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A COMPREHENSIVE REVIEW OF HELICOPTER NOISE LITERATURE

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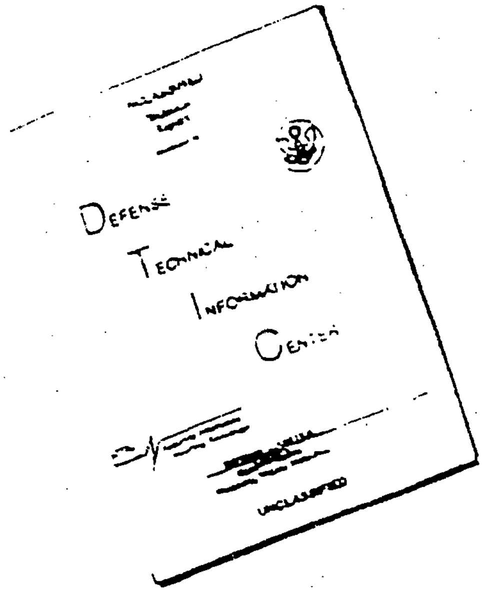

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16. Abstract

This report summarizes the state-of-the-art in helicopter noise. It includes a bibliography of reports on all components of helicopter noise including main rotor, tail rotor, engine and gearbox. Literature on helicopter noise reduction and subjective evaluation of helicopter noise were also included. Capsule summaries of important reports are included which describe the purpose of the report, summarizes the important results, compares the report with others on the same subject, and provides a critical evaluation of the work presented. It is concluded that the available prediction methodology provides a means for estimating helicopter sources on a gross basis. However, the mechanisms of noise generation are still not fully understood, although the experimental and theoretical tools are now available to conduct the definitive experiments and establish the mathematical models needed for accurate definition of helicopter noise generation mechanisms. Spectrum analyses of helicopter noise show that main rotor, tail rotor, and engine sources contribute significantly to annoyance. In cases where these sources have been heavily suppressed, gearbox noise will also appear as a significant contributor to annoyance. Therefore, quieter helicopters must include suppression of all of these components. For certification, the literature indicates that a new noise unit is required. This unit may use the effective perceived noise level concepts but should include corrections for impulsive noise, correctly address the influence of tones throughout the frequency spectrum, extend the spectrum of interest to very low frequencies, and correctly address the annoyance of noise components below 500 Hz. For assessing the community acceptance of helicopter noise, modification of the Day-Night Noise Level, L_{DN}, shows promise.

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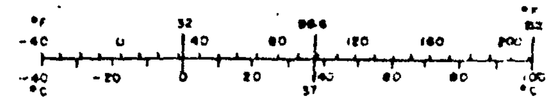
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10 000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

The helicopter is a complex vehicle from a noise standpoint. Significant noise producing components in the system include the main rotor(s), tail rotor, engine(s) and gearboxes. Differences in vehicle design philosophy cause differences in noise characteristics; e.g., some vehicles use a main rotor for lift with an antitorque tail rotor, other vehicles use fore and aft main rotors while others use meshing main rotors or dual contra-rotating main rotors without a tail rotor. Differences in rotor design philosophy also cause differences in noise characteristics since some manufacturers may use high tip speed two-bladed main rotors while other manufacturers may use as many as seven blades operating at lower tip speed.

Research to establish prediction techniques for all of the important helicopter noise producing components has been under way for many years. In many areas the acoustic theories relating the generated noise to aerodynamic and design parameters have been fairly well developed and appear to be adequate for current needs. However, as this report will show, there are many areas where the noise generation mechanisms are just now beginning to be understood and others where much further work is required. Also, the aerodynamic inputs required for the noise calculations are often inadequate for satisfactory noise estimates. It is thus apparent that the noise prediction methodology is inadequate due to the lack of tools required to define the unsteady aerodynamics (i.e., fluctuating blade loads) rather than in serious limitations in the acoustic theories. Fortunately, the helicopter as a military vehicle has benefited from noise control studies oriented toward reducing detectability. This has resulted in a body of knowledge which can be evaluated in terms of annoyance when helicopters are used as civilian transports.

The purpose of this report is to provide a current bibliography of reports describing studies of components of helicopter noise, provide capsule reviews of the more significant reports, summarize the state-of-the-art based on the literature, and discuss areas where further research is needed.

SUMMARY

In this report, the state-of-the-art in helicopter noise is reviewed. Areas evaluated include formulations of rotor (rotational, broadband, and impulsive), engine, gearbox, and helicopter noise prediction methodology; helicopter noise reduction techniques; and subjective response evaluation of helicopter noise. A bibliography of over 100 reports on these subjects is included along with capsule summaries of important reports from the bibliography.

Rotor noise consists of discrete frequency and broadband components. The discrete frequency components are referred to as rotational noise harmonics and occur at multiples of blade passage frequency. Rotational noise is a result of the rotating pressure field caused by the rotor blade loading due to thrust. Interaction with ingested turbulence, tip vortices and asymmetric inflow can significantly enhance harmonic content of rotational noise. Cyclic pitch and forward flight can give rise to a blade loading which varies once per revolution. Under certain conditions this can give rise to impulsive noise, characterized by highly annoying "banging" sounds. Broadband random noise in the rotor spectrum, formerly called "vortex" noise, is probably caused by interaction of the blades with inflow turbulence.

In calculations of rotor harmonic noise, the steady loading methods are inadequate to explain the high levels of measured harmonics. Unsteady loading of the blades is required to improve the correlation between calculations and measurements at high harmonic orders. In open-form solutions, instantaneous blade loads are computed at many angular positions and several radial stations during the rotation of the blades. These loads are then numerically integrated to define the noise at a given field point. This approach is generally costly as it requires long computation time. The computation time can be significantly reduced by assuming an analytic form for the azimuthal variation of blade loads (closed-form solution) rather than the many descrete points required for the open-form solution. The integration can then be done analytically. With few exceptions, such as for impulsive noise, closed-form solutions give comparable results to open-form solutions. Results using this methodology are greatly improved over the steady loading formulations. However, some deficiency in high frequency noise prediction remains. This has been improved by modifying the unsteady airload inputs to account for unsteady vortex effects as measured in wind tunnel tests.

It appears that the existing noise theories are adequate for good prediction of helicopter rotational noise. The limitations in the methodology appear to lie in the definition of the fluctuating aerodynamic blade loading inputs to the acoustic theory. Since the fluctuating blade loads cannot be well predicted analytically, empirical (or at least partly empirical) methods for estimating blade loads are required for predicting the rotational noise of helicopter rotors.

The origin of rotor broadband noise is probably the turbulence in the flow seen by the rotor blades. The prediction of rotor broadband noise based on rotor geometry and operating conditions using empirical procedures has proved acceptable. The success of such methods is misleading in that they do not model the detailed acoustic processes, but rely on generalization of existing test data. The recent impetus to study broadband noise is the result of reducing helicopter data with improved equipment that shows the higher frequency components of the spectrum to consist of peaks at blade passage harmonics superimposed on a lower level of broadband noise.

Impulsive noise is generally considered to be a special case of rotational noise. Two basic mechanisms are believed to be responsible for impulsive noise. Interactions between tip vortex filaments and the rotor blades are one major cause. Compressible aerodynamic effects are the other major cause. The major limitation in calculations of vortex filament interaction noise is the difficulty of specifying the details of the interaction of the filament with the blade. This is due to the complex trajectories of the vortex filaments and the blades. The impulsive noise that occurs during high speed cruise of a single rotor helicopter is believed to be caused by the compressible drag rise on the advancing rotor blade due to the high resultant of rotational and flight speed. As in other rotor noise prediction areas, the specification of the aerodynamic imputs for the calculations require further work.

Engine noise research has received recent attention because of its importance in turbofan engines. The noise components of engines identified in these studies are jet noise, combustion noise, turbine noise, and compressor noise. Jet noise in helicopters is not considered significant for current helicopters because of the low exhaust velocities of helicopter engines. However, it may become a significant component in future quiet helicopters. Combustion noise, which appears as a broadband noise which peaks near 400 Hz, is the dominant component of engine noise. Turbine noise appears at higher frequencies and consists of tones, pseudo tones, and broadband noise. Compressor noise occurs at high frequencies and is the lowest level component of engine noise. Compressor noise is easily suppressed with sound absorbent duct liners.

Two approaches to engine exhaust noise suppression can be used. The first approach reduces source noise by changes in design or operating parameters. This appears promising for future engine designs, but results in increased weight and size or increased fuel consumption in present engine designs. The second approach is the use of acoustically treated ducts to attenuate generated noise. This approach invariably adversely affects engine performance and also results in increased weight.

Gearbox noise is not generally a problem in current helicopters. However, quieter versions in the future will require gearbox noise suppression. Significant progress has been made in understanding gearbox noise mechanisms over the past eight years. This has included development of both analytical and empirical noise prediction procedures. The empirical methods are relatively easy to use and appear to offer reasonable accuracy in helicopter applications. Analytical methods, on the other hand, require a great deal of detailed design information to use and still require some empirical corrections for reasonable agreement with experiment. It appears that the empirical procedures should be used to estimate levels of existing gearboxes, while the analytical procedures are more useful in diagnosing noise problems in new gearbox designs and developing source noise suppression techniques.

The prediction of noise for complete helicopters has recently received some attention. The limited prediction procedures now available appear to be adequate for studies of community acceptance. These procedures are vehicle oriented and do not appear suitable for detailed studies of source noise, as they are usually semiempirical and use gross design and operating parameters rather than detailed aeroacoustic parameters.

A review of experimental programs to reduce the noise of existing helicopters showed that lower noise levels can be achieved, but at the expense of performance reductions and weight increases. Rotor noise reduction was attained by reducing tip speed, increasing rotor solidity by adding blades, and by limited blade aerodynamic improvements. Engine noise was reduced primarily by installation of inlet and exhaust mufflers. Gearbox noise was reduced primarily by installation of enclosures around the gearbox and by application of damping material to gears and shafting. These noise reduction techniques were effective, but might not be acceptable in commercial transport helicopters because of their weight and performance penalties. Further research is required in the noise reduction area to define rotor and engine configurations that are both quiet and efficient.

Subjective response to aircraft noise must be considered from two standpoints: aircraft noise certification and community reaction. In the first area, a scale is needed to measure the perceived level of an individual aircraft flyover sound. In the second area, a community acceptance calculation procedure which accurately evaluates the long term effects of aircraft noise on communities around airports is required. For noise certification, serious deficiencies exist in the existing rating scales because of the significant differences between helicopter noise and noise from other types of aircraft. Based on the data from the literature, it appears that the helicopter noise certification unit will use Effective Perceived Noise Level as the basis for development. Revisions appear necessary to: 1) revise the psychoacoustic response (Noy) curves and extend them below 50 Hz, 2) use integrated duration correction as used in FAR Part 36 rather than $10 \log_{10} (t/15)$ (where t is the time, in seconds, between 10 dB down points), 3) include the effects of impulsive noise, and 4) correctly account for the effect of discrete frequency noise below 500 Hz. The data from the literature support the use of some version of the L_{dn} concept for community acceptance evaluation. The basic unit for L_{dn} calculation might be dBA corrected for pure tones and duration as described above. Impulse noise penalties would also be included.

HELICOPTER NOISE SOURCES

Introduction

The principal helicopter noise sources are those associated with the main rotors or main and tail rotors, drive engine(s), and gearbox(es). All these sources give rise to a broadband noise spectrum extending over the entire audible spectrum and to discrete frequency noise, which may or may not be detectable to the human ear. Under certain conditions, helicopter rotors may generate impulsive noise, descriptively termed "blade slap" or "banging".

Rotors produce noise due to the rotating forces on the blades and the displacement of the air due to the blade section area. Also, at high tip speeds and/or high flight speed, the flow over the blade section may exceed sonic velocity and a local (and thus moving) shock is generated. Finally, fluctuating blade loads may occur due to interaction with atmospheric turbulence, tip vortices, or the flow from another rotor.

Engines produce noise over a broad frequency range The engine inlet compressor generally contributes to high frequencies and the engine exhaust dominates at low frequencies, although turbine tones may occur at high frequency.

Gearbox noise can be apparent in the noise signature of a helicopter due to direct radiation from the gear casing or from reradiation of the structure coupled to the gearbox.

Extensive literature exists on the understanding, description, and prediction of these sources. Studies range from simple empirical equations showing the relation of a few gross design and operating parameters to the resulting noise to extensive open form solutions requiring detailed design information which can be applied only by means of a high speed computer. The state-of-the-art in source noise understanding and prediction has by no means progressed to the point where all aspects of the problems have been fully developed. However, the fundamental noise problems are reasonably well understood and predictable in principle. Application of these theories to the design or redesign of helicopter components has generally resulted in noise reduction, although a deeper understanding in many areas, especially those related to broadband noise, is required for substantial reductions without undue performance and/or weight penalties.

The following discussion presents a review of the literature on the historical development of noise prediction methodology, summarizes the current understanding of basic mechanisms, and presents philosophy and results for the reduction of helicopter noise.

Rotor Noise

Rotor noise contains discrete frequency components and broadband components. The discrete frequency components are referred to as rotational noise harmonics and occur at multiples of the blade passage frequency. These are caused by the rotating pressure field caused by the rotor blade loading due to the thrust. Also, in cases where interaction with ingested turbulence or between rotors or with the tip vortices occurs, a rotating fluctuating pressure field results which can significantly increase the harmonic content of rotational noise. Cyclic pitch and forward flight can give rise to a blade loading which varies once per revolution. Under certain conditions (e.g., if the forward speed is such that the tip Mach number of the advancing blade exceeds some critical value), this can give rise to impulsive noise, characterized by highly annoying "banging" sounds. The impulsive noise is characterized by sharp peaks in the acoustic pressure time history. Random noise formerly was called "vortex" noise, but investigators now prefer "broadband" noise, since vortex shedding itself is not believed to be the principal mechanism.

Rotational Noise - Prior to the 1960's, Gutin's[1] method was used extensively for predicting the noise from propellers, fans, and rotors. In this theory, a distribution of sources which are fixed in space are "triggered" by the passing blades. The strength of the sources is determined by the rotor thrust and torque assumed to act at an effective radius, typically at 0.8 times the actual radius. This analysis is valid for a static propeller and at distance several diameters away (far-field noise). Hubbard and Regier[2] refined Gutin's fundamental equations without some of the simplifying assumptions of the original paper. This removed Gutin's restriction for far-field noise and allowed calculations of noise in the near-field to distances within one blade chord of the tip. Also, the actual radial blade load distribution could be utilized. Garrick and Watkins[3] extended Gutin's theory to the case of a propeller with forward speed for an observer moving with the same velocity as the source (i.e., a wind tunnel test). The results could also be applied to the case of a stationary observer, providing that the correct instantaneous distances were used and the frequencies corrected for Doppler shift. Finally, Watkins and Durling[4] combined these effects and included effects of a chordwise blade loading. However, these methods, which all assume that the blade loading is constant with time, were found to severely underpredict the levels of the harmonics beyond the second or third.

The realization that unsteady blade loading (i.e., a blade loading distribution which varied with time) could contribute significantly to the noise generated by a rotor prompted an extension of Gutin's approach and the development of new formulations for the noise produced by moving sources[5] and unsteady blade loading effects[6-10].

The approach of Loewy and Sutton[10] is a similar approach to that taken by Garrick and Watkins[3], but extended to include in-plane components of forward speed and azimuthal asymmetry. In this approach the sound pressure is computed at any field point by a numerical integration which utilizes, among other inputs, the lift per unit span as a function of radius and azimuth. In this manner any radial loading function and any periodic waveform of the blade loading at a given radial station can be input by judicious selection of radial and azimuthal steps of integration. This approach, while having flexibility, can become expensive due to the large number of calculations required in the numerical integration, particularly when using small steps, as is required for calculation of the higher rotational noise harmonics.

Schlegel, et al[6] used a similar approach. They used the blade loading harmonics which were measured on an actual helicopter rotor as inputs to a modified form of Gutin's theory. They conclude that the agreement between measured and predicted noise, as reproduced in Figure 1, is good at low frequency, but poor at high frequency, probably because of inadequate definition of high frequency harmonic airloads.

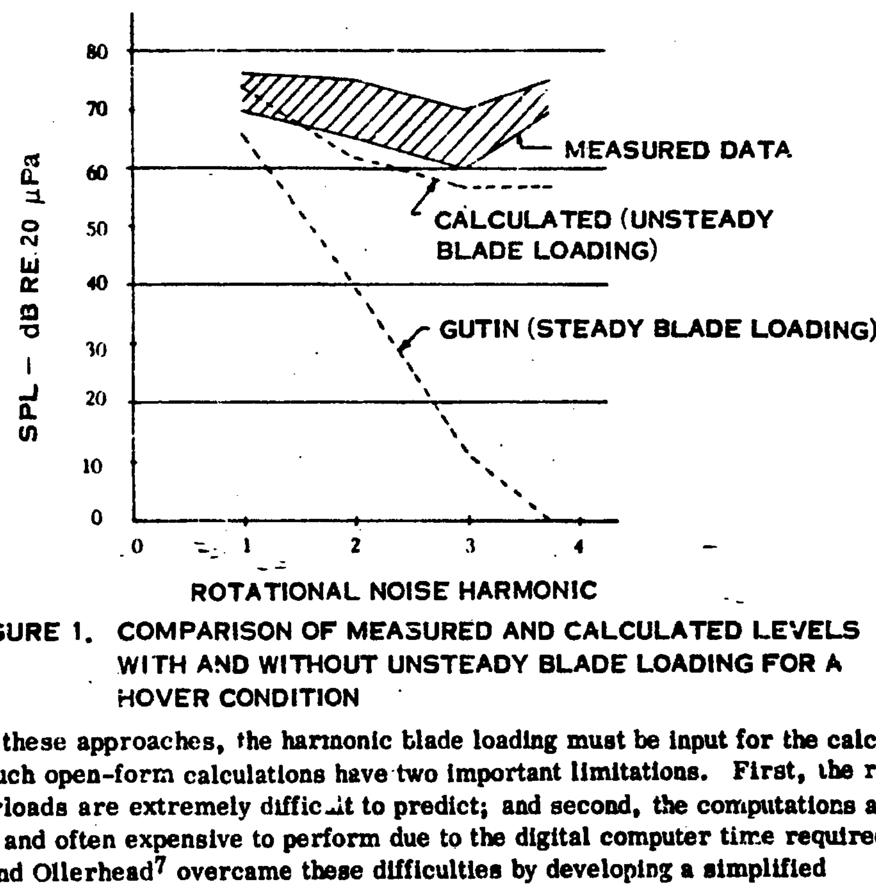

FIGURE 1. COMPARISON OF MEASURED AND CALCULATED LEVELS WITH AND WITHOUT UNSTEADY BLADE LOADING FOR A HOVER CONDITION

In both of these approaches, the harmonic blade loading must be input for the calculation. Such open-form calculations have two important limitations. First, the required airloads are extremely difficult to predict; and second, the computations are extensive and often expensive to perform due to the digital computer time required. Lowson and Ollerhead[7] overcame these difficulties by developing a simplified rotational noise analysis which uses generalized loading data instead of the detailed amplitude and phase information required by previous analyses. This simplified closed form method was shown to perform at least as well as the rather cumbersome, open-form solutions in many cases, as indicated in Figure 2.

Wright's approach[4] is similar to Loewy and Sutton's, except that certain assumptions are made regarding the radial loading distribution. Neglecting higher order terms in far-field approximations, Wright's formulation reduces to an analytical expression which does not require numerical integration. His significant conclusions are that the rotational noise is the dominant rotor noise mechanism and vortex noise is a negligible noise source at normal operating conditions. Also, the harmonic fall-off will be determined basically by the blade loading spectra, there will be noise radiation along the axis of rotation (in contrast with steady loading radiation results which would show no noise on axis), and the tip speed effect is independent of the number of blades, therefore removing the large power law dependence on blade number indicated by Gutin.

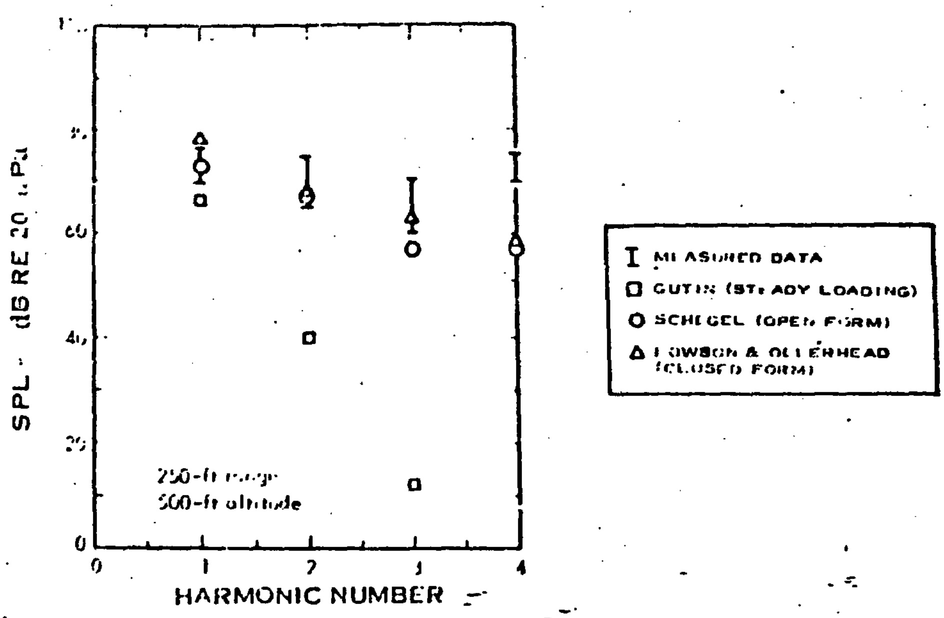

FIGURE 2. COMPARISON OF STEADY LOADING, OPEN FORM, AND CLOSED FORM THEORIES WITH MEASUREMENTS FOR A HOVER CASE

There are situations for which closed-form methods are not well suited. Basically, the methods are inadequate when large airload changes occur over a small portion of the rotor disc. This loading behavior produces highly directional harmonic noise and is commonly observed as impulsive noise (or "blade slap") on most tandem rotor helicopters and many single rotor helicopters. Since the closed-form solutions assume that the airload harmonics are randomly phased and that their amplitudes decrease exponentially with harmonic order, the noise is predicted to be constant azimuthally during hover and symmetrical azimuthally during forward flight. Impulsive noise is discussed in a later section of this report.

Much recent acoustic research work has returned to experimental rather than analytical studies. References 11 through 14 are examples of noise measurement studies intended for verification of existing noise prediction analyses as well as for studies of noise generating mechanisms. Reference 11 essentially verified and slightly refined Lowson and Ollerhead's simplifying assumptions. Reference 12 demonstrated the accuracy of Wright's theoretical approach using measured airload amplitude and phase data, whereas Reference 13 is oriented towards establishing a base for developing empirical formulae for rotational noise at a future date. Reference 14 demonstrates good correlation on-axis with Reference 7 and provides a preliminary aero-acoustic transfer function for rotational noise. If generalized aerodynamic inflow data are ever developed, the transfer function approach could become a useful new prediction tool.

Existing prediction methods for non-impulsive rotational noise predict some decay of harmonic level with increasing order. This behavior is predicted by open-form, numerical integration of distributed loads methods as well as by the simplified, point load methods. However, improvements in data analysis have shown that blade passing harmonics may extend into the mid-frequency range, as shown in Figure 3 (from Reference 7), and that levels frequently increase with harmonic order after an initial decrease for the first few harmonics. Consequently, agreement between predicted and measured harmonic levels deteriorates with increasing frequency.

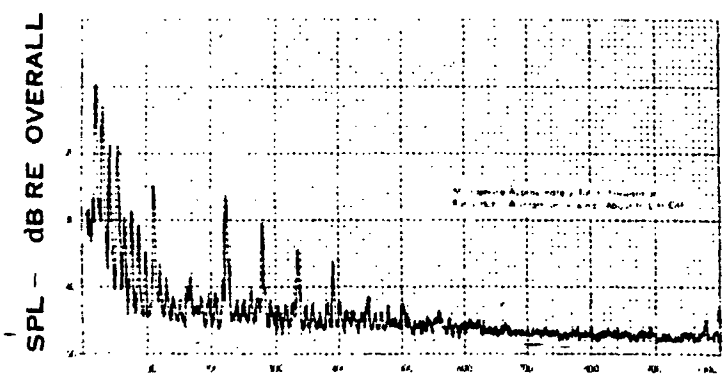

FIGURE 3. TWO-HZ BANDWIDTH ANALYSIS OF UH-1B NOISE SPECTRUM

Some preliminary studies by Sikorsky Aircraft[15] have shown significant correlation improvement by adding vortex-induced unsteady airloads to the airloads defined by Lowson's "loading law" decay approximation. The unsteady vortex effects are based on wind tunnel data measured with hot wire anemometers. Figure 4 illustrates that the unsteady vortex effects enable a closed-form analysis to predict the basic noise [illegible] of decrease followed by increase and final decrease. It is believed that [illegible] corrections for unsteady vortex effects could be developed with [illegible] different airfoil sections and tip configurations, coupled with noise [illegible].

In summary, it appears from a review of the literature that the existing noise method- [illegible] rotor rotational noise is adequate for good prediction of helicopter rotor [illegible]. However, the limitation appears to be in the aerodynamic blade loading inputs which are required to the noise methods. As Schlegel, et al[6], concluded from their studies, good agreement between calculation and measurements was obtained at low frequency where the aerodynamic input data were adequate, but poor agreement was obtained at high frequency due to the lack in aerodynamic data. The situation is further complicated in representing the entire dynamic flow field around a rotor during all modes of helicopter operation, particularly in the case of tandem rotors which interact and in the case of tail rotors which are in the main rotor downwash.

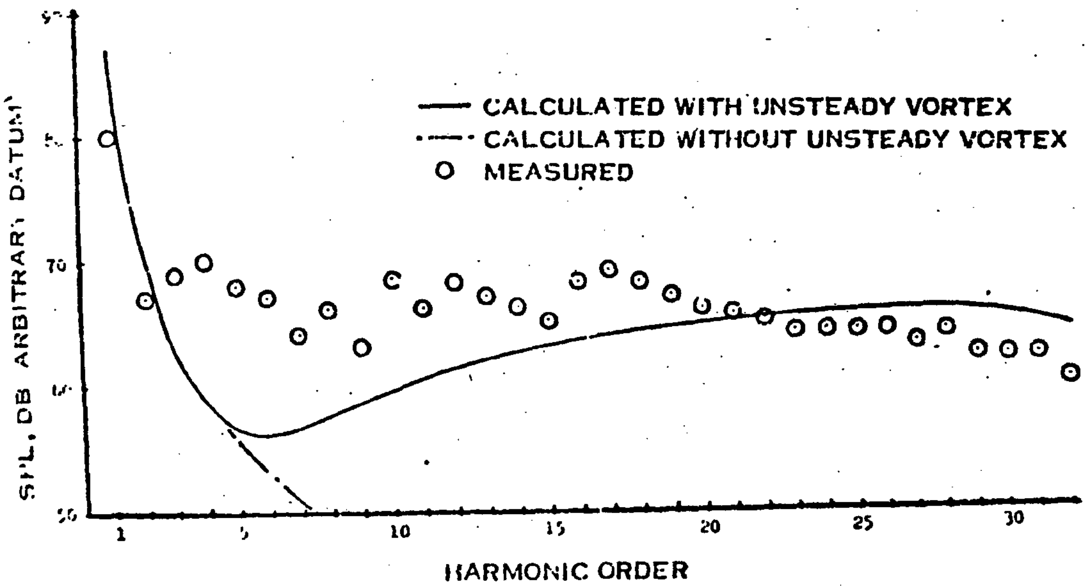

FIGURE 4. CALCULATED EFFECT OF VORTEX INDUCED UNSTEADY AIRLOADS

Broadband Noise - Opinions regarding the origins and behavior of broadband noise vary somewhat among investigators, but there is general agreement that turbulence in the flow seen by rotor blades is the basic physical mechanism responsible for broadband noise. Turbulence in the boundary layer also causes noise, but at a negligibly small amplitude compared to blade interaction with incoming turbulence. The frequency distribution of the broadband noise is determined by the velocity of the blade and by the size scale of the turbulence[14]. Principal areas of uncertainty concern the effects of velocity on the intensity and frequency distribution of broadband noise. Recent experimental work by Leverton and Pollard[16] fails to show the accepted Strouhal frequency scaling with velocity for full scale rotors. Ffowcs-Williams and Hawkings[17] make a convincing case for broadband noise varying with velocity as V^8 at tip Mach numbers above 0.5, instead of the V^6 dependence in common use as reported by Widnall[18].

