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# NOISE ENCOUNTERED IN ROTARY-WING AIRCRAFT

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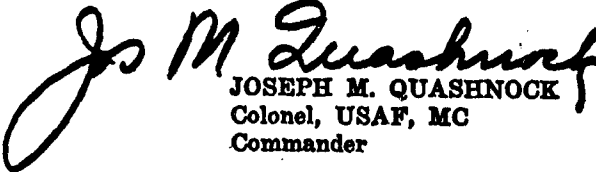
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## FOREWORD

This research was conducted in the Otolaryngology Branch under task No. 77508 between February 1962 and April 1969. The paper was received for publication on 8 October 1969.

This report has been reviewed and is approved.

  
JOSEPH M. QUASHNOCK  
Colonel, USAF, MC  
Commander

## ABSTRACT

The acoustic environment within rotary-wing aircraft consists of a mixture of noises. This report identifies, describes, and illustrates the primary and secondary noise-producing mechanisms associated with helicopter operation. The noise sources include main rotors, antitorque rotors, main and secondary transmission and gear-shaft distribution systems, and auxiliary power units. In addition to describing specific noise generators, the report presents composite noise envelopes illustrating typical noise environs of rotary-wing vehicles having different configurations of rotor-to-power plant matings. Alterations in internal noise which occur during conditions of hover and forward flight are described and aeromedical factors such as speech interference and potential auditory risk are identified.

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# NOISE ENCOUNTERED IN ROTARY-WING AIRCRAFT

## I. INTRODUCTION

Less than half a century has passed since the first crude, but workable, rotary-wing vehicle took to the air. Juan de la Cierva of Spain made the first breakthrough with his C-4 autogiro. His historic flight took place at Madrid, Spain, on 9 January 1923.

Those who observed this "first" had a vision of things to come but few, if any, could envisage the kaleidoscopic future which would be enjoyed by vehicles known as "helicopters." Operational applications to which rotary-wing aircraft may be adapted challenge the imagination. Truly, the helicopter has come of age.

This report explores and describes basic noise characteristics of rotary-wing aircraft. Not only is the noise generated by one vehicle different from that created by another, but the character of the noise produced by a given vehicle also tends to vary depending on the type of operational mission flown.

It is incongruous that the by-product of the helicopter—noise—has become a factor which places very real limitations on the operational use of these aerospace vehicles. Design engineers, medical personnel, and bioenvironmental engineers continually seek solutions to the noise problem. One advancement which has reduced the magnitude of both internal and external noise associated with the operation of helicopters is the use of turboshaft power plants. Even with the reduction in acoustic noise thus achieved, much still remains to be done. Every major designer and manufacturer of rotary-wing vehicles is aware of the need to reduce acoustic noise associated with the operation of these aircraft.

This report identifies, describes, and illustrates primary and secondary noise-producing mechanisms associated with the ground and airborne operation of rotary-wing aircraft.

## II. BASIC POWER PLANTS

Rotary-wing aircraft depend on either of two basic types of power plant: reciprocating or turboshaft (10). Since its first use in powered flight, dramatic improvements have been made in the reciprocating engine, but by the close of World War II it was evident that the development of the reciprocating engine was swiftly approaching a point of diminishing returns (9).

Although the evolution of the shaft-turbine engine is rather recent, its adaptation as a power plant for helicopters has been extensive. In fact, the wide acceptance and use of helicopters to fulfill a variety of needs is largely the result of the development of the shaft-drive turbine (9).

Ramjet and pulse-jet engines have not been developed and used as extensively as reciprocating and turboshaft engines but may be utilized to a greater extent in future aircraft. Unfortunately, these two types of engines generate rather intense noise and, therefore, their acceptance as primary power plants for use in rotary-wing vehicles requires further breakthroughs in acoustic design. In this report, the noise characteristics of each of the power plants of major concern are discussed. The noise of ramjet, pulse-jet, rocket, turbojet, and turbofan engines is not discussed in detail.

Many advantages are realized with the use of turboshaft engines: economy of operation,

reliability, ease of maintenance, reduced weight, and many other desirable features. Although reciprocating engines will continue to be improved and adapted to use in rotary-wing vehicles, the turboshaft family of engines will continue to enjoy preeminence.

### Reciprocating engines

Reciprocating engines, especially the larger and more powerful ones, present noise problems which are greater than those encountered with the use of turboshaft power plants. Generally, the magnitude of the noise created by reciprocating engines is greater both within the helicopter and at outside locations during almost all phases of ground and airborne operation. As will be demonstrated by this report, the primary noise-generating component associated with the operation of a helicopter powered by a reciprocating engine is the engine itself, whereas the noise produced by turboshaft engines used in helicopters assumes a secondary role of significance.

Noise generated by a reciprocating engine may be greatly influenced by the type of aircraft to which the engine is mated, the size and power of the engine, and the type of exhaust system employed. Also, the closer the engine is to occupied areas within a vehicle, the more significant will be the resulting noise generated by the power plant (6).

Noise generated by reciprocating engines may be quite complex. Many and varied internal components can have a direct influence on the noise. The most significant contributors are exhaust noise, engine-casing and resonance noise, noise from gears and shafts (including bearing supports), piston friction, and impacting noises (3, 9, 13).

*Engine-to-aircraft vibration.* During certain phases of operation reciprocating engines, especially large engines, may produce considerable vibration. This vibration may be propagated through the mountings of the engine to the fuselage structures of the vehicle. The vibrations are most noticeable

when the engine is operating at very low power (r.p.m.); when the engine is placed under heavy power loadings (especially if the engine is at a low power setting when the heavy power loadings are reapplied); and when internal components and moving parts are imbalanced or defective (14). The extent to which vibrations are noticeable depends strongly on the type of engine, its relative location with respect to occupied spaces, the type and condition of its isolation mountings, and the type of vehicle to which the engine is delivering power. One unique vehicle-to-engine mating is that found in the Sikorsky CH-37 series of helicopters, a design that propagates only minor engine-induced vibration. The CH-37 is powered by two large radial reciprocating engines, mounted within pods and attached externally to the fuselage by short pylons, one engine mounted on the left and the other installed on the right side of the main fuselage.

Structural vibrations may result within rotary-wing aircraft when high torque is placed on the engine by the rotors, or by the transmission system. In some instances, depending on the location and type of transmission mounted between the engine shaft and the main rotor shaft, the intense low-frequency vibrations produced by a rotor may result in direct feedback to the shaft of the engine, thus producing secondary engine vibrations (9).

*Noise from gears and shafts.* Since the main shaft of reciprocating engines rotates at speeds far greater than shaft speeds required for delivery to rotors and antitorque rotor units, provision must be made to reduce the higher speeds of the main shaft of the engine to the lower shaft speeds of the rotor. This requirement is especially important because the blade-tip velocities achieved by a large-diameter rotor can be very high even at relatively low revolutions. At a constant shaft speed, the larger the diameter of a rotor or propeller, the higher the blade-tip velocity. This physical phenomenon can be most easily imagined by visualizing a string of ice skaters performing a single-spoke wheel turn—the skaters at the outer ends of the spoke are traveling very fast, sometimes at the limits



of human capability; whereas the skaters near the hub of the spoke are moving around the circle very slowly.

It is, therefore, evident that the shaft speeds of large reciprocating engines could rotate rotor tips at velocities near the speed of sound. This could set up undesirable forces within the rotor system which could result in structural failures of both rotor and engine—hence, the development of reduction gearing. (See section IV for description of various types of gears.)

Although gear-reduction systems, as isolated components, may generate intense noise, they normally do not generate significant noise when utilized and operated as a functioning part of a complete engine (2). The only instance in which noise from these units might be considered significant would be in the event a sophisticated exhaust muffler system was used. Noise generated by a gear-reduction system employed with a reciprocating engine would probably be found in the planetary gear system which utilizes spur gears. In this case, the noise would result from gear teeth impacting and would be most pronounced during high speed and high gear force loadings (2, 3, 9, 12, 13). In any event, this noise would be significantly reduced by the structure of the engine housing and somewhat by the damping offered by the fluids present within the casings of the engine.

Gear-reduction systems in larger reciprocating engines produce more noise because of a higher ratio of gear reduction, particularly if these engines are placed in the fuselage area of rotary-wing aircraft.

*Exhaust system.* One of the major noises associated with the reciprocating engine is produced by the exhaust. Exhaust systems may be very simple devices (as in very small engines) or they may include intricate inter-related components. Generally, an exhaust system includes all manifolds or stacks that collect and conduct exhaust gases from the cylinders of the engine to points of discharge.

Generally, the closer the exhaust duct opening is to the engine cylinders, the greater is the noise resulting from cylinder firings. The magnitude of exhaust-generated noise is somewhat reduced when the exhaust gases travel through secondary paths which partially absorb kinetic energy before the gases are expelled through the exhaust port. Turbo-supercharger mechanisms are usually employed with fixed-wing aircraft but not with helicopters; therefore, noise associated with exhaust gas expulsion is not attenuated in rotary-wing aircraft to the same degree as in fixed-wing vehicles.

Mountings of the exhaust system may also influence the noise generated by the exhaust. If structurally mounted, the exhaust tubing is directly supported by the aircraft structure and mated to the engine by flexible coupling. Thus, a direct avenue of noise and vibration from the exhaust, as well as the engine, is established. If the exhaust tubing is engine-mounted (connected directly to the engine), noise and vibration are not communicated directly to the structure of the vehicle. Even when not transmitted structurally by direct contact, the exhaust noise can be propagated to surrounding structures and areas by acoustic excitation, especially if the exhaust port is near areas or compartments containing modes of natural frequency resonance (14, 15).

Engine exhaust noise is generated by the expulsion of the hot combined gases through a manifold exhaust tube or directly from the cylinders of the engine. This noise coincides with the periodic expulsions of the gases and is most pronounced in the lower frequencies. Exhaust noise is related to the number of engine cylinders, the rate of discharge (depending on engine speed), and the type of exhaust ducting and muffler system used. If the exhaust ducting system is such that excessive dynamic pressures are built up before the exhaust gases are dumped, the exhaust gases, when released, may create shock waves which generate a significant increase in the magnitude of the exhaust noise (9).

The dominant frequency of the noise generated by exhaust expulsions closely corresponds to the frequency of engine cylinder firings (9). Generally, the frequency spectrum of the noise produced by exhaust systems demonstrates progressive shifts into a slightly higher frequency range as engine speed increases. Increases in shaft torque usually create increases in engine cylinder pressures which tend to generate acoustic noise components that likewise increase in magnitude.

An example of exhaust noise is illustrated in figure 1. These measurements demonstrate engine and exhaust noise generated by the reciprocating engine in a CH-21C (Shawnee). The CH-21C is powered by a Wright R1820 radial, single-row, reciprocating engine. The engine is mounted within the fuselage aft of the cargo compartment (see fig. 5). Power from the engine is transmitted to the mid-transmission and from it, longitudinally, to the fore and aft transmissions where the rotational speed is reduced for delivery to the tandem rotors. The engine itself does not contain

gear-reduction systems. The speed of the drive shaft located between the engine and the main transmission, including the area between the transmissions, is the same as the engine shaft speed. The engine is also fitted with a single-stage, 2-speed supercharger unit for high-altitude operations. The measurements shown in figure 1 were completed while the engine was operating and the tandem rotors were disengaged. The measurements were completed on sod and the distances and angles were measured from the exhaust port on the right side of the vehicle.

A good example of the shift in the frequency spectrum of the exhaust noise which results from increased engine speed is shown in figure 1. These noise measurements were made at a position directly beneath the engine exhaust port. As the engine speed increased from 1,500 to 2,500 r.p.m., not only did the overall noise level increase about 5 dB, but there was a significant shift of the peak intensity from the 75-150 Hz octave band to the 150-300 Hz octave band. A noticeable increase also occurred in the acoustic energies produced in the higher frequency range.

