RECENT DEVELOPMENTS AT THE ULTIMATE NOISE BARRIER

John S. Gibson
Lockheed-Georgia Company
Marietta, Georgia, U.S.A.

Abstract

This paper presents a review of developments in the aircraft non-engine aerodynamic noise field as it relates to community noise. Noise of this type is caused by air flow over the aircraft surfaces, airflow around landing gear, unsteady aerodynamic forces on the wings, and trailing wakes and vortices. As this kind of noise represents the minimum noise that can be made by an aircraft in flight, it has been called the "ultimate noise barrier." The background of this noise phenomenon as an aircraft noise problem and the development of analytical and experimental techniques are discussed. Recent aerodynamic noise measurements of very large transport aircraft have confirmed predictions based on small aircraft technology. Unsteady aerodynamics of the wing and landing gear/wheel well turbulence are shown to be the two most significant noise sources. The possibilities for some aero noise reduction in the near future is good, and some reduction will be necessary if new aircraft are to meet the expected noise requirements of the 1980's.

Introduction

In the past several years the subject of non-engine aerodynamic noise (which is sometimes called "airframe" noise or "self-noise") has become of interest to the commercial aviation industry (Ref. 1). It has become a concern because it is a "barrier" to the overall reduction of aircraft noise. Even though engine noise can be dramatically reduced on the next generation of large transport aircraft, it can be reduced only so far before non-engine aerodynamic noise becomes audible. Non-engine aerodynamic noise (hereafter generally referred to as "aero noise") is not a new phenomenon; it has always been produced by aircraft but has been covered up or "masked" by the louder engine noises.

There are several sources of aero noise, as illustrated in Figure 1. These sources can be grouped into four basic areas: (1) airflow over the non-lifting airframe surfaces, (2) airflow around the landing gear and wheel well area, (3) unsteady aerodynamic forces and vortex shedding from the lifting surfaces, and (4) vortices and wakes trailing from the various parts of the aircraft.

The following discussion covers the background of the aero noise phenomena, its generation, the possibilities for suppression, and its current impact as a commercial aviation problem.

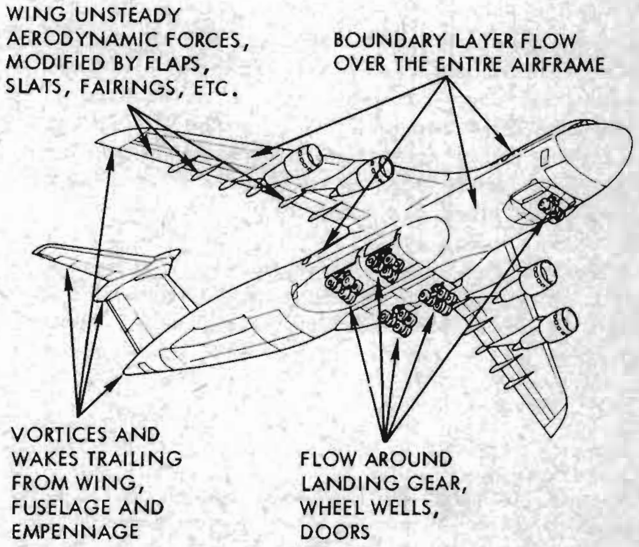


Figure 1. Aerodynamic Noise Sources

Background

The state of the art in the aero noise field is rather unrefined, and not generally well known. Therefore, a brief review of the development of aero noise technology is in order. The following background material through the year 1970 is largely taken from a literature search reported in Reference 1; however, the pertinent original references are also included.

Throughout recorded history, various references are given to stringed musical instruments which produce sound as air, or wind, is blown across the strings. The sound produced has been referred to as aeolian tones since about the 17th century. The first quantitiative investigation of this kind of sound was performed by Strouhal in 1878 (Ref. 2), whose experiements involved the tone of sound from a moving,cylindrical wire. His classic finding determined that the frequency of sound was independent of length or tension in the wire and was proportional to velocity and inversely proportional to diameter. He also noted that, at certain speeds, tone production was increased by apparent wire vibration. Shortly after Strouhal's original experiments, Rayleigh (Ref. 3) speculated that aeolian sound production was related to the instability of vortex sheets, and he noted that the directivity of peak sound was normal to the air flow.

Essentially no further work along these lines was done until 1914, when Kruger and Lauth (Ref. 2), who upon examining Strouhal's work and Benard's 1908 experiments concerning alternating vortices behind an object in running water, postulated that the production of parallel alternating vortex rows (which we now know as a Karman vortex street) was the source of sound. They further pointed out that, if the frequency of vortex production matched the natural frequency of the body causing the vortex production, then the body would vibrate resonantly, amplifying the sound. Little did they know that in 26 years time (1940), this very vortex production and structural resonance phenomena would completely destroy the Tacoma Narrows suspension bridge in the state of Washington, U.S.A. (Ref. 4). Work of a more modern nature began in 1924 (Ref. 2), when Richardson undertook a wind tunnel test program to determine the flow regimes where aeolian tone production from wires and cylinders occurred; in 1925 (Ref. 5) his investigations turned to similar experiments of airfoil shapes. After Richardson presented this work to the Physical Society of London, a Professor Hopewood stated that he had found that tying several pieces of cord or streamers to a taut wire being pulled broadside through the water reduced the "thrumming" sound. Then a Dr. Tucker said he had observed "high frequency notes" caused by aircraft wing struts and wires on oscillograph records. Hopewood's comment is probably the first documented concerning reduction of vortex noise by physical devices, and Tucker's observation is probably the first documentation of aerodynamic noise produced by aircraft structure (both comments in Ref. 5).

In 1934, Graham (Ref. 6) began searching in the animal world for clues to airfoil noise reduction in regard to propellers. He studied the aerodynamic peculiarities of owls, known for quiet flight, as a possible source of information. One of Graham's postulations was that the trailing-edge fringe noted on all primary wing feathers probably breaks up vortex formation at the wing trailing edge. In 1935, Stowell and Deming (Ref. 7) determined the basic vortex peaked broad-band noise spectrum for rotating cylindrical rods, and they found that the sound produced was proportional to air velocity to the 5.5 power ($V^{5.5}$). In 1944, Yudin (Ref. 8) published his work on the properties of vortex noise of various shaped rotating rods. He generally found a V^6 relationship. Also in 1944, Krzywoblocki (Ref. 9), who was interested mainly in structural effects, studied the nature of vortex formation and Strouhal number variation in the trailing-edge wakes of aircraft wings. In the late 1940's and 1950's, considerable work was done by several investigators, primarily at the Langley NACA (now NASA) Research Center concerning the definition of and prediction of propeller noise. Typical of this era was Hubbards' 1953 work (Ref. 10) on transport aircraft propeller rotational and vortex noise prediction. His vortex noise calculation procedure had blade area to the first power and V^6 terms.

During the 1950's and 1960's, numerous investigations provided better understandings of flow-structure interaction noise, particularly fan noise and helicopter rotor noise. During most of this period, little work was done directly related to wing or aircraft far-field radiated noise. One notable exception was the 1958 work of Hubbard and Maglieri, who measured the engine off gliding noise of a small single-engine aircraft as a part of an aircraft detection investigation (Ref. 11). Then at Lockheed Missiles and Space Company in 1968, noise measurements were taken by Shockley and Morimoto under a Schweizer SGS 232 sailplane in another aural detection program (Ref. 12). The primary objectives were to determine velocity and gross weight effects. Consequently, data were taken at 60 to 100 knots, and from 1250 to 1750 pounds gross weight. Altitude at the measurement points was 75 to 100 feet. Typical overall and octave-band sound pressure levels varied with V^5 to V^7, averaging very nearly V^6. The effect of weight over the narrow range investigated was inconclusive.