Much of the recent impetus to study broadband noise comes from improved data processing techniques and equipment. Narrow band analyses of rotor noise have shown discrete frequency components extending well beyond 150 Hz, which historically was believed to be the transition region between rotational noise and broadband noise for typical helicopter rotors. This means that significant rotational noise contributions are included in the observed noise behavior and in the broadband noise prediction methods that have been developed from experimental observations such as the well known Widnall[18] correlation of Figure 5. Work by Lowson, et al[14], and by Leverton

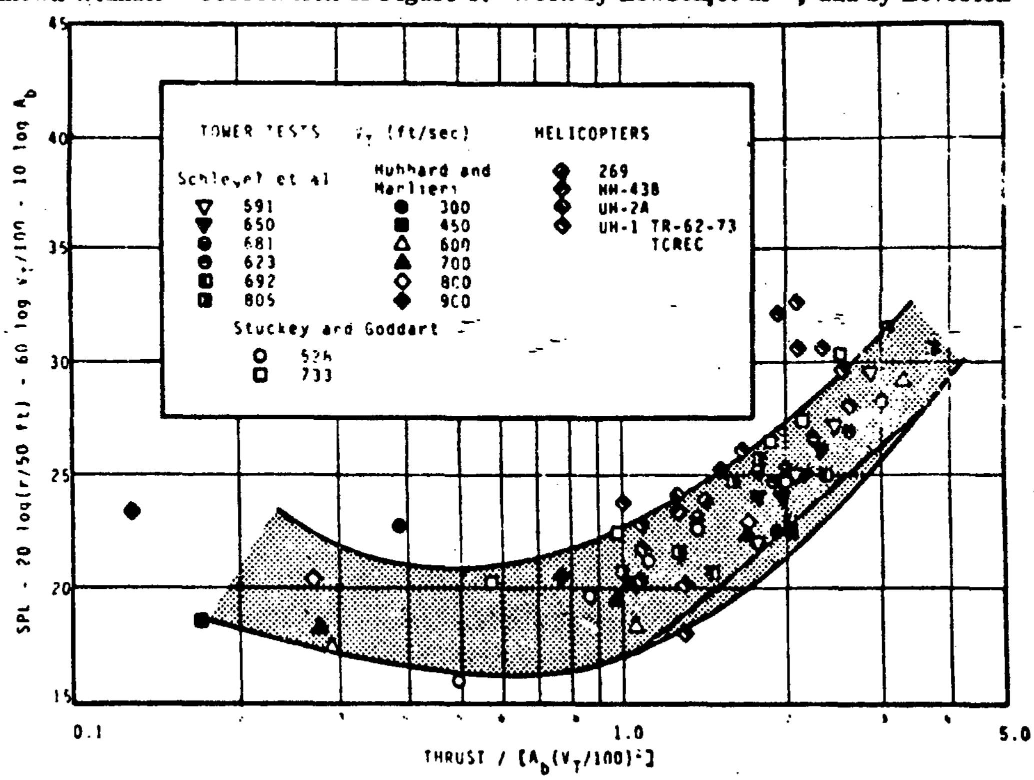

FIGURE 5. WHIRL TOWER AND HELICOPTER VORTEX NOISE.

and Pollard[16], emphasize that low frequency broadband noise could be different in nature (that is, have different causative physical mechanisms and acoustic behavior) than high frequency broadband noise.

Furthermore, the apparent agreement of predicted broadband levels and spectrum shape based on rotor geometry and operating conditions is misleading. These prediction methods may give reasonable estimates of octave band or possibly 1/3 octave band levels for typical rotors, but these methods do not really model the detailed acoustic processes that contribute to the total signal. Consequently, it is not presently possible to provide a detailed narrow band estimate of rotor noise based on detailed geometric and aerodynamic properties of a rotor system. Extensive experimental and analytical work still needs to be done to isolate the specific mechanisms that produce broadband rotor noise and to develop useful prediction models.

The preceding discussion indicates that detailed prediction methods are not available presently. Lowson, et al[11], found encouraging correlations using measured inflow turbulence in acoustic equations to predict broadband fan noise at low speeds, but this is not a method suitable for helicopter predictions. Methods, in general, have relied on octave band noise data from full scale rotors to develop empirical methods. In these methods, such as the "Schlegel" equations for broadband noise[6] gross geometry and operating condition (blade chord, blade area, tip speed, and rotor thrust) are the basic parameters. The form of these equations was modified somewhat by Munch[19] to obtain the form below:

$$SPL_j = 20\left[LOG(V_t) + LOG(T) - LOG(r')\right] - 10\left[LOG(B) + LOG(R) + LOG(c) - LOG(Cos^2\theta + 0.1)\right] + S_j + 19.4 \quad (1)$$

$$f_s = 746 + 0.716\, V_t - 240\, LOG(T) \quad (2)$$

This arrangement is easier to use since it uses the basic parameters of tip speed, V_t, thrust, T, distance, r', blade area, B, blade radius, R, blade chord, c, elevation angle, θ, and spectrum shape correction, S_j. Values of S_j for the j th frequency band used by Munch are shown in Figure 6. The term, f_s, is the center frequency in Hz for use with Figure 6. This method provides estimates of octave band levels in fairly good agreement with octave band test data, but some rotational noise contributions are included in this "broadband noise" as discussed previously.

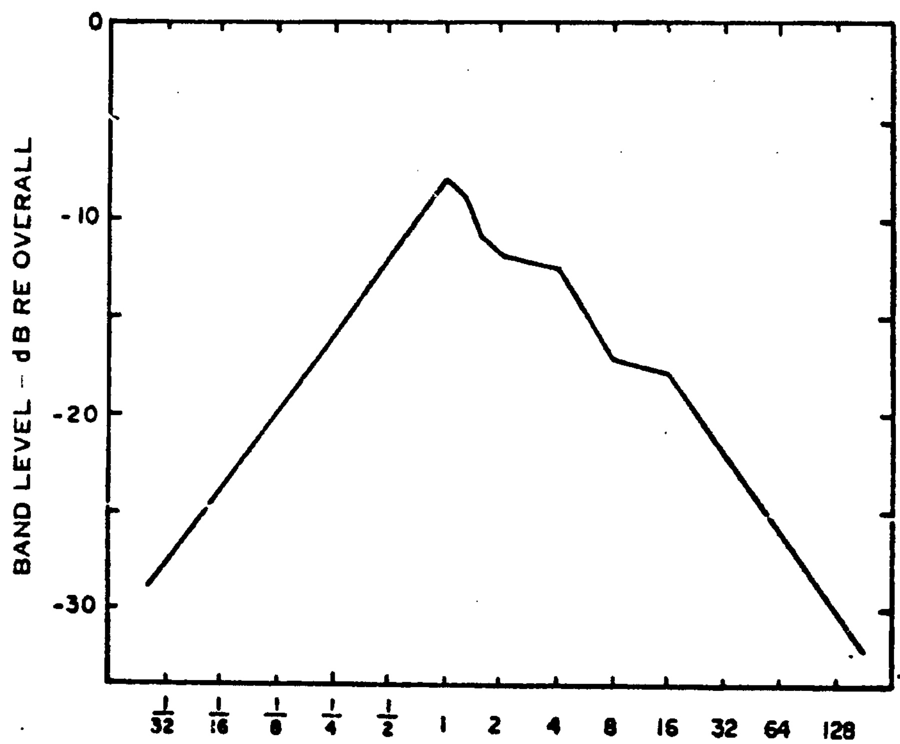

FIGURE 6. ROTOR BROADBAND NOISE SPECTRUM SHAPE

Empirical broadband noise methods tend to be most accurate for a moderate thrust condition which typically is near the design point for a given rotor. Predicted overall broadband levels normally fall within ± 3 dB of measured levels. Accuracy decreases rapidly, however, at low thrust and at high thrust. Problems are compounded by blade twist, which leads to recirculation through stationary rotors (i.e., when the blade wakes are reingested by the rotor) with attendant noise increases during operation at low blade pitch. At high thrust, blade stall and complex unsteady aerodynamic events in the tip region of the blades contribute to rapid increases in noise. Figure 5 illustrates the noise behavior discussed above.

<u>Impulsive Noise</u> - Impulsive rotor noise generally is considered to be a form of rotational noise. Narrow band analysis reveals many harmonics of noise that decay slowly with harmonic order, while oscillograms of the acoustic pressure characterize the noise as an impulse that occurs at the blade passage frequency of the rotor. Helicopters with tandem, overlapping rotors are prone to generate impulsive noise, but helicopters with single lifting rotors also can generate it.

Two basic mechanisms are believed to be responsible for impulsive rotor noise. Interactions between tip vortex filaments and rotor blades are one major cause. Com-

[illegible]pressible aerodynamic effects are the other major cause. These two mechanisms are not necessarily mutually exclusive, as Sternfeld, et al[11], demonstrate with their [illegible] vortex-induced shock formation on blades of a hovering rotor. Of the two mechanisms, blade vortex intersection has received the most attention. References 11 and 20-23 are samples of the numerous experiments on static rotor test stands, flight vehicles, and in wind tunnels that have demonstrated the important role that blade vortex intersections play in impulsive noise generation. Analytical models of blade vortex intersections have been developed (References 21, 22, 24) which appear capable of predicting waveforms that agree qualitatively with measured waveforms. Reference 22 shows particularly good agreement for a one-bladed rotor operating in a wind tunnel. The biggest problem lies in estimating the magnitude of the encounter with a real-life vortex filament. Tip vortex filaments follow complex trajectories, which makes the relative location and orientation of the blade and vortex very difficult to specify. In addition, the distribution of vortex core velocity and the decay of the vortex with time is difficult to assess experimentally as well as analytically. A further complication to the acoustic prediction problem is the operating point of the airfoil and its aerodynamic response characteristics, as pointed out in Reference 11.

Impulsive noise from tandem rotor helicopters involves many factors. Typically, a view looking down on the vehicle shows some degree of overlapping of the rotor discs. This overlap causes impulsive noise from two mechanisms. The major one is blade-vortex interaction, where the tip vortices from one rotor pass through the other rotor. The interaction can occur on either the forward rotor or the aft rotor, depending on relative trim of the rotors and on the flight condition. The second cause of impulsive noise in tandem rotors with overlap is called rotor/downwash interaction. The downwash of one rotor passes through the other rotor in the overlap region, causing a pulsative once-per-revolution change in loading on the rotor blades. This loading gives rise to impulsive noise. Boeing Vertol Company has conducted numerous studies of noise generation and noise reduction for tandem helicopters that established the importance of rotor/vortex interaction and rotor/downwash interaction. Substantive data generally are proprietary to the Vertol Company, but some quantitative trends are presented in Reference 25, which documents a study of civil helicopter noise. This study concludes that the only way to eliminate impulsive noise from rotor-rotor interference is to eliminate overlap and to control the vertical separation of the two rotors. Figure 7 is taken from Reference 25 to illustrate how separating the rotors influences noise.

The ability to predict noise from tandem rotor helicopters with overlap is not well established in open literature, although proprietary methodology may exist in some companies. In principle, if data are available from test or analysis to relate vortex interaction strength and downwash effect to a configuration, analytical models exist to estimate the noise waveform caused by pulsative changes in airloading on the rotor blades.

Impulsive noise that occurs during high speed cruise of single rotor helicopters is believed to be caused by compressible drag rise on the advancing rotor blades. The rotor noise of a large single rotor helicopter (Sikorsky S-65) was studied in Reference 23

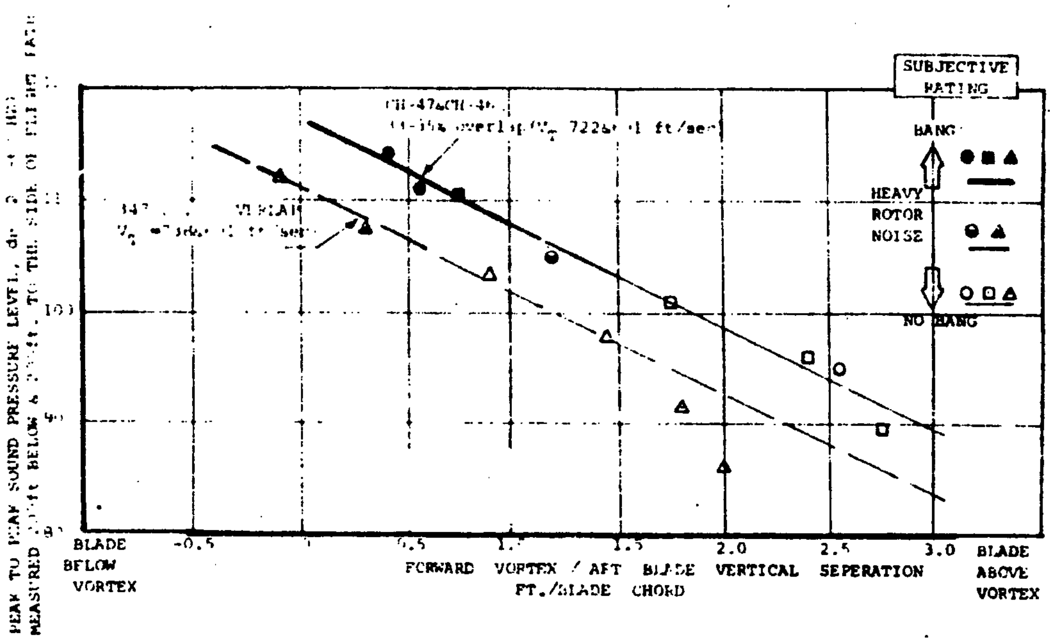

FIGURE 7. EFFECT OF BLADE–VORTEX SEPARATION ON IMPULSIVE ROTOR NOISE

during a program of simultaneous noise and rotor load measurements. Results show that during high speed cruise, unsteady airloads alone are not enough to predict rotor rotational noise in front of the helicopter. Arndt and Borgman[26] present a model for drag rise harmonic noise based on profile drag on the blades. Profile drag is shown to be a significant source of harmonic noise at high forward speeds, a source that would not be reflected in airloads from aerodynamic pressures measured on the surface of the rotor blades. Lyon, et al[27], approach the problem differently by tailoring the thickness distribution in the tip region to reduce noise near Mach 1.0. Results from both approaches are similar, since reducing blade thickness reduces noise (and drag) and reducing drag reduces noise. In practice, Arndt and Borgman's approach is fairly straightforward to apply if airfoil lift-drag characteristics are available. Available results from unpublished Sikorsky studies show fairly good agreement with measured data (Figure 8) when noise from compressible drag rise is added to noise from fluctuating airloads.

Drag near the tip of a helicopter rotor blade during high speed cruise is difficult to calculate accurately. Torsional blade bending modes combine with flatwise and edgewise bending and with rigid body flap and lead-lag motions to influence local angle-of-attack, drag, and noise. Obviously, unsteady aerodynamic response characteristics of the airfoil also influence the drag and noise. Consequently, it is important to

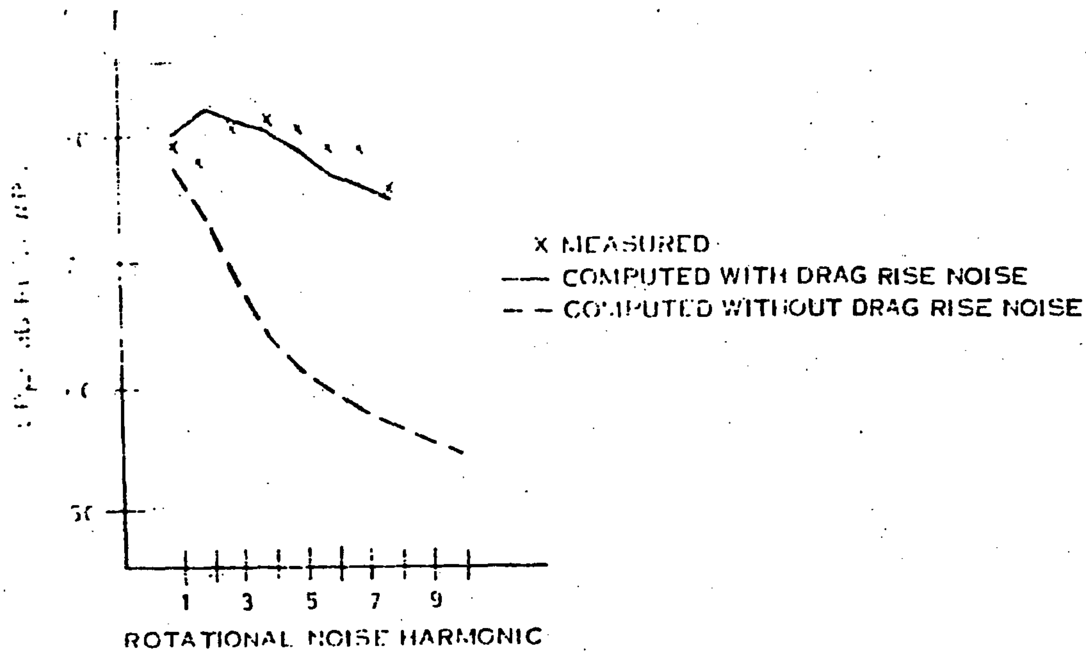

FIGURE 8. CALCULATED AND MEASURED EFFECT OF DRAG RISE NOISE AT 180 KTS CRUISE

realize that this drag rise noise model is not necessarily an accurate representation of the detailed aeroacoustic processes occurring during high speed cruise. The simple model does improve agreement between estimated and measured noise and is useful for that reason. More confidence needs to be developed in the ability of either Arndt and Borgman's method or Lyon's method to predict high speed impulsive noise levels. Flight tests or wind tunnel simulations are needed to establish this confidence and to produce a refined prediction method. It is conceivable that more sophisticated experimental studies will find that existing models have produced reasonable estimates of the gross acoustic properties without correctly modeling the actual noise generating processes (a situation similar to the case of broadband rotor noise). Detailed estimates of high speed impulsive noise may then require an entirely new analytical approach.

Engine Noise

Introduction - Generally, helicopters are powered by internal combustion engines which provide power to the main rotor(s), tail rotor(s), and accessories through various stages of shafting and gearboxes. Although early helicopters utilized reciprocating engines, most current designs are powered by turboshaft engines. Therefore, the discussion of engine noise sources in this report has been limited to turboshaft engines.

Turbine engine noise sources fall into two general categories: those originating outside the engine and those contained within the engine. The first category includes jet noise, while the second category includes combustion noise, turbine noise, strut noise (turbulent flow interaction), and compressor noise.

Jet Noise - Jet noise originates from the momentum exchange between the higher relative velocity of the exhaust gases and the ambient air. This momentum exchange gives rise to turbulent shear stresses which in turn produce pressure fluctuations and a radiated sound field. Thus, jet noise is generated entirely downstream of the engine exhaust duct. Lighthill's equation[1,2] is generally recognized as a valid mathematical description of the phenomenon of jet noise. In Lighthill's equation the far-field sound intensity of jet noise is shown to be proportional to the relative jet velocity raised to the eighth power and a characteristic dimension (usually the exhaust duct diameter) squared. As is indicated in Lighthill's equation, the jet noise is a strong function of the jet velocity. In typical helicopter application, the engine exhaust duct velocities at the exit are relatively low, since exhaust diffusers are used for maximum power extraction from the engine. Generally, exhaust velocities from helicopter engine tailpipes are less than 300 ft./sec. At such low velocity, the jet noise levels are very low and will not contribute to the overall engine noise until the other sources are extensively attenuated.

Combustion Noise - In turboshaft engines for helicopter applications, the combustion noise is the dominant source. This source of noise has been "discovered" fairly recently and was in the past associated with jet noise by investigators who found a deviation from the classical eighth power velocity dependence of jet noise (Lighthill's theory) for jet velocities below 1000 ft./sec. Bushell[3], in 1971, presented evidence that the low frequency noise which was unmasked at low engine exhaust velocities was associated with turbulence, internal struts, and flow through the combustors. It is not surprising that this source of noise has not gained prominence until recently, as it generally appears as low frequency broadband noise peaking in the vicinity of 400 Hz and is thus frequently confused with jet noise.

Combustion noise is produced by the unsteady combustion process in turbine engines. Because the combustor airflow is highly turbulent and the fuel injection system introduces variability in droplet size, the combustion process is, therefore, unsteady with time with varying heat release which in turn produces pressure fluctuations within the combustion chambers of the engine. These pressure fluctuations propagate downstream and give rise to a sound field.

Ho and Tedrick[4] have concluded from extensive analysis of noise measurements made on small turboshaft engines that the combustion noise is the most significant source for these small engines. A simplified procedure for predicting gas turbine exhaust noise related the overall sound power level to a noise factor based on the combustor inlet temperature, the combustor discharge velocity, and the effective diameter of the combustor. They identify combustion noise with a low frequency hump, characteristically at 125 Hz.

as an extension of this work[4,5]; they attempted to derive a modified noise factor by dimensional analysis by adding dependence on fuel-to-air ratio, combustor exit pressure, and combustor exit temperature to their original relationship.

Motsinger[6], working with data from a TF39 combustor and T-64 engine data, has offered a similar relation to Ho and Tedrick's without a fuel mixture term, but with a mass flow dependence.

A slight variation of Motsinger's equation is offered by Neitzel[7], in which the pressure ratio is raised to the 1.3 power instead of the 2.0 power and the combustor inlet-temperature-to-ambient-temperature ratio dependence is dropped.

Other investigators[8,9,10] present other forms of varying complexity for the prediction of combustion related noise. These seem to have in common, however, that the important parameters are the air flow rate, combustor exit temperature, and combustor exit pressure.

The above cited procedures all relate the overall sound power level to the combustion process. A procedure does not appear to exist for computing the combustion noise directivity pattern or spectrum shape. In the recently published report describing an interim prediction method for low frequency core engine noise to be used by the NASA Aircraft Noise Prediction Office, Huff, et al[11], suggested using Dunn and Peart's[10] directivity curve based on measured directivities from several engines. Also, they agree with Dunn and Peart's justification for adopting the SAE[12] spectrum for in-flight jet noise on the basis that jet noise and low frequency core noise are difficult to separate.

However, Kazin, et al[13], from analysis of engine data, have concluded that the directivity pattern of combustion noise depends on the engine exit geometry. Their data does not show as steep a reduction in the forward quadrant as does Dunn and Peart's, although both place the peak at or near 120 degrees from the inlet. The Kazin, et al, data appear to be more consistent with Strahle's work[14], who concludes that the low frequency combustion noise should have only weak directionality.

Finally, Kazin, et al, and Picket[15] conclude that the combustion noise spectrum shape will closely follow the turbulence spectrum at the entrance to the combustor. Kazin's data reveal a broad peak centered about 300 to 400 Hz, which is consistent with Mathews and Peracchio[16], and certainly more intuitively satisfying than arbitrarily assigning it a jet noise spectrum.

In summary, it appears that combustion noise processes are not as yet fully understood and the noise prediction methodology is not fully developed. However, several semi-empirical procedures have been developed which give reasonably good agreement with available test data. In particular, the procedure presented by Kazin, et al[13], (similar in part to that recommended by Huff, et al[11]) seems appropriate for current noise estimates due to its relative simplicity and good accuracy.

Turbine Noise - The noise mechanisms for turbine-generated noise are similar to those for compressor noise; i.e., fluctuating blade forces due to rotor stator interaction and turbulence in the flow. Turbine noise generally occurs at a higher frequency than combustion noise and includes tones and pseudo-tones as well as broadband noise. The fundamental frequency for turbine tones is generally above 4000 Hz due to the high rotative speeds and many blades of the turbine.

There is considerable broadening of the "tones", commonly called "haystacking". This phenomenon has been found to depend to a large degree on the relative axial location of coaxial fan duct termination in turbofan engines (Dunn and Peart[10] recommend that the turbine tone noise level predicted for the JT8D engine be reduced 10 dB for this engine, where the primary and fan flows mix internally) leading to the conclusion that this component of turbine noise is strongly influenced by propagation through the turbulent exhaust flow. Also, since the flow leaving the combustor is highly turbulent, random pressure fluctuations give rise to random perturbations of the vane and turbine blade loadings. In the case of the vanes, this phenomenon will produce broadband noise, whereas for the turbine blades it will generate narrow-band random noise which appears as "haystacks" at blade passing frequency and its harmonics.

Essentially, no analytical formulations for turbine noise exist, although the mechanisms are believed to be similar to those for compressors and thus compressor noise methodology can be adapted to the turbine noise case. However, there have been several attempts at empirical correlations of data obtained in turbine rigs and full-scale engines. Early attempts by Smith and Bushell[17] related the peak broadband noise level to the total mass flow and to a local speed of sound and blade relative velocity cubed. A similar relationship is given for the tone levels with the addition of a stator-rotor spacing term, although large scatter in the data detract from the usefulness of the relationship.

Dunn and Peart[10] present a turbine noise estimating procedure which is similar to that of Smith and Bushell. They show somewhat better agreement with data, primarily by virtue of selecting comparison data only from limited turbofan noise measurements.

Kazin, et al[13], have attempted to derive an analytical turbine noise prediction method based on noise generating mechanisms studies for fans and compressors. Although the procedure is claimed to accurately predict turbine noise levels, it is of limited value for general use due to the detailed design and operating parameters required for its use.

Since it has been demonstrated that the noise generated by turbines is related primarily to 1) a work parameter; 2) a velocity parameter and 3) blade row axial spacings, the relationships of Dunn and Peart[10] appear adequate for rough estimates of conventional engine designs, as their relation includes these primary variables.

[illegible] turbulent flow interaction with [illegible] for very small flow incidence [illegible]. At low [illegible] power, however, the turbine oper- [illegible] incidence with resulting flow sepa- [illegible] applications, this is not normally a problem, since power re- [illegible] and approach do not vary as much as for turbofans. [illegible] to the [illegible] which is induced on a strut by [illegible] flow. Although there does not appear to be an experi- [illegible] that the sound generated by an arbi- [illegible] flow, [illegible] et al[13], have proposed a [illegible] fraction to a mean velocity, [illegible] coefficient. The noise levels are shown to vary [illegible] coefficient to the 0.1 power [illegible] power of the velocity.

[illegible] noise has been identified in several engines as broad humps in the frequency spectrum which are not associated with rotor frequencies. These frequencies were found to correlate well with a Strouhal number of 0.15 to 0.22.

Compressor Noise – Many studies on the origins of compressor noise exist[18,19,20]. These generally agree that the primary noise mechanisms are rotor/stator interaction and ingested turbulence rotor interaction. Also, at supersonic tip speeds, compressors may generate combination tones (at multiples of shaft frequency) which may propagate through the engine and appear in the exhaust quadrant as well as in the inlet quadrant. In general, engine compressor noise is the lowest level component. Tones are usually high frequency and thus easily attenuated.

Early compressor noise analyses applied propeller steady loading noise theory (Gutin[21]). Subsequent analyses, by Lowson, extended Gutin's theory to the case of sources in arbitrary motion[22] which introduces acceleration terms to the basic equation. Lowson's results were subsequently extended by him to include effects of unsteady blade loads[23] due to wakes from upstream stator rows and turbulence ingested by the compressor. Recent developments[19,20] include additional details, such as definition of blade and vane geometry, and other effects, such as diffusion through the rotor and tip flows.

In general, analytical procedures require far more inputs (i.e., detailed design and operating characteristics) than are generally available to the casual user, and, therefore, are of limited general use.

Many empirical methods have been developed. These relate the noise to several important parameters of design and operation and can range from simple relationships, such as Allen[24] which requires only input power or pressure rise and discharge flow, to fairly sophisticated relations involving many parameters, such as that of Smith and House[18] which includes independent equations for tone and broadband components, rotor-stator separations, and high Mach number flow effects.

Perhaps one of the more complete empirical methods is that presented by [illegible] and Peart[10], which includes a procedure for estimating combination tone noise as well. This procedure has been found to correlate well with turbofan data and appears equally applicable to the case of an engine compressor by considering the first stage parameters only.

Engine Noise Suppression

Introduction - Basically, there are two approaches to reducing the noise from turbine engines. The first approach is to reduce the noise at the source by changes in design or operating parameters. Unfortunately, engine design technology has evolved without regard to noise reduction and, therefore, changes in engine design parameters for reducing the noise of today's engines generally results in some loss in performance, either as increased weight and size or increased fuel consumption. The second approach is in the use of acoustically treated ducts to attenuate the generated noise by viscous dissipation. This second approach invariably adversely affects engine performance and also results in increased weight due to the added materials.

Reduction of Combustion Noise - In order to maintain the same power output, the mass flow through the combustor has to be maintained. However, the combustor diameter can be increased so that the combustor discharge velocity can be reduced to maintain flow rate. It is for this reason that an annular combustor is quieter than a can-type combustor and the reverse annulus combustor is the best configuration from an acoustical point of view[5]. Strahle[14] suggests that a drop in combustor flow turbulence intensity would cause effective noise reduction. However, actual combustors depend upon a high turbulence level for flame stabilization as well as for burner performance optimization, so some performance penalty would be expected with reduced noise.

