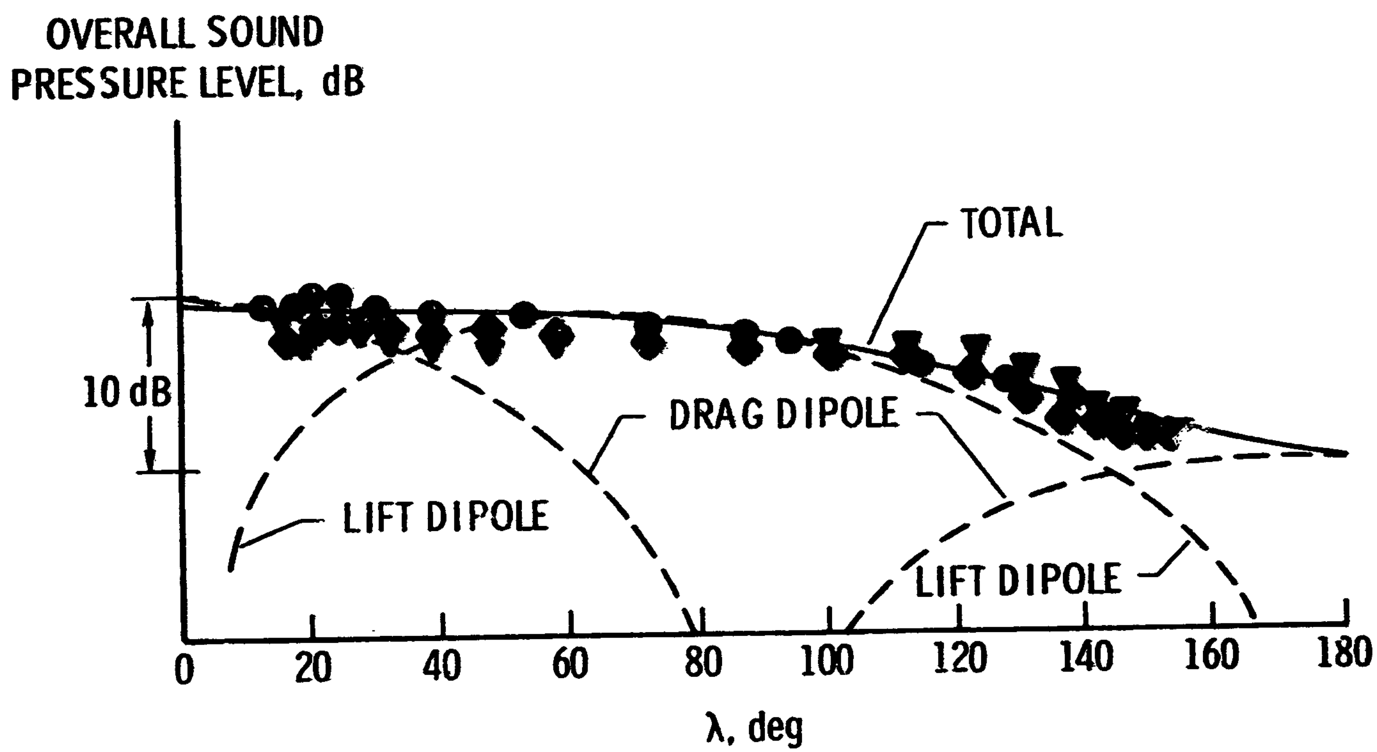

Figure 10. Directivity pattern of DC10 airframe noise in flyover plane compared to that calculated for dipoles oriented in the lift and drag directions.

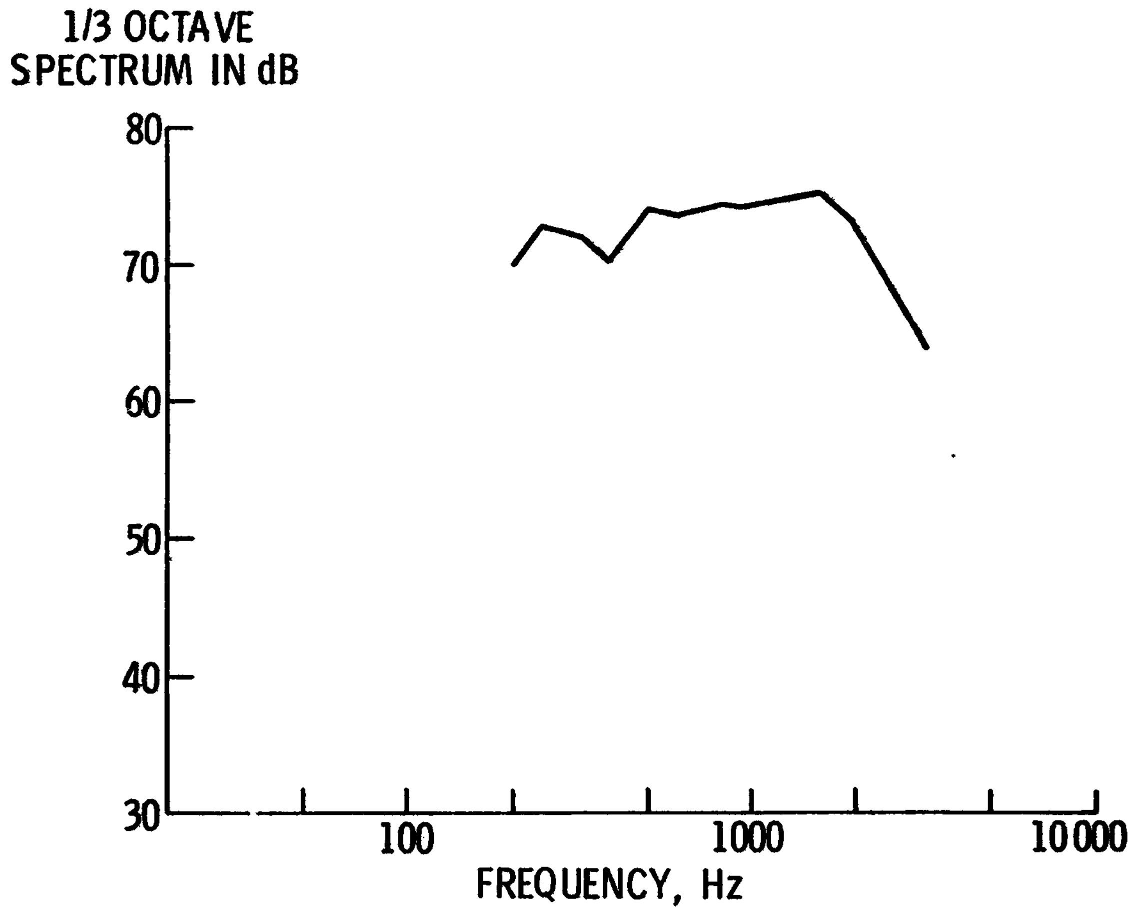

Figure 11. Spectrum of acoustic power radiated from 0.08 mm thick panel mounted in the side of a wind tunnel.

