N89-10856

NOISE OF THE HARRIER IN VERTICAL LANDING AND TAKEOFF

Paul T. Soderman
and
John D. Foster

NASA Ames Research Center, Moffett Field, CA 94035

Abstract

The noise of the Harrier AV8C aircraft in vertical takeoff and landing was measured 100 ft to the side of the aircraft where jet noise dominates. The noise levels were quite high - up to 125 dB overall sound level at 100 ft. The increased noise due to jet impingement on the ground is presented as a function of jet height to diameter ratio. The impingement noise with the aircraft close to the ground was 14 to 17 dB greater than noise from a free jet. Results are compared with small-scale jet impingement data acquired elsewhere. The agreement between small-scale and full-scale noise-increase in ground effect is fairly good except with the jet close to the ground. It is proposed that differences in the jet Reynolds numbers and resultant character of the jets may be partially responsible for the disparity in the full-scale and small-scale jet impingement noise. The difference between single-jet impingement and multiple-jet impingement may also have been responsible for the small-scale and full-scale disagreement.

Introduction

This report describes an experimental study of the noise of a V/STOL aircraft operating near the ground - specifically, the noise of the Harrier AV8C in vertical landing and takeoff. The apparent acoustic amplification of jets impinging on the ground has been the subject of several small-scale studies, but there is a lack of information in the literature on full-scale jet ground effects. The ground vortex itself, the main subject of this workshop, may affect the propagation of that noise; but this study was conducted without wind, so a true ground vortex was not present.

Historically, it would appear that military fighter aircraft noise has not been addressed because of the possible performance penalties from sound control equipment. However, there is now a concern among aircraft manufacturers and the military that the noise of high-powered STOVL-type aircraft may be sufficiently high, during vertical landing in particular, to a) damage the aircraft or stores due to acoustically induced vibrations, b) interfere with the pilot's communication and complicate his workload, and c) cause ear damage or interfere with the work of the ground crews assigned to launch and capture the aircraft. Those problems are all serious, but items (b) and (c) could conceivably be dealt with using improved ear protectors and communication equipment. Item (a) is more difficult. For example, damage to an air-to-air missile during landing for refueling could lead to loss of the aircraft in subsequent combat. It should be noted that current designs give a STOVL aircraft much more power than the Harrier, particularly designs aimed at supersonic flight, and therefore they will have much more capacity for noise generation.

The approach in this study was to measure the noise of the Harrier AV8C in vertical landing and takeoff with ground level microphones placed 100 ft from the aircraft. The results are then compared with data from small-scale studies (ref. 1 and NASA Contract NAS3-23708) done elsewhere to see if the small-scale data show ground effects similar to those measured with the Harrier. Some of the small-scale data indicate very high levels of acoustic tones when jets impinge perpendicularly on a simulated ground plane. Those tones are generated by an aeroacoustic feedback mechanism involving vortex rings in the jet, ground impingement, and acoustic radiation back to the nozzle. Since those studies have been done at a very small scale, their applicability to full-scale jet noise must be proven. The Harrier flight test did not confirm the presence of such a feedback mechanism.

Harrier AV8C Aircraft

The Harrier aircraft, a swept-wing transonic fighter, utilizes four vectored nozzles for thrust and lift. It is capable of STOL or VTOL operation. Figures 1(a) and (b) are photographs of the NASA AV8C Harrier aircraft. Figure 1(a) shows the nozzle deployment in a vertical landing and the small dams on the underside of the fuselage that are designed to block the flow of the jet upwash along the fuselage.

Figure 2 is a schematic of the turbofan Pegasus engine used in the aircraft. The fan bypass air is exhausted out the two front nozzles, and the turbine exhaust gas is exhausted out the two rear nozzles as shown. Typical temperatures and jet speeds are noted. The rear jet Mach number was nominally 0.93 based on sound speed in the jet. The front and rear nozzle dimensions are given in figure 3(a). The nozzles are rectangular and cut parallel to the corner vanes shown in figure 2. That is, the exhaust area is not perpendicular to the duct axis. This is also illustrated is figure 3(b), which is a photograph of a forward nozzle. The effective diameter of each nozzle, defined as the diameter of a duct with the same cross-sectional area as the rectangular nozzles (measured perpendicular to the duct axis), is approximately 1.5 ft.

Other sources of noise on the aircraft are the inlet fan and reaction-control jets. The inlet fan noise was avoided in this study by positioning the microphones to the side of the aircraft. The reaction jet noise was not identified in the data.

Test Procedure

The aircraft was landed on a concrete apron with the microphones positioned to the right side of the aircraft as shown in figure 4. That is a direction where the noise of the jets dominates the engine fan noise. The pilot approached the landing site, hovered at 100 ft altitude, and descended vertically at a uniform rate of around 2.5 ft/sec with a minimum of throttle adjustments. However, it is standard procedure to increase the throttle setting just before touchdown, followed by a sudden throttle cut before the wheels hit the ground. The throttle settings were not recorded, but by plotting the data as a function of altitude it is possible to separate throttle effects from ground effects on the noise. After a cool-down, the aircraft took off vertically to the same altitude, hovered for several seconds, and descended uniformly again. Most of the data are presented from the second descent. Recordings were also made ahead of the aircraft while it was on the ground to document the fan tone noise. During the flight test, the atmospheric conditions were as follows:

Temperature	69° F
Relative Humidity	18%
Barometric pressure	30 in Hg
Wind	3 knots maximum

The primary data microphone was 100 ft to the side of the landing center point. Actually, two microphones were used side by side at that location, one laid on the ground and one on a 4 ft tripod. As expected, the elevated microphone data show non-uniform ground reflections in the acoustic spectra, so that data is not presented. The ground microphone, on the other hand, had a uniform ground reflection of 6 dB across the spectrum, which was subtracted from the data. This is one of the procedures recommended by the S.A.E. for measuring jet noise.[2] A hand held sound level meter was used 300 ft from the aircraft in the same direction as the 100 ft microphone.

During the aircraft descents and ascents, the pilot announced his altitude readings using the aircraft radar altimeter. The radio transmissions were then noted on the acoustic data tape voice channel. Unfortunately, many of those radio transmissions were not heard in the instrumentation van because of the high noise from the aircraft. Therefore, it was necessary to interpolate between known aircraft altitudes assuming uniform descent or ascent rates. We also noted the time used to descend from or ascend to a known altitude. No time code system was available. The result of this is that the aircraft position was known only approximately. Plots of noise versus altitude show scatter caused by this uncertainty. However, the trends are readily apparent. It is clear that the flight test data cannot be considered as accurate as laboratory-quality data. On the other hand, the data represent results from a flight aircraft and, therefore, contain no errors resulting from scale effects or imperfect simulations.

Instrumentation

Figure 5 shows the acoustic instrumentation. The primary data microphone was a B&K 4133, 1/2-in. condenser microphone powered by a portable power supply/amplifier. The signal was transmitted 200 ft by coaxial cable to the instrumentation van and recorded on a Nagra tape recorder. The system was calibrated in the field with a single-tone piston phone. After the flight test, the data were processed in an HP 5423 FFT spectrum analyzer controlled by an HP 87 computer system.

Data Reduction

Ideally, ground effects are best measured by keeping the aircraft and instrumentation fixed while moving the ground plane. In the flight test, however, the ground and microphone were fixed and the noise source was moved. Thus, the distance from the noise source to the microphone (and subsequent noise levels) was constantly changing irrespective of the ground effect. Furthermore, free jet noise is directional so that, as the aircraft ascended or descended, the angle between the jet axis and the microphone changed, and the noise levels at the microphone changed irrespective of the ground effect. Both the distance and directivity effects had to be removed from the data to isolate the ground effect on the noise. The distance effect was removed by normalizing the data to the source/microphone distance with the aircraft at 100 ft altitude using free field decay rate (6 dB per double distance). The free-jet directivity effect was removed by normalizing the data to the exhaust nozzle/microphone angle at 100 ft altitude, which was 135° relative to the engine axis looking forward. Since jet noise 135° from the axis is louder than the noise 90° from the axis, for example, a correction factor was added to the noise at 90° equal to the difference in radiated jet noise at 135° and 90°. From ref. 2, it was estimated that the maximum correction factor was 15.5 dB at 400 Hz and 90°. The correction factor reduces for larger angles and higher frequencies as listed below. The jet directivities from ref. 2 are typical of isolated jet engines; but without actual directivity data from the Harrier (which is affected by the fuselage and wing) the directivity corrections must be considered as approximations. The corrections do not account for changes in directivity caused by jet impingement because that is an effect we did not want to remove from the data. The complete corrections are as follows:

$$L_{pn}(f) = L_{po}(f) + \Delta dB_1 + \Delta dB_2 + \Delta dB_3 \qquad \text{dB re } 2 \times 10^{-5} \text{ Pa} \qquad (1)$$

where

$L_{pn}(f)$ = sound pressure level corrected to source at $H = 100$ ft
$L_{po}(f)$ = sound pressure level measured flush with the ground
f = frequency, Hz
ΔdB_1 = $20 \log (d/141.4)$ distance correction
d = distance from microphone to aircraft center, ft (141.4 is distance to aircraft center at $H = 100$ ft)
ΔdB_2 = -6 ground reflection correction
ΔdB_3 = directivity correction from following table (selected frequencies listed)
θ = angle at jet exhaust between jet axis looking upstream and line to microphone

	ΔdB_3		
θ, deg	400 Hz	1000 Hz	8000 Hz
90-95	15.5	10.5	7.5
95-100	13.0	9.0	5.5
100-110	10.0	6.5	4.5
110-120	6.5	2.5	1.5
120-130	1.0	1.5	1.5
130-135	0	0	0

Where appropriate, the overall sound levels without distance and angle corrections are noted on the figures to represent the noise that would actually be heard at that aircraft position and operating condition.

The data corrections were applied to the constant bandwidth spectral plots before plotting. To get the overall sound levels, the spectral plots were integrated assuming incoherent addition of acoustic energy from band to band. The spectral analyses were made from 0 to 12.8 kHz using an effective bandwith of 37.5 Hz. Because of the aircraft motion, only two samples of data were averaged at any one altitude, each sample representing a 40 ms time window. The aircraft movement during the sampling time was small. However, due to the random nature of jet noise, the short sample times resulted in spectral plots with an apparent spread of ±3 to 4 dB. The noise level at any frequency was taken to be the middle point of that data spread. All data are labeled with the nondimensional altitude, H/D (where H is the aircraft nozzle altitude in feet, and D is the effective diameter of one nozzle, 1.5 ft). When the Harrier is on the ground, the value of H/D is approximately 3. (The center of the forward nozzle exhaust is 5 ft above the ground, and the center of the aft nozzle exhaust is 4 ft above the ground, for an average height of 4.5 ft.)