Moderate reduction of engine exhaust noise has been demonstrated using acoustic liners in the JT9D engine[5]. Conventional treatment concepts were utilized and required large backing depth to attenuate the low frequency noise components. This results in significant weight and space penalties. Bowes[25] showed substantial reduction in engine exhaust noise by the addition of a long treated tailpipe which redirected the exhaust slightly upward away from listeners and thus also benefited from directionality effects. He does not, however, indicate the incurred weight and performance penalties.

Reduction of Turbine Noise - By examining the important parameters governing turbine noise, it was found that increasing the spacing between the rotor and stator stages is the most attraive method for reduction of noise at the source. Although this does increase the length of the shaft, the associated performance loss is very slight.

Proper selection of blade and vane counts has been demonstrated to reduce the noise from turbofans by pushing the interaction modes into cut-off. This aspect of the Tyler-Sofrin theory[26] should be equally applicable to turbines. Another consideration is the [illegible] increasing turbine speed and/or increasing the number of turbine blades to raise the frequencies of the tones above audibility, and thus to benefit from reduced annoyance from very high frequencies and greater atmospheric attenuation. However, considera- tion should be given to the increase in aerodynamic losses through the turbine stage which [illegible] performance.

Yet another approach is to increase the number of turbine stages. This approach is beneficial due to the attenuation afforded by the downstream blade rows and the reduced work extraction from each stage. Thus, essentially only the noise from the last stage is propagated to the exit.

Finally, acoustic treatment may also be applied here. Again, as is the case for attenuation of combustion noise, weight and performance penalties will be incurred.

Reduction of Strut Noise - In [illegible] the empirical relationship between strut noise and strut geometry, changing any of the parameters will affect the noise. Specifically, flow velocity is a strong parameter. Thus, if the choice exists, locating the struts in low velocity areas rather than high velocity areas will result in lower noise. Similarly, reducing strut area and profile drag will reduce strut-generated noise.

In the case where separation of the flow over the strut may occur, a change in the angle of incidence to better line up with the flow or adding twist to the strut may result in lower noise.

Acoustic treatment used for reducing combustion and turbine noise will also attenuate strut noise located downstream of the disturbance. The optimum tuning of the treat- ment must then be based on the relative contributions of the three sources.

Reduction of Compressor Noise - Many studies have been conducted to alleviate the noise of fan stages in turbofans[19,20]. The results from these studies are equally applicable to the case of engine compressors. Significant reduction can be obtained by increasing the spacing between rotor and stator stages and by reducing the rotor relative velocity.

Compressor noise is especially well attenuated by acoustical lining materials since the components are usually high in frequency, the noise is propagating against the flow, and the air temperature is near ambient, where less exotic materials than those re- quired to endure the hot corrosive exhaust, as in the case for engine exhaust treat- ment, can be used.

Gearbox Noise

Gearbox noise is normally comprised of a series of discrete frequency signals occur- ring at each tooth engagement (or meshing) frequency in the transmission. Those dominant tones may exhibit sidebands, which are generally insignificant relative to the noise at meshing frequencies. Mesh frequency noise is radiated to the atmosphere by the casing or the structure to which it is attached. The radiating body is driven by the dynamic system comprised of gears, shafting and bearings. The dynamic system is excited by the meshing of gears, which is imperfect in all but ideal cases. Imperfect meshing induces an oscillating force as well as the intended constant force transmitted to the mating gears. This oscillating force is the cause of gearing noise. Both the generation of mesh frequency excitation and the path it takes to the final radiation point must be considered in predicting and reducing gearing noise. Both analytical and empirical solutions have been developed for gear noise prediction. The analytical form of solution, however, not only predicts noise levels, but can be used for identifying means of noise suppression at the source.

Empirical methods are generally used for prediction of gearing noise emission. There are several practical reasons for the use of these simplified methods over the highly detailed analyses now available for transmission noise prediction. The first is that the analytical methods require a detailed knowledge of both the design of the transmission and characteristics of the system, such as bearing load deflection characteristics. The second is the fact that aircraft transmissions are designed with substantial commonality in terms of loadings, speeds, and materials. Also, the normally complex casings and airframe configurations do not lend themselves to dynamic analysis at gear meshing frequencies, thereby adding a significant unknown in terms of sound output on top of the problem of computing excitations and emissions from the basic gearing.

Excitation of gearing systems at tooth-mesh frequency can be determined through the use of computer programs such as those described in Reference 1. These programs have been used in several studies which demonstrated that a reasonably accurate prediction of tooth mesh excitation and resultant system torsional response can be made. They have been improved and supplemented with lateral bending analyses of the gearing system elements (References 2 through 5), but have not been integrated into a total program which is capable of accurate noise predictions. It should be noted, however, that the detailed analysis of References 1 through 5 has made it possible to attain noise reductions by shifting resonant frequencies of some components out of the normal operating speed range.

The disadvantage of the detailed analytical approach to gear noise prediction characterized by these and other programs is threefold. First, the detailed information on gear quality and the dynamic characteristics of some elements of the gearing system are not generally known and must be estimated. This immediately transforms a rigorous analytical solution to a semi-empirical one. Second, the complexity of these methods requires computer programs which are difficult for most engineering organizations to use without extended study. Third, the accuracy of the programs attainable at the present time is limited.

As an alternative to the analytical procedures, there are graphical methods available for the estimation of mesh frequency excitation which account for the important parameters including power transmitted, tooth loading, pitch line velocity, tooth profile error, tooth profile roughness, tooth spacing error, tooth alignment error, pitch, contact ratio, approach and recess angle, pressure angle and backlash. It is felt that this type of prediction, presented in Reference 6, is valid in estimating this excitation. However, an equally important part of the total estimation process, that of translating the excitation into radiated noise, is subject to large error.

Transmissions, and helicopter main transmissions in particular because of stringent weight limitations, are comprised of many complex components which do not readily lend themselves to dynamic analysis at meshing frequencies. The casings are probably the most difficult part of the transmission to analyze because of their complex shapes and largely varying cross sections. Highly detailed analyses, such as the finite element approach, are necessary to define impedances and mode shapes. Lacking such analyses, empirical or statistical means are used to estimate the casing's effect on radiated noise.

The casing is the single most important element in the chain of events leading to gear mesh noise emission by virtue of its influence on dynamic element mounting impedance and its ultimate radiation of mesh frequency vibration as noise. The fact that no practical analysis exists for determining its dynamic characteristics makes the empirical approach to gearbox noise prediction necessary for the present, although such methods are somewhat inexact.

Helicopter transmissions are designed to transmit a rated power with minimum weight. They are manufactured with a high degree of quality control and tight tolerances to maintain safety margins required. These requirements, along with similar reduction ratios from engine to rotor on most helicopters gives this family of transmissions enough commonality to allow a good deal of generalization and an empirical method to be used in predicting emitted noise levels. A method such as this is found in Reference 6. In this method, the manufacturing characteristics of a gearbox are used to classify the noise and the sound power level of the noise is plotted as a function of transmitted power. Figure 9 shows the sound power level versus transmitted power curve from Reference 6. Since helicopter gearboxes are manufactured to high accuracy standards, their noise should lie in the class B or C area of Figure 9. Levels predicted in this way appear consistent with unpublished Sikorsky data.

Reference 6 also provides some empirical information on the noise reduction that can be achieved with various modifications to gearboxes. These are shown in Table 1. (Note that the reductions for each variable are not necessarily additive).

In summary, significant progress has been made in understanding gearbox noise mechanisms. This progress has included the development of both analytical and empirical

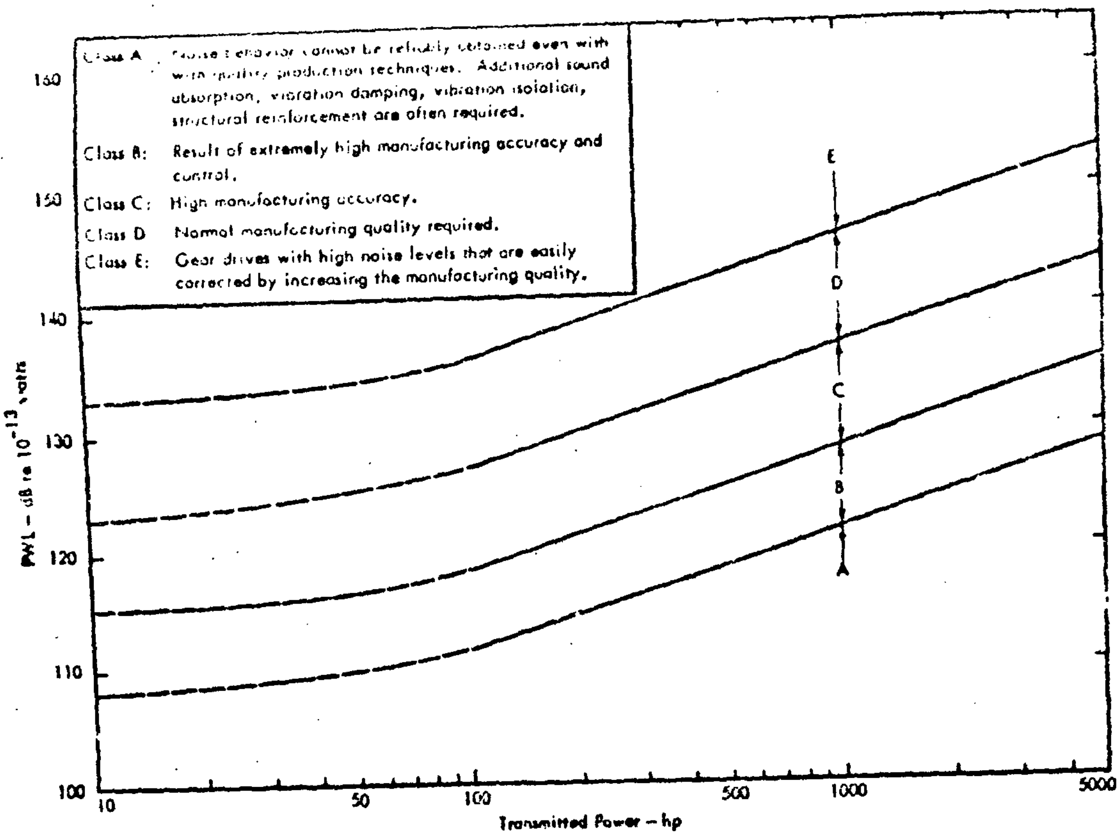

FIGURE 9. NOISE QUALITY CLASSIFICATION FOR GEARED SYSTEMS

prediction procedures which can be used for new gearboxes. Empirical methods are relatively easy to use and appear to offer reasonable accuracy for gearboxes such as the lightweight, highly loaded, close tolerance aircraft units used in helicopters. Analytical methods, on the other hand, require a great deal of detailed design information to use and still require some empirical corrections for reasonable agreement with experiment. However, the analytical procedures do provide insight into problem areas and likely noise reduction modifications which can not be determined with the empirical methods.

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[illegible]	0.2	Filled gearbox quietest but [illegible] other [illegible]

HELICOPTER NOISE PREDICTION

Despite all of the work that has been done to develop prediction methods for the sources of V/STOL noise, attempts to formulate comprehensive methods for predicting the noise from a complete vehicle have occurred only recently. The two major studies that specifically address helicopters are reported in References 1 and 2. Both studies deal with noise from main rotor, tail rotor, and engines. Noise from gearboxes is ignored, which is a legitimate simplification in most cases, especially at distances typical of flights over populated areas. Reference 1 considers the special case of tilt-rotor vehicles, but uses the same prediction method as is used for helicopters.

Both studies use the closed-form rotational noise method of Lowson and Ollerhead[3] as the best practical tool that is presently available. The selection of loading harmonic decay constants, called "loading laws", is based on acoustic test data. Neither reference specifically deals with the effects of rotor-rotor interference on tail rotor noise, since relatively little information is available in the literature. Broadband rotor noise is predicted with empirical methods. Although different studies are referenced in developing the broadband method, both vehicle noise methods use forms of the so-called Schelegel equation[4] with a directivity correction as proposed by Lowson and Ollerhead in Reference 3. Engine noise prediction also uses empirical procedures in each method. A sample of the agreement obtained with the method of Reference 2 is shown in Figure 10, below.

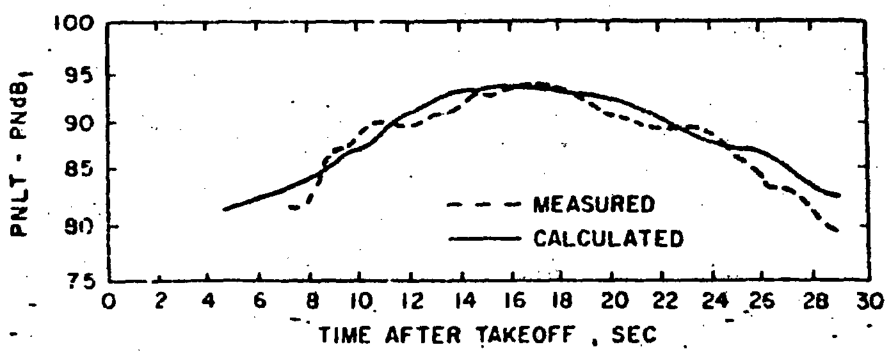


FIGURE 10. TAKEOFF NOISE CORRELATION

The agreement between measured and predicted noise levels is quite good and is adequate for use in studies of community acceptance of noise using tone corrected perceived noise level, PNLT. Similar correlation has been obtained between predicted and measured A-weighted sound pressure level, SPL(A). It is important to note, however, that the referenced vehicle noise prediction methods have demonstrated good agreement with gross characteristics of the noise, namely PNL and SPL(A). Calculation of more complex measures of subjective reponse which may be needed to assess tone content and impulsive noise require revisions to the referenced methods.

HELICOPTER NOISE REDUCTION TECHNIQUES

Control of helicopter noise requires that all of the sources of noise, including main rotor, tail rotor, engine, and to a lesser extent, gearbox be considered. Studies of noise sources and their prediction for each of these components of the helicopter inherently address the noise reduction question, since the influence of operating and configuration parameters on noise generation is part of any noise prediction technique. Other sections of this report address the noise prediction techniques in detail. Therefore, in this section only the noise reduction techniques investigated experimentally will be discussed.

Of most interest are the noise reduction experiments conducted on the Hughes OH-6A, the Sikorsky SH3D and the Kaman HH-43B. The OH-6A is a light observation helicopter of 954 kg (2104 lbs.) gross weight with a four-bladed main rotor and a twin bladed tail rotor. The HH-43B is a larger helicopter used for Air Force Rescue missions of 3175-4308 kg (7000-9500 lbs.) gross weight with two meshing twin bladed main rotors. The SH3D is a large troop transport type helicopter of 7080 kg (15611 lbs.) gross weight with five-bladed main rotor and five-bladed tail rotor.

Analysis of the OH-6A noise signature as shown in Figure 11 (from Reference 1) clearly indicated that main rotor, tail rotor, engine exhaust and gearbox noise all contribute substantially to the total noise. In order to suppress main rotor noise the design tip speed was reduced from 648 ft./sec. to 434 ft./sec. In order to maintain performance, five main rotor blades were used instead of four. The main rotor tips were changed from the standard rectangular tip shape to a trapezoidal shape with a 2 degree twist. To suppress the tail rotor noise its speed was reduced from 3120 rpm to 1630 rpm. To maintain performance, a four-bladed rotor 14% larger in diameter than the standard rotor was used. The angles between blades were 75 and 105 degrees instead of the conventional equal spacing. Also, high lift cambered airfoils were used instead of the standard symmetrical airfoils. Gearbox noise was suppressed by use of lower pitch gears with higher contact ratios. These gears were also machined to higher accuracy and had better surface finish than the standard gears. Damping material was applied to the webs of some gears and to the core of some drive shafts to reduce ringing noise resulting from gear clash. Modifications to the engine as well as external muffling was used to suppress the engine. The basic engine modifications[2] consisted of 1) shot peening the first stage turbine nozzle to create a sonic inlet block; 2) balancing all rotating components to closer than normal tolerances to reduce engine casing vibration and 3) clipping several stages of compressor vanes to increase blade/stator spacing and thus reduce inlet siren noise. These engine changes resulted in an exhaust peak reduction of 2 dB. The engine exhaust muffler consisted of a tuned double expansion reactive type muffler exiting into a large tuned resonating chamber[2]. Engine inlet noise was suppressed by lining the inlet fairing and plenum chamber of the test vehicle with 1-inch thick open cell polyurethane foam. Peak attenuation of engine noise was found to be over 30 dB for this system[1].

The early test efforts on the HH-43B indicated that the rotor engine and gearboxes contributed to the noise signature. Engine noise components are inlet radiated broadband flow noise and discrete tone compressor noise, case radiated mechanical and combustion noise, and exhaust radiated broadband flow noise[3]. Inlet noise was suppressed by a reverse flow inlet duct, as shown in Figure 12, with a multi-layer reactive liner. Case radiated noise was suppressed by installation of vibration isolators between the engine and its supporting structure and by a high transmission loss enclosure around the engine compartment. Exhaust noise was suppressed by the exhaust duct shown in Figure 13, which includes a lined absorber section for attenuation of engine and in-duct generated noise and a diffuser section which allows for uniform expansion of exhaust gases to nearly zero relative velocity. Additional reduction is achieved by directing the exhaust nearly directly aft as opposed to the downward directed exhaust of the standard aircraft.

It was found that the vibration isolation and installation of an engine enclosure were not effective in reducing the aircraft noise signature. The inlet noise suppression was effective, particularly the suppression of the compressor blade passage tone. Reduction of as much as 10 dB in the mid-frequency range was achieved with the exhaust muffler.

Many changes were made to suppress gearbox noise discrete tones at frequencies equal to the gear clash frequency and its harmonics. These changes included the use of a gear set with good wear patterns and minimum tolerances, plating of gear teeth to improve surface finish, the use of high viscosity oil, misphasing of right and left drive gears, elastomeric isolation of the planetary ring gears and installation of external sound proofing. Octave band analysis did not show any improvement for these changes. However, the changes did result in a subjective improvement as they reduced the levels of the discrete tones in the spectrum. The external sound proofing was not effective in reducing aircraft noise signature.

Rotor modifications included increasing the diameter from 47 ft. to 50.34 ft., increasing blade chord from 15.69 inches to 18.69 inches, thinning and drooping the leading edge, and slightly tapering the tip. These modifications caused a reduction of higher frequency noise components, but an increase in low frequency noise. Reducing the tip speed from 540 to 462 ft./sec. reduced noise throughout the frequency spectrum by 3 dB. With the reductions achieved, the rotor was still the dominant noise source throughout the audible spectrum.

Initial analysis of the SH3D[4] indicated that the total external noise spectrum is dominated at various frequencies by the main rotor, tail rotor and engines. Main rotor and tail rotor rotational noise at multiples of 16.9 and 100 Hz, respectively are dominant in the low frequencies with a mixture of rotor and engine noise contributing to the mid and upper frequencies.

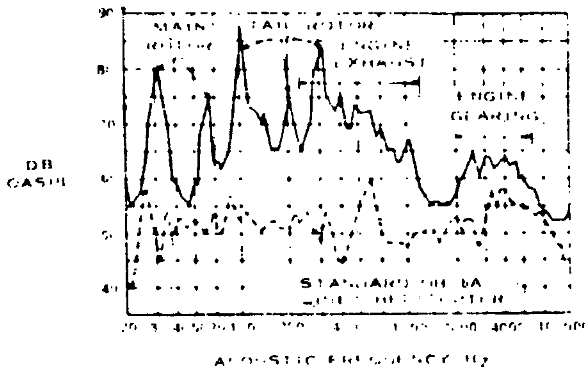


FIGURE 11. OVERALL NOISE COMPARISON IN HOVER (FRONT VIEW AT 150 FEET FROM AIRCRAFT)

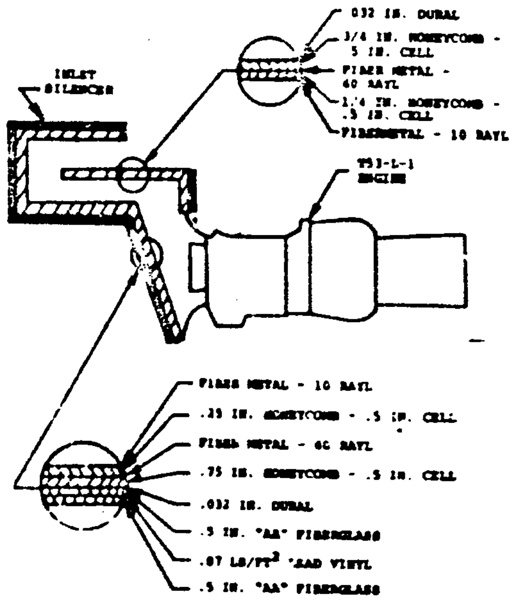


FIGURE 12. INLET SILENCER CONSTRUCTION

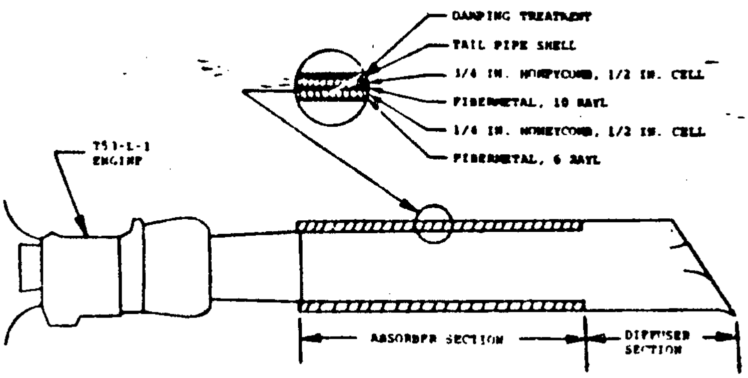


FIGURE 13. EXHAUST SILENCER CONSTRUCTION

Main rotor noise was treated by reducing tip speed from 662 to 597 ft./sec. and changing from 5 standard square-tipped blades to six twisted trapezoidal tip blades. The tail rotor was treated by reducing tip speed from 657 to 442 ft./sec. and by doubling the number of blades from 5 to 10. Further attenuation for cruise flight was gained by modifying the aft vertical pylon to a cambered airfoil configuration, thereby removing some of the anti torque load from the tail rotor in this flight regime.

The engines were attenuated by inlet and exhaust silencers. Although the silencer performance was not measured on the engine, tests with no flow showed peak insertion loss of approximately 25 dB around 1000 Hz.

A comparison of noise generated by the standard and modified helicopters showed that noise is attenuated at nearly all frequencies with the most noticeable change occurring at the tail rotor blade passing frequency. Tail rotor noise was reduced to the point where it was almost insignificant for the modified vehicle. Also, high frequency noise components were reduced by 3 to 10 dB over a wide frequency range.

Although it could not be shown in the 1/3 octave band spectrum plots, the character of the noise was entirely different for the original and modified aircraft. The standard SH3D was easily identified as a helicopter by its characteristic main rotor rotational noise and tail rotor "buzz". The modified SH3D sounded like a low speed muffled turbojet during flyby[4].

Noise reduction methods described above for the three helicopters involved in the quiet helicopter program were for the most part, straight-forward techniques with proven effectiveness. Rotor noise reduction was attained via reduced tip speeds, increased solidity, and limited blade aerodynamic improvements. Engine noise reduction was attained primarily by muffling. Gearbox noise was reduced primarily by shielding and damping.

The techniques employed were effective, but resulted in performance reductions and weight increases in general. They move the helicopters' operating parameters away from those which were originally selected on the basis of performance and economic considerations.

Further research is required to define rotor and engine configurations which are both quiet and efficient.

SUBJECTIVE RESPONSE TO HELICOPTER NOISE

Introduction

For more than twenty years efforts have been made to develop noise rating scales which accurately predict the subjective response to aircraft noise. The difficulties of conducting meaningful tests, where the results are determined by listeners judging various sounds, has led to considerable confusion about the relationship between one rating system and another. Also, there are two distinct objectives which must be considered in developing the rating scales: 1) a scale to measure the perceived level of an individual aircraft flyover sound which can be used for noise certification and 2) a community acceptance calculation procedure which accurately evaluates the long term effects of aircraft noise on communities around airports. In the following discussion, the work on various units for noise certification and community acceptance of helicopters are discussed. Then, the direction for establishing better units for helicopter noise assessment are discussed.

Noise Rating Units for Helicopter Noise Certification

Background - At the present time, most noise rating methods are based on PNdB or dBA. PNdB is a computed unit based on sound pressure level and frequency for one-third octaves or full octave bands of noise. The dBA may be read directly from the output of a sound level meter having an A-weighting network. Several research studies have been conducted to establish the relative merits of these methods as predictors of annoyance. Pearsons evaluated subjective response to recordings of helicopter noise in comparison with transport aircraft noise[1]. He found that PNL was slightly more accurate than weighted sound pressure level such as dBA, and that adjustments to PNL for tones and duration did not improve its accuracy. Hecker and Kryter[2] determined that tone corrections below 500 Hz reduced the accuracy of various units and suggested that the use of tone correction for low frequencies be deemphasized. Ollerhead[3] studied the subjective response to low frequency high intensity noise. The annoyance curves he defined departed from existing curves below 1000 Hz. Figure 14 (from Reference 4) shows that this is significant, since the large amount of low frequency helicopter noise is the main difference between helicopter and other aircraft sounds. Sternfeld, et al[5] compared response to simulated helicopter noise, tilt-rotor noise, and jet transport noise, and found little difference among peak values of PNL, dBA, and dBC as annoyance predictors.

The work by Ollerhead[4,6,7] is considered particularly significant in establishing the state-of-the-art in noise rating scales. In his work, a fairly extensive experiment was conducted with a large number of aircraft sounds including turbojets and turbofans, piston engine propellers, turboprops, and helicopters. His most recent summary of this work[6] contains some surprising conclusions. First, it was found that all rating scales are equally poor in rating helicopter noise. Second, an integrated duration

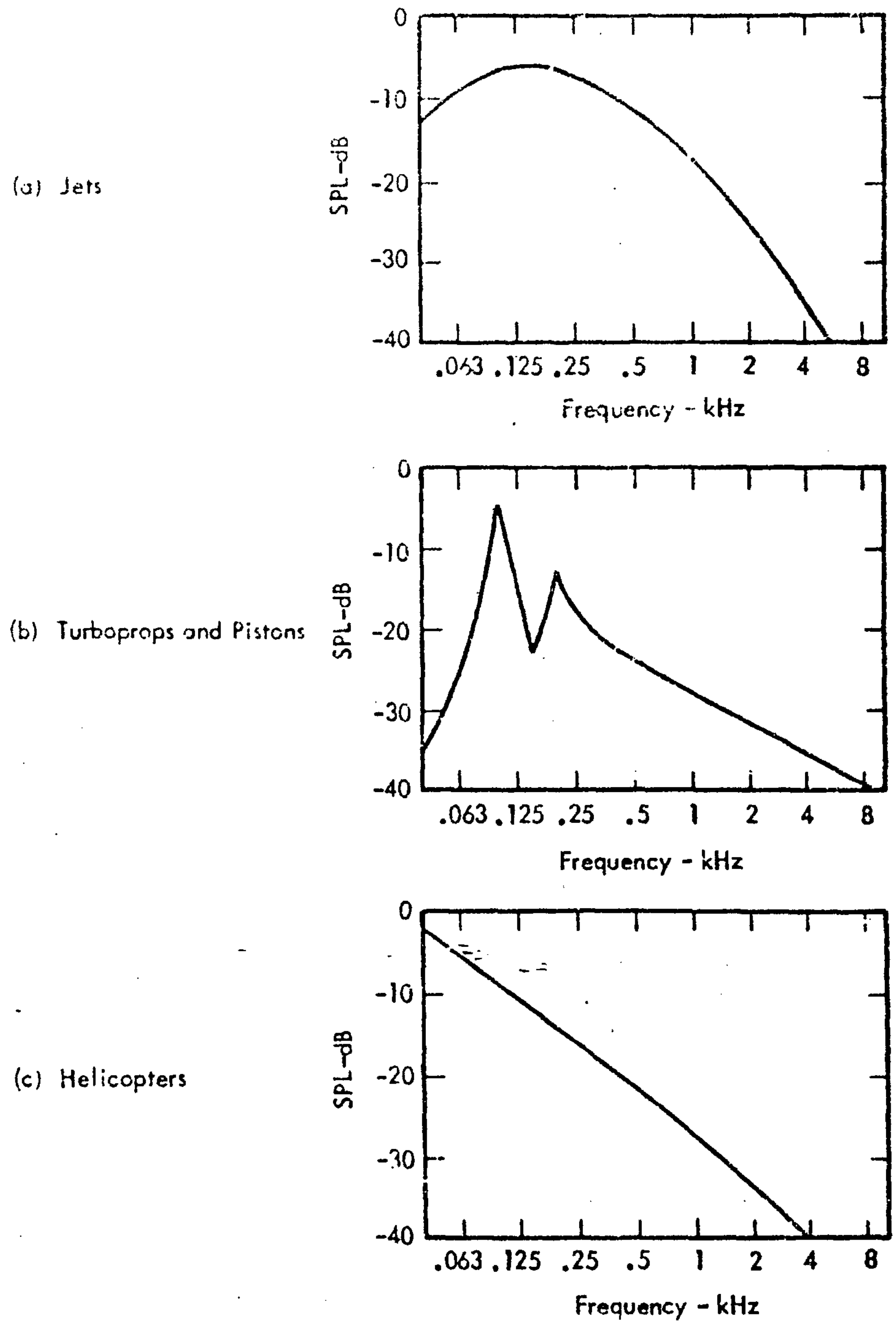


FIGURE 14. "TYPICAL" 1/3 OCTAVE BAND LEVEL SPECTRA FOR DIFFERENT AIRCRAFT CATEGORY SOUNDS

correction (as in FAR Part 36) is particularly beneficial, probably because of the long duration associated with some of the very low speed flyovers. The duration correction based on 10 dB down points (i.e., as 10 $\log_{10}$ (t/15), where t is the time in seconds between 10dB down points) was significantly inferior to the integrated correction. Third, the simple energy summation process performed by the weighted sound pressure level circuits is rather sensitive to the particular choice of network. Thus a linear (flat) weighting function overestimates the perceived level of an aircraft sound, A-weighted level underestimates perceived noise, and D-weighted level (based on the inverse of the 40 Noy contour) shows a very small mean error. Fourth, the tone correction used in the EPNL procedure does not perform as intended, except when applied to turbojet and turbofan sounds. It is recommended that the tone correction be eliminated for tones identified below 500 Hz.

