Effects of Noise on Commercial V/STOL Aircraft Design and Operation

HARRY STERNFELD JR.* AND ERNEST HINTERKEUSER†
The Boeing Company, Philadelphia, Pa.

The acoustical signatures of several classes of large V/STOL aircraft were predicted, synthesized electronically, and evaluated for annoyance. Perceived noise levels were established in a manner similar to that which has been employed for jet airplanes. The paper describes the methods of simulation and testing and discusses the results in terms of criteria for successful commercial operations and the noise reduction research which will be required to attain this goal.

Introduction

THE problem of aircraft noise and its effect on the public has been one of increasing concern in the past few years. The development of the jet airplane, and its increasing size and power, combined with the rapid growth in air traffic density, have tended to focus attention on the need for criteria which could be used for regulatory purposes, or to evaluate the acceptability of new and proposed aircraft. The associated problem of predicting public reaction to sounds of a type with which they are already familiar is difficult enough in itself, but the problem of predicting the reaction to sounds of the future which has not yet been experienced, such as many categories of V/STOL aircraft, presents even greater difficulties. Before examining one approach which has been taken to this problem,[1] a brief review of methods which have been used to describe the characteristics of noise are as follows:

1) *Over-all sound pressure level*: This unit, which is a logarithmic measure expressed in decibels, is the simplest form of acoustical measurement. It merely expresses the maximum pressure experienced without regard to frequency or any other effect.

2) *Weighted sound pressure level*: Since human hearing does not have a flat frequency response, sound level meters incorporating weighting networks (which essentially provide the instrument with a hearing response more typical of the human ear) were designed. Sound level measurements made with such meters are usually referred to in terms such as dbA or dbB where A and B describe particular frequency weighting networks. The notation dbC is essentially that of a flat response and is therefore the same as over-all sound pressure level.

3) *Octave band spectrum*: Recognizing that noise must be described by both amplitude and frequency, a common measurement system used to describe the full range of frequencies is sound pressure level by octave band. In this case, the spectrum is analyzed through filters, each of whose center frequency is twice that of the preceding one. This describes the noise in terms of 8 or 9 sound pressure levels, each associated with its own center frequency. Although these measurements do describe both the amplitude and the frequency characteristics of a given sound, they are not convenient to use when one thinks of criteria or evaluation numbers because they do not provide a single index which represents any specific characteristic of the particular sound.

4) *Loudness level*: In an effort to return to a single number rating which might be more indicative of the effect which a complete spectrum would have on an individual the concept of loudness level was developed,[2] in which the sound pressure level in each octave band was given a weighting which was a function of hearing sensitivity in that octave band. This provides more emphasis on the middle frequency range in which hearing is most acute and deemphasizes the extreme ends of the spectrum. The unit of the loudness level is the phon.

5) *Perceived noise level*: Recognizing that loudness level might not necessarily describe a more subjective reaction such as annoyance, Kryter[3] introduced the concept of perceived noise level (PNdb). This method which was originally used for jet aircraft noise ratings, is similar in application to loudness level, but the weighting scale was developed based on annoyance criteria rather than simply on equal loudness.

6) *Effective perceived noise level*: Recent research, still in progress, has further refined the PNdb concept by inclusion of factors to express the added annoyance due to time duration to which a subject is exposed to the noise, and the presence of pure tones, which usually prove more irritating than broad band noises of the same sound pressure level. The unit of effective perceived noise level is EPNdb.

The most widely accepted answers to the need for noise level description to date have been the development of the latter two measures. The PNdb type of regulation is currently in use in prescribing jet noise operating limits at various airports; while the EPNdb type of measurement is under careful consideration both for replacement of present PNdb type of local regulation, and also by the FAA, as the method for providing certification criteria for new aircraft.

While the development of a noise criterion index which will apply uniformly to all aircraft sounds, or even better to all sounds, should be an ultimate objective of researchers in psychoacoustics, this goal is not clearly attained by any of the present or proposed methods, in that universality of application is yet to be demonstrated. The concept of the program described in this paper is to examine the potential impact of noise regulation limitations on the operation of V/STOL aircraft and to assess the areas of noise reduction research which might be indicated in order to conduct an urban V/STOL operation without undue mitigating factors due to noise.

