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INTERIOR NOISE IN
MILITARY HELICOPTERS

by

CHARLES E. PEREZ, JR., 1943-

A THESIS

Presented to the Faculty of the Graduate School of the

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MASTER OF SCIENCE IN MECHANICAL ENGINEERING

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Approved by

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ABSTRACT

The Temporary Threshold Shift (TTS) or temporary hearing loss caused by excessive interior noise in military helicopters results in a critical degradation of the acoustically unprotected infantryman's ability to detect the existence or the approach of the enemy by hearing under combat conditions. The overall problem of noise reduction in helicopters consists of: (1) identifying the various noise sources, and (2) employing appropriate noise control techniques. Identification of the source is accomplished by the frequency correlation of 1/10-octave band analysis of the interior sound levels measured within the helicopter cabin with near-field sound generated by the sound sources. Reduction of the overall interior helicopter noise can be accomplished by attenuation or interdiction along the noise "path", and/or by redesign of the source to reduce the sound generated in the first place. In the case of the helicopter, attenuation or interdiction of the noise consists of: (1) padding or insulating the source with lightweight absorption materials, (2) vibration isolation of the source, and/or (3) the wearing of ear protection by the passengers. This study proposes the installation of lightweight leaded vinyl sheet as an interior measure until redesign can be accomplished to permit adequate vibration isolation. Ear protection is recommended for all crew and passengers, but it is realized that cost and storage space may be prohibitive.

ACKNOWLEDGEMENT

I would like to express my gratitude to a number of people who have been instrumental in the preparation of this dissertation. The obvious recipient of my indebtedness is my wife, whose continual encouragement and faith greatly aided me when my progress was negligible and my results frustrating. Also prominent in my feeling of appreciation is Dr. Leslie R. Koval and Dr. Thomas R. Faucett, whose advice and guidance during the course of my studies was invaluable.

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I am also indebted to the University of Missouri - Rolla, the Mechanical Engineering Department, and particularly Ray S. Schaffart for his help in solving many equipment problems which were encountered during the course of my investigation. My appreciation must also be extended to Mrs. Eunice French whose typewriter skill and patience greatly aided me in the preparation of this manuscript.

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dBA = A-weighted decibel scale 3

dB = decibels reference 0.0002 microbar 7

Hz = Hertz, equivalent to cycles per second 7

SPL = Sound Pressure Level in decibels 7

i = index number of rotor stages 11

B = number of rotor blades 11

Ω = rotor angular velocity 11

m = harmonic order in Fourier series 12

M = Mach number. 12

n = harmonic of sound pressure 12

c = speed of sound 12

u = $nB - n$ 12

x = coordinate 12

y = coordinate 12

r = distance from far field point. 12

ΘB = blades stagger angle 12

J = Bessel function. 12

L_m = complex form of the m^{th} harmonic of the unsteady lift acting on the rotor blades 12

TL = acoustic transmission loss in decibels 28

s = surface area 28

τ = fraction of total area affected. 28

P = root-mean-square pressure. 33

ρ = density of medium. 33

dBC = C-weighted decibel scale 68

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I. INTRODUCTION

The purpose of this project has been to study the interior noise levels in military helicopters. The magnitude of the interior noise and the correlation of these noise levels with the apparent noise sources were investigated. The helicopters investigated were the UH-1H utility helicopter and the OH-6A observation helicopter.

An increasingly important factor recognized recently in the military is the intense interior noise levels in military helicopters and its effect on individual hearing loss. A limiting factor on any quieting technique is the requirement that the added weight of the noise reduction method and/or absorption materials should not detract from the aircraft's mission in any way. On the other hand, the noise reduction must also protect the passengers from a temporary hearing loss, termed temporary threshold shift (TTS), which will adversely affect the combat passenger's sense of hearing so that upon disembarkation he cannot detect either the presence or the approach of the enemy. Additionally, there is increasing concern for the legal aspects of hearing damage to both passengers and crew.

In this study, interior noise levels were investigated to determine the correlation between the noise levels observed and the noise sources on two military helicopters so that appropriate noise reduction techniques may be specified.

II. LITERATURE REVIEW

A. Helicopter Noise

1. Small Gas Turbine Noise

To understand noise generation in gas turbine engines, a short review of a typical engine process is in order. Air enters the compressor stages of the engine where it is compressed and directed through the diffuser sections into the combustion stages of the engine. In the combustion section, fuel is injected, mixed with air, and burned. The hot, expanding gases are directed through guide vanes where they impinge on the turbine, thereby providing the power to drive the compressor sections, the engine accessories, and the gear-reduction systems. The gear-reduction systems supply controlled torque to both the main and the tail-rotor systems. After the gases have passed through the turbine stages they flow through the exhaust casing and finally out into the atmosphere.

Gasaway[1*] points out that helicopters powered by gas turbine engines are generally not as noisy as reciprocating engines of similar power. This fact is also confirmed by Cox[2]. A trend of helicopter engines for various gross weights is displayed in Figure 1.

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*These numbers refer to the list of references at the end of the thesis.

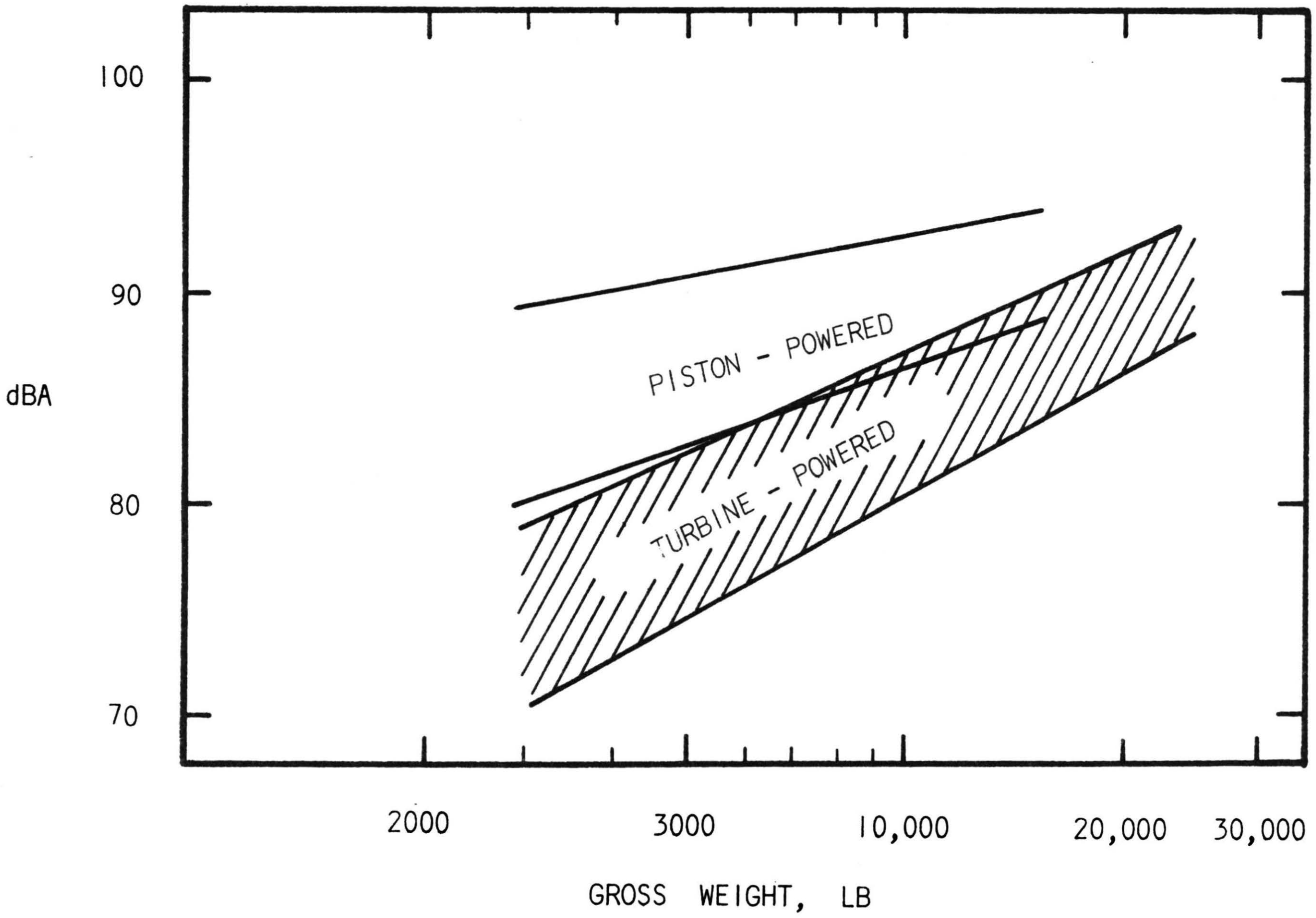


Figure 1. Trend of helicopter noise levels

Although the evolution of the shaft-turbine engine is rather recent, its adoption as a power plant for helicopters has been extensive. Gasaway[1] reports that there are many advantages inherent in the use of turboshaft engines: economy of operation, reliability, ease of maintenance, and reduced weight. Although there are many types of gas turbine engines, all have common basic characteristics. They are an integrated gas turbine engine that supplies power, utilizes a gear-reduction transmission system to reduce very high shaft speeds to a slower rotor and antitorque shaft speed, and depends upon a rotor or propeller to obtain the thrust necessary for powered flight. Even though a gas turbine is utilized as the basic power plant, very little thrust is derived from the jet exhaust of the engine.

Gasaway[3] further reported that turbine shaft exhaust noise is of little relative significance because the gas turbine engine is small and the majority of the thrust is converted into torque power. The major sources of noise are: compressor stages of the turbine, structural vibration in the engine area, and the engine drive system including bearing, gear, shaft distribution, and accessory drive system. Gasaway[1] points out that as helicopter forward speed increases, another major source of noise becomes more significant, that of aerodynamic noise. Because this paper is concerned with current helicopter models, aerodynamic noise assumes a relatively lower significance as a noise source.

Helvey[4] states that the evaluation of the acceptability of sound levels generated by a helicopter does not usually include frequencies outside the hearing range of humans, even though such pressure fluctuations could have serious effects on the human mechanisms. But because helicopter noise includes such diversified noise sources and for the identification of these noise sources, all contributing frequencies are included with special emphasis on those frequencies which most affect human beings.

2. Rotor-Propeller Noise

Widnall[5] reports that aerodynamic noise is produced by the main rotor, the tail rotor, and the engine and is classified as rotational noise, vortex noise, and blade slap. Barry, Magliozzi, and Standard[6] further divide rotational noise into two sections, loading noise and thickness noise. Loading noise reaches a maximum just behind the propeller plane and thickness noise becomes a maximum in the propeller plane and is zero on the propeller axis. The rotational noise results in a series of harmonic tones at frequencies which are multiples of the blade passing frequency. The blade passing frequency in Hertz (Hz) is calculated by multiplying the number of blades by the propeller rpm and then dividing this product by 60.

Wood[7] attempts to explain vortex noise by drawing attention to the partial vacuum formed behind rotating propeller blades generating unstable vortex cavities which collapse on the blades thereby producing pressure fluctuations perceived as noise. Barry, Magliozzi, and Standard[6] assume that the source of vortex or broad-band noise is an oscillating force normal to the blade chord. The amplitude and frequency of this force are related to the flow conditions and blade geometry in a manner which would correspond to Yudin's[8] theory. Widnall[5] states that vortex noise is considered to be the additional noise radiated by propeller operation in a fluid of slight viscosity due to the turbulent flow over the blade sections and in the rotor plane. Brown and Ollerhead[9] confirm the fact that vortex is regarded as having random characteristics with a wide band spectral content.

Bausch, Munch, and Schlegel[10] investigated the rotor impulsive noise, termed "blade slap", of a single rotor and found that the noise during cruise and during hover conditions differ in their noise generation mechanisms. Cruise blade slap results from the combination of acoustic effects of high subsonic tip Mach number and the aerodynamic effects of drag divergence. Hover blade slap results from frequency oscillations in airloads commonly caused by blade-wake interaction. Widnall[11] confirms the production of this blade slap during forward flight of a helicopter.

Stepniewski and Schmitz[12] state that rotational noise and blade slap have much in common in the physical sense. In both cases, there is an element of interaction between wake vortices and the blade. Widnall[5] describes the smooth transition from rotational noise into blade slap condition. When blade slap occurs it dominates all other noise sources. If a helicopter operates in a flight condition which avoids blade slap, an important source of noise is vortex noise. In any case, Ribner[13] observes that the overall noise generation rises sharply as the tip Mach number exceeds unity.

3. Fan-Compressor Noise

Gasaway[3] cautions that the noise of multi-stage compressor units is usually determined by the first-stage compressor units, but in some instances the latter stages may contribute to the total noise. Smith and House[14], in their excellent review of gas turbine engine noise, define various noise sources within an engine, such as typical compressor noise represented by the noise spectra in Figure 2.

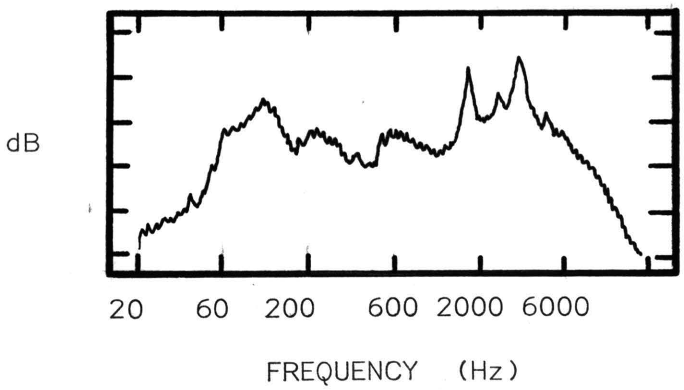


Figure 2. A typical compressor noise spectrum.

An excellent theoretical treatment of sound in blade rows is contained in R. K. Amiet's paper[15], where he deals with the two-dimensional problem of a plane wave impinging on a lattice of flat plate foils. Kistler[16] observes that a fan differs from a propeller in that a fan operates within a duct and the flow into the fan is also generally not uniform over the blade disk. Morse and Ingard[17] further state that sound propagation in a duct, such as a compressor within a gas turbine engine, may be described in terms of modes at given frequencies. For example, for a certain frequency distribution, only a discrete set of patterns of pressure and velocity are permitted in the duct. Some modes will propagate down the duct and some will decay exponentially with distance from their source. Compressors generate unsteady flow effects due to the presence of moving blades arranged as rotors and stators, as in Figure 3.

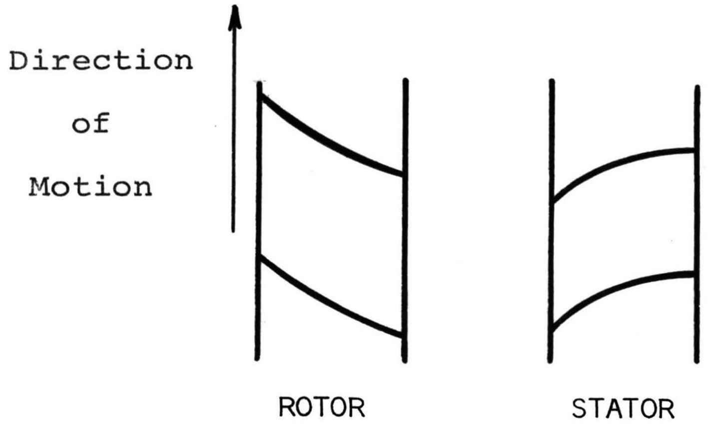


Figure 3. Typical compressor blade arrangement.

Parker[18], Hess and Smith[19] show that each blade is associated with the nonuniformity of the local velocity field, and the pressure fluctuates and is sensed by the ear as noise. As the Mach number is low in helicopter compressors, it is possible to calculate the potential flow around arbitrary shapes with comparative ease.

Walker and Oliver[20] identify the principal noise sources as the effects of the rotor blades cutting the wakes of the next downstream stator row, causing fluctuating pressures which produce noise. The sources at each blade are discrete, but repetitive, so that by the time they have traveled a distance of one blade spacing they appear as sound waves of varying amplitude. These sound waves have a large component with a fundamental frequency equal to the rotor blade passing frequency, since this is the frequency at which the wakes are being cut.

Burdsall, et al[21] produced a very complete study on fan-compressor noise and identified three distinct types of noise in the fan noise spectrum: discrete noise, combination-tone noise, and broadband noise. All three seem to be mutually independent in their generation. Heldenbrand and Tedrick[22], Smith and House[14] tend to group compressor noise into two elements, harmonic (tonal) and broadband (white) noise. Morgan and Suciu[23] investigated measurement techniques and used a typical fan noise spectra as an illustration of the noise from a gas turbine engine compressor. Figure 4 shows the shape of a typical compressor

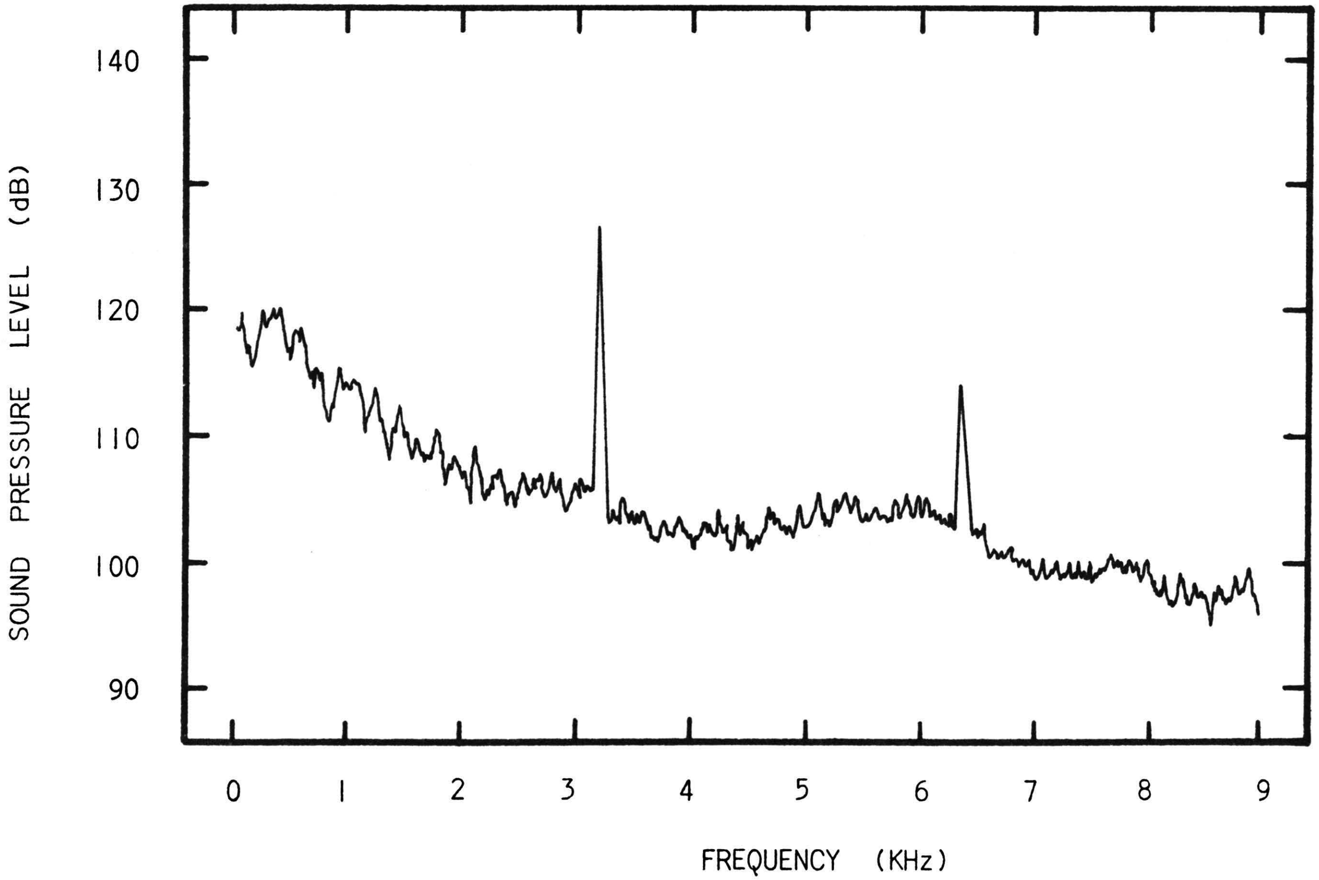


Figure 4. Frequency spectrum of a typical fan

spectra including the fundamental blade-passing frequency component and a component at the second harmonic of the blade passing frequency. Morgan and Suciu[23] state that the analysis of this type of data presented in Figure 4 can lead to such information as the radial distribution of the sound energy in the duct, maximum sound pressure level at any point in the duct, axial mode of decay of the energy, and integrated sound power from the front and aft end of the fan-compressor.

Heldenbrand and Tedrick[22] identify the cause of broadband noise as the action of turbulence and other irregular flow disturbances upon the compressor blades. The tonal spikes of harmonic noise can be identified with the fundamental frequency of a rotating blade stage, calculated by

$$F_i = B_i \Omega_i$$

where F_i is the fundamental blade-passage frequency in Hertz of the i^{th} stage rotor, B_i is the number of blades on that rotor, and Ω_i is the rotor rotational speed in revolutions per second. Other combination-tones can also be identified in the spectrum, although the exact mechanism of their combination is not well understood.

Abdelhamid and Schaub[24] explore even further an expression with which to compute discrete frequency noise levels caused by unsteady forces on the rotor and stator blades due to potential and viscous interactions. Figure 5 shows an arbitrary coordinate system for a blade.

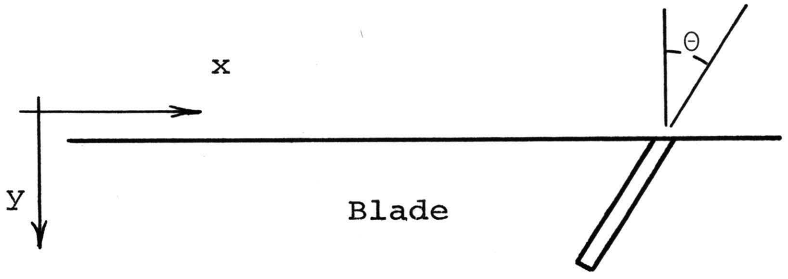


Figure 5. Typical compressor blade.

Abdelhamid and Schaub[24] have developed an expression for the sound pressure at n^{th} harmonic of the blade passing frequency, generated by the rotor and observed at the far field point (x,y). This expression is written as:

$$P_n = \sum_m \frac{n\Omega B^2}{2\pi cr} \{i^{(u-1)} L_m (\frac{x}{r} \sin \Theta - \frac{u}{nBM} \cos \Theta) J(nBM \frac{y}{r})\}.$$

Neglecting turbulence effects, this means that the inlet flow distortion will generate discrete-frequency noise under either of two conditions: one, if there is a small number of rotor blades and two, if the inlet distortion profile contains spikes of large values which lead to unsteady forces on the rotor blade strong in higher harmonics. Smith and House[14] agree that the unsteady forces on the rotor blades and vanes cause the generation of discrete noise. Burdsall, et al[21] explains that the interaction theory, verified by experiments on both small model compressor and full-scale engines, established the existence of spinning pressure patterns within the inlet duct. Burdsall, et al[21], also report that the effect of various parameters on discrete noise was determined through the process of correlation and normalization of test data. These investigaters found that the most important parameters are:

a. Rotor field cut-off ratio.
b. Rotor total pressure rise.
c. Fan diameter.
d. Interaction-mode propagation.

Actually, for most typical compressors having many blades, this cut-off ratio is almost equal to the relative tip Mach number. The data correlation indicates that the tone level is related to the total pressure rise by a factor approximately equal to ten times the logarithm of the pressure rise. Fan diameter, through fan area, effectively doubles the combination-tones and the broadband noise. Interaction-mode propagation concerns blade-vane interaction theory, rotor-stator spacing, and directivity of propagation modes.

Burdsall, et al[21] also explains that the second type of fan noise is a multiple pure-tone noise termed combination-tone noise. It is composed of a large number of pure tones spaced at integral multiples of the shaft rotating frequency. This type of noise radiates only from the compressor or fan inlet and is generated by a pattern of shock waves rotating with a supersonic set of rotating blades. Near the rotor, the shock pattern is reasonably regular and the resulting spectrum consists of a very large blade-passing tone and comparatively small fan-shaft rotational harmonic tones.

The third type of fan noise investigated by Burdsall, et al[21], occurs at all fan operating speeds and has a relatively smooth spectrum shape termed broadband noise. It is random in character and is primarily due to unsteady forces on the blades, the random inflow turbulence interfacing with the blade row, and air scrubbing over surfaces such as the blade and vane rows and the duct walls. Unlike periodic fan noise components which can be traced to specific generating mechanisms, broadband noise is produced by various sources within the fan. The major possible sources are:

a. Blade and vane vortex shedding.
b. Blade, vane, and flow-path wall boundary layer turbulence.
c. Interactions between residual turbulence in the inlet flow and blade and vane pressure fields.
d. Interaction between blade and vane pressure field and the turbulent wall boundary layer.

The relative strength of these possible sources has not been specified yet and this list is not necessarily complete. Because of this, it is not possible to formulate analytical expressions relating fan broadband noise to actual operating parameters. Therefore, empirical procedures are required.

Heldenbrand and Tedrick[22] discuss how the sources of random sound can be related to two basic situations. The first situation is the production of noise on a blade due to the boundary layer set up on that blade and is termed "self-generated" noise. The second situation is the noise produced by passage of the blade through turbulence generated upstream of the blade and is termed "externally-generated" noise. This externally-generated noise has a larger component in the lower frequency range.

Smith and House[14] report that with both basic situations the size distribution of the eddies govern the characteristic spectral shape. They also report that turbulence in the approach stream is the strongest of the broadband noise generating mechanisms. It should be noted that no one type of fan-compressor noise should be reduced at the expense of another as each type controls the noise level at some point within its operating range.

4. Transmission, Gear-Reduction, and Shaft Distribution Noise.

Gasaway[3] reports that, in general, the total system in helicopters includes torque distribution shafts from the power plant, transmission and gear-reduction sections, and final distribution shafts. Noise generated by gear and shaft systems is greatest in helicopters where the transmission units are located within, or near, the main fuselage. Lowson[25] mainly investigated the far field noise radiation of the helicopter, but also pointed out that at very short distances inside the helicopter, gearbox noise becomes the prominent and most important noise source.

Table 1 illustrates the relative significance of various noise-generating mechanisms on the frequency spectrum of internal helicopter noise. Badgley, et al[27] notes from this figure that the engine drive system, especially the speed reduction gears and the accessory systems, are the most important contributors to interior noise levels in the UH-1D utility helicopter. In another study, Badgley, et al,[28] relates the transmittal of noise to the passengers and crew after it leaves the gearbox as illustrated in Figure 6. The upper path shows how the noise in the air surrounding the gearbox housing passes through the compartment bulkhead to the passenger's and crew's ears. The lower path shows how the gearbox vibration is transmitted to the cabin interior through the helicopter structure.

Badgley, et al,[27] describes the gearbox noise-generating mechanism in more detail. The production of certain components of overall internal noise by a power train gearbox requires the vibration of portions of the gearbox casing or of the supporting structure or both. These vibrations may be caused by the application of dynamic forces to the casing at the gear mesh frequencies or their multiples. This condition exists in the usual rotor-drive gearbox design in helicopters, in which an input shaft supports a single bevel gear. This input shaft is usually mounted on three or four rolling-element bearings.

Bradley[29] states that the major sources of noise in a gear unit are:

Table 1. Frequency distribution for UH-1D noise generating mechanisms.

Frequency	Mechanism
750	multiples of upper planetary mesh frequency
1,250	
2,000	
2,000	multiples of lower planetary mesh frequency
4,000	
6,000	
5,500	ring-gear natural frequencies, second mode
7,500	
10,800	ring-gear natural frequencies, third mode
11,000	
11,500	
3,900	ring-gear natural frequencies, first mode
4,100	
5,800	
9,500	
13,000	

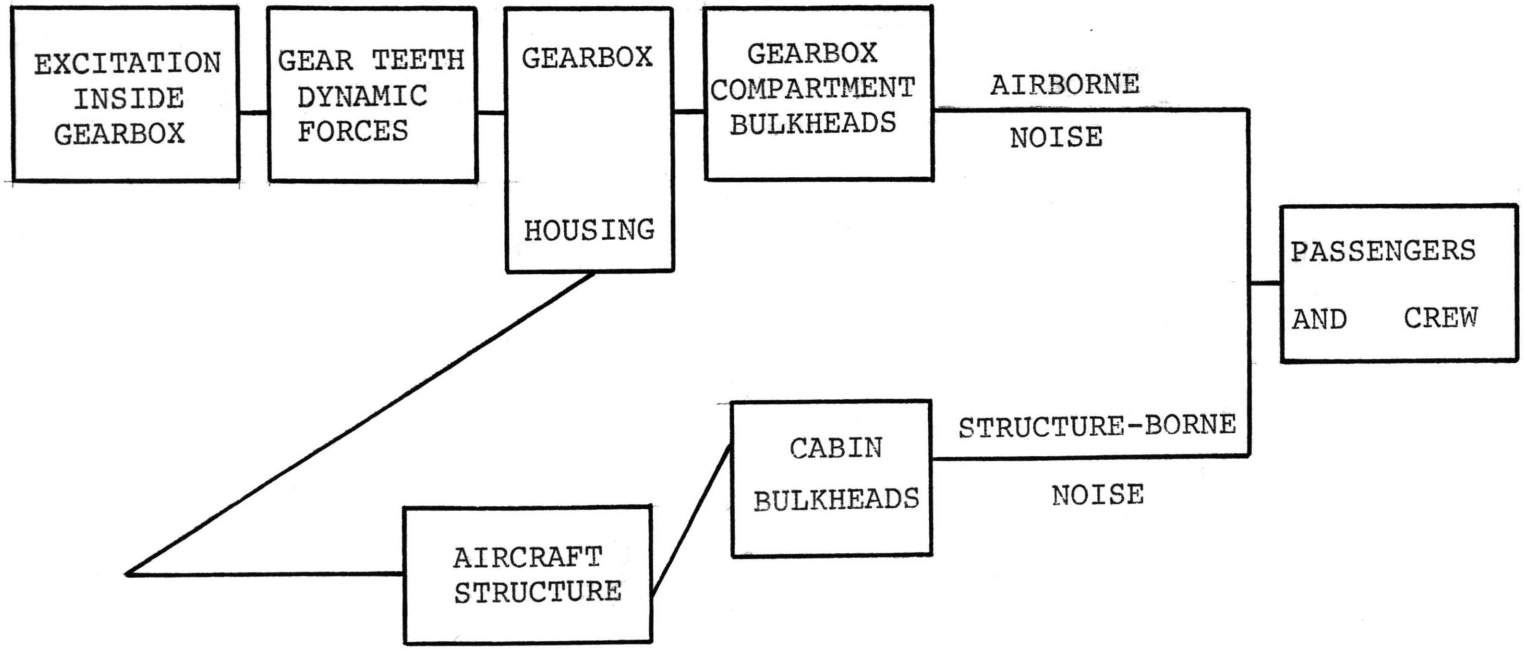


Figure 6. Transmission of helicopter gearbox noise.

a. Tooth meshing errors.
b. Natural resonances.
c. Bearing imperfections.
d. Windage.
e. Sounds of auxiliary equipment such as lubrication systems.