In another recent study, Sternfeld[5] found that helicopter annoyance was under-estimated by 4.5 PNdB compared to jet transport noise annoyance. For example, rotorcraft noise at a PNL of 94-96 was rated equal in annoyance to jet transport noise at a level of 100 PNdB. Leverton[8] has studied helicopter noise extensively and finds that existing methods are inadequate for rating helicopter noise. This is true for low frequency rotational noise components (including tail rotor) as well as for impulsive noise.

An additional source of inaccuracy of existing Perceived Noise Level and A-weighted Noise Levels is their inability to rate impulsive rotor noise. Relatively little quantitative testing has been done to define human response to repetitive acoustical impulses. Munch and King[11] surveyed the literature during a study of community noise acceptance and found that the presence of impulsive noise increases subjective annoyance by 4 to 6 PNdB. Consequently, considering the findings of Sternfeld[12], the annoyance of helicopters with impulsive noise is likely to be underestimated by 8-11 PNdB compared to the annoyance of conventional transport aircraft.

From the preceeding discussion, it is apparent that existing methods of rating helicopter noise are inadequate. Shortcomings arise from the frequency range of the noise and from the characteristics of the acoustic waveform. A new unit or new units are required in order to accurately predict subjective response to helicopter noise. Of the existing methods, however, no one unit is clearly superior to the others.

New Rating Scales For Helicopter Noise Certification - Based on the deficiencies noted above it appears that a new noise rating unit is required. The new noise rating unit outlined below is intended for noise certification testing of individual aircraft. It should be emphasized that instrumentation and data processing for such testing are elaborate and extensive compared to facilities for monitoring and evaluating community noise levels. Recommendations are made in a later section for a community acceptance unit that parallels the certification unit.

Present indications are that a noise certification unit should be developed along the lines of EPNL. It should include at least the following attributes:

1. Revised psychoacoustic response curves that extend below 50 Hz and cover an adequate range of intensity.

2. Integrated duration corrections as in FAR Part 36 rather than corrections based on the time between the 10 dB down points.

3. Criteria and penalties for the presence of impulsive noise.

4. Corrections for discrete frequencies that adequately represent human response below 500 Hz.

No attempt is made here to specify how this unit will be developed. Psychoacoustic testing obviously is required. This poses difficulties, since noise simulation at low frequencies further complicates the usual complex problem of human response tests. Definitive tests may require the use of actual helicopter flyovers (as opposed to recordings and syntheses) to be sure that all of the spectrum characteristics and psychological effects are accurately presented to the listeners during the test program.

Community Acceptance Calculations

Background – The two basic sets of noise criteria to which a helicopter will be subjected are certification and community acceptance. Certification criteria define the noise that the vehicle will be allowed to generate for typical takeoff, landing, and cruise operations. Community acceptance criteria relate this certification noise to the community by considering the total effects of operating many types of aircraft for multiple flights at various times of the day over or into various parts of the community.

The determination of absolute community acceptance of noise through application of objective measures requires consideration of a large number of elements. It involves combining the noise generated by many flights of varying aircraft types using many approach/takeoff paths to arrive at a noise exposure number which is descriptive of the net effect on those exposed. This net effect is also influenced by the time of day at which the noises occur, the type of community in which they occur, and in many cases, the ambient noise levels generated by sources other than aircraft in the area. The following discussion elaborates on candidate methods for rating acceptability of noise and relates these methods to helicopter noise.

Table 2, from the recent report by Hinterkeuser and Sternfeld[10], summarizes the factors considered in various community noise rating methods. The use of L_{dn} as the unit for community acceptance evaluation of helicopters is recommended by Hinterkeuser and Sternfeld because: 1) it includes the consideration of the ambient noise in the com-

TABLE 2. FACTORS INCLUDED IN VARIOUS COMMUNITY NOISE RATING METHODS

NAME \ FACTORS INCLUDED	Symbol	Units	Temporal Distrib.	Time of Day	Flts/Hr or/Day	Season	Previous Community Exposure	Ambient Level	Ambient Temporal Distrib.	Impulse	Community Attitudes	Basis for Analysis
London Guideline		dBA		✓	✓							Maximum Level
Composite Noise Rating	CNR_C CNR_A	dBA PNdB		✓ ✓	✓ ✓	✓ ✓	✓ ✓	✓ ✓		✓ 	 ✓	Maximum Level
Community Noise Equivalent Level	CNEL	dBA	✓	✓	✓							Average Energy
Noise Exposure Forecast	NEF	EPNdB	✓	✓	✓							Total Energy
Weighted Equivalent Perceived Noise Level	WECPNL	EPNdB	✓	✓	✓	✓						Average Energy
Noise Pollution Level	NPL	(any)	✓		✓			✓	✓			Average Energy
Day-Night Level	L_{dn}	dBA	✓	✓	✓			✓	✓			Average Energy
Local "Nuisance" Ordinances		dBA or SPL		✓								Maximum Level
Single Event Noise Exposure Level	SENEL	dBA	✓									

quantity; 2) considers the time distribution of noise and number of flights per hour. The authors do suggest that the penalty of 10 dB for night time operation may be too small. They state that daytime complaints are associated with interruptive factors such as speech interference and distraction while night time complaints may be associated with awakening or prevention of sleep.

In another recent report by Munch and King[11], the L_{dn} concept is endorsed with some modification. They recommend that a penalty of 5 to 10 dBA be added to the single event noise exposure level (SENEL) for an aircraft producing impulsive noise. This is in agreement with the Hinterkeuser and Sternfeld[10] findings. Munch and King[11] also recommend the use of tone corrections to the SENEL as calculated for Tone Corrected Perceived Noise Level, but only applied to tones above 500 Hz. This is in agreement with Ollerhead[6].

In summary, it appears that L_{dn} with significant modifications is the choice for community acceptance evaluation of helicopters.

<u>Noise Units for Community Acceptance Evaluation</u> - As stated in References 10 and 11, community acceptance criteria must include the ambient noise environment, and should be reasonably easy to use. It is clear that existing weighted sound pressure level and perceived noise level are equally good (or equally bad) as predictors of annoyance and References 10 and 11 recommend use of Day-Night Level (L_{dn}) based on dBA as a community acceptance unit. The L_{dn} unit recommended in Reference 11 uses the SENEL unit, dBA corrected for pure tones and duration. Of course, there is no reason to assume that a new weighting network or a new EPNL procedure could not be used in place of dBA to improve the accuracy of the L_{dn} unit. The new network would include revised, extended low frequency characteristics patterned after the subjective response results discussed earlier. It is possible that a revised N-weighting network (the N-weighting scale is sometimes referred to as the D-scale and is the inverse of the 40-noy contour) would be preferable to a revised A-weighting network. Naturally, impulse penalties and tone corrections patterned after the new certification unit would be used in the new community acceptance unit.

CONCLUSIONS

In general, it is concluded from the study reported here that significant further effort is needed in all areas of helicopter noise prediction, reduction and subjective evaluation to approach the level of understanding now achieved in turbojets and turbofans. The single area where the state-of-the-art is nearly adequate is in the turboshaft engine. Here, because of the interest in core engine noise of turbofans, substantial progress is being made to understand the mechanisms of noise generation and develop noise prediction methodology. It is true, however, that this new understanding has not yet been incorporated in any existing turboshaft engines. Therefore, the results of the learning from the current work will not appear until a new generation of engines is designed.

Gearbox noise has been studied both experimentally and analytically with some success. It appears that the tools for prediction must be tried in a quiet helicopter design to establish where the current methods are deficient.

In the rotor noise source area, existing prediction methods appear adequate to establish general trends or gross properties of the acoustic field for most common helicopter configurations. Tandem, coaxial, meshing or variable geometry rotors may require further study. From a more basic aeroacoustic standpoint, it appears that the basic theories now in use should be checked carefully against noise generated by helicopters in flight. This will require measurement of aerodynamic inputs for these predictions. The objective of such a program should be a careful study of cause and effect in rotor noise generation. Tail rotor noise requires this same attention, particularly the evaluation of interference between the main and tail rotor.

While it is not likely that a commercial transport helicopter, designed with community acceptance as a goal, would ever produce impulsive noise, work is required to define the design boundaries which will insure that impulsive noise is not produced.

Noise reduction of complete helicopters has only been demonstrated in ways that reduce efficiency. Increases in weight for the modifications to date have been unacceptable in a commercially configured vehicle. Work is therefore required to develop noise reduction techniques with minimum impact on performance.

In the subjective evaluation of helicopters, further work is needed to improve the accuracy of the existing units. Improvements to the EPNdB to account for the differences between helicopters and other aircraft are required. Some of this work may also be applicable to community acceptance evaluation procedures.

APPENDIX A
CAPSULE REVIEWS OF SELECTED REPORTS

Rotor Noise Capsule Summaries

Arndt, R. E. A and Borgman, D. C., "Noise Radiation from Helicopter Rotors Operating at High Tip Mach Number". Paper presented at the 26th Annual National Forum of the American Helicopter Society, Washington, D. C., June 1970.

Purpose

The purpose of this paper was to present the results of an investigation of high Mach number effects on the noise generated by helicopter main rotors and to review the role of drag divergence and blade thickness in the noise radiation from rotors operating at high tip Mach number. A mathematical model for rotational noise was developed based on an adaptation of the Gutin theory to the case of non-uniform inflow (more specifically for the particular case of non-uniformity due to drag divergence caused by operation of a rotor at a combination of high tip speed and high forward speed) and utilizing published drag data for symmetrical airfoil sections operating through their critical Mach number range. Application of the mathematical model to the case of rotors tested in the Ames 40-by-80-foot wind tunnel gives good agreement with the observed tremendous increase in the level of the higher harmonics for a small change in tip Mach number.

Summary

The paper reviews several classic approaches to the calculation of lift noise generated by a rotor including those of Gutin[1*], Garrick and Watkins[3], Schlegel[6], Lowson and Ollerhead[7] and Loewy and Sutton[10]. Although each of these approached the problem in a different way, the results in general were not satisfying. A brief review of other sources, such as broadband noise and thickness noise, completes the background on helicopter main rotor noise sources.

The main purpose of this paper was to review the role of drag divergence and blade thickness in the noise radiation from rotors operating at high tip Mach number. The approach taken was to modify the Gutin theory for non-uniform inflow and consider a particular case of non-uniformity, namely the drag divergence due to the operation of a rotor at a combination of high tip speed and high forward speed.

A Fourier series expansion of an assumed pulse loading is used in the development of an expression for the harmonic thrust and torque coefficients. Following a development of the velocity potential for acoustic radiation based on Gutin and applying several simplifications, the rms value of the nth rotational noise harmonic is given by the expression

$$P_n = \frac{b\,n\,\omega}{2\pi\sqrt{2}\,ra..} \sum_{j=-\infty}^{\infty} \left(\alpha_j\, T_{\cos}\,\delta + \frac{b\,n - j}{b\,n}\, \beta_j\, \frac{Q}{M_e R_o} \right) J_{bn-j} \left(b\,n\,M_e \sin\delta \right)$$

*The numbers refer to the entries in the appropriate section of the REFERENCES.

where b — number of blades

ω - rotational speed of rotor

r - distance to observer

a - speed of sound

α_j - Fourier coefficient in blade loading

T - thrust

δ - angle between thrust line and observer

β_j - Fourier coefficient in blade loading

Q — torque

M_e - Mach number based on effective radius

R_e - effective radius

For uniform loading, all components are zero except for $\alpha_o = 1$ and $\beta_o = 1$ which reduces the above equation to the Gutin relationship.

The drag rise experienced by the advancing blade of a rotor when the forward speed is such that the tip Mach number exceeds some critical value is a form of non-uniformity in loading investigated in the next section of the paper. After drawing a simplified expression for a drag rise coefficient, C_D', it is expanded into a Fourier cosine series and the results substituted into the modified Gutin equation for rotational noise.

As an illustration of the sensitivity of the drag increase to Mach number and the effects of tapering the blade tip, Figure 1 shows the calculated drag rise coefficient plotted as a function of the rotation angle (where 90 degrees is perpendicular to the direction of flight). A large increase in drag is shown for a small change in Mach number.

In closing the discussion, the authors present a few sample calculations for comparison with measurements conducted in the Ames 40-by-80-foot wind tunnel. Two comparisons, here reproduced as Figures 2 and 3, illustrate the comparison between calculation and measurements for a relatively low tip speed, where drag divergence effects are small, and at a higher tip speed, where the drag divergence effects become significant for both a standard tip blade and a tapered tip blade. Although the results show a large discrepancy in the lower harmonics, the tremendous increase in the higher harmonics (about 20 dB) for a small change in Mach number is well predicted by the theory developed by the authors.

The authors conclude that drag divergence can be important for tip Mach numbers above 0.85, sources other than rotational noise contribute to the higher harmonics, an improved analysis of vortex noise is required, thickness noise is important only for the lower harmonics, and the use of tapered tips appears to be a good way to reduce the noise at high tip Mach number.

Summary (Cont)

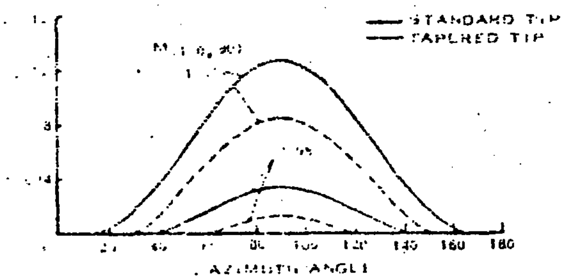


FIGURE 1. DRAG INCREASE DUE TO COMPRESSIBILITY EFFECTS

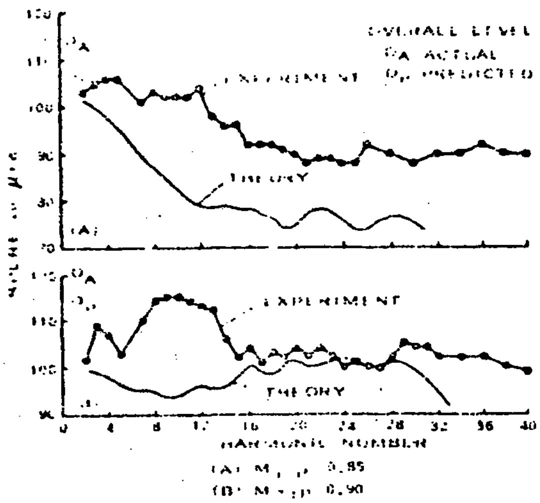


FIGURE 2. SOUND PRESSURE LEVEL SPECTRA, THEORY VS EXPERIMENT STANDARD TIP BLADE

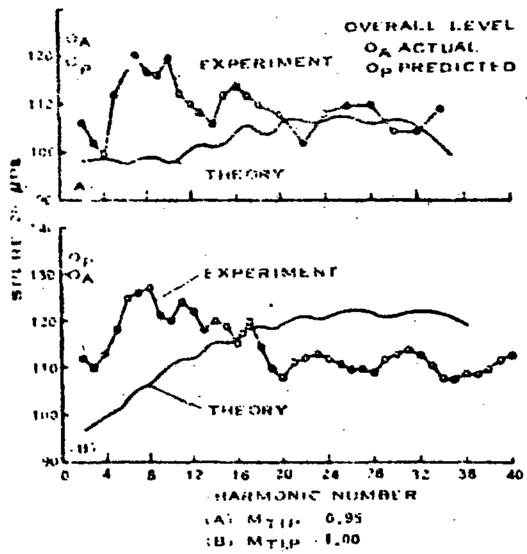


FIGURE 3. SOUND PRESSURE LEVEL SPECTRA, THEORY VS EXPERIMENT TAPERED TIP BLADE

Comparison With Similar Papers

This paper presents a mathematical model to explain the substantial increase in the higher harmonics of rotational noise observed in helicopter main rotors operating at a combination of high tip speed and forward flight. The analysis presents a closed form solution based on the assumptions of a periodic change in blade loading due to compressibility effects experienced by the blade advancing into the flow.

Others have attempted to explain the increase in the levels of the higher harmonics due to non-uniform loading of the rotor blades. Schlegel, et al[6] used a similar approach in extending Gutin's[1] analysis directly to the case of non-uniform blade loading. Their expression, however, is not in closed form and a computer solution is presented which requires blade loading as input.

Comparison With Similar Papers (Cont)

This paper approaches the problem of impulsive noise due primarily to a fluctuation in lift noise, in contrast to Lyon's[27] analysis to explain blade "pop" (i.e., sound generated by the compressional wave patterns that are produced at speeds near Mach 1) in terms of the fluctuating thickness noise caused by the periodic change of the relative tip speed of the blade advancing into then away from the inflow due to forward motion of the aircraft, or the blade/vortex interaction work of Widnall[22], Leverton[20], and Filotas[24]. It is interesting to note that both Arndt and Lyon show comparatively similar agreement with the same test data even though Arndt attributes the impulsive noise to fluctuating lift and Lyon attributes it to fluctuating displacement due to blade thickness. Neither Arndt's nor Lyon's analyses show excellent correlation with the test data, primarily due to the neglect of other sources, with Arndt underpredicting at low frequency and low tip Mach number and both tending to overpredict at high frequency and high tip Mach number.

Evaluation

The approach is sufficiently simple and straight-forward to be readily integrated with other, established rotational noise prediction methods. Compressibility effects, however, may also result in other noise sources, such as the so-called buzzsaw which has been observed in supersonic tip speed fans. In this case, the rotating shock becomes a source of noise in itself, as well as causing a change in blade loading. Further, periodic blade loading may arise due to vortex interaction. Thus, although the theoretical development presented in this paper may be a valid model of the noise generated by changes in blade loading due to drag rise, it in itself is probably not a complete and sufficient description of the sources of helicopter rotor impulsive noise. This is, in fact, supported by the comparison with test data which shows only fair agreement in absolute level, although it does show reasonable agreement with the trends in noise level with tip Mach number.

Cox, C. R., "Subcommittee Chairman's Report to Membership on Aerodynamic Sources of Rotor Noise," Presented to 28th Annual Forum, American Helicopter Society, May 1972.

Purpose

This report was prepared to summarize deliberations of the Noise Subcommittee of the American Helicopter Society, pertaining to noise from low disc loading aircraft. The Subcommittee examined existing knowledge about the aerodynamic sources of noise and the ability to predict noise, and also considered the areas where additional basic research is required.

Summary

Noise is defined in terms of mechanisms rather than subjective characteristics of the noise. Regarding adequacy of theory, existing theories or new analyses using existing knowledge could predict noise if adequate aerodynamic data were available. Lack of such data is the principal obstacle, particularly for tail rotors. In addition, the report identifies advances in test instrumentation that are required to provide missing experimental data. Research programs are recommended to develop generalized rotor noise theories and basic experimental aerodynamic data. Specific areas include dynamic surface pressure measurements on the rotor blades, determination of wake system characteristics, and investigation of flow field characteristics.

Comparison With Similar Papers

This paper is intended to summarize the state of rotor aeroacoustic knowledge as of 1972 in general terms. In this regard, it differs from surveys oriented toward specific investigators, such as surveys by Hubbard[28] and by Morfey[29].

Evaluation of Paper

The Subcommittee's findings apply to the present state-of-the-art and offer sound general guidelines for continuing research.

Filotas, L. T., "Vortex Induced Helicopter Blade Loads and Noise," Journal of Sound and Vibration, Volume 27, Number 3, 1973, pp 387-398.

Purpose

The author seeks to model blade/vortex interactions and provide the Fourier coefficients of airload to be used in the Lowson and Ollerhead[7] expression for rotational noise. The resulting method can then be used to define effects of blade/vortex interactions on rotor impulsive noise.

Summary

A model is developed consisting of a finite aspect ratio wing and a series of infinitely long, parallel vortex filaments. Spacing between vortices and the height of the wing above the vortex filaments are adjustable, as is the angle between the wing and a filament. Linearized aerodynamic theory is applied to determine the transient wing lift response to an encounter with a single filament, and the total response to a complete array of filaments is obtained by superposition. The response is expressed as harmonics of loading which are compatible with the acoustic analysis of Lowson and Ollerhead.[7]

This model is used to calculate noise for a simple laboratory representation of blade-vortex encounters consisting of a wing mounted in a wind tunnel with upstream generated vortices convecting past the wing. Calculated sensitivity of the noise to aspect ratio and vortex separation is presented. Aspect ratio is shown to have a small effect, while vortex separation and spacing strongly influences far-field noise. Noise is inversely proportional to the third power of wing height and is greatest when the horizontal spacing is about five times the height.

Comparison With Similar Papers

Other investigators (e.g., Widnall[22]), have used a wing and vortex filament model but the present paper extends this approach to a finite aspect ratio wing and cyclical loading rather than a single encounter. Subsequent work by Widnall extended the present approach and obtained good agreement between measured and calculated acoustical waveforms for a one bladed rotor.

Evaluation of Paper

The approach appears to be effective based on preliminary results by Bausch[15] and Widnall[22]. If efforts to parameterize blade-wake encounters are successful, impulsive rotor noise from this source should be fairly well defined.

Hosier, R.N., Ramakrishnan, R., and Pegg, R.J., "The Prediction of Rotor Rotational Noise Using Measured Fluctuating Blade Loads," Presented at the 30th Annual National Forum, American Helicopter Society, Preprint No. 801, May 1974.

Purpose

The report describes a study to measure rotor noise and high frequency blade loads simultaneously, and to examine the correlation between measured and predicted noise. Effects of chordwise loading distribution on correlation and of loading phase on correlation also are evaluated.

Summary

The study produced good agreement between measured and calculated rotational noise. Best agreement was obtained using a concentrated (chordwise) load, while least satisfactory results were obtained using a rectangular chordwise distribution. Phasing of the oscillatory airloads was found to affect only the calculated level of the fundamental noise harmonic. In addition, the authors found that the contribution of the aft 60% of the blade chord to the integrated loading coefficient tended to worsen agreement between predicted and measured noise harmonics. Airloads based on the forward 40% of the chord produced much better agreement than airloads based on the entire chord. Noise predicted from full-chord loading coefficients tended to grossly over-estimate the noise harmonic levels.

Comparison With Similar Papers

Correlation results seem to be consistent with findings of previous work regarding usefulness of concentrated loading (spanwise and chordwise) for predicting noise from a hovering rotor. Present results agree with other investigators that rectangular chordwise loading is not a good approximation for use in the acoustic model.

Evaluation of Paper

The study is useful as a source of synchronized noise and airload data acquired under controlled conditions. These results illustrate that good loading data yields good noise correlation as long as a valid acoustical analysis is used. It may then be concluded that the aerodynamic data presently is the weakest component of rotor noise technology.

Hubbard, H. H., Lansing, D. L., and Runyan, H. R., " A Review of Rotating Blade Noise Technology," Journal of Sound and Vibration, Volume 19, Number 3, 1971, pp 227-249.

Purpose

The authors seek to provide a general technical background related to noise from rotating blades, and to present a bibliography of recent (post 1968) work in the field.

Summary

A brief discussion of propulsion/ventilation concepts involving machines with rotating blades is followed by a description of aerodynamic sources of both rotational and broadband noise. The importance of unsteady, periodic loading is noted for rotational noise, while the need for a statistical random process approach is noted for broadband noise. Presently, much broadband noise prediction work is based on gross physical properties of the rotor system rather than on the underlying physical mechanisms. Effects of ducts enclosing rotating blades are discussed qualitatively, noting changes in source amplitude and directivity. A comprehensive bibliography is presented for 1968-1971 dealing with propeller and rotor noise, compressor and fan noise, and duct acoustics.

Comparison With Similar Papers

Conclusions and recommendations of this paper are in general agreement with other surveys of rotating blade noise technology.

Evaluation of Paper

The discussion is useful for an overview of the noise problems for rotating blade machinery. The bibliography and references represent a good cross-section of significant information in the subject areas noted.

Johnson, H.K., "Development of a Technique for Realistic Prediction and Electronic Synthesis of Helicopter Rotor Noise," USAAMRDL Technical Report 73-6, March 1973.

Purpose

This report documents the development of a method for predicting both broadband and rotational rotor noise and for synthesizing the acoustic waveform for use in human factors studies of rotor noise.

Summary

An elaborate method is presented utilizing an empirical data base to predict rotor noise. Correlation is shown for two Boeing configurations and one Bell configuration. Predicted and measured spectra are similar.

Comparison With Similar Papers

The present study is unique in having both the noise prediction and analog simulation combined. Shortcomings of the prediction accuracy appear to be related to inadequate input data, a problem common to all present methods.

Evaluation of Paper

The development of a method to predict the acoustic waveform of rotorcraft is highly desirable, but it is premature to accept the subject method as a design tool. Correlation must be demonstrated for multi-bladed rotors in hover and at high forward speed. If good results are obtained, this method should become a useful design tool.

Leverton, J.W., "The Noise Characteristics of a Large 'Clean' Rotor, Journal of Sound and Vibration, Volume 27, Number 3, April 1973. pp 357-376.

Purpose

The present study seeks to measure the noise characteristics of a full-scale, two-bladed rotor installed with the thrust axis pointing down to avoid recirculation effects, and to compare measured results with trends given by theoretical and semi-empirical prediction methods.

Summary

Three separate components of rotor noise are identified: rotational (discrete frequency) noise, low frequency broadband noise, and high frequency broadband noise. Variations of rotor noise with thrust, tip speed, and elevation angle are presented. Leverton's data seem to depart from previously accepted behavior of broadband noise and overall sound pressure level with both thrust and tip speed. Rotational noise is not treated in detail. The author hopes to develop empirical formulae for each noise component in future work.

Comparison With Similar Papers

The present paper is one of a limited number of reports on full scale rotor noise with potential for defining noise directionality as well as acoustic sensitivities to changes in operating parameters.

Evaluation of Paper

Results are useful in comparing the three source regions, but more investigation is required to establish that the presented behavior is not influenced by the test stand configuration. Broadness of rotational peaks and behavior of SPL with thrust and speed suggests that the inflow might be turbulent rather than "clean" as the author had hoped. If the installation is responsible for these acoustic characteristics, the general applicability of the results might be limited.

Leverton, J. W., Helicopter Noise - Blade Slap, Part 1: Review and Theoretical Study, NASA CR-1221, October 1968.

Purpose

This study was undertaken to define what is known about blade slap and to attempt to formulate criteria for the occurrence of blade slap.

Summary

A review of available literature leads the author to identify interactions between rotor blades and strong tip vortices as the main cause of blade slap. A "Blade Slap Factor" is developed which appears to agree with available data for tandem rotor vehicles and for few-bladed single rotor helicopters. The intensity of blade slap noise is predicted to vary as the sixth power of the rotational tip speed.

Comparison With Similar Papers

This paper is one of the earlier efforts to study blade slap (impulsive rotor noise) caused by blade vortex interactions. It contains test data from experiments conducted as part of the study, plus survey data from helicopter manufacturers and operators. These data could be useful to other investigators.