Program Concept

A basic premise of the program was that sufficient experience existed with regard to the public acceptance of jet noise

Received October 18, 1968; presented as Paper 68-1137 at the AIAA 5th Annual Meeting and Technical Display, Philadelphia, Pa., October 21–24, 1968; revision received September 9, 1969. This paper is based on research supported by NASA Contract NAS 1-7083.

* Chief, Acoustics Unit, Vertol Division.
† Engineer, Acoustics Unit, Vertol Division.

compared with the regulatory limits which were being imposed in order to establish a limit which the public at large would at least tolerate. These limits, in fact, were initially derived by obtaining the reaction of people to the noise of jet aircraft as compared with those of reciprocating engine aircraft with which they were already familiar. Research of this type led, for example, to establishing a limit of 112 PNdb for operation in the Port of New York Authority area. The concept of our program was to use the jet airplane as the reference standard and determine those levels of sounds from various V/STOL configurations which might be expected to evoke similar public response to those of the jet airplane when operating at today's limits. Since in this case we are dealing with aircraft which have yet to be designed or constructed, much less flown, the task divides into the following elements: 1) predict sound pressure levels for each design and synthesize, on magnetic tape, the acoustical signatures of each predicted spectrum, 2) perform comparative subjective response testing in order to equate the acceptable levels for each V/STOL aircraft signature with those of current jet airplanes, and 3) evaluate the results in terms of impact on aircraft design and operation.

Prediction and Synthesis of Future Aircraft Sounds

The basis for the aircraft designs selected for the present research project was a study of VTOL and STOL short haul transports conducted for the NASA Ames Research Center.[4,5] In that program, VTOL and STOL aircraft were analyzed in order to determine those most suitable for commercial short haul operation, and also the research which might be required to bring them to full operational status. The study included aircraft design, operational techniques, noise and public acceptance, acquisition costs, direct operating costs, technical risks, and research requirements. Ground rules covering aircraft design included a 500 statute mile nonstop range and 60 passenger pay load capabilities. The designs selected for this noise study were a fan lift VTOL, jet lift VTOL, tilt wing, stowed rotor helicopter, and a tandem rotor helicopter, in addition to a Turbofan STOL aircraft. Octave band sound pressure levels and pure tone components for each of the aircraft were predicted for the takeoff and cruise mode. Because of the disimilarity in propulsive mechanism each aircraft employs in takeoff as opposed to level cruise flight, the resulting acoustical signatures may be strikingly different in the two operating regimes even for the same aircraft. To simulate the acoustical signature of a proposed aircraft configuration in believable and subjectively convincing detail including spectral content, time-amplitude variation, directivity, and Doppler shift, detailed analyses of the noise properties were first conducted.

Although some of the signatures were produced all, or in part, by electronically reshaping tape recordings of similar configurations, these techniques are reasonably straight forward and will not be described. The method of synthesizing tapes from purely electronic sources is, however, believed to be unique and worthy of description. Broad band sounds such as engine exhausts were produced by random or white noise generators and were then filtered and shaped as required. Pure tones, such as inlet whine, were generated by suitable oscillators. Each separate component was then recorded on a single channel of a multichannel tape recorder for subsequent combining.

Since the sounds produced did not contain the qualities imparted by motion of the source (directivity, time variation or Doppler shift), these had to be introduced artificially. The first two of these effects were combined by the following procedure: the various synthesized sounds were combined on three tracks of a magnetic tape in proper proportion to produce the forward directed spectrum, the side directed spectrum and the aft directed spectrum. The output of each track was connected to a separate amplifier-speaker combination, mounted on a vehicle, and driven past a stationary microphone-recorder system (Fig. 1). The distance was determined by vehicle and ambient noise levels. The result was a gradual buildup of sound with time as each component of noise would predominate: first the source with the approach noise, then the side directed noise, and then, on the fade-away portion of the sound, the aft directed noise. These tests were conducted out-of-doors permitting believable sound signatures to be recorded since the turbulence present in the atmosphere, even over short distances, provided realistic fluctuations in noise amplitudes.