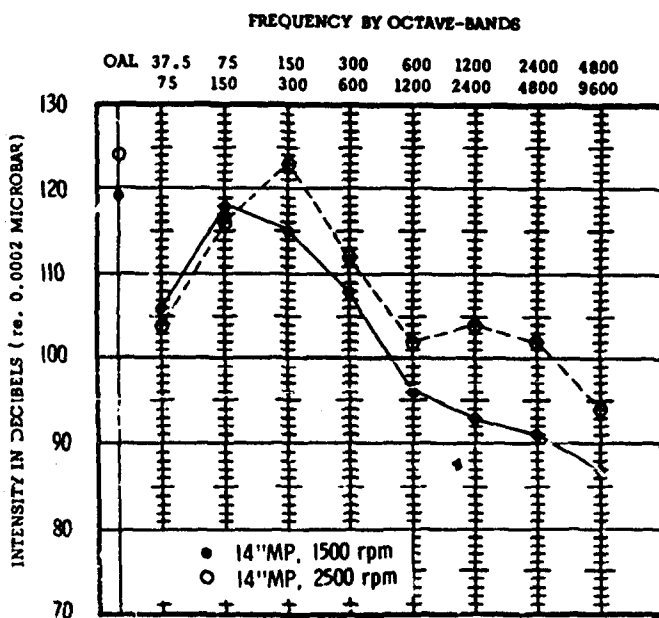


FIGURE 1

Example of engine exhaust noise measured in the vicinity of a CH-21C. Only the engine was operating and the rotors were not engaged.

Exhaust noise is predominantly low frequency, but higher frequency components are also generated. These latter are most pronounced at positions near the exhaust ports and most intense when the engine is operating at high power. This feature is also evident in the spectrum shown for the higher speed illustrated in figure 1.

Generally, the noise generated by the exhaust of reciprocating engines is most pronounced within the lower frequency range; therefore, acoustic components which are most intense are not highly directional.

An example of the directional characteristics of exhaust noise can be seen in figure 2. The measurements were made at a distance of 50 ft. from the center line of the left engine, and at positions of 0, 90, and 135 degrees from the front of the engine. The aircraft was a CH-37B. The rotors were rotating slowly, and did not produce noise levels great enough to

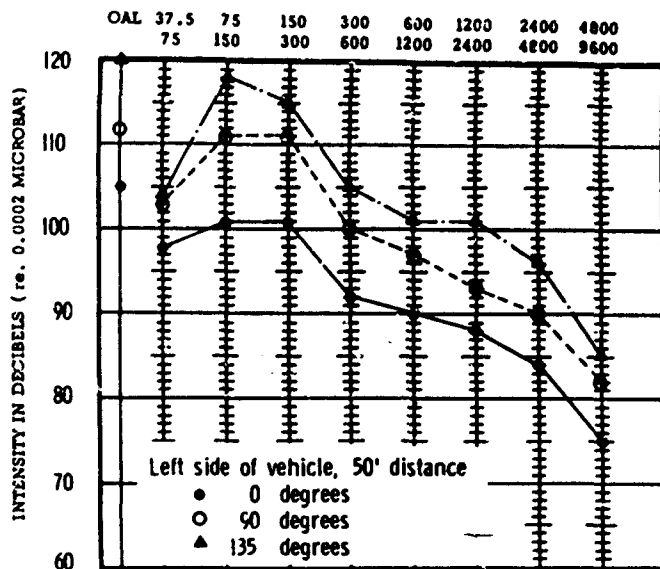


FIGURE 2

Noise levels measured at 3 locations near a CH-37B. The left engine was operating at 2,600 r.p.m. and 16 inches of manifold pressure, and the rotor was windmilling (measurements obtained at distances of 50 ft. from left engine pod directly in front of engine).

mask the noise being generated by the exhausts. The exhaust system on the CH-37B, a 2-port type located in the rear of the engine, dumps the exhaust gases directly aft of the engine. Note that as one moves toward the rear of the engine, the intensity of the noise increases. Since the most intense noise is distributed in the lower frequency ranges, the overall noise increased 5 dB when the observer moved from directly in front of the engine to a position of equal distance, but directly to the side of the engine, and increased another 8 dB when the observer moved aft of the engine to a position of about 135 degrees.

### Turboshaft engines

The size, type, and power ranges of turboshaft power plants are quite varied, and although design and construction characteristics differ from one type to another, all have certain basic characteristics: (1) each type has an integrated gas turbine engine that supplies the basic power; (2) each unit utilizes a gear-reduction transmission system to reduce the

very high engine shaft speeds to a slower rotor and antitorque shaft speed; (3) each system depends on a rotating rotor or propeller to obtain the thrust necessary to obtain powered flight; and (4) even though a gas turbine engine is utilized as the basic power plant, very little thrust is obtained from the jet exhaust from the engine. In the basic types of turbo-prop and turboshaft engines thus far utilized for fixed- or rotary-wing aircraft, these four basic characteristics are the same.

A basic functional component of turboshaft power plants is the rotor system which will be discussed in detail later. The major components to be considered here are the basic engine and the gear-reduction transmission systems, since these two components actually make up the inherent primary functioning parts of a given turboshaft power plant.

Turboshaft power plants contain functional components that closely parallel those found within turbojet engines. The basic difference is that the motive power supplied by the turboshaft engine is in the form of output shaft energy, whereas the turbojet power plant provides motive force by ejecting high-velocity exhaust gas through the tailpipe. Since the motive force of turboshaft engines is obtained by utilizing exhaust forces to propel turbine stages within the engine to deliver power to the output shaft, the exhaust gases which pass through the exhaust opening are greatly reduced.

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 and mixed with the 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 system which, in turn, supplies controlled torque to the rotor system. After the gases have passed through the turbine stages they continue to flow through the exhaust casing and are finally expelled into the atmosphere.

Since the main shafts of these engines operate at very high speeds, gear-reduction systems must be utilized to reduce the revolutions per minute to a lower shaft speed, but since the thrust provided by the rotor system is dependent on rotor blade pitch and, in turn, rotor speed, exhaust noise is not intense.

*Engine noise.* Turboshaft engine noise emanates from various noise-generating mechanisms. Some of the primary noise-producers are the compressors, turbines, and direct structural vibration. Noise generated by turboshaft engines is created in the compressor stage(s) of the gas turbine generator and radiates through the intake duct to the outside. Recently, significant reductions in the magnitude of noise produced by the compression stages of turboshaft engines have been achieved by the use of specially designed intake ducts and airflow channels (9).

The compressor sections of one large family of turboshaft engines fitted in several helicopters employ 5- or 6-stage axial flow (initial) and a single centrifugal stage (T-53 turboshaft engines).

Turbine shaft exhaust noise is of little significance because the gas turbine engine is small and the majority of the thrust is converted into torque power. In any event, a small degree of kinetic thrust is obtained from the exhaust which flows through the exhaust duct of the engine.

In general, the major noise problem associated with the operation of turboprop power plants arises from the compressor. Compressor noise is most evident during ground operations and is most pronounced at locations in front of the engine. Compressor noise is most evident in the higher frequency ranges and tends to become less evident as engine speed increases. Because of the distinct spectrum differences between the noise generated by the rotors and that generated by the compressor, the compressor noise may be quite noticeable even though it is less intense than rotor-generated noise.

Some of the major sources of noise generated by turboshaft engines are (1) compressor stages of the engine; (2) exhaust gases emanating from the engine exhaust duct nozzle; (3) structural vibration of engine, engine mountings, and areas surrounding engine (this includes acoustically induced structural vibration); and (4) the engine drive system, including bearing, gear, shaft distribution, and accessory drive systems (2, 3, 9, 12). Of these, compressor and turbine noise, direct-drive (nonreduced) shaft noise, and engine exhaust noise are of major concern. The majority of turboshaft engines are mated to rotary-wing aircraft and the noise generated by the rotor and antitorque rotor gear-reduction units also represents a significant problem.

*Compressor noise.* Compressor noise is the result of disturbances caused by the passage of air through the compressor stages of the engine. The frequency characteristics of the compressor noise are determined by the rotational speed of the compressor blades, the number and relative position of the stator blades, and the number of blades in the compressor unit. The noise of multistage compressor units is usually determined by the first-stage compressor units, but in some instances the latter stages may contribute to the total noise. Multistage compressor units usually vary in diameter. Normally the larger wheels are located nearer the intake and may have a different number of blades per wheel or unit. Differences in the number of blades, varying compressor disc diameters, and varying rotational speeds create different fundamentals and harmonics. As the engine operates at a varying speed, the spectra of the noise also vary or shift frequency. Generally, as the speed increases, the most intense acoustic components generated by the compressor move into the higher frequency range (9).

The noise produced by the compressor: (1) is most intense in the higher frequency range; (2) usually contains narrow-band noise components; (3) is highly directional in its pattern of propagation; (4) becomes less audible as the speed of the engine increases; (5) attenuates rapidly with increasing distance;

and (6) is easily attenuated by fuselage structures and by acoustic treatment of intake (9).

*Exhaust noise.* Noise associated with the exhaust of most turboshaft engines is not an outstanding problem because most exhaust energy generated by the engine is converted into torque shaft energy by the turbine stages of the engine before being expelled through the exhaust port. Thus the exit velocity of the exhaust gases is relatively low (3). These factors, combined with turbulent mixing of the exhaust, create an exhaust noise that is significantly reduced from that associated with exhausts of pure jet engines.

*Shaft noise.* Most turboshaft engines that are employed in rotary-wing aircraft applications are mounted near occupied areas and are usually mounted horizontally. Therefore, they require a rather complex transmission and shaft distribution system. Almost all turboshaft engines contain a shaft gear-reduction system which is integrated within the engine (the externally mounted gear-reduction and shaft distribution systems will be discussed later). Since most turboshaft engines are mated directly to the fuselage structure of the vehicle, noise and vibration generated by the engine are transmitted directly through the structures of the vehicle. Compressor noise, even though present, is not readily noticeable at internal stations, but the noises produced by rotating shafts and gears within the engine may produce quite significant noise levels.

An example of noise generated by a turboshaft engine is shown in figure 3. These measurements were obtained at two locations within a Sikorsky UH-3C with the rotor disengaged and only the left turboshaft engine operating at 72% r.p.m.

### III. ROTORS AND ANTITORQUE ROTORS

Rotor systems are powered by either reciprocating or turboshaft engines. Noise generated by rotor systems is usually complex and varies considerably depending on the particular type of mating of rotor or antitorque rotor

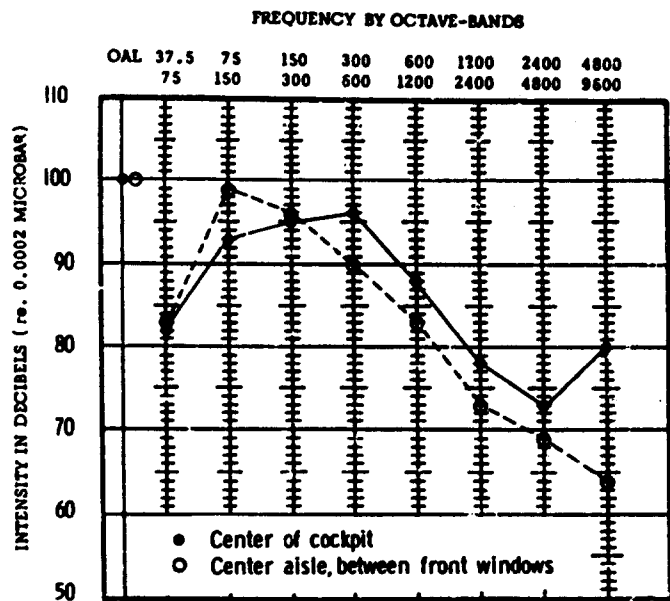


FIGURE 3

*Samples of noise levels measured within a UH-3C during ground operation with only the left turboshaft engine operating at 72% r.p.m. and the rotor disengaged.*

systems to power plants. Normally, the higher the speed of rotors and the greater the torque applied to the systems, the more significant will be the noise they generate (9). Highly developed propellers and rotors capable of handling high torque forces are commonly mated to powerful reaction or reciprocating-type engines.