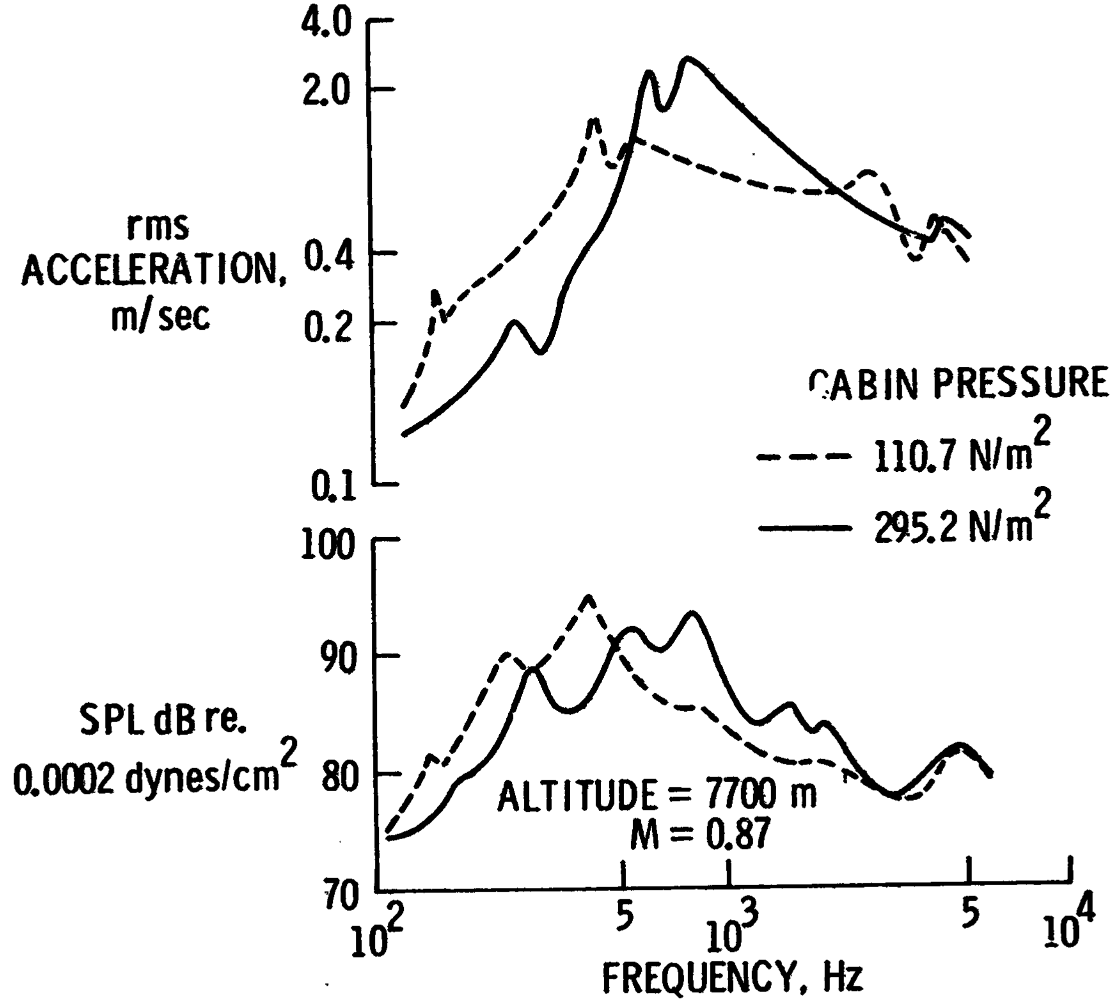

Figure 12. Radiated sound pressure levels and skin acceleration levels of B-720 airplane fuselage panel for two different values of cabin pressure.

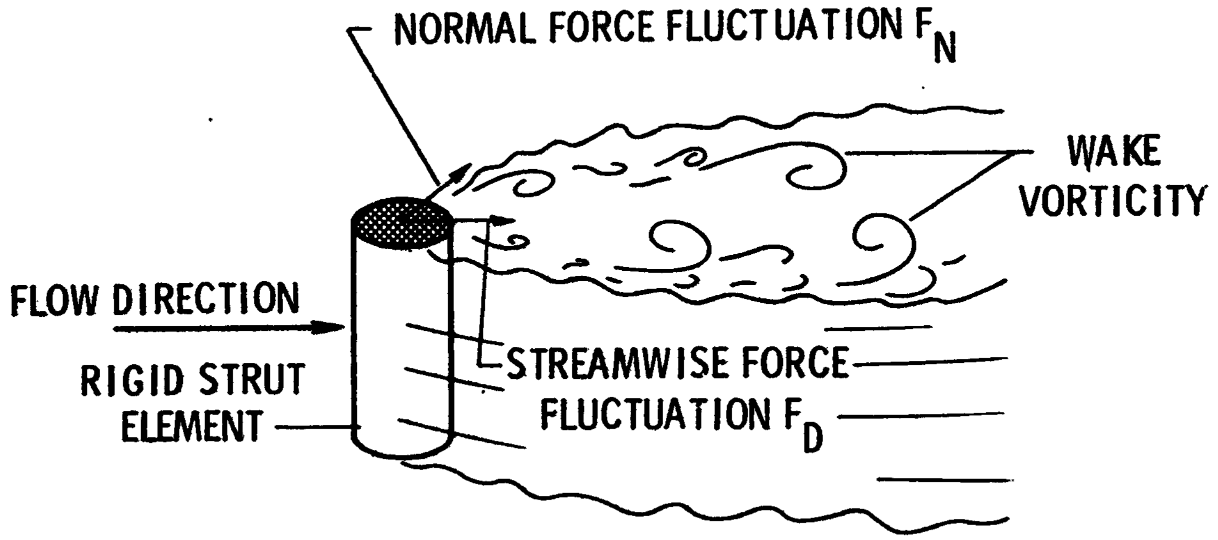

Figure 13. Schematic diagram of wake-generated forces on a cylindrical segment in an airstream.

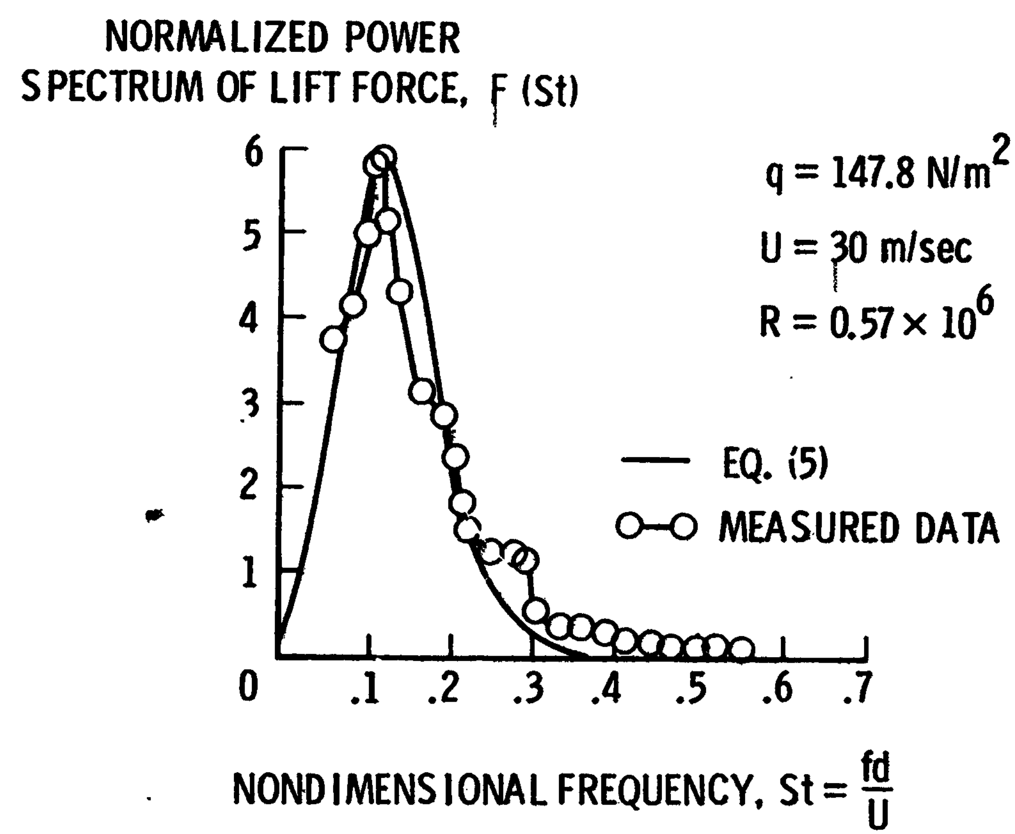

Figure 14. Normalized power spectrum for the lift force on a circular cylinder at a Reynolds number of 570,000.