Tooth mesh and mesh-related frequencies are often the predominant noises in a gear unit. Another major source of noise generated by gear units is a result of various natural resonances. These resonances cause excessive vibration, noise, and/or wear if they coincide, or lie near to one of the prime operating frequencies.

It might be expected that the noise generated by a pair of gears would be composed of a very strong component at the tooth contact (T.C.) frequency and that any other noise would be of secondary importance. Berry[30] found that gear noise is distributed over a wide spectrum and that there may be strong contributions to the overall noise at frequencies well above that of tooth contact. For example, the noise at twice the tooth contact (2 x T.C.) frequency is often found to be more intense than that at the T.C. frequency. Figure 7 shows a 1/3 octave analysis of helical involute gear noise with the gears running at two speeds, 1000 rpm and 4000 rpm. This figure shows that the noise level at 4000 rpm is larger at twice the tooth contact (2 x T.C.) frequency than that at the tooth contact (T.C.) frequency.

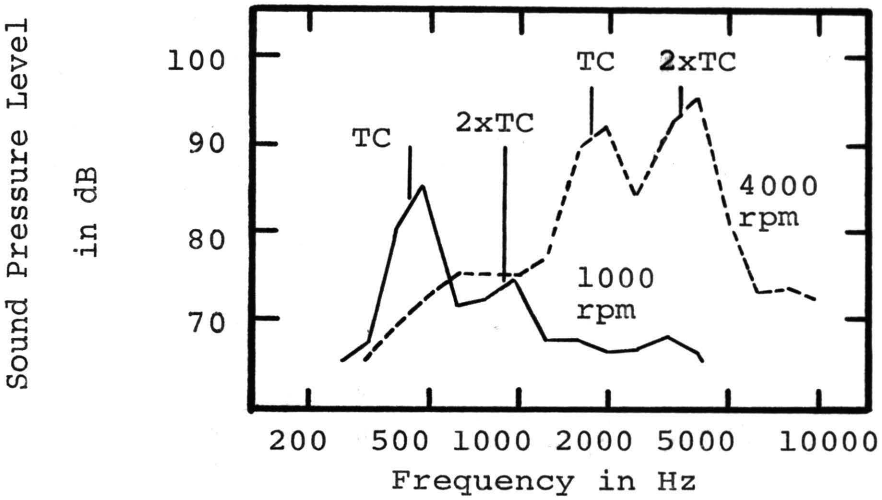


Figure 7.[30] 1/3 Octave analysis of involute gear noise.

Berry[30] also reports on the effect loading may have on noise levels of gears operating at various rotational speeds. Table 2 shows the magnitude in decibels of the two major noise components located at the T.C. frequency and at 2 x T.C. frequency. These magnitudes are displayed at two speeds, 1000 rpm and 4000 rpm, at various degrees of loading, 44 to 1408 in-lb, and for three different gear assemblies, type A, B, and a rubber assembly. This table indicates that at lower speeds, the noise in the tooth contact (T.C.) frequency region increases with loading but at higher speeds the noise decreases with an applied load. The noise at twice the T.C. frequency decreases with an increase in load at higher speeds.

King[31] investigated additional effects on the overall noise in gears. He points out that rolling and sliding metal-to-metal surface contact, with neither surface perfectly smooth or geometrically correct, is the mechanical reason for

Table 2. Effects of gear loading on noise levels*

Gear Assembly	Loading in-lb	Sound Pressure Level in Decibels 1000 rpm T.C.	1000 rpm 2xT.C.	4000 rpm T.C.	4000 rpm 2xT.C.
A	44	79.0	76.5	98.5	99.5
	176	77.0	78.0	98.5	97.5
	352	86.0	76.5	93.5	96.5
	704	88.5	77.5	92.5	91.0
	1408	91.0	74.5	92.5	86.5
B	44	75.0	75.5	92.0	90.0
	176	75.0	75.5	93.0	90.0
	352	76.5	75.5	93.0	91.0
	704	77.5	77.0	91.5	89.0
	1408	85.0	74.0	86.5	83.5
RUBBER		69.5	71.0	--	--

*Adapted from a paper by Berry[30].

gear noise. He also stated that the probable physical cause of gear noise is directly related to the required inflexibility of the gear teeth.

Gasaway[3] lists a few of the major types of gears that contribute to the noise generated by rotary-wing aircraft:

a. Bevel gears.

b. Worm gears.

c. Planetary and sun gears.

Bevel gears are used as shaft distribution units where the torque-distribution shaft must distribute power to the tail or antitorque rotors. Hatfield[32] and Gasaway[33] add that bevel gears usually operate at high speeds and the noise pattern they generate is directly influenced by the number of gear teeth impacting and meshing. Gasaway[3] further explains that worm gears are commonly used in the extension and retraction of landing gears, flaps, or spoilers. Worm gears normally operate at relatively slow speeds and the noise pattern generated is associated with gear-meshing and possibly the electric motor used to furnish torque to the worm gears. Planetary gear systems are used in gear-reduction units for both rotor and propeller systems and usually consists of pinion or spur-reduction gearing, or both. Specific design of helicopter gearing types are covered in Badgley, et al[27].

Hatfield[32], Gasaway[33], Cox and Lynn[34] add the fact that the housings for these transmission systems contain a complex mixture of noise generating components because of the variety of gear types, sizes, and rotational function. Gasaway[35] reports that gear assemblies used in most systems require a gear housing or gear box. The gear box serves to support entrance and exit shafts, to confine and retain lubricants, and to provide a noise and vibration shield against internally generated noises.

Gasaway[26] draws attention to other noise generating mechanisms in rotary-wing aircraft such as torque-distribution shafts, bearings, bearing supports, couplings, and secondary shaft distribution units. Power distribution shafts and related shaft-restraining devices usually generate high frequency components which are directly related to the shaft rotational speed.

5. Ball-bearing, Electric Motor, and Combustion Noise

Berry[30] describes the spectrum of ball-bearing noise as highly complex, consisting of distributed noise together with many discrete components. The main noise content, at normal running speeds of the bearings, occurs at frequencies above 800 Hz, that is, well above the shaft and ball rotational frequencies. Gasaway[3] confirms that higher frequency noise is related to torque, bearing, and support friction as well as the power-shaft rotational speed.

Berry[30] also reports that one of the main parameters of a ball-bearing is its diametrical clearance and that this is often regarded as having a major effect on noise. But he observes that diametrical clearance is of minor importance at all but the lowest speeds, as indicated in Figure 8.

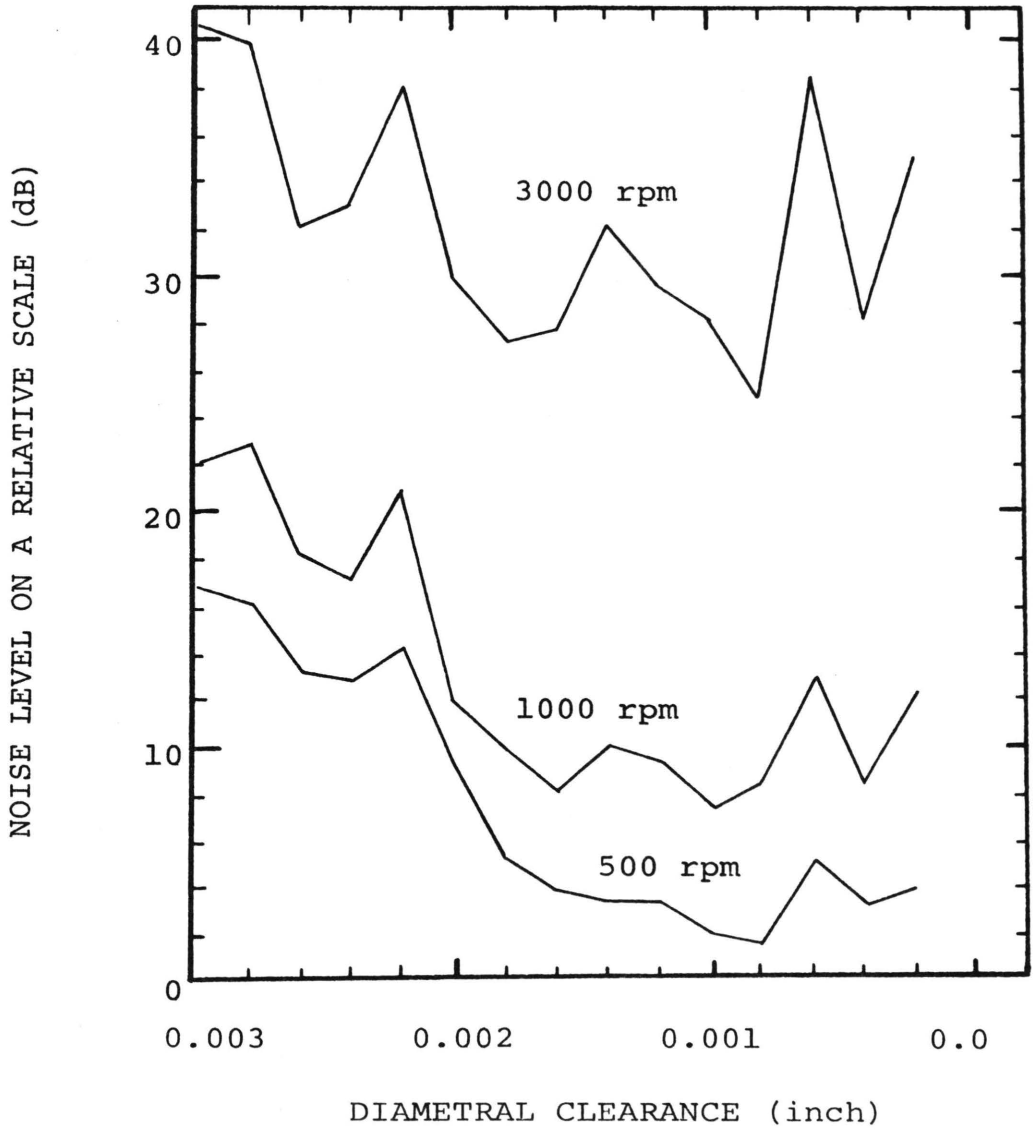


Figure 8. Variation of ball-bearing noise for various speeds and diametral clearance

Table 3, adapted from King[31], shows a frequency analysis of noise of ball-bearings at two speeds, 500 rpm and 1000 rpm. The greatest single factor contributing to bearing noise is the departure from sphericity of the bearing balls. A closer tolerance such that errors are in the range 2.5×10^{-6} inch to 5×10^{-6} inch may be specified in order to keep the range of noise levels within acceptable limits. Another source of noise is that caused by a ripple superimposed on an otherwise circular or lobed track. The effect of an error of this type was found to be of the order of 4 to 6 db in the case of outer races, and 2 to 4 db in the case of inner races, both over the frequency range from about 800 to 2500 Hz.

Gasaway[26] reports that noise generated by electric motors and dynamotors is of little magnitude significance but may be quite annoying, especially in the mid-frequency region, because of the presence of narrow-band components. Almost all high-speed electric motors generate a noise which contains discrete components of a distinct shape but which is not generally evident at most occupied areas within a helicopter.

Helderbrand and Tedrich[22] describe combustion noise and "singing flames", a type of combustion noise. Singing flames generate only discrete tones due to the resonance between the vibration of the flame on its burner with that of the surrounding enclosure. The production of noise by combustion flames is not limited to the singing flames only. Combustion noises seem to be related to every little irregularity in and around the flame since a steadily burning flame, such as that in a

Table 3. Frequency analysis of ball-bearing noise.*

Frequency Hz	Sound Pressure Levels in dB 500 rpm	1000 rpm
157	44	--
205	50	47
275	--	46
306	44	51
322	--	53
450	52	70
775	53	50
850	47	64
940	--	62
1170	40	--
1220	--	51
1280	--	47
1530	40	53
1840	--	63
2140	39	49
2640	37	--
2720	--	49
3600	--	63

*Diametral clearance = 0.015 inch; grease lubrication; microphone at 1 meter.

gas turbine engine, makes practically no noise. Turbulence, unsteady burning, local expansion and explosion, and aerothermal coupling can all be termed noise-generating mechanisms caused by flow non-uniformity.

6. Metal Panels and Soundproofing

This section deals with basic physical and mechanical properties of selected materials and structures with most of the emphasis on aluminum panels and a phenomena termed acoustic "transmission loss". Transmission loss (TL) is defined by Franken, et al[35] as being more-or-less basic property of a panel and, therefore, a TL may be specified for a panel independent of the application. TL is not a natural phenomenom but rather a mathematical description of how well a panel blocks sound.

Richards and Mead[36] state that a finite panel can transmit several different wave motions:

- a. Longitudinal (compressional) waves.
- b. Flexural (bending) waves.
- c. Transverse (shear) waves.
- d. Torsional (twist) waves.
- e. Rayleigh (surface) waves.

The most important type from the acoustic point of view is the flexural wave motion, associated with relatively large transverse displacements and which is easily excited by sound waves in the air. Ver and Holmer[37] note that wave motion in finite panels is different from wave motion in infinite panels because of the presence of edges which produce reflected waves. Interaction between these incident and reflected traveling bending waves produce standing-wave patterns, resulting in previously mentioned transverse panel motions of large amplitude.

Ver and Holmer[37] also observe that the vibrational behavior of finite-sized plates is a logical extension of the theory of infinite plates where the same radially-spreading waves encounter the boundaries of the plate, thereby reflecting a part of the energy. The reflection process builds a reverberant field which may be considered as separate from the direct wave motion. If the plate is lightly damped, as in aluminum, and the power loss across the plate boundaries is small, the vibration field of the plate is dominated by this reverberant field. The only exception in helicopters is in the immediate vicinity of the engine, gears, and rotor where the direct field is dominant.

Richards, Mead[36], Ver and Holmer[37] agree that it is not sufficient to limit the discussion to simple aluminum panels. The use of windows and the installation of thermal acoustic insulating blankets on the helicopter interior requires the consideration of sound transmission through composite panels. Ver and Holmer[37] specifically investigated the sound power transmitted through a composite barrier and developed an equation for the transmission loss of the composite:

$$TL_c = 10 \log \frac{S_1+S_2}{\tau_1 S_1+\tau_2 S_2} .$$

Figure 9 shows the transmission loss of a two-element composite

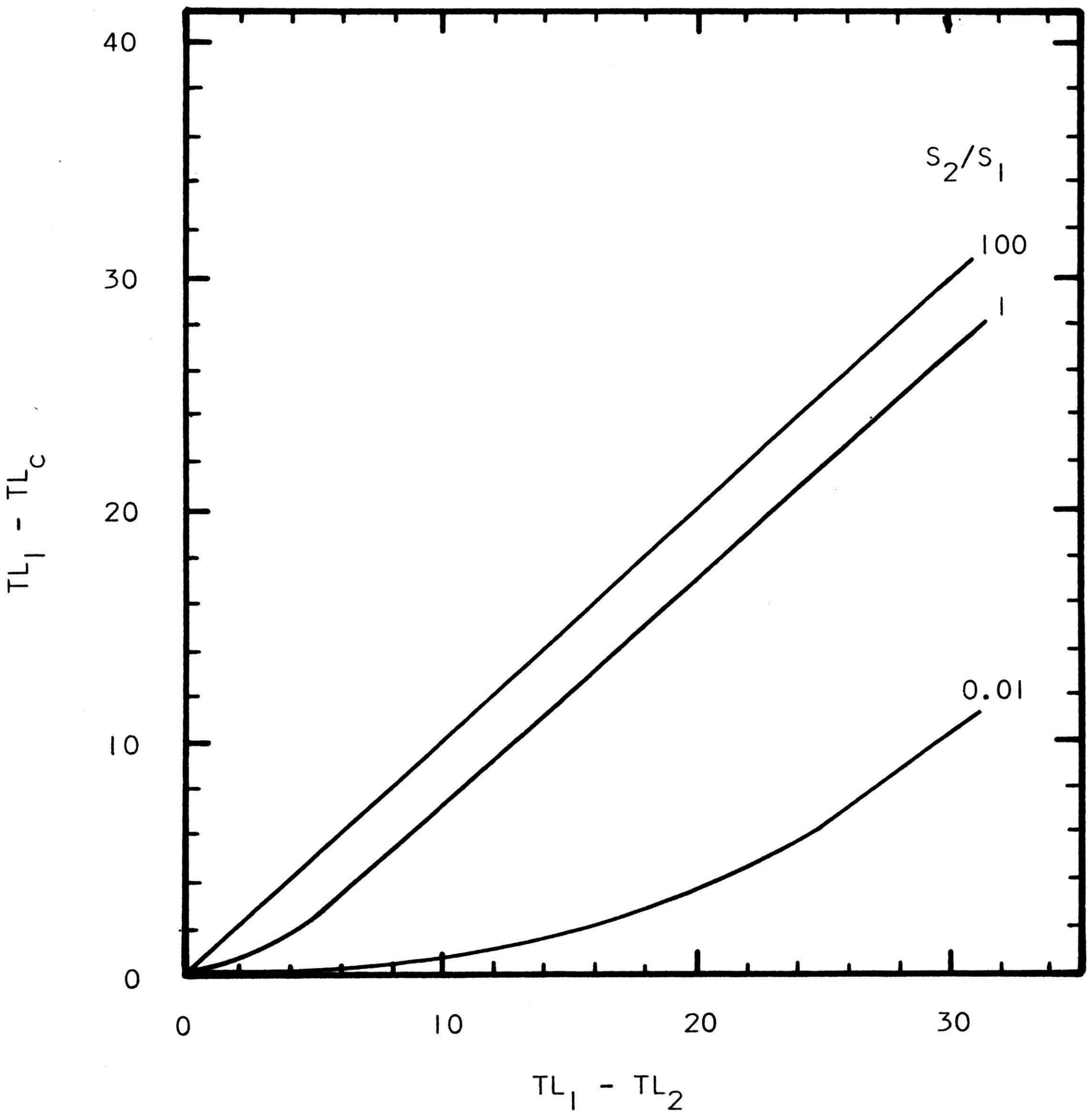


Figure 9. Transmission loss of a two-element composite barrier such as a window installed in an aluminum panel

barrier, such as a window in an aircraft fuselage, as a function of the relative transmission loss of the components. Wood[7] states that double glazing of windows adds greatly to the insulation efficiency, especially if there is a heavy mounting and a reasonable air space. Table 4 lists transmission losses for selected panel materials of sizes usually found in aircraft and including both single and double glazed windows.

Ver and Holmer[37] explains that a porous material, such as an acoustic blanket used as a sound insulating layer, attenuates a sound wave partly by converting acoustic energy of the sound that penetrates the material to heat by means of internal-damping effects and partly by acting as a reflective surface. AAVSCOM[41] reported that the soundproofing blanket used in the UH-1D/H helicopters is a quilted blanket consisting of materials conforming to MIL SPEC MIL-I-7171[42], Type I, Figure 2, and 1/2 inch in thickness. The construction is essentially a chopped fiberglass core with vinyl coated textile facing on both sides. Eyelets are provided for attaching the blankets to the walls and the ceiling of the cabin interior. Cut-outs are provided for protruding cargo tie-down hooks and other necessary equipment and hardware located on the helicopter bulkheads and ceiling. Ver and Holmer[37] point out that the addition of a porous blanket is practically useless for increasing sound attenuation at low frequencies but can be very efficient at high frequencies. The vibratory motion of an aluminum panel will

Table 4.

Transmission loss of selected panel materials at 500 Hz.*

Panel Construction	Thickness in.	Density lb/ft^2	Transmission Loss dB
21 oz glass			
sngl glaz	0.0937	1.3	27
dble glaz 1 in. air	1.1875	2.6	42
1/2 in. air	0.6875	2.6	36
1/4 in. air	0.4375	2.6	32
1/8 in. air	0.3125	2.6	27
5'x6.5' Alum	0.1250	1.0	27
Alum Airc Skin	0.0500	NA**	25
18 gauge steel & channel frame	0.0478	2.0	30
Plexiglas***	0.1250	NA	24
Plexiglas	0.2500	NA	29
Safety glass	0.2850	NA	33
Glass	0.2500	3.0	31
Gypsum wallboard	1.0000	4.5	31

*Adapted from Wood[7], Ver and Holmer[37], Lead Industries Association[38], Nordby[39], and Kinsler-Frey[40].

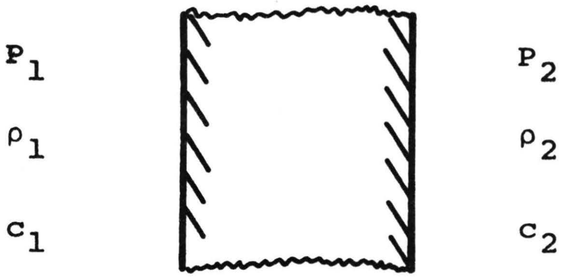
**Not available

***Registered trademark, Rohm and Haas Co., Philadelphia, Pa.

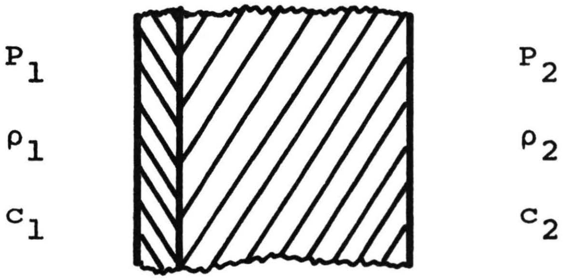
be unaffected by the addition of a lightweight blanket adjacent, but not bonded, to it.

Sweers[43] describes a panel construction with high acoustic resistance against fatigue, the honeycomb core sandwich panel. Figure 10 shows a cross-sectional comparison between the basic types of panel arrangements. Two additional advantages of the sandwich panels are the inherent lightness and the fact that this type of panel does not require heavy outer skins. Jackson[44] confirms the high stiffness-to-mass ratio possible through the use of the honeycomb sandwich panel. He also observes a transmission loss of 20 to 30 dB at frequencies below 100 Hz. Additional data on sandwich construction using a rigid polyurethane foam core is contained in the investigation by Ford, Lord, and Walker[45].

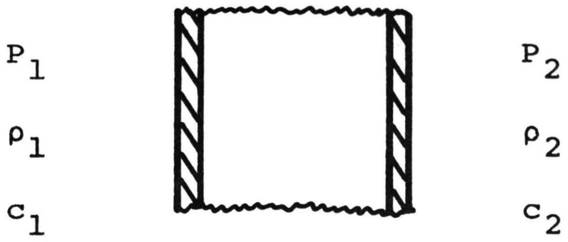
Transmission loss (TL) is covered in more detail including a simple summary to estimate the TL of a panel in the investigation conducted by Franken, et al[35]. Ver and Holmer[37] recall that the transmission loss afforded by a panel and a thermal acoustic blanket may be negated by another acoustic phenomenon termed "flanking transmission". This can occur because of air holes in the panel, gaps around the perimeter of the panel, or other openings in the helicopter cabin. Flanking-transmission paths must be eliminated or reduced to a minimum. Franken, et al[35] reports that in aircraft structures, it is practically impossible to eliminate all flanking paths. As a result, the TL of most aircraft structures, including many double-wall fuselages and accepting the weight penalty, is limited to a maximum value of from 50 to 60 dB.



a. Simple aluminum panel.



b. Acoustic blanket freely-hung against panel.



c. Sandwich panel construction.

Figure 10. Typical panel and soundproofing arrangements.

B. Noise and Hearing

Gasaway[46] reports that helicopter internal noise is increasingly being recognized as one of the major problems which must be overcome if helicopters are to be a safe and comfortable mode of transportation in the future. Apparently internal noise levels have not always been previously considered. However, there is an increasing concern for the legal aspects of hearing damage to both passengers and crew in helicopters. Additionally, an Army Material Command report[47] states that the records of the Veterans Administration (VA) list well over 50,000 veterans who indicate loss of hearing as a primary disability. The same report estimates the annual cost to VA for compensation, hearing aids, batteries, and repairs is over $36 million and that the cost is increasing at the rate of $3.5 million per year. The nature and extent of the problem are seen when present noise levels are compared with existing and proposed noise specifications. That noise can and does cause hearing loss among persons who are routinely exposed to excessive levels of noise is evidenced by the growth of state, industrial, and national safety regulations.

Tobias[48] confirms that there is a hearing loss problem when he states that audiological experience suggests that pilots have hearing losses, but that the degree of hearing loss is not adequately established by Federal Aviation Administration (FAA) records. However, some work has been done on the actual measurement of pilot hearing loss. It should be noted that pilots and crew usually wear ear protection while passengers do not during exposure to noise in helicopters. Table 5, adapted from Fletcher[49], illustrates a study on hearing loss for 8 rotary-wing pilots with from 575 to 3733 hours of flight time accumulated. In addition to pilots, Weissenburger[50] points out the scope of the hearing problem and its applicability to almost all phases of life in the United States. Table 6 shows the possible target population for noise conditions which are hazardous to hearing. Figure 11 shows an even further distribution of sound levels in the manufacturing category. Ingard[51] states that it has been estimated that the average acoustic noise power output in the United States is increasing at the rate of approximately 25% per year.

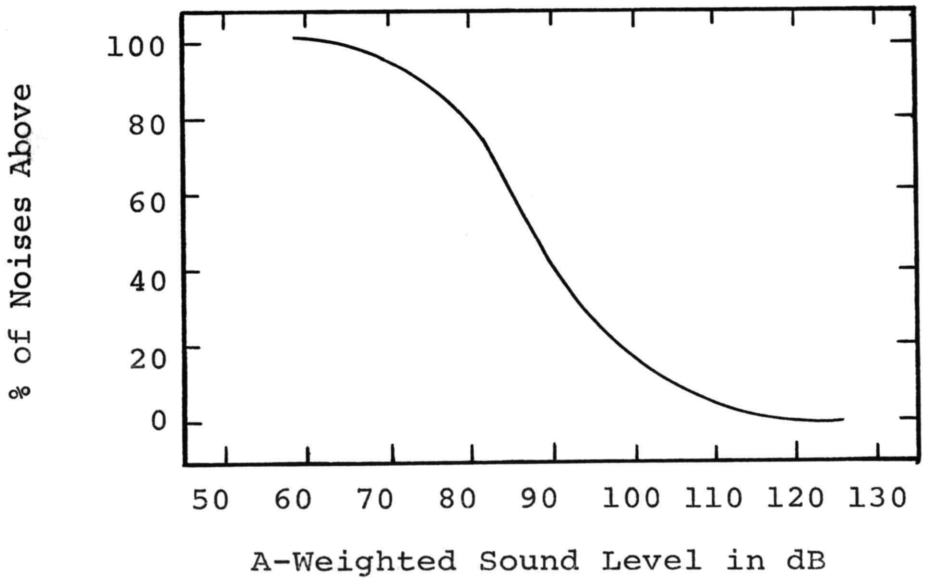


Figure 11.[50] Distribution of sound levels in manufacturing.

Table 5. Hearing loss for 8 rotary-wing pilots.

Frequency Hq	Hearing Loss in dB Right Ear	Left Ear
500	12	12
1000	8	10
2000	2	10
3000	15	23
4000	12	22
6000	24	27
8000	1	3
9000	5	12
10,000	9	17
11,000	15	15
12,000	27	20
13,000	20	25
14,000	25	28
15,000	33	30
16,000	48	45
18,000	56	55

Table 6. Potential target population for hazardous noise.

Industry	Number of Production Workers
Mining	549,261
Construction	1,301,969
Manufacturing	9,412,768
Transportation	1,133,113
Farming (mechanized farms only)	4,815,000
Grand Total	17,212,311

Littler[52] describes a recent assessment of presbycusis, the type of hearing loss associated with age, and he states that this type of hearing loss in normal females is not significantly different from that in normal males up to the age of 54 years. Table 7 summarizes hearing loss data from Littler[52] on presbycusis from a random sample population and from Gatley[53] on hearing loss in men caused by noise exposure in a 90 decibel environment, both using age 20 as the zero point.

There are two main results of excessive noise which affect the human ear, permanent threshold shift (PTS) and temporary threshold shift (TTS). Permanent hearing loss has been discussed previously with appropriate examples of this type of loss. Luz and Hodge[54] define temporary threshold shift simply as the difference in the threshold of audibility measured before and after exposure to sounds. They further expound that TTS is known to recover as a linear function of the logarithm of time when TTS is induced by exposure to continuous noise. Ingard[51] adds that TTS affects the ear by causing the hearing threshold to deteriorate such that a larger value in decibels is required to make the ear respond. The hearing threshold returns to normal after a rest period. Wood[55] explains a study conducted to determine distances at which spoken numbers may be heard, with a 50% accuracy, by persons with various hearing losses. Table 8 summarizes selected data from this study. It should be noted that the investigation was conducted in a place without reflections.