Many factors have a direct influence on the noise generated by a rotor or antitorque rotor; i.e., revolutions per minute, tip speeds, blade pitch, number of blades, and the like. It is, therefore, rather difficult to illustrate one particular factor without including other contributive noise factors. For this reason, we will first describe basic noise characteristics and noise-modifying elements.

#### Main rotor system

The components which generate and modify rotor noise are complex, and slight operational changes can result in rather significant changes in the noise.

Noise, resulting from rotors, is produced by aerodynamic disturbances or direct structural (mechanical) vibrations, or both. In most instances, the noise emanating from aerodynamic disturbances is the most significant. Two acoustic components comprise the bulk of the noise associated with propellers and rotors—rotational noise and vortex noise (2).

*Rotational noise.* Rotational noise is generated by the rotor blades as they rotate. This noise is directly related to the frequency of blade passage and is associated with the total thrust and torque developed by the rotor blades. The frequency of the noise generated by the rotors is multiple and is determined by the frequency of the blade passage.

Rotational noise is associated with several aerodynamic forces. Forces of drag and lift are created within the air which surrounds the blades of a rotor or propeller. These forces cause disturbances of the air medium which result in both positive and negative pressure changes. At a fixed position near the rotors, the fundamental frequency of these pressure displacements corresponds to the frequency of blade passage.

It is generally accepted that rotational noise is primarily a function of the total thrust produced by the blade of a rotor or antitorque system. Thus, if the number of blades is increased, the total intensity of the noise is reduced (9).

At relatively slow tip speeds the main rotational noise is the dominant noise. As tip speeds increase, the noise present in the higher frequency range becomes evident. The higher frequency noise is the product of vortex noise produced by the main rotors and antitorque rotor. In some instances, high-speed gear transfer systems may contribute high-frequency noise.

The frequency components of rotational noise are easily identified as multiples of the frequency of blade passage. Since rotational noise is directly related to blade passage frequency, this noise contains discrete frequency

components. To accurately define these components one must acquire a narrow-band noise analysis. Blade passage frequency is high, and, since the discrete frequency components are multiples of blade passage, several discrete components may be present in a single octave-band measurement. For this reason, sound pressure level (SPL) readings obtained by octave-band analysis do not indicate or define the number or magnitude of the individual discrete frequency components present in a given octave.

*Vortex noise.* The blades of a rotating rotor system produce vortices which take the form of audible noise, called vortex noise. When a blade rotates at slow tip speeds, the directivity of the noise is in the form of concentric spheres which are a function of local stresses on the medium. At high tip speeds a distortion of vortex noise pattern occurs. High blade speed causes the directivity pattern of the noise to elongate from a concentric sphere shape. The distribution of the maximum noise has moved to a position just forward, above, and below the advancing blade.

Vortex noise travels with a rotating blade, and, as a result, vortex noise measured by the observer has undergone modulations due to the blade passage frequency. Vortex noise from rotors contains frequencies that are directly related to the blade-tip speed. The directivity pattern of vortex noise rotates with the rotating blade and is consequently modulated by the frequency of blade passage (2).

*Rotational noise vs. vortex noise.* Vortex noise results from stresses which are imposed on the surrounding air through which the blade passes. Vortex noise is distributed in the higher frequency ranges and is influenced by the aerodynamic flow of air over the blade and also by the frontal area represented by the blade. Vortex noise is the most significant single noise associated with the main rotor system.

In many instances, even though the rotational noise produced by the rotors is more intense than that generated by other noise

sources, it is subjectively less noticeable because the fundamental and lower harmonics are not within the most acute range of man's hearing. Thus, in the majority of cases, the antitorque rotational noise and the vortex noise of the main rotor are subjectively more noticeable (2, 3, 12).

The influence of thrust on 2-blade rotor systems produces more noise than on 3- or 4-blade systems when operating at lower blade loadings (2, 9). Generally, as blade loading increases, the significance of vortex noise increases and the significance of rotational noise decreases. Essentially, a 2- or 3-blade rotor system, at equal hovering efficiency, produces approximately the same amount of vortex noise, but the rotational noise level of the 3-blade rotor system is appreciably lower than for a 2-blade rotor system. These two conditions are basically true when equal thrust is being produced by the rotor-blade system.

Increased rotational and vortex noise results from main rotor thrust increases obtained during flight.

*Blade-tip speed.* The greater the number of blades in a rotor system, the lower will be the requirements for high blade-tip speeds. In other words, a 3-blade rotor system requires slower blade-tip speeds than a 2-blade rotor system in order to produce an equal amount of total rotor thrust.

Since the noise from rotor systems is generated by the blades, the pattern of the noise rotates with the blades. The maximum noise radiation is found at positions opposite the direction of thrust and at angles of about 30 degrees from the center line axis of the blade.

Various aerodynamic parameters, including number of blades, blade-tip speed, thrust, and blade loading, determine the contribution of rotational and vortex noises to the overall noise generated by main and antitorque rotors. Of these various parameters, blade-tip speed is the most significant. In most instances, a reduction in blade-tip speed results in a more significant reduction in the overall noise than any other single factor.

Both noise components, rotational and vortex, increase with blade-tip speed. However, rotational noise tends to achieve a greater change with increases in blade-tip speed than does the vortex noise. The significance of the noise sources varies depending on the size of the vehicle. Small helicopters with high-speed rotors produce rotor noise that usually dominates the acoustic energies generated by the antitorque rotors. During rotor stall, sound pressure levels increase at all frequencies, but particularly at the higher end of the spectrum.

*Other rotor-noise generators.* Low and high blade angles or pitch show significant differences in the frequency and intensity of the noise produced by rotors, particularly at higher frequencies. As disc-loading increases, sound pressure levels at all frequencies increase, particularly in the higher frequency ranges. Investigations of waveforms at different rotor-tip speeds show that the peaks occur at frequencies of blade passage. One significant feature noted is that the peak is accompanied by high-frequency fluctuation just forward of the blade, and low-frequency fluctuation just aft of the blade. Waveform analysis further suggests that Doppler effects may play a significant role in the generation of these peaks. These peaks may dominate at higher tip speed and particularly at low values of disc-loading. The noise appears to be increased by turbulent air (similar to the situation when a blade rotates in or near the wake of a preceding blade) (2, 12, 13).

Other factors that may contribute to the intensity of noise levels are the degree, type, and condition of acoustic treatment; aging of the primary and secondary systems of the vehicle; condition of rotors (a defective or imbalanced rotor system may result in rather severe vibrations); and conditions of seals at windows and at cargo and escape hatches. In addition, during ground and hover operations, such factors as terrain features will influence the noise generated by the vehicle.

*Blade slapping.* One of the noises associated with helicopters is the acoustic phenomenon referred to as "blade slapping" or "rotor

slapping." Blade slapping does not always occur, but, when it does, it is a significant and dominating noise. Blade slapping is more pronounced in larger vehicles and is more likely to occur in tandem-rotor helicopters than in single-rotor vehicles. Blade-slapping noise is distinctly audible and falls within the lower frequency range, usually below 600 to 800 Hz. The peak noise level resulting from blade slapping is between 100 through 500 Hz. The noise produced by blade slapping is very intense and, since it covers a broad frequency range, easily masks the less intense noises generated by other components.

During flight at low airspeeds a probable cause of blade slapping is the rapid change in angle of attack which a blade experiences as it encounters its own wake or that of the previous blade (2). A possible increase in compressibility may increase the severity of the effect as the angle of attack changes. Abrupt changes in blade angle cause increased lift; consequently, the trailing wake system is also changed abruptly. These abrupt changes in wake lead to an impulse-type noise which produces wide frequency distributions. Less severe angles of blade attack can alter the characteristics of the boundary layer on the blade and the vortex noise may be reinforced at blade-passage frequency. As a blade passes through trailing vortices, the results of sudden force variations on the blade elements near the rotor tip can produce rotor-slapping noise (3, 9).

Rotor slapping does not usually occur during a climb maneuver (3). During climb the traveling vortices of the rotor blades are directed away from the blades; whereas, during a partial power descent, when rotor slapping is quite common, the rotors are moving through their own wake. During high-speed flight the effect of rotor wake is less pronounced and thus the slapping noise is probably not the product of rotor wake. Increased rotor speed, necessary for high-speed flight, probably causes shock waves to form on the advancing blade, while local shock waves may explain the rotor slapping that occurs during high-speed flight (2).

Blade slapping is more common in tandem-rotor helicopters during almost all phases of powered flight because of the trailing vortices that are present from both rotor systems. Twin 2-bladed rotors in tandem configuration seem to have a greater tendency to produce blade slapping throughout various flight profiles. Research on the Bell HSL helicopter has shown that the sudden rise in the sound pressure level associated with blade slapping occurs periodically at the blade passage frequency for a single rotor. Blade slapping, associated with the CH-47A, seems to occur during most flight conditions (2). It is generally believed that blade slapping occurs as the aft rotor leaves the region of forward to aft rotor overlap. Significantly different noises may be generated by tandem- or 2-rotor systems during cruise conditions due to the interaction between the 2 rotors (the disturbed air from the front rotors is transmitted to the rear rotor system). In hovering, there is apparently little interaction between the 2-rotor systems. Rotor-slapping noise of tandem-rotor vehicles may be reduced by decreasing the total area of blade overlap and by increasing vertical separation between the passage plane of the rotors.

*Rotor noise reduction.* Generally, the total noise generated by rotors can be reduced by reducing blade-tip speeds. As mentioned, this factor, alone, will help reduce both rotational and vortex noise. As a second alleviating factor, greater thrust distribution can be provided through the rotor system. This can be achieved by simply increasing the number of rotor blades required to provide a given thrust. For instance, increasing the number of blades in a rotor system from 2 to 3 would result in increased total thrust, and would generate less noise. Of course, these recommendations appear to propose simple solutions; unfortunately, significant reductions in the overall noise associated with helicopters are far more difficult to achieve.

It is obvious that ever more vigorous efforts must be directed at reducing noise generated by rotors and antitorque rotors. Whereas the noise generated by the power plant used to rank parallel with that produced by blade sys-



tems, now, main rotor and antitorque rotor noise constitutes the greatest problem, simply because the use of turboshaft power plants has significantly reduced the magnitude of the noise emitted from the engine.

### Antitorque systems

The rotational noise generated by antitorque rotors is usually the most pronounced of the various noises generated by such systems. A critical look at the frequency spectrum of antitorque rotor noise reveals the presence of discrete sound pressure levels at multiples of the blade-passage frequency (2, 12).

Subjectively, the noise produced by most antitorque rotor systems is greater than either rotational or vortex noise generated by the main rotor. However, tail rotor noise, especially from high-speed antitorque rotors, may be significantly reduced.

Noise generated by the main rotors is predominantly low frequency, and noise generated by the antitorque system is usually distributed within a somewhat higher frequency range. Thus, any method designed to reduce the total noise of a helicopter fitted with main and antitorque rotor systems must consider both of these noise generators.

Generally, the noise associated with main rotor operations, primarily distributed within the low-frequency range, is subjectively less annoying or irritating than the higher frequency noise generated by high-speed antitorque rotor systems. The difference in subjective response to these two different types of noise is due to the psychophysiologic response of the human auditory system. Noise from antitorque rotors is especially irritating and annoying if it contains narrow-band frequency components (3, 4, 8, 9, 11, 15).