Results and Discussion

Flight Test Data

Figure 6 shows Harrier acoustic spectra measured during takeoff for nozzle-height-to-diameter ratios (H/D) of 3 and 70; i.e., in- and out-of-ground effect. The spectra are typical of broadband jet noise and do not contain visible tones. Because of the short, 2-sec sample time and the narrow bandwith, the scatter in these spectra is around ±4 dB. The noise increase due to the ground appears to range from 10 to 20 dB. However, time records to be shown indicate that the noise increases near the ground were inflated by a high throttle setting used for the rapid takeoff. Thus, the ground effects on the noise in figure 6 are exaggerated. The landing data, however, were taken with a much more uniform throttle setting that was similar to the setting at hover. Figures 7(a)-(b) show similar spectral data measured during landing at values of H/D of 3 and 20 compared to the out-of-ground effect data at H/D = 70. The Harrier noise during landing at H/D = 3, the lowest altitude, was louder by 5 to 15 dB than the out-of-ground noise. At H/D = 20, the ground amplification was 4 to 13 dB. Because of the random fluctuations in jet noise and the short average times used, the data scatter makes it difficult to get accurate differences in the two curves. There is further uncertainty because of possible errors in aircraft position discussed above. These uncertainties can be reduced by plotting continuous time records of the Harrier noise using wider filters. Before leaving the narrow band data, it is important to note that the compressor tones measured ahead of the aircraft during cool-down with low engine speed, shown in the spectrum of figure 8, are not visible in the ground-effect data measured to the side of the aircraft where jet noise dominates.

Figures 9(a)-(c) show time records of the takeoff and landing noise measured in 400, 1000, and 8000 third-octave bands. These data were also digitized with 2-sec average times. But with wide bandwidths, the data scatter is considerably reduced compared to the narrow band data. Two curves are shown, one with raw data, the other with data corrected for ground reflection, source-microphone distance, and jet directivity variations as discussed above. At approximately 2 sec on the time scale, the aircraft engine speed was increased. Takeoff occurred at around 8 sec, which was the highest throttle condition and maximum noise condition. The aircraft ascended vertically to 100 ft by approximately 14 sec and hovered briefly, then descended vertically with a uniform throttle setting. Touchdown occurred at around 58 sec. Although the results show some scatter, a fairly uniform increase in noise is evident during descent. Comparing the noise levels at hover with the noise at other altitudes during descent, the difference is assumed to be due to the jet/ground interaction. The takeoff phase of the flight is ignored because of the higher throttle settings required to climb.

Figure 10 shows the increases in landing noise relative to the noise at H/D = 70 taken from figures 9 (a)-(c). At touchdown, the amplification of the sound was 14-17 dB. The amplification decreased more or less uniformly to zero with increases in H/D from 0 to approximately 60.

At this point it is not clear how much of the noise was amplified by the ground and how much was simply reflected and redistributed. For example, a random noise (like jet noise) will reflect off a hard surface, such as concrete, and increase the average noise above the surface by 3 dB (6 dB for a flush mounted microphone). With a wing and fuselage above the source, sound parallel to the ground would go up more than 3 dB because, as the wing-to-ground distance is decreased, the acoustic energy would be forced outward to the side. This directivity effect is complicated by the hot exhaust upwash, which can refract sound waves. On the other hand, Preisser and Block[1] showed large increases from a small, cold jet impinging on a ground plane even without a wing present, indicating that other phenomena besides reflections and refractions are important.

Comparison With Small-Scale Test Results

Figure 11 shows the experimental setup from two small-scale studies of jet impingement noise. The left sketch shows an experiment currently being conducted by K. Ahuja and associates at Lockheed-Georgia (NASA Contract NAS3-23708). A 0.264-in. diameter nozzle projecting from a simulated fuselage is being used to study jet impingement on a metal plate. The nozzle/plate separation distance is adjustable. Acoustic, aerodynamic, and flow visualization measurements are made using heated and unheated jets. The right sketch shows a similar experiment using a 2.5-in. diameter nozzle used by Preisser and Block at NASA Langley.[1] Preisser and Block measured the acoustic radiation and the unsteady pressures on the ground plane.

Figures 12(a) and (b) are preliminary results from the Lockheed-Georgia study (NASA Contract NAS3-23708) showing acoustic spectra with and without the ground plane installed. Figure 12(a) shows very large noise increases due to ground impingement at H/D = 2 (around 20 dB broadband noise increase, plus the appearance of very loud tones another 20 dB above the broadband noise). Even at H/D = 20, the noise increase due to the jet/ground interaction was over 10 dB as shown in figure 12(b). Using flow visualization, Ahuja traced the tone generation to a feedback loop mechanism illustrated in figure 13. At certain values of H/D and acoustic frequencies, sound from the jet impingement radiates to the jet nozzle and excites a flow instability which coalesces into a series of ring vortices in the jet. The ring vortices strike the ground and radiate sound back to the nozzle to excite further vortex rings to create a resonant, coherent flow structure and subsequent strong tone radiation. This feedback phenomenon has been described by others such as Krothapalli,[3] who demonstrated the same coherent flow and tone radiation from narrow rectangular jets impinging on a ground plane.

Preisser and Block[1] at NASA Langley also found large increases in jet overall sound levels (OASPL) due to ground impingement as illustrated in figure 14. However, they found no distinct tones and make no mention of resonant flow conditions. (Note that they show zero impingement noise on the ground, which contradicts the Harrier flight test data.) They attribute the noise increase above the ground to increased turbulence and unsteady pressures on the ground and in the jet due to impingement. The location of the strongest noise sources was at the outer portion of the impingement region, between 1 and 3 jet diameters from the center of the jet stagnation point on the wall. The primary difference between the two small-scale studies is the jet diameter. The nozzle used at NASA Langley[1] had a diameter about 9 times that of the nozzle used at Lockheed-Georgia. The jet speeds were similar, and both jets were cold. Thus, the Reynold's number of the Langley experiment based on diameter ($Rn = 7.8 \times 10^5$) was 9 times that of the Lockheed-Georgia experiment ($Rn = 8.8 \times 10^4$) for the data shown here. This suggests that the tones and resonant flow conditions found by Ahuja and associates may have been a low Reynolds number phenomenon that does not exist at higher Reynolds number. Certainly, no significant tones were found in the Harrier flight test ($Rn = 1.2 \times 10^7$), though the existence of multiple jets may have obliterated resonant flow in the jets in any case. Other resonant flow fields such as vortex street shedding are known to be Reynolds number sensitive. This is not to say that coherent flow structure cannot be found in jets. On the contrary, other researchers[4] have used conditional sampling techniques to document the presence of a large-scale structure in what would seem to be randomly turbulent jets. Neuwerth[5] found ordered turbulence structure in a jet operated at a Reynolds number of 1×10^6, which caused large noise increases including tones, when impinged on a flap system. (The feedback tones were generated for $H/D < 6$.) Nontheless, Reynolds number and, consequently, scale effects are very important to jet/ground impingement studies both acoustically and aerodynamically. It is probable that as Reynolds number is increased, the role of coherent structure and resonant tone generation becomes weaker relative to the unsteady pressures and noise from random turbulence. A careful study of Reynolds number and scale effects on jet impingement aerodynamics and acoustics should be made before results of small-scale studies can be used with confidence.

A comparison of the full-scale Harrier flight test results and the two small-scale experiment results are made in figure 15. Admittedly, a comparison of multiple-jet impingement noise and single-jet impingement noise may be unfair, but the trends are of interest. The noise increase due to the ground effect is plotted versus H/D. The Ames 400 Hz third-octave band data is compared with the Langley[1] overall noise measured 55° from the horizon and with the Lockheed-Georgia data measured at 27.2 kHz. (Note that the 27.2 kHz data is not the strong tone in figure 12(a); that tone would be 45 dB above the out-of-ground data.) The Ames Harrier data was dominated by low frequencies, so the 400 Hz data should show the same ground effects as overall noise. At the same time, the 400 Hz Harrier data will scale to the Lockheed-Georgia 27.2 kHz small-scale data (assuming that the jet noise scales with Strouhal number based on jet diameter). The comparison of the full-scale and small-scale data is fairly good with two exceptions; the Lockheed-Georgia data show much greater ground effect at low values of H/D, and the Langley data show faster decay of ground effect with increase of H/D. With so few small-scale data points, it is not clear if the differences between the Ames and Langley data are due to data scatter or actual trends. Similarly, it is not clear if the differences between the Ames and Lockheed-Georgia data is due to Reynolds number effects or due to multiple-jet interactions which affected the flow field and subsequent impingement noise. In any case, the lack of agreement indicates that more work is required to resolve the differences between full-scale and small-scale jet/ground impingement studies.

Concluding Remarks

The short flight test of the Harrier AV8C in vertical landing and takeoff showed that the noise levels to the side of the aircraft are quite high - up to 125 dB overall noise level. The sound levels were amplified and redirected by the ground such that the noise levels over a large frequency range increased 14-17 dB relative to the free jet noise during landing. It is not clear how much of the increase was due to redirection of the sound and how much was due to amplification caused by impingement. The noise increase due to ground effect became weaker as the jet height was increased and became small above a jet height-to-diameter ratio (H/D) of 60. There is some uncertainty in the actual levels versus height because of a) uncertainties in aircraft location, b) short data sample times, and c) assumptions about jet directivity irrespective of ground effect.

Comparisons of the ground effects on jet noise with small-scale data acquired elsewhere indicated that jet impingement aerodynamics and acoustics may be Reynolds number sensitive. One small-scale experiment resulted in the generation of strong tones, while the other small-scale experiment did not, presumably because of the higher Reynolds number flow in the second case. No significant tones were found in the Harrier flight test data. The Harrier full-scale data and published small-scale data showed the same trend; that is, jet impingement noise increases as the jet approaches the ground. However, the magnitudes of the impingement noise and the decay rate with jet height were different when comparing full-scale and small-scale data. It is not known if Reynolds number effects or the multiple-jet interactions accounted for the differences. Though coherent flow structure can exist in almost any jet, it is proposed that the role of coherent structure and subsequent tone generation will become weaker (relative to that of random turbulence and noise) if jet Reynolds numbers are increased or if multiple jets interact to break up the coherent structure. Finally, it appears that a careful study of jet impingement noise at different scales is required to resolve questions about the accuracy of small-scale simulations and resulting correlation with full-scale jet impingement.