Table 7. Permanent hearing loss.

Frequency Hz	Age Years	Exposure Time Years	Hearing Loss in dB Presbycusis	Hearing Loss in dB Noise Exposure
500	20	0	0	0
	30	10	2	3
	40	20	3	5
	50	30	4	9
	60	40	7	18
1000	20	0	0	0
	30	10	2	3
	40	20	3	5
	50	30	6	9
	60	40	9	18
2000	20	0	0	0
	30	10	3	6
	40	20	4	14
	50	30	7	20
	60	40	10	26
4000	20	0	0	6
	30	10	3	35
	40	20	7	49
	50	30	11	50
	60	40	17	50

Table 8. Maximum distances to detect spoken numbers.

Hearing Loss in dB	Distance from the Source in feet Average Whisper	Quiet Voice	Med Loud Voice
0	39.5	222	1250
5	22.2	125	704
10	12.5	70	395
15	7.0	39.5	222
20	4.0	22.2	125
25	2.2	12.5	70
30	1.25	7.0	39.5
35	0.70	4.0	22.2
40	0.40	2.2	12.5
45	0.22	1.25	7.0
50	0.12	0.70	4.0
120	Totally	deaf	

There are many factors that make it difficult to obtain accurate information about the degree of hazard and to specify a damage-risk criteria involving a helicopter noise environment. Albers[56] found that intermittent noise is much less serious in producing TTS than is continuous noise. Low-frequency noise is less likely to produce TTS than high-frequency noise of the same dB-level. Noise exposure which results in an appreciable shift in hearing is not acceptable. This thesis investigation is concerned with the effect of TTS on combat troops riding as passengers, without ear protection, in helicopters and then disembarking from the noisy helicopter environment into the relative quiet of a jungle landing zone. Table 9 summarizes data from Barry, Magliozzi, Standard[6], Hand, McLaughlin[57], Morland, Garinther, and Sova[58] illustrating jungle acoustic properties. The data is presented for the frequencies from 63 through 4000 HZ.

Ingard[51] observes that the specific effects of noise on man that are relevant to noise control are hearing damage and various annoyance aspects. Basic research on hearing is still going on and the exact hearing mechanism of hearing damage is only partly understood. Various studies have been made to specify the specific limits of audibility in decibels for most of the population. Wood[7] cautions that these limits vary greatly for different observers. Table 10 shows a compilation of both low and high frequency audible limits.

Table 9. Aural detectability in a jungle environment.

	Noise Levels in dB				
Frequency Hz	Ref 6 Daytime	(Ambient) Nighttime	Ref 57 Daytime	(Ambient) Nighttime	Ref 58 (Criteria)
63	37	35.3			
80	34	32			
100	33.5	30	20	12	
125	34.5	29	21	13	38
160	35.5	29.5	21	12	
200	36.5	29.5	22	13	
250	37.5	30.5	22	14	22
315	38.5	31.5	21	16	
400	39	32.5	21	16	
500	39.5	33	23	19	13
625	39.5	32.5	23	19	
800	39	32.5	22	20	
1000	38.5	33.5	27	28	6
1250	38	37			
1600	38	42			
2000	39	47.5			6
2500	41	53.5			
3150	44	59			
4000	47	63			12

Table 10. Minimum audible sound-pressure levels.

Frequency	Ref #59	Ref #6		Ref #58	Ref #60	
Hz	M*	M	B**		1951 ASA	1963 ISO
1.5	132.3					
10	104.1					
20	89.5			70		
25	83.0		64			
30			59			
50	58.6		43	52		
80		43				
100	42.5		25	38		
125					54.5	45.5
200		30	14	25		
250		18			39.5	24.5
500		13	4	10	25	11.0
1000		10	3	0	16.5	6.5
1500						6.5
2000				-4	17	8.5
3000						7.5
4000					15	9.0

*Monoaural

**Binaural

C. Noise Reduction Procedure

Ingard[51] divides noise reduction into two main areas, (i) analysis of the noise exposure, and, (ii) the actual noise reduction effort. Under analysis, he includes direct measurement of the noise spectra, an investigation of the transmission paths, and finally the calculation of noise exposure. The second area is tailored to the specific problem area uncovered during the analysis phase. Beranek[61] organizes noise control a little differently as follows:

a. Direct noise measurement.
b. Investigation of directivity pattern.
c. Study of transmission path characteristics.
d. Determination of appropriate criteria.
e. Calculation of amount of noise reduction required.

Noise control of the source in the design stage is often the most effective and least expensive of the control measures. Beranek[61] confirms that noise reduction of the source, either by redesign or modification, is preferable to changing the characteristics of the various transmission paths or by trying to attenuate the noise levels at the observer. Ingard[51] agrees with these two procedures and adds another, that of generating a new source completely out-of-phase with the original source to make use of acoustic "cancellation". This last concept is not practical for use in helicopters because of the excessive equipment weight required to produce the cancellation effect.

D. Helicopter Noise Criteria

There is no one noise criteria established for use both inside and outside of helicopters. When queried by this author, the Environmental Protection Agency (EPA)[62] stated that they had recently completed a comprehensive study of the noise problem primarily concerning environmental noise. The EPA also stated that it has not issued any regulations restricting noise levels inside helicopters as these levels are covered primarily under occupational hazard criteria specified in the 1969 Walsh-Healy Act[63]. The Occupational Safety and Health Act of 1970 (OSHA)[64] adopted the Walsh-Healy standards for permissible exposure times to certain noise levels expressed in A-weighted decibels for those companies engaged in interstate commerce. Figure 12 illustrates the permissible dBA values for certain durations.

Figure 12. Permissible noise exposure.

Duration Hrs./Day	dBA
8	90
6	92
4	95
3	97
2	100
1.5	102
1.0	105
0.5	110
0.25	115

It should be noted that a computation of the total daily exposure of noise for any one individual must take into account the sum of the individual contributions at each dBA level.

The military service has various standards, termed "military standards" or "design notes", which act as the framework for future design efforts. Table 12 shows maximum decibel standards set by various military and non-military documents and organizations.

For the purpose of this investigation the flat, and in some cases the C weighting, networks are used for the correlation of total noise with its sources. The A-weighting network is used to show the effect of interior noise on individuals and to propose noise reduction materials and procedures to lower excessive values to within the appropriate criteria. Gasaway[65] assessed the value of the A-weighted network as auditory criteria and found that this weighting, electronically most like the ear's response to sound, may eventually replace other currently accepted criteria which employ octave-band measurements. Gasaway and Sutherland[70] list, as organizations which have adopted the A-weighted network as a primary criteria, the U. S. Department of Labor, the American Conference of Government Industrial Hygienists, the American National Standards Institute, and the American Speech and Hearing Association. Also, one of the reasons for widespread adoption of dBA is its relative simplicity compared to other noise criteria. It does not require an acoustician to use it.

Table 11. Criteria for maximum octave-band noise levels.

	Military Standards			Non-Military Standards	
Frequency Hz	HEL Std S-1-63B*	MIl Spec A-8806a**	TB 251***	WH 90 dB Contour+	CHABA WG 46‡
63	120	104	--	--	--
125	115	104	--	105	--
250	110	104	92	96	92
500	102	96	85	91	89
1000	94	90	85	87	86
2000	89	86	85	85	84.5
4000	89	75	85	85	84
8000	92	75	85	87	85.5

*Human Engineering Laboratory Standard[66]

**Military Specification[67]

***Technical Bulletin[68]

+Walsh-Healy Act[63]

‡Working Group 46[69] of the National Academy of Sciences Research Council Committee on Hearing, Biacoustics, and Biomechanics (CHABA)

III. EXPERIMENTAL

A. Test Program

In this work, the total interior helicopter noise was correlated to separate noise sources through a comparison of the various frequency spectra of the total interior noise with those of the individual noise sources. These shapes were analyzed in the laboratory from data obtained with a microphone, sound-level meter, vibration meter, and tape recorder during three UH-1H flights and one OH-6A flight. The flights were made courtesy of the U. S. Army and involved the execution of various flight maneuvers such as hover, steady climb, level flight, descent. Selected measurements were also made while on the ground. Noise surveys were also taken during various flight maneuvers to illustrate the distribution of the sound field within the helicopter cabin. All acoustic data was measured in decibels referenced to a pressure of 0.0002 microbar. An attempt was also made to correlate a selected source vibration spectra to its contribution to the total cabin noise spectra but there was not enough data procured to substantiate the results.

Richards and Mead[36] investigated the problems inherent in the calculation of noise levels in aircraft cabins and found that interior cabin noise in low-speed aircraft depends mainly on noise radiated by external sources. They describe a procedure to estimate average internal noise levels but this procedure depends upon knowing the transmission characteristics of the aircraft skin and soundproofing. While estimates are theoretically available, these characteristics are not known in practice and a crude estimate is made using a simple theory based on the mass law. For the purpose of this study, the interior noise was typified by a representative plot of one of the three flights for any particular maneuver with no attempt at the calculation of numerical deviation or correlation coefficients.

B. Equipment and Instrumentation

1. UH-1H Utility Helicopter, "Huey"

The UH-1H Bell helicopter* is a thirteen-place all-metal helicopter with one main two-bladed rotor and a tail rotor and powered by a gas turbine engine. The basic mission of the UH-1H is mainly that of a utility aircraft with design features which permit transportation of personnel, litter patients, or cargo and which permit other liason-type flight operations. The fuselage consists of two main sections, the forward or cabin section and the aft or tail boom section as shown in Figure 13.

The forward fuselage section consists primarily of two longitudinal beams with transverse bulkheads and metal

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*General description and helicopter diagrams adapted from TM 55-1520-210-34[71].

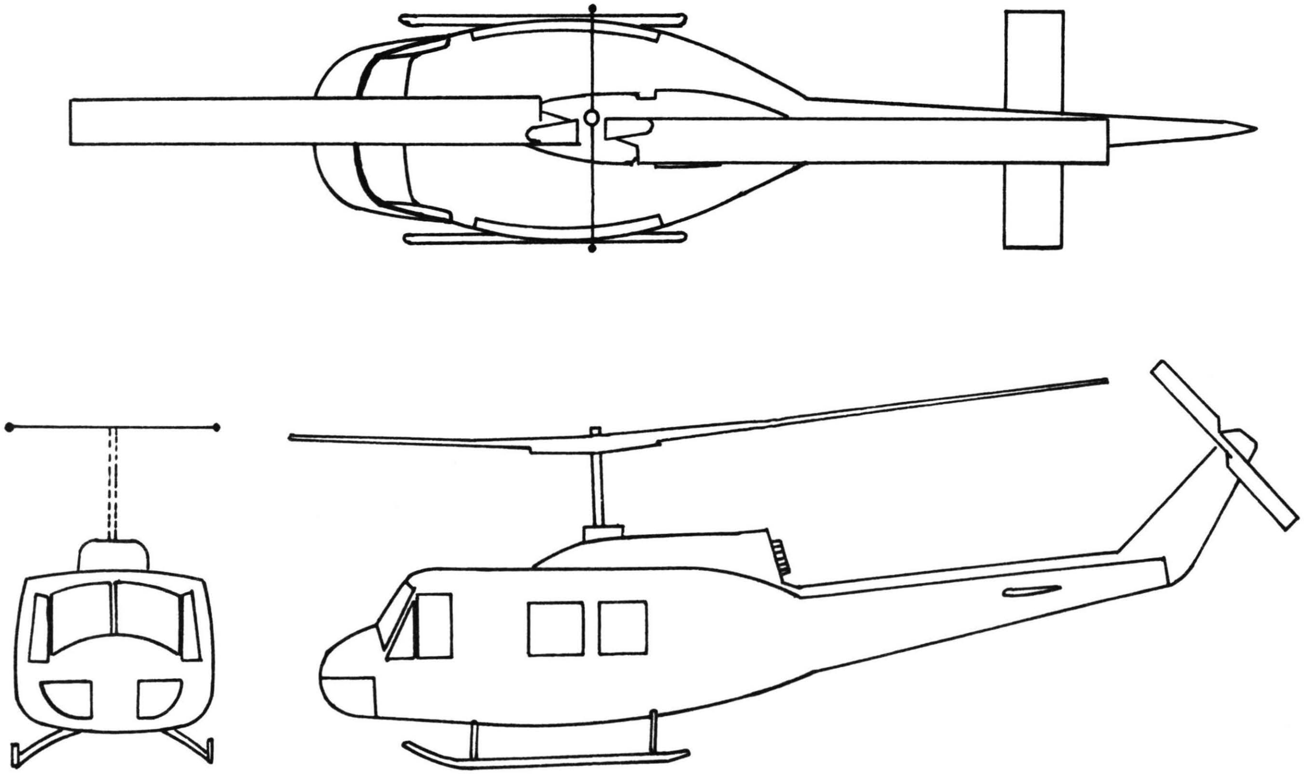
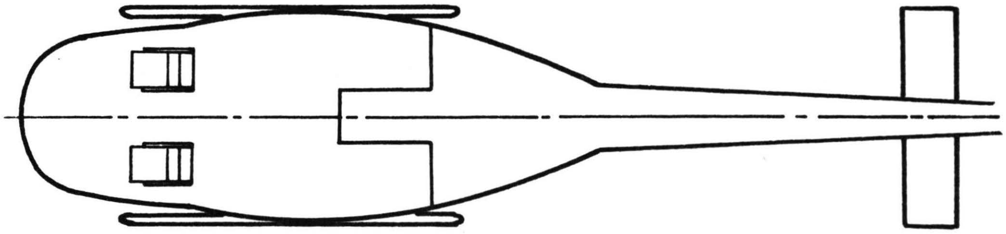


Figure 13. UH-1H helicopter

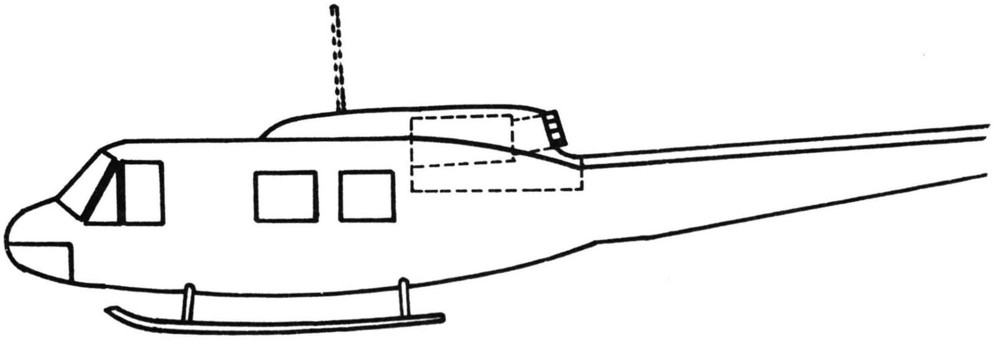
covering. The beams provide the supporting structure for the cabin section, landing gear, fuel tanks, transmission, engine, and tail boom. The rear of the tail boom supports the tail rotor, vertical fin, and the synchronized elevator. The landing gear is of the skid type, attached to the fuselage at four points. The cabin area contains a large floor area aft of the pilot and co-pilot of approximately 220 cubic feet for normal cargo or personnel as illustrated in Figure 13.

The UH-1H helicopter is equipped with the Lycoming T-53-L-13 gas turbine engine rated at 1250 hp but torque-limited by the pilot to 1100 hp. The engine, along with its accessories and drive system, is mounted aft of the cabin and above the fuselage on a platform deck as shown in Figure 14. The engine and drive system are enclosed by a cowling which may be opened or removed quickly to allow maximum accessability for servicing and extended maintenance.

Maslennikov, et al[72] report that the T-53 turbine engine makes use of the axial-centrifugal compressor with a subsonic multistage axial part and a reverse-flow evaporative type of annular combustion chamber, installed around axial turbines. The compressor and free turbine revolve in opposite directions, making it possible to eliminate the nozzle box before the first stage of the free turbine. Power from the free turbine is transferred forward through the hollow shaft of the rotor of the turbocompressor, which with reduction gears, provides universal utilization of the



a. Top view of interior layout



b. Side view showing engine mounting and rotor positioning

Figure 14. UH-1H design features.

engine. The free-power part of the turbine engine eliminates the need for a clutch and provides free, smooth, and trouble-free engagement of the helicopter's rotor.

The helicopter transmission is mounted forward of the engine and coupled to the power turbine shaft at the cool end of the engine by means of a short drive shaft. The transmission is basically a reduction gearbox functioning to transmit engine power at a reduced shaft rpm to the main rotor and the tail rotor. The transmission incorporates a freewheeling unit at the input drive and a two-stage planetary gear train. The tail rotor is powered by a take-off on the aft section of the transmission.

The rotor system consists of a main rotor, antitorque tail rotor, and a rotor system indicator. The main rotor is a two-bladed, semi-rigid, see-saw type powered from the two-stage planetary transmission. The tail rotor is a two-bladed, semi-rigid hinged type powered from the take-off at the lower end of the main rotor transmission.

2. OH-6A Observation Helicopter, "Cayuse"

The OH-6A Hughes helicopter* is a four-place all-metal helicopter with one main rotor and one tail rotor powered by a gas turbine engine. The basic mission of the OH-6A is in the combat observation category but can be modified to carry cargo, armament, or personnel and may be used for target acquisition, reconnaissance, command, and control.

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*General description and diagrams adapted from TM 55-1520-214-10[73].

The fuselage consists of the forward or cabin area and the aft or tail boom section as illustrated in Figure 15.

The OH-6A helicopter is powered by an Allison T-63-A-5A gas turbine engine rated at 317 hp driving a four-bladed main rotor and a tail-mounted antitorque rotor through a two-stage speed reduction transmission. Maslennikov, et al[72] report that the T-63 is a free turbine turboshaft engine consisting of a multi-stage axial-centrifugal compressor, a single combustion chamber, a two-stage gas producer turbine, and a two-stage power turbine which supplies the output power of the engine. The T63 engine is made with an unusual structural arrangement, the basic power element of the engine is the gear box and the drive of the units located in the middle part of the engine. The shaft which connects the compressor with the compressor turbine passes inside the hollow shaft of the free turbine, the power of which is transferred through a reduction gear to output shaft, offset relative to the axis of the engine. Power take off from the reduction gear is possible both forward and at the back. The T63 engine is located aft of the cabin area as shown in Figure 16.

3. Acoustic Measurements

Testing was performed aboard military helicopters during various flight maneuvers and the subsequent data analysis was conducted in the acoustic laboratory of the University of Missouri - Rolla. The acoustic laboratory has frequency analysis equipment which yields a 1/3 or 1/10 octave-band

Figure 15, OH-6A helicopter

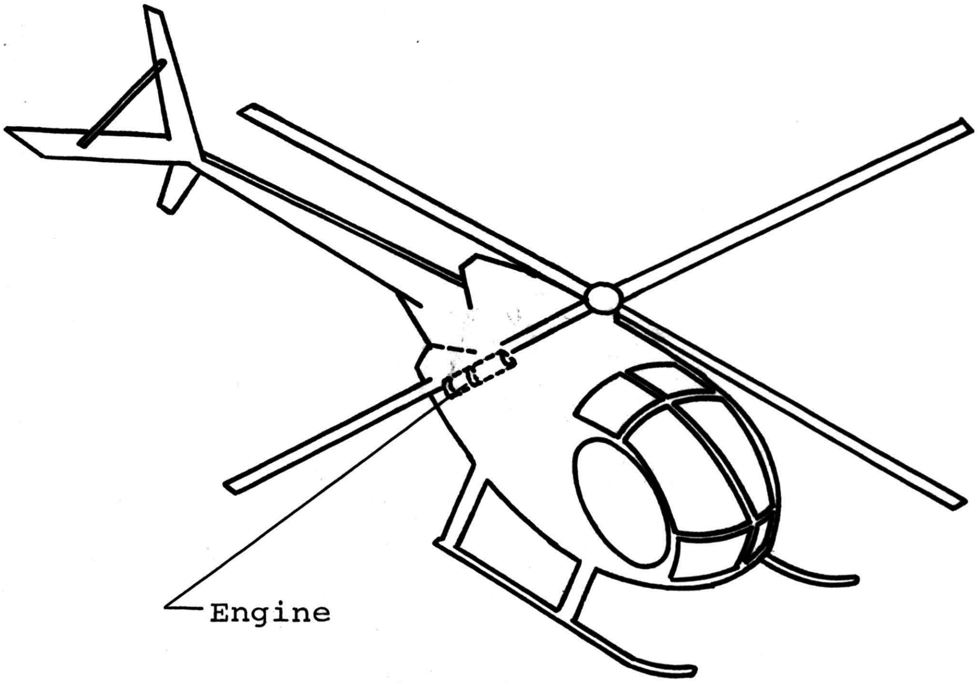


Figure 16[71]. OH-6A design features.

frequency spectrum. Additional available equipment includes a chart recorder to produce a permanent record and associated signal-monitoring devices such as a digital voltmeter and an oscilloscope.

Noise-level measurements were taken in helicopters with the doors closed and the soundproofing in place. All recorded data was subjected to 1/10 octave analysis after it was determined that a 1/3 octave-band analysis did not provide distinct peaks at certain frequencies. The 1/10 octave-band analysis was conducted for various flights on different days and similar maneuver spectrum analysis were compared. Examination of such data help to identify each source by comparison with known parameters of the dynamic systems, such as gear contact frequency and shaft rpm. To augment the 1/10 octave-band analysis, noise-level surveys were made using the different electrical weighting networks at sound level meters. Table 12 summarizes the characteristics of the three types of electrical weightings, at 1/3 octave-band frequencies, used in this study. At best, noise measurements on a moving vehicle are difficult. Transient conditions always present and exact environmental and geometric conditions are difficult to repeat but this has been minimized by measuring distances to the microphone position from known locations.

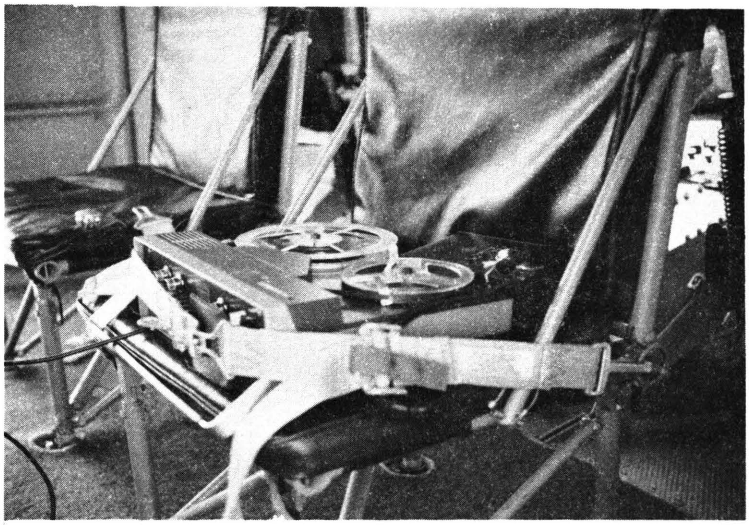
Some acoustic measurements are affected by atmospheric pressure, but a check of level flight sound-level measurement altitude of 2000 feet showed that the atmospheric correction was less than 1 dB at 2000 feet according to Peterson and Gross[74]. Peterson and Gross[74] also discuss the effects of an observer on measured data. During measurements in the UH-1H, the observer could place the sound level meter on the passenger seat and move away. But in the OH-6A, the observer could not get away from the meter but did stay out of the direct radiation from the main noise sources and the sound level meter. Figures 17 and 18 illustrate typical cabin locations of the sound level meter, tape recorder, and the accelerometer.

To accomplish a frequency shape comparison, one measurement was made within 6 inches of the turbine exhaust while

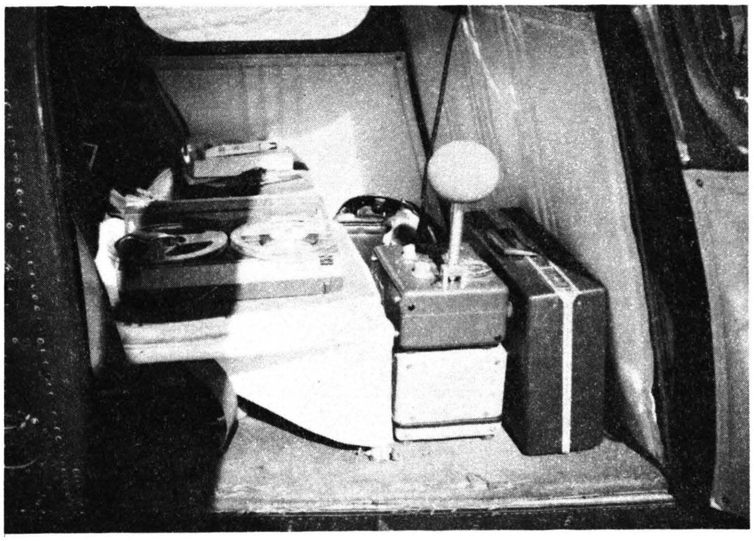
Table 12. A, C, and 20 KHz electrical weighting networks*.

Frequency Hz	A-Weighting dB	C-Weighting dB	20 Hz dB
10	-70.4	-14.3	0
12.5	-63.4	-11.2	0
16	-56.7	- 8.5	0
20	-50.5	- 6.2	0
25	-44.7	- 4.4	0
31.5	-39.4	- 3.0	0
40	-34.6	- 2.0	0
50	-30.2	- 1.3	0
63	-26.2	- 0.8	0
80	-22.5	- 0.5	0
100	-19.1	- 0.3	0
125	-16.1	- 0.2	0
160	-13.4	- 0.1	0
200	-10.9	0	0
250	- 8.6	0	0
315	- 6.6	0	0
400	- 4.8	0	0
500	- 3.2	0	0
630	- 1.9	0	0
800	- 0.8	0	0
1000	0	0	0
1250	+ 0.6	0	0
1600	+ 1.0	- 0.1	0
2000	+ 1.2	- 0.2	0
2500	+ 1.3	- 0.3	0
3150	+ 1.2	- 0.5	0
4000	+ 1.0	- 0.8	0
5000	+ 0.5	- 1.3	0
6300	- 0.1	- 2.0	0
8000	- 1.1	- 3.0	0
10000	- 2.5	- 4.4	0
12500	- 4.3	- 6.2	0
16000	- 6.6	- 8.5	0
20000	- 9.3	-11.2	0

*These numbers assume a flat, diffuse-field (random incidence) response for the sound-level meter and microphone.

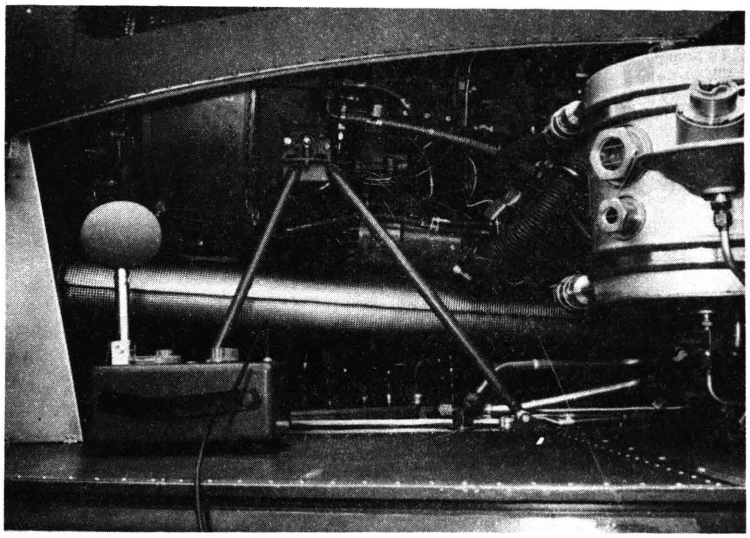


a. UH-1H

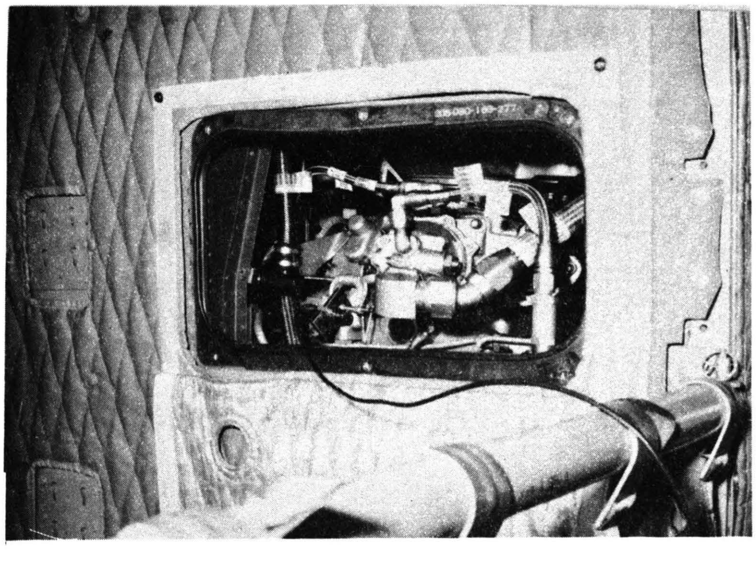


b. OH-6A

Figure 17. Location of acoustic instrumentation.



a. Sound-level meter near UH-1H turbine engine.



b. Accelerometer on UH-1H gear casing.

Figure 18. Location of acoustic and vibration instrumentation.

idling on the ground. In another measurement, the sound-level meter was placed on the ground directly beneath the rotor tip and centered on the rotor hub. These measurements would indicate the portion of the total frequency spectrum affected by the sources mentioned by showing a peak or large magnitude shape at certain frequencies. A windscreen was used on the microphone during outside tests.