Evaluation of Paper

Results are useful in surveying possible mechanisms responsible for blade slap, and blade/vortex interactions are felt to be a significant cause. Attempting to apply the blade slap factor criteria to high speed flight of single rotor helicopters is not considered to be realistic, since compressibility effects are likely to control the impulsive noise generation.

Leverton, J.W., Helicopter Noise - Blade Slap, Part 2: Experimental Results, NASA CR-1983, March 1972.

Purpose

This report presents the experimental results of the overall study, including a subjective evaluation of the noise and a revised "Blade Slap Factor" design criterion.

Summary

It is shown that the occurrence of blade slap generally increases peak-to-peak rotor noise by 10dB. Blade slap components of noise are seen in narrowband spectra as long as it is subjectively detectable in the original noise signal. Model testing is found to give data as informative and valuable as that obtained from full scale testing. Limited subjective reaction data indicates that helicopter noise without blade slap must be approximately 6 dBA louder than helicopter noise with blade slap in order to be equally annoying. A Blade Slap Factor (BSF) criteria curve is presented, although results may not apply to large, multi-bladed, single rotor helicopters.

Comparison With Similar Papers

The present report completes documentation of the study reported in Part 1, NASA CR-1221, 1968.

Evaluation of Paper

The collection of noise data for full scale and model hardware is useful. Subjective results are too limited to be accurate but do give a broad-brush feel for the subjective effects of blade slap. The applicability of the blade slap factor criterion needs to be demonstrated.

Leverton, J.W., and Pollard, J.S., "A Comparison of the Overall and Broadband Noise Characteristics of Full-scale and Model Helicopter Rotors," Journal of Sound and Vibration, Volume 30, Number 2, 1973. pp 135-152.

Purpose

This paper compares broadband noise generated by model rotors and full-scale rotors. Both low frequency and high frequency broadband noise components are considered, with emphasis on tip-speed dependency, thrust dependency, and directional characteristics.

Summary

Far-field noise data are analyzed in terms of low-frequency broadband noise and high-frequency broadband noise for both full-scale and model rotor systems. Noise spectra for the two systems are similar, except for expected frequency shifts between model and full scale. Sensitivity of low frequency broadband noise to velocity is from the sixth to the eighth power for full scale, contrasted with the fourth to sixth power for model scale. This behavior is different from other investigators reporting a velocity squared dependence at constant thrust. Dependence of noise frequency on velocity is found to vary in a Strouhal fashion for model rotors contrasted with no clear behavior for full scale rotors. These full scale results disagree with results of previous investigators.

High frequency broadband noise is found to be nearly independent of thrust at constant velocity and to vary as the fourth power of tip-speed at constant thrust, although the behavior depends strongly on measurement location relative to the rotor. The mechanism responsible for this noise is not clearly understood. High frequency broadband noise generally does not control the overall noise level, but it can be a significant factor in subjective reaction to the noise.

Comparison With Similar Papers

As stated by the authors, the subject results differ from those of previous investigators regarding the effects of velocity on noise amplitude and frequency. The present paper contains both model and full scale data, while most other papers are restricted to one or the other.

Evaluation of Paper

The experimental study provides a useful base for further research into noise generating mechanisms, which hopefully will explain differences between model and full scale behavior. Data from this study and other studies should be reviewed to determine the reasons behind discrepancies about velocity and thrust dependence.

Loewy, R. G., and Sutton, L. R., "A Theory for Predicting the Rotational Noise of Lifting Rotors in Forward Flight, Including A Comparison With Experiment," Journal of Sound and Vibration, Volume 4, Number 3, 1966. pp 305-344.

Purpose

This work attempts to provide a method for predicting rotor noise from unsteady airloads. Noise calculations using the developed analysis are compared to available measurements.

Summary

Expressions are developed relating the noise field to oscillating pressures imposed on the air by rotor blades. A swept area representation is used in conjunction with specified chordwise loading distributions. Limited comparisons of measured and calculated noise show poor correlation.

Comparison With Similar Papers

This study is one of several that demonstrated the importance of unsteady loading in the rotor noise problem. The prediction method involves a numerical integration and therefore is slow and cumbersome to use, as are other methods using this approach. The correlation between predicted and measured noise is somewhat worse than results presented by other investigators.

Evaluation of Paper

The technical approach and final prediction method are similar to those of other people studying rotor noise in the same time frame. The relatively poor agreement between predicted and measured noise is probably a result of inadequate blade loading data and questionable noise data rather than severe defects in the analysis.

Lawson, M. V., and Ollerhead, J. B., "Studies of Helicopter Rotor Noise," USAAVLABS TR 68-60, January 1969.

Purpose

Objectives of the reported study are to analyze the problem of helicopter rotor noise radiation and to develop analytical expressions for calculating noise from rotors. Existing theoretical and experimental information are the starting point for the study.

Summary

Discrete and broadband contributions to total rotor noise are described, and the importance of discrete frequency noise out to several hundred hertz is noted. Experimental data are reviewed and general trends with tip speed and thrust are noted. Analytical expressions are derived for a simplified closed-form acoustic solution and an "exact" solution requiring numerical integration. The simplified solution is nearly as accurate and much faster (i.e., requiring much less computer time) than the exact solution. Design charts are presented for estimating levels of rotational noise harmonics as functions of equivalent Mach number and elevation angle from the rotor disc plane.

Comparison With Similar Papers

This study is one of several conducted during the mid-to-late 1960's concerning helicopter rotor noise. It agrees with the others regarding the importance of unsteady loading. The present study is unique in the development of charts for estimating rotor rotational noise.

Evaluation of Paper

This report is very useful, both for a technical overview of the noise problem and for the simplified prediction method it contains. The concepts of airload exponential decay laws, random phasing, and spanwise correlation lengths have become well accepted since they produce reasonably good noise predictions from manageable input data. Basic shortcomings of the method are its inability to simulate acoustic radiation from highly unsymmetrical loading on a rotor, and its inability to model the effects of subtle changes in airfoils, planforms, etc. Much more basic research is required to develop the aerodynamic data base and aeroacoustic transfer function in order to remove prediction limitations. The subject approach and simplified method will remain popular, at least until the necessary research is done.

Lowson, M.V., Whatmore, A.R., and Whitfield, C.E., "Source Mechanisms for Rotor Noise Radiation," NASA CR-2077, August 1973.

Purpose

The work was performed to investigate sources of subsonic rotor noise. Various theories are reviewed for discrete frequency noise and broadband noise. Theory and past experiments are compared, and results of present tests of a low speed fan are discussed.

Summary

Fundamental theories relating to noise from turbulence and unsteady coherent loading are discussed to lead into a comparison between theory and experiment. Particular emphasis is placed on velocity dependence and frequency dependence for dipole and quadrupole source models. Theoretically, broadband dipole noise will tend to vary as the sixth power of velocity while quadrupole noise should vary as the eight power of velocity. Existing data, including that produced by the subject work, do not resolve the dipole versus quadrupole question.

Major conclusions are that discrete frequency noise results from inflow distortion and large scale inflow turbulence, low frequency broadband noise results from smaller scale inflow turbulence, and high frequency broadband noise results from a self-interaction at the blade tips. This last source of noise is not identified in past literature, according to the authors.

Comparison With Similar Papers

This study is compatible with other literature on aerodynamic sources of noise. It is somewhat unique in having hot wire anemometer data (rotating and fixed probes) to define the input flow field that produces the noise data.

Evaluation of Paper

This paper is useful in establishing firm theoretical and experimental foundations for basic noise generation studies. Promising results for the discrete frequency aeroacoustic transfer function and for broadband noise correlation help direct future work. The quadrupole vs dipole question needs further investigation.

Lyon, R.H., Mark, W.D., and Pyle, R.W. Jr., "Synthesis of Helicopter Rotor Tips for Less Noise," Journal of the Acoustical Society of America, Volume 53, Number 2, 1973. pp 607-618.

Purpose

In order to reduce noise at high forward speed, the author seek to develop a calculation method for generalized airfoil thickness and lift distributions that are predicted to be less noisy at Mach numbers approaching 1.0.

Summary

The present work extends earlier efforts by the authors to relate noise from the tip region of helicopter rotor blades to blade thickness and blade lift. The contribution of lift to noise is shown to be much less than the contribution of thickness, so emphasis is placed on minimizing thickness noise radiation. Some candidates for low noise tip distributions are presented.

Comparison With Similar Papers

The subject paper is more abstract than most, since it develops generalized thickness and lift functions that can be satisfied mathematically by many different designs. Other papers tend to concentrate on reducing compressible drag of specific airfoils by changing sweep, thickness, and angle of attack.

Evaluation of Paper

The results appear to be valid in a mathematical sense, but the practical validity of the approach must be demonstrated by the design and test of airfoils based on this method.

Morfey, C.L., "Rotating Blades and Aerodynamic Sound," Journal of Sound and Vibration, Volume 28, Number 3, 1973. pp 587-617.

Purpose

This paper is written to provide a survey of fundamentals of aerodynamic noise generation by blades.

Summary

The author traces the historical evolution of current understanding of the noise generation processes involved with rotating airfoils. Early work on propellers is mentioned and advances into unsteady aerodynamics and cascade theory are noted. Noise generation and radiation from rotors in a free field is emphasized along with the effects of ducts on the acoustic field of fans and impellers. References and an extensive bibliography are presented.

Comparison With Similar Papers

Historical development is traced somewhat more extensively than other papers. Results of specific investigators are discussed in addition to generalizations regarding noise generation and propagation.

Evaluation of Paper

This paper contains a useful overview of acoustic technology for rotors and fans, and useful bibliographic data for more detailed study in specific areas.

Sadler, S.G., Johnson, H.K., and Evans T.D., "Determination of the Aerodynamic Characteristics of Vortex Shedding From Lifting Airfoils for Application to the Analysis of Helicopter Noise", Rochester Applied Science Associates, Inc., RASA Report 73-02, 1973.

Purpose

The present study was undertaken to experimentally define the characteristics of vortex shedding from airfoils in a wind tunnel as a foundation for understanding and predicting vortex noise of helicopter rotors.

Summary

Airfoils were tested in the United Aircraft Research Laboratory acoustic research tunnel to gather blade surface pressure data and corresponding noise data. Surface pressures were adversely affected by the transducers on the airfoil. Presumably, noise data also suffered from this effect. Two values of Strouhal number were found, but repeatability of results was found to be poor.

Comparison With Similar Papers

Present results do not compare well with other investigations.

Evaluation of Paper

Inconsistencies in the test data make it difficult to apply the results of the study to helicopter noise.

Schlegel, R.G., and Bausch, W.E., "Helicopter Rotor Rotational Noise Prediction and Correlation", USAAVLABS Technical Report 70-1A, November 1970.

Purpose

The program objectives were to measure airloads and noise simultaneously and to use these data to evaluate correlation between measured and predicted noise.

Summary

The rotational noise prediction method reported in 1966 by Schlegel, et al[6] is extended to use higher frequency airloads and to use any arbitrary chordwise distribution of airload. Good correlation is claimed for the first 4 harmonics of noise. Correlation generally improves when the measured chordwise loading distribution is used instead of a hypothetical rectangular distribution. Source motion terms appear to be important and should be included in the prediction method.

Comparison With Similar Papers

Results of the subject work generally agree with other reports in that high frequency airloads and chordwise distribution were found to influence noise significantly. This report summarizes high frequency differential pressure data measured on the rotor blades. Such data generally is not available elsewhere, especially for a flight vehicle operating at high forward speed.

Evaluation of Paper

Although the modified noise prediction method produces better correlation than the original method, the need for high frequency airload data to calculate noise makes the method difficult to use. This is a common problem with all existing methods that predict noise by integrating over the rotor disc. Since the needed loading data rarely is available, the added complexity does not generally result in more accurate predictions than closed-form methods have demonstrated. The airload data could be useful in future studies.

Sternfeld, H., Bobo, C., Carmichael, D., Fukushima, T., and Spencer, R., "An Investigation of Noise Generation on a Hovering Rotor, Part II", U.S. Army Research Office - Durham Report D210-10550-1, November 1972.

Purpose

This paper presents results of a study to develop an improved version of Lowson and Ollerhead's noise prediction procedure called HERON II. Experiment, analysis, and correlation are presented.

Summary

A noise prediction computer program that predicts the acoustic pressure time history, from which noise harmonics are extracted by Fourier analysis, is developed. This basic computer program requires detailed input data to describe spanwise and chordwise loading distribution as well as azimuthal loading distribution. Hypothetical inputs were used and showed insensitivity of noise to spanwise distribution. Amplitude and phase of loading harmonics were found to affect noise significantly. Based on the sensitivity study, simplifications were made to the noise prediction program to remove the need for complicated input data. Simplifying assumptions of Lowson and Ollerhead are validated.

Comparison of model and full scale rotor noise harmonic spectra shows excellent agreement one diameter from the rotor hub. Scale factors believed to be critical are thrust coefficient divided by solidity, C_T/δ, and tip Mach number, M_t. Broadband noise does not scale as well, with model levels being lower than full scale.

Experimental investigation of acoustic sensitivity to airfoil section and planform showed no clear cut improvements over the total tip speed-thrust ranges considered. Some noise reductions were noted at lower tip speeds (650 ft/sec).

Impulsive hover noise of an isolated rotor is thought to be produced by shock formation or movement on the upper surface above lift divergence. These shocks are attributed to the passage of a tip vortex close by the blade in question. Blade loading and tip speed are believed to be less important parameters than the airfoil section lift divergence boundary. Ability to predict the occurrence and amplitude of this noise is limited by a lack of adequate information on vortex core size, strength, and location relative to the blade.

Comparison With Similar Papers

The analytical approach parallels that of Lowson and Ollerhead[7]. The present paper checks many of the simplifying assumptions used by Lowson and Ollerhead to develop their simplified, closed-form noise prediction method. These assumptions

Comparison With Similar Papers (Cont)

are found to be valid, and the number of loading harmonics is found to be less than the mb $(1 + M_t)$ specified by Lowson and Ollerhead. Experimental data for similar rotors with from 3 to 5 blades are presented, but no attempt at comparison with other studies is made.

Evaluation of Paper

The paper contains reassuring validation of the simplifying assumptions of Lowson and Ollerhead, and some additional simplification are presented. Test data contained in this report might be useful when combined with data from Leverton and Lowson for noise mechanism research and verification. The role of oscillating shocks in single rotor noise deserves further investigation.

Whatmore, A. R., and Lowson, M. V., "Some Effects of Ground and Side Planes on the Acoustic Output of a Rotor", NASA CR-132306, July 1973.

Purpose

The authors seek to simulate the effects of rotor/airframe interactions on radiated noise in tests of a simple model.

Summary

Basically, sideplanes increase lower order rotational harmonics significantly for fuselage - propeller separations less than 0.25 propeller diameters. Ground planes very close to the rotor can decrease rotational noise and increase thrust output significantly.

The subject paper is unique in dealing with side planes and ground planes representing fuselage structure. Other papers deal specifically with guide vanes and support struts encountered in compressors and ducted fans.

Evaluation of Paper

The acoustic effects of the side plane-rotor tip separation are useful for design of turboprop, prop-fan, prop-rotor, and propeller installations. The effect of the ground plane is not believed to be applicable to rotor-fuselage interactions for large diameter rotors.

Widnall, S. E., "A Correlation of Vortex Noise From Helicopter Rotors", Journal of Aircraft, Volume 6, Number 3, May-June 1969. pp 279-281.

Purpose

The work was done to see if a general collapse of noise data could be obtained on operating condition and geometry of different rotors.

Summary

Data from several references, including whirl tower and flight vehicles, collapsed to a band approximately 5 dB wide. The collapsed data show a general trend with the mean blade lift coefficient squared (C_L^2) near typical design point and deviation from C_L^2 for both highly loaded and lightly loaded rotors.

Comparison With Similar Papers

This paper takes data from several other reports. Parameters for the collapse, such as thrust, tip speed, and C_L, are those commonly applied for so-called "vortex noise".

Evaluation of Paper

The data presented in the subject paper are useful for a "first pass" estimate of the overall level of "vortex noise", with quotation marks indicating that this is the popular name given to noise above 150 Hz by researchers through the mid to late 1960's. The data also are useful as a reference for measuring how much noise reduction is obtained with new noise control rotor systems.

Widnall, S., "Helicopter Noise Due to Blade-Vortex Interaction", Journal of the Acoustical Society of America, Volume 50, Number 1, 1971. pp 354-365.

Purpose

This work was performed to develop expressions for noise from blade-vortex interaction using linear unsteady aerodynamic theory.

Summary

Expressions are derived and calculations performed for sound power, directionality, and frequency spectrum based on sinusoidal gusts to represent the velocity field induced by the vortex. Two-dimensional airfoil data are used. Comparison of measured waveforms for a one-bladed rotor with predicted waveforms showed good agreement.

Comparison With Similar Papers

This paper is one of several dealing with rotor noise due to blade vortex interactions. It is more extensive than most, however, since predicted sound power, sound directivity, and sound spectrum are presented. Also, the comparison with measured data lends additional credibility to the results.

Evaluation of Paper

The subject paper presents a fairly complete analysis of blade-vortex interaction. It should be particularly valuable as a starting point from which to explore effects of unsteady, 3-dimensional aerodynamics on analytical models of blade-vortex interactions.

Wright, S. E., "Spectral Trends in Rotor Noise Generation", AIAA Paper No. 73-1033, Presented at AIAA Aero-Acoustics Conference, October 1973.

Purpose

This paper was written to report trends observed in studies of measured noise from fans, propellers, and rotors.

Summary

The author's analysis indicates that the "minimum" noise generated by a rotor should depend only on thrust and rotor "self noise". The author feels that only this minimum noise is readily predictable, since so-called "excess noise" is influenced by so many environmental variables. Strouhal scaling of broadband frequency is observed, and a data collapse is presented. The dependence of generated noise is noted to be on the fifth power of the velocity.

Comparison With Similar Papers

Wright's results should be checked for compatibility with recent work by Leverton[13] and Lowson[14] regarding noise mechanisms and rotor acoustic behavior. Both frequency dependence and velocity dependence are in dispute among investigators.

Evaluation of Paper

The results presented in this paper are useful as a base for further studies of noise from fans and rotors. In particular, the data should be useful in trying to define effects of velocity on noise amplitude and frequency.

[illegible] Generated by Asymmetric Disk [illegible] Volume [illegible], Number 2, 19[illegible], pp 223-24[illegible].

[illegible]

[illegible] steady rotating forces on rotor [illegible] objective in doing this is to improve cor- [illegible] spectra.

[illegible]

[illegible] directionality of rotational noise [illegible] able air-loading data which is [illegible] markedly improved correlation [illegible]

[illegible]

[illegible] of [illegible], Schlegel[8], Loewy[10], Leverton[20], [illegible] loads in the rotational noise generation of rotors. Wright [illegible] problem of needing good estimates of [illegible] estimates of rotational noise.

Evaluation of [illegible]

[illegible] theoretical development gives results [illegible] acceptable correlation with measured data [illegible], et al[12] used Wright's acoustic prediction method [illegible] correlation work at NASA reported in 1974.

Engine Noise Capsule Summaries

Eatock, H.C., Plucinsky, J.C., and Saintsbury, J.A., "Designing Small Gas Turbine Engines for Low Noise and Clean Exhaust", AIAA Paper No. 73-1154 Presented at the CASI/AIAA Aeronautical Meeting, October, 1973.

Purpose

This report outlines work being done at Pratt & Whitney Aircraft of Canada, Limited on the control of noise and emissions of small gas turbine engines to meet FAA and EPA regulations. Design features contributing to the low noise signatures of current JT15D and PT6 engines are discussed together with some early results from programs to minimize noise from advanced PT6 turboprop installations.

Summary

Although the PT6 engine was designed before many of the engine noise generating mechanisms were fully understood, it does incorporate advantageous noise reduction features. The free turbine eliminates the clutch requirements for helicopters and allows for selecting speed for minimum noise. Moreover, the gas path configuration is different from the conventional engine. This generally results in a buried engine inlet with a multiplicity of right angle bends which effectively impede noise transmission. An example is shown which illustrates the effectiveness and importance of installation ducting on inlet noise.

The measured exhaust noise spectrum of the PT6 in octave bands is relatively flat, with appreciable low frequency noise. This noise is internally generated and believed to result from the interaction of turbine flow turbulence with the exhaust duct. No attempt is made to separate combustion noise from overall noise. Over a broad range of powers and power turbine speeds, the noise output correlates with a V^6 relationship where V is the velocity at entry to the exhaust ducts. However, different exhaust ducts produce noise differences of 4 to 5 dB.

A broad correlation of exhaust noise from different shaft engines suggest that engine noise levels vary proportionately with shaft horsepower (SHP). Individual engine power/noise variations are less consistent as the PT6 follows a $(SHP)^4$ while other free turbine engines vary from $(SHP)^{1.7}$ to $(SHP)^{5.3}$.

Pratt & Whitney Aircraft of Canada, Limited is engaged in further work on engine internally generated exhaust noise including the effect of exhaust duct geometry on the overall generation and radiation.

Comparison With Similar Papers

This report is of much more limited scope than the reports resulting from the Air Force sponsored Turboshaft engine study at AiResearch[5]. Also, the DOT sponsored program at General Electric[13] describes a more in-depth study of noise generation mechanisms than found in this report.

[illegible]

This is a limited discussion of the noise of small turboshaft and turbofan engines. [illegible] general trends are shown which suggest that larger differences exist in exhaust noise of similar engines. Important effects of installation are demonstrated, but predictions cannot be done with the information reported. This paper is perhaps of greater interest in emission control rather than noise control or prediction.

Grande, E., "Core Engine Noise", AIAA Paper No. 73-1026, October 1973.

Purpose

This paper assesses sources of core noise in a turbofan engines. It is concluded that combustion noise is the dominant contributor to core noise, although turbine noise due to interaction with combustor-generated turbulence may be significant. A core noise prediction procedure is formulated which considers the noise generation in the combustion chamber and the noise transmission through the turbine and the primary exhaust nozzle. Comparison of the predicted and measured core noise levels for one low bypass ratio and one high bypass ratio turbofan engine shows satisfactory agreement. The work on prediction methods of core engine noise, though not directed toward turboshaft engines, is of interest in helicopter noise prediction and will be discussed below.

Summary

Core noise consists of numerous and only partly identified sources of noise including:

1. Combustion noise
2. Low frequency noise generated in the turbine as a result of interaction with upstream turbulence for the combustor
3. Noise generated in flow passage discontinuities such as turbine exit struts
4. Turbulence level and swirl in mean flow upstream of the nozzle exit

Combustor noise has been assumed to constitute the major source of core noise in two separate prediction procedures by Gerend, et al[3] and Ho and Tedrick[4]. Gerend, et al express the core noise as functions of combustor exit temperature, turbine inlet area, and turbine pressure ratio. Ho and Tedrick express combustor noises as functions of temperature rise, combustor flow, and fuel air ratio. These prediction procedures suggest that noise generation is dependent on the combustion parameters upstream of the turbine inlet.

The remainder of this paper is limited to considering combustion noise as a source of core noise. Three separate problems are considered in attempting to predict the core noise resulting from combustion. These are:

1. Noise generation in combustor
2. Noise transmission through turbine
3. Noise transmission through primary engine tailpipe

Summary (Cont)

The effect of the exhaust nozzle on noise transmission is approximately modeled by considering the radiation from the open end of a uniform circular pipe. Using several simplifying assumptions it is shown that low frequency noise transmission through the exhaust nozzle varies inversely with nozzle temperature.

Combustion noise generation is examined by modification of the theoretical model of Strahle[14] to permit comparison with empirical results of Ho and Tedrick[4]. It is found that the empirical correlation agrees fully with the modified theoretical model except for a factor of the square root of the combustor temperature.

Using the preceding analytical development, the noise of two large turbofans with different bypass ratios are predicted and compared with measured acoustic data. The measured data, corrected for the predicted jet noise, appear to agree with the core noise prediction to within ± 1 dB. However, the engine parameters used are based on simplified performance calculations for the two engines, and may be somewhat inaccurate. Furthermore, similar comparisons with other engines are necessary to assess the validity of the prediction method.

Comparison With Similar Papers

The analysis and prediction scheme described extend the empirical work of Ho and Tedrick[1] from burner combustor noise to the core engine noise of full scale turbofan engines. The extension of the theoretical work of Strahle[14] to permit comparison adds credence to the burner prediction method of Ho and Tedrick, but the extension to the small engine combustor noise prediction method was not examined. The resulting prediction method of Grande[9] compares in part with the prediction method of Ho and Tedrick for burner rigs, but not for engine core noise. The derived prediction methods for transmission coefficients through the turbine and exhaust nozzle have not been examined by other investigators.

Evaluation of Paper

The prediction methods of this report have not been sufficiently validated to be of much use in predicting core engine noise of helicopter.

Grande, E., "Exhaust Noise Field Generated in the JT8D Core Engine - Noise Floor Presented by the Internal Noise Sources", J. of the Acoustical Society America, Volume 55, No. 1, January 1974.

Purpose

This paper presents the results of an experimental/analytical study to determine the strength of the acoustic radiation generated in the combustion and turbine stages of a JT8D core engine and transmitted through the primary jet exhaust duct. Results show that internally generated noise is a significant component of core engine noise. The work is of interest in helicopter noise studies because turboshaft engines may also exhibit appreciable noise from these sources.

Summary

The acoustic field within an extension of the core engine tailpipe of the JT8D engine was measured by an array of microphones flush mounted on the duct walls. A theoretical analysis was made to develop a mathematical description of the sound field within the engine to permit interpretation of the cross-power spectral densities of the microphone signals and to determine the amplitudes of the propagating modes. Good agreement was determined between the measured and theoretically determined cross-power spectral density. The transmitted power was determined and far-field sound pressure levels were calculated using directivity patterns from model scale jet measurements in which the dominant noise field was generated in a plenum upstream of the jet nozzle.

The results show that internally generated noise is a dominant noise component from the core engine at large angles from the jet axis for low engine power settings. This suggests that in turboshaft engines, with their high work extraction in the turbine stages and low core engine jet velocities, the internally generated noise is a significant noise source.

Comparison With Similar Papers

This paper shows that observed levels of "core engine noise" measured in the far-field of turbofan engine can be accounted for by measurements of the acoustic field within the core engine tailpipe. This study adds additional validity to previous work which has suggested that internally generated noise upstream of the exhaust nozzle is a source of significant noise. No attempt has been made here to determine the source of internal noise nor to relate the noise generated to other engine operating parameters.

Evaluation of Paper

No prediction methods, trends, or relation to other operating parameters are available in this report. Thus the report is of limited interest for direct application to turboshaft engine noise prediction.

[illegible], R.W., [illegible], R.N., Crande, L., Brown, L., Sutherland, L., [illegible], [illegible], C.L., [illegible], P.T., Goodman, B.M., "Small Turbine [illegible] Reduction", Air Force Aeropropulsion Laboratory Technical Report AFAPL-TR-73-79 (Six Volumes), July-December, 1973.

Purpose

This six volume report summarizes the work conducted under contract F33615-71-C-1457 between the AiResearch Manufacturing Company of Arizona and the Air Force Aero Propulsion Laboratory. The objective of the work was the development of the technology base necessary to reduce the noise signature of small turboprop and turbofan engines to minimize their detectability in low altitude reconnaissance/surveillance military missions. The program summarized included 1) development of prediction methods for all the sources of small turboprop (turboshaft) and turbofan engines, 2) development of a duct acoustic treatment design method, 3) tests of materials suitable as acoustic duct liners, 4) acoustic tests of an unsuppressed turbofan including comparison with predicted spectra, 5) acoustic tests of various inlet mufflers and exhaust duct treatment, and 6) an analysis of the performance and weight panalties for noise suppression.

Summary of Executive Summary-Volume I

This volume summarizes the technical objectives and desired end products of the program. Results of the three test phases of the program and conclusions from the overall program are included. Of interest is the overview of the program provided in figure 1 (pg. 2) of this volume. Here it is shown that the work in the program was divided into three major categories, 1) development of noise prediction techniques, 2) developing effective noise suppression techniques including associate performance and weight panalties and 3) conduct of engine tests to demonstrate correlation with prediction of suppression techniques developed in the other phases of the program.

For engine noise prediction, the engine noise sources are divided into three main areas: inlet noise, exhaust noise and mechanical noise. Inlet noise is that produced by the fan and/or compressor radiated both forward and rearward from the front of the engine. Its noise spectrum consists of discreet frequencies at the fan and compressor blade passing frequency and harmonics along with broadband noise. Fan and compressor noise are predicted by an improved version of the method developed by Smith and House[13]. The improved version presented in this report allows prediction of the noise of centrifugal compressors in addition to the axial compressors treated by Smith and House.

Exhaust noise consists of jet noise and core noise. Jet noise is produced by the primary and/or secondary air leaving the engine and mixing with the ambient air. Core noise is produced within the engine and escapes via the primary exhaust nozzle.