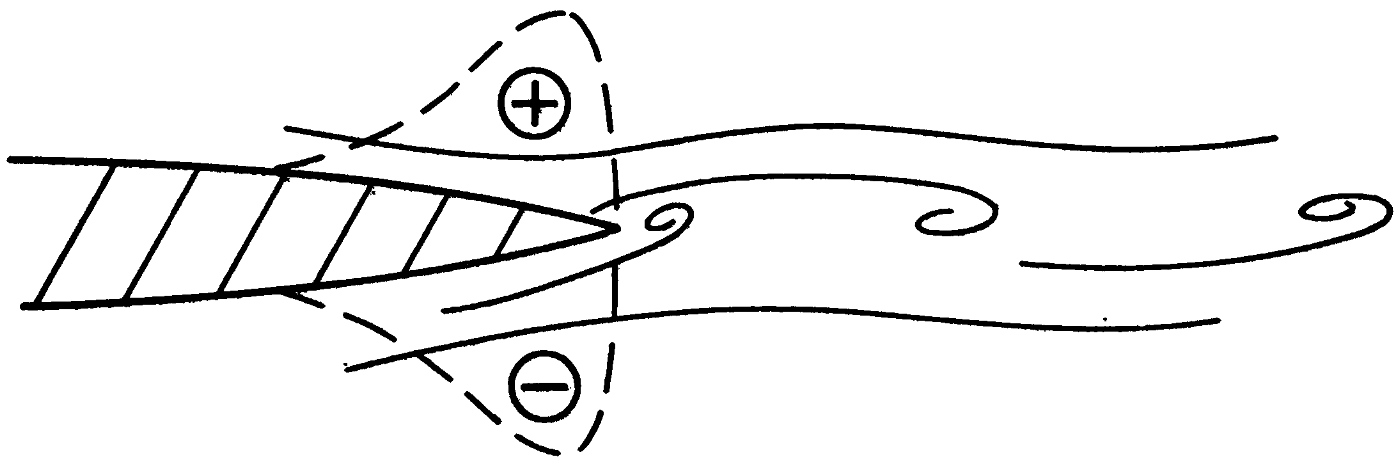

Figure 15. Schematic diagram of the flow field near a trailing edge and the wake-induced instantaneous pressure loading.

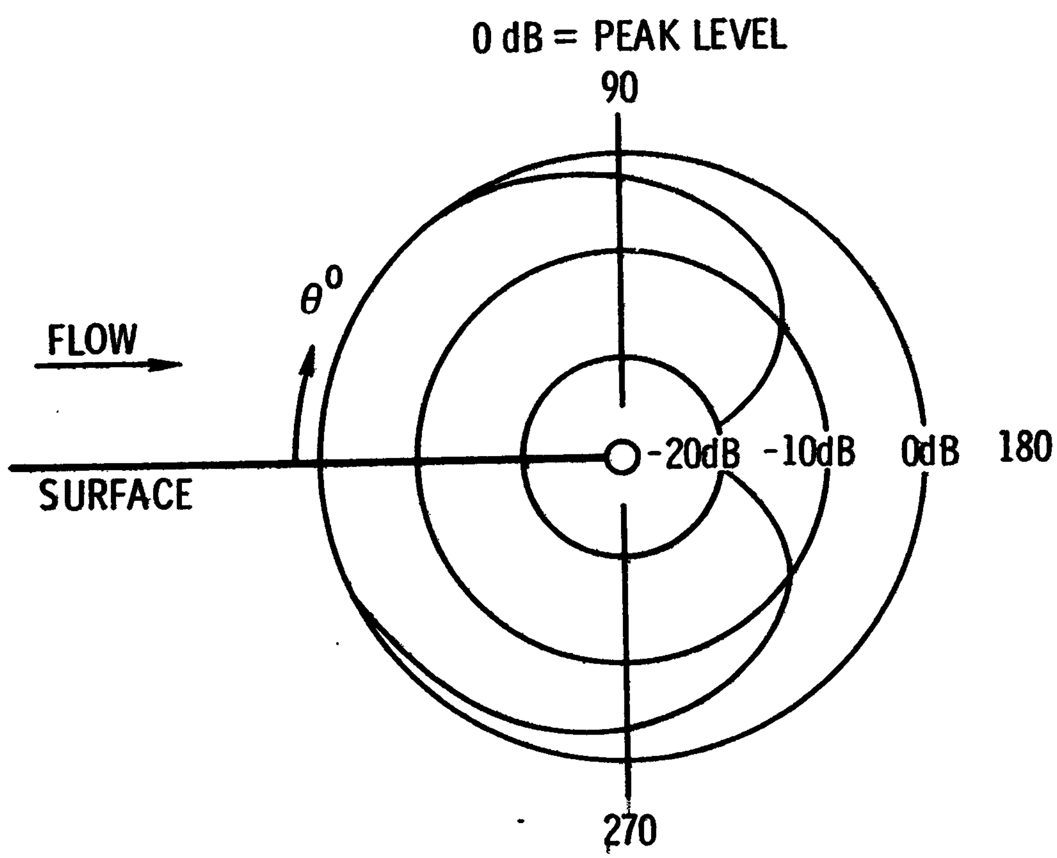

Figure 16. Directivity pattern of a baffled dipole due to flow off the edge of a finite surface.