References

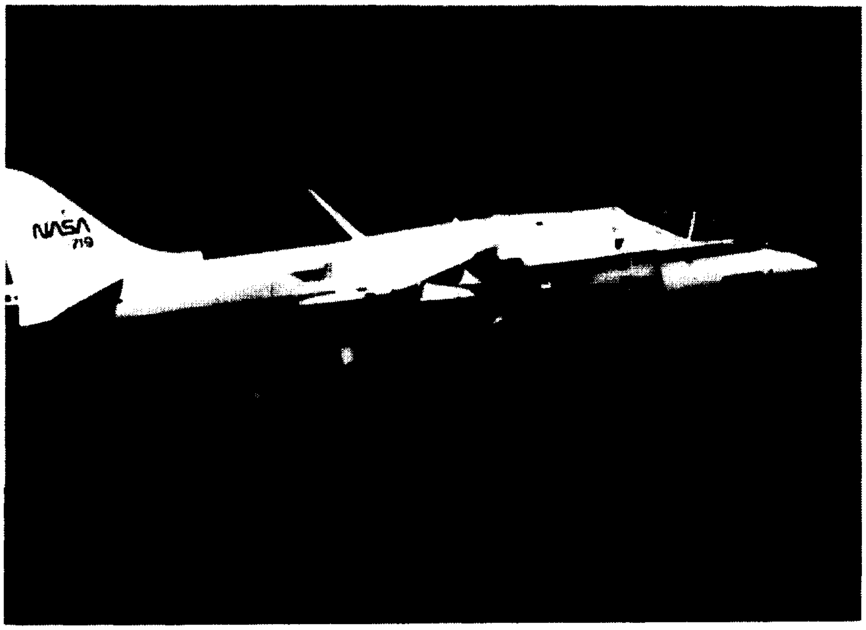
1. Preisser, J.S.; and Block, P.J.W.: An Experimental Study of the Aeroacoustics of a Subsonic Jet Impinging Normal to a Large Rigid Surface. AIAA Paper 76-520, 3rd AIAA Aero-Acoustics Conf., Palo Alto, CA, July 1976.

2. SAE Committee A-21: Practical Methods to Obtain Free-Field Sound Pressure Levels from Acoustical Measurements Over Ground Surfaces. SAE Aerospace Information Report 1672B, June 1983 (See Appendix D).

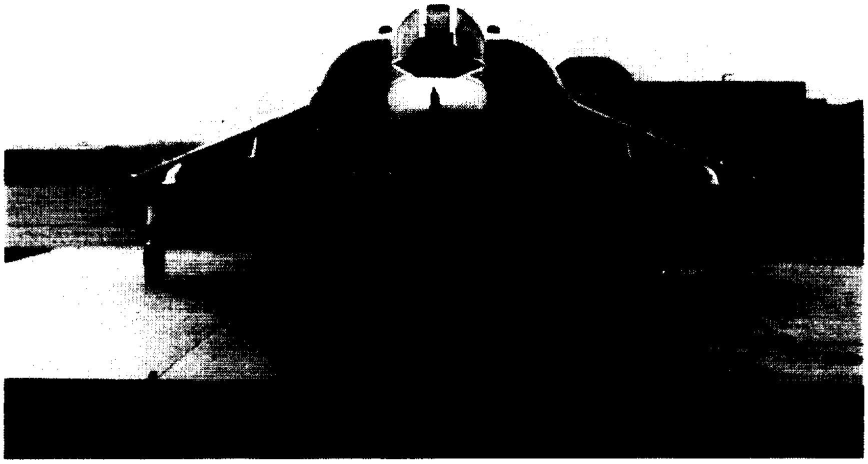
3. Krothapalli, A.: Discrete Tones Generated by an Impinging Underexpanded Rectangular Jet. AIAA J., Dec. 1985, pp. 1910-1915.

4. Crow, S.C.; and Champagne, F.H.: Orderly Structure in Jet Turbulence. Boeing Sci. Res. Lab. Doc. D1-82-0991, 1970.

5. Neuwerth, G.: Flowfield and Noise Sources of Jet Impingement on Flaps and Ground Surface. AGARD CP-308, Proceedings of Conf. on Fluid Dynamics of Jets with Applications to V/STOL, 1981, pp. 13.1-13.7.



(a) SIDE VIEW DURING HOVER



(b) FRONT VIEW ON GROUND

Figure 1 - Harrier AV8C aircraft.

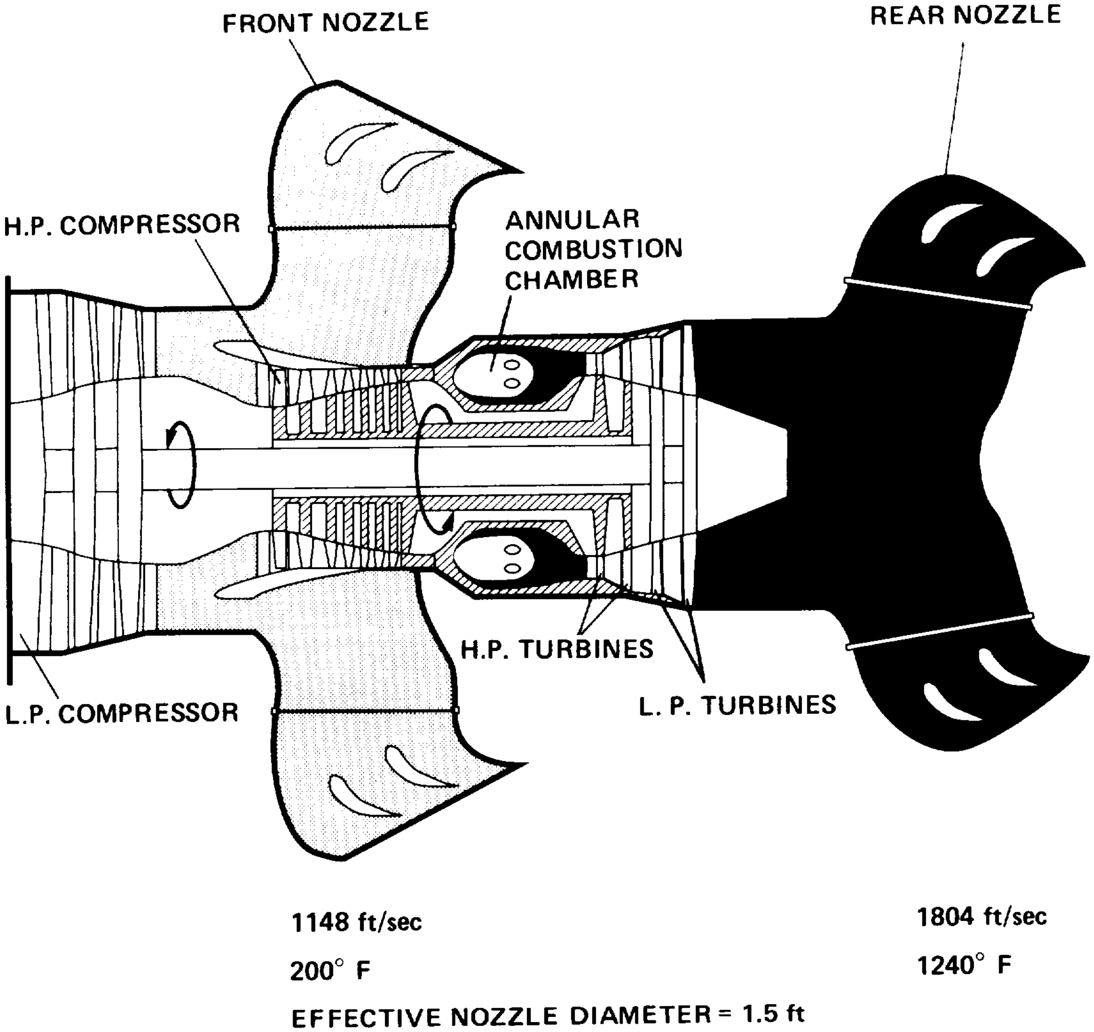
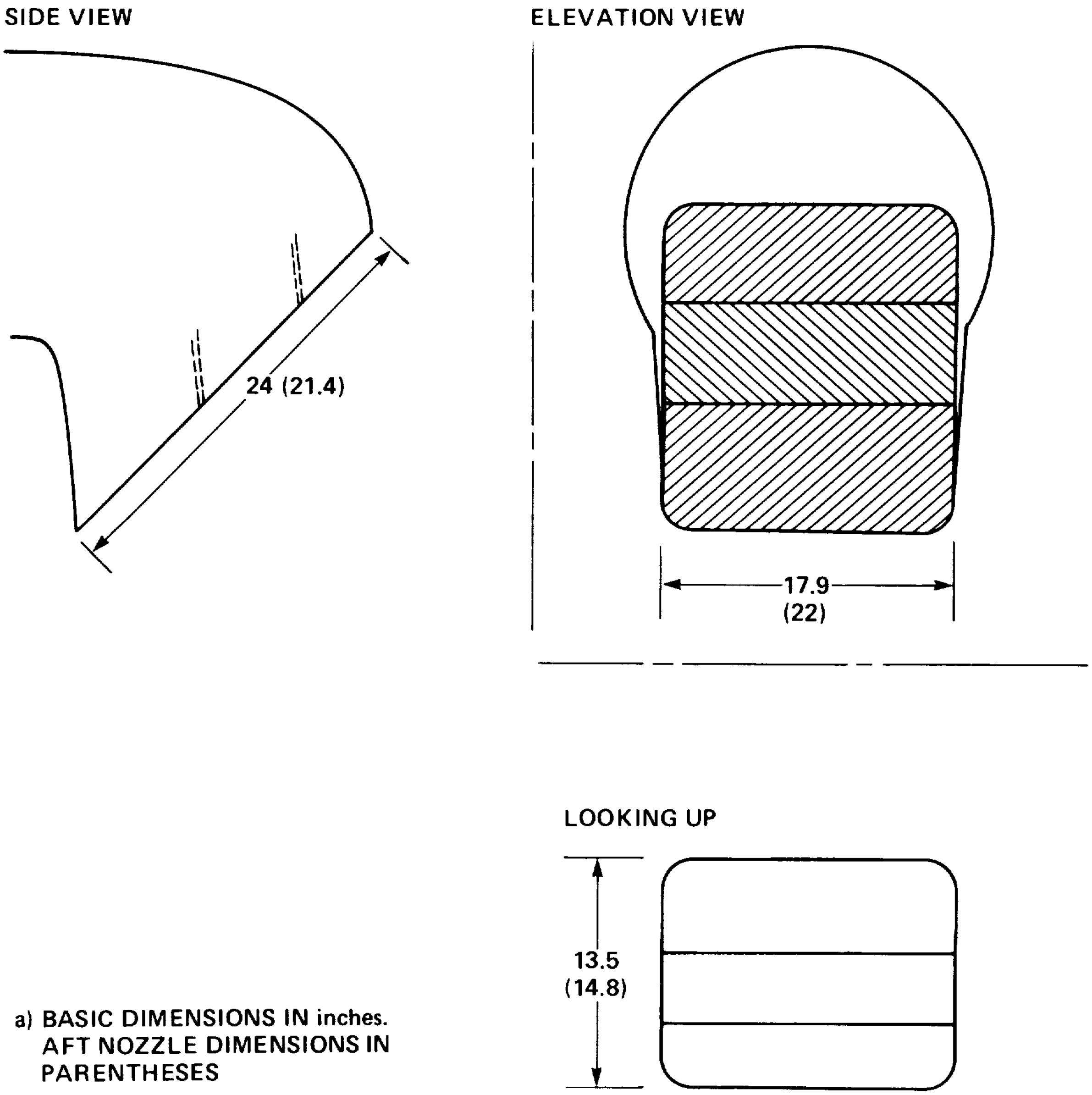
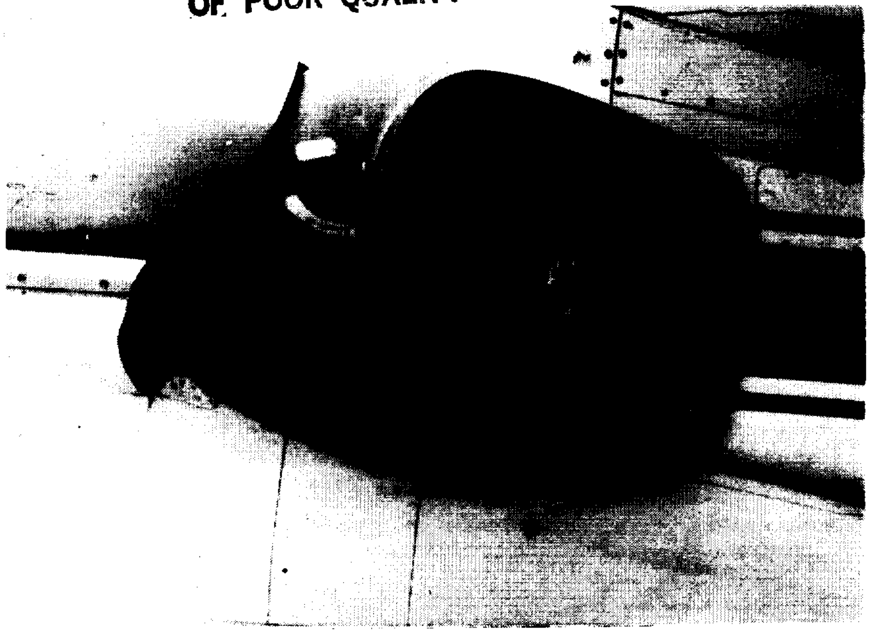