Jet noise is predicted from a method based on the standard SAE procedure[12]. Core noise is assumed in this report to be combustor noise. However, it is pointed out that further expansion of the core noise prediction methodology will result from the DOT/FAA sponsored program conducted by General Electric[13]. Combustion noise is believed to be one of the most significant core engine noise sources in small turboshaft engines.

Mechanical noise consists of gear noise, auxiliary equipment noise, and casing noise. In turboshaft engines, gear noise must be considered, as gearboxes are used to drive the propeller, rotor or auxiliary equipment. Auxiliary equipment noise is that produced by fuel and lubrication pumps mounted on the outer case of the engine. Casing noise is due to fluctuating forces produced in the engine, either from aerodynamic or mechical causes which are transmitted through the engine casing and result in external noise radiation.

Gear noise is predicted with an empirical procedure, since little basic work has been done to allow predictions from basic noise generating mechanisms. The spectrum of gear noise is dominated by discreet frequency peaks. For spur gear systems, the dominant frequency component corresponds to the tooth meshing frequency or its second harmonic. The wide variation in gear systems makes an accurate prediction procedure impossible to develop at this time. Therefore, the report recommends use of measured spectrum shapes for gearboxes of similar geometry to the one of interest. Then the empirical procedures can be used to extrapolate the spectrum to the desired configuration.

Little information on auxiliary equipment noise was found in this study. An order of magnitude prediction procedure is included based on a fuel injection pump prediction procedure. The casing noise prediction procedure was developed from generalization of AiResearch and Boeing measurements and is considered to be a function only of mechanical horsepower generated by the engine.

The procedures discussed above are included in a computer program. Of interest is the correlation between measured and predicted turboshaft engine noise shown in figures 10, 11, and 12 of this report. Overall directivity in figure 10 is seen to be generally good except in the aft quadrant from 80° to 150°, where predicted levels are as much as 6dB high. Figure 11 shows quite good correlation between measured and predicted inlet noise. There does, however, appear to be tones in the measured spectrum at 1000 and 4000 Hz which are not predicted by the method. Figure 12 shows the exhaust noise comparison. Here, the lack of agreement at mid frequencies around 600 Hz is distrubing. The lack of similarity in the measured and predicted spectrum shape suggests that further work is required in predicting turboshaft engine exhaust noise.

[illegible] Summary-Volume I (Cont)

Three duct liner design procedures are discussed in the report: 1) an analytical/semi-empirical procedure which determines the optimum liner impedance for sound absorption analytically and determines the material which matches this required impedance by a semi-empirical procedure, 2) an analytical self-optimizing procedure developed by the Air Force, and 3) an empirical procedure based on generalization of the results of many other investigators working in the duct liner design area. Comparisons of predictions and test for duct liners are presented.

Turboshaft engine tests were conducted with and without suppression to show the accuracy of unsuppressed engine noise predictions and to establish the optimum suppression system. Attenuation achieved in 1/3 octave bands is summarized. Also the performance weight penalties for suppression are summarized. A few examples are also shown to indicate how the large suppression packages might be integrated with an airplane.

Summary of Noise Prediction Methods-Volume II

This volume summarizes the background study necessary to develop the engine noise prediction procedure which was discussed above in the Volume I summary. More acoustic theory on the mechanisms important in engine noise generation are included than in Volume I. Test data from AiResearch engine tests is evaluated as an aid to developing accurate prediction methods. Several comparisons between measured and predicted directivities and spectra of turbofan and turboshaft engines are presented.

Summary of Suppression Design and Prediction Methodology/Materials Tests-Volume III

The background from the literature on duct liner attenuation prediction is reviewed. Also, the results of basic tests on various candidate duct lining materials are presented. Measurements include levels of acoustic airflow resistance as a function of steady airflow velocity through a sample, airborne acoustic absorption, and resistive and reactive components of acoustic impedance. This information is of value in establishing the duct lining material which most closely approaches the optimum liner material specified in the duct lining design procedure. The prediction methodologies discussed in Volume I are described in detail and predictions of 1/3 octave band attenuation levels are compared with measurements.

Summary of Turboprop Engine Demonstration Tests-Volume IV

The full scale turboshaft engine noise tests to establish the levels of unsuppressed engine noise and the effect of various candidate inlet and exhaust silencers are summarized in this volume. Aerodynamic and weight penalties as functions of various

Summary of Turboprop Engine Demonstration Tests-Volume IV (Cont)

operating and configuration parameters are also summarized. The application of the optimum inlet and exhaust silencer configuration to turboprop and turbofan aircraft installations is shown in artists concepts of quiet reconnaissance/surveillance aircraft.

Summary of Data Tabulations-Volume V

All of the engine test and acoustic materials test data from the program are compiled in this volume. Operating conditions for the engine during the tests are included to allow interpretation of the test data. This is a set of definitive data, as the engine is driving a quiet dynamometer during the test so only engine sources are present.

Summary of Noise Prediction Program Users Manual-Volume VI, Part I

A computer program listing of the engine noise prediction procedure is presented in this volume. This volume also includes discussion of operation of the program and some sample cases.

Summary of Duct Design and Attenuation Program Users Manual-Volume VI, Part II

Program listings for a theoretically and an empirically based duct lining design procedure are presented in this volume. A discussion of the differences between the two procedures, discussion of the operation of the programs, and sample cases are also included.

Comparison with Similar Papers

This report must be compared with papers in three areas: 1) turboshaft engine noise prediction, 2) turboshaft engine noise evaluations, and 3) duct lining prediction methods. In the turboshaft engine noise prediction area, the work of Smith and House[15], which was used as a reference, cannot be considered complete, although it was the pioneering report on engine noise prediction. The work in progress by General Electric[13] is a more in-depth treatment of turboshaft engine noise prediction and also includes an emphasis on source noise and how the sources can be suppressed, while this report emphasizes the prediction of current technology engines. In the turboshaft engine noise evaluation area, many tests have been conducted. However, the data in this report is well documented and the engine was driving a quiet dynamometer, so the data will be of long term value to researchers in engine noise. Many duct lining prediction methods of analytical or empirical nature exist. The value of the method developed in this study is the resulting computer program, which can be easily used by other duct liner designers. It is not clear that any of the duct liner prediction procedures are the best at this time. Many comparisons between measurements and predictions are shown which verify the accuracy of one or another method. However,

Comparison with Similar Papers (Cont)

the source noise of a propulsor as well as the way in which a duct liner operates on the noise produced is still not completely understood and therefore any current prediction procedure will have limitations. The continuing work by both government and industry researchers will be required for the development of accurate prediction procedures.

Ho, P.Y. and Tedrick, R.N., "Combustion Noise Prediction Techniques for Small Gas Turbine Engines", Inter-Noise 72 Proceedings, October 1972.

Purpose

This report is a preliminary release of part of the work described in detail in Air Force Aero Propulsion Laboratory Technical Report (APAPL-TR-73-79). The objective of the work reported was the development of noise factors to predict the combustion noise of small gas turbines. Equations are shown which permit prediction of acoustic power level generated by a given design and farther, to predict the effects of changing engine design parameters. The work on turboshaft engines is of interest in helicopter noise prediction and is discussed here.

Summary

One of the most significant sources of noise from small turboshaft engines is the combustion process. The temperature, velocity, and density gradients that exist in the high-speed combustion flow cause a characteristic low pitched roar. This combustion noise is a highly complex phenomenon compounded by interaction with the blades of the turbine section.

To develop an understanding of the engine parameters that control the generation of combustion noise, two approaches have been used in this report. First, an empirical evaluation of potential noise factors affecting exhaust noise was conducted. Second, a similar expression was derived dimensionally based on the energy output and this factor was compared with data from both combustion rig and engine tests.

The equations developed provide a method for the small turbine engine designer to predict the acoustic power generated by a given design and also to predict the effects of changing design parameter. However, no attempt is made to determine the differences between rig and engine results.

Comparison With Similar Papers

This paper is derived from Garrett AiResearch Report No. S.D. 8005, May 10, 1972 by the same authors. It covers part of the work described in detail in a six volume report called "Small Turbine Engine Noise Reduction," Air Force Report AFAPL-TR- 795 written by several authors from AiResearch Manufacturing Co. in 1973. The correlation factor developed in this paper is used for core engine noise prediction in Mahady, et al[27]. A comparison of this correlation factor with others for combustion noise prediction by Kazin, S.B. and Emmerling, J.J.[28] shows significant differences.

[illegible]

[illegible] paper presents a [illegible] method for small turboshaft engines of a [illegible] similar [illegible]. However, the correlation is not shown to be applicable to [illegible] of [illegible]. Moreover, the [illegible] difference between [illegible] test indicates the correlation is [illegible].

Huff, R.G., Clark, B.J. and Dorsch, R.G., "Interim Prediction Method for Low Frequency Core Engine Noise", NASA TMX-71627, November 1974.

Purpose

The purpose of this paper is to select a low frequency core engine noise prediction method for interim use in the NASA Aircraft Noise Prediction Program. A review of the literature and compilation of numerous available procedures shows significant differences in prediction methods and suggests the primitive state of core engine noise understanding. The prediction method selected for combustion noise is derived from turboshaft engine noise data and is of particular interest in the prediction of helicopter noise.

Summary

Low frequency core engine noise has been observed and measured on a variety of existing engines. However, the core engine noise is difficult to separate from other, more significant noise sources. In most cases core engine noise has been deduced from turbofan engine tests with suppressed fan noise and operating at low power to minimize jet noise. Jet noise, estimated by existing prediction techniques is deducted from the total engine noise. The residual core engine noise is consequently limited and of questionable accuracy.

A survey of the literature shows in general that the source of core engine noise is internally generated. Some of the probable sources are:

1. The combustion process
2. Flow around internal obstructions
3. Scrubbing of the duct walls
4. Local temperature fluctuations or hot spots flowing through the turbine and nozzle

A number of different correlations and resulting prediction schemes have been reported covering limited groupings of engine sizes and types. A variety of parameters with different power relationships have been proposed from results of engine tests, component tests, and theoretical studies. The parameters effecting core noise which are most frequently found in literature are:

1. Combustion chamber temperature and temperature rise raised to powers from 2 to 4.
2. Combustion chamber pressures and pressure ratio raised to powers from 1 to 3.

[illegible]

a. [illegible]

b. [illegible] raised to powers from 1 to 4

c. Velocities raised to powers from 1 to 2

d. Dimensions raised to powers from 1 to 3

[illegible] clear that no general agreement has been reached on the important governing [illegible]. The state-of-the-art for predicting levels of core engine noise, spectra, [illegible] is neither sophisticated nor accurate. Much is required to improve [illegible].

[illegible] prediction method given in the report is for the low frequency core [illegible]. Contributions due to combustion and internal flow are included. No [illegible] of prediction procedure is made due to the general lack of substantiating data. The choice presented here is based on simplicity and availability of required information. Essentially the equation given is that of Motsinger[6] for the [illegible] of the overall sound power level. Added curves give the directionality and spectrum shape of the noise. The recommended directionality is taken from Dunn and Peart[10] and the recommended spectra shape is essentially the SAE spectrum for jet noise[12]. The frequency of the peak of the spectrum is also taken from Dunn and Peart [illegible]. It is suggested that a peak frequency of 400 Hz be substituted if the calculated frequency falls outside the range of 300 to 1000 Hz.

[illegible] review of Research in Progress discloses that considerable work is being done to improve the understanding and prediction of core engine noise. An extensive list of recommended additional research indicates broad areas where information is lacking. Finally, the report concludes with pertinent remarks which clearly indicates that the state-of-the-art for predicting core engine combustion noise in the far-field is in its infancy."

Comparison With Similar Papers

Numerous papers have been published which provide a partial review and comparison of prior work on core engine noise. New information is generally added and [illegible], new or revised parameters, and consequently new or different prediction procedures are proposed. This report presents no essentially new information, but is [illegible] an excellent overall survey, condensation, and summary of many published reports on core engine noise.

Both applied research, which makes use of engine data, and fundamental research, [illegible] component testing, are considered. A convenient table lists the references and identifies the type of information contained in each. Pertinent information from each reference is discussed and the prediction equation and parameters are collected in table form to permit comparison and evaluation.

Evaluation of Paper

The equations and curves contained in this report permit the prediction of core engine noise of turboshaft engines. While questions remain as to the validity and accuracy of the method it appears to be the best available at this time. The procedure has the advantage of simplicity and commonality, but is probably limited in application. Continuous improvements in the method can be expected for some time to come.

The review and summary expose the problems in defining and predicting core engine noise. A short overview of extensive work in progress, numerous recommendation, and concluding remarks constitute a valuable commentary on primitive state-of-the-art of core engine noise.

[illegible] Low Frequency Core Engine Noise, [illegible]

[illegible]

This report discusses the impact of low frequency core engine noise on overall aircraft engine noise. A relationship is established between combustion parameters and core engine noise by examination of component combustion and engine test data. [illegible] to permit the prediction of low frequency core noise in terms of acoustic power level, directionality and spectral content. The majority of the work was sponsored by the Department of Transportation, Federal Aviation Administration, Aircraft Safety and Noise Abatement Division, Contract DOT-FA[illegible]. The applicable information on turboshaft engines and suppression of core engine noise is of interest in helicopter noise prediction and is discussed below.

Summary

A background review of combustor testing reported in several references shows significant differences in reported test results for the wide variety of conditions tested. There appear to be unresolved discrepancies in the correlation of acoustic power with combustion parameters for both air rig combustor noise and engine combustion noise. While the basic controlling parameters appear to be air mass flow, from which the velocities can be calculated, and the fuel/air ratio, which is related to temperature rise, there is a conflict in the relative effect of these parameters.

Measured noise results from combustor component test are shown which correlate with the first power of mass flow and the second power of the temperature rise. Two different designs of combustor, atomizing and carbureting, show a distinct difference. It is suggested that this difference may be accounted for by flame speed as indicated by Strahle and others. Unfortunately flame speed was not measured in this test program.

Suppression of combustor noise by absorption presents unique problems including 1) operation in a high-temperature environment 2) changes in absorption characteristics of acoustic liners with temperature changes, and 3) large volume resonators required to obtain low-frequency suppression. A single degree of freedom acoustic liner was tested directly downstream of the combustor. Suppression of about 10dB over a wide bandwidth clearly establishes an incentive to develop more compact suppressor designs for aircraft engines.

Engine low frequency noise (Core Engine) prediction has been deduced from an examination of several sets of engine data. Measured noise results from engine tests are correlated with the first power of mass flow, the second power of the temperature rise, and the square of the ratio of the density of the air entering the burner to a reference (ambient) density.

Summary (Cont)

In order to complete the prediction procedure, spectrum and directivity have also been prepared. These were derived by examination of data from all three types of engines and component data and represent a best fit to the data.

Comparison With Similar Papers

This paper is derived from recent work by General Electric under DOT/FAA Contract No. DOT-FA72WA-3023[13]. The emphasis here is on understanding core engine noise of larger engines. In contrast, the work of Shahady, et al[27] is concerned with small turbopropulsion engines. The resulting prediction methods from these references differ significantly.

Results shown in this paper are included in a 3 volume report of the G. E. work under DOT-FA72WA-3023. This collection includes identification of most, if not all, component noise sources, noise generation and suppression, and prediction methods for all significant noise sources from turbopropulsion engines.

Evaluation of Paper

This paper presents new information regarding the correlation and prediction of core engine noise. The discussion illustrates some of the difficulties and uncertainties of available prediction methods. Since the information here is limited the reader is referred to the final report.

[illegible], and Matta, R.K., "Core Engine Noise Control Program", Report No. [illegible]-3023, May-June 1974.

Purpose

The recently completed GE final report to the FAA (Contract DOT-FAA72WA-3023) on Core Engine Noise Control is a state-of-the-art report on the origin and evaluation of significant noise sources contributing to Core Engine Noise.

This report is intended to be a definitive, summary report including the identification, generating mechanisms, controlling variables, and prediction methods for evaluating important sources of core engine noise together with propagation effects.

Summary

The final report consists of three volumes as follows:

Volume I - Identification of Component Noise Sources

Volume II - Identification of Noise Generation and Suppression Mechanisms

Volume III - Prediction Methods

Volume I - Identification of Component Noise Sources

GE has defined core engine noise as the contribution from jet noise, combustor noise, turbine noise, interaction noise, obstruction noise, casing radiation, compressor noise, gear, bearings and pumps noise. An investigation was made to determine the generating mechanisms, controlling variables, means of identification, and the effect on engine design if reduction were required for each of eight core engine noise sources. The various sources are evaluated and rank ordered by predicting the noise contribution of the individual components by the methods derived during the course of the Core Engine Noise Control Program. The predictions are made for each of three hypothetical cycles for bypass ratio of 4, 7, and 11 respectively, which were formulated to encompass a range of commercial aircraft powerplants. It is determined that combustor noise, jet noise, turbine and turbine/jet interaction noise and obstruction noise will constitute the major noise sources, while casing radiation and compressor noise will act as secondary sources.

Volume II - Identification of Noise Generation and Suppression Mechanisms

The mechanisms of noise generation and suppression for the various core engine noise sources in turbofan engines were defined from analytical and experimental programs. Model, component, and engine test by GE over a period of several years were used to substantiate the results of analytical work to determine the basic parameters governing core engine noise generation. The results are given in general form to be applicable to a wide variety of cycles

Volume II - Identification of Noise Generation and Suppression Mechanics (Cont)

Suppression concepts were identified by analysis and experience with prior suppression studies on high velocity jet noise and fan/compressor noise research. These concepts were validated through model, component, and engine tests.

Detailed experimental results and analytical evaluation are given for the following major sources and effects:

Jet Noise

Coaxial Effects

Suppression Effects

In Flight Effects

Combustor Noise

Combustor Noise Generation

Combustor Noise Characteristics

Combustor Noise Suppression

Turbine Noise

Turbine Noise Generation

Turbine Noise Characteristics

Interaction Noise

Obstruction Noise

Casing Radiation

Compressor Noise

Volume III - Prediction Methods

Prediction methods for core engine noise are formulated for low velocity coannular jets, combustors, low pressure turbines, interaction between turbine tones stages and fan/core jet streams, obstructions in the flow passages and casing radiation. The development is based on an analytical investigation and model, component, and engine test described in Volume II. The results are in general form to be applicable to a wide variety of cycles including present and future turbofan engines. The prediction methods were validated with measured acoustic data where possible.

[illegible]

[illegible] the core nozzle jet noise prediction is conventional and is related to [illegible]. Variations with core jet temperature and hence jet density are [illegible] exponent function of the jet density. To derive the noise [illegible] coaxial system, the prediction method corrects the single jet levels by a correction factor dependent upon the area ratio of the system and the velocity ratio of the [illegible] spectral characteristics and the directivity index of the coannular jets are [illegible] modified Strouhal number.

[illegible] noise from engines has been found to correlate with air flow rate, fuel [illegible] flow and the temperature rise resulting from the combustion, and the density at the inlet to the combustor. A correlation has been devised for 1) turbojet, 2) turbofan and 3) turboshaft engines. The spectral distribution is predicted using a general spectral shape that of the [illegible] because it was found that all engine combustors produce essentially identical shapes. Directivity is predicted from normalized test data from several engines.

Three methods are shown for the prediction of turbine noise. These are: 1) a preliminary method to yield PNL at maximum angle, 2) a comprehensive prediction method to provide complete turbine noise spectrums and 3) a technique for evaluating the effects of aeromechanical configuration variations on the noise generation. The results are extensive procedures for predicting overall noise, spectra, and directivity of both turbine discrete tones and broadband noise.

The interaction of a turbine tone with the fan/core jet stream turbulence results in a drop in the peak sound pressure and spread in the signal bandwidth. This is termed "haystacking". This results in changes in turbine noise spectra shape and directivity and can affect perceived noise. Prediction means are presented to determine the reduction in peak noise and the frequency spreading. The correlation is considered a first approximation until additional data become available.

A method is presented to predict the overall power levels and one-third octave band power level spectra for acoustic radiation from struts placed in a uniform smooth flow. No means are provided to yield the directivity of these noise sources.

Under certain circumstances, casing radiation can have a measurable effect on engine noise spectrum. Casing radiation is not strictly another noise source, but is most easily treated as such using simplified prediction procedures. The procedure provides only near-field levels without directivity.

Comparison With Similar Papers

Many prior reports have discussed individual sections of the material published in this three volume report which represents the work done on core engine noise studies

Comparison With Similar Papers (Cont)

at GE over a period of several years. None of the material is essentially new, but has been revised, improved and validated with new and additional data.

The report collects, summarizes, and updates information spread through several references.

Evaluation of Paper

Working equations and curves are presented which permit prediction of core engine noise using readily available engine parameters.

It should be emphasized, however, that extensive research work continues in progress at many centers and that analytical methods are not advanced enough to provide general solutions. Updating and revision of the recommended prediction procedures will continue.

[illegible] Interim Prediction Method for Turbine Noise. [illegible]

[illegible]

[illegible] purpose of this paper is to select a turbine noise prediction method for interim [illegible] Aircraft [illegible] Program. A review concludes that state-of-the-art [illegible] methods are primitive and that the selected method is [illegible].

[illegible]

Turbine noise has been observed and measured on a variety of existing engines. However, [illegible] noise and operational data from only a few of these engines are [illegible] for meaningful attempts to correlate turbine noise levels, directivity and spectra as a function of engine geometry and operational parameters.

17

A review of the work of Smith and Bushell indicates that this first published turbine noise correlation is based on the assumption that turbine and fan noise generation are of similar origin. Two types of noise, discrete tones and broadband noise are [illegible] separately correlated. Reasonable success was achieved in correlating broadband noise, but tone noise could not be correlated.

Dunn and Peart[10] modified the formulation derived by Smith and Bushnell to give best fit with additional limited turbine noise data. Deviations of data points from predicted levels range up to [illegible] dB for the fundamental tone and ±9 dB for broadband noise.

Additional test data available at NASA Lewis Research Center on several aircraft noise compared by the correlation method of Dunn and Peart. The comparison is inconclusive and indications are that predictions would be poor for other turbofan engines.

Despite the obvious limitation of available data, the turbine noise prediction method presented by Dunn and Peart is recommended for interim use in the NASA Aircraft Noise Prediction Program. Predicted levels are in rough agreement with measured turbine noise levels from a number of turbofan engines in current use. [illegible] broadband noise and discrete tones have been related to relative tip velocity of the turbine last stage, primary mass flow and local speed of sound (temperature) at the turbine exit. Noise levels of turbine tones are modified by the additional parameter of stator rotor spacing.

Equations and figures are presented to permit prediction of far-field turbine noise level, directivity, and one third octave band spectra as a function of engine parameters.

Comparison With Other Papers

This paper reviews the work of others on turbine noise and selects what is considered to be the best available prediction scheme. The review does not include the latest work of the GE FAA Core Engine Noise Control Program[15] or Mathews and Peracchio[16]. The added results of these more recent experimental and analytical investigations should significantly improve and extend the turbine noise prediction capability.

Evaluation of Paper

Curves and figures are presented which will permit prediction of far-field turbine noise with limited confidence. As a temporary interim approach, the prediction procedures offer the advantage of simplicity and commonality. Publication of more recent work will probably result in significant changes in the prediction scheme.

[illegible], "Sources of Noise in Aero-Engines", 1st International Symposium on Air Breathing Engines ([illegible]).

[illegible]

This report presents an overall view of noise sources in air breathing engines. [illegible] sources identified are the fan and/or compressor, turbine, jet and inter- [illegible] tailpipe noise. [illegible] of the detailed analysis necessary to understand [illegible] shown as well as the types of experimentation which must be [illegible] to separate noise generation mechanisms. Studies have revealed that tail- [illegible] noise becomes significant as other sources are reduced by design or [illegible].

[illegible]

Fan noise has become the dominant aero-engine noise source with the move to high bypass ratio engines, but important sources including tailpipe (core engine) noise are becoming apparent. A vast amount of work has been done which shows that fan noise [illegible] multiple pure tones from interaction of the rotor pressure field with outlet guide vanes which, together with non-uniformity of rotor blades, propagates [illegible] tones. Multiple pure tones also arise from shock waves at the leading edge with supersonic tip speed and these are also compounded by non-uniformities in stagger and pitch. This is of interest in helicopter noise only to the extent of similarity among compressor, turbine, and fan noise.

The main difficulty in assessing turbine sources from engine measurements has been the separation of this noise component from other sources such as fan and compressor. [illegible] show that on the perceived noise level scale, the present standard of suppressed fan and turbine noise for the R. B. 211 are of about equal intensity at approach power. Efforts to separate and identify possible tailpipe sources suggest flow separation of the exhaust unit struts and/or exit swirl from the turbine.

Comparison With Similar Papers

Core engine noise is revealed as an important source of engine noise in this paper. This work [illegible] summarizes much of the prior work on fan noise previously published and [illegible] needs for further exploration of noise generation mechanisms. Many of these sources have since been explored in detail and are more specifically described in other reports.

Evaluation of Paper

This paper is of interest only as a historical review of major noise sources in turbofan engines. None of the material can be used directly in predicting helicopter noise.

Mathews, D. C. and Rekos, N. A., "Progress in Core Engine and Turbine Noise Technology", AIAA Paper No. 74-948, August 1974.

Purpose

This paper surveys the present (1974) state-of-the-art in both core engine and turbine noise technology. The characteristics of both low frequency core noise and high frequency turbine noise are reviewed and several possible noise generating mechanisms are indicated. Results of a test program using a JT3D turbofan engine are described which show the effect of major noise sources and propagation effects. Noise control of sources and the need for further research is discussed.

Summary

Core engine noise is that generated by a variety of components inside the engine gas generator and exhaust system, including combustors, turbines, and flow obstructions. For the purposes of this paper, core engine noise is defined as the low frequency noise (less than 1000 Hz) that remains when predicted jet noise is subtracted from measured engine spectra. Probable sources are:

1. Direct noise from the burner resulting from pressure fluctuations during combustion.

2. Indirect burner noise from velocity and temperature fluctuations interacting with the turbine.

3. Noise due to turbulence and swirl in the exhaust.

4. Noise generated at the nozzle lip by interaction with flow turbulence.

Direct combustion noise is caused by the time unsteady heat release of the combustion process. The combustor airflow is highly turbulent and the fuel spray consists of random size droplets. Observed pressure fluctuations indicate a noise source which may propagate through the downstream engine components to the far-field. Quantitative estimates of direct combustion noise have been difficult to obtain, but this source must be considered potentially significant.

Indirect combustion noise caused by the convection of burner generated turbulence and temperature fluctuations has been analyzed in several recent theoretical studies. Pickett[15] has shown that these fluctuations interact with a mean pressure gradient such as exists across a turbine stage or exhaust nozzle to produce propagating acoustic waves. Predicted spectra and power levels agree with data suggesting that this is a possible major noise source.

Summary (Cont)

Strut noise is caused by flow impingement and flow separation from struts and other object in the exhaust stream. Experimental studies show this noise varies with the sixth power of the exit velocity and may be dipole in nature. Quantitative procedures are not available for predicting the noise generated by separated struts in a duct.

Strut noise may also be generated by fluctuating lift forces induced by turbulence. There appears to be no verified technique for predicting noise by an arbitrarily shaped body in turbulent flow within a duct.

Nozzle lip noise is generally thought to be caused by the convection of exhaust turbulence past a nozzle lip which imparts momentum fluctuations to the fluid near the lip. Several theoretical and experimental studies have suggested lip noise intensity varies with the sixth power of jet velocity. Cross-correlation studies have verified that this type of noise produces significant contribution in the far-field.

Far-field noise depends not only on the strength of noise sources, but also on propagation through turbine blade and vane rows and through the nozzle. It is unlikely that transmission problem will be solved rigorously because of the complexity of geometry and flow in the core engine. Studies have determined that primary variables are the mode order of the incident wave, the wave number, duct flow velocity and temperature. The structure of the shear layer between the jet and surrounding fluid is also important as is evidenced by a difference in noise between single and co-axial exhaust flow configurations.

Because of the complexity of the core engine sources and the torturous propagation path, several prediction methods have been proposed empirically relating core noise to overall engine cycle parameters. These predictions may not apply to all engines because of significant differences in component and installation geometries. A review of several prediction schemes shows that these should be considered to be preliminary and further work is needed.

Some preliminary results from extensive tests of a JT3D engine are shown. A low frequency peak centered at 400 Hz protruding above the predicted jet noise spectra is identified as core engine noise. The general spectrum of JT3D core noise is depicted, as inferred from many spectra at various angles and engine speeds. Cross-correlation techniques were used to confirm that low frequency internally generated noise contributed to the far-field spectrum, which peaks at about 400 Hz. The measured turbine stage velocities and pressure drops, together with the rms temperature fluctuations and the characteristic length scale of hot spots were inputted into an indirect combustion noise theory. Predicted power levels were in good agreement with experimental data. Predicted spectra peak at 400 Hz, as did the experimental data.