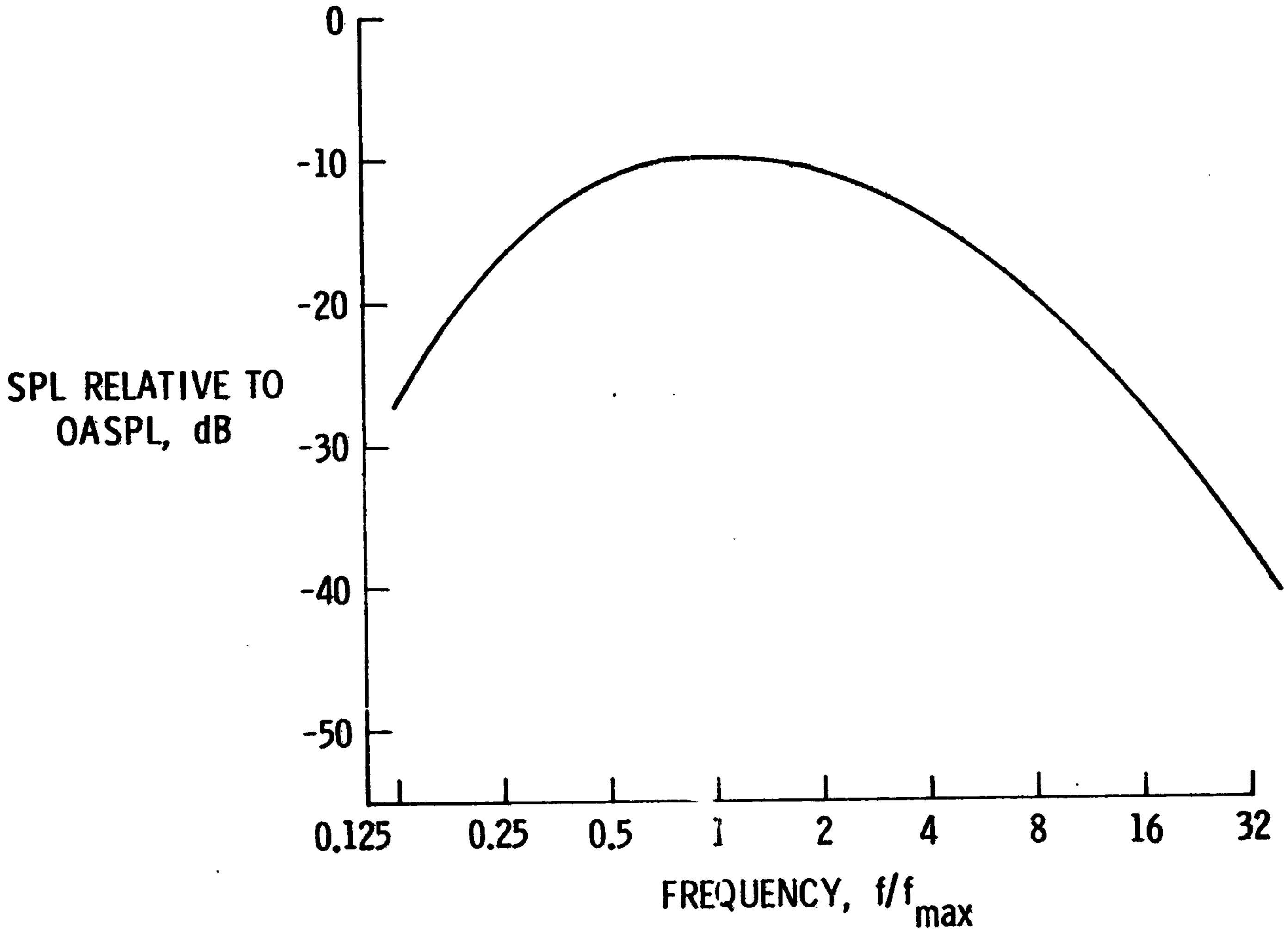

Figure 17. Nondimensional spectrum of trailing-edge noise directly below the edge.

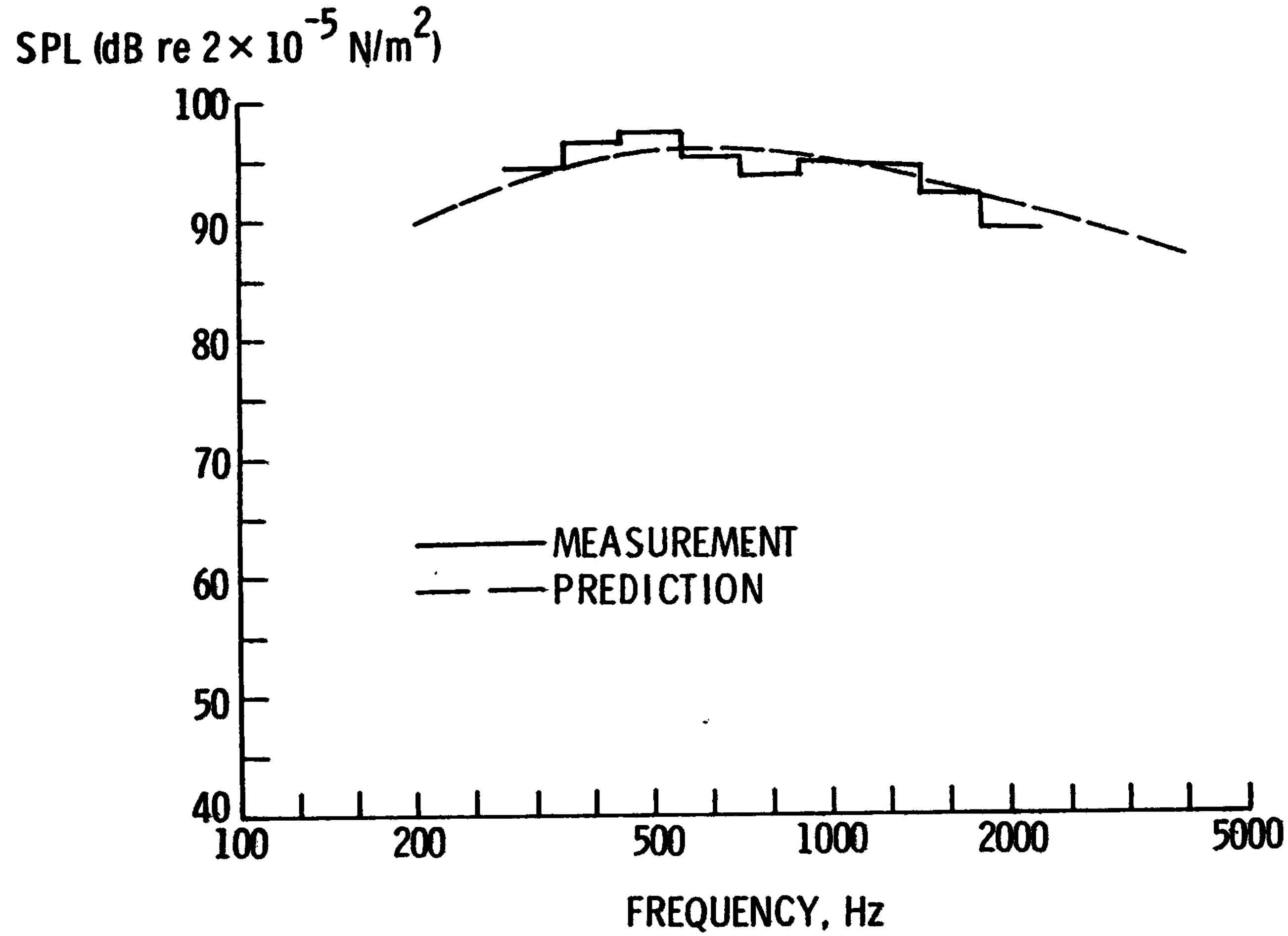

Figure 18. Comparison of measured and predicted noise spectra from an airfoil in incident turbulence for $M = 0.362$.