Specific instrumentation included a sound-level meter, a portable single-channel tape recorder, and a ceramic microphone. Calibration of the microphone and sound-level meter combination was accomplished with a General Radio Sound-Level Calibrator Type 1562-A, which emits a discrete 114 dB pure tone at frequencies from 125 Hz to 2000 Hz. Upon calibration, the sound-level meter (General Radio model 1551-C) is accurate from 20 Hz to 20,000 Hz and from 24 dB to 150 dB. The sound-level meter (SLM) was equipped with a ceramic microphone (General Radio model 1560-P5). This type of microphone uses a piezoelectric material which, when strained by the force produced by a sound pressure, generates an electrical charge. The diaphragm is used as a force collector and is backed by a crystal, making this transducer more rugged than a condenser type of microphone. The Tanderg model 11 battery-powered tape recorder operates on one channel and at two tape speeds, 3 3/4 and 7 1/2 ips. A vibration meter (General Radio model 1553) with an Endevco accelerometer was used to record accelerations.

The noise samples, recorded through the SLM's electric weighting networks onto the magnetic tape of the Tandberg and then cut into 30" tape loops, were processed through a sound and vibration analyzer (General Radio model 1564-A). A data recorder (General Radio model 1525-A) was used in its tape loop configuration to play the tape loops into the analyzer. The frequency analyzer was set to provide 1/10 octave-bands from 2.5 Hz through 25,000 Hz. These noise samples processed through the analyzer were automatically recorded by a graphic-level recorder (General Radio model 1521-B). The graphic-level recordings were then compared for similar shapes at certain frequencies therefore allowing a correlation between the noise source and its contribution to the overall spectrum.

IV. RESULTS

A. Noise Survey

Clay, et al[75], review the flight of four UH-1B helicopters performing normal field-mission assignments over a period of 3 months. The data compiled was organized such that it may be used to establish design criteria for new helicopters and for modification of existing aircraft design criteria. The two most important points which indicate the importance of examining the level-flight maneuver are that a condition of steady-state operation prevailed for 75 percent of the flight time and consisted of cruise, hover, steady climb and steady descent. The second point is that at the steady-state condition, 82 percent of the time the helicopter was at air speeds between 75 knots and 95 knots, where knots is a term for nautical miles per hour. If the assumption is made that the UH-1H flight performance parallels that of the UH-1B, then the UH-1H will operate primarily in the steady-state condition between the airspeeds of 75 knots to 95 knots. This was in fact the case for observed data.

Ideally, to conduct a proper noise survey, repeatable parameters must be used. But in the case of interior helicopter noise surveys, the interior sound pressure is continually varying with altitude, airspeed, and weather. The parameters found to control the first two factors are blade attack angle, rotor rpm, turbine power output shaft speed, and percent of gas turbine speed used. The combination of variations of these parameters will actually maneuver the helicopter through various phases. For each noise survey, these parameters were recorded so that a later flight might closely simulate that of the previous flight. The main variable not exactly controllable was the weather. However, the weather conditions for each flight day, including the amount of turbulence, outside air turbulence, and wind speed, were recorded to allow a very general ambient comparison of flights. Table 13 presents a thumbnail sketch of the flight parameters.

While a noise survey and magnetic tape recordings were made for the OH-6A helicopter, it is felt that because only one flight was made, the data gives no reliable indication of general trends. The noise survey is presented in this section and the OH-6A helicopter frequency spectrum analysis is presented as Appendix A. In contrast, three flights were accomplished with two consecutively-numbered UH-1H helicopters, so it is felt that the data presented is representative of the UH-1H helicopter in various flight maneuvers. While data on other maneuvers is presented, the level-flight maneuver was selected for a more intensive analysis as this is the primary steady-state condition.

Figure 19 depicts the interior of the UH-1H helicopter arranged with the usual passenger seating. The numbers indicate microphone locations with the sound-level meter placed on the passenger seat (14" high) and the observer moved at least 3 feet from the microphone. Table 14 summarizes

Table 13. Flight parameters.

	FLIGHT				
	6/22/72	9/25/72		10/12/72	
	Level Flight	Idle	Level Flight	Idle	Level Flight
UH-1H Ser#	70-16285	70-16285	70-16285	70-16285	70-16285
OAT	19°C	71°F	20°C	30°C	18°C
Turbulence	heavy	light	light	none	none
N_1*(%)	-	-	89.8	88	91
N_2** (rpm)	-	-	6600	6600	6600
rotor (rpm)	-	-	340	330	330

	11/1/71		10/19/72	
	Idle	Level Flight	Idle	Level Flight
OH-6A Ser#	65-12918	65-12918	66-14404	66-14404
OAT	-	-	5°C	-2°C
N_1 (%)	61	92	61	89
N_2 (%)	69	103	68	102
rotor (rpm)	325	475	350	475

* N_1 = gas turbine engine speed

**N_2 = engine output shaft

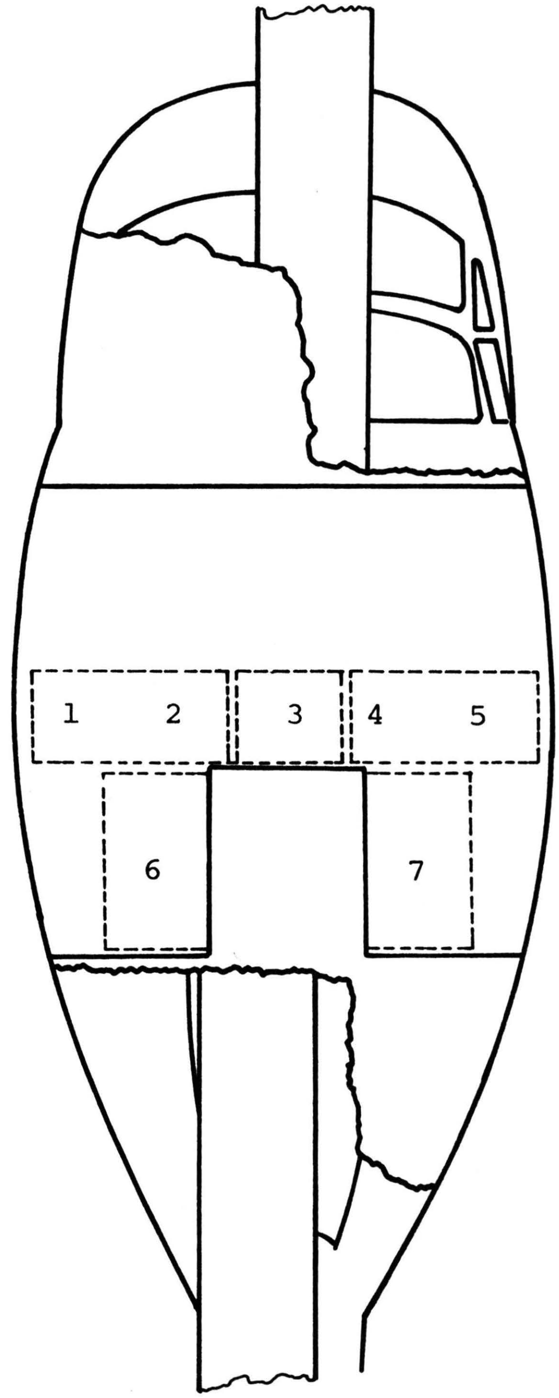


Figure 19. UH-1H interior plan

Table 14. UH-1H noise survey.

	LOCATION						
WEIGHTING SCALE	1	2	3	4	5	6	7
6/22 cruise doors open							
C	-	-	115 dBC	-	-	-	-
A	-	-	96 dBA	-	-	-	-
9/25 cruise							
C	104 dBC	105 dBC	-	105 dBC	106 dBC	111 dBC	109 dBC
A	95 dBA	95 dBA	-	95 dBA	97 dBA	96 dBA	99 dBA
10/12 Idle							
20 KHZ	105 dB	105dB	104 dB	105 dB	105 dB	108 dB	107 dB
C	104 dBC	104dBC	102 dBC	102 dBC	104 dBC	106 dBC	106 dBC
A	95 dBA	95dBA	92 dBA	94 dBA	94 dBA	95 dBA	96 dBA
cruise							
20 K	116 dB	116dB	115 dB	116 dB	116 dB	116 dB	117 dB
C	112 dBC	112dBC	111 dBC	111 dBC	112 dBC	112 dBC	114 dBC
A	96 dBA	97dBA	97 dBA	97 dBA	95 dBA	95 dBA	96 dBA

*Doors closed unless specified otherwise the data obtained by moving the SLM around the helicopter to the numbered locations. Additional noise levels were recorded in the UH-1H for locations beneath the cabin ceiling forward of the passengers and they were found to range between 94 dBA and 106 dBA. It should be noted that the 106 dBA measurement was for the most turbulent day encountered, and that 98 dBA is considered more representative as an upper limit.

Figure 20 depicts the interior of the OH-6A helicopter with the four seats represented by four squares. The dashed lines on the drawing show the actual locations of the rotor hub relative to the rear passengers. Table 15 summarizes the noise data obtained, but, because of space limitation, it should be noted that the observer could not move further away than 1 foot from the microphone. In both helicopters, it was noted that the sound field was fairly diffused without distinct standing-wave modes of sound vibration, but with slightly larger noise magnitudes as the gear, rotor, and transmission systems were approached. Also, both helicopters had all standard sound proofing installed and doors were closed. Exterior noise measurement, during idle on the ground, was made for both helicopters. The UH-1H displayed sound levels of 98 dBA to 108 dBA, and the OH-6A, 92 dBA to 97 dBA within the area swept by the main rotor.

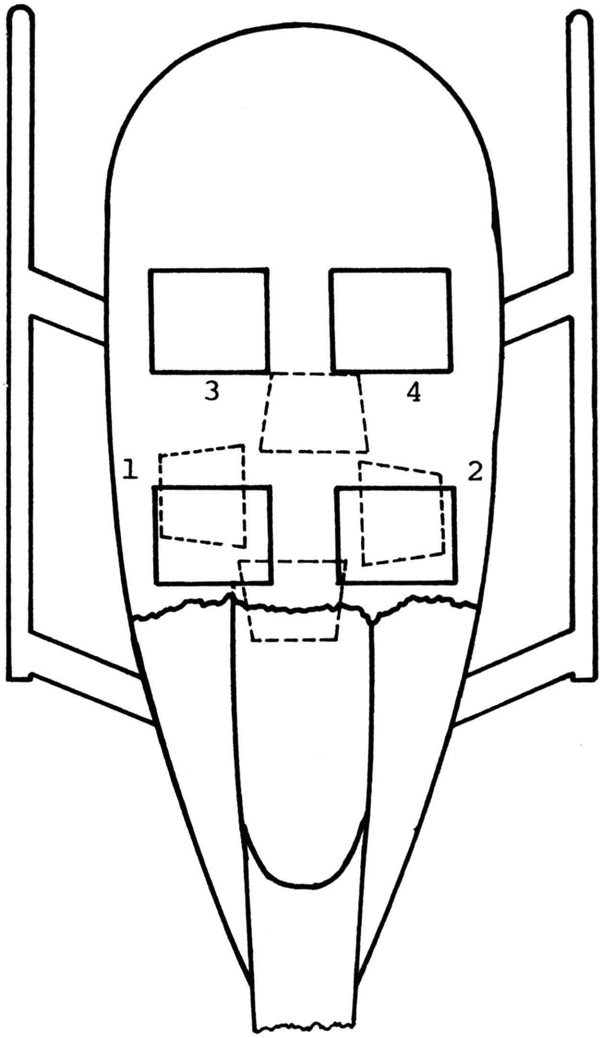


Figure 20. OH-6A interior plan

Table 15. OH-6A noise survey.

10/19/72 flight*

	IDLE			LEVEL FLIGHT WITHOUT WIND SCREEN		
	A	C	20 KHZ	A	C	20 KHZ
1	98	100	102	108	109	111
2	97	99	100	107	108	108
3	100	101	102	112	112	114
4	99	102	102	108	112	112

*Locations 1 and 2 are near fuselage skin at the seat level. Locations 3 and 4 are centered on pilot and copilot seat backs at head level.

B. Frequency-Spectrum Analysis

Two approaches were used for the presentation of the data in the frequency-spectrum analysis. The first approach is a graphical comparison of octave-band levels calculated from a 1/3-octave-band analysis and octave-band levels found in the literature. Also considered in this comparison are two duration-criteria curves from Sommer, et al[76], one for exposures limited to 30 minutes and one limited to 60 minutes.

According to Clay's survey[75], the average length of a flight in 1965 and 1966 on four UH-1B's, was 219/758 hours or about 17 minutes. But these flights were tailored to the acquisition of airborne data and were also conducted prior to the Vietnam military buildup. It is estimated that an average post-Vietnam flight length should be closer to 30 minutes. Figure 21 displays the summation of helicopter data from Gasaway[65], Young and Blazie[77], and the two damage-risk-criteria curves from Sommer, et al[76]. This figure makes it very clear that the UH-1H, with doors closed and sound proofing installed, is still sufficiently noisy to merit noise-reduction considerations for any flights exceeding the 60-minutes criteria-curve duration. Note also the distinct frequency spectrum difference between the UH-1C model and the UH-1H model at about 500 Hz. The H-model helicopter exhibits a definite peak in magnitude near this frequency. Otherwise, the curves are similar in shape.

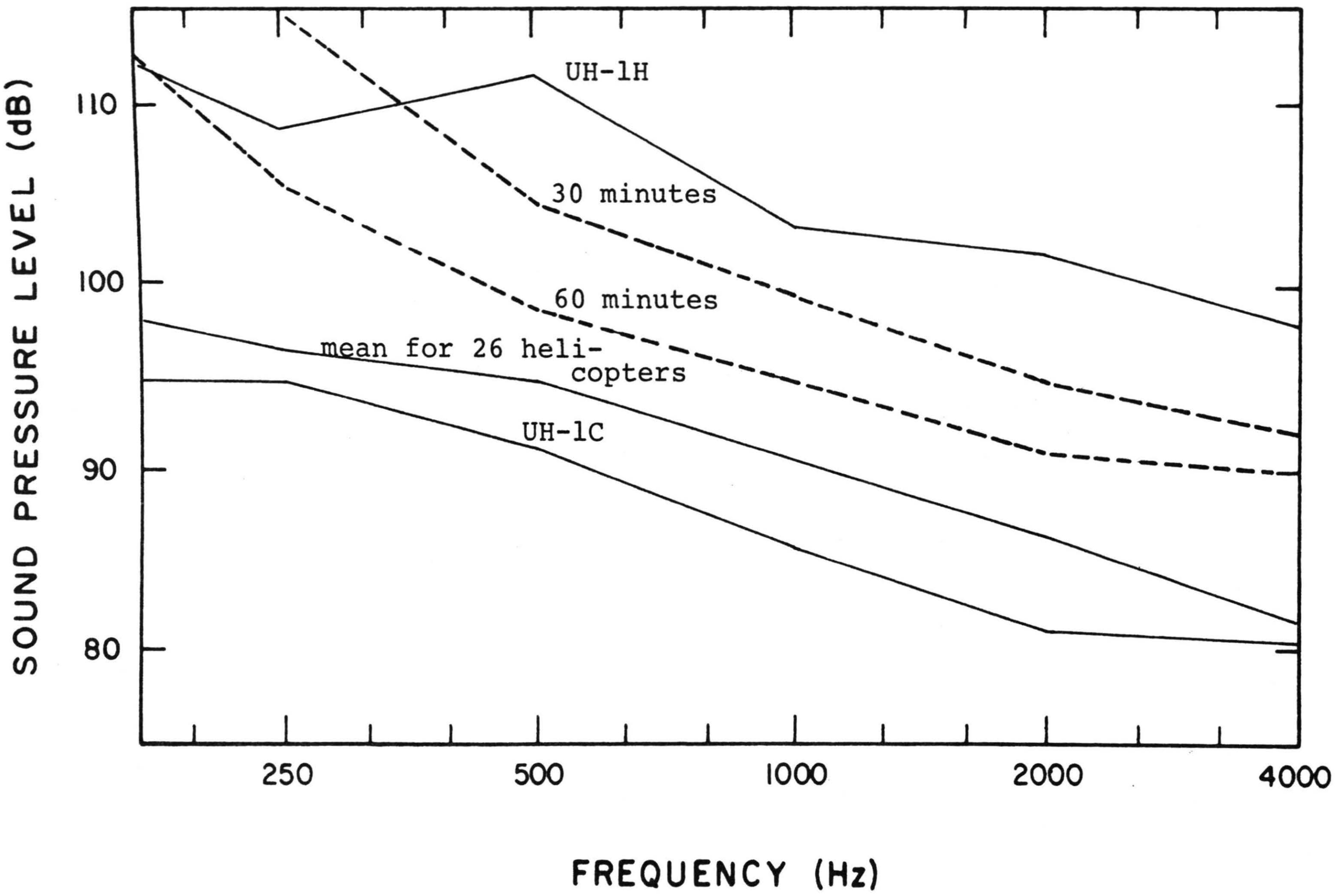


Figure 21. Single rotor, turbine powered helicopter noise

The second approach used in this thesis is a two-part analysis, dealing with a low-frequency region (10 Hz to 250 Hz) and a high-frequency region (250 Hz to 4000 Hz). The graphs are divided into two portions for flexibility and accuracy of comparison; the low and high frequency parts used for the correlation process, and the high frequency part for damage-risk criteria. The high frequency portion of the total spectrum was chosen for intensive examination because the human ear automatically attenuates the lower frequencies without any artificial or external assistance. Tape loops acquired from various helicopter maneuvers were analyzed, charted on standard 1/3 and 1/10 octave frequency spectrum paper, and then replotted on two graphs, a low-frequency graph and a high-frequency graph. These graphs were plotted with two thoughts in mind. The unweighted 20 KHZ and the "C", electrical network to be used for the source-to-noise correlation process, and the A-weighting network was to be used to assess the risk of hearing damage. Where the curves do not show on the graphs, the magnitudes are lower than the smallest ordinate shown on the graph. The plots are a 1/10-octave analysis of the tape loops to show the presence of any peaks. Some graphs have been plotted showing both the A and C, or the A and 20 KHZ, scales to demonstrate both the overall contribution and to show how the A-weighting attenuates the lower frequencies.

Generally, the graphs of the various helicopter maneuvers have been arranged in the order of the helicopter operating sequences for a typical flight. Figures 22 and 23 show the frequency content while still on the ground with the engine operating at flight rpm. The results using both the A and C-weighting networks are displayed. Figure 22 shows the large difference in weighting networks in the lower frequency range. Figure 23 shows how the A-weighted spectrum finally matches the C-weighted spectrum in the higher frequency range as expected. Note that the largest dB-value occurs in the low frequency region, 100 dBC, while the highest value in the high frequency range is about 95 dBC or 94 dBA.

The next maneuver considered is a hover, i.e., suspension of the helicopter 3 to 6 feet above the ground with no forward motion. Figures 24 and 25 show the frequency shape of the September 25, 1972 hover on both the A and C-weighted networks. Figures 26 and 27 illustrate the October 12, 1972 flight hover maneuver with the sound-level meter set on the 20 KHZ scale. The overall increase in magnitude of about 5 dB over the ground-flight rpm runup is probably due to the loading of the two rotor blades with the lift required to keep the helicopter in the air. Peak increases of 15 dB are apparently multiples of the rotor blade-passing frequency, 11 HZ, up to 3 multiples or 33 HZ. The blade passing frequency is simply the product of the number of blades (2) multiplied by the rotor rpm (330) and then divided by 60 sec./min. The high-frequency plot shows a slight increase between 225 and 630 HZ over ground-flight rpm, but a decrease

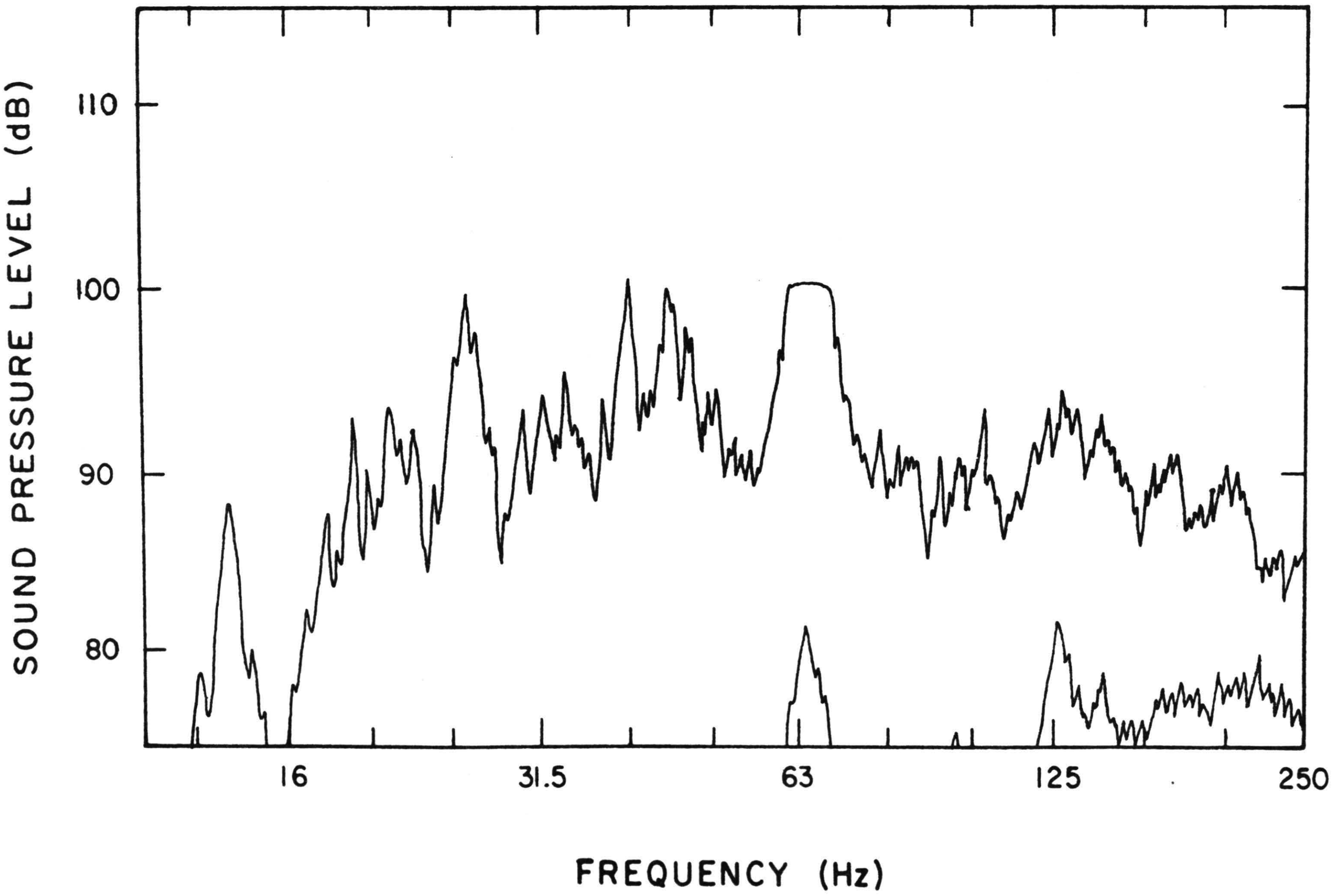


Figure 22. Flight rpm on the ground, low frequency

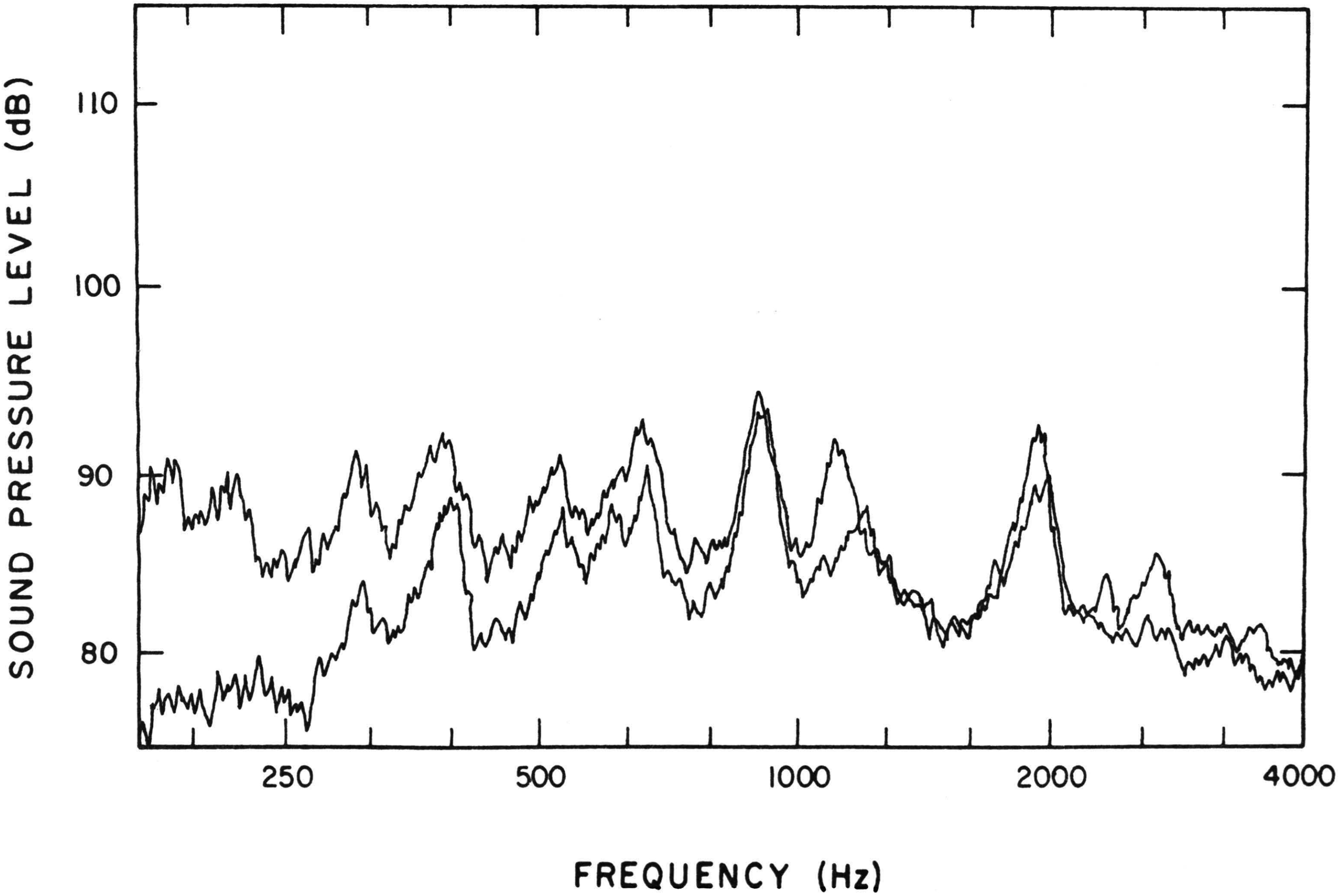


Figure 23. Flight rpm on the ground, high frequency

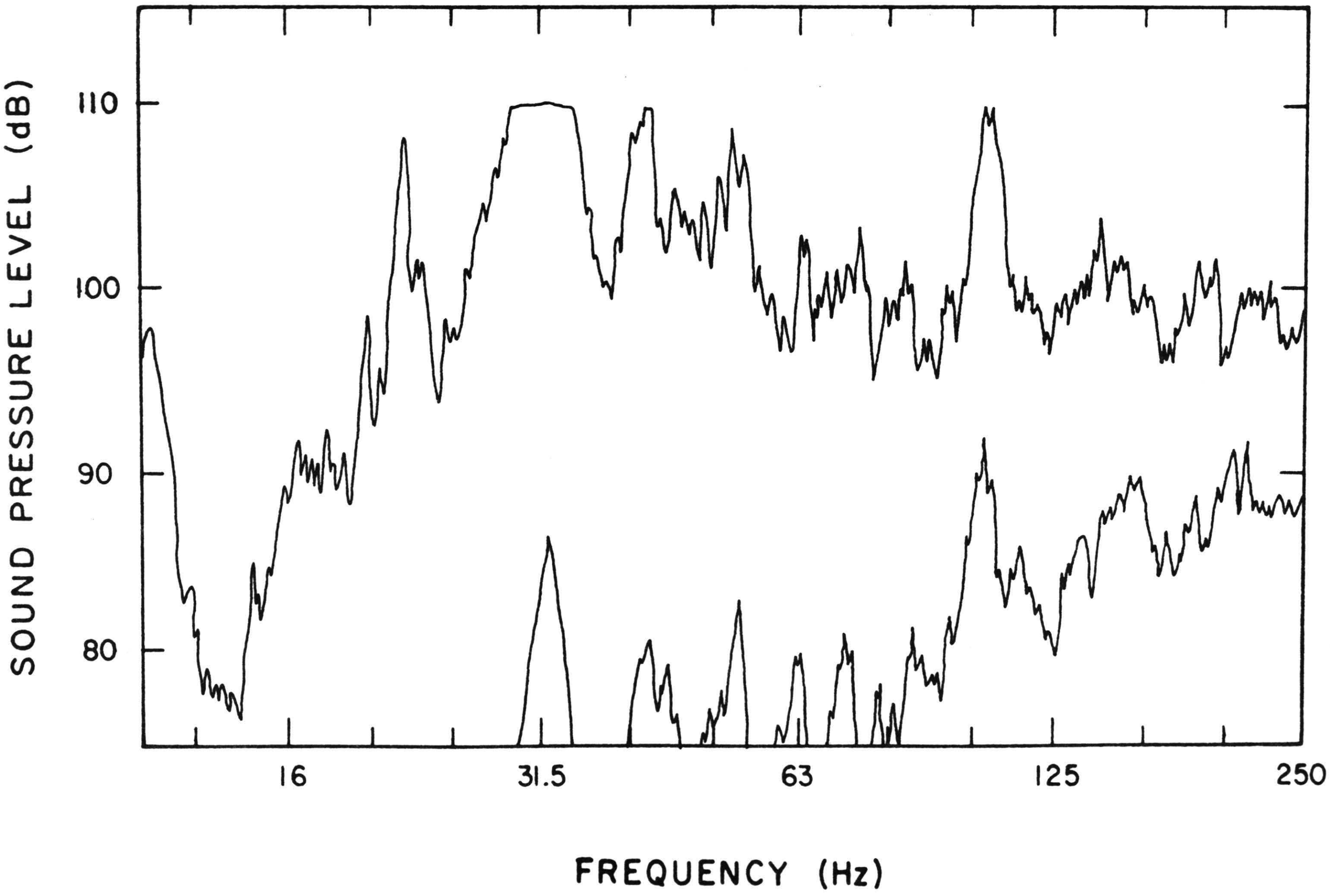


Figure 24. Hover, low frequency (9/25/72)