Figure 2 - Pegasus engine and exhaust ducting. Velocities and temperatures are for nominal V/STOL operation.



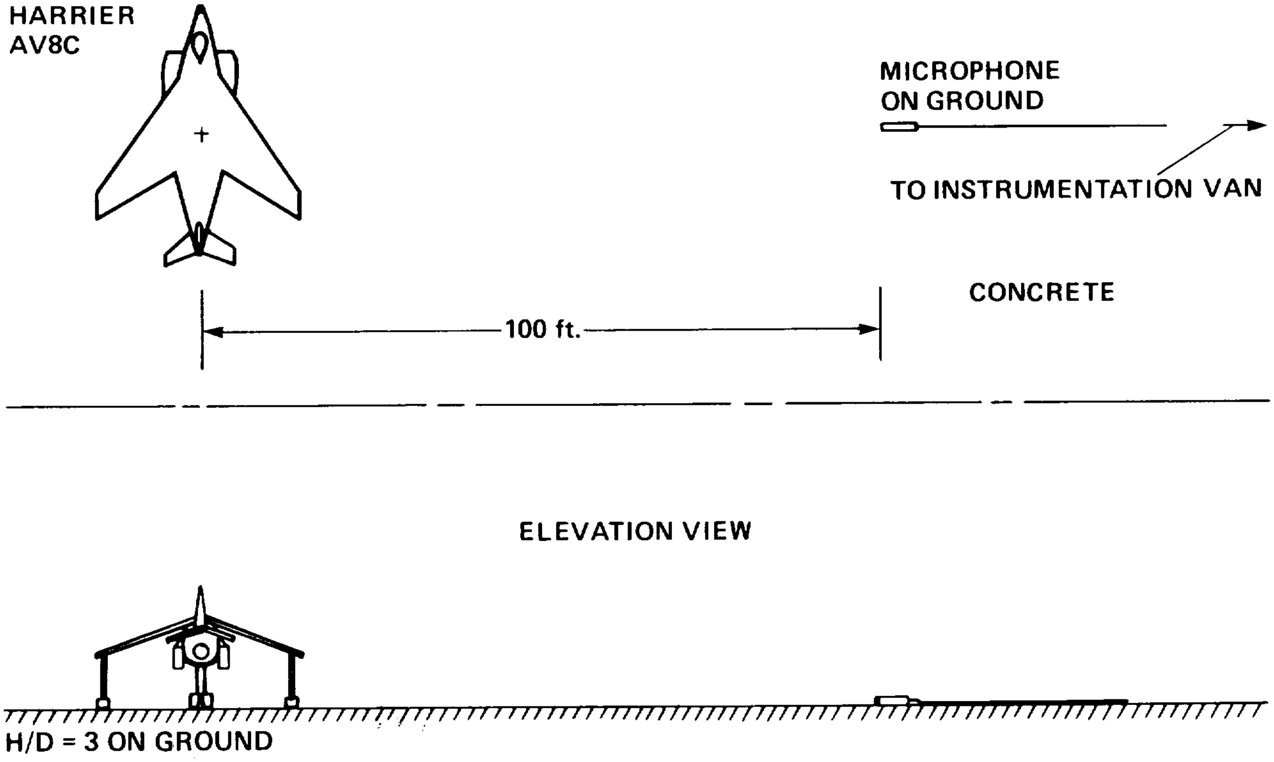
a) BASIC DIMENSIONS IN inches.
AFT NOZZLE DIMENSIONS IN
PARENTHESES

Figure 3 - Exhaust nozzle geometry and dimensions.



(b) FORWARD NOZZLE IN CRUISE ORIENTATION

Figure 3 - Concluded.



PLAN VIEW

ELEVATION VIEW

Figure 4 - Flight test setup showing microphone location relative to aircraft at touchdown. Instrumentation van was 300 ft from aircraft.

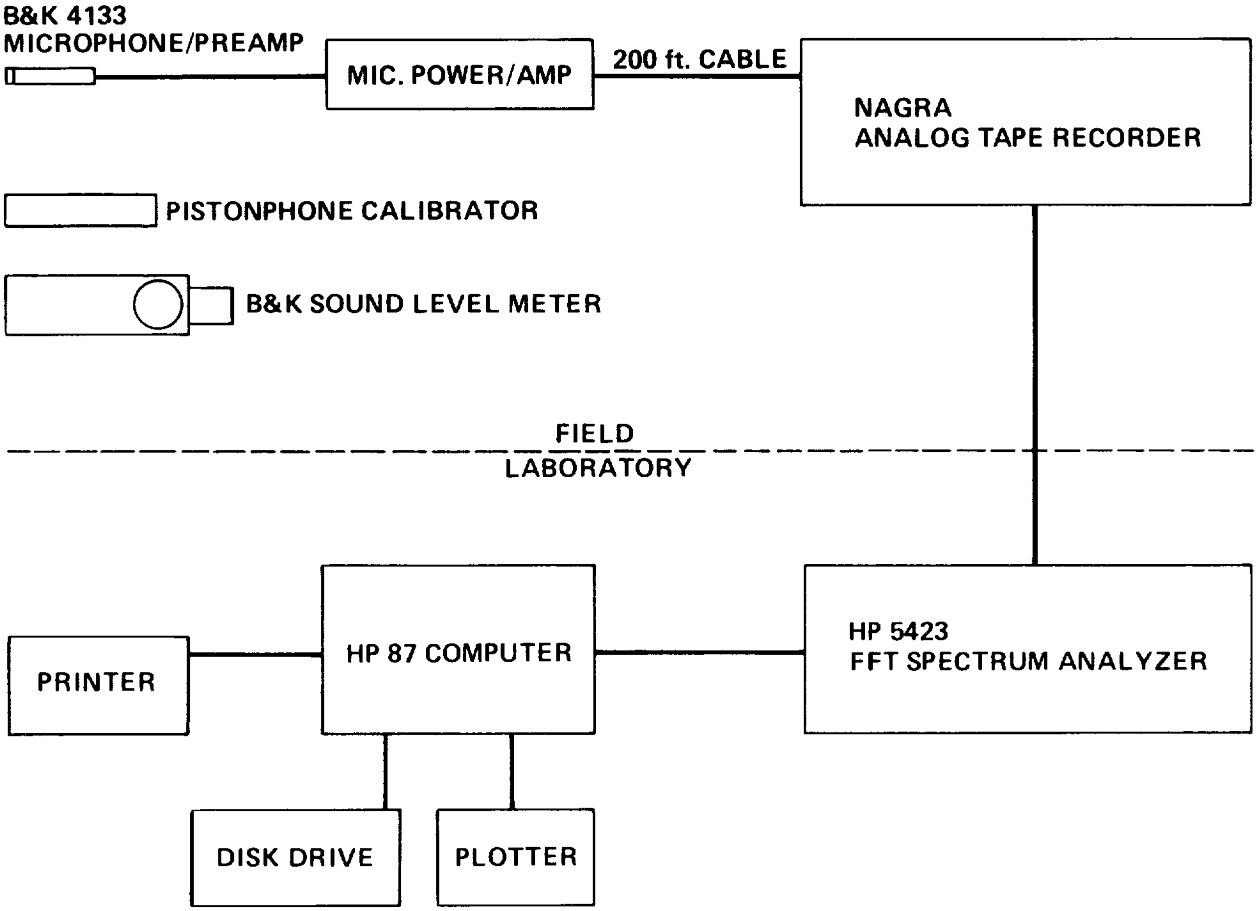


Figure 5 - Acoustic data acquisition and reduction instrumentation.