Intense noise associated with high-speed antitorque rotors can be reduced by simply increasing the number of blades in the antitorque system. Increasing the number of blades allows a reduction in both revolutions per minute and diameter of the antitorque

rotor because, as the number of blades is increased, there is a greater distribution of horsepower per blade. Aircraft manufacturers seem to be generally aware of this factor, and future helicopters which utilize antitorque rotor systems will probably have 3, 4, or even 5 blades.

### Modes of operation

The overall noise of a helicopter varies for different modes of operation. During hover, the pressure disturbances resulting from the passage of the rotor blades are fairly constant, especially at locations near the center axis of the rotor. Slight variations in pressure disturbances may occur due to directional or control alterations during the hover maneuver, but such disturbances are usually of little significance. During forward flight the rotors create a variation of pressure disturbances due to asymmetrical loadings of air acting on the blades (9). In order to obtain and maintain forward flight, the blades in the rotor system vary in pitch and angle of attack as they rotate 360 degrees around a central axis. The variations of the mechanical movement of the blades create a variation in pressure displacement as the blades rotate.

Hover maneuvers require a greater amount of rotor torque than does forward flight. When a helicopter is hovering, greater power is required to maintain a constant lift. During forward flight the rotors require less power or torque because the helicopter has obtained a certain amount of momentum.

Increased torque required during a hover maneuver results in a greater demand on the power plant and this increased demand results in more intense noise. Generally, as the amount of torque delivered from a power plant increases, a greater amount of strain and stress is applied to the components of the engine which deliver the shaft horsepower. As these components receive greater stress, greater noise is generated by each component (9).

Precise examples of antitorque rotor noise are difficult to demonstrate since most tail

rotors operate only when the main rotors are engaged; therefore, noise samples also contain acoustic components emitted from the main rotor and the engines. Figure 4 illustrates noise measurements which were obtained at four locations near a Fairchild-Hiller OH-23G helicopter during ground operation. The engine was operating at 3,200 r.p.m. and at 20 inches of manifold pressure. The four locations represent near-field (50 ft.) measurements from 0 degrees (directly in front) to 135 degrees (45 degrees to right side of the tail of the vehicle). The contribution of anti-torque rotor noise to the overall spectrum is somewhat evident in the levels recorded within the higher frequency range.

#### IV. TRANSMISSION, GEAR-REDUCTION, AND SHAFT DISTRIBUTION SYSTEMS

Many helicopters employ large transmission and gear-reduction systems (10). Such systems reduce the speed of the power plant shaft to the lower number of revolutions per minute that is delivered to rotor and anti-torque rotor systems.

In general, the total system includes torque distribution shafts from the power plant, transmission and gear-reduction sections, and final distribution shafts. The noise generated within occupied areas by gear and shaft systems is greatest in rotary-wing aircraft where transmission units are located within or near the main fuselage. The noise spectrum generated by transmission systems powered by reciprocating engines usually contains lower frequency components than similar transmission systems powered by gas turbine engines. The higher frequencies produced by gas turbine transmissions result from the higher gear-meshing speeds of gas turbine power plants. For instance, a gas turbine engine may produce an engine shaft speed of 17,000 r.p.m., whereas a reciprocating engine may produce an engine shaft speed of 3,000 r.p.m. If both of these shaft inputs must be reduced to a rotor speed of 212 r.p.m., then it is evident that gear-transmission and shift systems mated to the gas turbine engine will rotate at a higher speed than the gear-transmission and shaft systems mated to a reciprocating engine. Thus, the higher the rotational speeds of the gear systems within the transmission, the higher will be the frequency components generated by the meshing and impacting of the gears (9).

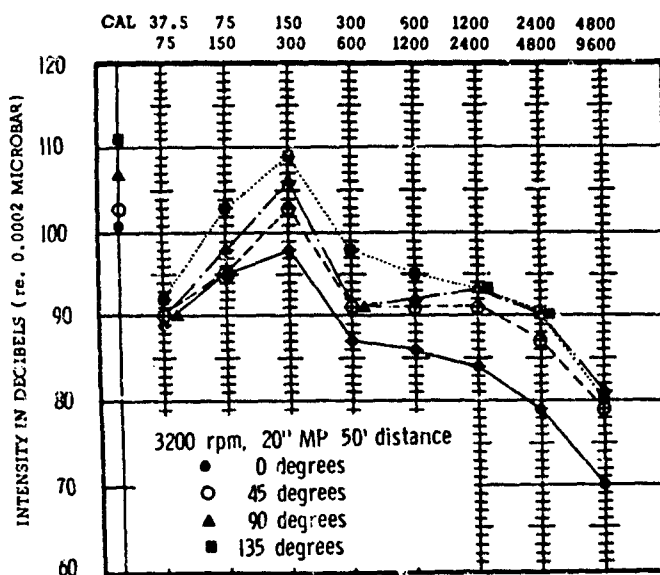


FIGURE 4

Noise levels measured at 4 azimuth locations near an OH-23G at distances of 50 ft. The engine was operating at 3,200 r.p.m. and 20 inches of manifold pressure.

#### Gears

A number of types of gears are used in conjunction with gear-reduction, transmission, and distribution systems. These gears vary in shape, size, weight, complexity, and in the manner of application, but there are two main types—gears that contact in parallel shafts (in-line), and gears which make contact at nonparallel angles, usually less than 90 degrees. Parallel, in-line gears are commonly used in reciprocating engines and also for mating the power plant to auxiliary rotational systems. Nonparallel gear matings are commonly used in helicopter applications where the shaft of the main rotor is at a different angle than the center line shaft of the power plant. A few of the major types of gears that contribute to the noise generated by rotary-wing aircraft are:

*Bevel gears.* Bevel gears have conical pitch surfaces and are used to make shaft contacts at angles less than 90 degrees. The two shafts must be in the same plane. The gears are used as shaft distribution units in many helicopters with antitorque rotors where the torque-distribution shaft must distribute power to the tail rotors.

*Worm gears.* Worm gears transfer rotational motion from one shaft to another. They transfer shaft motion at right angles. This type of gear system offers several advantages. The wheel gear shaft can be rotated in either direction by changing the rotational direction of the worm drive and, because the gear systems are mated at right angles to each other, they occupy a relatively small space. Worm gears are commonly used in the extension and retraction of landing gears and flaps, or spoilers.

*Planetary and sun gears.* These gear systems are specially located and arranged to create a rotational reduction between the center shaft and the exterior shaft. A centrally located shaft, the "sun gear," is connected to the rotation of the outer shaft by three "planetary" gears. Planetary gear systems are used in gear-reduction units for both propeller and rotor systems, and usually consist of pinion or spur-reduction gearing, or both.

Impacting and meshing of gears during rotation may stimulate natural frequency resonances, but friction created during gear contact is the major source of noise associated with gear movements. The major frequency spectrum resulting from gear-tooth contact is dependent upon the frequency of contact, the harmonics and natural frequency characteristics of the gears, the gear housing, and the gear shafts. Gear assemblies usually require a gearbox. The gearbox serves to support entrance and exit shafts, confine and retain lubricants, and provide a shield against noise and vibration. Gear housings are important sources of noise propagation. The housings or gear cases are resonant chambers and, when in contact with structures and components of the vehicle, provide a direct pathway for propagation of noise and vibration generated within the transmission housing.

## Power drive system

The majority of helicopters utilize shaft distribution systems to deliver torque to main rotors, antitorque rotors, and auxiliary components and systems. Within these systems the transmissions, gear-reduction units, couplings, bearings and bearing supports, and drive-shaft systems may generate noise. Usually, the greater the amount of rotor torque, the more intense will be the individual components of the noise resulting from gear friction and impacting (3, 9). Frequently, these power-drive systems contribute significantly to the internal noise environment, but produce little, if any, noticeable noise at far-field positions.

The total noise produced by power-drive systems is complex and composed of a variety of noise elements produced by subsystems, parts, and components.

In addition to gears as a significant source of noise in most helicopters, there are other noise generators which should be considered. Torque-distribution shafts, bearings, bearing supports, couplings, and secondary shaft distribution units contribute to the total internal noise, especially within tandem-rotor helicopters which employ long distribution shafts between the power plant and the rotor. Tandem-rotor helicopters are designed in such a manner that the power distribution shaft passes through the upper part of the fuselage above the passenger compartment. Power shafts and their related components usually generate higher frequency noise that is directly related to shaft speed, torque, and bearing and support friction.

*Vertol CH-21C.* Figure 5 depicts the relative complexity of transmission and shaft distribution systems found within the Vertol CH-21C. The CH-21C is a tandem-rotor helicopter powered by a single Wright R-1820 radial-type reciprocating engine. The engine is mounted within the rear fuselage, just aft of the cargo-passenger area. Power is transmitted from the engine to the midtransmission and from it, longitudinally, to the fore and aft transmissions. The midtransmission serves

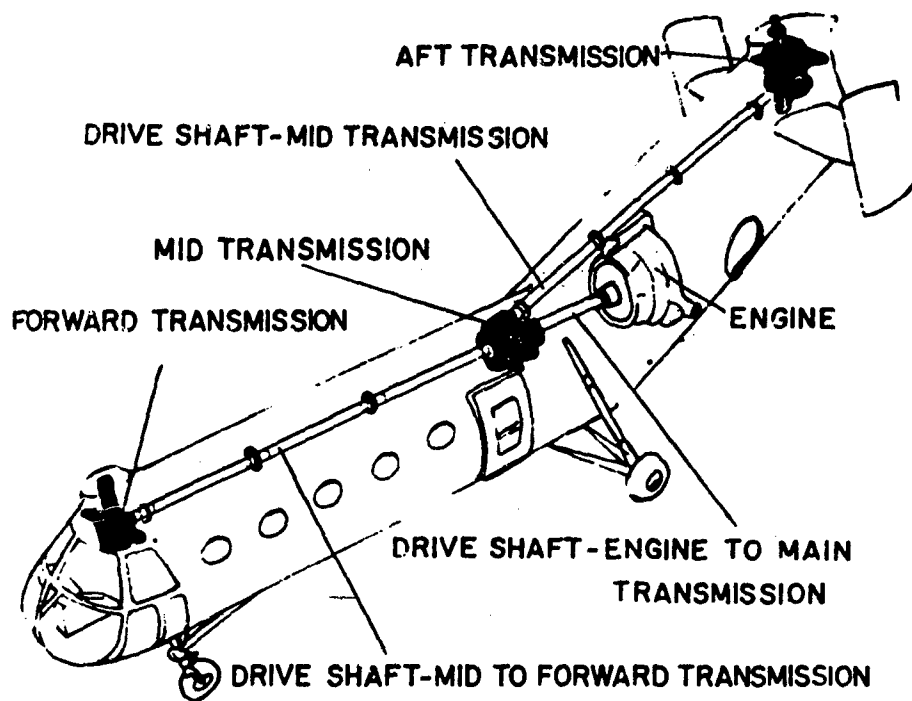


FIGURE 5

*Illustration of engine, transmissions, and gear-shaft distribution units in a CH-21C helicopter.*

only to distribute shaft power delivered from the engine, and gear reduction is achieved only at the forward and aft transmissions. For this reason the single drive shaft between the engine and the midtransmission, and the shafts from the midtransmission to the forward and aft transmissions, rotate at the same speed as the engine; thus the midtransmission gear system has a speed equal to that of the engine.

Figure 6 contains plottings of noise levels measured within a CH-21C during conditions of normal cruise: level flight at 1,000-ft. altitude with the engine operating at 2,500 r.p.m. (rotor at 250 r.p.m.), and 37 inches of manifold pressure, and at 70 knots (indicated) airspeed. The two spectra shown in figure 6 represent differences in noise measured at left side and center aisle locations at the far aft end of the cargo-passenger area. The noise levels measured within the 1200 to 2400 Hz octave band

result from transmission and gear-shaft distribution units installed in areas near the places of measurement.