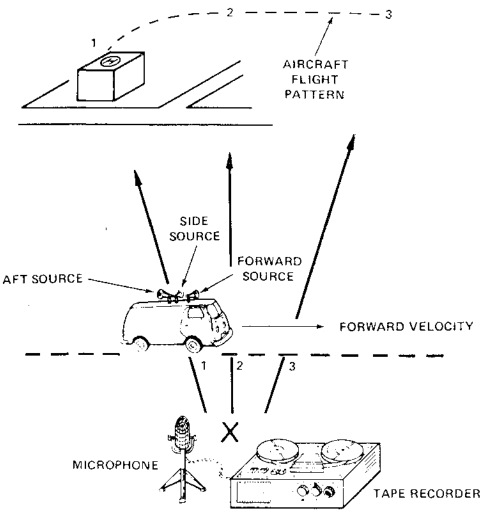

Fig. 1 Simulation of time history and directivity effects.

In the field, the levels coming from each of the three speakers were adjusted separately to obtain the correct sound distribution. A portable sound level meter with built-in octave-band filters was used to check the level of each speaker around the vehicle azimuth while it was parked, so that an approximately correct distribution of the sound was beamed from the entire vehicle for the simulated flybys. After some experimenting with the amount of lateral distance from the microphone and vehicle speed, and slight changes in the volume level coming from each of the three speakers, a good simulation of aircraft noise was obtained.

Upon returning to the laboratory, a final reshaping of the spectrum envelope by means of a $\frac{1}{3}$ octave band equalizer was made to match simulation and prediction. If required, adjustment of the appropriate amplitude-time history was made by rerecording the sound with slight variations in playback gain setting controlling over-all recording level as a function of time.

An actual aircraft sound amplitude-time history is illustrated in Fig. 2A. Part B of the figure shows a first approximation to this sound using a shaped broad-band random noise generated electronically whose amplitude as a function of time was controlled by a potentiometer on the random noise generator (volume control). It can be seen that the natural random amplitude fluctuations due to unsteady atmospheric effects are absent. The sound does not seem real to a listener even if variations in the handling of the volume control are introduced. However, as illustrated in Part C, the technique illustrated in Fig. 1 resulted in a most realistic simulation.

Doppler shift effects were the remaining features to be inserted into the acoustical signature. It was assumed, because of the relatively low airspeeds required during hover-to-transition, that Doppler shift would make a relatively minor contribution to the over-all subjective effect of the terminal noises. Its omission was felt to be justified in view of the work involved in inserting it into the sounds for these small speed variations. However, at cruise, this might become sub-

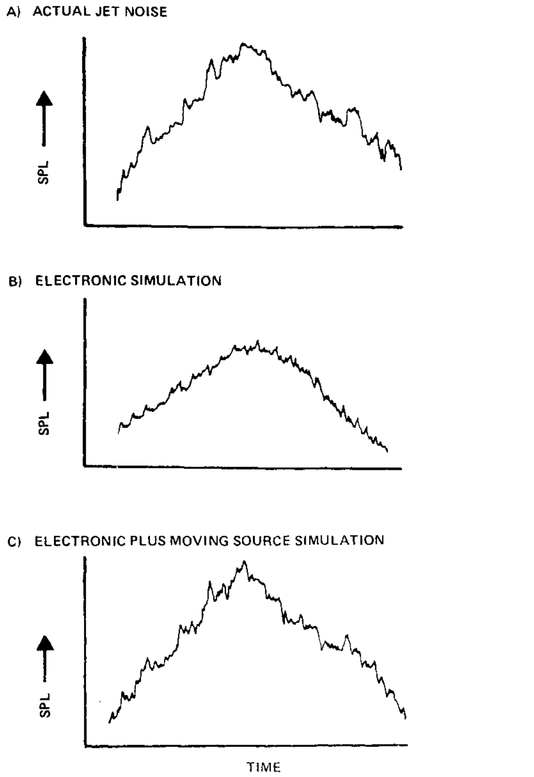

Fig. 2 Comparison of electronic and moving source simulation.

jectively important and would certainly enhance the credibility of the simulated sounds. For those sounds requiring Doppler shift simulation, the following method for inserting this effect was used: the record made up of the component noises combined in the field by the vehicle flyby technique was stretched on the approach and condensed on the departure sides of the peak of the amplitude-time history (Fig. 3a). This was done by having the vehicle driven more slowly at the beginning than at the end of the simulated flyby. Later, in the laboratory, this noise was rerecorded on a variable speed tape recorder at different tape speeds to obtain the desired over-all frequency shift variation with time. Figure 3b illustrates this technique. Due to limitations of the recorder amplifier characteristics at the extremely low end of the frequency spectrum (less than 40 Hz), there was a limit to the amount of frequency shifting which could be done without compromising the fidelity of the original sound of the tape. However, even though only a limited amount of Doppler shift could be introduced by this technique, the aural effect was definitely much superior to that achieved without any frequency shifting.