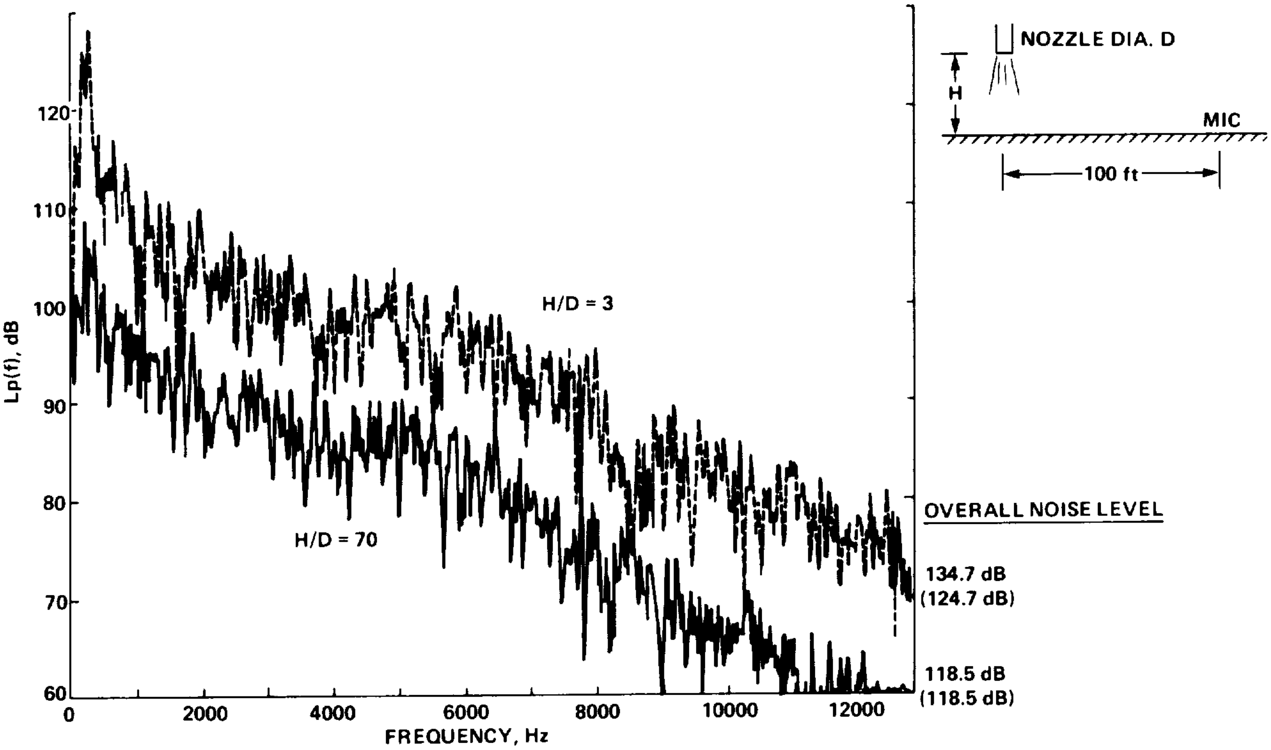
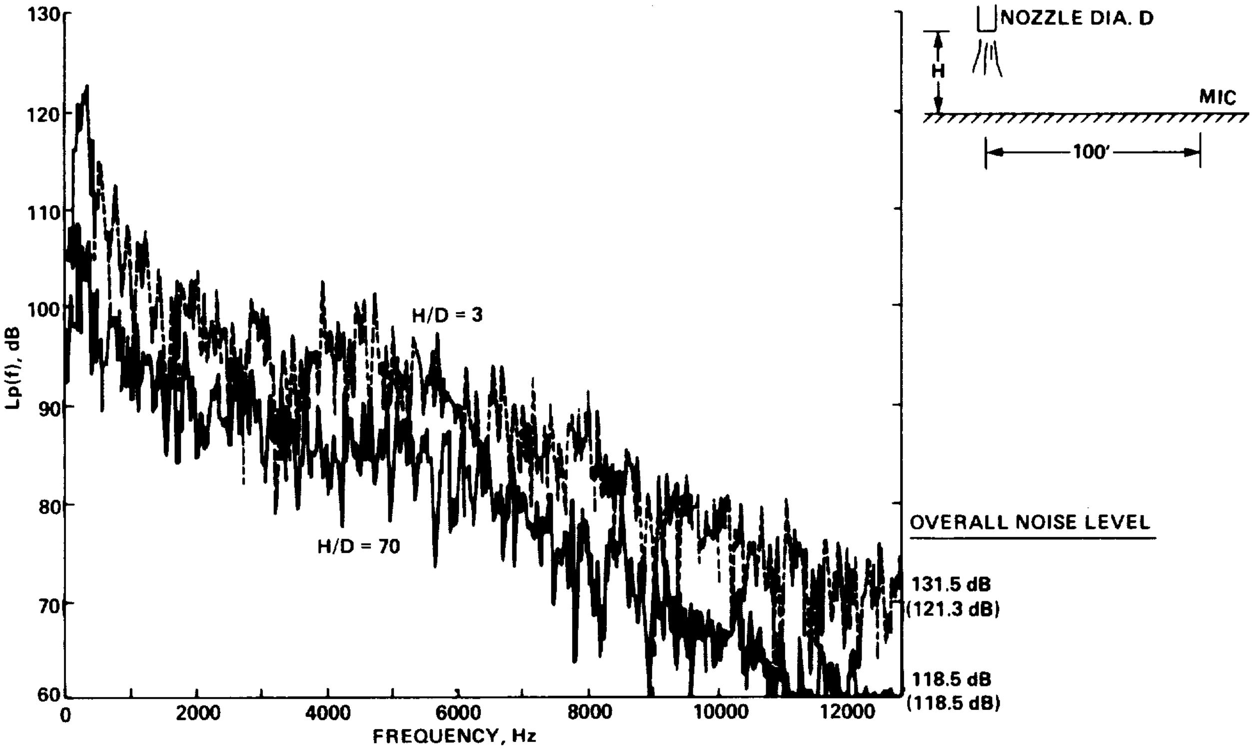
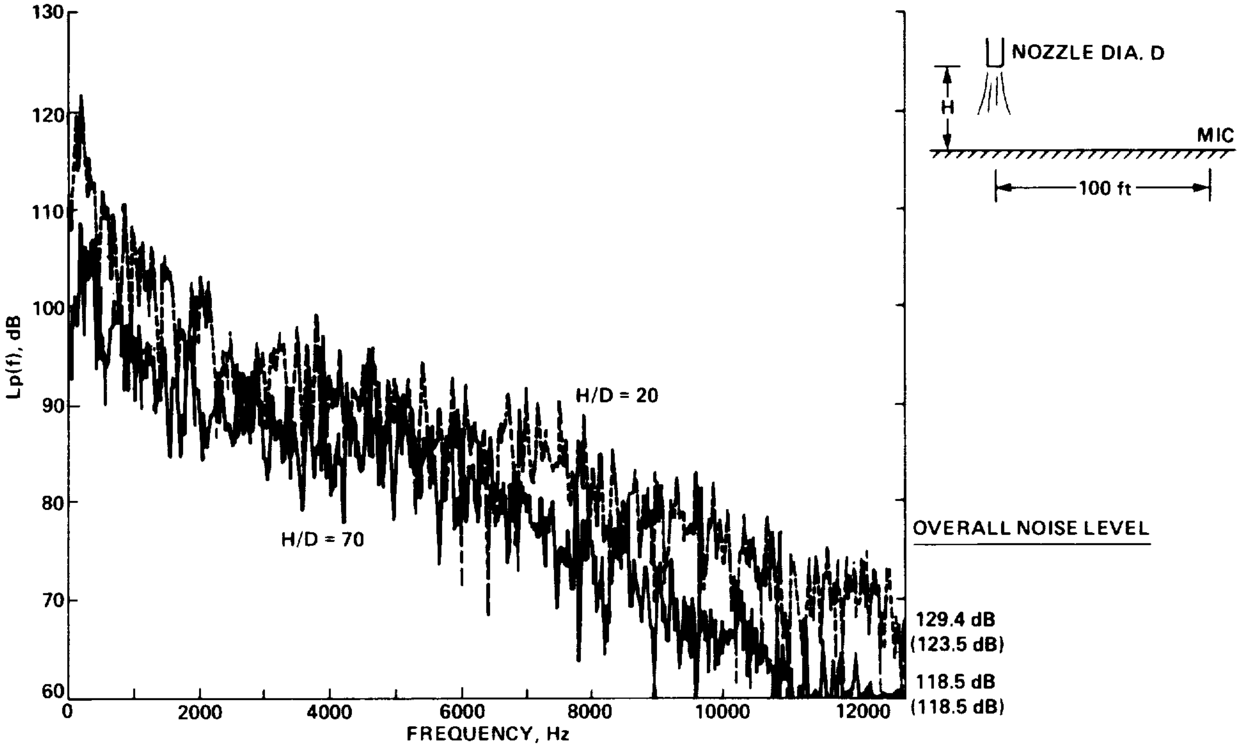


Figure 6 - Takeoff noise at H/D = 3 and 70. Acoustic differences caused by distance and jet directivity have been removed from spectra and overall noise levels except for numbers in parentheses.



a) H/D = 3 AND 70



b) H/D = 20 AND 70

Figure 7 - Landing noise at three values of H/D. Acoustic differences caused by distance and jet directivity have been removed from spectra and overall noise levels except for numbers in parentheses.