*Acoustic blankets.* Installation of acoustic blankets can significantly reduce the magnitude of the acoustic noise which is emitted from a transmission unit. Figure 7 dramatically illustrates the amount of noise reduction which may be achieved. The two spectra were derived from measurements obtained within a Bell UH-1A helicopter during normal cruise. Although the overall levels indicate little difference, the two spectra reveal a dramatic alteration. In fact, within the highest octave a reduction of 24 dB is evidenced.

In some instances, use of acoustic pads and blankets is almost essential. Figure 8 illustrates a noise exposure which, without the use of acoustic blankets and pads, would constitute

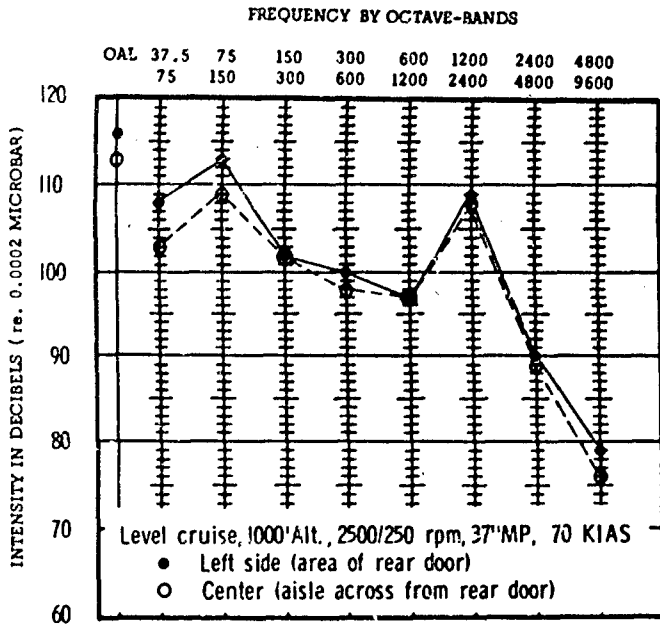


FIGURE 6

Comparison of noise levels measured in a CH-21C at center aisle and left side during cruise at an altitude of 1,000 ft. with engine at 2,500 r.p.m. (rotor at 250 r.p.m.) and 37 inches of manifold pressure. The vehicle was cruising at 70 knots.

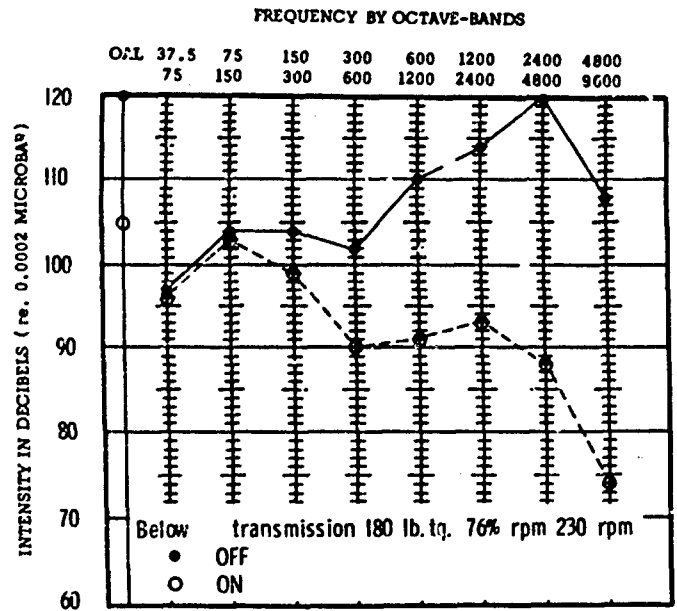


FIGURE 8

Noise levels measured within a CH-47A at a location below the front transmission unit during operation at 180 lb. torque, 76% r.p.m., and rotors operating at 230 r.p.m. Measurements were made with acoustic blankets installed and with acoustic blankets removed.

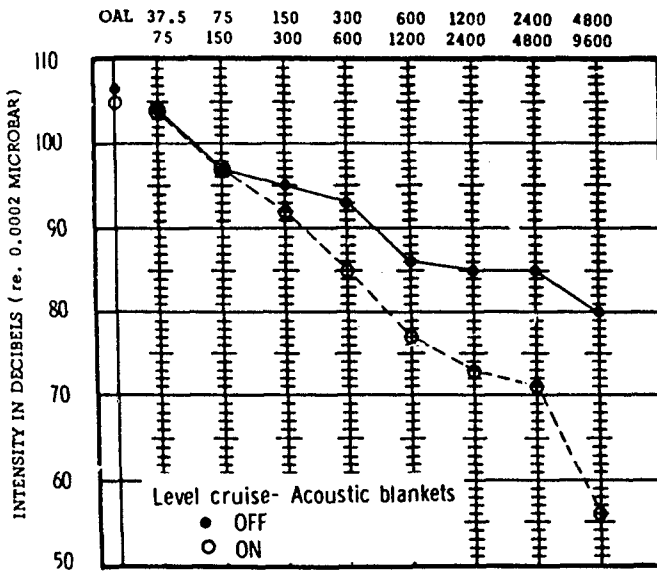


FIGURE 7

Noise levels measured within a UH-1A during normal cruise with acoustic blankets installed and with blankets removed.

a definite potential hazard to unprotected ears. These measurements were obtained at head level in the front (troop commander) seat within a Boeing-Vertol CH-47A. The levels were measured with both engines operating at 76% r.p.m. and delivering 180 lb. of torque. Fortunately, the acoustic treatment utilized within the CH-47A greatly reduces the magnitude of the noise generated by the forward transmission unit.

An interesting operational fact should be stressed here. Although the use of acoustic treatment materials can result in rather significant reductions in noise, especially within higher frequency ranges, operationally, the use of such acoustic baffles may not be acceptable. For example, aircrews flying missions in Southeast Asia, especially in active combat zones, often prefer to remove acoustic blankets so that possible hits from ground fire may be more easily detected. Naturally, when the acoustic blankets are removed, the noise creat-

ed by internally mounted transmissions and gear-shaft distribution systems receives little, if any, reduction.

*Effect of increased torque.* It has been fairly well demonstrated that increased torque applied through a gear system will result in an increase in noise. Generally, increasing torque while maintaining a constant speed will increase the noise produced by increased meshing and impacting forces of gears within the transmission system.

It is interesting to note that increased torque without changes in engine speed usually causes an increase in the level of the noise and does not cause a shift in the frequency distribution pattern of the noise.

*CH-47A.* An illustration of the transmission and shaft distribution system of a CH-47A is shown in figure 9. The CH-47A is a tandem twin-turbine rotary-wing aircraft designed for heavy-duty operations. The helicopter is

powered by two Lycoming T55-L-5 turboshaft engines mounted on the upper aft section of the fuselage. The engines simultaneously drive 2 tandem 3-bladed rotary blades through a combining transmission, drive-shafting, and gear-reduction system. The forward transmission is mounted above the aft section of the cockpit. The aft transmission, combining transmission and drive-shafting, is located in the aft section above the main cargo and entrance door. Drive-shafting from the combining transmission to the forward transmission is housed within a tunnel on the top of the fuselage. The combining transmission combines the power delivered by the engines and transmits it at reduced shaft speed to the forward and aft transmissions where additional gear-reduction is achieved. The various transmissions provide a total gear-reduction of 66 to 1. Noise emanating from the various transmission systems is quite complex and varies from one gear-reduction unit to another. For instance, noise emanating from the forward transmission will contain relatively simple

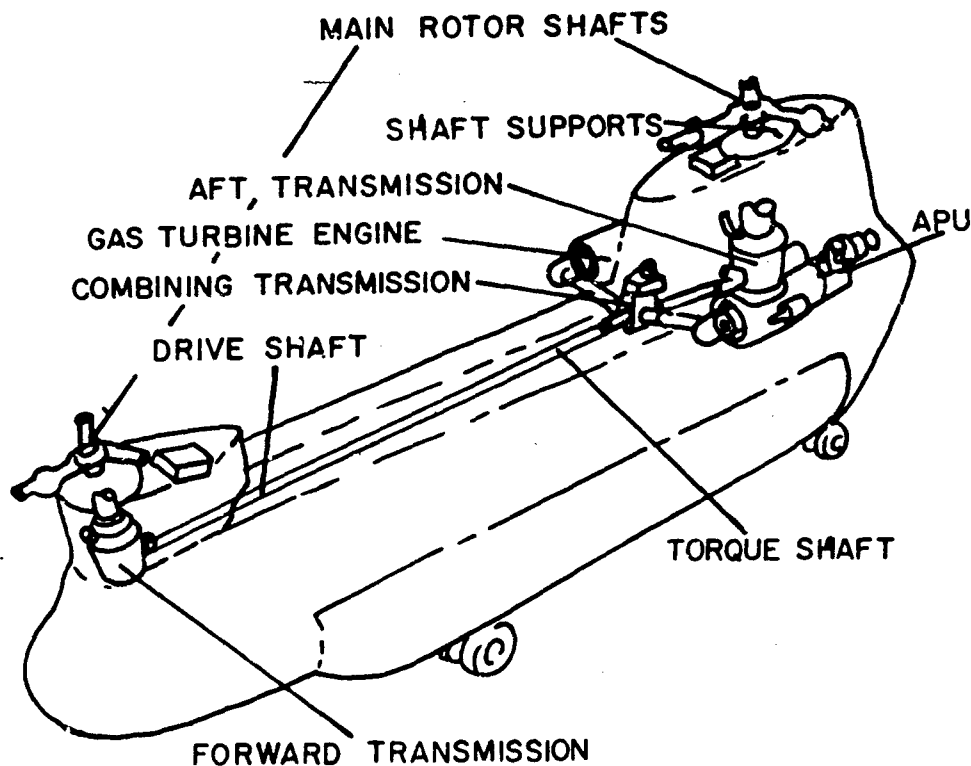


FIGURE 9  
Diagram of various noise-generating components installed within a CH-47A helicopter.

noise components, whereas the total noise generated near the aft transmission area will contain a mixture of transmission and other types of noises. Noise exposures in the aft sections of the helicopter will be a mixture of noise components emanating from the compressor and turbine sections of the engines, the combining transmission, and the main aft transmission.

Figure 10 demonstrates the general complexity of the noises produced within the cargo area of the CH-47A during a hover maneuver. At the forward position, between the first windows, noise from the forward rotor is evident in the lower frequency range, and noise emanating from the forward transmission is evident at the 1200 to 2400 Hz frequency range. At windows 3 and 4 the transmission noise decreases, but noise due to overlapping of the rotors becomes more pronounced, especially in the area at the fourth window from the front. Then, at the aft location between the fifth windows, noise generated by the rotating sections and components of the engines (combining transmission and aft trans-

mission) creates a significant increase in the noise levels above 600 Hz.

*Control of transmission noise.* Rotor noise may be more intense than transmission noise because the noise generated by the transmission, especially the combining- and gear-reduction transmissions, is distributed with a higher frequency range and usually contains narrow-band noise components. In general, if a transmission system is located above occupied areas, the noise environment generated within the helicopter will be considerably more intense than if the same unit were mounted aft or forward of occupied areas (3, 6).

Controlling the noise produced by power-drive systems is not an easy task. The noise produced by internal components of a transmission system is of greatest significance if the frequency of the noise approaches natural modes of resonance in the casing wall. High-frequency noise can be controlled more easily than low-frequency noise. Proper acoustic treatment may help reduce the intrusion of the higher frequencies into occupied areas of the vehicle. In many instances acoustic treatment will not reduce the overall level of the noise, but will significantly reduce the "loudness" of the noise. The noise generated by power-drive systems can be radically altered and reduced as better engineering technics and materials are made available.