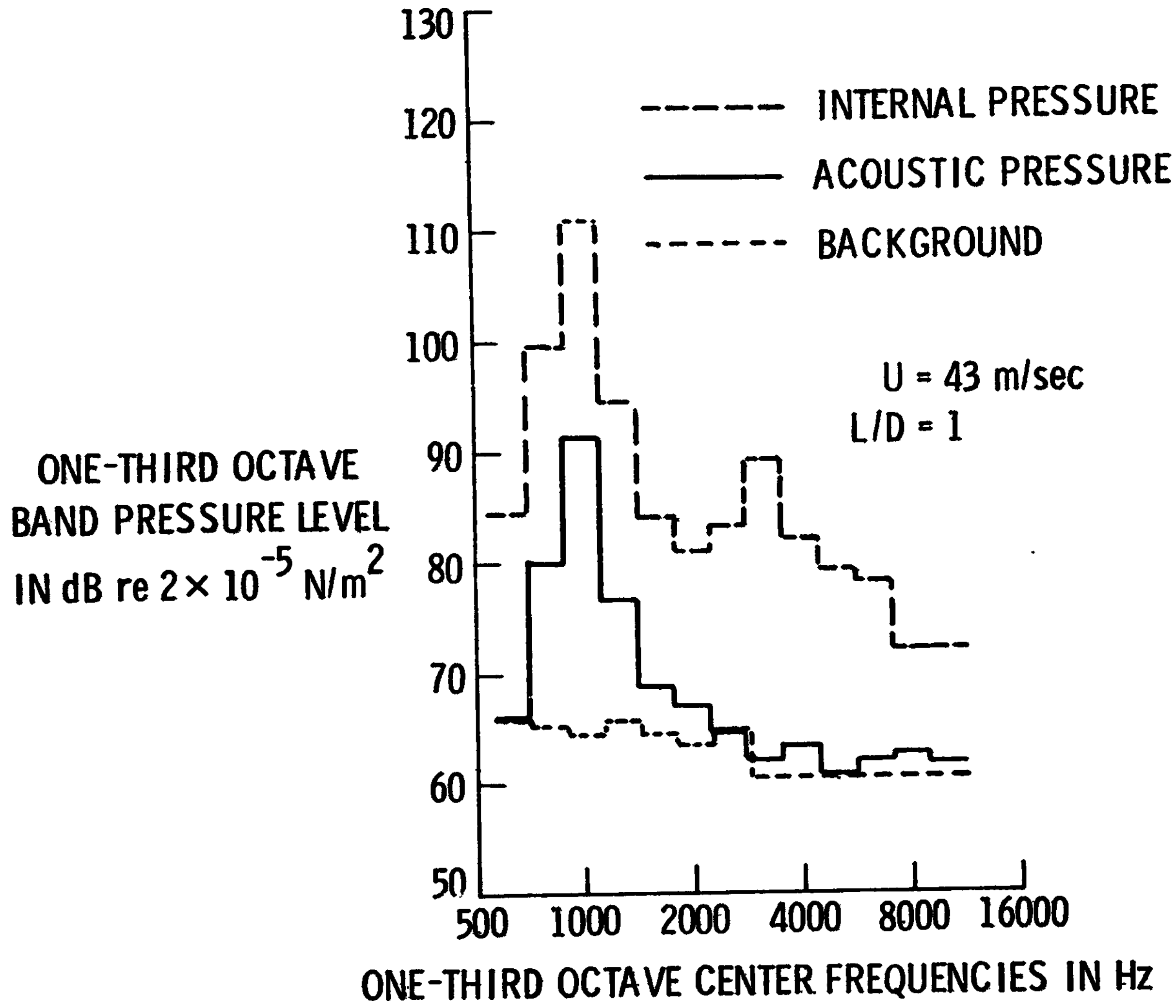

Figure 19. Comparison of the acoustic pressures radiated by a flow excited cavity with the fluctuating pressures within the cavity.

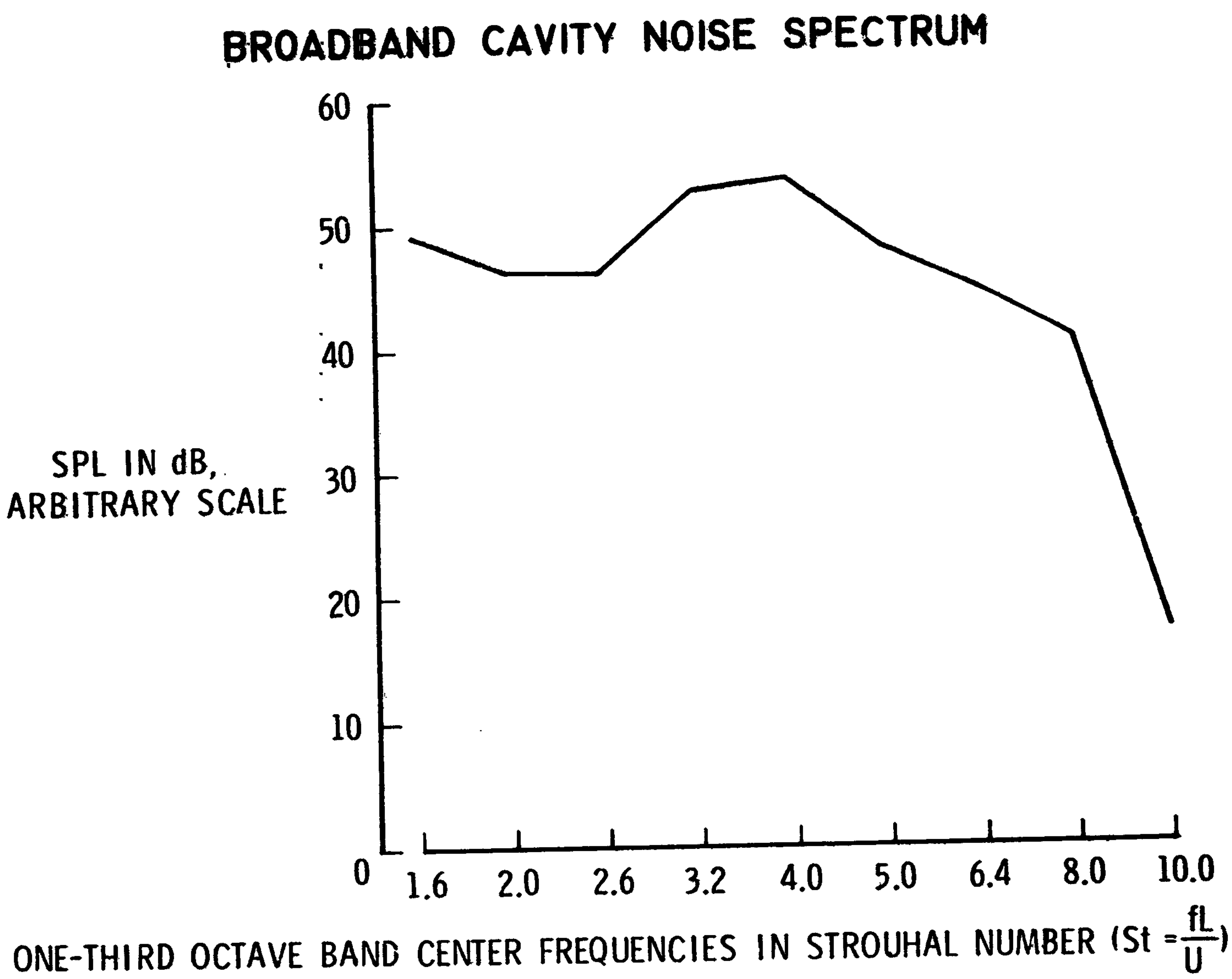

Figure 20. Broadband noise spectrum produced by a flow excited cavity for L/D = 2.0.