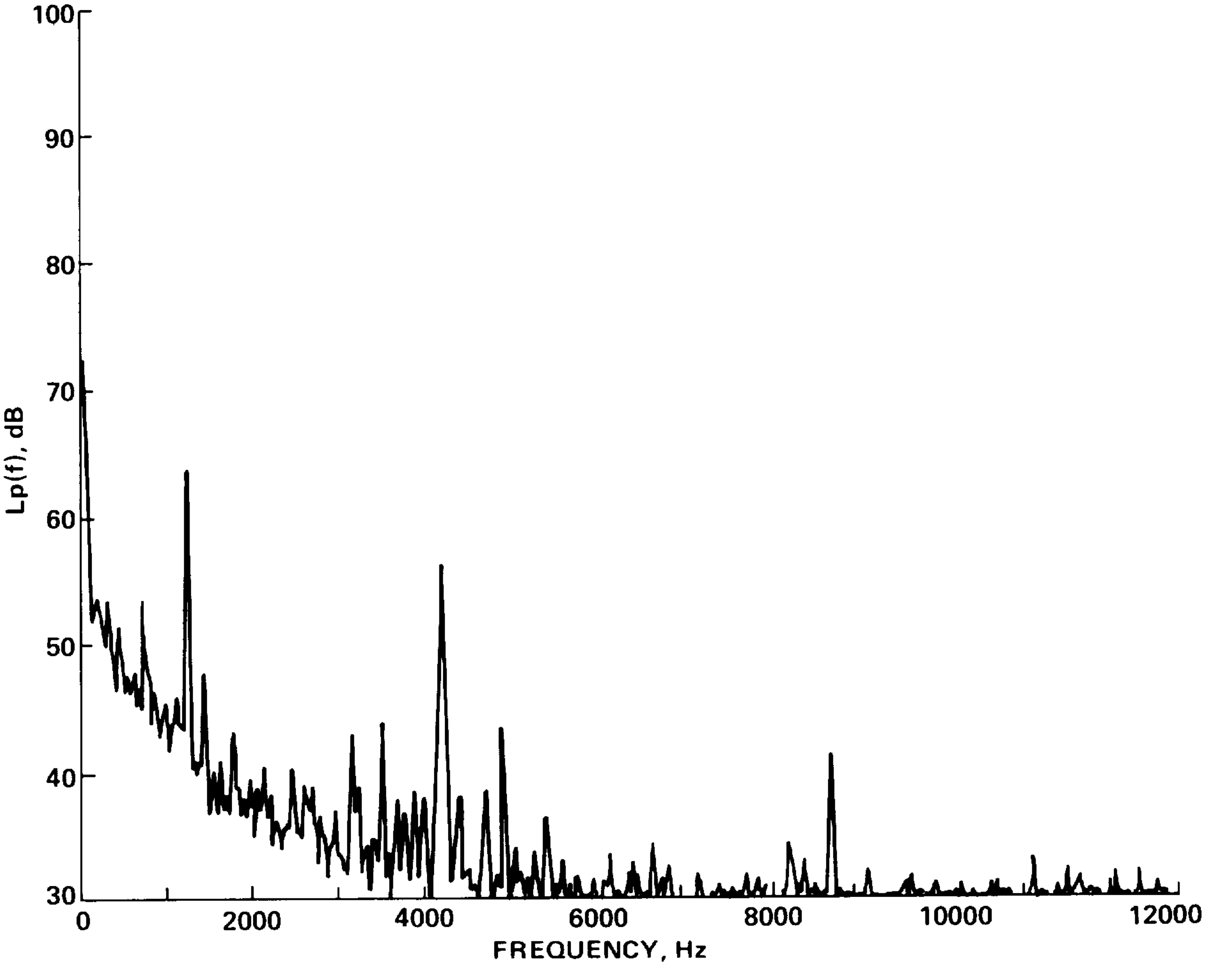
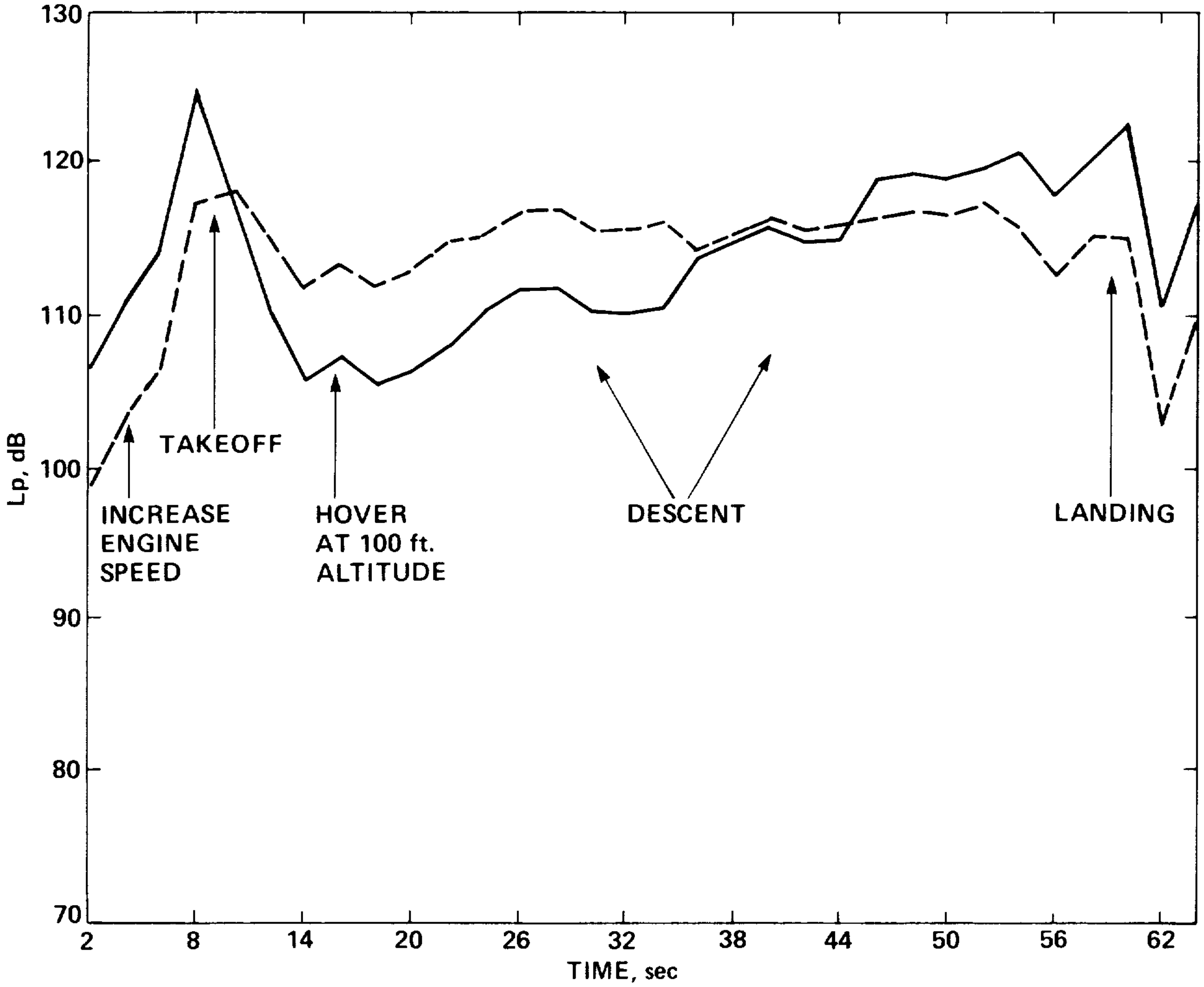


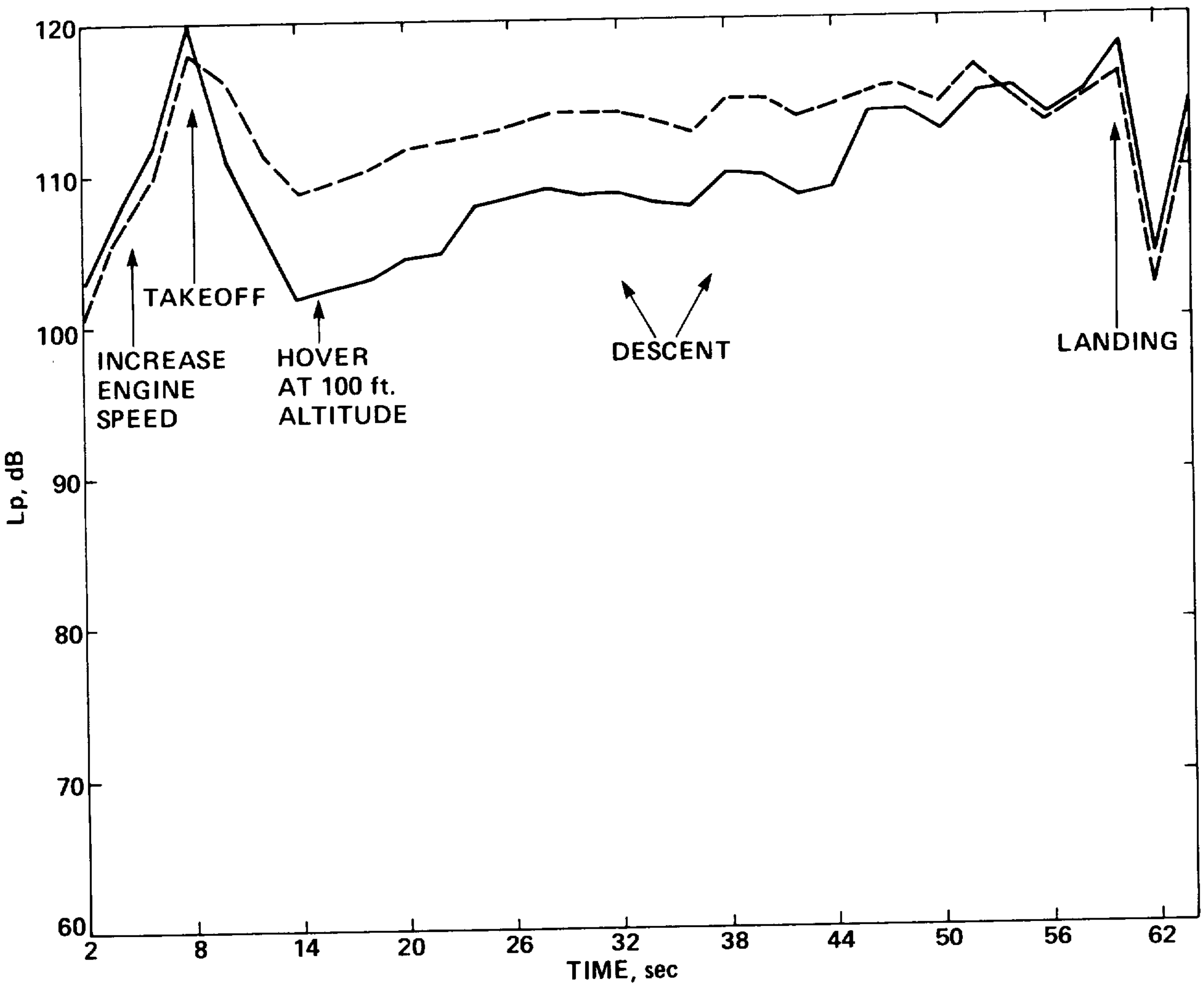
Figure 8 - Noise spectrum ahead of the aircraft while operating on the ground. Compressor tones are visible.