Research must continue in efforts to abate noise generated by transmission and power-train components. Ideally, reductions should be obtained by alterations and design modifications of the basic noise-generating mechanisms and components. Weight penalties are imposed when reductions in noise must be achieved by placing acoustic blankets and pads between the noise source and occupied spaces.

## V. AUXILIARY POWER UNITS

Modern aircraft require a variety of auxiliary systems which provide electrical power, hydraulic- and air power, heating and air-conditioning, compressed air, and other facilities. The majority of the auxiliary systems are

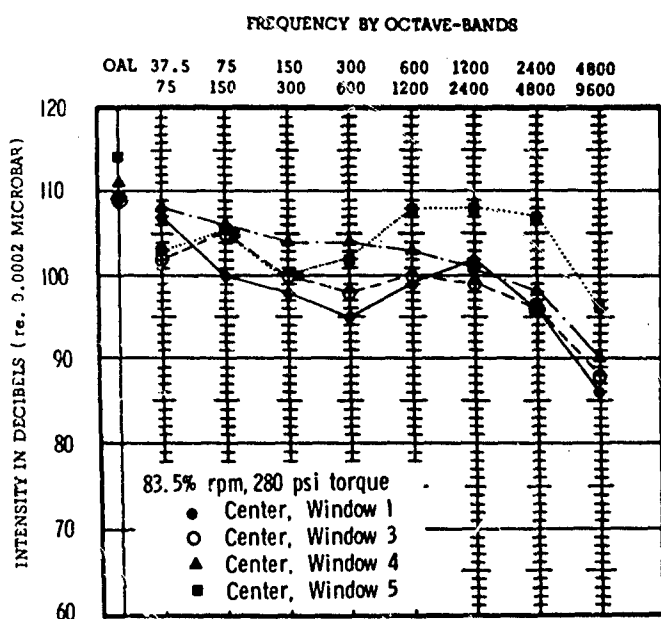


FIGURE 10

Noise levels measured within CH-47A during hover. Levels measured at head positions along left side of troop passenger area.

portable, but some units may be installed within the aircraft. Generally, an auxiliary power unit provides a method of driving aircraft accessories without extracting power from the main engines. Auxiliary power units may provide shaft power to drive pneumatic accessory power-transmission systems and pneumatic starters, or may be used to supply both shaft power and compressed air. These units may also provide electrical alternating current, direct current, or a combination of alternating and direct current (9). Most of these units produce acoustic energies of sufficient magnitude to warrant consideration as noise hazards. Generally, units using reciprocal engines create most of their noise in the frequency ranges below 600 Hz, whereas those powered by gas turbines produce most of their acoustic energy in the higher frequency ranges.

Each of these various types of ground support equipment possesses different noise characteristics, and not all produce potentially hazardous noise. Those which use an internal power unit usually create some degree of noise while operating. In some cases the noise generated by individual units is of concern. Many auxiliary units are operated for long periods of time during ground checkout and maintenance operations. In many instances, maintenance personnel receive a more hazardous noise exposure from the ground support equipment than from the noise produced by the engines of the aircraft (3). Usually, the more intricate and complex the weapon system or aircraft, the greater will be the demands for use of auxiliary ground support units to operate the various systems (4).

During normal operation of ground power units, as engine loading increases, the noise level tends to increase because of increased torque required from the engine. Even though the exhaust (where the noise is usually found to be most intense) is located at a position opposite the control panel, it should be remembered that, when the unit is parked next to an aircraft or engine, the operator panel is usually placed so that a full view of the aircraft or engine is afforded the operator of the ground power unit. For this reason, noise

generated by the exhaust is propagated at locations between the ground power unit and the aircraft—thus personnel working on the aircraft may receive a significant amount of noise. For the most part, ground power units are fitted with quite effective mufflers but, since the major noise component is generated within the lower frequencies, the amount of noise attenuation provided by personal ear protection devices is limited.

Utilization of gas turbine-powered auxiliary power units will probably increase and broaden in scope of application, especially for aircraft powered by reaction power plants. As more and more turbine-powered aircraft are developed and added to the inventory for use in military operations, the need and utilization of such ground power units will increase. Needless to say, the noise exposures generated by these units are usually intense, and a factor to consider is that personnel are required to work around such units for extended periods of time. The degree of significance imposed by such work schedules is dependent on the duration of exposure incurred by ground maintenance personnel.

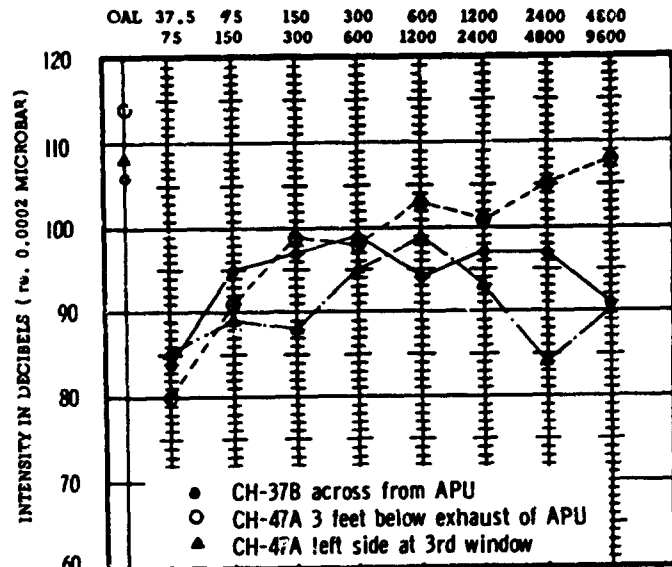


FIGURE 11

Examples of noise generated by internally mounted auxiliary power units.



Figure 11 provides three samples of noise generated by two types of auxiliary power units. The unit fitted in the CH-37B is powered by a small reciprocating engine and the unit installed within the CH-47A is powered by a small gas turbine. Normally, these units operate only during ground operations and are usually turned off during normal phases of flight.

## VI. AERODYNAMIC AND BOUNDARY-LAYER DISTURBANCES

Aerodynamic noise generated by disturbances in the boundary layer surrounding a moving body is common to almost all aircraft and, when associated with high-speed aircraft, may result in quite significant noise problems. The degree of significance is directly related to the speed of the vehicle and the relative location or position of the occupant within the aircraft. At present, most helicopters operate within a relatively narrow range of airspeeds—from low to high cruise.

Noise from aerodynamic disturbances has assumed a role of major significance because of the increased airspeeds now obtainable by the majority of fixed-wing military aircraft. As airspeed increases, especially at lower altitudes, noise due to aerodynamic disturbances assumes greater importance. At higher altitudes, aerodynamic noise is of less significance at equivalent speeds. Although most helicopters are not capable of operating at airspeeds in excess of about 150 knots, the newer genus of rotary-wing aircraft, especially compound vehicles, encounters aerodynamic disturbances which result in increased noise.

Boundary-layer disturbances are associated with high-speed aircraft and are gaining significance because of increased performance characteristics of newer aircraft. Noise due to aerodynamic disturbances is of primary concern because it increases the intensity of the middle and higher frequencies which results in a greater degree of speech interference. At present, boundary-layer noise is not a serious problem, but as rotary-wing aircraft attain faster speeds the importance of this type of noise can be expected to increase.

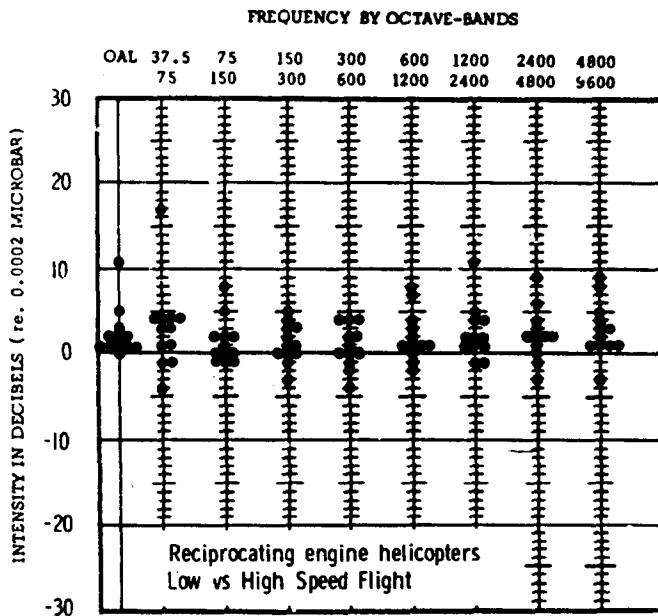


FIGURE 12

Changes in noise levels occurring between low- and high-speed cruise measured within the cockpits of 12 rotary-wing aircraft powered by reciprocating engines.

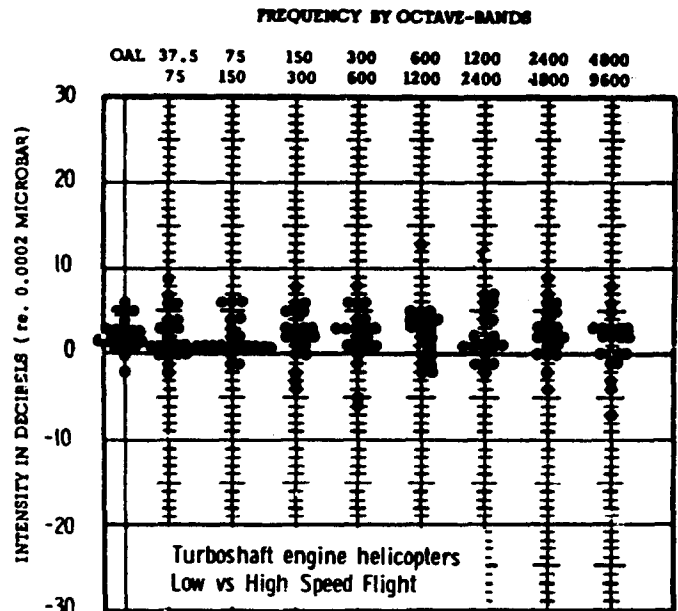


FIGURE 13

Changes in noise levels occurring between low- and high-speed cruises measured within the cockpits of 21 rotary-wing aircraft powered by turboshaft engines.

The effect of increased power and airspeed on the noise measured within the current inventory of rotary-wing vehicles is shown in figures 12 and 13. Figure 12 contains plottings which demonstrate the influence increased airspeed has on the noise measured within 12 different rotary-wing aircraft powered by reciprocating engines. In general, changes which result from increasing flight operations from low (normal) to high cruise appear to be about evenly distributed.

The data plots contained in figure 13 represent changes in noise recorded within the cockpits of 21 different rotary-wing aircraft powered by turboshaft engines. Although the increments are not dramatic, a trend does appear. In fact, a comparison between data reported in figures 12 and 13 reveals: (1) the proportion of data points which decreased was only 18% for vehicles powered by reciprocating engines and 14% for those fitted with turboshaft power plants, and (2) the proportion of data points which remained unchanged was 11% for reciprocating engine helicopters and 10% for those powered by turboshaft engines. Yet, 78% of the data points reported for helicopters mated to reciprocating engines increased, and 76% of the data points noted for turboshaft-powered vehicles demonstrated an increase. Although the magnitude of the increments which were recorded is not dramatic, the fact remains that, for both types of vehicles, the noise recorded within the cockpits of these vehicles does tend to increase with increments in engine power and airspeed. This trend is certainly worthy of receiving further study. One feature of the acoustic data recorded for these two groups of vehicles is the finding that the effect of increased power and airspeed appears to be equally distributed throughout the frequency spectrum range encompassed by these measurements.

## VII. OTHER FACTORS WHICH INFLUENCE NOISE

### Weight

Figure 14 illustrates the change in noise encountered within the cockpit of a Sikorsky

CH-54A which results from increases in gross weight. The change shown resulted when the gross weight of the vehicle was increased by 13,000 lb. The noise data from which the effect of increased weight was obtained were measured during hover flight. The increases noted below 1200 Hz resulted from increments in blade-loading and engine-rotor torque and the decrease noted above 2400 Hz emerged because rotating components within the transmission-power train were placed under torque stress and therefore noise due to meshing and impacting decreased.