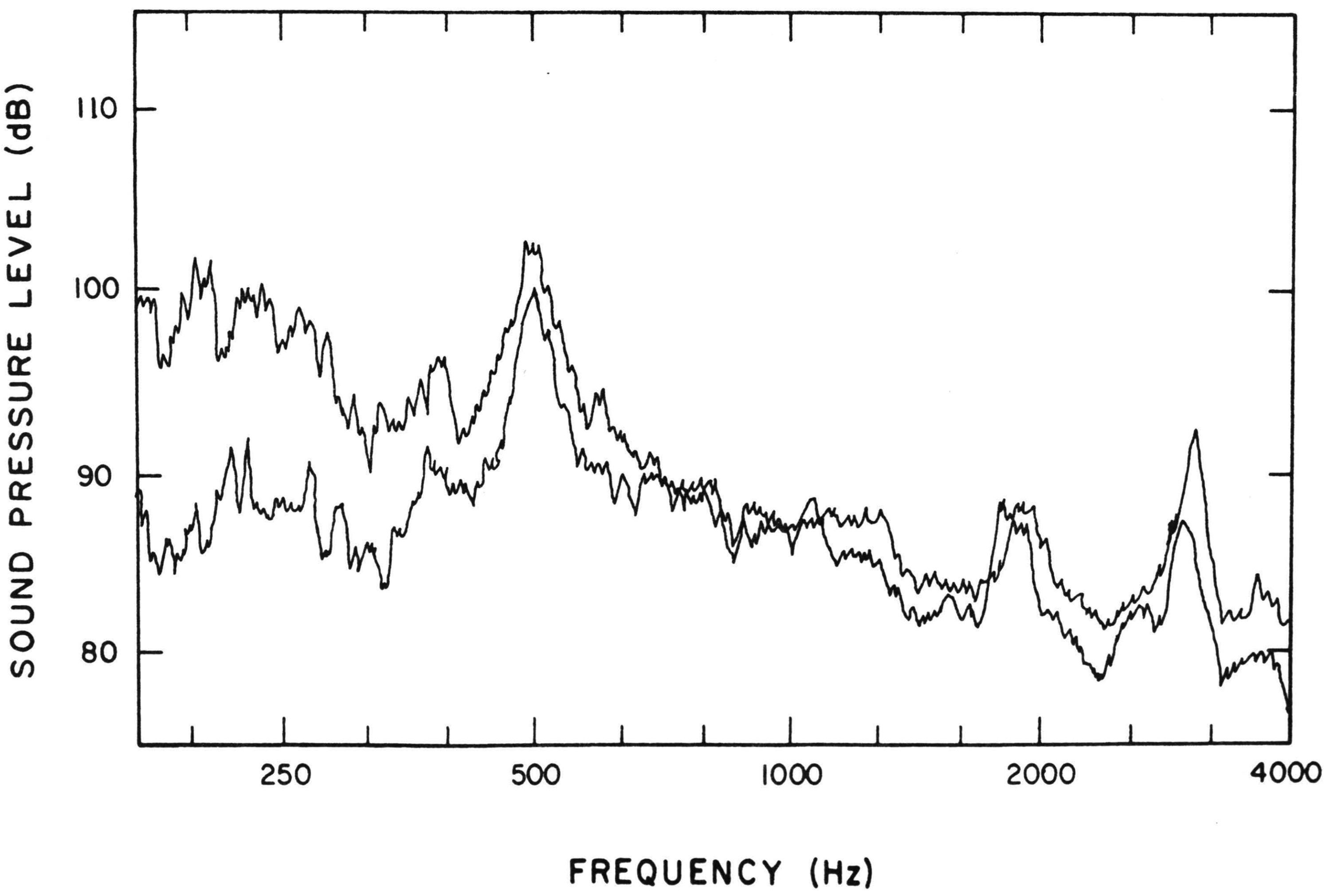


Figure 25. Hover, high frequency (9/25/72)

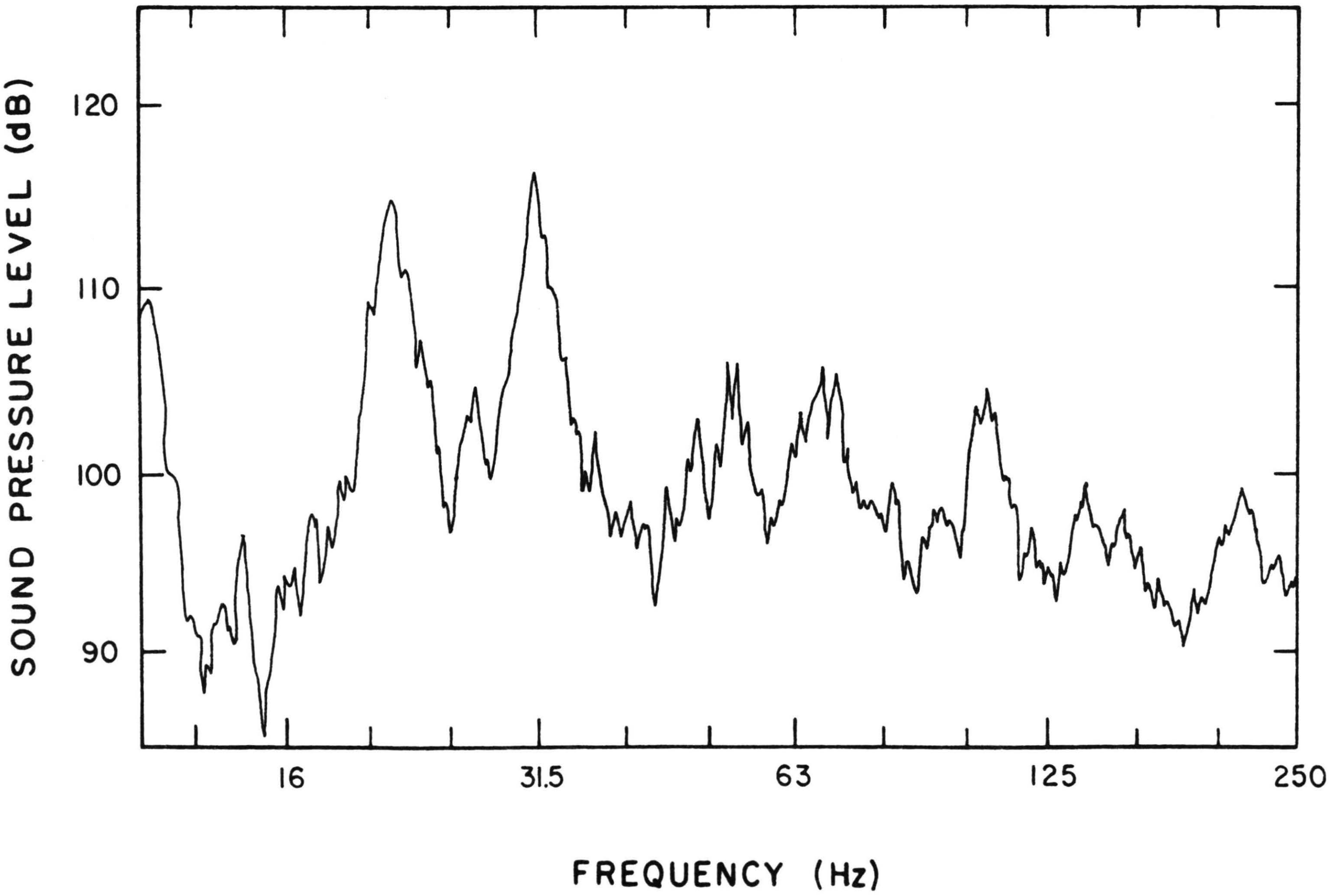


Figure 26. Hover, low frequency (10/12/72)

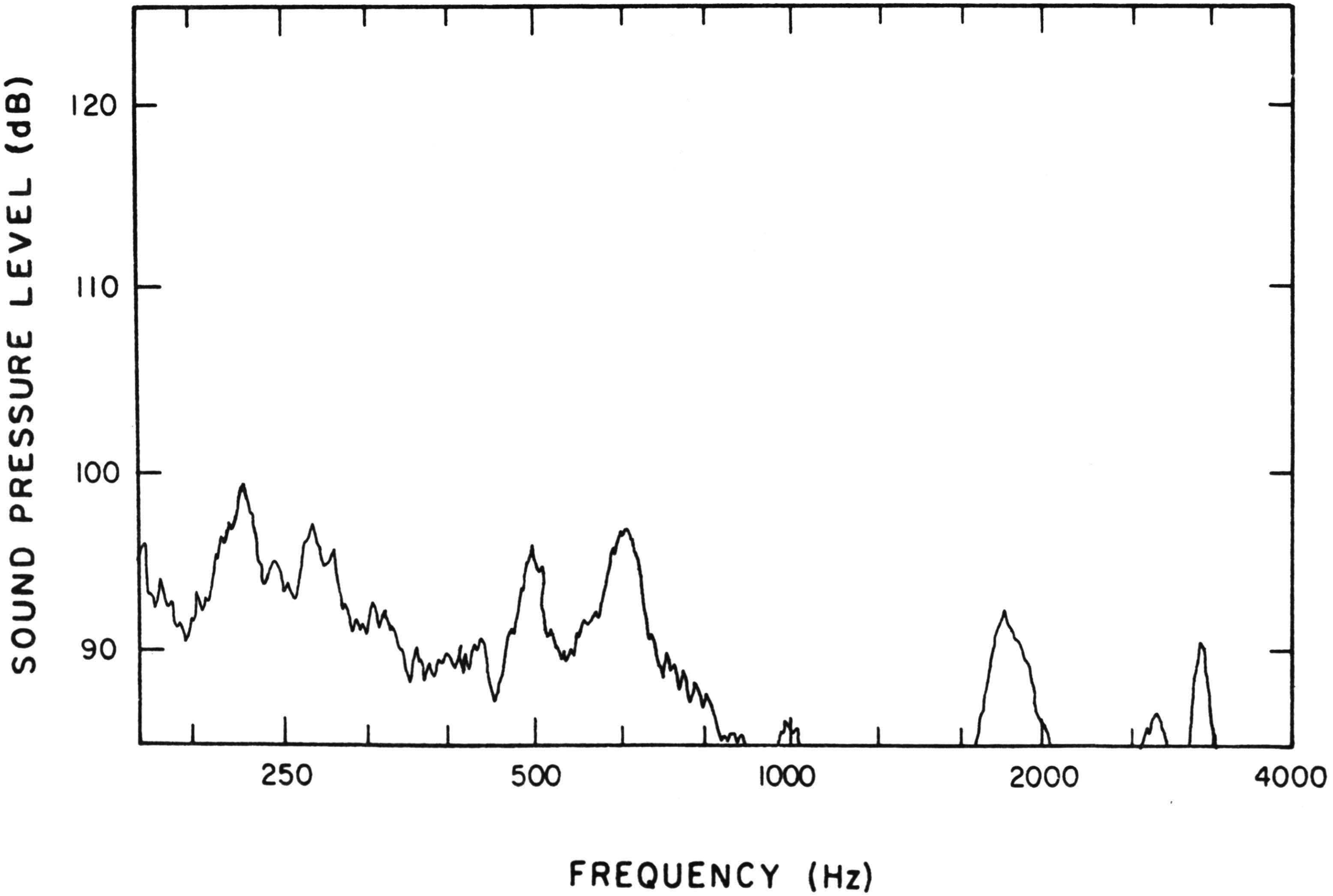


Figure 27. Hover, high frequency (10/12/72)

or no change after 630 HZ. Spikes near the frequencies of 900 HZ, 1100 HZ and 3300 HZ, are smoothed out by the hover condition.

Figures 28 and 29 illustrate the frequency content of the steady-climb condition. This type of maneuver has a frequency shape similar to the hover condition, but has some magnitude differences. The largest peaks in the low-frequency range was at about 20-21 HZ (122 dBC) with the next largest magnitude at 10 HZ and 32 HZ (118 dBC). Two low-range frequency peaks appeared for the first time in this maneuver, about 42 HZ and 110 HZ (113 dBC). In the high-frequency range, the steady-climb shape closely follows the hover shape, but is about 5 dB higher.

Level flight is represented by 3 sets of graphs each showing data using one of the three electrical weighting networks, A, C, and 20 KHZ. Figures 30 and 31 show the frequency spectra as measured without any electrical weighting in the sound-level meter-tape-recorder system.

This set of graphs maintains the frequency shape of steady climb with a general overall decrease in magnitude. Figures 32 and 33 show the shape as recorded using the C-weighting network of the sound-level meter. This set shows a 10 dB low-frequency attenuation from the unweighted network and a decrease of about 5 dB per octave in the high-frequency region. Figures 34 and 35 depict the influence of the A-weighting network and do not seem to present any surprises. As expected, the low frequencies are sharply