C-3



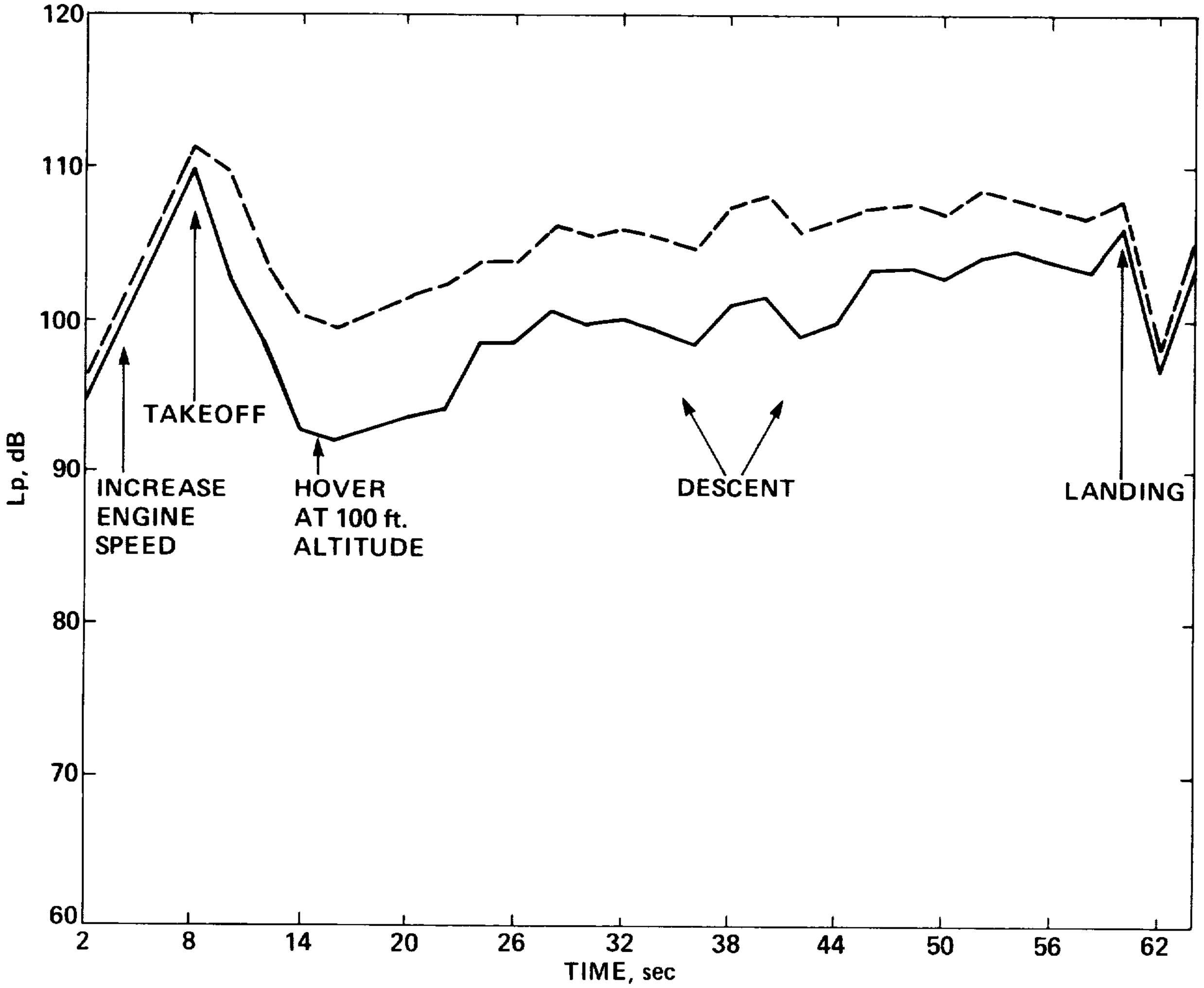
a) 400 Hz THIRD OCTAVE BAND

Figure 9 - Time record of Harrier noise during vertical takeoff, climb, hover and descent to landing; noise measured in third-octave bands for 2 sec averaging times. The dash line is uncorrected data; the solid line is data corrected for ground reflection, aircraft distance, and jet directivity effects.



b) 1000 Hz THIRD OCTAVE BAND

Figure 9 - Continued.



c) 8000 Hz THIRD OCTAVE BAND

Figure 9 - Concluded.

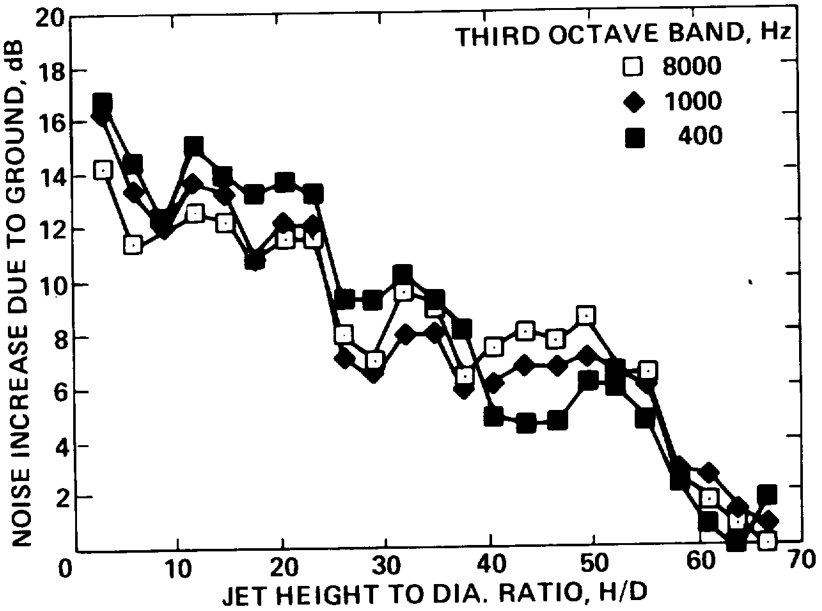
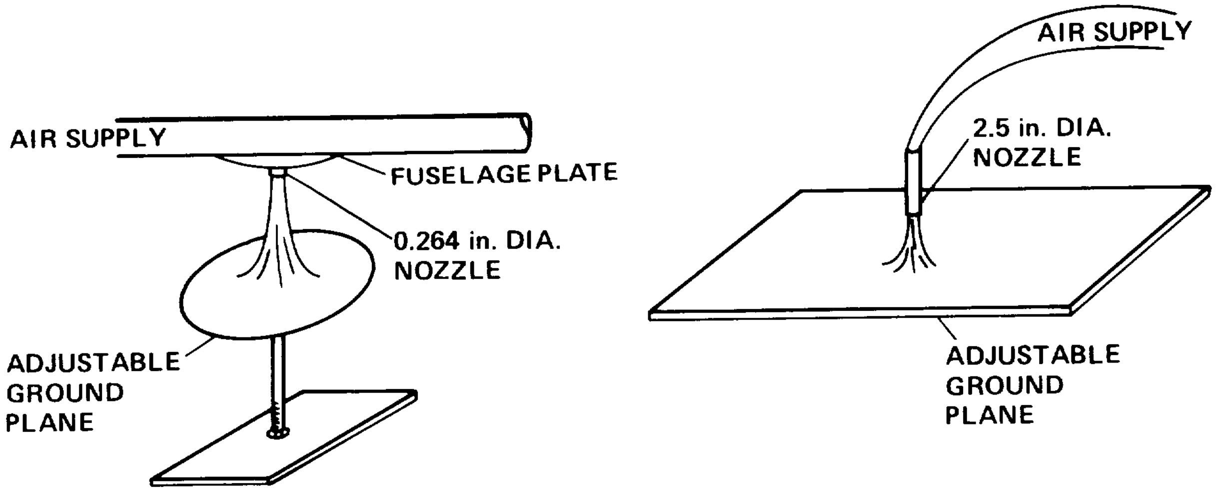


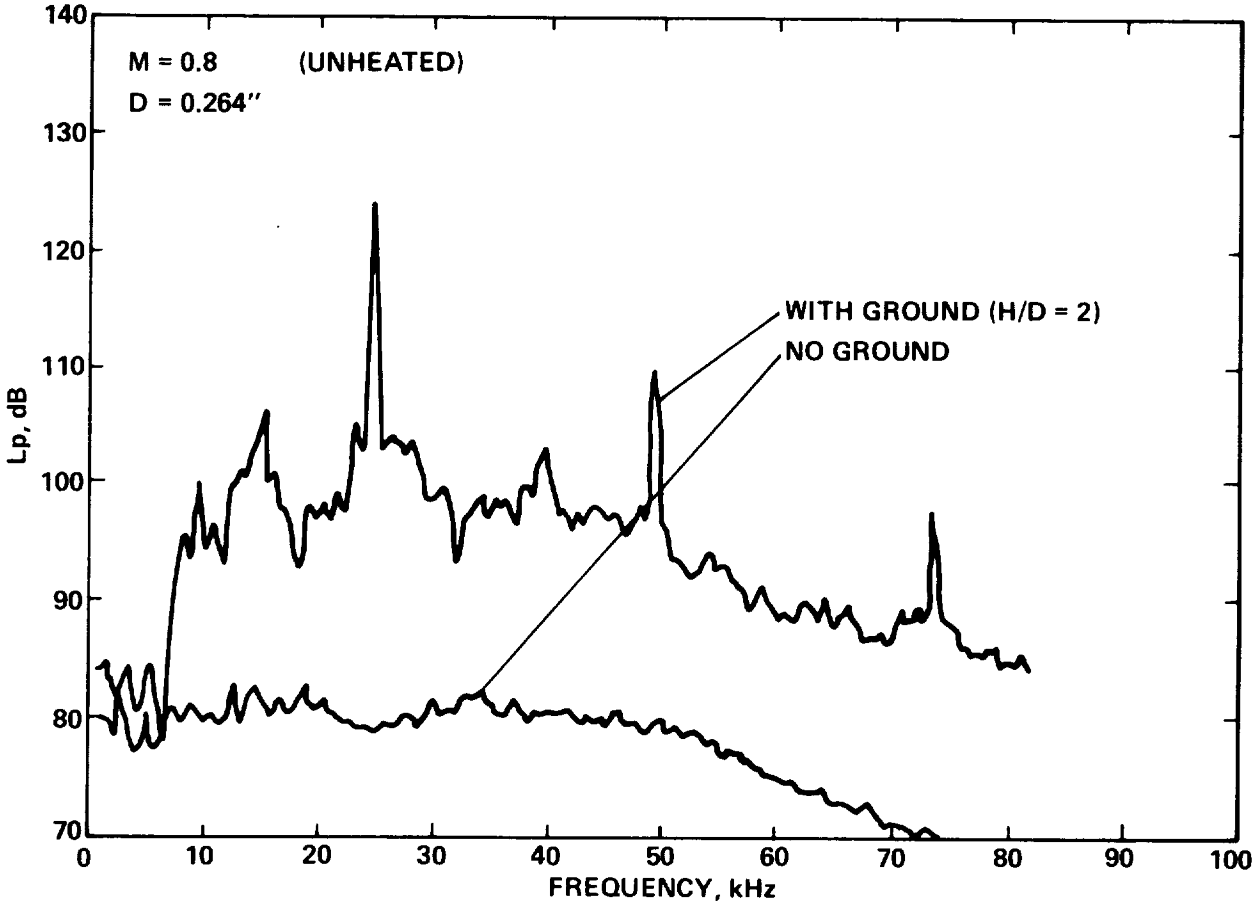
Figure 10 - Summary plot of landing noise relative to noise at H/D = 70 from data in figures 9(a)-(c).