The simulated sound now included all the important aural characteristics necessary to reproduce the effect of transient aircraft noise. All that remained to be done was to adjust the octave band spectrum to its final envelope according to the predictions and to finalize the duration times between the 20-db downpoints (from the peak over-all sound) by means of a potentiometer. These last adjustments were performed in the manner previously described and resulted in the final master tape. Figure 4 illustrates the complete synthesis procedure.

Test Procedure

As discussed in the program concept section, the general approach taken in this study requires determination of the level of a given sample of noise that is judged to be equally annoying to the reference sound of the jet airplane. In order to achieve this objective the following conditions must be met: 1) the spread of test levels must be large in order to ensure inclusion of the decision point within the range tested and 2) the spacing of the points should be close enough to allow good definition of the decision point.

The number of test points had to be limited to a number which could be accommodated within a reasonable program. It is obvious that these requirements are in conflict, but the spread of test levels can be greatly reduced if it is possible to approximate the decision point by preliminary testing, and then refine the definition with the large sample test program.

To provide this approximate identification of the point at which the stimulus sound could be judged equally annoying as the reference, a preliminary subjective test was performed. This was done in the Vertol Division Acoustical Laboratory. Subjects were asked to listen to the reference and stimulus sounds in succession as many times as they wished and to adjust the volume of the stimulus to a level which produced equal annoyance to the reference. The volume of the reference, (a jet airplane sound of 112 PNdb out-of-doors) could not be adjusted. By this method, it was possible to narrow down to 4 levels for each of the aircraft sounds, 2 above and 2 below the anticipated midpoints of equivalent annoyance. However, these 4 levels were not to represent simple settings of a volume control but actual spectra, shaped by apparent effects of distance and atmospheric sound absorption in order to simulate 4 different distances of the aircraft from the intended indoor listener. Therefore, atmospheric and structural attenuations were calculated and introduced by means of a spectrum shaper.

Thus, we synthesized the sounds of all the aircraft in both terminal and cruise modes and at a wide enough variation of apparent distances in order to assure a subjective reaction range from acceptable to unacceptable for each case. The final test tape was prepared in which each sound was presented along with a comparison sound for a jet airplane. The jet airplane level always simulated 112 PNdb out-of-doors. Each pair was presented twice, once with the jet first and once with the V/STOL first. The entire tape was randomized so that no predictable pattern of aircraft sounds or level progressions was presented.

The test subjects were asked to indicate, in each case, which of the sounds, the VTOL or the airplane, they thought would be more annoying if heard regularly in their homes 20–30 times a day. The detailed methodology used for the conduct of the test was kept as identical as possible as that employed by Kryter in his original subjective testing which led to the PNdb method for jet airplane evaluation as reported in Ref. 3. In order to further assure similarity in doing the programs, Kryter served as a consultant to this program. The test was conducted using, as subjects, approximately one hundred students from a local college. It should be noted that the method of paired comparisons, as employed, has the

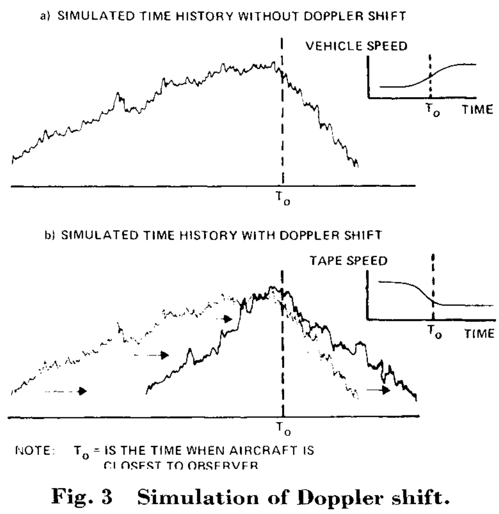

Fig. 3 Simulation of Doppler shift.

advantage that it tends to cancel out many physical, psychological, and other differences between subjects which might be present in an absolute judgement test.