In 1969, Smith, et al., of the USAF Flight Dynamics Laboratory conducted aural detection related noise measurements (Ref. 13) on three sailplanes: a Schweizer SGS 232, an SGS 233, and a Libelle. These experiments covered a gross weight range from 552 to 1340 pounds. To determine the effects of sailplane velocity and gross weight was again the major objective. Measuring altitudes were generally from 50 to 150 feet and sailplane airspeeds of 50 to 135 feet per second. As in the case of the earlier Lockheed tests, tests of gross weight effect were inconclusive. However, the airspeed effect showed a strong velocity to the sixth power dependency. A generalized overall sound pressure level (OASPL) relationship was found to be:

$$\begin{aligned} \mathrm{OASPL} = {} & 10\,\mathrm{Log}_{10} V^6 - 10\,\mathrm{Log}_{10} R^2 \\ & + 10\,\mathrm{Log}_{10} A - K \quad \mathrm{dB} \qquad (1) \end{aligned}$$

where: V = sailplane velocity in ft/sec; R = altitude in feet; A = wing turbulent area in ft^2 (wing area less laminar flow area); and K = constant = 42 (average for three sailplanes).

In 1970, Healy at the Lockheed-California Company undertook a program to measure the noise of several gliding aircraft (Ref. 14) in order to get a better understanding of aero noise phenomena, and to provide an empirical method of noise prediction for aural detection purposes. The aircraft used were a Prue-2 sailplane, Cessna 150, Aero Commander, Douglas DC-3, and a Convair 240, covering a gross weight range from 1,300 to 39,000 pounds. Measurement altitude ranged from 300 to 800 feet generally with some sailplane measurements as low as 180 feet, and airspeed varied from 58 to 192 knots. The noise measurements were analyzed and normalized in a form convenient for rapid noise prediction. The resulting empirical relationship for overall sound pressure level was:

$$\mathrm{OASPL} = 10\,\mathrm{Log}_{10}\left(\frac{v^4}{h^2} \times \frac{W}{c_L} \times \frac{C}{b}\right) + K \quad \mathrm{dB} \qquad (2)$$

where: v = airspeed in knots; h = altitude in feet; W = gross weight in pounds; c_L = coefficient of lift; C = average wing chord in feet; b = wing span; K = constant, which includes environmental variables, equal to 8.4 for standard day and for aerodynamically "clean" configurations. Gross weight, W, is essentially equal to lift, which is proportional to v^2. Thus, the overall SPL is related to v^6.

The peak frequency relationship for the measured broad band spectra was found to be:

$$f = S\left(\frac{v}{t}\right) \quad (3)$$

where: f = peak frequency, Hz; S = Strouhal number equal to 1.85; v = airspeed in knots; t = mean wing thickness in feet.

The noise phenomena observed showed a peak in amplitude when the aircraft was directly overhead, i.e. major aerodynamic forces perpendicular to microphone. The dipole-like characteristics, frequency relationships, and other considerations lead to the conclusion that the most predominant of the several aerodynamic noise sources is wing trailing-edge unsteady aerodynamics and associated vortex shedding.

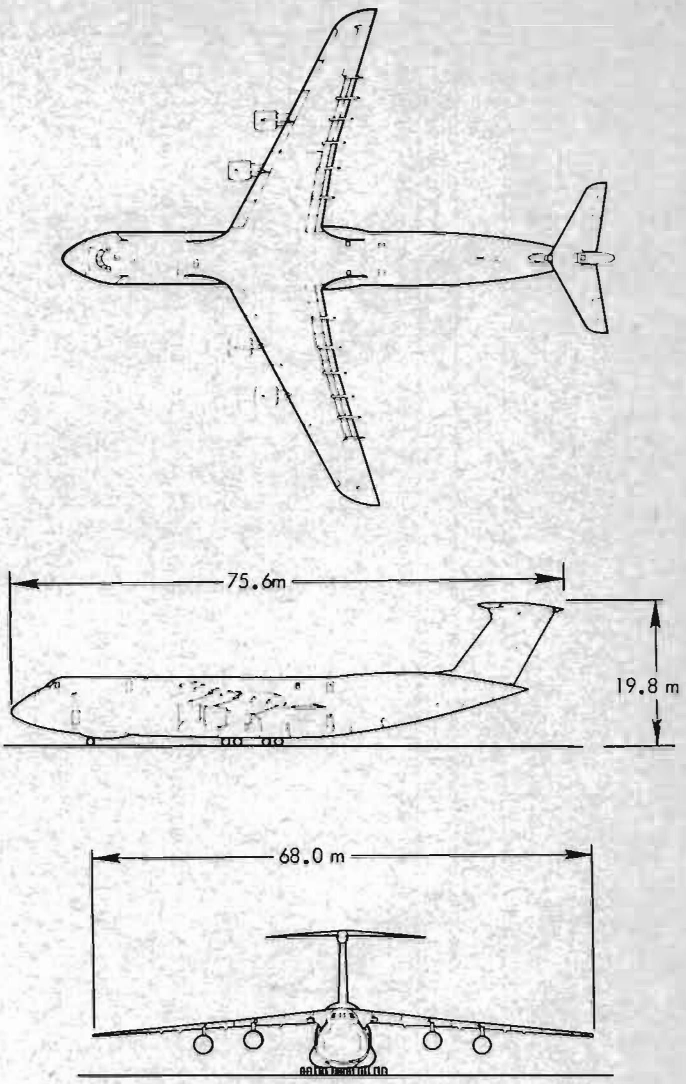
In late 1971 and early 1972, investigation of the aero noise problem as related to the community noise environment of new large transport aircraft was undertaken (Ref. 1). These were analytical studies, based on the small aircraft and glider data. The results of the investigation indicated that the landing case would be the worst problem. The predicted landing noise for a 600,000 lb aircraft at the FAR 36 criteria point was 97 EPNdB.

In late 1972, Boeing reported that they had made preliminary aero noise measurements of a 747 aircraft (Ref. 15). In early 1973, a series of aero noise measurements was made under low-level flyovers of a Lockheed/USAF C-5 Galaxy transport; preliminary trends were reported in Ref. 16. The large-aircraft noise measurements verified that the aero noise predictions were real and that aero noise could be a real "barrier" to the overall noise reduction of large aircraft.

Recent Developments - Large Aircraft Measurements

The aero noise measurement and analysis program on the Galaxy transport is now complete. This was a joint Lockheed and NASA program, and much of the following discussion is taken from the program final report, Reference 17.

It was known that the "Galaxy" (Figure 2), with high bypass turbofan engines, has very low jet noise at low engine power settings. The predicted landing aerodynamic noise spectrum peaked in the low frequency range on the order of 20 dB above the jet noise level. Therefore, noise measurements made under the aircraft would be essentially a measure of non-engine aerodynamic noise, up to the frequency range where turbomachinery noise would interfere. Turbomachinery noise is characterized by strong discrete frequency peaks that are easily identified, so there is no doubt where in the frequency spectrum non-engine aero noise is no longer separable from these other noise sources. With this test technique, measurements were made on the ground with the aircraft in flight at various landing approach speeds and flap settings and gross weights ranging from 245,000 to 282,000 kilograms. Several interesting trends and conclusions were found from analysis of the experimental data obtained. These are described in the following sections.