LOCKHEED-GEORGIA
NASA CONTRACT NAS3-23708
K.AHUJA et al.

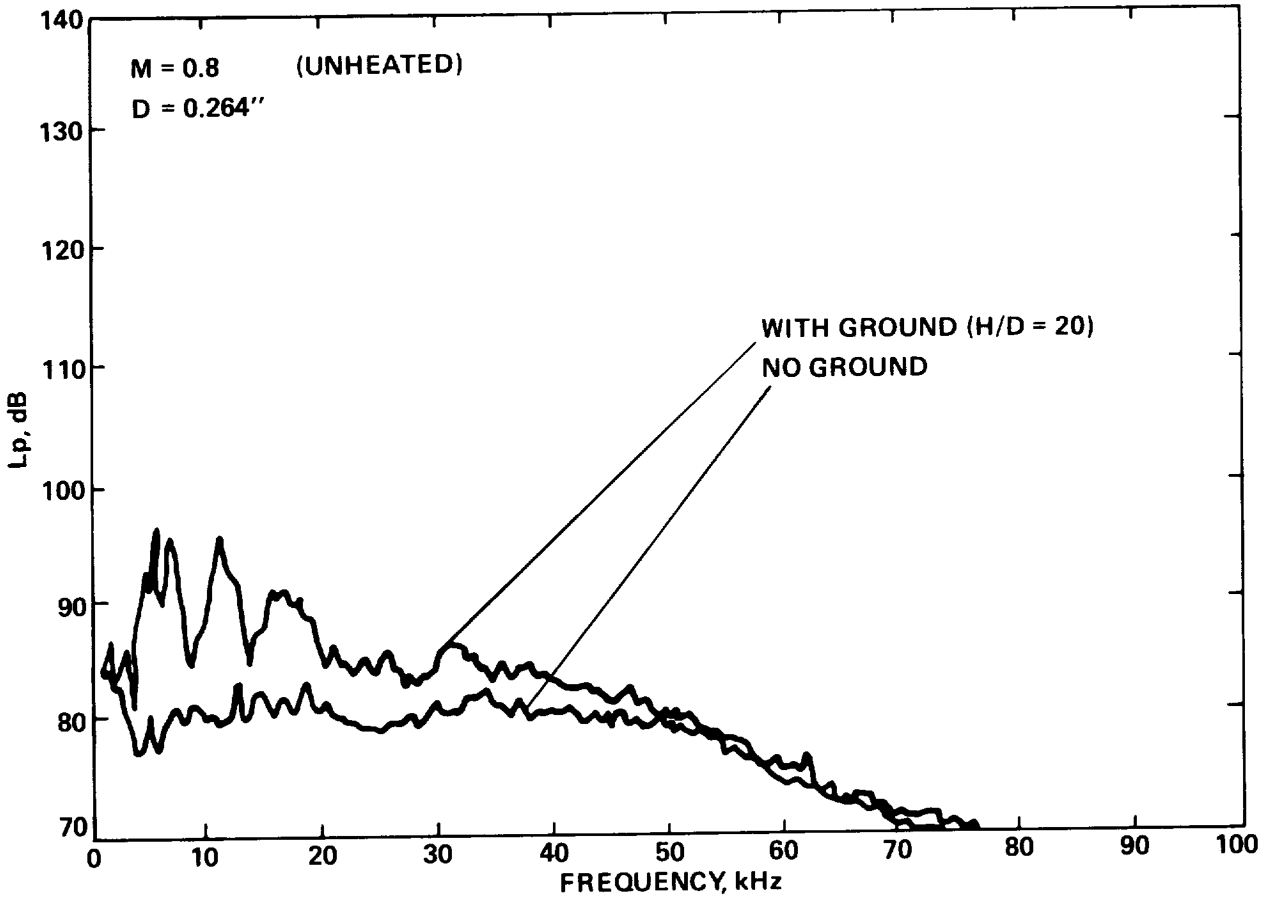
NASA LANGLEY
AIAA PAPER 76-520
PREISSER AND BLOCK (ref. 1)

Figure 11 - Experimental setup for two small-scale studies of jet impingement on simulated ground planes.



a) H/D = 2

Figure 12 - Ground effect on jet noise from Lockheed-Georgia study by K. Ahuja and associates.



(b) H/D = 20

Figure 12 - Concluded.

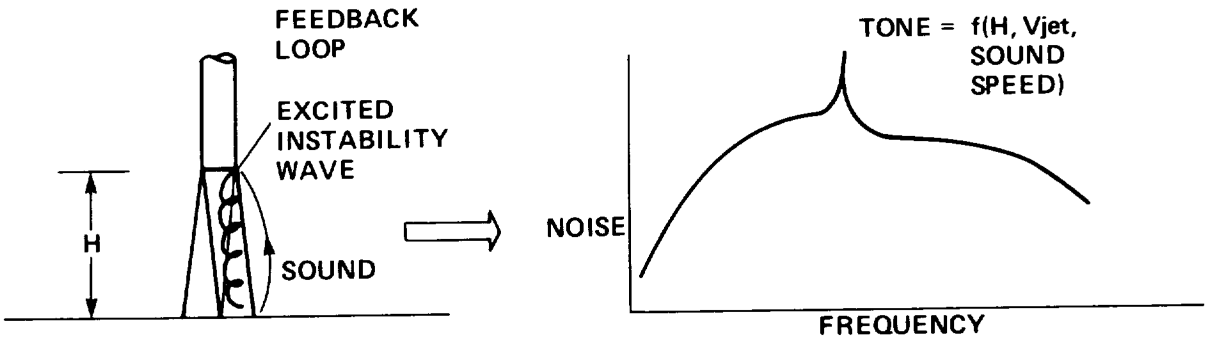


Figure 13 - Illustration of probable aeroacoustic feedback loop responsible for jet impingement tones shown in figure 12.

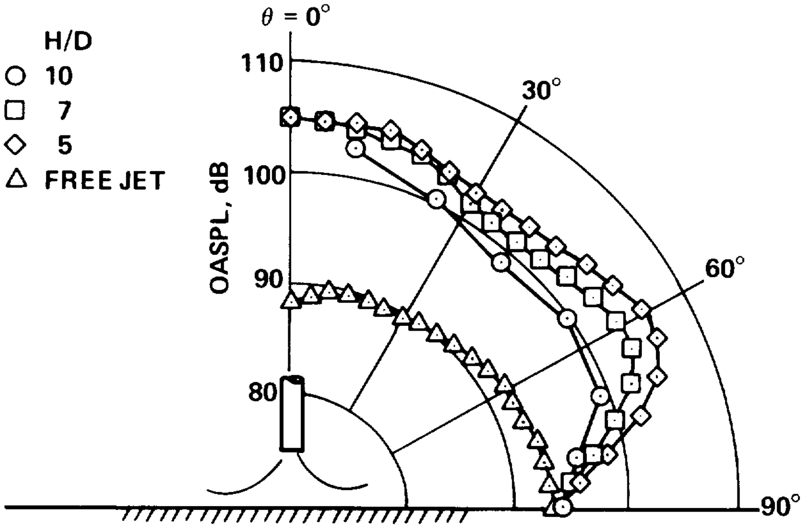


Figure 14 - Ground effect on jet noise from Preisser and Block (ref. 1). Mj = 7; r/D = 48 (r/D = mic distance from stagnation point/jet dia).

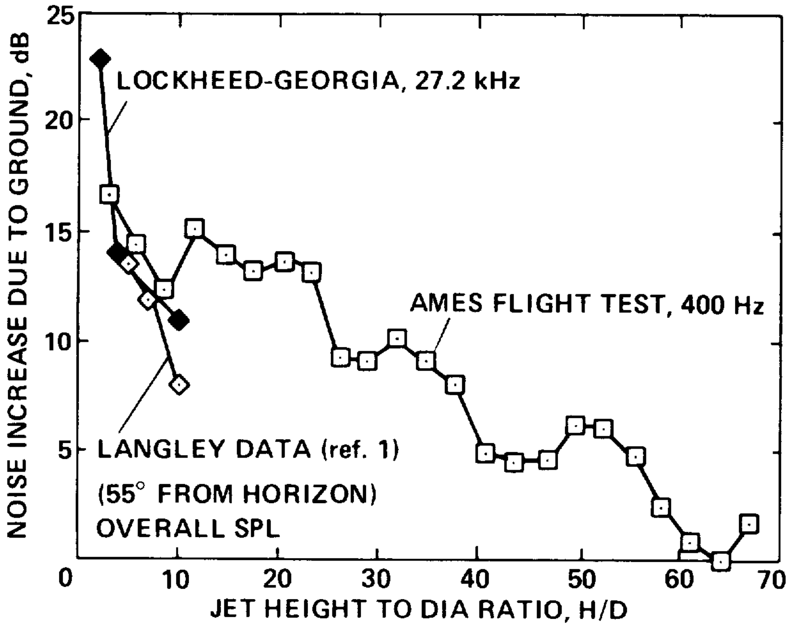


Figure 15 - Comparison of full-scale Harrier ground-effect data with small-scale results. The difference between sound levels measured in- and out-of-ground effect at various values of H/D are plotted.