Evaluation of Results

The fundamental approach of this program which had as its objective an assessment of the noise produced by various aircraft configurations, sought to determine that PNdb level measured outdoors which, for a given configuration, will cause the same public reaction from people indoors as a jet airplane producing 112 PNdb outdoors. The 112 PNdb was selected as the reference level because it is the current criterion used by the Port of New York Authority. The PNdb level for a given test configuration which evoked the same response as the 112 PNdb jet noise was referred to as the comparative perceived noise level of the aircraft.

The method of arriving at the comparative perceived noise level is illustrated in Fig 5. It should be understood that the absolute value of the comparative perceived noise level is not highly significant in itself. The significant measure of an aircraft's potential lies in the difference between the predicted noise level of the aircraft (expressed in PNdb) and the comparative perceived noise level, which indicates the requirement. This may be illustrated by the following simple equation: NR = PNL − CPNL, NR = noise reduction required, PNL = predicted level in PNdb, and CPNL = comparative level in PNdb. Figure 6 is included to show the comparative peak noise levels of the various configurations under study. In cruise it is noted that most of these values are quite close to the jet reference level. This is simply because most of these configurations convert to either jet or turboprop airplanes in the cruise mode, while in the terminal operation, with its more unusual propulsion devices and longer exposure time, the comparative PNdb is considerably lower than in cruise, indicating a lower level of tolerance by the listeners.

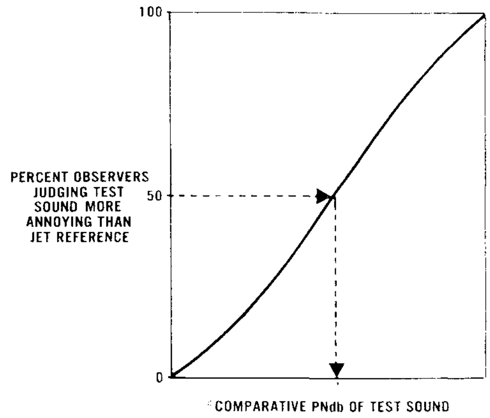

Fig. 5 General method of obtaining comparative peak perceived noise level.

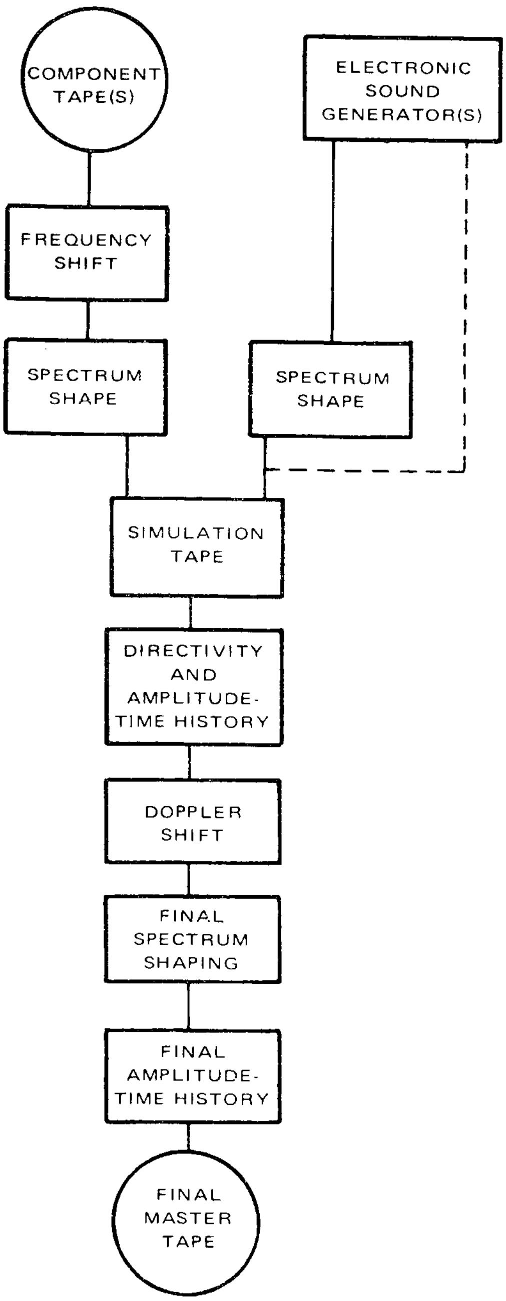

Fig. 4 Synthesis of aircraft sound from component tapes and electronic instruments.