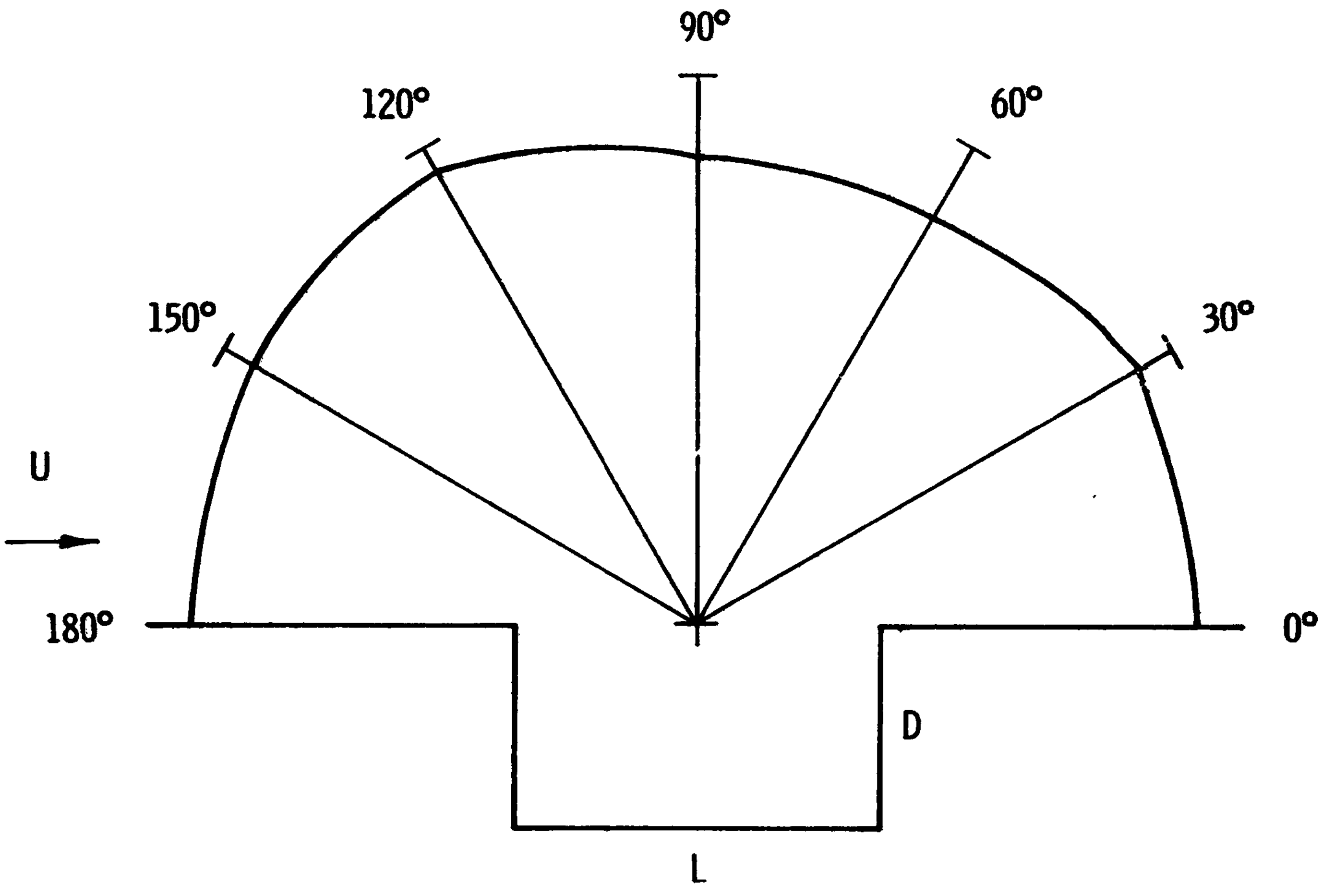

Figure 21. Calculated directivity pattern of broadband noise radiated from a flow excited cavity for L/D = 2.0.

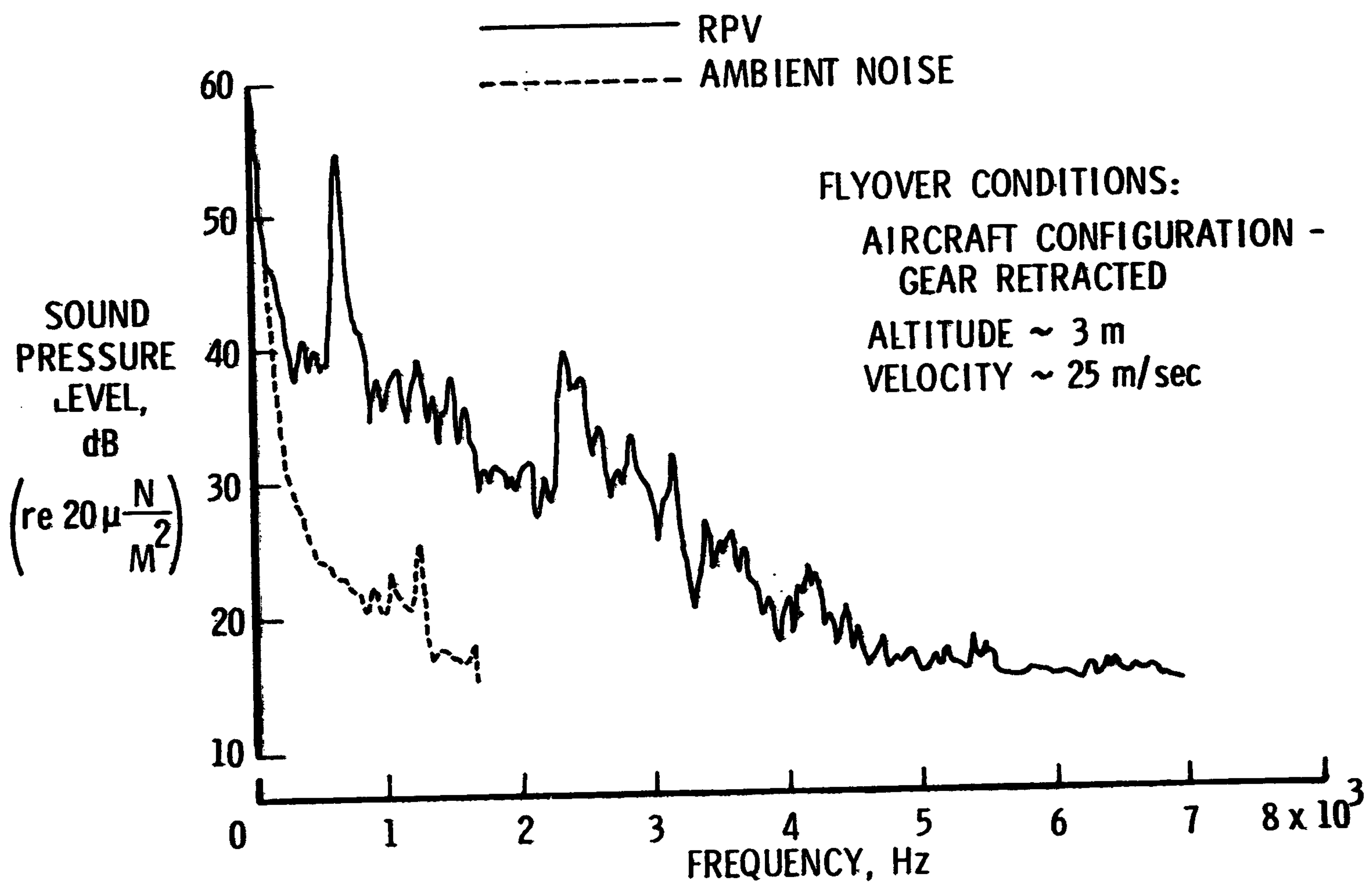

Figure 22. Sample airframe noise spectrum produced during an RPV flyover.