Generally, the magnitude of the noise associated with the operation of a large rotary-wing vehicle will increase when blade-loading increases. Usually, this effect is most pronounced within the lower frequency range.

### Autorotation

Generally, flight profiles which employ autorotation (such as on routine training operations or real emergencies) result in increases in noise. Figure 15 shows three

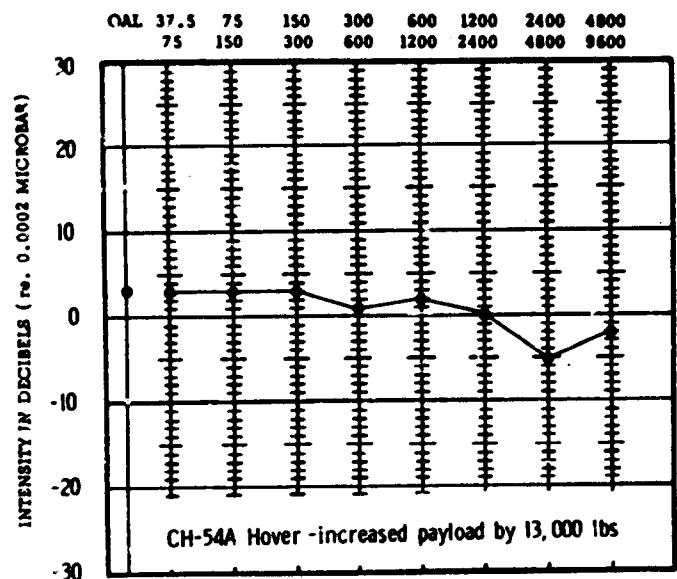


FIGURE 14

*Example of changes in noise levels resulting from increases in gross weight measured within the cockpit of a CH-54A. These two levels were obtained during conditions of hover with increases in gross weight of 13,000 lb.*

spectra of noise measured within a Bell UH-1A during three conditions of flight: autorotation, cruise, and hover. The most noticeable change in internal noise resulting from the autorotation maneuver occurred within the lowest 2 octave bands. This noise increment came from high-pitch blade loadings and lasted only for a short duration. The autorotation maneuver was measured during a simulated engine flame-out. Since the power plant was still operating at a low power setting, noise components associated with engine to power train disturbances were evident, especially within the highest octave—4800 to 9600 Hz.

Noise which results from autorotation is not a significant problem because of its short duration.

### Doors, hatches, and windows

Efforts directed at reducing noise by use of acoustic treatment procedures and materials are often thwarted when noise pathways, such as windows, doors, and hatches, are left open. Normally, rotary-wing aircraft are neither

pressurized nor air-conditioned, except for heating. Since most operate within low-altitude air spaces, the interior environment is subject to external temperature variations and, even on a relatively cool day, the interior may be warm enough to warrant opening side windows and vents. An open window or door, of course, provides access for intruding noise. Some vehicles are flown their entire usable life without ever having the removable doors installed, especially in hot, arid, and tropical areas. If installed at all, the doors are closed only to protect the crew from rain.

An example of the difference in noise levels within a vehicle flown with the doors on, and with the doors off, is shown in figure 16. These measurements were obtained within a Fairchild-Hiller OH-23D during conditions of hover. The intrusion of noise created by various noise-generating mechanisms located outside the cockpit is evident.

### VIII. COCKPIT NOISE

Experience obtained from flying in many types of rotary-wing aircraft reveals certain

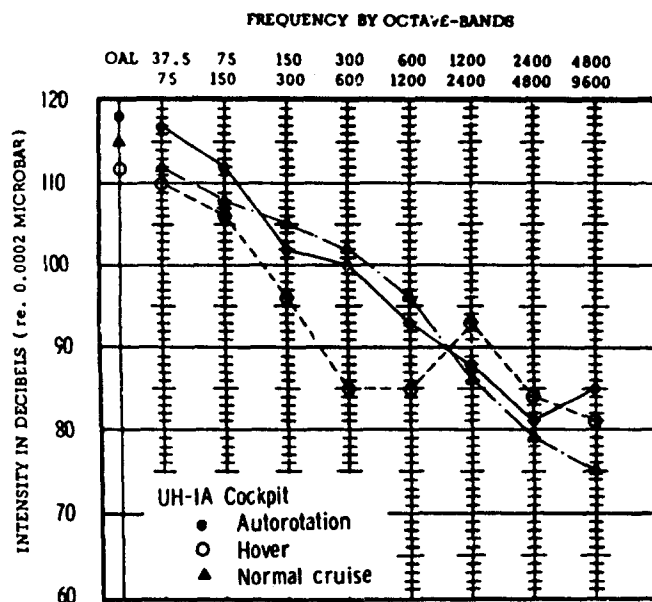


FIGURE 15

Three conditions of noise measured within the cockpit of a UH-1A; i.e., autorotation, hover, and normal cruise.

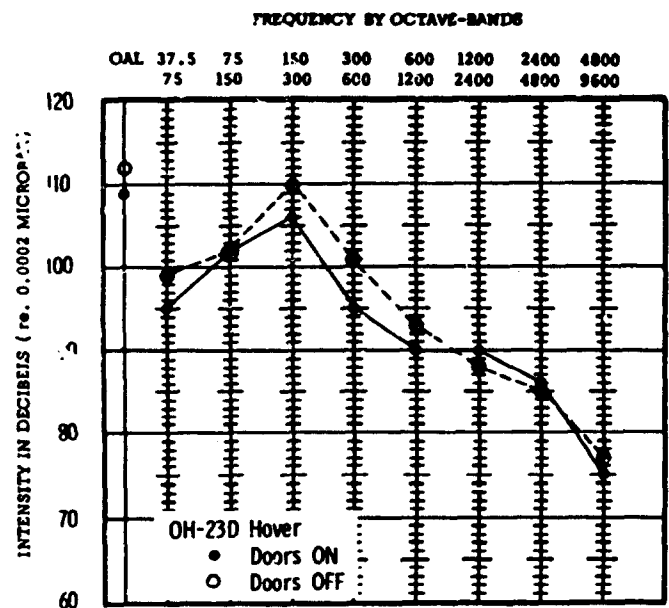


FIGURE 16

Comparison of noise levels measured within the cockpit of an OH-23D during hover with side doors in place and with side doors removed.

characteristics of the noise associated with helicopters. The following is an attempt to formulate certain general characteristics which are evidenced by selected groups of rotary-wing vehicles. One method by which generalities can be identified and demonstrated is the use of data groupings. Figures 17 and 18 contain a total of 540 data points which contain plottings of overall and octave-band measurements obtained within the cockpits of 60 rotary-wing aircraft during conditions of normal cruise. Figure 17 illustrates the envelope which evolved from plotting data obtained from 25 rotary-wing aircraft powered by reciprocating engines, and figure 18 illustrates the noise envelope which resulted from plotting data obtained from rotary-wing vehicles powered by turboshaft power plants. Generally, study of these two groups reveals that the noise within vehicles powered by reciprocating engines yields exposures somewhat higher than those found within the cockpits of helicopters powered by turboshaft power plants.

This finding is further supported by examination of median levels from these two groups (fig. 19). The most evident difference

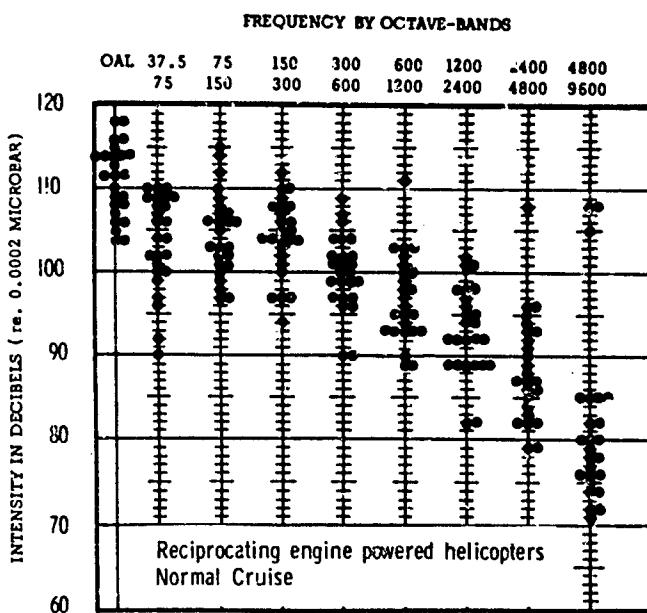


FIGURE 17

Plottings of noise levels measured within the cockpits of 25 rotary-wing aircraft powered by reciprocating engines during conditions of normal cruise.

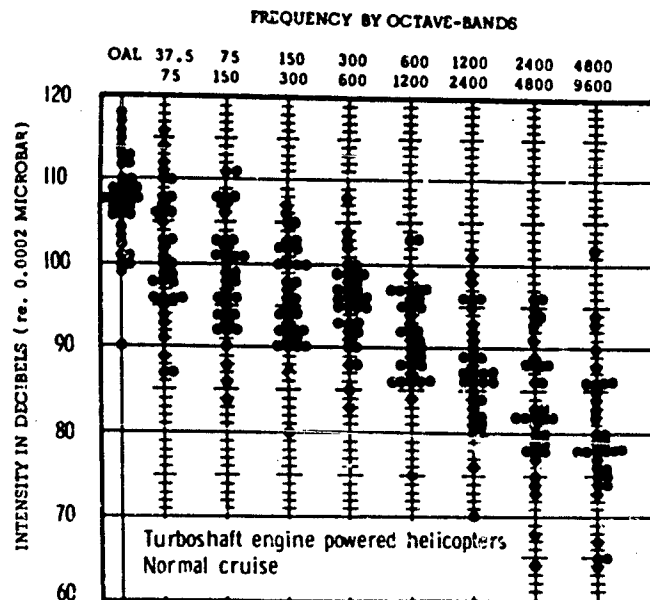


FIGURE 18

Plottings of noise levels measured within the cockpits of 35 rotary-wing aircraft powered by turboshaft engines during conditions of normal cruise.

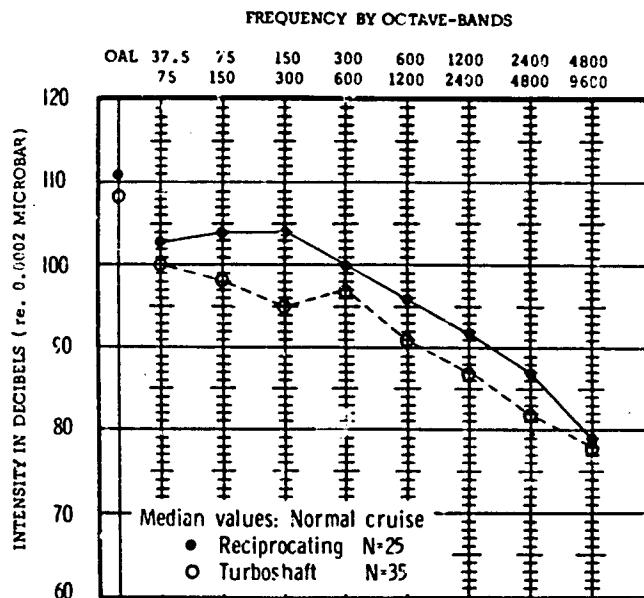


FIGURE 19

Comparison of median levels recorded for conditions of normal cruise within the cockpits of rotary-wing aircraft powered by reciprocating and turboshaft power plants.

between the two groups falls within the frequency range below 300 Hz.