Summary (Cont)

Peak polar overall sound pressure levels (60-1000 Hz) are shown to correlate well with primary jet velocity. Calculated core engine noise levels increase with velocity to approximately the [illegible] power. The directivity characteristics of core engine noise for the JT3D are shown. No noticeable changes in directivity were observed with variations in engine operating conditions.

When the core engine exhaust flow was surrounded by the co-axial fan stream, a reduction of 1 to 4 dB was seen at an angle of 120° from the engine inlet. This suggests that nozzle exit impedance conditions are affected by the external flow field. Attempts to determine the contribution of lip noise using the trailing edge noise analysis of Hayden[29], were unsuccessful, although the predicted spectra peak at a frequency of 400 Hz. Establishing the significance of lip noise will require additional work.

Turbine noise is dominated by turbine tones with broadband "haystacking" that occurs in the region of the tones. Turbine tones are generated by interactions of rotor wakes with downstream stators and interactions of stator wakes with downstream rotors. Other sources of discrete turbine tones may include the effects of non-uniform inflow from burner generated "hot spots" and turbulence. Factors affecting turbine tone intensity include rotor speed, stage work, size, turbulence intensity, stream density, number of stages, and rotor/stator spacing.

Recent evidence suggest that "haystacking", the broadband noise from turbines, is not internally generated, but is related to the propagation of turbine tones through the turbulent exhaust flow. Growing evidence shows that "haystacking" can be attributed to scattering of turbine tones by turbulence in the exhaust flow of both the core engine and fan streams.

Several current prediction schemes are in use which are based primarily on empirical correlations of test data. The procedures follow those developed for fans and compressors. Pratt & Whitney has developed a prediction system by correlating data from JT9D, JT8D and JT3D engine. Significant noise reduction is possible both by modification of the source and by using acoustic treatment in the primary tailpipe. The latter is both heavy and expensive because of the extreme environment.

Measured far-field turbine noise spectra from JT3D tests were examined and a comparison to predictions from the Pratt & Whitney procedures show good correlation. The correlation includes the effects of a significant contribution of the turbine work parameter.

Observed differences in turbine noise spectra are believed related to differences in the exhaust flows which the turbine noise propagates through. When no turbulent shear layer is present, the turbine tone is higher and the broadband "haystacking" is

Summary (Cont)

less pronounced than in spectra obtained with a coplanar fan stream. The tone energy is scattered and redistributed to adjacent frequencies by the added turbulence in the fan shear layer.

Comparison With Similar Papers

This paper is derived from various experimental core engine and turbine noise programs, including a recently completed extensive noise test program on a Pratt & Whitney JT3D engine. Though similar in content and conclusions to other prior work, additional information and understanding is presented. The importance of the indirect combustion noise as a possible noise source is emphasized and the effect of the propagation path for both core noise and turbine noise have been demonstrated with increased detail. From the survey presented here of prior core noise and turbine noise tecanology, together with results and conclusions presented in this paper, it is clear that more work is required to verify and extend the range of present prediction procedures.

Evaluation of Paper

This is a valuable summary of much of the work being done on core engine noise by Pratt & Whitney. Only limited results are available, however, and neither the core engine noise nor turbine noise can be predicted with the published results. Moreoever, the emphasis is on engine noise of larger turbofan engines and results have yet to be compared over a range of engine sizes and types.

Master, D. [illegible] "[illegible] Prediction From Engine and Drive Train", [illegible]

Purpose

The purpose of this paper is to characterize some of the possible sources of vibration within reciprocating, internal combustion engines that may contribute to the noise observed when exhaust and intake have been adequately muffled.

Summary

The acoustic power radiated by a reciprocating internal combustion engine can be assumed to be proportional to the surface radiation efficiency, structure area, and the vibration within the structure. Principal sources of vibration, in descending order of importance, are the combustion process, piston slap, gear meshing and fuel injection. Noise is radiated by elastic deformation of the structure. Observed frequency dependence suggests that the radiation may be characterized as a dipole source due to bending of the structure.

Combustion noise is related to thermal efficiency of the engine. The most accepted method of reduction is to reduce operating speed. Piston slap noise is produced by the transverse impacts that occur between piston and cylinder. Gear meshing noise is most evident at frequencies related to the gear tooth contact frequency and is most sensitive to load changes and the precise shape of the gear profile. Fuel injection noise is due primarily to pressure fluctuation within the fuel pump and vibration within the injector.

For a wide variety of diesel engines, the noise generated by combustion is related to operating speed and cylinder diameter. An equation and constants are given to predict A-weighted decibels 3 feet from the machine for several classes of engines.

The noise produced by piston slap can be estimated from an expression for the ratio of the acoustical to vibratory power. Inputs must be determined from the physical characteristics of the radiating structure and the vibratory power from piston slap.

The noise produced by piston slap can be estimated from an expression for the ratio of the acoustical to vibratory power. Inputs must be determined from the physical characteristics of the radiating structure and the vibratory power from piston slap.

The noise radiated by an automotive gearbox exited by gear meshing can be estimated using simple equation which provide level and spectral distribution. Predicted levels are related to transmitted horsepower and gear speed.

Summary (Cont)

It is concluded that noise reduction by either reducing radiation efficiency or the magnitude of the vibration forces requires an understanding of the mechanisms of the source and a knowledge of the engine design parameters.

Evaluation of Paper

This is a brief overview of sources of noise in reciprocating internal combustion engines. Prediction methods are indicative, but too limited to predict noise levels from helicopters using internal combustion engines.

Pickett, G. F., "[illegible] Turbulence and Temperature Fluctuations", Eighth International Congress on Acoustics, July, 1974.

Purpose

In this paper an analysis is presented which shows that significant low frequency noise can be generated by the passage of velocity and temperature "eddies" through large pressure gradients such as exist across turbine blade and vane rows. Results from this analysis, using measured temperature fluctuations from a Pratt & Whitney JT3D engine, are compared with measured low frequency core noise data.

Summary

Various mechanisms have been proposed to explain the observed low frequency noise of turbofan engines which cannot be accounted for by jet noise alone. It is reasonable to expect that noise sources exist upstream of the nozzle which are produced by unsteady flow velocities interacting with blades, vanes, struts and nozzle exit. An additional mechanism involves the large fluctuations in temperature and axial velocity produced by the burner passing through successive turbine stages.

The general analysis presented by Pickett includes noise generation due to fluctuating lift and drag forces at the vane or blade row in addition to the noise generated by vorticity (turbulence) and entropy (temperature) convecting through the disc. The contribution due to convecting temperature is considered in detail. The method considers small unsteady perturbations of the mean flow through an "actuator disc" that represents either a turbine rotor or nozzle guide vane stage. The analysis also accounts for the large changes in mean stream flow variables that are a design feature of turbine stages and a factor in the noise generating mechanism. It is shown that noise levels due to temperature fluctuations are dependent on the rms intensity and transverse correlation length scales of the fluctuations in addition to steady turbine operating parameters. Furthermore, the peak intensity occurs at a frequency dependent on the axial correlation length scale of the temperature fluctuations.

Predicted values of generated noise are compared to measured JT3D low frequency noise. Measured values of the various turbine stage velocities and pressure drops were inputted together with the rms temperature fluctuations and the characteristic length scales of the hot spots (obtained from cross-correlation of adjacent quick-response thermocouples). Predicted power levels of noise were found to be in good agreement with measured noise. Also, the predicted spectra, largely a function of the axial hot-spot length scales and axial convection velocity, peak at 400 Hz as does the measured noise.

Because the predicted and measured noise levels are in reasonable agreement, it is deduced that core engine noise can be accounted for by the temperature fluctuations convecting through the turbine.

Comparison With Similar Papers

The possibility that a time varying temperature were traveling through a velocity gradient is another source of sound (entropy noise) has received little attention in the literature. Strahle[14] discussed entropy noise but made no evaluation of its contribution to core engine noise. Several recent theoretical approaches[30, 31] have studied noise generation by convection of "hot spots" through a mean pressure gradient. The analysis by Pickett considers both vorticity and entropy fluctuations. The application of Pickett's analysis is perhaps the first attempt to quantify the entropy noise. Predicted spectra and power levels from measured parameters compare well with measured data, indicating another noise source to be included in core engine noise prediction procedures. No attempt has been made to establish the level of entropy noise relative to the more generally accepted direct burner noise from the combustion process.

Evaluation of Paper

This paper presents an analysis and means of predicting the level and spectra of entropy noise in the core engine. However it is unlikely that the procedure can soon be integrated as a separate component source in usable prediction methods. The complex input parameters required to evaluate the entropy noise are not generally available and results have not been demonstrated to be universally applicable.

[illegible], P.A., [illegible], and Hildenbrand, R.W., "Reduction of Noise from Small Turbopropulsion Engines", AIAA Paper No. 74-59, Presented at the AIAA 12th Aerospace Sciences Meeting, January 1974.

Purpose

This report is a summary of the work described in detail in Air Force Aero Propulsion Laboratory Technical Report AFAPL-TR-73-79[5]. The objective of the work was the development of the technology base necessary to reduce the noise signature of small turboprop and turbofan engines to minimize their detectability in low altitude reconnaissance surveillance military missions. The program summarized was rather extensive and included 1) development of prediction methods for all the sources of small turboprop (turboshaft) and turbofan engines, 2) development of a duct acoustic treatment design method, 3) tests of materials suitable for acoustic duct liners, 4) acoustic tests of an unsuppressed turbofan (the AiResearch TFE 731-2) and an unsuppressed turboprop engine (the AiResearch TPE 331-5-251) including comparison with predicted spectra, 5) acoustic tests of various inlet mufflers and exhaust duct treatment, and 6) an analysis of performance and weight penalties for noise suppression. The work on turboshaft engines and their suppression is of interest in helicopter noise prediction and will be discussed below.

Summary

Fan and compressor noise prediction methods are based on work reported by Smith and House[13] with modifications to improve correlation with turboprop engine data and allow prediction of centrifugal compressor noise.

Jet noise above 1000 ft./sec. exhaust velocities is predicted by the SAE jet noise method[12] plus empirical directivity curves. At exhaust velocities below 1000 ft./sec. the paper states that predictions are based on Bushell's method[3]. In this exhaust velocity region, the noise is generated internal to the engine and is called core engine noise. The only core engine noise source predicted explicitly in the paper is combustor noise. It is stated that combustion noise is one of the most significant core engine noise sources for small turbofan and turboprop engines. The combustion noise is predicted to be a function of temperature rise in the combustor, combustor discharge velocity, combustor diameter, fuel and air weight flow, and a reference acoustical power output at the combustor exit.

Since a gearbox is required to provide the torque at the proper rpm to drive a propeller or rotor, the paper considers gearbox noise as part of the engine. The reader is directed to the next section of this Appendix for a discussion of the gear noise prediction method described.

Summary (Cont)

Auxiliary equipment noise, such as fuel and lubrication pumps mounted on the outer case of the engine, are of interest for very quiet systems such as reconnaissance surveillance propulsion systems. They are probably unimportant as a far-field noise source in transport helicopters. The paper states that very little work has been done on these sources, but it does include a prediction method for a fuel injection pump based on Prandle's work[32].

Casing noise is that which is transmitted to the far field through the walls surrounding the engine components. An empirical prediction procedure for sound power radiated is presented for turboprop engines which is a function of mechanical horsepower generated by the engine.

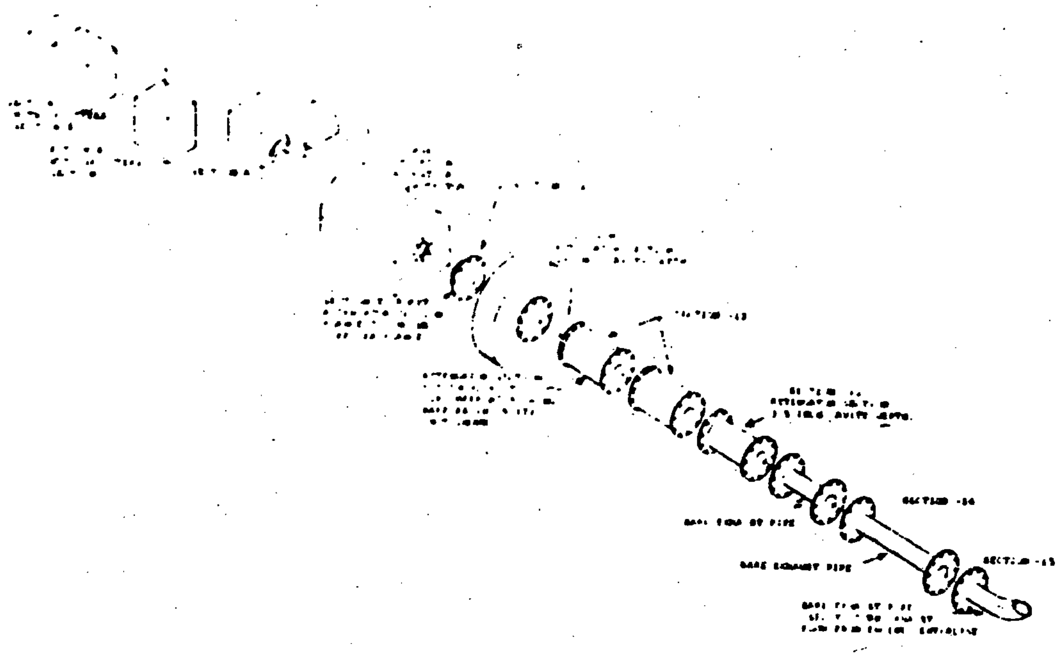
Three acoustic duct lining design procedures are described briefly in the report with greater information available in AFAPL-TR-73-79. The first method based on the work of Cremer and Nelson is analytical in nature, but uses an empirical impedance model for materials used in the liner design. The second method is only mentioned briefly and it is stated that it is a self-optimizing method based on simultaneous solution of the governing differential equations and that it avoided some of the simplifying assumptions of the first method. A single comparison of a liner design is presented which shows that the two methods give significantly different results. The third method is empirical and is based on generalization of the results of many tests of duct liner configurations.

General results of acoustic materials tests are presented for zero flow, room temperature conditions. Sample results of interest are: 1) addition of acoustic absorbing materials behind perforated face sheets increases absorption coefficient and acoustic resistance, 2) little is gained in using sound absorbing material behind fibermetal since air cavities tuned to the design frequency provide significant noise attenuation over several octave bands, 3) bulk absorbers show only a slight frequency dependence on material thickness and absorb sound across a wide range of frequencies.

Acoustic tests of an AiResearch TPE 331-5-251, 840 SHP turboprop engine were conducted while the engine was driving a quiet dynamometer. Unsuppressed tests were conducted to establish comparisons between predicted and measured noise spectra. The report indicates that good correlation was achieved. The engine was then tested with modular inlet, casing and exhaust supression systems as shown in the figure on the next page.

Casing suppression results are not indicated in the report. Inlet suppressor tests showed splitters in large or small inlet duct sections provided little additional attenuation, but marked by increased performance losses. Therefore, the best inlet suppressor consisted of a relatively simple large plenum designed with no direct line of sight transmission path.

Summary (Cont)



EXPLODED VIEW OF ATTENUATION ASSEMBLIES
USED WITH THE TPE331 ENGINE

The exhaust attenuator concept selected for the testing reported utilizes two principal techniques to reduce low frequency noise: 1) a length of tailpipe which will shift the fundamental resonance of the tailpipe to a frequency where the ambient background noise is higher and therefore masks the engine noise and 2) a multi-tube design to convert low frequency noise (large wavelengths) to high frequency noise (small wavelengths) which can readily be absorbed. Twelve exhaust duct configurations were tested. Of particular significance was the test which showed that doubling the length of treatment does not double the attenuation. This has been found by other researchers. With the optimum suppression system, more than 30 dB reduction was obtained in the inlet quadrant at frequencies of 1000 Hz and above. In the exhaust quadrant, attenuation of more than 15 dB at frequencies of 1000 Hz and above was achieved.

The final item addressed in the paper is the effect of inlet and exhaust suppression equipment on performance and weight. As expected, the trends presented show suppressor duct weight rising rapidly as frequency of suppressor peak attenuation falls below 1000 Hz. This is due to the required depth (thickness) of the treatment. The

Summary (Cont)

measured pressure loss associated with various exhaust ducts is compared with calculations. Some disagreement between calculation and test is indicated. A maximum of 1% loss in horsepower at the full load high flow condition is indicated.

Comparison With Similar Papers

This paper is derived from a six volume report called "Small Turbine Engine Noise Reduction," Air Force Report AFAPL-TR-73-79 which was written by several authors from AiResearch Manufacturing Company in 1973. Also, a paper titled "Progress in the Development of Optimally Quiet Turboprop Engines and Installations," SAE Paper 730287, April 1973, by R. M. Tedrick and R. W. Hildenbrand was derived from the six volume report. The Shahady, et al paper is a very good summary of the work reported in AFAPL-TR-73-79. While AFAPL-TR-73-79 includes the computer programs developed to predict engine noise and design duct treatment in addition to a greater emphasis on turbofan noise, the Shahady, et al paper provides a better overview of the accomplishments of the program reported in AFAPL-TR-73-79. Other reports emphasizing acoustic testing and development of prediction methods for small turboshaft engines do not exist. The recent work by General Electric under DOT/FAA Contract No. DOT/FA72WA-3023[13] does include investigation of similar sources in great experimental depth, but the emphasis is on understanding turbofan core engine noise of larger engines.

Evaluation of Paper

This is a very valuable summary of the six volume AFAPL report for a researcher. General trends in turboshaft engine noise will not be found. Also actual calculations cannot be done with the limited information reported. These require use of AFAPL-TR-73-79.

Fedrick, R. N., and Hildenbrand, R. W., "Progress in the Development of Optimally Quiet Turboprop Engines and Installation," SAE Paper No. 730287, Presented at the Business Aircraft Meeting, April 3-6, 1973.

Purpose

This report summarizes the turboshaft engine noise evaluation work reported at a later date in more detail in Air Force Aero Propulsion Laboratory Technical Report AFAPL-TR-73-79. The purpose of the paper was to summarize the turboshaft engine information prior to release of the final Aero Propulsion Laboratory Report in a way that would be useful to manufacturers of business aircraft.

Summary

The following summary is limited in scope as more information will be found in the AIAA paper by Shahady, et al[27] or the Aero Propulsion Laboratory Report[5] which are reviewed elsewhere in this Appendix.

Comparison With Similar Papers

This paper is limited in scope compared with the AIAA paper by Shahady, et al. Also the prediction procedures for engine noise and duct liner design which are found in AFAPL-TR-73-79 are not included in this paper.

Evaluation of Paper

It is suggested that the reader interested in the summary or the results of the Small Turbine Engine Noise Reduction contract conducted by AiResearch Manufacturing Company for the Air Force Aero Propulsion Laboratory refer to the AIAA paper by Shahady, et al or the Executive Summary, Volume I, of AFAPL-TR-73-79 as both of these reports are more complete than the report reviewed here.

Thiem, G.E., "Noise From Diesel Engines", Inter-Noise 73, August 1973.

Purpose

This paper discusses some results of experimental vibration and noise measurements on diesel engines. Vibration isolation of external engine parts, stiffening, and sound reducing shells are shown to be effective means of reducing noise.

Summary

In nearly all modern diesel combustion systems the combustion pressure is the strongest exciting force for structure - borne and radiated noise. Noise reduction by improvement in mechanical exitation sources is limited to 2-4 dB(A) for technical and economic reasons. It is necessary to improve the structure so that less vibration reaches the outer walls to be radiated as noise.

All parts of the external engine surface contribute to the external noise. Seldom does one part contribute as much as half the noise. Nearly all parts must be treated to achieve improvement of 4 to 5 dB(A).

Noise near the oil pan can be reduced by as much as 11 dB(A) by careful isolation. Stiffening of external wall can reduce local levels of noise by as much as 10 dB(A) in single third octave bands. The most effective means of noise reduction are thin sound reducing shells of low bending resistance and high critical frequency. Reductions of 19 dB(A) were measured with plain sheet steel and it was found that mounting is more important than damping. Sound absorbent material in the clearance between shell and case wall had little effect. Measured levels of engine noise were reduced 19 to 21 dB(A) using a total enclosure with vibration isolating attachments.

The best design solution for reducing noise appears to be a new design with central support engine structure surrounded by a vibration isolated housing, "which forms a kind of wet enclosure".

Evaluation of Paper

This may be of interest in predicting the case radiated noise reduction which can be achieved with relatively simple enclosures. No means of predicting sources noise levels are contained in this report.

Gear Noise Capsule Summaries

Badgley, R. H., and Hartman, R. M., "Gearbox Noise Reduction: Prediction and Measurement of Mesh-Frequency Vibrations Within an Operating Helicopter Rotor Drive Gearbox", ASME Paper No. 73-DET-31, September 1973.

Purpose

The purpose of this study was to verify the accuracy of analytical methods for predicting the vibration and noise generation of gearboxes by determining correlation between predicted and measured data.

Summary

This study was performed on a CH-47 main rotor drive gearbox. However, the analysis is applicable to gearboxes of all kinds. The paper presents a good description of the several analyses required to make the prediction of total noise and vibration emission at gear clash frequencies. Also, the correlation between predicted and measured response of several parts of the dynamic gearing system is presented. The list of references covers the work sponsored by USAAMRDL over the past few years in developing analysis and noise reduction techniques for transmission noise.

Comparison With Similar Papers

This is an extension of the work performed by Badgley and Laskin[3], Laskin, et al[1], and Sternfeld, et al[5].

Evaluation of Paper

This report shows that an application of detailed dynamic analysis to a transmission can identify near resonant conditions for components. This study shows examples of this and also shows the results of corrective measures which yielded noise and vibration reduction. The analysis is lengthy, but necessary to locate possible vibration/noise problems in the prehardware stage. It considers dynamic system torsion and bending plus casing response.

Badgley, R.H., and Laskin, I., "Program for Helicopter Gearbox Noise Prediction and Reduction", USAAVLABS Technical Report 70-12, March 1970.

Purpose

The work described in this report was done to demonstrate the application of analytical tools to the CH-47 power train to predict noise levels. Actual CH-47 transmission noise levels were measured for comparison. CH-47 transmission casing vibratory response was measured. The sensitivity of noise level predictions to several transmission design parameters was determined and investigation of tooth profile modification as a means of attaining reduced transmission noise was explored.

Summary

This work shows the ability of the previously developed analyses to predict differences in transmission noise radiation via modifications to reduce torsional excitation and gear tooth dynamic force levels.

Comparison With Similar Papers

This is a follow-on to the work performed by Laskin, et al[1].

Evaluation of Paper

This a slightly refined analysis compared to that of Reference 1. However, it still does not treat the lateral bending dynamic response of transmission components. It appears to predict the spectrum shape of noise and vibration, at least to the extent that some clash levels are higher than others, using torsional vibration of the system with some empirical conversions.

Barlow, W.H., McClusky, W.C. and Ferris, H.W., "OH-6A Phase II Quiet Helicopter Program", USAAMRDL Technical Report 72-29, September 1972.

Purpose

This study was conducted to reduce detectability of the OH-6A Helicopter by reducing externally radiated noise.

Summary

This report presents external noise narrow band spectra showing the presence of main and tail rotor gearbox clash noise for the quiet version, where this gear noise is not masked by rotor and engine noise. It shows gearbox noise levels of 59, 55 and 54 dB at 150 feet in hover for the tail rotor gearbox, second stage of the main gearbox, and the necessary drive section of the main gearbox, respectively.

Comparison With Similar Papers

The work described was performed as part of the same general effort as that undertaken by Bowes[7].

Evaluation of Paper

This is one of the few reports available showing the presence of far-field gear clash noise from a helicopter. Gear noise was unmasked by reducing rotor and engine noise. It provides useful data for estimating far-field radiated gear noise.

Bowes, M.A., "Test and Evaluation of a Quiet Helicopter Congiruation HH-43B", USAAMRDL Technical Report 71-31, January 1972.

Purpose

The purpose of this effort was to reduce detectability of the HH-43B helicopter by reducing externally radiated noise emanating from the main rotors, core engine, and gearboxes.

Summary

This report presents external noise narrow-band spectra showing the presence of main transmission gear clash noise. Levels at 200 feet in 10 foot hover were 74 and 64 dB for the input bevel and planetary system clash, respectively. Changes to the transmission resulted in reductions of 10 and 8 dB for the two clash peaks. Transmission noise reduction measures incorporated were: installation of a selected gear set exhibiting good wear patterns and minimum tolerances, plating of the teeth with lead indium, use of high viscosity oil, misphasing of left and right hand rotor drive gears, elastomeric isolation of planetary ring gears, removal of some auxiliary components, and partial sound proofing of the transmission.

Comparison With Similar Papers

This work was performed as part of the same general effort as described in Barlow, et al[8] and Pegg, et al[9].

Evaluation of Paper

This is one of the few reports available which shows the presence of far-field gear clash noise from a helicopter. Gear noise measurement was made possible by reducing noise from other sources (rotors, engine) which normally masks it. It contains useful data for estimating far-field radiated gear noise.

Grande, E., et al, Small Turbine Engine Noise Reduction, Volume II, Noise Prediction Methods", Air Force Aero Propulsion Laboratory Technical Report AFAPL-TR-73-79, Volume II, December 1973.

Purpose

The section of concern here (Section II - Part 5, Gear and Mechanically Radiated Noise) reviews the literature in gearing noise prediction and generates a basic noise prediction method via charts.

Summary

Gearing noise prediction is discussed in detail from excitation through mechanical radiation. The various parameters involved with excitation, including unbalance, tooth impact, friction, and pocketing, are described and analyzed. It is determined that tooth impact is the dominant mechanism for externally radiated gear noise which occurs at meshing frequency.

Tooth impact excitation is caused by imperfect meshing of involute gear teeth. This imperfect meshing is caused by inaccuracies in both tooth spacing and profile, by deflections of the teeth caused by loads, and by movement of the pitch circles of the gears due to shaft, bearing, and casing deflection.

Tooth impact causes mesh frequency vibration to be introduced into the system. This vibration is transmitted mechanically through the system to points where it is dissipated through damping or acoustic radiation.

The details of tooth impact excitation are discussed and dependence on operating, design, and quality control parameters are identified.

A prediction method is offered to account for as many of the pertinent excitation, transmission, and radiation parameters as are identified in the cited literature. These include, in part, power transmitted, tooth loading, pitch line velocity, tooth profile error, tooth profile roughness, tooth spacing error, tooth alignment error, pitch, contact ratio approach and recess angle, pressure angle, helix angle, tooth face width, backlash, phasing, housing response, bearing type, installation and lubrication.

The authors conclude that "the wide variation in gear system construction makes accurate prediction of the gear noise spectrum an impossible task, at least with the present level of knowledge of gear noise generation and radiation." It appears that the best available methods for gear noise prediction constitute only a rough cut at the final spectrum. It is claimed that the levels of the dominant meshing frequencies can be predicted within 2 dB, which is highly questionable based on the known variability of casing and related surface radiation properties.

Comparison With Similar Papers

This report reviews the detailed gearing noise prediction methods of References 1, 2, 3, 4, 5 and others and concludes that they are of limited usefulness.

Evaluation of Paper

This is an excellent summary of gearing noise prediction methods including those that require considerable detailed knowledge of the transmission design and those which are more practical and more easily used. The prediction method proposed is applicable to a wide range of gearing types, sizes and quality. Helicopter transmissions occupy only a small portion of the range of variables covered.

Hartman, R. and Badgley, R., "Model 301 HLH/ATC Transmission Noise Reduction Program", USAAVLABS Technical Report (Contract DAAJ01-C-0810), January 1973.

Purpose

This study was conducted to reduce Heavy Lift Helicopter transmission noise by identifying problem areas analytically and making design changes to reduce clash frequency vibration and noise.

Summary

Dynamic testing was performed on a CH-47C helicopter transmission with internal instrumentation to measure strains, accelerations, and displacements of rotating components, and external instrumentation to measure case acceleration and noise. Test results were used to verify prediction methodology which, in turn, was used to analyze the dynamic response of the HLH transmission components.

Comparison With Similar Papers

This is a follow-on to work reported by Laskin, et al[1], Badgley and Hartman[2], and Badgley and Laskin[3].

Evaluation of Paper

This report provides some of the most detailed analysis of transmission clash frequency dynamics to-date. However, details of the computation methods used for system coupling (except for torsional) and casing response are not included. It provides good tracking of the flow of clash frequency energy from the source to ultimate points of radiation.

Laskin, I., Orcutt, F. K. and Shipley, E. E., "Analysis of Noise Generated by UH-1 Helicopter Transmission", USAAVLABS Technical Report 68-41, June 1968.