MAX TAKEOFF GROSS WT. - 346,777 kg

Figure 2. Galaxy General Arrangement

Aerodynamic Configuration Effects

One of the objectives of the experimental program was to determine the differences between the spectrum shapes for an aerodynamically "dirty" aircraft (with landing gear, flaps, and leading-edge slats extended) and an aerodynamically "clean" aircraft (all devices retracted). Photographs of the various configurations are shown in Figures 3, 4, and 5. The first, Figure 3, is the takeoff configuration, shown for information only, since no data were taken at this condition. The main difference between the takeoff configuration and landing configuration (Figure 4) is that landing has 100% flap extension, whereas takeoff has 25% flap extension. Typically, the horizontal stabilizer setting and aircraft angle of attack are similar for both cases, and the leading-edge slats and landing gear are fully extended in both cases. Figure 5 shows the "clean" configuration with all landing devices retracted.

Figure 3. Takeoff Configuration

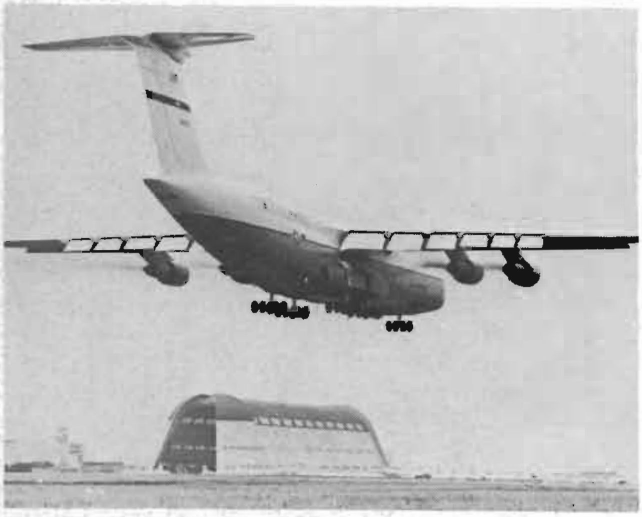


Figure 4. Landing Configuration

Figure 5. Clean Configuration

Figure 6 is the aero noise spectrum (with engine noise removed in the dashed area) resulting from a "clean" configuration flyover. This spectrum has a peaked broadband shape that corresponds to predicted fluctuating lift force/ vortex shedding noise from the wing. The measured peak frequency in the broadband area corresponds rather closely to the predicted Strouhal frequency for wing-flow noise. The apparent semi-discrete frequencies occur in a fairly high Reynolds number range (4.0×10^6 to 6.0×10^6, based on wing thickness), even though one recent laboratory investigation could find no discrete frequency emission from a small airfoil at Reynolds numbers above 2.4×10^6 (Ref. 18).

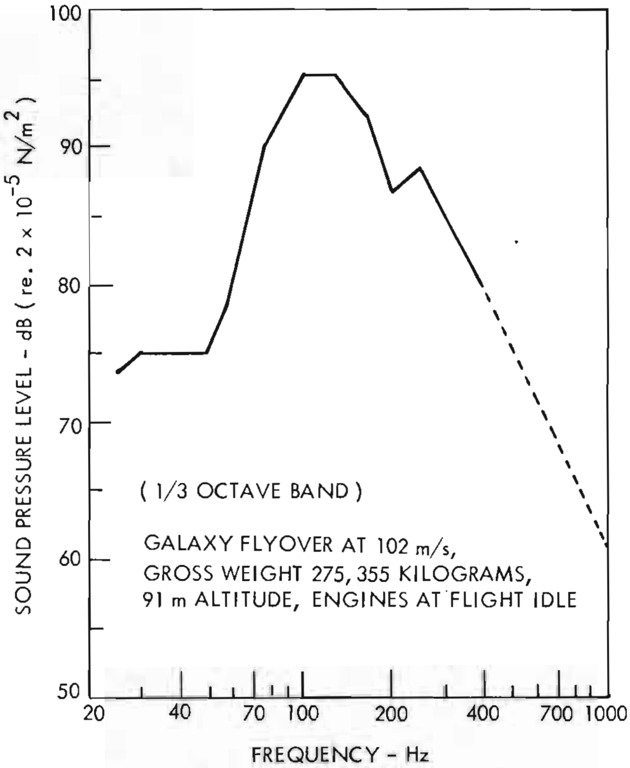


Figure 6. Noise Spectrum For "Clean" Configuration

Figure 7 is a "clean" configuration narrow-band (1 Hz bandwidth) plot showing that not only does a wing fundamental appear, but also an array of additional discrete frequencies appear throughout the spectrum. This and all other cases shows a second harmonic. In some cases the harmonic was higher than the fundamental. It is suspected that angle of attack, which was not constant during the tests, could have caused considerable variations in fundamental-to-harmonic relationships. The characteristic frequency of fluctuating drag forces also is double the frequency of the larger fluctuating lift forces. It does not appear that fluctuating drag-force noise could be as significant as fluctuating lift-force noise, since drag forces are much smaller and predominantly radiate noise in the plane of the airfoil, unless some sort of interaction occurs between the two sources.

Figure 8 is an inflight third-octave-band plot of a typical "dirty" configuration test run. The spectrum is again full of peaks, with rather high levels below the wing

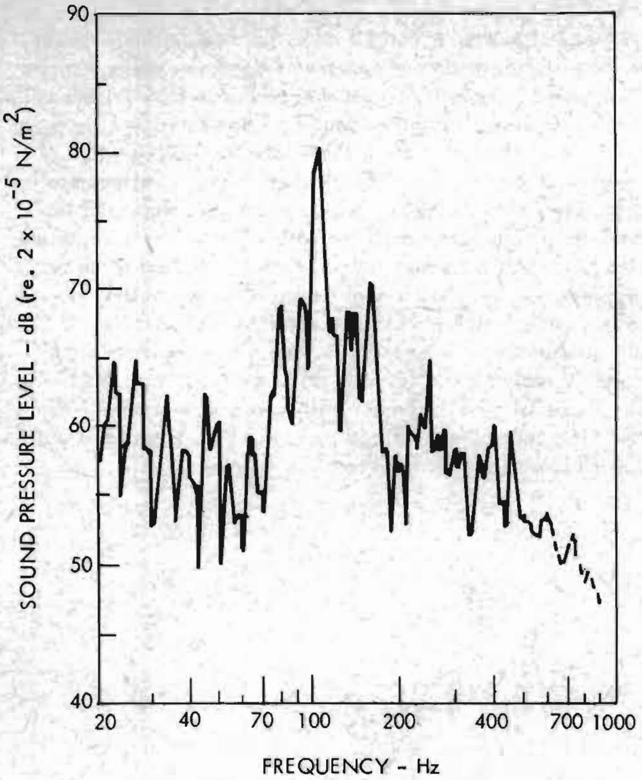


Figure 7. Narrow Band Spectrum - "Clean" Configuration

fundamental. Therefore, the combined effects of lowering landing gear and extending flaps and slats have greatly broadened the spectrum. In narrow-band form (Figure 9), this same spectrum indicates that most of the increases in noise level are due to discrete or semi-discrete frequency emissions rather than to broadband emissions such as might be expected in boundary-layer noise. There is also some indication of suppression of the wing fundamental, possibly due to some interaction of the wing and landing gear flow fields.