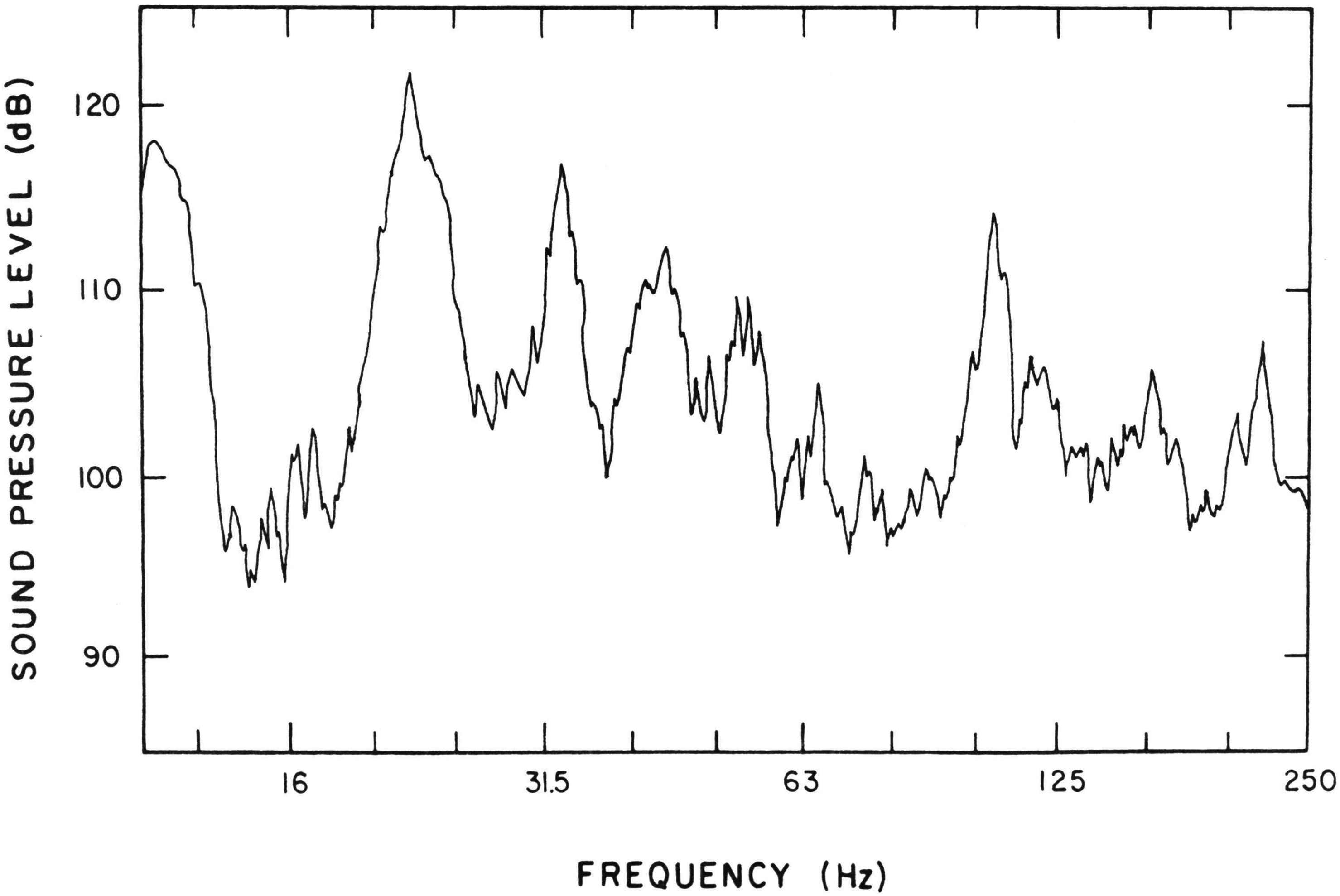


Figure 28. Steady climb, low frequency

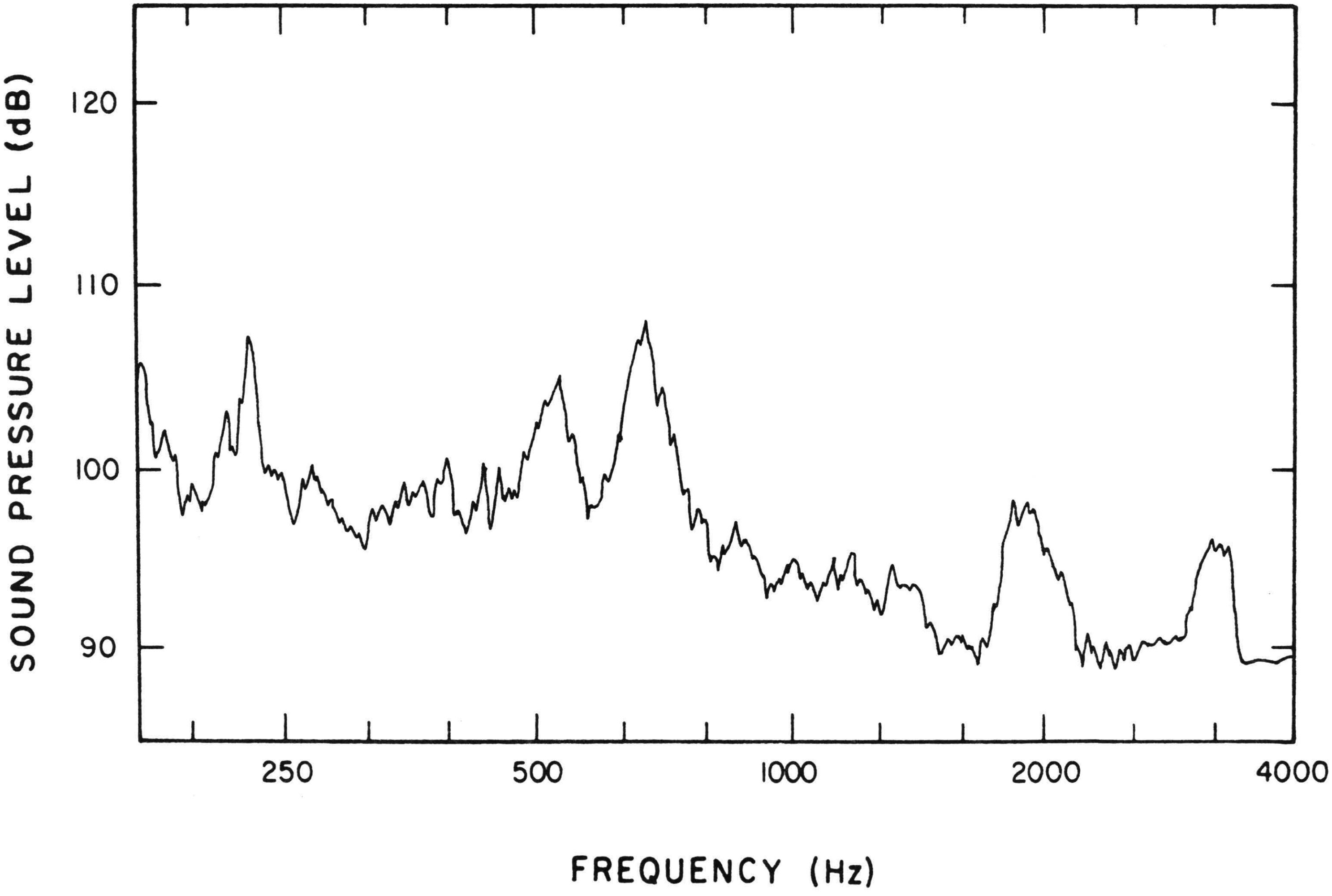


Figure 29. Steady climb, high frequency

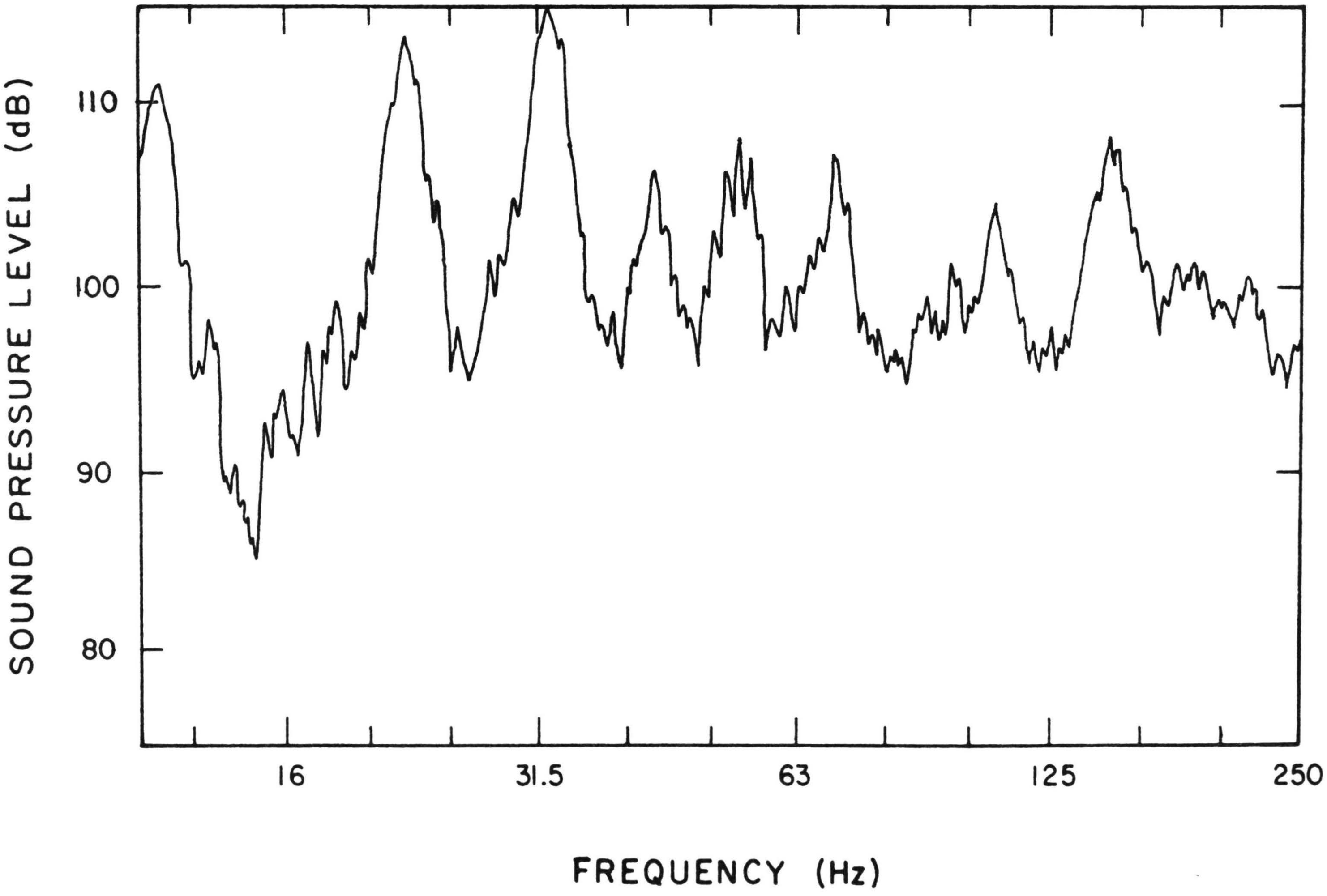


Figure 30. Level flight, low frequency, 20 KHz

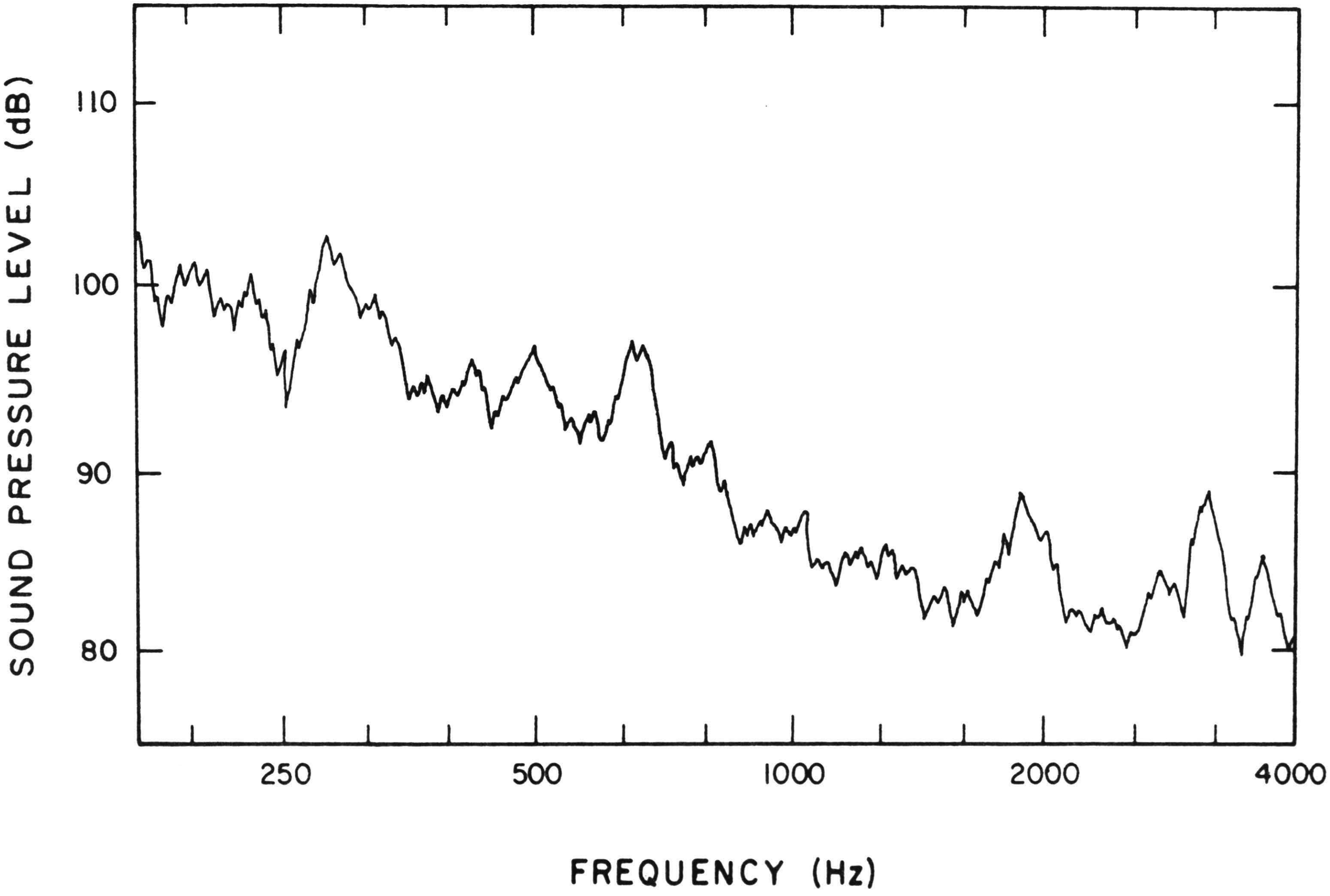


Figure 31. Level flight, high frequency, 20 KHz

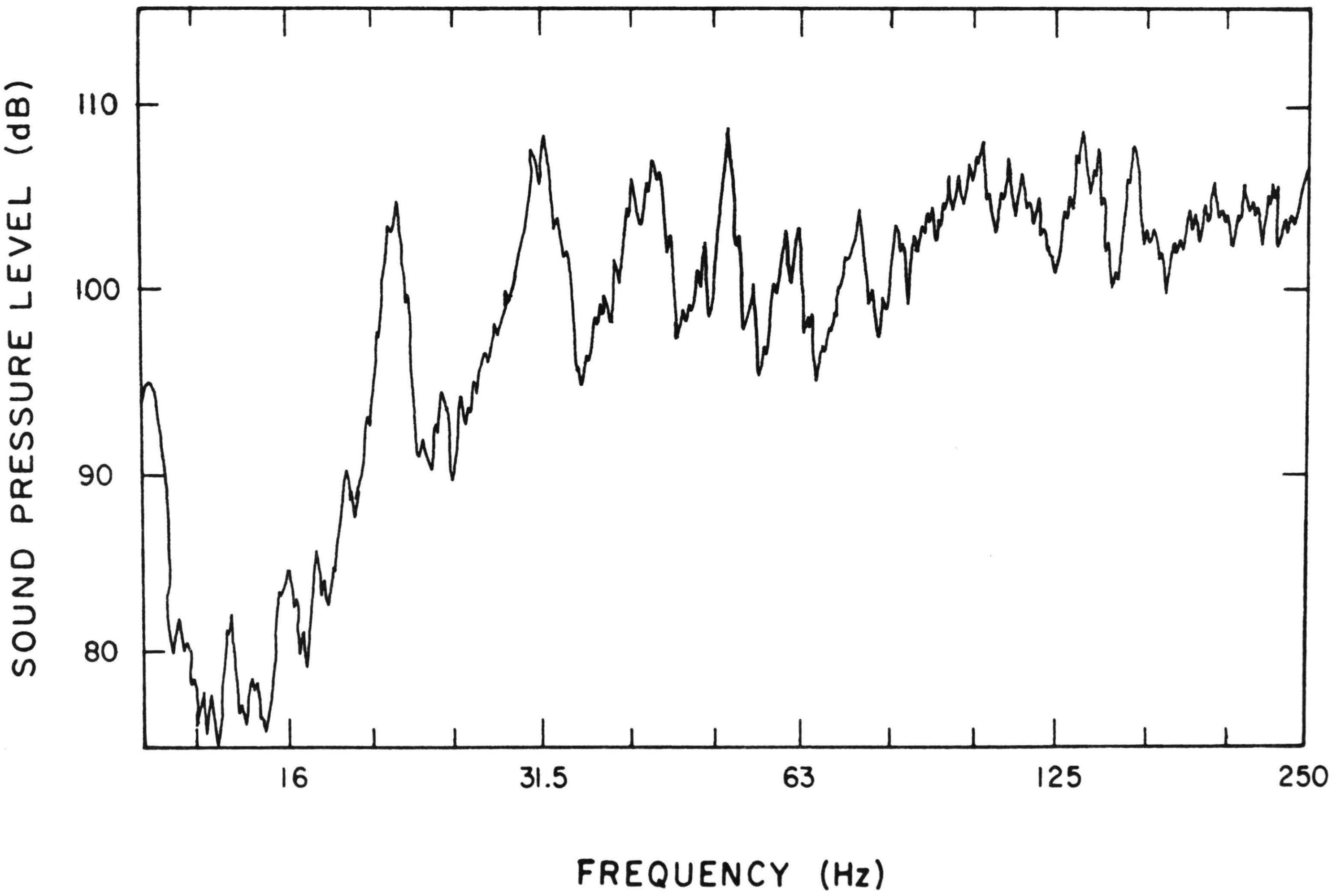


Figure 32. Level flight, low frequency, C-weighting

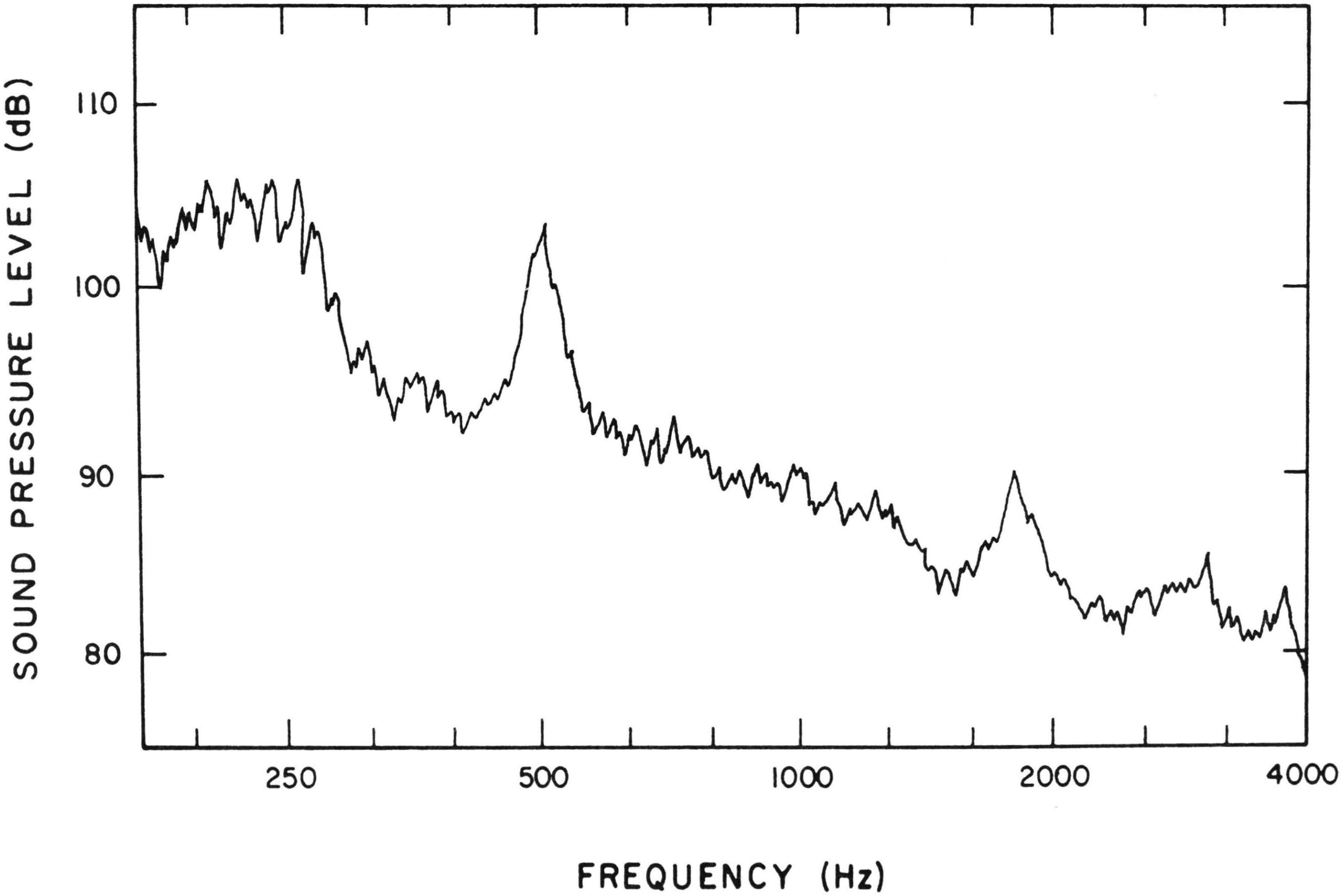


Figure 33. Level flight, high frequency, C-weighting

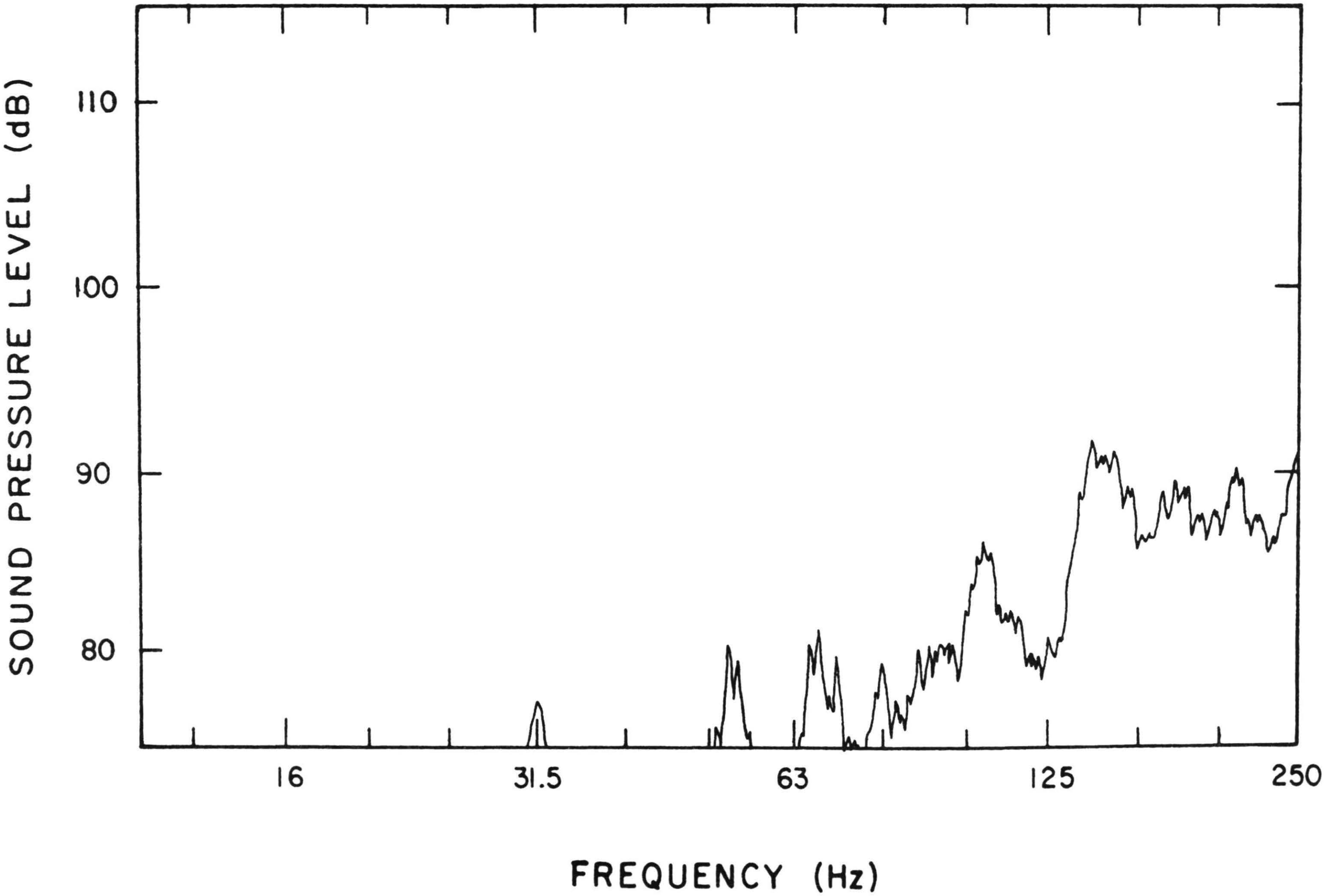


Figure 34. Level flight, low frequency, A-weighting

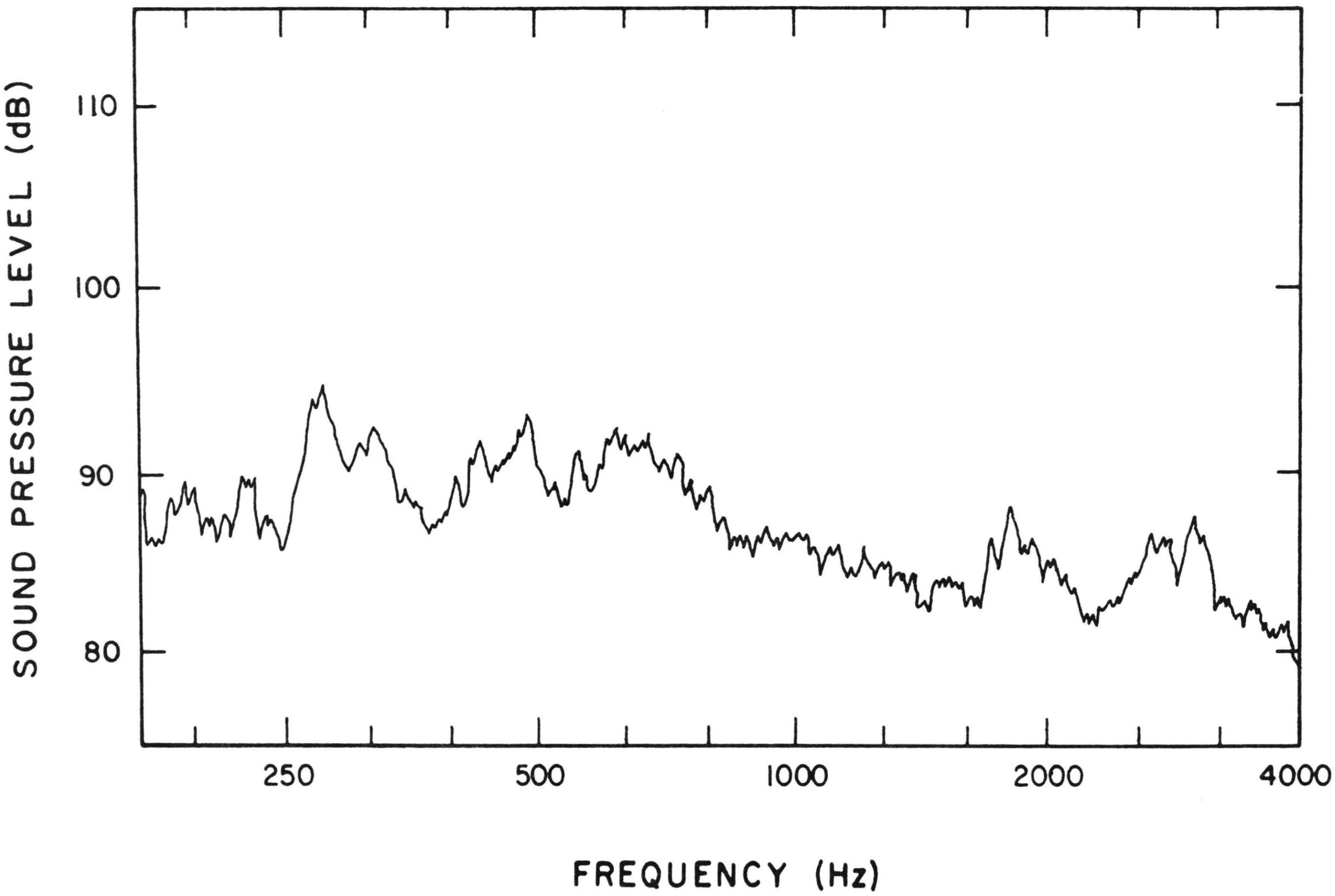


Figure 35. Level flight, high frequency, A-weighting

attenuated by the A-weighting network.

Descent from level flight introduces the opportunity for "blade slap", or a slapping noise, because of the unique time-varying pressures produced by the rotating rotor blades. This particular 1/10-octave-band analysis seems to be more jagged, probably because of the presence of many little pure-tone spikes caused by each air cavity collapsing on the rotor blades. Figures 36 and 37 display the frequency spectra of the descent maneuver using the 20 KHZ scale, using the C-weighting network in Figures 38 and 39, and the A-weighting network in Figures 40 and 41. A comparison of Figures 38 and 39 with the one set of graphs for steady climb show generally increased SPL values for the descent, mainly because of the increased blade loading in this maneuver. In the low-frequency range, the steady climb magnitudes are 5 dB larger than the descent values at all frequencies, except near 70 HZ and 140 HZ where the descent values are about 3 to 5 dB above the steady-climb values. In the high frequency range, the descent falls below 90 dB at about 1000 HZ while the steady-climb values do not drop below 90 dB until after 4000 HZ.

Selected noise sources were also subjected to a 1/10-octave-band analysis and then plotted on two sets of graphs. The first set consists of turbine noise, rotor noise, and noise on the engine platform. Figures 42 and 43 show the individual effects of each of these sources. Turbine noise seems to have pronounced low-frequency peaks at 31.5 HZ, 53