Purpose

The purpose was to develop effective technology for the computation of helicopter gearbox operating noise and to apply the derived technology to an analysis and evaluation of the UH-1 helicopter main transmission.

Summary

In this report, two basic programs which were developed for the prediction of gearbox noise at clash frequencies are described. The first program consists of a torsional (Holzer) analysis of the system taking the compliance of mating gears into account. The second program determines the excitation introduced into the system at the various meshing points based on the geometry of the system, including the various types of error occuring in aircraft quality gears. Noise is determined empirically, equating clash frequency torque oscillations with noise generated.

Comparison With Similar Papers

This study forms the basis for the analysis of gearbox noise carried out in several follow-on programs including those reported by Badgley and Hartman[2], Badgley and Laskin[3], and Sternfeld, et al[5].

Evaluation of Paper

The work required to predict transmission noise is prohibitive, considering the poor results attained in forecasting absolute levels. However, the technique, if it can be made to work, is helpful in identifying possible torsional resonances at up to clash frequencies. The complete lack of consideration of lateral bending of components and dynamic component mounting impedances eliminates one very important part of the overall problem from any consideration.

Pegg, R. J., Henderson, H. R. and Hilton, D. A., "Results of the Flight Noise Measurement Program Using A Standard and Modified SH-3A Helicopter", NASA Technical Note D-7330, December 1973.

Purpose

This Technical Note reports the noise characteristics of a standard SH-3A helicopter and a version modified for lower noise generation.

Summary

This report presents hover external noise narrow band spectra showing tail rotor gearbox noise level of 55 dB at 750 Hz and at a lateral distance of [illegible] feet and 270 degrees azimuth at 10 foot hover. Power to the gearbox is approximately [illegible] horsepower at this condition.

Comparison With Similar Papers

This work was performed as part of the same general effort as reported in References 7 and 8.

Evaluation of Paper

This report contains far-field test rotor gearbox noise useful for estimating purposes.

Schlegel, R. G. and Mard, K. G., "Transmission Noise Control - Approaches in Helicopter Design", ASME Paper 67-DE-58, May 1967.

Purpose

This effort was conducted to define a number of methods which may be employed to reduce the level of clash frequency noise generated by transmissions.

Summary

This report provides design criteria for several schemes proven to be useful in reducing transmission noise emission in helicopter and other transmissions. Tables describe the degree of noise reduction available through the employment of each of these measures.

Comparison With Similar Papers

This report covers a broad spectrum of possible gear noise reduction measures, some of which are treated in more detail in other reports.

Evaluation of Paper

General guidelines are presented for low noise gear design. The only specific technique detailed is that of phasing planetary system gear clash for cancellation in the ring and sun gears.

Sternfeld, H., Schairer, J. and Spencer, R., "An Investigation of Helicopter Transmission Noise Reduction by Vibration Absorbers and Damping", USAAMRDL Technical Report 72-34, August 1972.

Purpose

The purpose of this study was to determine the transmission noise reduction potential of dynamic gear vibration absorbers and gear damping by testing in a helicopter transmission.

Summary

Noise reductions attained were as high as 5 dB for some of the schemes tested. However, these reductions were local in nearly all cases, resulting in little or no change in the total noise and vibration output of the transmission system. Further studies are called for to identify the reasons for this result in terms of casing response.

Comparison With Similar Papers

This is an application of the gear noise analysis techniques of References 1 and 3 to reduction of clash frequency and noise.

Evaluation of Paper

The report shows that some noise reductions are attainable via energy absorbing systems. However, the relatively small reductions achieved indicate that the total dynamic system behavior must be better understood if significant reductions in net noise radiation are to be achieved via the techniques evaluated.

Adcock, B. D. and Ollerhead, J. B., "Effective Perceived Noise Level Evaluated for STOL and Other Aircraft Sounds", FAA-NO-70-5, May 1970.

Purpose

The author's intention was to determine the ability of the Effective Perceived Noise Level (EPNL) and other scales to predict the responses of subjects to the sounds of a variety of aircraft, including those powered by turbofan, turbojet, piston and turboprop propulsion systems.

Summary

Testing indicated that the differences between the various rating scales are typically of the same order as the experimental error incurred in performing the tests. It is suggested that future effort be directed to explaining the deficiencies of the various rating systems which cause them to yield substantial differences between the rated and judged noisiness of the various classes of aircraft.

Comparison With Similar Papers

The conclusions generally agree with others (e.g., References 1, 2, 5, 6 and 11) that dBA is a reasonable compromise unit for quantifying helicopter noise annoyance.

Evaluation of Paper

The most significant result from this study is that all of the rating schemes tested attained similar standard deviations about their regression lines, indicating similar accuracy for forecasting the subjective annoyance of the STOL and CTOL sounds tested. The rating scales evaluated were: PNL, PNLT, LL(S), LL(Z), SPL(A), SPL(B), SPL(C), SPL(D), and CASPL. Hence, for turbofan, turbojet, and propeller driven STOL aircraft, any of the above ratings is equally good (or bad) at predicting subjective reaction from the community.

Anonymous, "Impact Characterization of Noise Including Implications of Identifying and Achieving Levels of Cumulative Noise Exposure", Environmental Protection Agency Aircraft Airport Noise Study Report NTID 73.4, July 27, 1973.

Purpose

The purpose of this noise study was to determine the merits and shortcomings of methods to characterize the impact of noise of present or proposed airport/aircraft operations on the public health and welfare, determine which method is most suitable for adoption by the Federal Government, and determine the implications of issuing Federal regulations establishing a standard method for characterizing the noise from aircraft airport operations and of specifying maximum permissible levels for the protection of the public health and welfare.

Summary

This report proposes the use of L_{dn} for the objective evaluation of environmental noise. It recommends a level of $L_{dn} = 60$ as realistic and acceptable for control of hearing loss, speech communication, annoyance and general health. It recommends lowering of the allowable level by from 2 to 5 dB for environments where pure tones are known to be present. The constituents of L_{dn} are given, including a single event parameter called Sound Exposure Level which is applicable to a single aircraft passage.

Comparison With Similar Papers

This document forms a strong, well supported case for the use of the recommended community noise criteria. It forms the basis for the studies reported by Hinterkeuser and Sternfeld[10] and Munch and King[11] which were aimed specifically at the helicopter application.

Evaluation of Paper

The report forms an excellent case for the adoption of $L_{dn} = 60$ as the ultimate goal for the noise environment. However, it does not take fully into account the realities of the current noise environment where this limit is commonly exceeded and where its imposition would be meaningless and would impose severe limitations on many segments of the business community. It acknowledges that the proposed goal should be subject to a schedule for implementation but does not detail such a schedule or interim goals.

Cox, C. R., "Helicopter Noise Reduction and its Effects on Operations", Paper No 352, Proceedings - 25th American Helicopter Society Forum, May 1969.

Purpose

To present the factors that influence the reduction of helicopter noise and discu their effect on helicopter design and operation.

Summary

This paper compares helicopter noise with other types of environmental noise, indicates that certain flight conditions are associated with above-normal levels of noise generation by certain types of rotors, and presents trends of the variation of rotor noise with several operating and design parameters.

Comparison With Similar Papers

Noise parametric trends presented agree generally with those of the remainder the literature. Flight conditions generating higher than average noise levels are covered in more detail in Reference 15.

Evaluation of Paper

This paper uses only Perceived Noise Level as an indicator of helicopter annoyance and deals only with the 3000-pound, two-bladed, single-rotor helicopter.

Edge, P. M., Chambers, R. M. and Hubbard, H. H., "Evaluation of Measures of Aircraft Noise", Proceedings of NASA Aircraft Safety and Operating Problems Conference, NASA SP-270, Volume 1, 1971.

Purpose

This report discusses the status of development of measurement units to properly represent human responses to aircraft noise.

Summary

This paper identifies various ways in which aircraft noise affects people including annoyance, speech interference, etc. It summarizes subjective testing procedures, types of rating units, peak versus effective measures of noise impact, and references the relevant studies performed up to the date of the report.

Comparison With Similar Papers

None.

Evaluation of Paper

This is a summary of the state of the art in measurment of human response to noise in 1971. Quantitative data is not presented.

Fidell, S. and Pearsons, K. S., "Study of the Audibility of Impulsive Sounds", NASA CR-1598, May 1970.

Purpose

This study was conducted to perform experiments to investigate the effect of phase, duration, intersignal interval, repetition, and frequency on the perceived noisiness of impulsive signals.

Summary

Six experiments were performed in an anechoic chamber to investigate the effects of physical parameters on impulsive noise subjective noisiness. Five transient waveforms (not repetitive) were used for testing. It was found that: the phase spectrum of an impulsive signal is irrelevant in establishing its perceived noisiness, the ear's sensitivity to noisiness of impulsive signals resembles an energy summation process for which no specific time constant was found, and the common correction contours (such as dBA, dBN, and PNL) may undercorrect in the low frequency regions.

Evaluation of Paper

The work presented is not necessarily applicable to repetitive impulsive noise such as that from a helicopter. The psychoacoustic consequences of these results, which were performed for single transient impulse noises, are not substantiated for repetitive impulses.

Halwes, D. R., "Flight Operations to Minimize Noise", Vertiflite (American Helicopter Society), February 1971.

Purpose

To determine the flight conditions which cause high noise levels in a medium transport helicopter.

Summary

A Bell 205 class helicopter was flown through an extensive flight program to identify the flight regimes which generated blade slap noise. These regimes are presented in the form of an area to be avoided on a plot of airspeed versus rate of climb or rate of descent. There were four categories of blade slap identified: intermittent slap, continuous slap, loud slap, and maximum slap. It was found that the areas generating the higher blade slap levels can be avoided by making pilots aware of them and altering their flight techniques appropriately. Reductions of Perceived Noise Level on the order of 10 PNdB were attained by using the modified flight profile.

Comparison With Similar Papers

This paper supplements the work on trajectory effects in which may be found in References 9, 10, 11, 13 and 14.

Evaluation of Paper

This paper provides a clear indication of the importance of blade slap in dominating helicopter noise levels when it occurs. Since PNL was used in evaluating the relative annoyance of the helicopter with and without blade slap, the actual subjective difference to observers is probably much greater than the measured difference indicates.

Hecker, M. H. L. and Kryter, K. D., "Comparisons Between Subjective Ratings of Aircraft Noise and Various Subjective Measures", FAA NO-68-33, April 1968.

Purpose

This study was undertaken to evaluate various established and proposed objective methods of measuring aircraft noise relative to their ability to predict subjective ratings of the acceptability of noise produced by present-day commercial aircraft.

Summary

Paired comparison tests were performed using tape recorded flyovers of several types of aircraft during take-off and landing operations. Objective measures were computed for the level of each sound and for a comparison (reference) sound for each aircraft operation. The relative accuracy with which the objective measures predicted the subjective ratings was expressed in terms of the variance in the computed values of each objective measure. The smallest variance was associated with a measure that takes into account the spectral properties of a given flyover for its entire duration and also the presence of pure tones or other narrow-band energy concentrations.

Comparison With Similar Papers

The data suggests that A-weighted SPL is a practical compromise to rate aircraft noise annoyance. The results presented herein are consistent with those of Pearsons[1], Sternfeld, et al[5], Ollerhead[6], Adcock[7], and Munch and King[11].

Evaluation of Paper

The paper indicates that, for maximum or peak values, a weighted Sound Pressure Level (SPL) is as good or better than the Perceived Noise Level (PNL), which requires a calculation rather than simply a direct readout. A tone correction seems to improve correlation as does a duration correction (an integrated duration correction is preferable). It appears that the use of a tone correction with diminished weighting below 500 Hz and an integrated duration correction applied to any one of several basic human hearing response weighting functions results in a relatively accurate objective noise rating scale. Attempts to "fine tune" a rating scale from this list of requirements seem to constantly run into the law of diminishing returns in terms of reduced standard deviation between objective and subjective measurements of noise. Impulsive noise is not treated at all here nor is any low frequency helicopter type rotational noise.

Hinterkeuser, E. G. and Sternfeld, H., "Subjective Response to Synthesized Flight Noise of Several Types of V/STOL Aircraft", NASA CR-1118, August 1968.

Purpose

To evaluate subjective response to the far-field noise characteristics of several types of V/STOL aircraft sized to carry 60 passengers over a 500 mile range.

Summary

The acoustical signatures of several V/STOL aircraft were analytically predicted, and tape recordings synthesizing these sounds prepared. Test subjects rated these sounds on a PNL basis against jet sounds. The various V/STOL configurations are rated against one another for terminal and cruise operation with the results varying for each type of operation.

Comparison With Similar Papers

This paper does not provide as much information on the validity of the various rating schemes as do other references. It rates types of V/STOL aircraft for relative noise generation.

Evaluation of Paper

All comparisons were made on the basis of PNL and rated against jet noise. Evaluations were made in an untreated room where the reproduction of low frequency rotor noise, particularly blade slap, may not be good.

Hinterkeuser, E. G. and Sternfeld, H., "Civil Helicopter Noise Assessment Study - Boeing Vertol Model 347", NASA CR-132520, May 1974.

Purpose

To forecast the certification and community noise acceptance criteria for helicopters in the 1975-1985 time period. To determine the noise reductions required on the Boeing-Vertol 347 helicopter to meet these criteria and the means of achieving them.

Summary

The certification limit recommended is 95 Effective Perceived Noise Level decibels (EPNdB) at points located 500 feet to each side of the touchdown/takeoff point and 1000 feet from this point directly under the approach and departure flight path. Community acceptance would be measured as Equivalent Noise Level (L_{eq}), based on dBA, with separate limits for day and night operations. Modifications required to the model 347 helicopter to meet these requirements include: new blade tips, rotor blade geometry modifications, increased fuselage length, and engine silencing.

Comparison With Similar Papers

This is a parallel study to that reported by Munch and King[11] with basic difference only in the recommendation for use of EPNL over dBA in rating basic helicopter noise.

Evaluation of Paper

This was a comprehensive study which considered many current systems of rating aircraft and community noise annoyance. It concludes that the A-weighted sound pressure level provides the best means to denote acceptable community noise by allowing the helicopter to generate a time average noise level equal to the noise level in the community without the helicopter in cases where the community ambient noise is greater than the allowed L_{eq} levels of 60 and 50 for day and night, respectively.

Leverton, J. W., "Helicopter Noise - Are Existing Methods Adequate for Rating Annoyance or Loudness?", Journal of The American Helicopter Society, April 1974.

Purpose

To establish the validity of using Perceived Noise Level (PNL) or A-weighted sound pressure level (dBA) for rating the effects of helicopter noise on listeners.

Summary

This work demonstrates that the existence of blade slap or tail rotor whine in a helicopter noise spectrum makes the rating measures far from accurate. The paper recommends that a new approach to the rating of helicopter noise be developed.

Comparison With Similar Papers

It is possible that a blade slap noise rating factor could be called for in this paper.

Evaluation of Paper

This paper makes a good case for the inaccuracy of conventional noise rating schemes in dealing with spectra containing impulsive noise.

Munch, C. L., "Prediction of V/STOL Noise for Application to Community Noise Exposure", Department of Transportation Report No. DOT-TSC-OST-73-19, May 1973.

Purpose

The objective of this program was to develop a computer program for the prediction of Effective Perceived Noise Level (EPNL), tone corrected Perceived Noise Level (PNLT), and the A-weighted sound pressure level (dBA) of a V/STOL vehicle as it flies along a prescribed takeoff, cruise, and landing flight path.

Summary

The objectives described above are achieved. Procedures used to predict noise radiation by helicopter rotors, propellers, turboshaft engines, lift and cruise fans, and jets are described in detail. A program and users' guide are furnished. Impulsive type rotor noise from helicopters is not treated, nor is noise from deflected jets, augmentor wings, blown flaps, and other high-lift devices for which definitive prediction methods were not yet available.

Comparison With Similar Papers

This is a good program to evaluate operational and design change impact on noise levels of a variety of aircraft.

Evaluation of Paper

This report shows excellent correlation for turboshaft powered helicopter and turboprop STOL cases which were the only ones checked. It is considered a very useful program for providing aircraft noise input to V/STOL port planning studies.

Munch, C. L. and King, R. J., "Community Acceptance of Helicopter Noise: Criteria and Application", NASA CR-132430, 1974.

Purpose

To define criteria for noise of civil helicopters to make their operations acceptable to the community neighboring terminals and flight paths and to evaluate a current generation civil transport helicopter against this criterion to determine the operating conditions, terminal area requirements, and acoustical modifications necessary for compliance.

Summary

The criterion found to be compatible with communities was the Day-Night Noise Level (L_{DN}) at a constant level of 60 dBA for ambients up to 58 dBA and an "impact to ambient" of 2 dBA for ambients above this level. This criterion was found to be in accordance with multinational aircraft noise regulated levels, with state regulations, and with community noise ordinances in existence at the time. It was determined that the unmodified helicopter met the criterion in cruise flight at typical altitudes, but modifications to the main and tail rotors and the engines were necessary for terminal area operations to attain realistic land area requirements.

Comparison With Similar Papers

This is the best case made for use of dBA and L_{DN} in evaluating aircraft noise and community impact. The study is parallel to that of Reference 10.

Evaluation of Paper

This was a comprehenisve study which considered most current systems of rating aircraft and community noise annoyance. It concludes that the A-weighted sound pressure level provides the best combination of accuracy and practicality for use in rating community reaction to helicopter noise. It uses this number as the basis for a comprehensive rating scheme which combines the effects of sound level, sound duration, ambient noise level, time of day, number of flights, and the human hearing response. A unique criterion is also developed to identify the presence of rotor blade slap in a helicopter noise signature and to quantify the effect.

Ollerhead, J. B., "Acoustic Considerations in the Design of a Quiet Helicopter", Wyle Laboratories Technical Report WR70-3.

Purpose

The purpose of this study was to relate certain helicopter design and operation parameters to the production of noise and its resultant aural detection.

Summary

This paper reviews acoustic factors to be considered in the design of quiet helicopters and the basics of aural detection, discusses Lowson type methodology for rotor noise prediction, and presents some trends for design and operation parameters to yield up to 20 to 1 reductions in aural detection distance relative to conventional helicopters designed with no regard to the aural detection problem.

Comparison With Similar Papers

Although quantitative comparisons of annoyance versus aural detectability are difficult to make, this paper could supplement References 9, 10, and 13 in outlining design practice for low noise generation in helicopters.

Evaluation of Paper

No unique information is presented, but a good review of noise prediction and aural detection prediction techniques is provided in this report.

Ollerhead, J. B., "Scaling Aircraft Noise Perception", Journal of Sound and Vibration, Volume 26, No. 3, 1973.

Purpose

To perform extensive experimentation to determine the practical differences between numerous alternative methods for calculating the perceived levels of individual aircraft flyover sounds.

Summary

One hundred and twenty recorded sounds, including jets, turboprops, piston aircraft, and helicopters were rated by a panel of subjects in a paired comparison test. The results were analyzed to evaluate a number of noise rating procedures in terms of their ability to accurately estimate both relative and absolute perceived noisiness over a wider dynamic range (84-115 dB SPL) than had generally been used in previous experiments. The performances of the different scales were examined in detail for different aircraft categories, and the merits of different band level summation procedures, frequency weighting function, and duration corrections were investigated.

Comparison With Similar Papers

This is a short form of the author's report, Reference 4. This is an extensive study using better noise reproduction than most others.

Evaluation of Paper

Several conclusions from this study are: perception of low frequency harmonic sound (from helicopters particularly) needs further study as poor correlation was attained; the influence of doppler shift on perceived noisiness is not conclusively know, as it seems important in laboratory simulations but not in actual aircraft flyovers; tone corrections are not particularly beneficial below 500 Hz and should be ignored in this range, three dB per doubling of the number of exposures is accurate. The data shows slight superiority of PNL and EPNL over dBA and EdBA (effective A-weighted sound pressure level). Standard deviations between subjective and objective data were 4.6 and 3.5 for PNL and EPNL, respectively, and 4.9 and 4.2 for dBA and EdBA, respectively for helicopter noise.

Ollerhead, J. B. and Lowson, M. V., "Problems of Helicopter Noise Estimation and Reduction", AIAA Paper No. 69-195, February 1969.

Purpose

To present a solution for the prediction of helicopter rotor rotational noise and design charts for reduction of this type of noise.

Summary

This paper presents a closed form solution for the prediction of helicopter rotor rotational noise and design charts identifying parametric changes for its reduction. Noise reduction requirements are derived on the basis of aural detection of the helicopter.

Comparison With Similar Papers

This paper discusses noise reduction as keyed to aural detection, as was done by Ollerhead[12]. Aural detection is generally controlled by rotor rotational noise in helicopters. This type of noise is also significant in annoyance in some cases.

Evaluation of Paper

This paper does not deal with the subjective evaluation of helicopter noise as a whole. However, it is useful in defining criteria for and the means to reduce rotational noise at extremely large distances, where it is first detected aurally.

Pearsons, K., "Noisiness Judgments of Helicopter Flyovers", FAA DS-67-1, January 1967.

Purpose

To determine the applicability of several objective rating measures in predicting the subjective response to helicopter flyover noise.

Summary

Tests were conducted in which 21 college students judged the noisiness of eight recorded helicopter flyover noises versus a jet transport flyover noise and a shaped band of noise. Tests were conducted in an anechoic chamber using primarily the method of paired comparisons. The results indicate that the calculated Perceived Noise Level (PNL) is the best predictor of noisiness, followed closely by the N-weighted sound pressure level (dBN) and the A-weighted sound pressure level (dBA). Duration and pure-tone corrections applied to the calculated PNL did not improve the prediction accuracy of this measure.

Comparison With Similar Papers

This work was aimed solely at helicopter noise. The conclusions are similar to those of References 2, 5, 6, 7 and 11.

Evaluation of Paper

This report indicates that dBA is approximately the same accuracy as PNL in judging the subjective annoyance of helicopter noise.

Pearsons, K. S. and Bennett, R. L., "Handbook of Noise Ratings", NASA CR-2376, April 1974.

Purpose

To provide compilation, in a concise form, of information describing the multitude of noise rating schemes which are in use today.

Summary

This book contains descriptions, title, unit, definition, applicable standards, purpose, background, calculation method, and example of usage for nearly all current noise rating schemes. Categories of rating schemes covered are: direct ratings of sound level (Sound Level Meter type weighting functions which are not amplitude varying), computed loudness and annoyance ratings (including those variants dealing with tone, duration, and number of repetition corrections), communication interference ratings, and community response ratings.

Comparison With Similar Papers

This report provides a summary of all of the noise rating schemes discussed and evaluated in the papers summarized in this section.

Evaluation of Paper

This is an excellent "single source" of material on all of the significant methods of rating noise effects on man.

Stepniewski, W. Z. and Schmitz, F. H., "Possibilities and Problems of Achieving Community Noise Acceptance of VTOL", International Council of the Aeronautical Sciences, ICAS Paper 72-34, September 1972.

Purpose

The purpose of this study was to investigate the reduction of the acoustical annoyance of VTOL aircraft by reduction at the source through aircraft design and by flight path management.

Summary

This paper presents first a review of noise standards. Typical transport aviation noise standards are shown which project 85 EPNdB by 1985. As current state-of-the-art rotary wing VTOL transports indicate an annoyance level of approximately 95 EPNdB, this goal requires a 10 dB reduction in noise level. However, recent studies have shown that a relative elevation of the noise level above that of the background represents a very important criterion of the acoustic tolerance. The results of the study indicate that up to 10 EPNdB above daytime background noise level will result in essentially no reaction from the community, whereas a 20 EPNdB increase will cause widespread complaints. It is also pointed out that PNL or EPNL may not be suitable for true indications of subjective reaction to the noise from different types of aircraft.

In the second part of the paper, the reduction of noise at the source is discussed. Although an attractive overall criterion for assessing the penalties of noise reduction is the direct operating cost, it is difficult to calculate and does not permit a direct step-by-step evaluation. Thus, the authors present their results as weight and/or performance penalty vs. noise reduction attainable. They present the major noise sources, which are in order of decreasing importance: blade slap, tail rotor rotational noise, main rotor noise, turbine engine noise, and transmission noise. The phenomenon and alleviation of each source are discussed in turn, including a discussion of the associated weight and performance penalties for noise reduction. Rotary wing, tilt rotor, and lift fan concepts are discussed.

It is concluded that for two typical suburban communities, a reduction in noise level at the source of about 10 PNdB is required for current state-of-the-art rotary wing aircraft, and more than 20 PNdB for lift fan concepts. However, reducing the rotor tip speed (the most powerful noise reduction effect) for a 10 PNdB noise reduction will result in large weight and performance penalties. Flight trajectory management has potential for reducing "footprint" area, but there are too many variables (specified level of annoyance, whether buffer strips are used, ambient noise level, etc.) for general assessment of the benefits of this approach.

Comparison With Similar Papers

This paper presents a general overview of the major noise sources in Helicopters and other VTOL aircraft and their alleviation. Other general noise source mechanisms are discussed by Ollerhead[12], Cox[13], and others, and this paper presents no new information in this area. The data from the Model 347 has been discussed elsewhere by Hinterkeuser and Sternfeld[10] as has the use of trajectory changes by the same authors[14].

Evaluation of Paper

This paper presents a good comprehensive review of the major noise sources in VTOL aircraft and means for alleviating the noise at the source and through take-off and landing flight path optimization. Although essentially no new information is presented, it does give the reader a good overview of the VTOL aircraft noise picture.

The major elements in assessing the community acceptance of VTOL aircraft operation are well presented. However, this paper would be strengthened if it addressed the basic problem of assessing subjective reaction to very different noise signatures (i.e., from rotary wings to tilt rotors to lift fans) using PNdB units, which have been shown to be inadequate for helicopters in general, particularly in the case where blade slap occurs[1,2,8,11].

Sternfeld, H., Hinterkeuser, E. G., Hackman, R. B. and Davis, J., "Acceptability of VTOL Aircraft Noise Determined by Absolute Subjective Testing", NASA CR-2043, June 1972.

Purpose

To determine the relative subjective acceptability of two VTOL aircraft sounds using absolute subjective testing methodology and to investigate the effects of the application of noise criteria to VTOL aircraft.

Summary

A program was conducted in which test subjects evaluated the simulated sounds of a helicopter, a tilt wing and a turbojet aircraft (used as a reference). Over 20,000 evaluations were made while the test subjects were engaged in work and leisure activities. The effects of level, exposure time, distance and aircraft design on subjective acceptability were evaluated. It was found that the helicopter and tilt wing sounds had to be 4 to 5 PNdB lower than the reference sound to be judged equal in annoyance for sounds 15 seconds in duration. It was also found that the effects of noise duration decrease when durations exceeded 120 seconds and that good correlation was obtained between subjective ratings and acoustical measurements of helicopter and tilt wing VTOL sounds. Peak PNL, dBA, and dBC produced similar correlation.

Comparison With Similar Papers

The results presented in this paper correlate with those of References 1, 2, 6, 7 and 11.

Evaluation of Paper

This report indicates that PNL, dBA, and dBC produce similar results in predicting annoyance of VTOL noise and that they all underpredict the annoyance relative to subjective evaluation.

Wells, R. J., "Jury Ratings of Complex Aircraft Noise Spectra Versus Calculated Ratings", Acoustical Society of America, 80th Meeting, November 1970.

Purpose

This paper presented the results of a study which had the objective of determining the accuracy of several noise rating systems in predicting the annoyance of several fixed wing aircraft noise spectra.

Summary

Engine noise spectra (15 in all) were reproduced inside an anechoic listening facility and judged by a sound jury for annoyance. The method of adjustment procedure was used by the subjects to set the test sound relative to a constant jet noise type reference sound. The objective noise rating measures tested were: PNLT, ANL (Annoyance level), PNL, dBA, dBB, dBC, and dBD. It is concluded that the ANL seems to rate actual engine noise spectra better than any of the other measures considered in the study. It is also concluded that the close agreement between results obtained with the two parallel methods of analysis (i.e., electrical signal analysis versus analysis of the acoustic signal in the test chamber) indicates that, with sufficient care, precise electrical analysis can be made and may actually be better where questions of tone correction are involved.

Comparison With Similar Papers

The ANL parameter has not attained general usage as have the PNL and spectrum weighting functions evaluated in References 1, 2, 5, 6, 7, 10, 11, 16 and 17.

Evaluation of Paper

Duration was not one of the factors considered in this study. Only the spectrum weighting functions and pure tones were used as variables. Only two of the seven rating scales yielded standard deviations out of line with the rest. These were dBC and dBB. Of the remainder, ANL produced the lowest standard deviation (1.17). It appears that the added complexity of computing the values of PNLT, ANL, and PNL are not worth the extra trouble considering the similar correlation attained with the simple weighted functions dBA and dBD. It also appears that dBA would be preferable from the point of view of availability on sound level meters and analysis equipment.

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