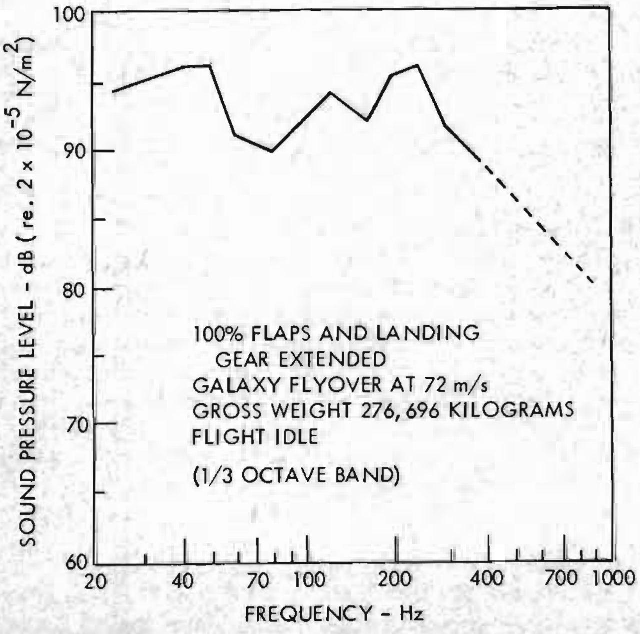


Figure 8. Noise Spectrum For "Dirty" Configuration

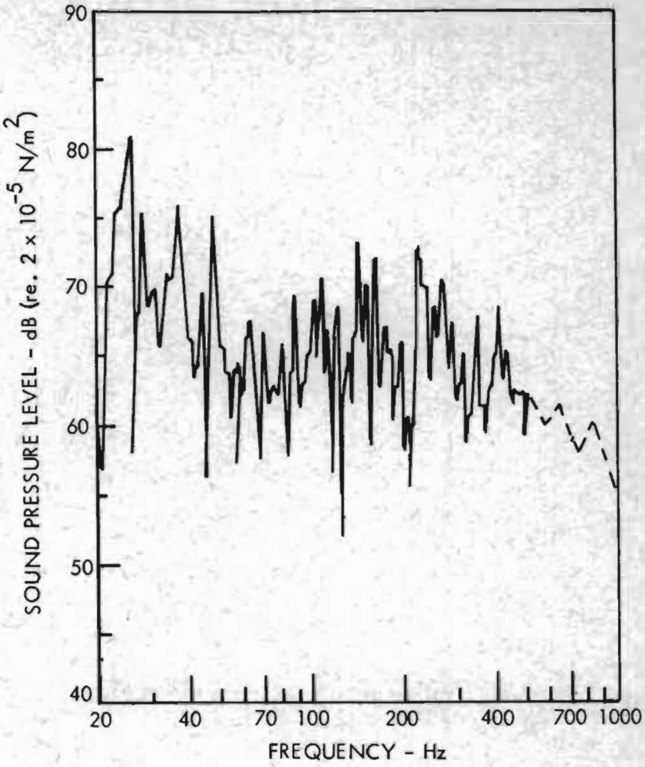


Figure 9. Narrow Band Spectrum - "Dirty" Configuration

Another series of test runs was made to try to improve the definition of flap alone effects. Here, only flap extension was varied as a test parameter, and the landing gear were retracted. However, due to the nature of the test procedure, velocity and angle of attack were not constant for the three test runs. These results also did not conclusively show the flap extension effects. Compared with the first test series, the relative amplitude of the wing fundamental and harmonic reversed in one case (0% flap). This is shown, along with two other flap extension spectra, in Figure 10. When the second series of runs are normalized to the same velocity and altitude, the intermediate flap setting gave the highest level and full flap the lowest, further confusing the issue. One point which could have affected the results (in addition to angle-of-attack effects) of the second test series was the fact that the aircraft altitudes were very low, from 36 meters to 50 meters; this probably put the microphone in the acoustic near field of the wing noise source. It should be recalled that the wing source itself is almost 68 meters across. Therefore, it is felt that the second series of test results should not be compared with the first series on an absolute basis.

The following discussion is a possible explanation of the absence in either series of the strong flap effects which were expected. The aircraft has six individual flaps on each wing, each separated by a flap track fairing, as shown in Figure 4. The result is that, with increasing flap extension, the wing trailing edge is becoming irregular with flap segments of different sizes and fairings protruding aft. At high flap angles, there is also an air gap between a portion of each adjacent flap, as shown in Figures 3 and 4. The overall effect is an irregular wing trailing edge that probably breaks up or decorrelates any large-scale fluctuating lift

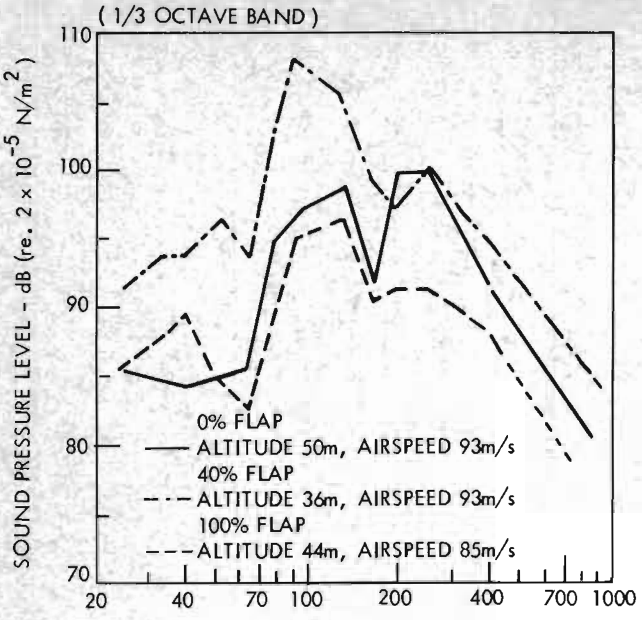


Figure 10. Noise Spectra for Variation of Flaps, Retracted Landing Gear

and turbulence formations, thereby reducing noise. This is the same concept that was thought to be one of the features of the "quiet" flight of owls which was studied in 1934 by Graham (Ref. 6).

The effects noted in this test are not expected to be the same on all aircraft. Most aircraft have one or two long flaps, from which strong, correlated turbulence phenomena could be expected. Therefore, on most current aircraft, greater increases in noise level with increasing flap extension may be expected than was experienced here.

Trailing Vortex Wake Noise

After one of the low flybys, when the aircraft was about 1600 meters away, the trailing vortex wake was clearly audible. Figures 11 and 12 show the measured one-third-octave and narrow-band spectra of this noise phenomenon. To a ground observer, vortex wake noise is characterized by a low-frequency "rushing" sound similar to low-velocity jet noise, with the addition of some faint "crackling" or "popping" sounds. The "crackling" sound is believed to be associated with the beginningsof vortex breakup. As the peak frequency and levels are rather low, this noise source (i.e., the downstream vortices) is not expected to be a problem, except that it might sustain low-frequency noise levels sufficiently to lengthen the time between the 10 dB down points on a flyover noise time history. This could possibly increase the level of an Effective Perceived Noise Level calculation. The wing tip vortices, however, near the wing, are characterized by high velocities and could be contributing to peak flyover noise levels.