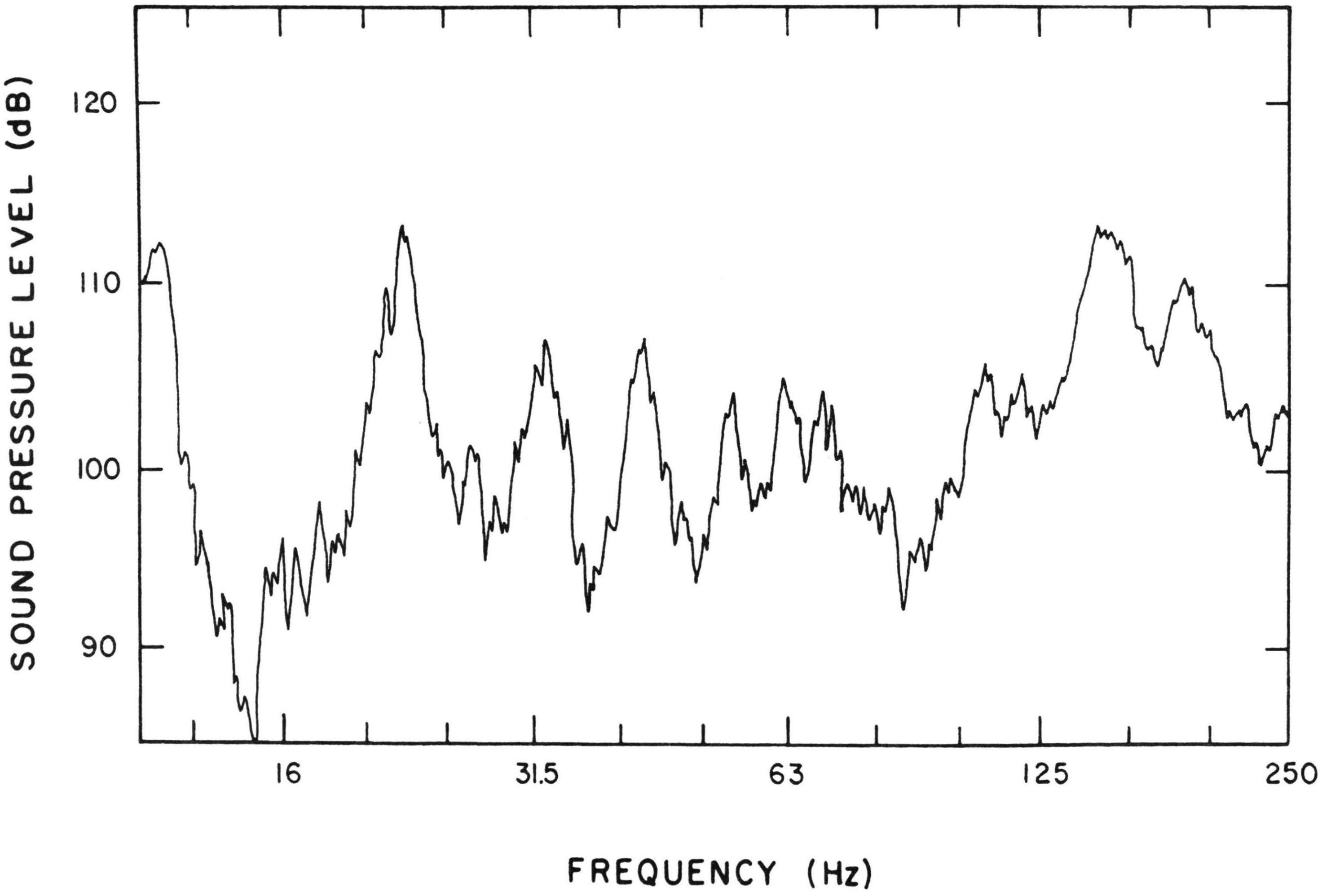


Figure 36. Descent, low frequency, 20 KHz

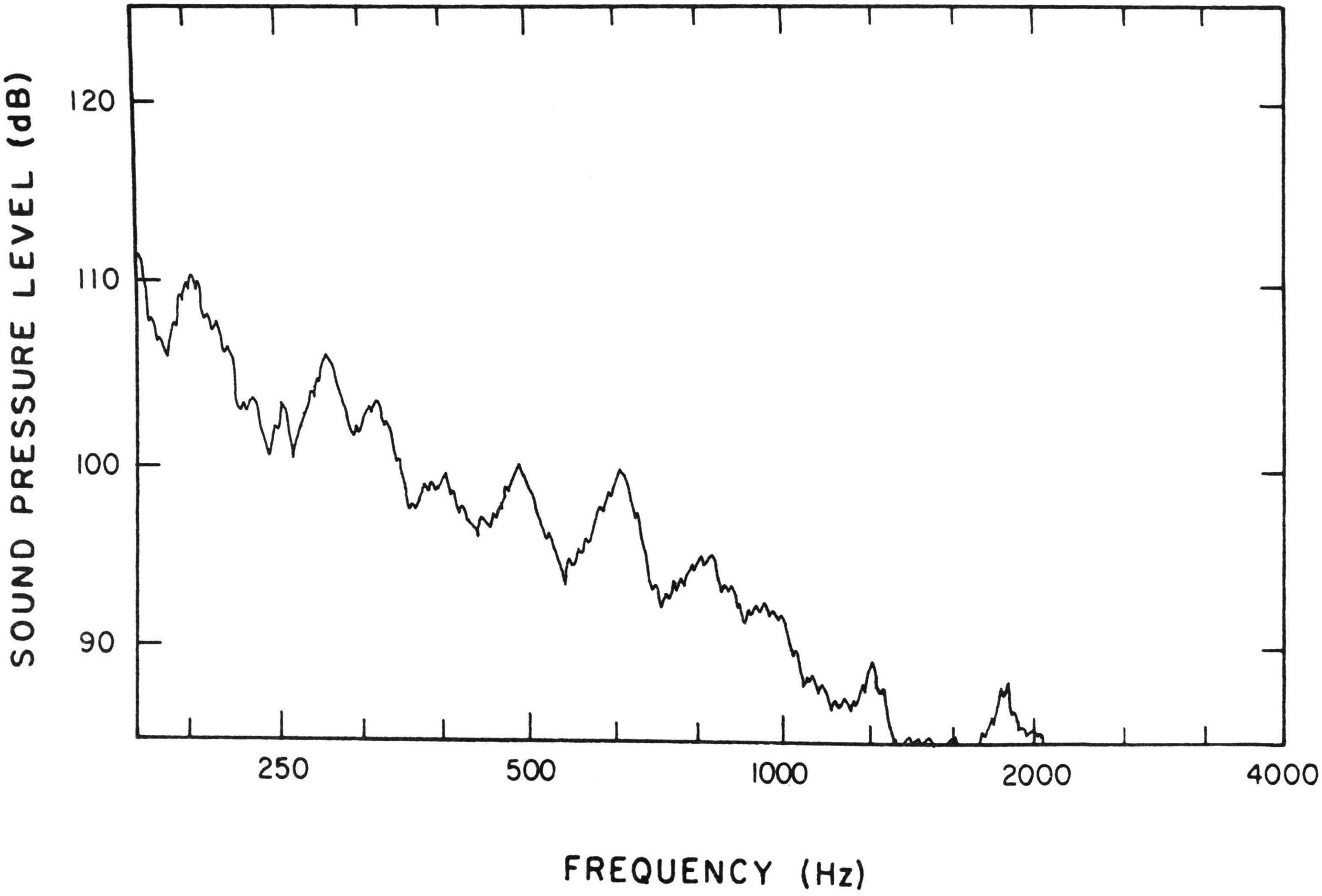


Figure 37. Descent, high frequency, 20 KHz

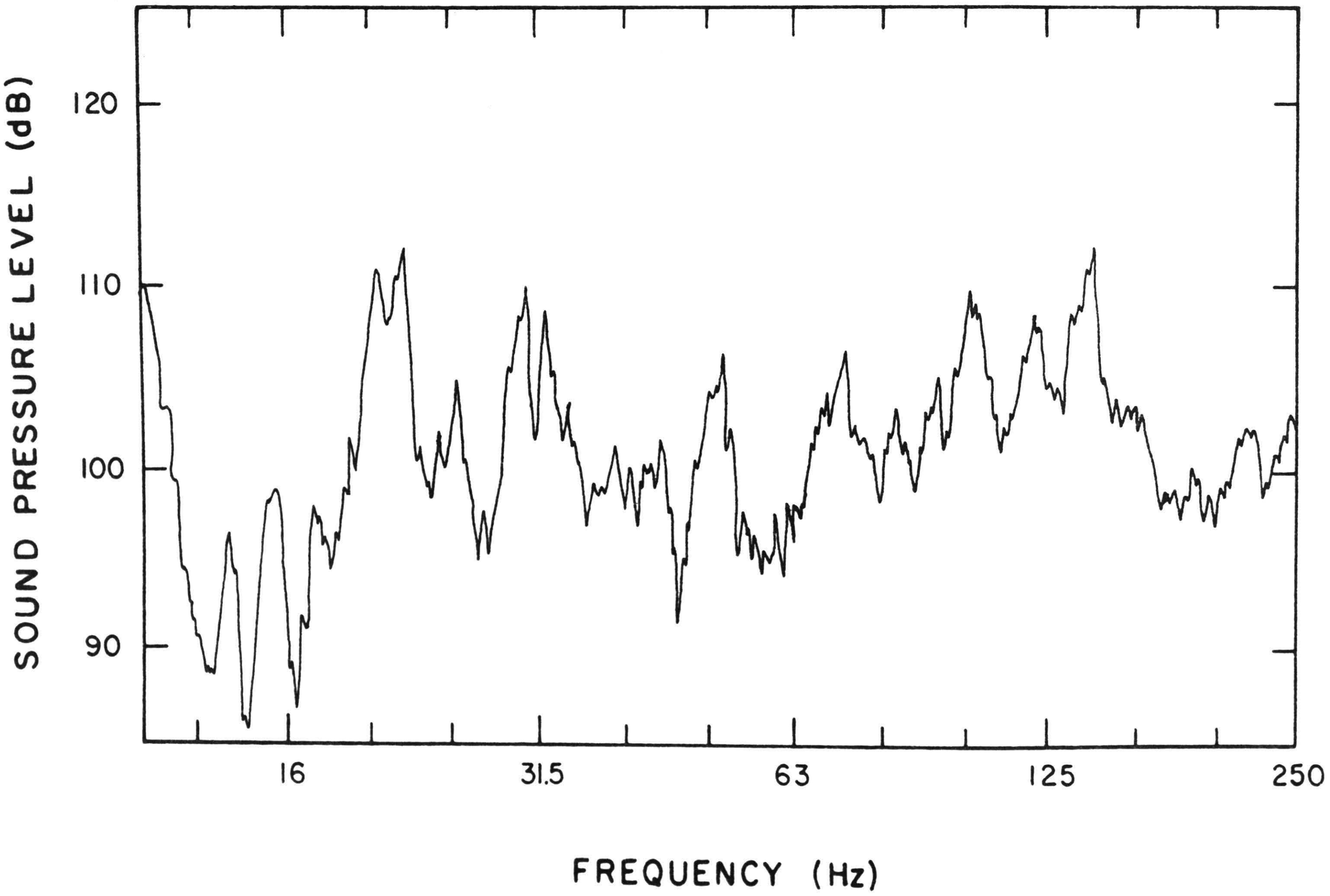


Figure 38. Descent, low frequency, C-weighting

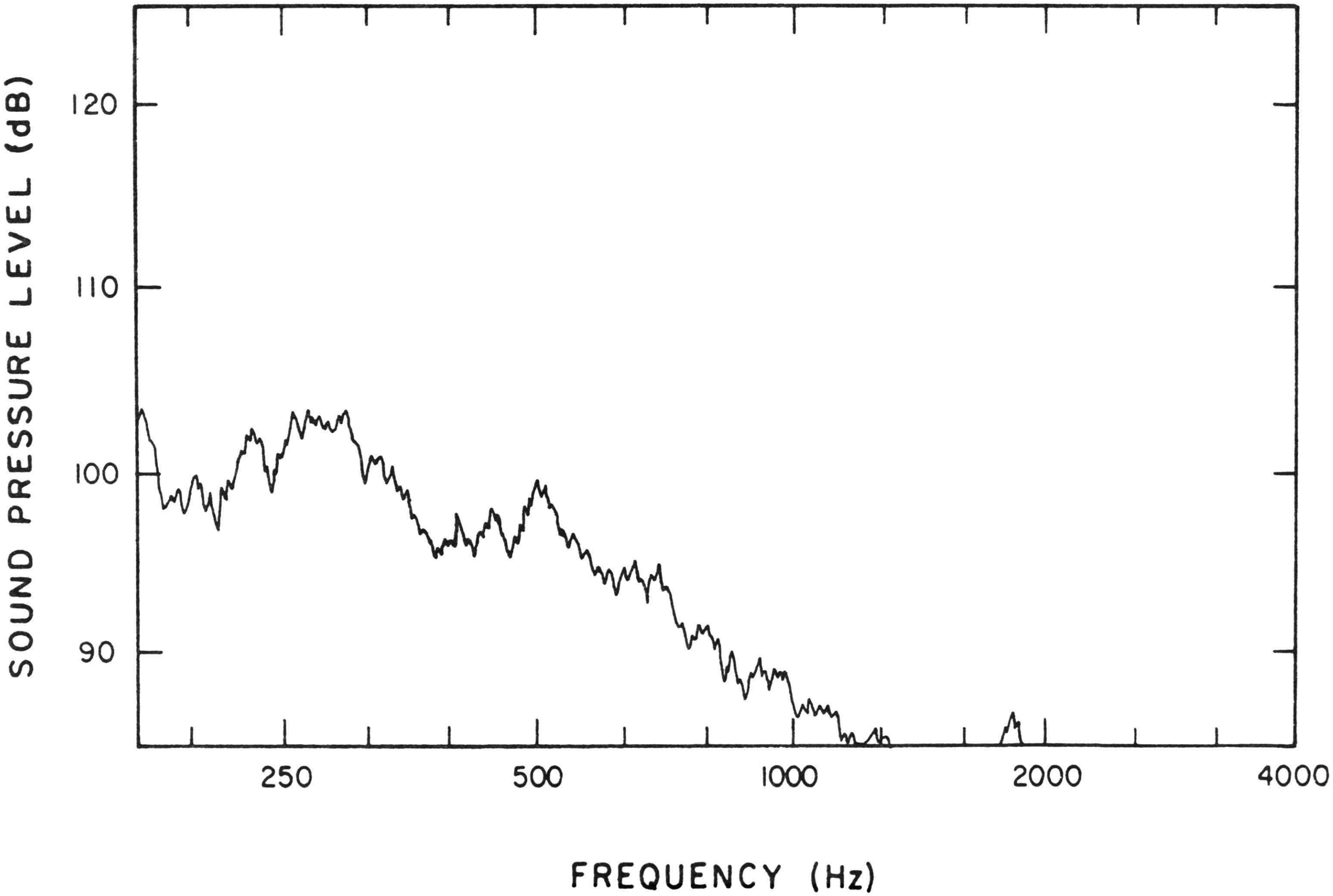


Figure 39. Descent, high frequency, C-weighting

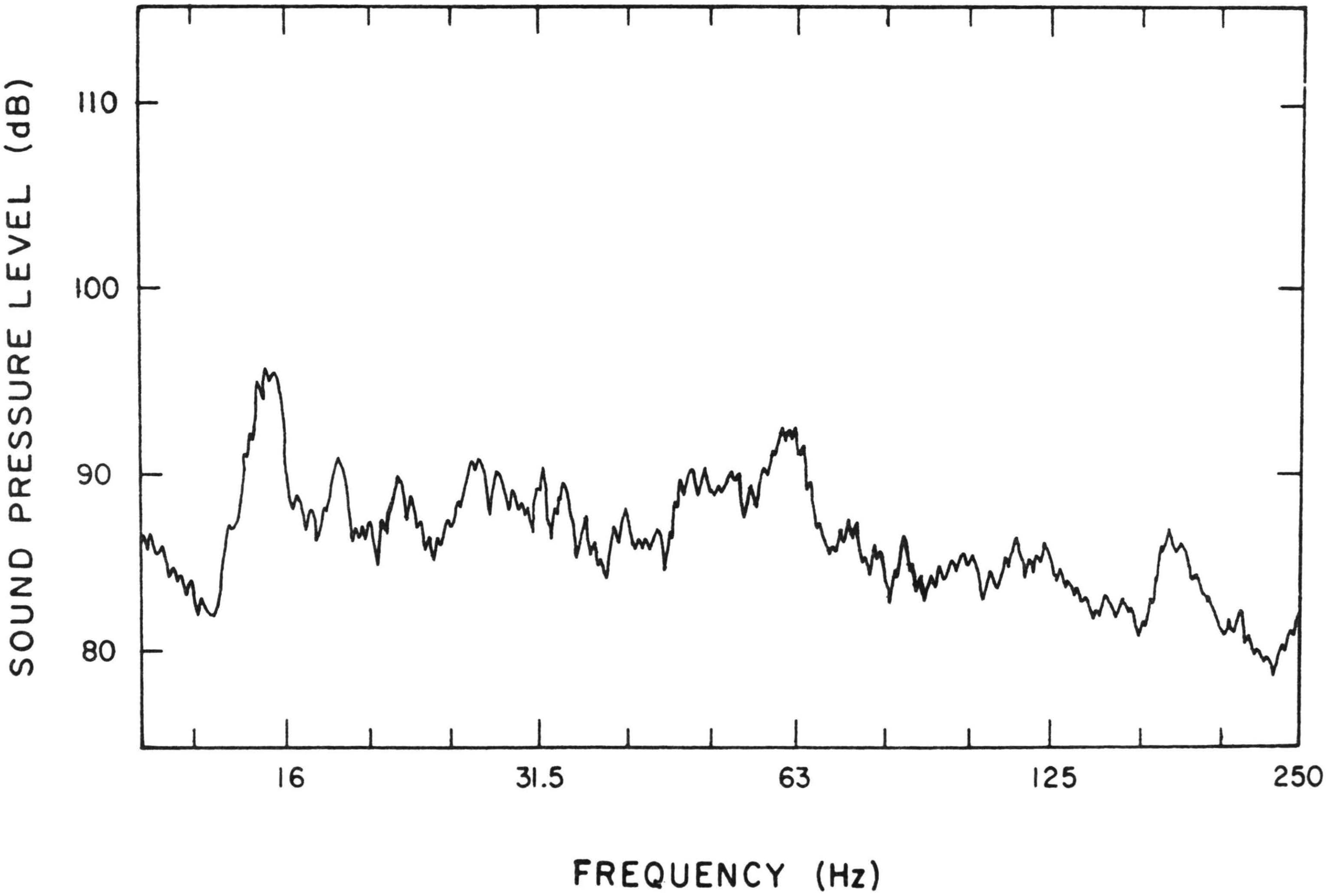


Figure 40. Descent, low frequency, A-weighting

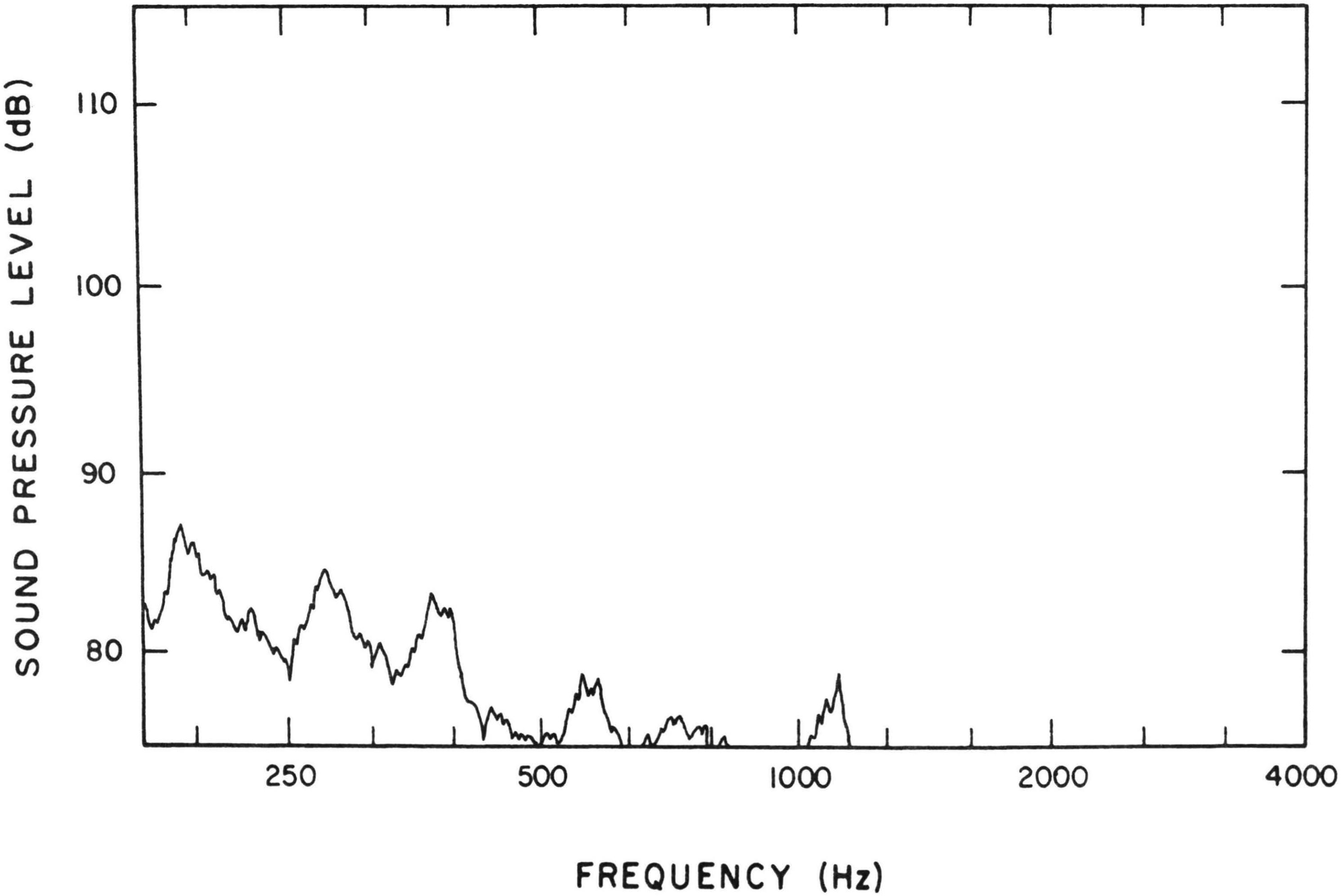


Figure 41. Descent, high frequency, A-weighting

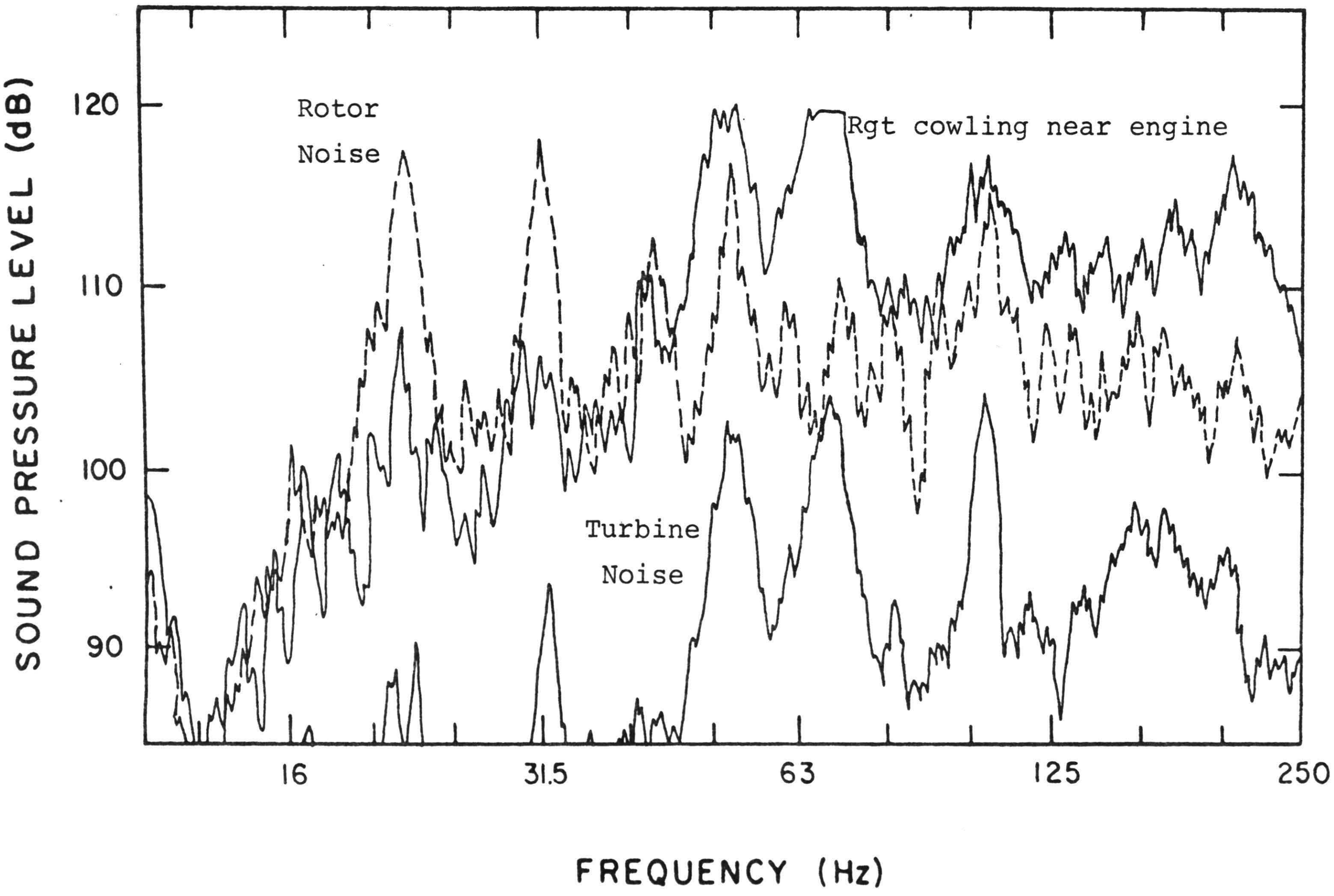


Figure 42. Selected noise sources, low frequency

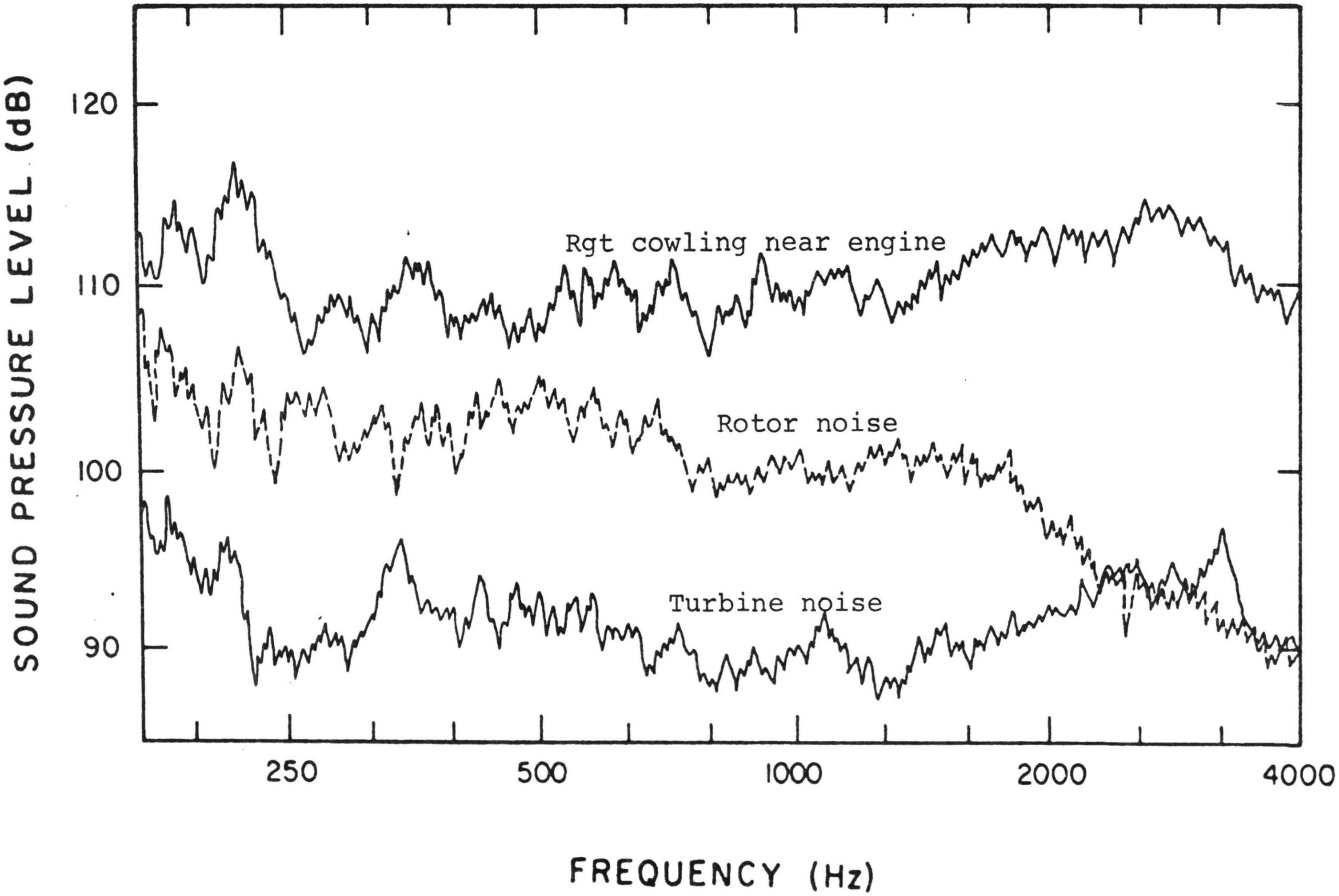


Figure 43. Selected noise sources, high frequency

HZ, 70 HZ, and 100 HZ. In the high-frequency region, it takes the form of background noise with four definite peaks near 315, 475, 1100, and 3150 HZ.

Rotor noise has very large peaks in the region 20 HZ to 100 HZ and then begins to generally decrease at a rate of about 2 dB per octave. The noise measurement made on the engine platform with the right cowling removed increases through the low-frequency range at about 6 dB per octave, levels off at about 63 HZ, and maintains a gently upward trend through the high-frequency region up to 3000 HZ. The two dominant peaks, located at about 50 HZ and 63 HZ, protrude about 10 dB above the background noise.

C. Spectrum Analysis Correlation

The correlation of the sound levels produced by helicopter noise sources with their contributions to the overall noise level was based on three methods. The first attempt drew upon past information to provide the general guidelines and initial approximations. The second method was the compilation of the main UH-1H noise-generating mechanisms from military manuals, government technical documents, and non-government publications. The third method compares the frequency plots of the noise sources with similar frequency plots of the overall noise level. When the noise sources coincide with the overall noise, that frequency is noted and tabulated. In this manner, the most important contributors are identified.

The first method relies on Table 1 of this study to furnish the frequency distribution of gear noise-generating mechanisms for a similar model helicopter, that of the UH-1D. Figure 44 illustrates data adapted from Stuckey and Goddard[78] directing attention to main and tail rotor noise contributions in the UH-1A helicopter. Summaries note that this is data on work done by previous authors. It was found that this information is not enough to adequately describe the actual correlation but rather was a starting point. The second method, summarized in Table 16, more accurately describes the main noise-generating mechanisms of the helicopter studies, the UH-1H. The third method, that of actually comparing shapes of analyzed data, proved to be the most accurate, combined with initial approximations furnished by methods 1 and 2. The analyzed data was replotted on both low and high-frequency graphs, graphs of maneuvers matched by frequency spectrum shape with various known noise sources, and then annoted at the contribution frequencies with the appropriate name of the source. Figures 45 and 46 display the results of this shape matching between the source and its affect on the cabin noise spectrum. Note that the large peak in the low-frequency region, about 10 Hz, is not included in this analysis as it lies below the frequency response of the microphone used to record the original data.*

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*General Radio 1560-P5 microphone

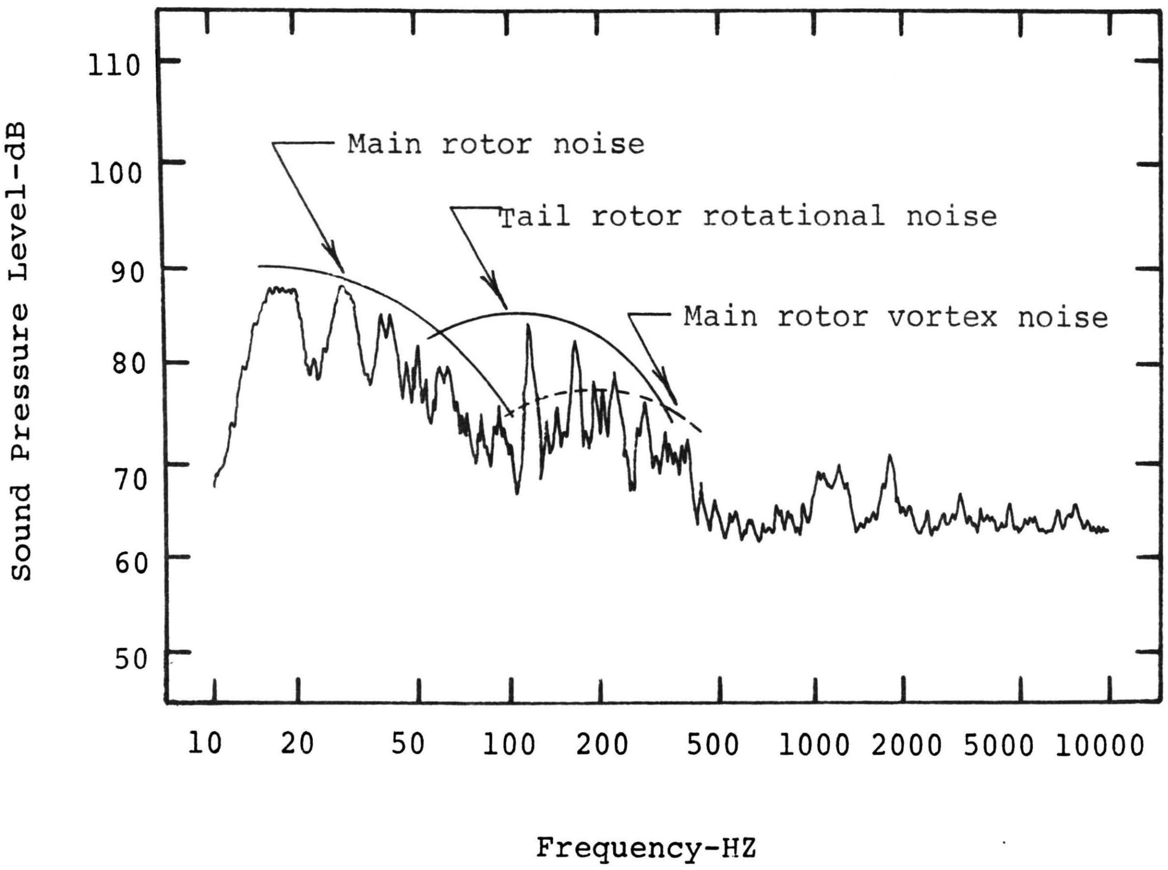

Figure 44. UH-1A noise spectrum

Table 16. Main UH-1H noise-generating mechanisms.*

Frequency	Item	
5.5	main rotor	rotor
643	2nd stage planetary	main transmission
1074	90° bevel	tail rotor transmission
1863	tail rotor output shaft	main transmission
1935	42° bevel	tail rotor transmission
1986	1st stage planetary	main transmission
2727	Tach drive shaft gear	acces. drive gearbox
2833	lower center shaft bevel	main transmission
2973	oil shaft gears	acces. drive gearbox
3190	input drive shaft-6600 rpm	main transmission
3590	2nd stage pinion	engine gearbox
4162	acces. drive gear	acces. drive gearbox
4510	generator quill	main transmission
6150	1st stage pinion	engine gearbox
10595	acces. drive pinion	acces. drive gearbox

*Adapted from Johnson and Katz[79]

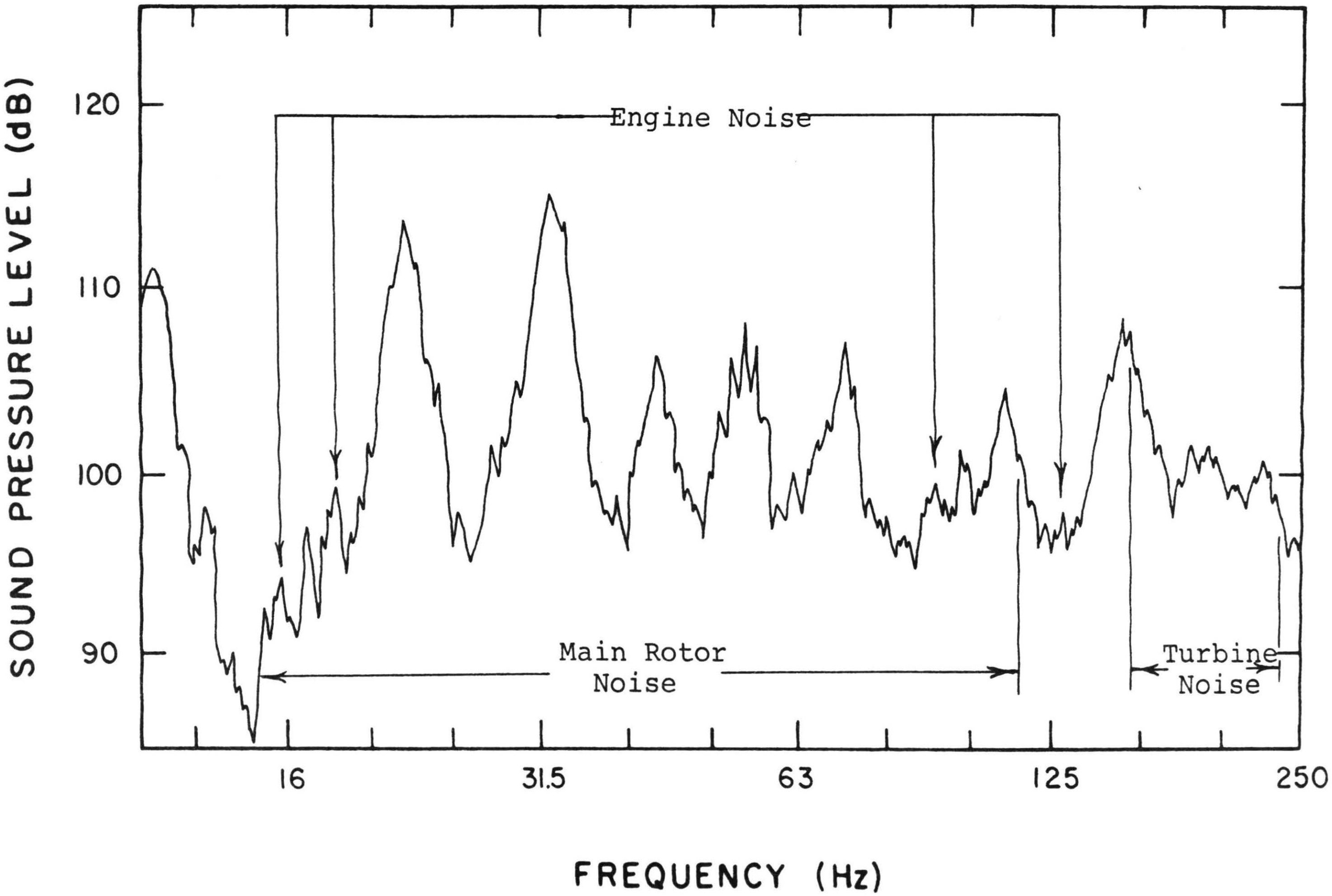

Figure 45. UH-1H noise correlation, low frequency

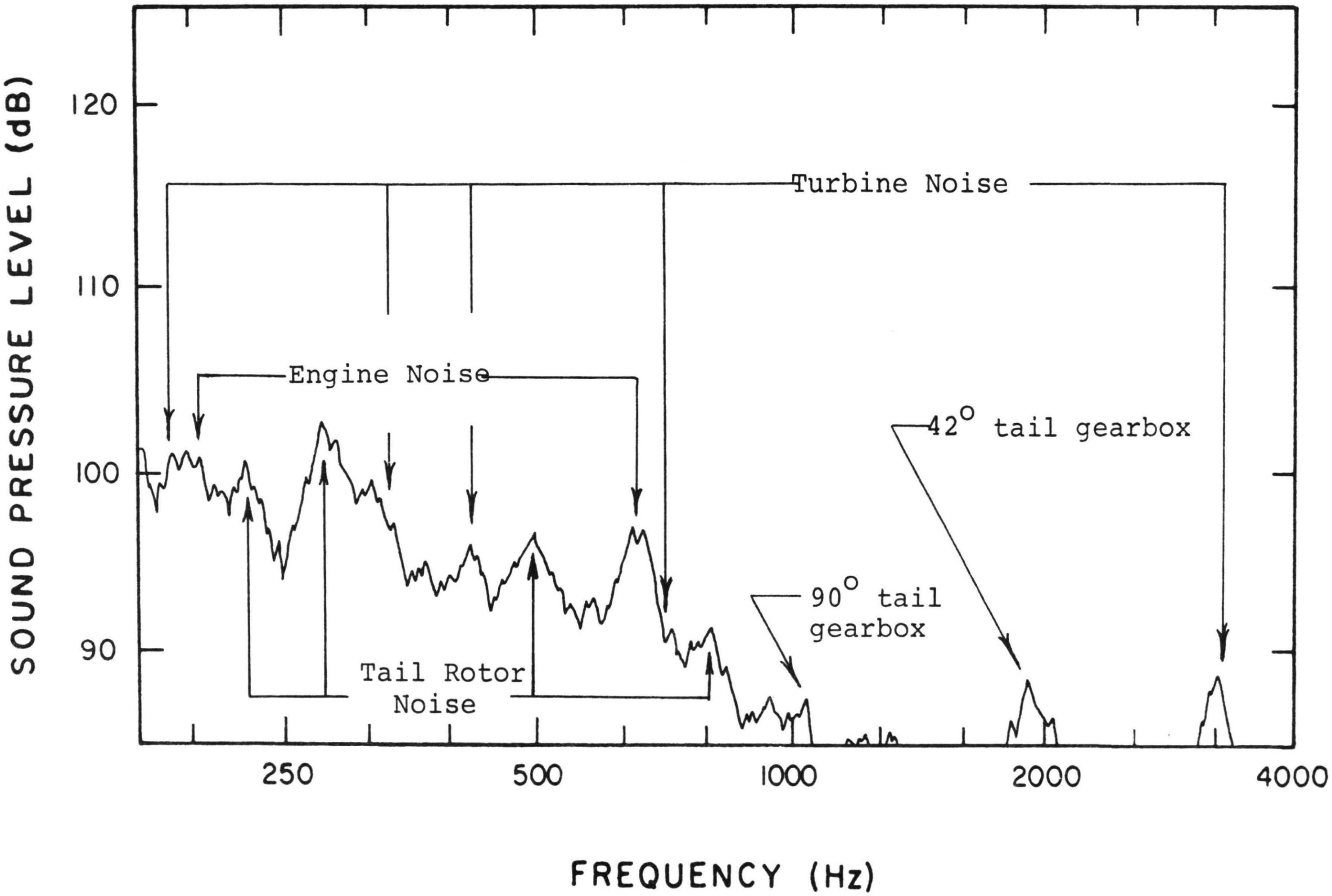

Figure 46. UH-1H noise correlation, high frequency

D. Discussion of Results

The most important fact resulting from this study is that noise levels, even with sound proofing installed and doors closed, are still too high. Additionally, this excessive noise is caused by engine noise and main rotor noise in the low-frequency region, by turbine noise in the mid-frequency region, and by a combination of engine noise, turbine noise, tail rotor noise, and gear noise in the high-frequency region. Noise reduction must consider all sources as a whole and not just eliminate one source.