This same type of data grouping can be extended to study other effects, such as differences which occur during hover flight. The data shown in figures 20 and 21 represent 378 data points which evolved from measurements obtained within the cockpits of 42 rotary-wing aircraft during hover flight. The envelope shown in figure 20 evolved from data obtained within 19 helicopters powered by reciprocating engines. Figure 21 depicts data obtained within 23 vehicles fitted with turboshaft engines. Casual study of the two sets of data reveals obvious differences. Obviously, the envelope shown for helicopters powered by reciprocating engines represents higher levels than that shown for vehicles fitted with turboshaft power plants. Figure 22 further reveals the extent of the differences noted between the two groups of aircraft. Plottings of the medians obtained from these two groups of data disclose the extent of these differences. The most obvious difference occurs within the frequency range between 75 and 4800 Hz.

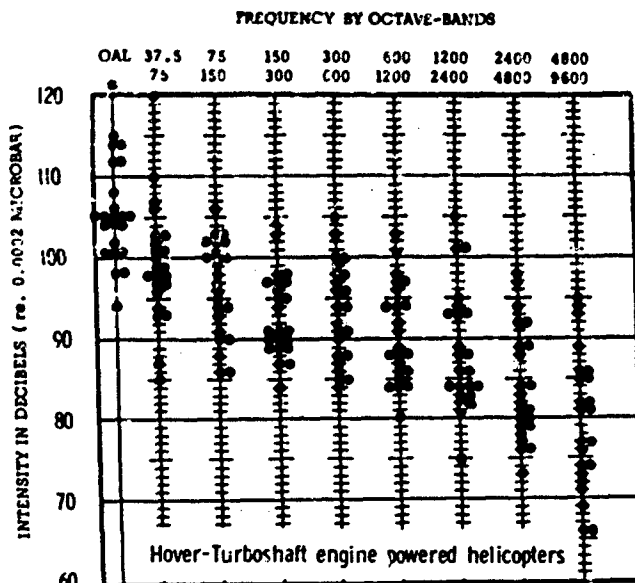


FIGURE 21

*Plottings of noise levels measured within the cockpits of 23 rotary-wing aircraft powered by turboshaft engines during hover.*

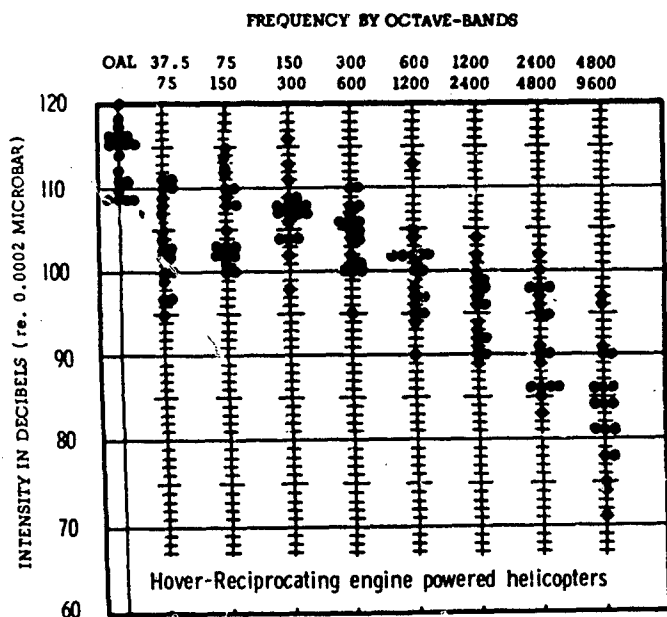


FIGURE 20

*Plottings of noise levels measured within the cockpits of 19 rotary-wing aircraft powered by reciprocating engines during hover.*

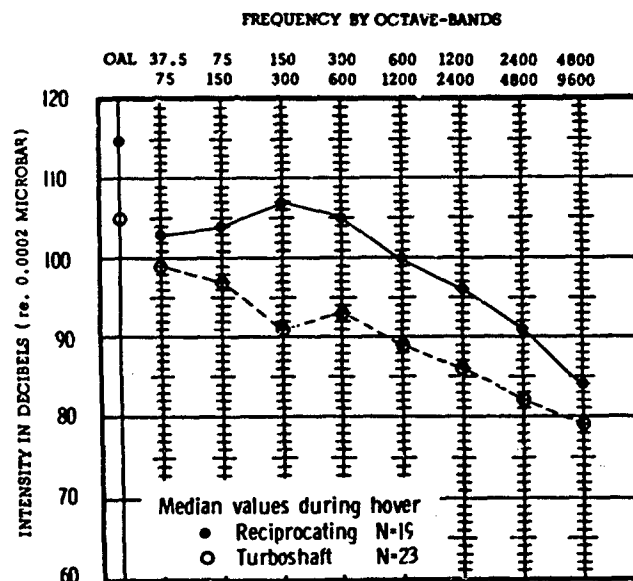


FIGURE 22

*Comparison of median levels recorded for condition of hover within the cockpits of rotary-wing aircraft powered by reciprocating or turboshaft power plants.*

Using the median values which emerged from the data illustrated in figures 17, 18, 20, and 21, further revelation can be obtained. Figure 23 illustrates median values for aircraft powered by reciprocating engines during conditions of normal cruise and hover. During hover, the median levels demonstrate an increase which is between 4 to 5 dB greater, within all octaves above 300 Hz, than that portrayed during normal cruise. Apparently, conditions of hover achieved by vehicles powered by reciprocating power plants contribute increments in noise which are greater than those experienced during flight at normal cruise.

Comparison of median values derived from data computed for conditions of cruise and hover within the cockpits of helicopters powered by turboshaft engines is shown in figure 24. Obviously, conditions of hover do not result in increases in noise which are as pronounced within turboshaft-powered vehicles as those demonstrated for aircraft powered by reciprocating engines.

### IX. UNDESIRABLE EFFECTS OF HELICOPTER NOISE

The most undesirable feature of noise within rotary-wing aircraft is interference with speech and electroacoustic communication. Figure 25 illustrates relative levels of speech interference (SIL) (average of 600-1200, 1200-2400, and 2400-4800 Hz) which resulted from the study of noise exposures measured within 136 fixed-wing aircraft and 27 rotary-wing vehicles (7). The data shown in figure 25 identify the ranges of speech interference encountered within the cockpits during conditions of low (normal) and high airspeed. The circles in black identify the mean values. Figure 25 reveals that the range of data (SIL) measured within rotary-wing aircraft powered by reciprocating engines varies less between vehicles than that plotted for vehicles powered by turboshaft engines, but mean values of speech interference are about 10 dB higher within vehicles powered by reciprocating engines than within turboshaft-powered helicopters.

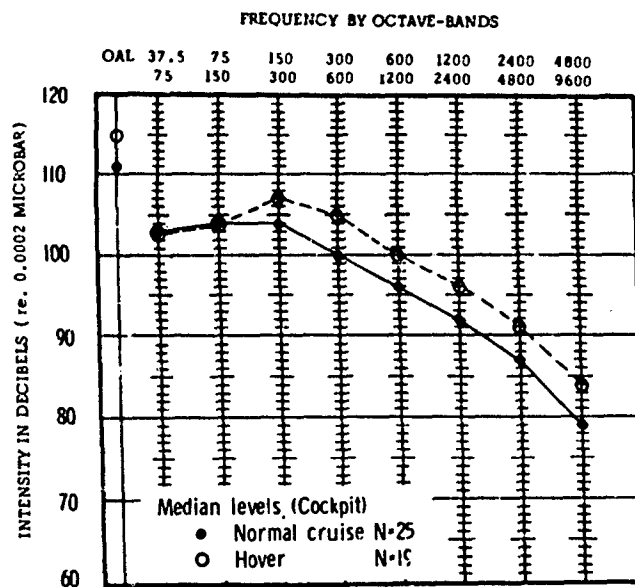


FIGURE 23

Plottings of median levels of noise exposures recorded within the cockpits of rotary-wing aircraft powered by reciprocating engines during conditions of normal cruise and hover.

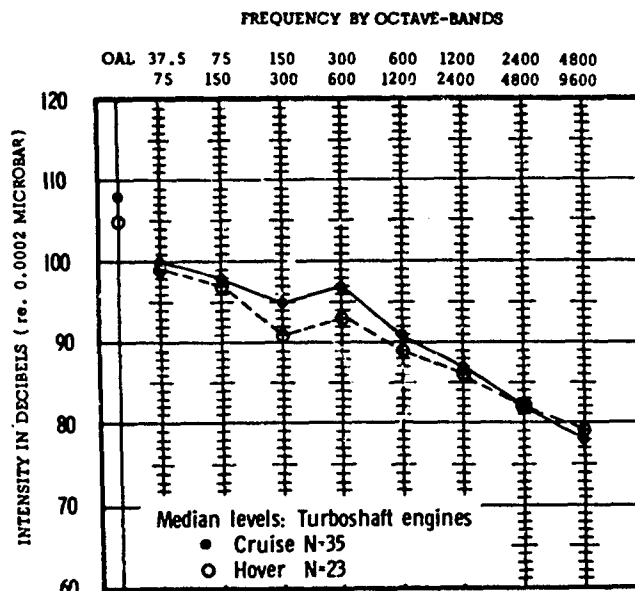
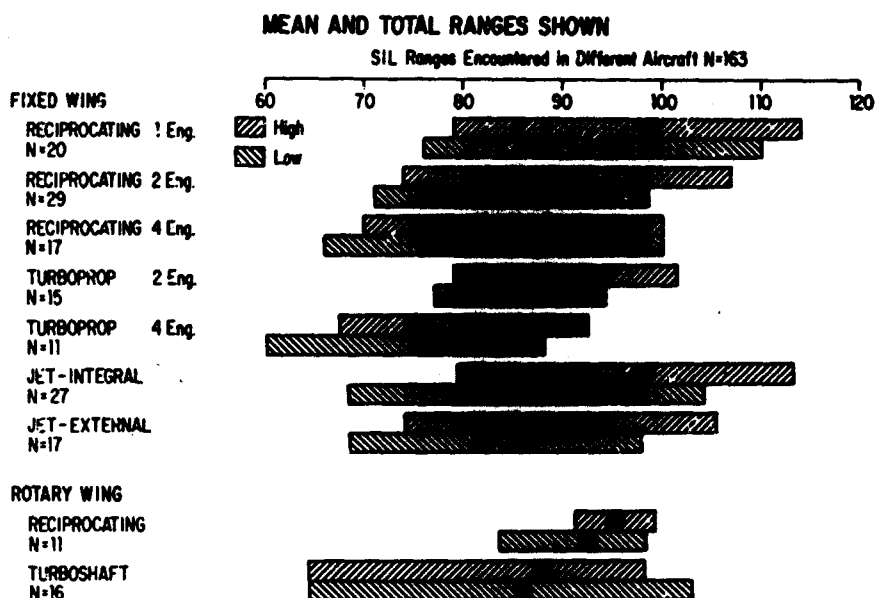


FIGURE 24

Plottings of median levels of noise exposures recorded within the cockpits of rotary-wing aircraft powered by turboshaft engines during conditions of normal cruise and hover.



**FIGURE 25**

*Comparison of the means and ranges of noise levels resulting in speech interference recorded within 136 fixed-wing and 27 rotary-wing vehicles during conditions of low (normal) and high cruise.*

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13. ABSTRACT

The acoustic environment within rotary-wing aircraft consists of a mixture of noises. This report identifies, describes, and illustrates the primary and secondary noise-producing mechanisms associated with helicopter operation. The noise sources include main rotors, antitorque rotors, main and secondary transmission and gear-shaft distribution systems, and auxiliary power units. In addition to describing specific noise generators, the report presents composite noise envelopes illustrating typical noise environs of rotary-wing vehicles having different configurations of rotor - to - power plant matings. Alterations in internal noise which occur during conditions of hover and forward flight are described and aeromedical factors such as speech interference and potential auditory risk are identified. ( )

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