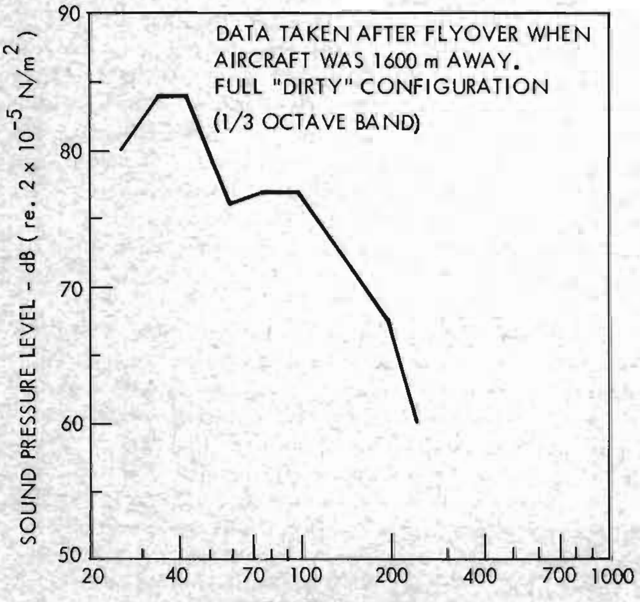


Figure 11. Galaxy Trailing Vortex Noise

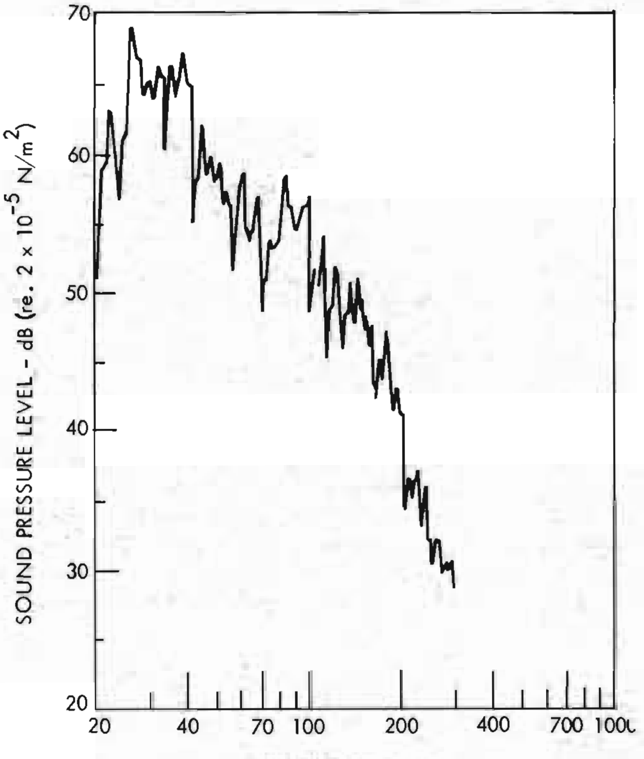


Figure 12. Narrow Band Spectrum - Trailing Vortex Noise

Aero Noise Time-History

Time histories in each one-third octave band, up to and including the fan fundamental, are given in Figure 13. This flyover was at an altitude of 36 meters, airspeed 93 meters/second, with 40% flap extension and retracted landing gear. The zero time point corresponds to the time of peak wing noise (100 Hz one-third-octave band); minus time is before peak, and plus time is time after the peak. Peak wing noise time corresponds approximately to the time the wing inboard trailing edge is directly over the measuring station.

Examining the time histories, starting at the low-frequency end, it is evident that there is a double-peak trend, most pronounced at 63 Hz. As the frequency goes higher, a new double-peak trend appears at 100 Hz (peak wing noise), and a triple peak at 125 Hz. At 200 Hz, a

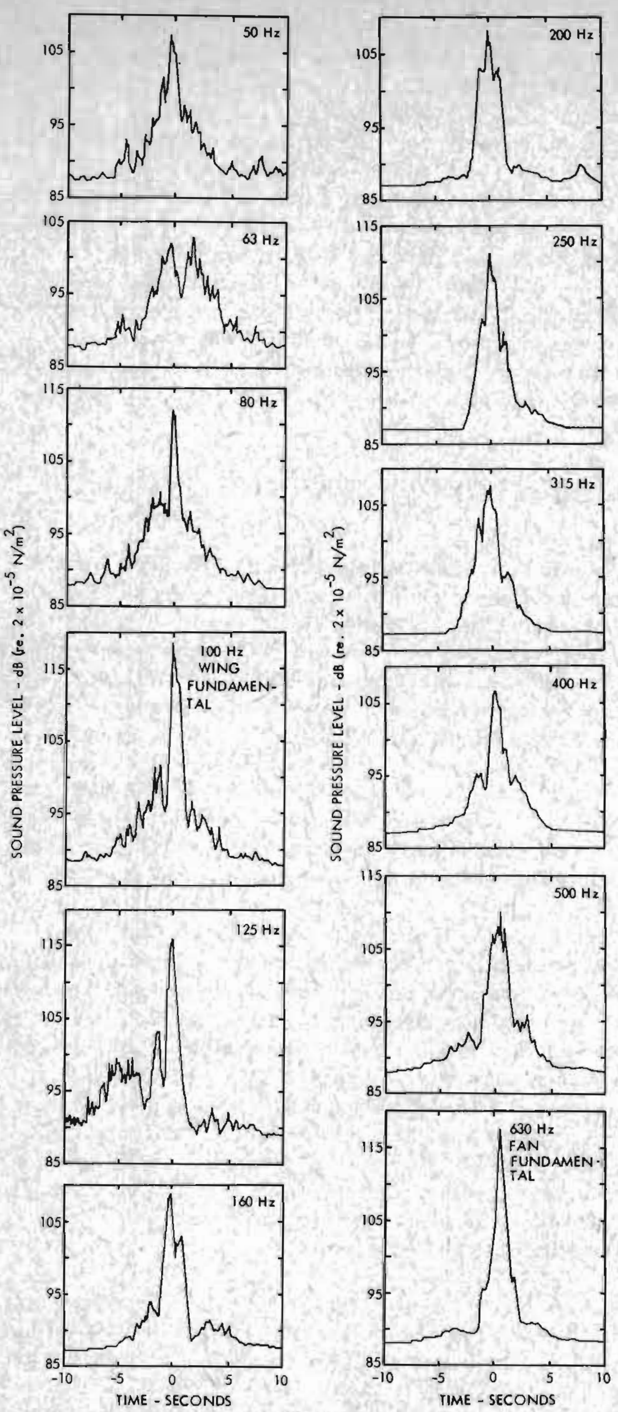


Figure 13. Aerodynamic Noise Flyover Time History (1/3 Octave Band)

new triple peak is evident, close together in time with the central peak predominant. Going on to much higher frequencies, it is evident that the fan noise fundamental peaks at 630 Hz, just after zero time. This corresponds to known static fan noise directivity, which would not be affected significantly by the relatively low aircraft forward speed. The numerous small peaks and valleys provide much in the way of questions which cannot yet be answered. Some peaks may be due to fluctuating drag forces on certain aerodynamic surfaces. These would be expected to peak at points other than directly overhead. They may also be the result of harmonics of the primary fluctuating forces, and some could result partially from the effect of ground to microphone interference. It is also interesting to note that peak wing noise (100 Hz) and peak fan noise (630 Hz) have similar rise-and-fall characteristics as a function of time. These rise-and-fall times are similar to those of the total noise of other current unsuppressed turbofan engine aircraft at similar altitudes with low engine power.