The 1/10-octave analysis using the A and 20 KHz weighting networks for the level flight maneuver was used to estimate the octave band levels. The 1/10 octave-band levels were combined into 1/3 octave-band levels then combined by the energy method to give estimated octave-band levels. Realizing the inherent rounding-off errors, the estimation was purposely made conservatively. As a check on its accuracy, the estimated octave-band levels resulted in an overall sound level of 119 dB, or equivalent 101 dBA. These figures compare favorably with the actual noise survey conducted in UH-1H helicopter during level flight, which produced maximum values of 117 dB and 97 dBA. The computed estimations are within 2 and 4 dB, respectively, and verifies the correctness of the use of 1/10-octave frequency analysis.

Figure 47 shows the three curves which are the basis for the discussion of required noise reduction. The top curve is the flat weighting curve of interior noise in the helicopter cabin and the dashed line is the same maneuver, level

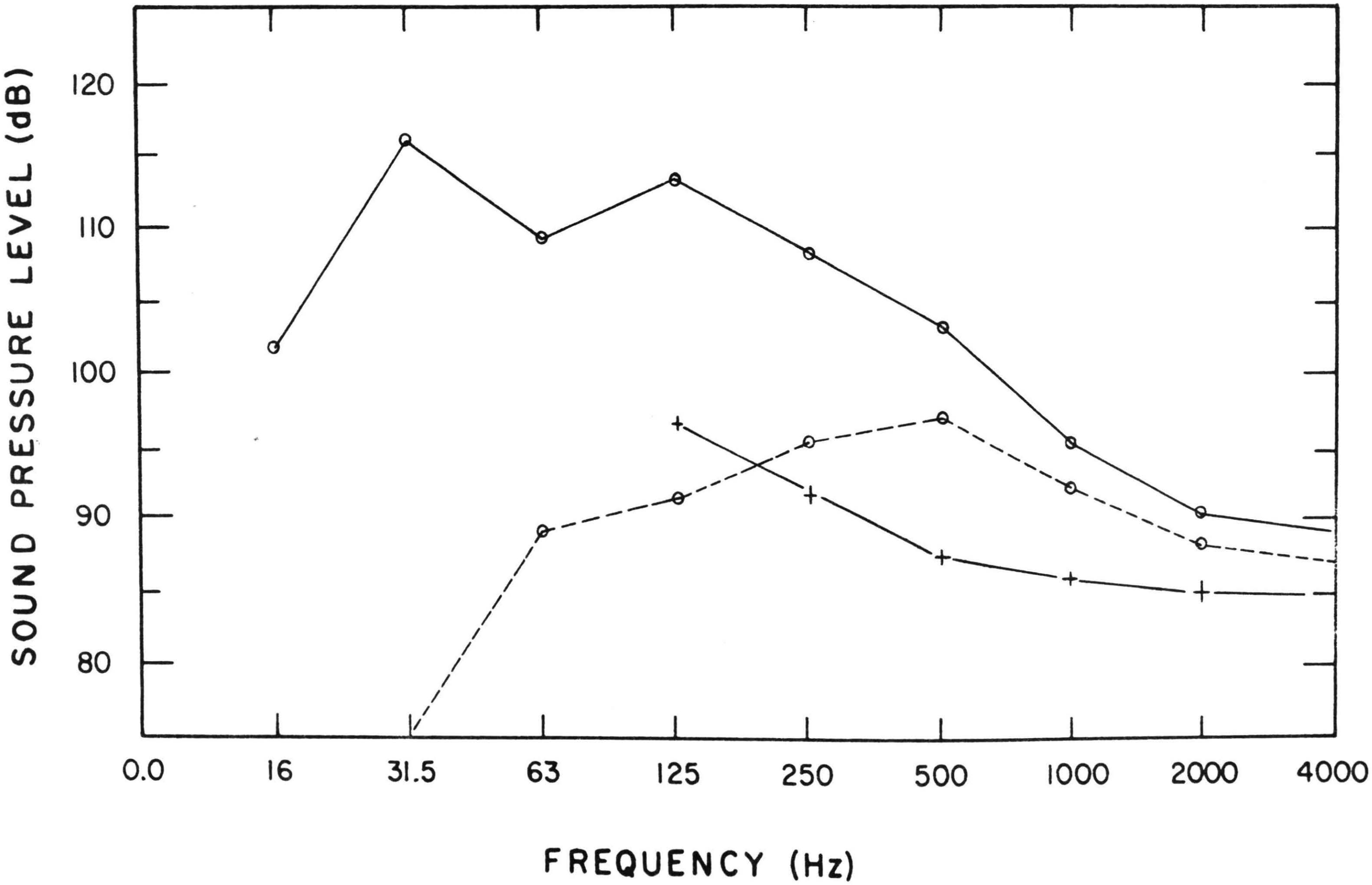

Figure 47. UH-1H measurements and 8-hour exposure criteria

flight, but weighted on the A network. The curve in-between is a general exposure criteria curve from Sommer, et al[76], for an 8-hour day. The attenuation required for a person exposed to this helicopter noise over a period of time is then the difference between the dBA curve and the exposure-criteria curve. Figure 48 shows how much attenuation is required at specified frequencies.

Interior helicopter noise produces adverse effects on the occupants of the aircraft. Noise control techniques can reduce these effects from its inception. Lowson[80] notes that there is little possibility of eliminating all sources of noise, but if the noise could be reduced, it is better to design from the start to meet any required noise limitations. Sternfield[81] suggested that attention to noise control, in considering initial layout and component arrangement of the aircraft, can be made to pay rich rewards by taking maximum advantage of the natural attenuation of the helicopter structure. He also suggested that noise may be further reduced by providing circuitous air borne routes for directly radiated noise wherever possible. Seebold[82] provides an incentive for designing-in the applicable noise control, because he states that after startup, noise-control procedures are generally less effective and more expensive. Loewy, et al[83], points out that there are even more physical reasons why prior design should include noise control. He states that it is generally accepted that, for reduction of frequencies below about 200 HZ, the reductions must be

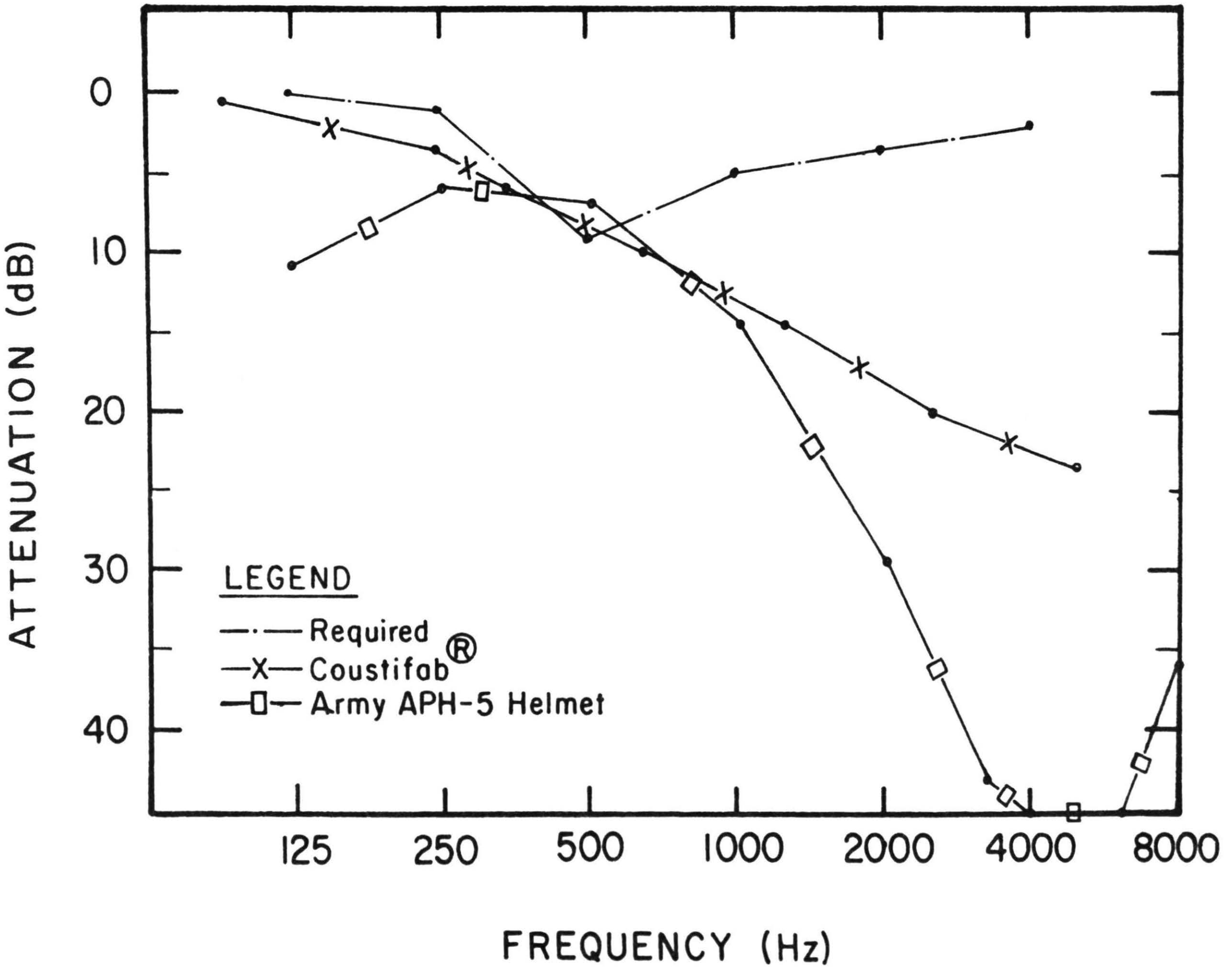

Figure 48. Required attenuation and solutions

achieved at the source because of the weight penalty caused by enough additional treatment for significant attenuation.

Generally, there are three main elements in all acoustical problems; the sources, the path, and the receiver. There are four methods of noise control used in helicopters, noise control by design, noise control at the source, sound proofing, and ear protection. If noise control by design is not feasible, then the three other methods must be used. Sternfield[81] lists three acoustical paths noise may take to invade the passenger compartment: airborne path, dynamic system conduction, and direct radiation. All three paths must be effectively blocked before adequate noise control is achieved. Miller, Branch, and Sternfield[84] list general steps for the application of treatment after the noise sources are identified and the transmission paths traced.

In the case of noise control of the helicopter, specific treatments to the cabin include:

(1) Skin-damping tape
(2) Wall and ceiling blankets
(3) Cabin bulkheads
(4) Windshield improvement
(5) Door sealing
(6) Ventilation-duct treatment
(7) Floor covering.

Additional, more complex, treatments which should be considered are the substitution of sandwich-type aluminum fuselage skin for the thin solid skin currently in use. If this type of skin, which effectively absorbs a larger magnitude of sound than one of solid construction, cannot be used for all cabin surfaces, then it should at least be used for the roof of the cabin as a minimum measure. The cabin's roof receives almost all of the main rotor's direct noise radiation and this should be designed for maximum attenuation within the weight limitation.

In the field of noise control, however, simply writing a specification gives very little assurance that noise limits will be met. Suggested solutions to the control of noise in the UH-1H helicopter should be tested in laboratories for exact acoustic performance. Many solutions were considered but most were rejected because they simply did not provide the required acoustic attenuation or they did not meet the weight limitation. In this study, it was assumed that a weight of 1/5 lb. per square foot was a reasonable weight limitation for the UH-1H. Figure 48 indicates the attenuation required in the cabin for unprotected ears. Figure 48 also displays two possible solutions, a lead-loaded vinyl and the Army APH-5 helmet. Because not all crew and passengers will have an APH-5 helmet, it is recommended that consideration be given to the installation of the lead-loaded vinyl specified. The representative commercial product specified is .14 lb./ft.^{2} Constifab ^{R} and is a fiberglass fabric coated with the lead-loaded vinyl. It is acoustically limp, flexible, and thin, but high in density. The estimated cost of installation is about $1 per square foot. Other weights were considered but while heavier sheets gave larger values of sound attenuation, they were simply too heavy for a military helicopter flying military missions. The vinyl specified will bring overall noise pressure levels down to meet the 60 minute duration specified earlier as a criteria or down to about 88 dBA on an average.

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VITA

Charles Estephen Perez, Jr., was born in Arlington, New Jersey on September 6, 1943. Between the ages of six weeks and five years, he traveled to Denton, Texas; Peekskill, New York; San Francisco, California; and Tokyo, Japan. Following Japan, Mr. Perez attended various elementary schools in New Orleans, North Little Rock, Chalmette (near New Orleans), and Wahiawa (Hawaii). He attended junior high and high schools in Pemberton, New Jersey and Rolla High School, Rolla, Missouri, where he subsequently graduated in June 1961.

In September 1961, Mr. Perez began work toward a Bachelor of Science Degree in Mechanical Engineering at the University of Missouri - Rolla supported in part by a Fort Leonard Wood Officer's Wives Club Scholarship and part-time employment with a Rolla firm. Mr. Perez was married November 19, 1966, received his degree in January 1967, and accepted employment as a Development Engineer with E. I. duPont in Louisville, Kentucky. He was called into military service in February, 1967 and subsequently served in Georgia, the Federal Republic of Germany, Alabama, and the Republic of Vietnam. In Vietnam, he was awarded the Bronze Star Medal.

Mr. Perez began a program leading to a Master of Science Degree in Mechanical Engineering in January, 1971, under the U. S. Army's Advanced Civilian Schooling Program. He is a citizen of the United States of America.

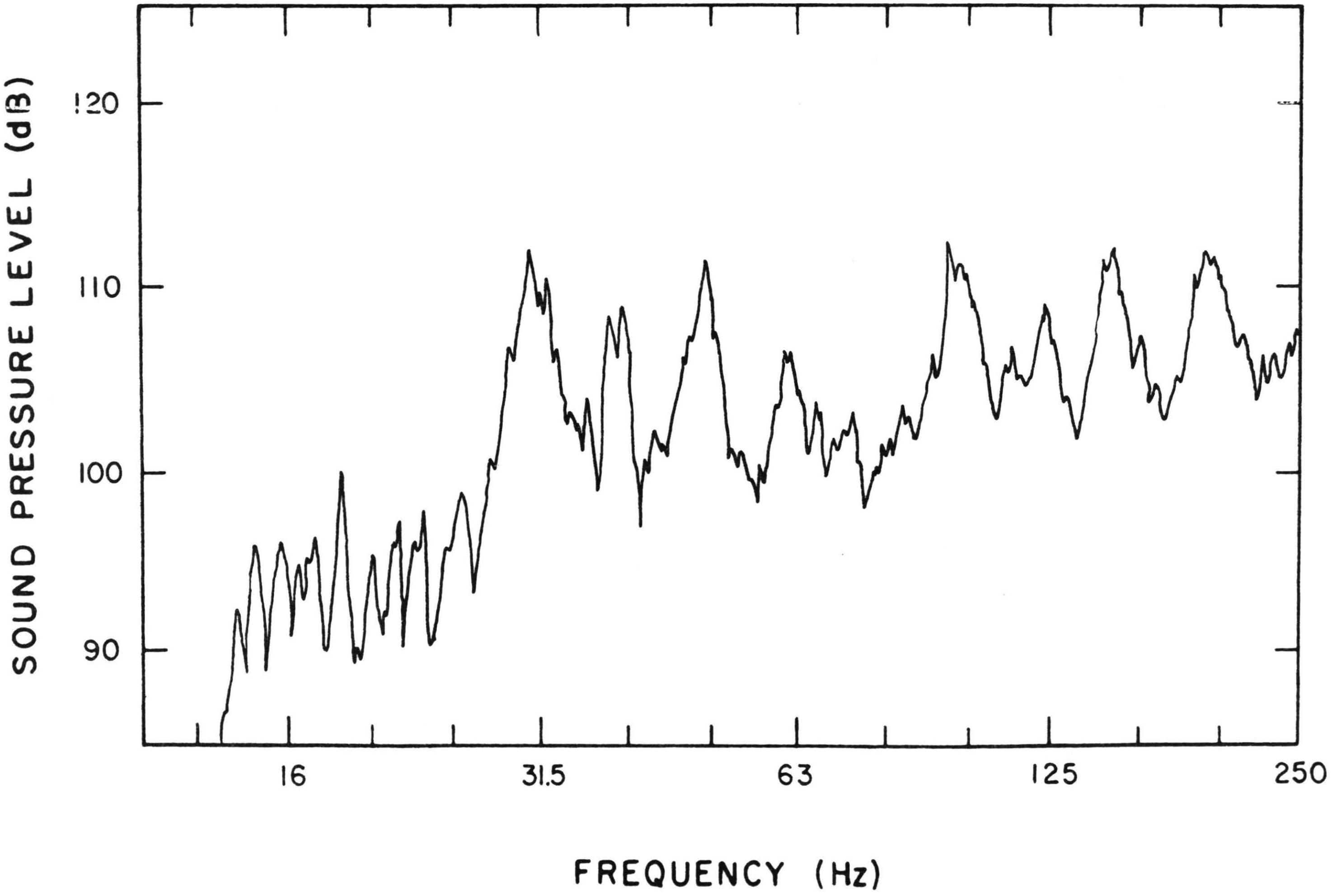
APPENDIX A

OH-6A FREQUENCY ANALYSIS

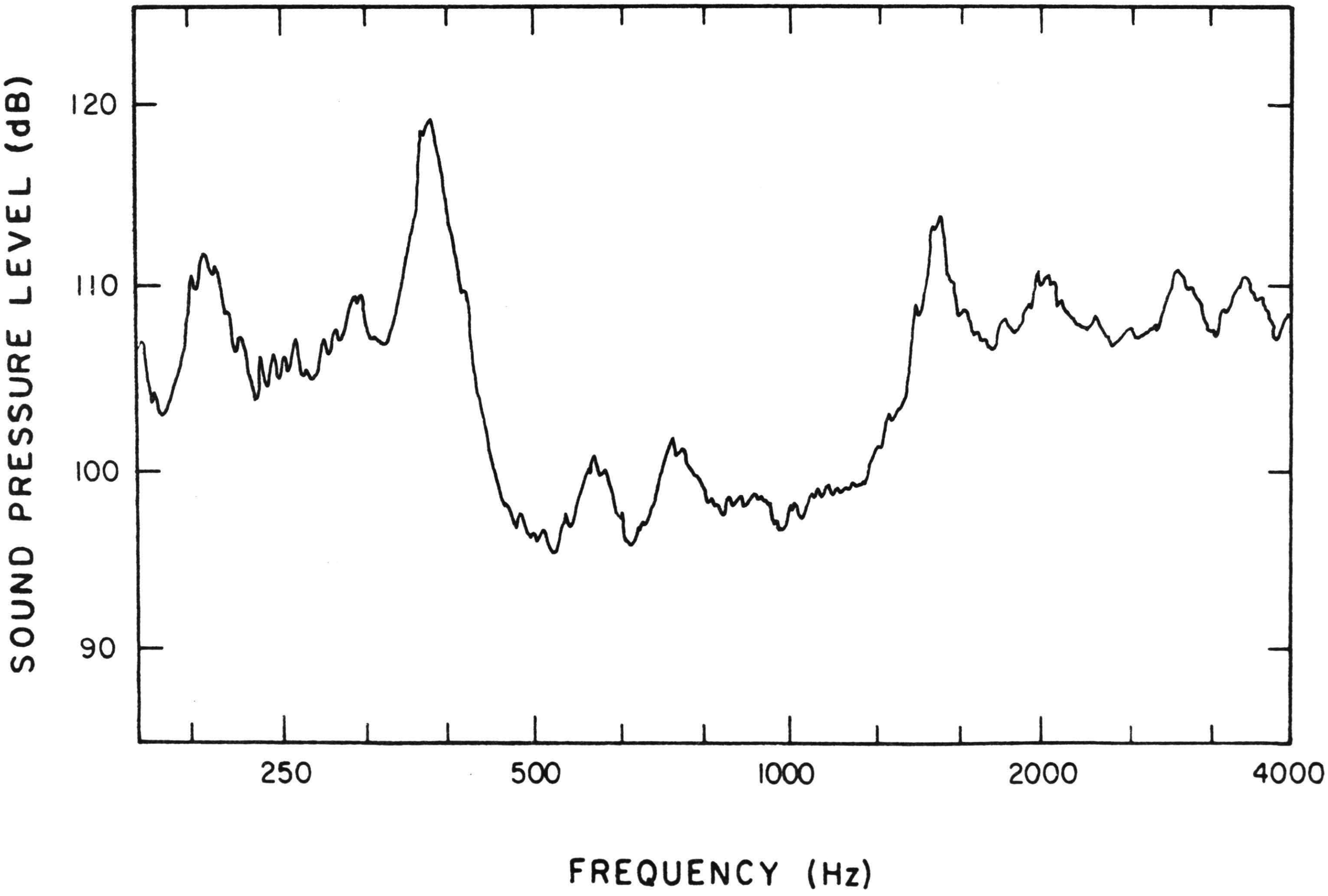
One complete test flight was completed with the OH-6A helicopter performing similar maneuvers as the UH-1H helicopter. An analysis, similar to that done with the data resulting from UH-1H frequency analysis, was accomplished for data resulting from the OH-6A flight. As before, level flight was chosen as the most convenient maneuver condition and the results of the frequency analysis are displayed in Figures A-1 and A-2. It is interesting to note that the OH-6A unweighted or "flat" frequency spectrum contains major dB peaks in a higher frequency range than that found in the UH-1H. In the frequency range from 31.5 HZ to 315 HZ, pure tones and thin harmonics can be recognized but with no one being predominant. After a predominant db peak near 400 HZ, the magnitude drops 20 dB until 1500 HZ where a steady value is reached.

Figures A-3 and A-4 display the effect of the A-weighting scale on the cabin noise levels. This weighting seems to emphasize the pure tone located near 400 HZ and attenuates the lower frequencies. In the higher frequency region above 1500 HZ, the A-weighted frequency spectrum is very similar to that of the unweighted frequency spectrum, both average about 102-104 dB.

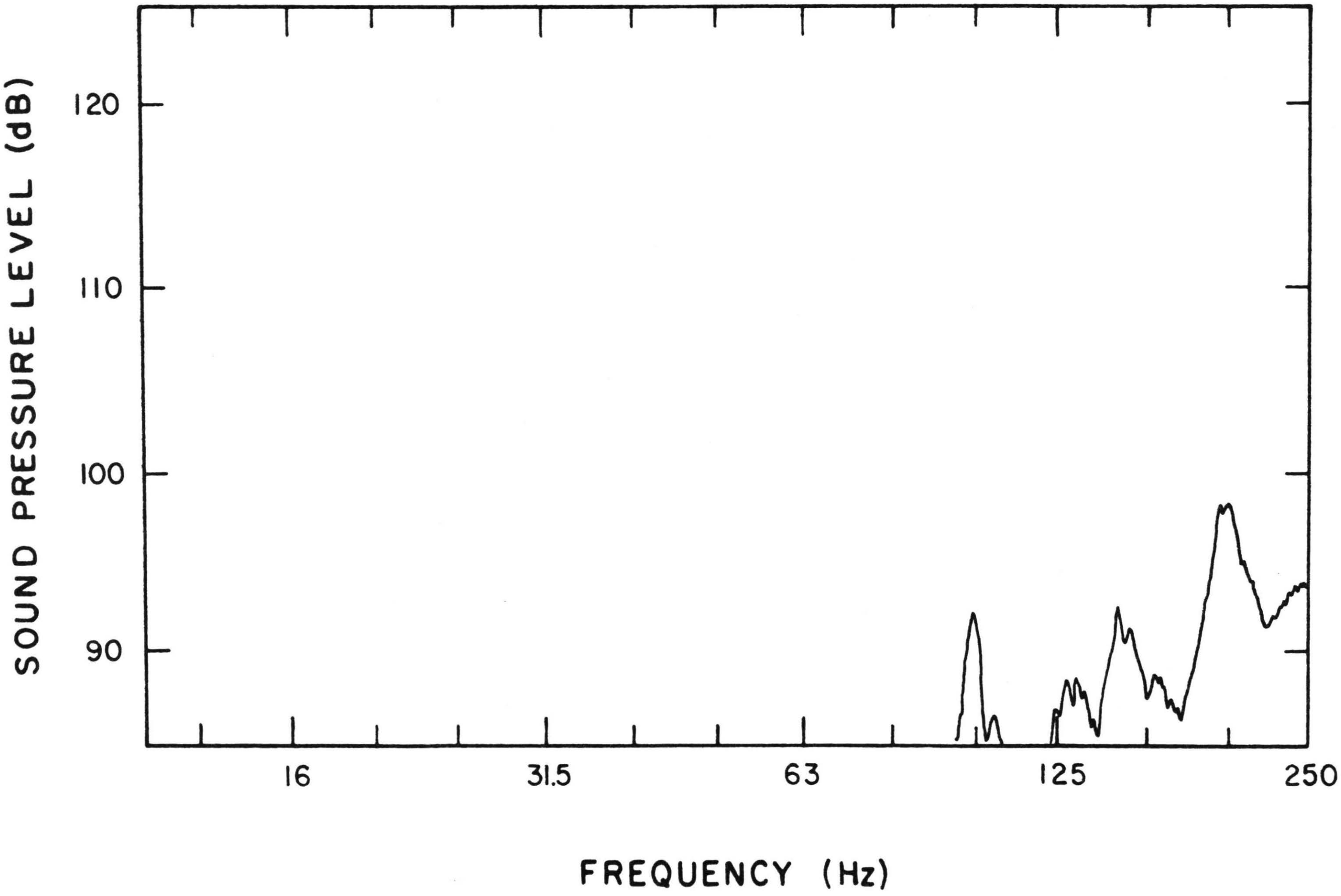
Because only one flight was completed, the data presented herein should be taken as an indication only of the possible causes of OH-6A cabin noise. Additional flights, concentrating on level flight or a similar steady-state condition, should be accomplished and the data recorded for laboratory analysis and comparison.



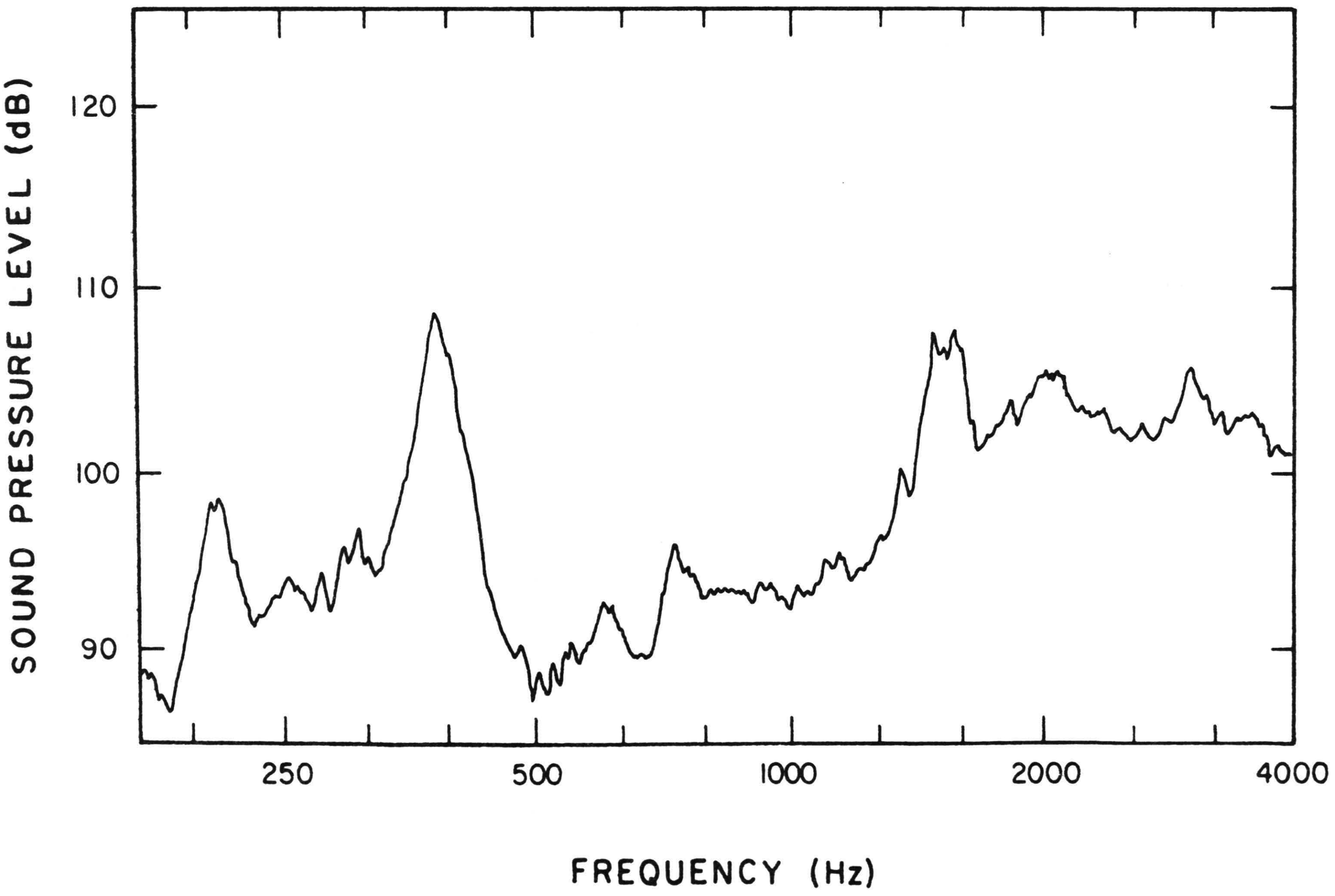
A-1. OH-6A level flight, 20 KHz scale, low frequency



A-2. OH-6A level flight, 20 KHz scale, high frequency



A-3. OH-6A level flight, A scale, low frequency



A-4. OH-6A level flight, A scale, high frequency