Recommendations for Noise Reduction

The predictions made for the acoustical signatures of each of the aircraft tested were for those aircraft as designed during the referenced NASA short-haul transport study.[4,5] In general, these aircraft were optimized from performance and economic viewpoints and no major concessions were made to noise reduction, nor did any configurations as presented in the study include auxiliary devices for the purpose of noise attenuation. In applying the results of this study to these

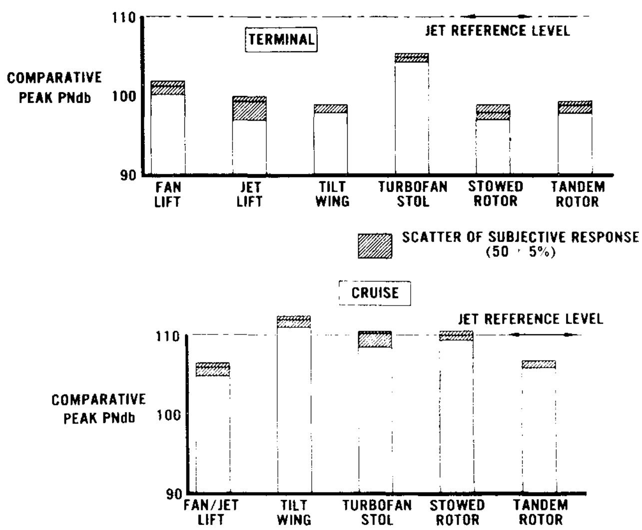

Fig. 6 Comparative peak perceived noise level of predicted outdoor V/STOL aircraft sounds.

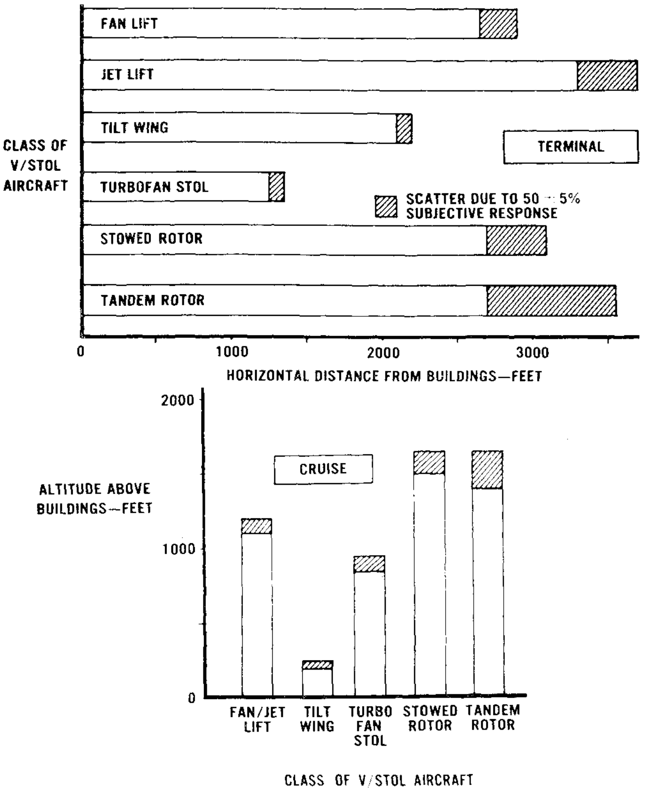

Fig. 7 Required distance and altitude to set outdoor comparative peak perceived noise level of short-haul V/STOL aircraft if no noise reduction techniques are applied.

aircraft, there are 2 avenues of approach open. The first is to determine the operational restrictions which might be applied to each configuration, in terms of distance to be maintained between the aircraft and populated areas, in order to elicit no serious public reaction.