Noise-Source Study

In a previous section, the basic noise effects of the two primary noise sources, wings and landing gear/wheel well, were discussed. It was also known that wing fundamentals generally fell in the range of 100 to 125 Hz, and a prominent harmonic at twice those frequencies. When the landing configuration was measured, numerous peaks above and below the wing fundamental appeared. It would be informative to know what causes these additional noise peaks, as well as some of the minor peaks in the "clean" configuration spectra. Figure 14 contains predicted near-field noise generation frequencies for several likely noise sources, other than the wing, over a range of aircraft velocities from 50 to 100 meters/second. Very little is known about how these other aerodynamic phenomena propagate to the ground, and no attempt is made here to calculate such propagation. Typical noise source frequencies that do match up with ground-noise measurements may be propagating and warrant further investigation.

The following discussion is thus based on limited technology and limited experimental data and is intended primarily to stimulate further investigations. The following discussion revolves around the data presented in Figure 14.

	FREQUENCIES (Hz) FOR AIRSPEEDS OF		
NOISE SOURCE	50 M/S	75 M/S	100 M/S
Nose Wheel Well	17	26	34
Main Wheel Well	8	12	16
Nose Landing Gear	41	61	81
Main Landing Gear	32	49	65
Engine Pylons	82	123	164
Horizontal Stabilizer	131	196	261
Vertical Stabilizer	56	33	111
Boundary Layer - Fwd.	600	900	1200
Boundary Layer - Mid	300	450	600
Boundary Layer - Aft	150	225	300
Fuselage Wake	4	6	8
Nacelle Airflow		Unknown	
Wheel Well Door Vibration	35	35	35

Figure 14. Predicted Fundamental or Peak Frequencies for Other than Wing Noise Sources

Wheel Wells - The nose and main wheel well cavities typically would produce strong discrete frequencies with some broadband noise. This results from aero/acoustic resonances that occur in the cavities with flow over them, and the turbulent flow interaction within and coming from the cavity. At relatively low speeds, such as those of landing aircraft, a modified Strouhal relationship, based on cavity length, works well for predicting peak frequencies for large wheel-well type cavities. Figure 14 shows that most predicted frequencies in the test velocity range fall below 25 Hz, and the measured data obtained are valid only down to about 20 Hz. However, it does appear that some low-frequency peaks in the very low-frequency range (see Figure 9) could be cavity resonances, and perhaps the peak that occurs just above 20 Hz in several spectra is the primary resonance of the nose-wheel-well cavity.

Landing Gear - The landing gear wheels themselves create broadband noise due to random turbulence created by the flow over them. The landing gear struts have some vortex shedding and turbulence which would produce discrete frequencies and broadband noise. Calculated frequencies, based on a Strouhal relationship as a function of strut diameter, cover the range from just over 30 Hz to 81 Hz. Since there are so many measured peaks in this range, it is difficult to identify any particular one as being definitely from this source, but it is a good possibility.

Aerodynamic Shaped Surfaces - The aerodynamic surfaces, other than the wing, are the pylons, the vertical stabilizer, and the horizontal stabilizer. Noise should be generated by vortex shedding and turbulence in a similar manner to that of the wing. Figure 14 shows that the frequency range from 33 Hz to 261 Hz could have contributions from these sources. It is difficult to identify any particular measured peaks, but the possibility of correlation does exist both above and below the wing fundamental.

Airflow Over Airframe - This source, usually referred to as "boundary layer noise," does produce rather high local surface fluctuating pressure levels, but it is generally known to radiate poorly. It is readily heard inside the fuselage. The noise generated is very broadband, and the peak frequencies on the fuselage, for example, cover a wide range: 150 to 1200 Hz. As much of this noise is masked by engine noise, no particular effects can be identified on the ground. On a large aircraft, however, the surface areas involved are large, and it is conceivable that some of the measured broadband background noise does come from this source. It will probably not be significant until some of the other sources are reduced.

Fuselage Wake - Fuselages with upswept aft ends, like that of the Galaxy, can produce a wake of shed vortices and turbulence in a manner similar to a plain cylinder (Ref. 19). This type of fuselage acts like a cylinder at an angle to the flow. The resulting noise spectrum could contain discrete frequencies and broadband noise. Predicted peak frequencies are in the inaudible range, as indicated in Figure 14. While this phenomenon can be felt as vibration inside an aircraft under certain conditions, it is not thought to be a significant far-field noise source. The turbulence field produced does eventually become a part of the trailing vortex wake of the aircraft, and its noise is measurable as described in a previous section.

Nacelle Airflow - With the engines at very low power, there is a possibility that some broadband noise is generated from air spillage from the inlet and consequent flow around the engine nacelle. The level and peak frequencies of such noise are unknown.

Structural Vibration - The possibility of structural vibration as a noise source was found in one instance. Figure 9 shows noise peaks at 25 and 35 Hz. Vibration data from the main wheel-well door area was found to have similar double-peak response frequencies in the range of 30 to 40 Hz. While the inflight vibration data were not taken at the identical flight conditions as the noise test, this does point up the strong possibility that structural vibration (possibly aero/acoustically induced) may cause some noise radiation to the ground.

Studies of Noise Sources and Noise Reduction Possibilities

Noise Sources

To find practical noise suppression concepts that are applicable to this problem, it is first necessary to have a good basic understanding of the noise sources involved. The wing-related sources and the landing gear/wheel well sources are rather complex, but the fundamentals for a technology base already exist. In the "wing" noise mechanism area, a considerable amount of work is now in progress in the United States and Europe. Several examples of recently published works may be found in References 18 and 20 through 30. The existing technical foundation should be able to be extended soon to include accounting for multiple spanwise flap elements and other geometrical variations.

In the "cavity" noise reduction area, progress is also being made on both sides of the Atlantic. Typical work is described in References 31 through 35. We should soon be able to account for various cavity configurations with landing gear protruding through the cavities. Other noise sources have also been investigated, such as fuselage boundary layer flow (Ref. 36, 37), flow past projections, flow separation, and base pressure fluctuations. Descriptions of several of these sources are summarized in Reference 38. In most cases, the technical coverage is limited to the near field. Additional work is needed to better evaluate all of these sources in the far field.

Currently, there are several full-scale aircraft aero noise measurement programs as well as noise source analysis and prediction programs in progress. These include work by Lockheed, McDonnell-Douglas, Boeing, the USAF, and NASA in the U.S.A., and the British Aircraft Corp. and the R.A.E. in England. Results from these programs should become available in the near future.

Noise Reduction

The possibilities for some noise reduction already exist. In the case of "wing" related noise, much of the noise-reduction work underway to reduce the "blown flap" noise of STOL aircraft may be applicable. For instance, in the U.S.A. several NASA-sponsored programs (including current work at Lockheed) have been investigating the noise-reduction possibilities of the porous treatment of flap surfaces and boundary layer control by air blowing to reduce trailing-edge velocity gradients and turbulence (Refs. 39, 40). Also related are attempts at boundary layer and turbulence control by "owl wing" type serrations and irregularties on airfoils (Refs. 21, 41, 42). Several additional investigations of helicopter rotor noise reduction also appear to be applicable, such as rotor tip trailing vortex wake modification (Refs. 43, 44).