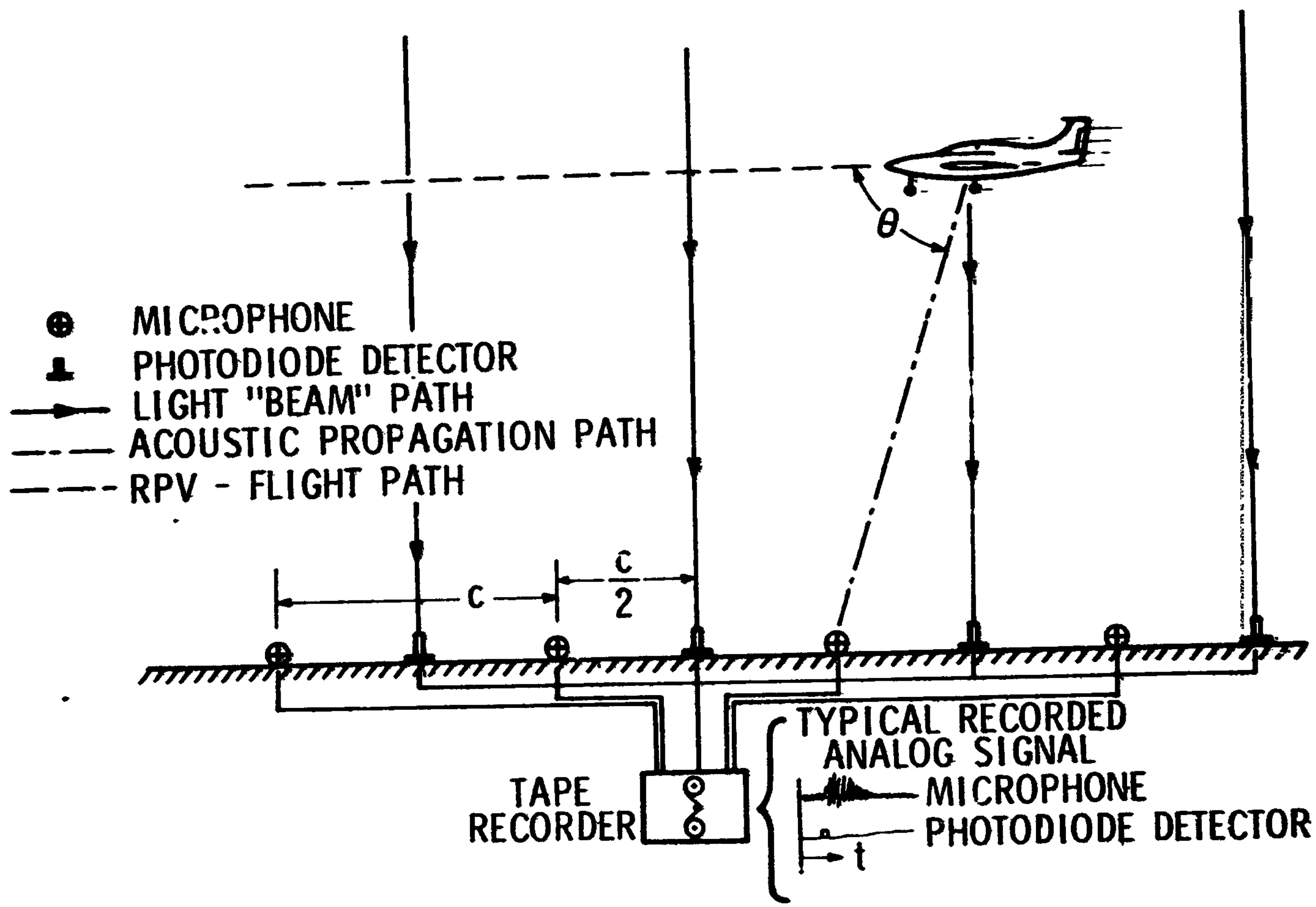

Figure 23. Schematic diagram of instrument array for RPV flyover noise measurement.

Figure 24. 0.03-scale model of Boeing 747 RPV mounted on drop helicopter.

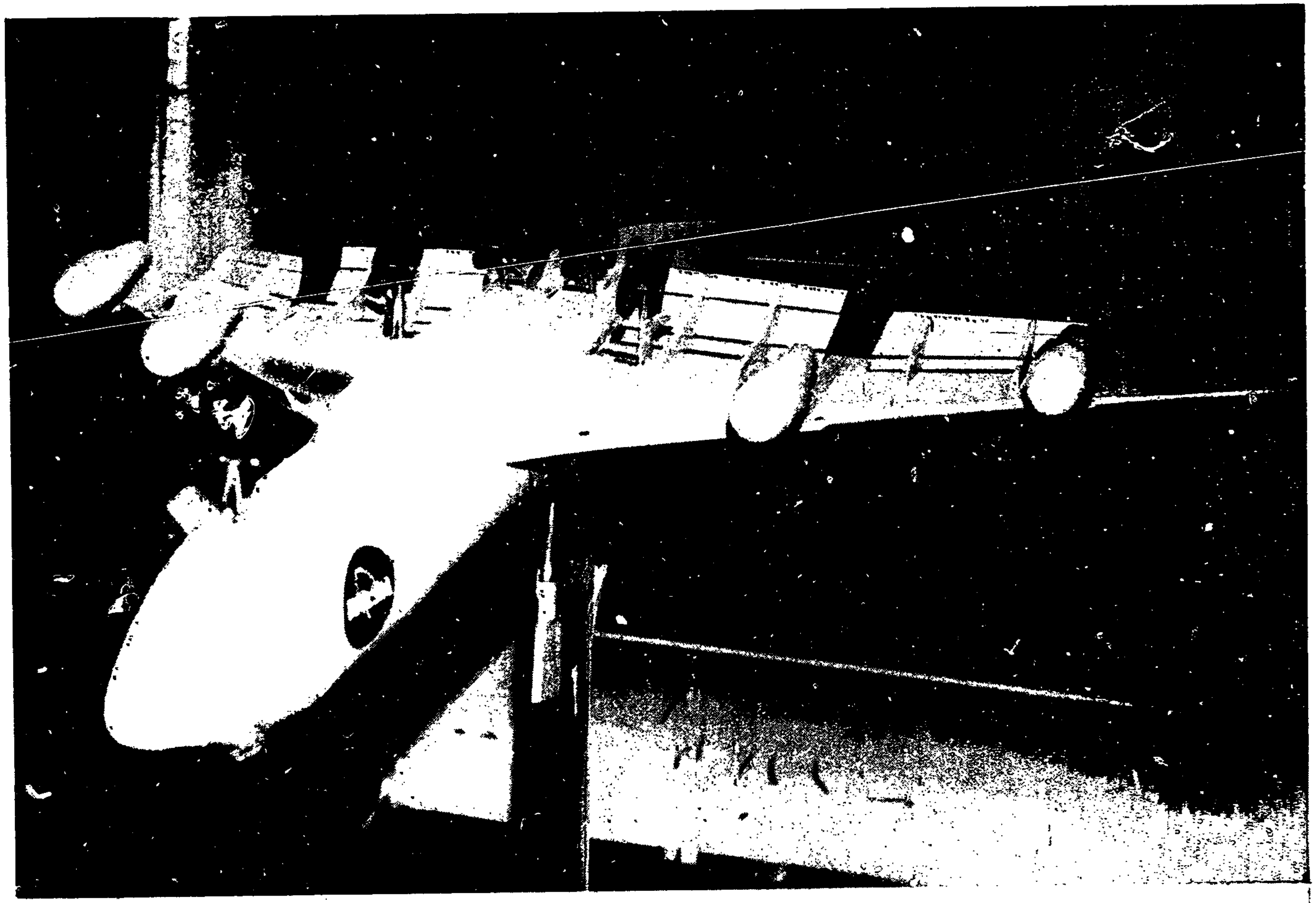

Figure 25. 0.03-scale model of Boeing 747 in NSRDC wind tunnel.

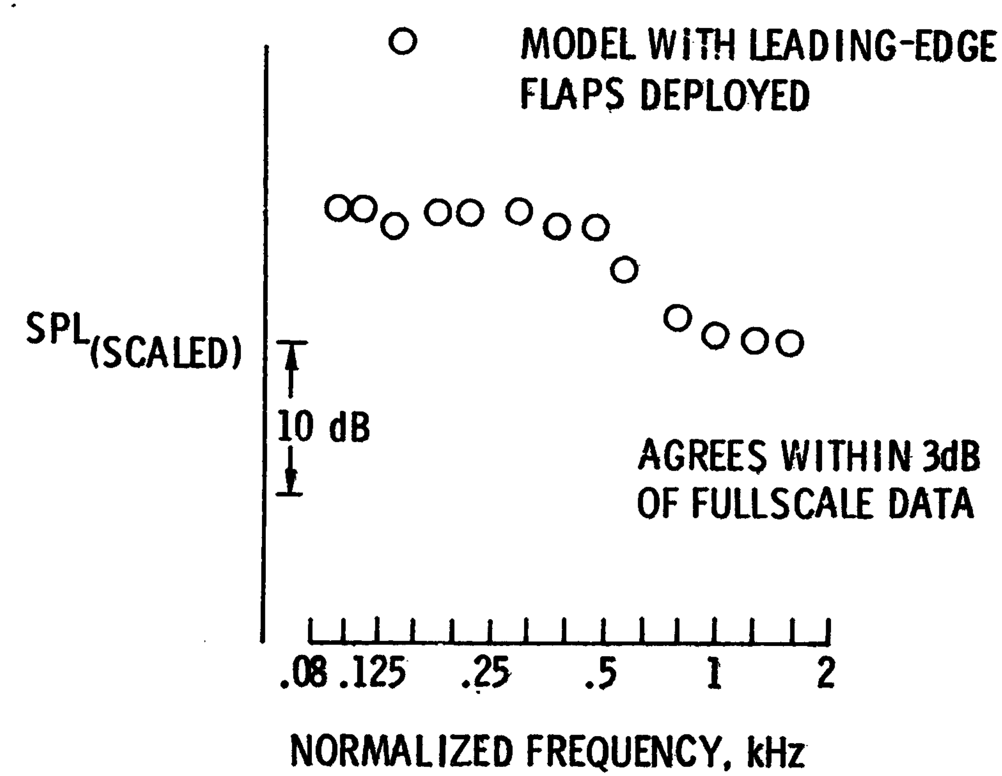

Figure 26. Comparison of model and full-scale airframe noise spectra of Boeing 747 for the leading edge flap deployed condition.