Figure 7 illustrates the aircraft to observer distances and altitudes which must be maintained by these future V/STOLs in order not to exceed the stated criteria. Although sideline distances from runways of the order of 3000 ft and cruise altitudes of the order of 1–2000 ft would be considered extremely modest restrictions to place on airplanes, it is apparent that such restrictions would not permit economical operations for V/STOLs serving urban areas. The requirements for noise reduction, therefore, come about not because V/STOL configurations are predicted to be inherently extremely noisy aircraft when observed from the same distance as today's fixed wing airplanes, but rather because the requirements for close operation to the urban population are much more stringent than those which have been previously faced.

Since distance in itself cannot be expected to solve our problem, the remaining practical course is to seek noise reduction at the aircraft itself. The results of this study can be used to form a guide line for determining the components producing aircraft noise and the amount of noise reduction required for each component by application of the following procedures: 1) set target altitudes or distances, 2) calculate PNdb predicted at these altitudes or distances, 3) determine comparative PNdb subjectively, 4) subtract the comparative PNdb from item 2 to determine the perceived noise level reduction required, 5) examine the sound spectrum of each aircraft noise component to determine its effect on perceived noise level, 6) successively reduce the predominant source until a different source becomes primary in setting the perceived noise level, and 7) repeat 5 and 6 until the desired perceived noise level is attained.

Calculations of this type were performed for the conditions of 500-ft horizontal separation (terminal operation) and 500-ft altitude over the observers in cruise operation selected as typical operational requirements. Based on these assumptions using the procedure previously outlined, the data shown in Fig. 8 were developed to indicate the source noise reduction which would be required for each configuration, and may also be used to present an overview of the information reclassified by noise reducing component.

Some general conclusions which can be derived from Fig. 8 are that power-plant intake noise reductions from 15 to 30 db are required for all configurations during terminal operation. Although existing technology has indicated the feasibility of attaining such reductions on specific engine configurations, the successful application of these inlet noise reduction techniques to the sometimes unconventional V/STOL engine configurations has yet to be demonstrated and may, in this process, prove to be a major technical problem on certain aircraft. However, if these problems are overcome to solve the terminal operation noise problem, there should then not be any constraints, in most cases, for cruise operation.

Similarly, engine exhaust noise may present a substantial obstacle in the application of several of the V/STOL's to the intercity transport problem. Turbofan and turbojet engine equipped V/STOL configurations in particular will, according to a 500-ft terminal operational constraint, require from 10 to 15 db of exhaust noise reduction. Exhaust noise reductions of lower order than this have been demonstrated; reductions up to the required decibel level might possibly require state of the art advances in exhaust noise control. It should be noted that apparently no exhaust noise reduction is necessary for any of the turboshaft powered VTOL's in either terminal or cruise operation.

In the area of helicopter rotors, noise reductions of rotational and vortex blade noise of 10–15 db will be required to make several of the proposed concepts as subjectively acceptable as today's jet noise. A more specific example of the usefulness in applying the information in Fig. 8 is in the area of propeller noise. With regard to the tilt wing, it is seen that 15-db propeller noise reduction is needed for a terminal operation at 500 ft, but none for cruise at 500 ft. The reason for this is that the tilt wing propeller, being highly loaded in hover, is overdesigned for the cruise condition and, therefore, operates at low loading and tip speed in that mode. The stowed rotor configuration, however, does require 10-db reduction of propeller noise in cruise because, since it does not need its propellers to hover, they were designed to be smaller than those of the tilt wings and are more highly loaded and must operate at higher tip speed. Therefore, if acceptability at 500 ft is to be a requirement, the propeller on the stowed