Since the aircraft velocity plays such an important role, the design of new aircraft could incorporate lower landing speeds to reduce aero noise. Other aerodynamic design factors which appear to influence noise reduction were indicated previously in Equation (2). A more recent study by Revell ties aero noise reduction to the overall drag reduction of an aircraft (Ref. 30).

In the landing gear/wheel well area, several possibilities are evident. The previously mentioned "cavity" noise studies show how to predict and minimize cavity-type noise by basic design. It is also known that the proper location of objects (such as landing gear struts) can decrease the acoustic/aerodynamic responses in cavities. Additional work along these lines should result in low noise configurations. Various types of fairings and flow deflectors can improve the unsteady flow and noise effects. Recent work at Lockheed (Refs. 45, 46) has also shown how structural and aerodynamic (air blowing or suction) concepts can stabilize unsteady flow fields and vortex shedding from cavities, bluff bodies, cylinders, and airfoils. With this basic technology available, advances in the state of the art should be possible in the near future.

Effects on Current Noise Reduction Programs

Since landing approach is the most severe aero noise case (because engine noise will be reduced and the approach altitude is low), this discussion will concentrate on the landing noise problem. Figure 15 shows an upper solid line corresponding to the U.S.A. FAR 36 (also ICAO Annex 16) landing criteria, and solid lines enclosing a band of values that represent the projected non-engine aero noise levels of conventional turbofan transport aircraft. Since most of these aircraft have somewhat similar approach speeds and aerodynamic characteristics, it is not surprising that the result is a trend of approximately 3 EPNdB per doubling of gross weight. Much more work needs to be done before aircraft with greatly differing aerodynamic characteristics can be evaluated properly. However, preliminary indications are that SST type aircraft will be on or slightly above the conventional aircraft range and STOL aircraft will be on or slightly below.

The increasing noise level (EPNdB) trend would be expected to drop off in rate of increase with gross weight at some point. This would occur since larger and larger aircraft would have lower peak frequencies which would result in lower EPNdB increases, even though the total acoustic power would continue climbing at approximately gross weight to the first power.

If no suppression of the non-engine aerodynamic noise sources is assumed, the noise reduction potential of transport aircraft will be in the range of 6 to 15 EPNdB below FAR 36, depending on aircraft weight and aerodynamic characteristics. The majority of conventional transports fall in the range of 8 to 11 EPNdB below FAR 36. It is obvious that in many cases some aero noise suppression will be required if the aircraft noise regulations expected in the 1980's (on the order of 10 EPNdB less than curret criteria) are to be met.

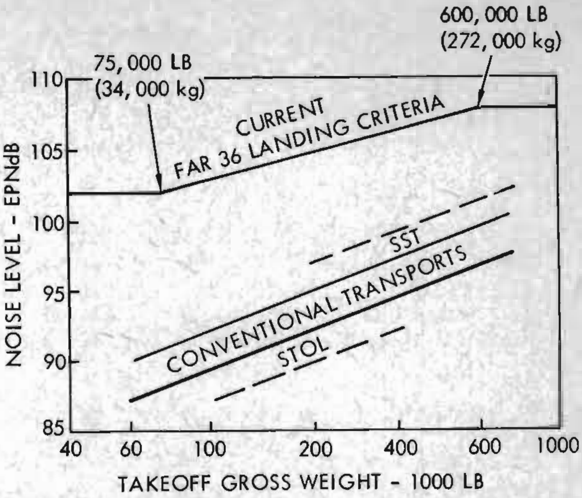


Figure 15. Projected Trends for Non-Engine Aerodynamic Noise Relative to FAR 36 (Also ICAO Annex 16) Noise Criteria

It should be pointed out again that takeoff flyover and sideline aero noise levels for new large aircraft are expected to be less critical than landing approach noise. It appears that the landing problem is currently so much more severe that some landing noise reduction must be obtained before serious consideration of the two takeoff cases is needed. However, noise reduction schemes that are effective for "wing" noise on landing should also be effective for takeoff and sideline.

Concluding Observations

The non-engine aerodynamic noise environment for large transport aircraft is real. In some cases this aero noise barrier can reduce the effectiveness of new engine noise reduction programs, especially for the landing approach case, unless some aero noise reduction is achieved.

Technology fundamentals for this new concern already exist, and a better understanding of the nature of the multiple noise sources is currently being evolved. The noise sources associated with the landing gear and wheel well are equal to or more important than the sources associated with the wing for the current generation of conventional transports. The degree of relative importance depends on the specific aircraft configuration under consideration.

Noise reduction technology fundamentals are emerging, and the state of the art can be expected to be advanced rapidly. Therefore, some reduction in the magnitude of the "Ultimate Noise Barrier" can be expected in the next generation of transport aircraft.