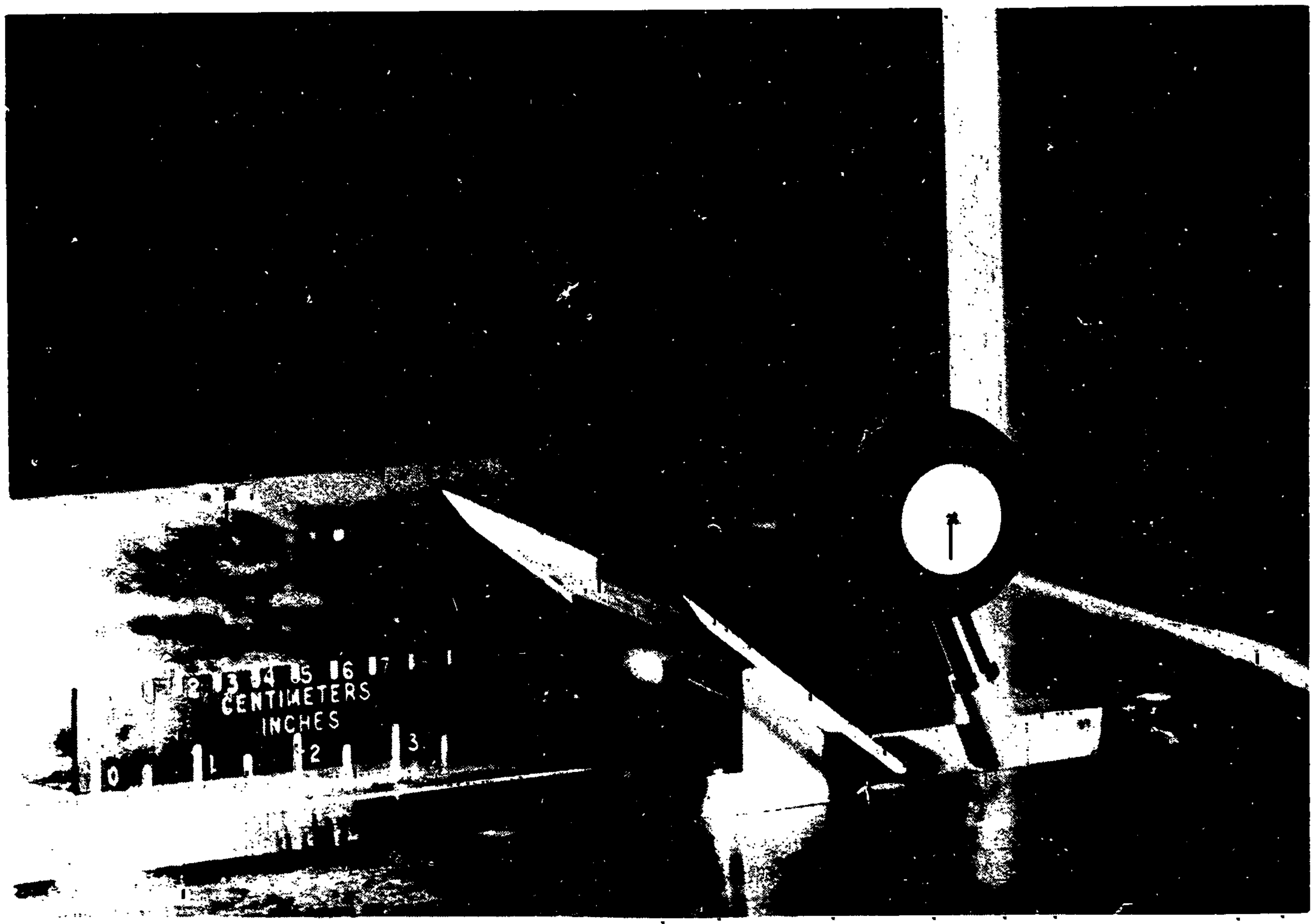

Figure 27. Cavity noise test apparatus in Langley open jet anechoic chamber.

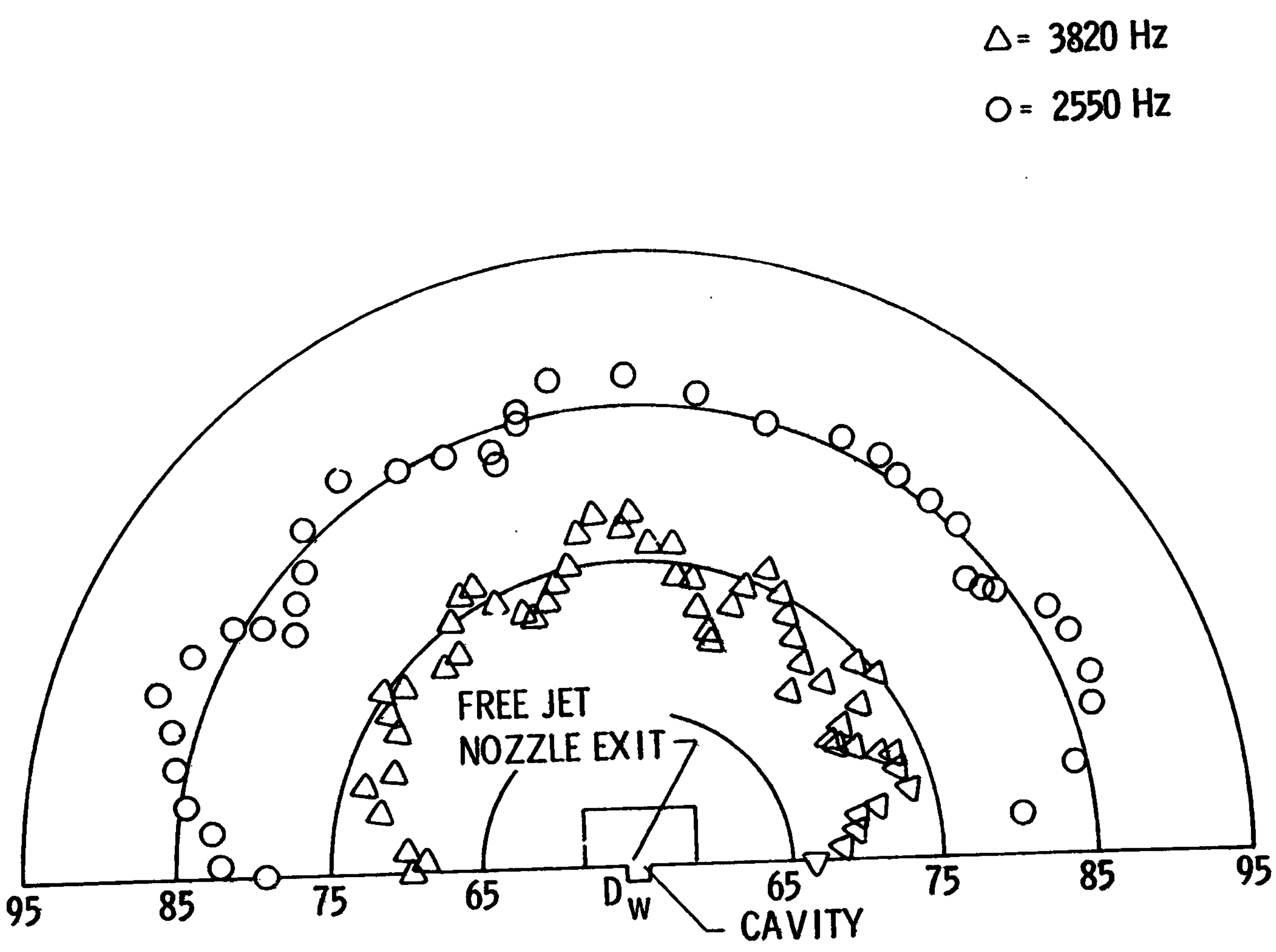

Figure 28. Directivity pattern of cavity radiated noise in plane normal to flow for U = 119.36 m/sec, L = 4 cm, and D = 5 cm.