References

1. J. S. Gibson, "The Ultimate Noise Barrier - Far Field Radiated Aerodynamic Noise," INTER-NOISE 72 Proceedings, pp. 332-337, Oct. 6, 1972, Washington, D.C.
2. E. G. Richardson, "Aeolian Tones," Proceedings of the Physical Society of London, Vol. 36, 1924.
3. J. W. S. Rayleigh, The Theory of Sound, Second Edition (1894 Vol. I, 1896 Vol. II), Dover Reprint, 1945.
4. J. P. DenHartog, Mechanical Vibrations, McGraw Hill, 1956.
5. E. G. Richardson, "Critical Velocity of Flow Past Objects of Airfoil Section," Proceedings of the Physical Society of London, Vol. 37, 1925.
6. R. R. Graham, "The Silent Flight of Owls," Journal of Royal Aeronautical Society, Vol. 38, 1934.
7. E. Z. Stowell and A. F. Deming, "Vortex Noise from Rotating Cylindrical Rods," NACA TR 519, February 1935.
8. E. Y. Yudin, "On the Vortex Sound from Rotating Rods," NACA TM 1136 (Translation), 1947.
9. M. Z. Krzywoblocki, "Investigation of the Wing-Wake Frequency with Application of the Strouhal Number," Jour. of the Aero. Sci., Vol. 12, Jan. 1945.
10. H. H. Hubbard, "Propeller Noise Charts for Transport Airplanes," NACA TN 2968, 1953.
11. H. H. Hubbard and D. J. Maglieri, "An Investigation of Some Phenomena Relating to Aural Detection of Airplanes," NACA TN-4337, 1958.
12. R. M. Shockley and Y. Morimoto, "SGS-232 Sailplane Acoustic Test," Lockheed Missiles and Space Company, LMSC/D150040, March 1969.
13. D. L. Smith, et al., "Measurements of the Radiated Noise from Sailplanes," FDL TM-70-3-FDDA, Wright-Patterson AFB, Ohio, July 1970.
14. Anon., "Far Field Aerodynamic Noise Measurement Program," Lockheed-California Co., LR23640, June 1970.
15. V. L. Blumenthal, et al., "Aircraft Environmental Problems," AIAA Paper 73-5, Washington, D.C., Jan. 8-10, 1973.
16. J. S. Gibson, "Non-Engine Aerodynamic Noise - The Lower Limit to Aircraft Noise Reduction," INTER-NOISE 73 Proceedings, Copenhagen, Denmark, August 22-24, 1973.
17. J. S. Gibson, "Non-Engine Aerodynamic Noise Investigation of a Large Aircraft," NASA CR-2378, 1974.
18. R. W. Patterson, et al., "Vortex Shedding Noise of an Isolated Airfoil," United Aircraft Research Labs Rpt. K810867, Dec. 1971.
19. J. G. Theisen and J. Haas, "Turbulence Upset and Other Studies on Jet Transports," Journal of Aircraft, Vol. 5, No. 4, 1968.
20. A. M. Kuethe, "Effect of Streamwise Vortices on Wake Properties Associated with Sound Generation," Journal of Aircraft (1972), Vol. 9, No. 10.
21. R. A. Kroeger, et al., "Low Speed Aerodynamics for Ultra-Quiet Flight," AFFDL TR 71-75, March 1972.
22. R. E. Hayden, "Noise from Interaction of Flow with Rigid Surfaces: A Review of Current Status and Prediction Techniques," B.B.N. Rpt. 2276, Aug. 1972.
23. J. E. Ffowcs-Williams and L. H. Hall, "Aerodynamic Sound Generation by Turbulent Flow in the Vicinity of a Scattering Half Plane," Jour. of Fluid Mech. (1970), Vol. 40, Part 4.
24. D. M. Chase, "Sound Radiated by Turbulent Flow off a Rigid Half-Plane as Obtained from a Wave Factor Spectrum of Hydrodynamic Pressure," Jour. Acou. Soc. of Amer. (1972), Vol. 52, No. 3, Part 3.
25. A. S. Hersh and W. C. Meecham, "Sound Directivity Pattern Radiated from Small Airfoils," Jour. Acous. Soc. of Amer. (1973), Vol. 53, No. 2.
26. C. E. Hanson, "An Investigation of the Near Wake Properties which Lead to Generation of Vortex Shedding Sound from Airfoils," Proceedings of 7th ICA, Budapest, Hungary, August 1971.
27. L. T. Clark, "The Radiation of Sound from an Airfoil Immersed in a Laminar Flow," Transactions of the ASME, October 1971.
28. C. K. W. Tam, "Discrete Tones of Isolated Airfoils," submitted to the Jour. Acous. Soc. of Amer., 1974.
29. G. J. Healy, "Measurement and Analysis of Aircraft Far-Field Noise," NASA CR-2377, 1974.
30. J. D. Revell, "On the Calculation of Aerodynamic Noise Generated by Large Aircraft at Landing Approach," Paper JJ9, 87th Meeting of the A.S.A., New York, April 26, 1974.
31. H. H. Heller, G. Holmes, E. E. Covert, "Flow Induced Pressure Oscillations in Shallow Cavities," AFFDL Report TR-70-104, December 1970.
32. H. E. Plumblee, J. S. Gibson, and L. W. Lassiter, "A Theoretical and Experimental Investigation of the Acoustic Response of Cavities in an Aerodynamic Flow," AFFDL Report WADD-TR-61-75, March 1962.
33. J. E. Rossiter, "Wind Tunnel Experiments on the Flow over Rectangular Cavities at Subsonic and Transonic Speeds," R.A.E. Tech. Rpt. 64037, October 1964.

34. M. G. Morozov, "Acoustic Emission of Cavities in Supersonic Airflow," News of the Academy of Sciences of the USSR, No. 2, 1960, pp. 40-46 (Translation by AFFTD, No. FTD-MT-24-296-68).

35. L. F. East, "Aerodynamically Induced Resonances in Rectangular Cavities," Journal of Sound and Vibration (1966), Vol. 3, No. 3.

36. J. S. Gibson, "Boundary Layer Noise Measurements on a Large Turbofan Aircraft," Paper 1-10, 70th Meeting of the A.S.A., Jour. Acou. Soc. of Amer. (1965), Vol. 38.

37. W. V. Bhat, "Flight Test Measurement of Exterior Turbulent Boundary Layer Pressure Fluctuations on a Boeing Model 737 Airplane," Jour. Sound and Vib., (1971), Vol. 14, No. 4.

38. K. Eldred, "Structural Vibration in Space Vehicles," Chap. III, Aerodynamic Excitation, AFFDL TR 61-62, December 1961.

39. R. E. Hayden, Y. Kadman, and R. C. Channaud, "A Study of the Variable Impedance Surface Concept as a Means for Reducing Noise from Jet Interaction with Developed Lift-Augmenting Flaps," NASA CR-112166, 1972.

40. R. E. Hayden, et al., "A Preliminary Evaluation of Noise Reduction Potential for the Upper Surface Blown Flap," BBN Report 2478, Nov. 1972.

41. A. S. Hersh, P. T. Soderman, and R. E. Hayden, "Acoustic and Aerodynamic Investigation of Leading Edge Serrations of Lifting Surfaces," paper submitted to the AIAA, October 1971.

42. R. E. Arndt and R. T. Nagel, "Rotor Noise Attenuation with Leading Edge Devices," Paper, 83rd Meeting of the Acou. Soc. of Amer., April 20, 1972.

43. R. M. Spencer, M. Sternfeld, and B. W. McCormick, "Tip Vortex Thickening for Application to Helicopter Rotor Noise Reduction," USAAMLABS TR 66-1, Sept. 1966.

44. S. A. Rinehart, "Study of Modification of Rotor Tip Vortex by Aerodynamic Means," Rochester Applied Science Associates Report 70-02, Jan. 1970.

45. J. J. Cornish, "High Lift Applications of Spanwise Blowing," ICAS Paper No. 70-09, 7th Congress of the ICAS, Rome, Italy, Sept. 1970.

46. J. G. Theisen, "Vortex Periodicity in Wakes," AIAA No. 67-34, 5th AIAA Aerospace Sciences Meeting, New York, Jan. 1967.

DISCUSSION

H. Wittenberg (Dept. of Aerospace Engineering, Delft University of Technology, Delft, the Netherlands): I should like to ask you how you can separate the contributions of the engines and of the aerodynamic sources to the noise during the tests of the Lockheed Galaxy in approach. The figures you showed on the approach noise, do they include the engine noise contribution?

J.S. Gibson: The answer to the first question is as follows.

Measured static jet noise from the Galaxy's high bypass engines is on the order of 20 dB lower in level throughout the frequency spectrum than the expected aerodynamic noise from the moving airframe. At approach flight speed, this jet noise would be even a little lower in level due to the forward speed effect on jet noise.

Measured static turbo-machinery noise, at the approach engine setting, begins at a frequency of about 700 Hz, and is equal or greater in level than the expected aerodynamic noise. No significant forward speed effects would be expected in this case.

The result of the preceding is an "acoustic window" in the total engine noise spectrum, bounded by a low level background of jet noise, up to a frequency of 700 Hz where turbo-machinery noise interferes. Peak airframe aerodynamic noise was expected to be in the 100-200 Hz range at a level well above the jet noise background, and would then be expected to appear in the "window" when a noise measurement of an approach flyover is made. This is in fact exactly what did happen, thereby showing that the basic aerodynamic noise prediction for the Galaxy was valid. Further confirmation was obtained when the measured aerodynamic noise peak frequency varied as predicted by a Strouhal relationship dependent on aircraft airspeed.

The answer to the second question is no. All the figures shown had engine turbo-machinery noise removed. No change in the low frequency range was made to account for jet noise, since it was about 20 dB lower in level and therefore inconsequential.