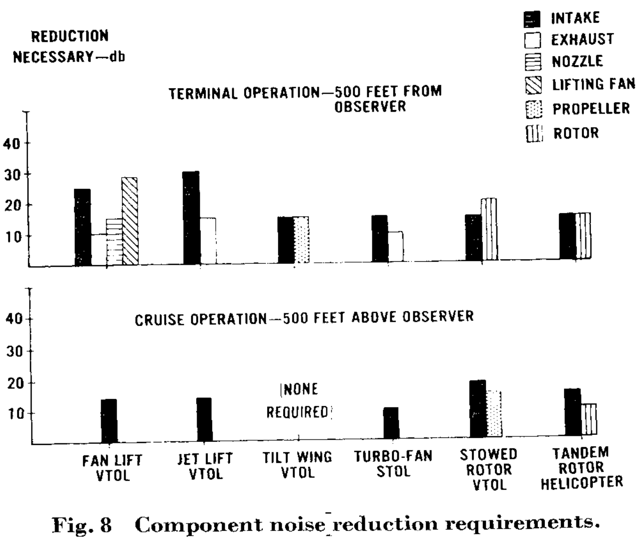

Fig. 8 Component noise reduction requirements.

rotor aircraft could be resized based on noise rather than performance.

Attainment of specific acoustical requirements was not a constraint in the initial design of these aircraft. Figure 8 clearly serves to show that we cannot continue to design aircraft without giving consideration of, and perhaps, concession to noise level reduction, and still expect to put on the market a product which would meet with public acceptance.

References

[1] Hinterkeuser, E. G. and Sternfeld, H. Jr., "Subjective Response to Synthesized Flight Noise Signatures of Several Types of V/STOL Aircraft," CR-1118, Aug. 1968, NASA.

[2] Stevens, S. S., "The Measurement of Loudness," *The Journal of the Acoustical Society of America*, Vol. 27, No. 5, 1955.

[3] Kryter, K. D., "Scaling Human Reactions to the Sound from Aircraft," *The Journal of the Acoustical Society of America*, Vol. 31, No. 11, Nov. 1959, pp. 1415–1429.

[4] Fry, B. L. and Zabinsky, J. M., "Feasibility of V/STOL Concepts for Short Haul Transport Aircraft," CR 743, June 1967, NASA.

[5] Scherrer, R. et al., "NASA-Lockheed Short-Haul Transport Study," *NASA SP-116*, April 1966.

MAY-JUNE 1970 J. AIRCRAFT VOL. 7, NO. 3

Helicopter Gust Response at High Forward Speed

JAN M. DREES* AND KEITH W. HARVEY†
Bell Helicopter Company, Fort Worth, Texas

An analytical study was made of the response of helicopters and compound helicopters to discrete gusts. A sophisticated mathematical model was developed. The effects of the gust's shape, gradual penetration, nonsteady aerodynamic rotor flow, and aeroelastic blade behavior were investigated. The responses of a wide variety of configurations were determined, and many parameters, such as forward speed and rotor loading, were varied. The results indicate that the added considerations of sine-squared gust profile, nonsteady aerodynamics, and gradual penetration have a primary effect on the gust loads. The results have been synthesized into a simple empirical expression that offers a convenient method for designers to determine the gust response of contemporary high-speed pure, winged, and compound helicopters. The existing helicopter gust requirements were found to be inadequate.

Nomenclature

c = const
C_T = rotor-thrust coefficient
g = gravitational constant
H = ramp length, ft
K_g = gust-alleviation factor
K_{gw} = wing-gust coefficient
L_w = wing lift, lb
R = rotor radius, ft
S = rotor area, ft
T_{hover} = rotor thrust in hover, lb
V_g = gust velocity, fps
W = gross weight, lb
Δn = gust load, g
ΔT = rotor thrust increase, lb
$\Delta\lambda$ = inflow ratio increase
μ = advance ratio
μ_g = mass ratio
ρ = air density, slug/ft^3
σ = rotor solidity ratio

Introduction

ROTARY-wing aircraft experience milder reactions to gusts than do most fixed-wing aircraft. One of the earliest reports on this subject is a paper by Focke,[1] in which pilot reactions in a helicopter with side-by-side rotors are compared with those in a fixed-wing airplane. A similar test was conducted later by NACA,[2] with instrumentation to measure normal forces in the aircraft flying through turbulent air.

The relatively mild behavior noted in rotary-wing aircraft is not substantiated by simple theoretical considerations. It has been customary to determine the normal rotor forces due to sharp-edged gusts by using charts such as those developed by NACA.[3] Since this method does not take into account rotor limits at high advance ratios, as discussed by Livingston and Murphy[4] and by Ham and Young,[5] it yields very conservative results.

The requirements of MIL-S-8698(ASG)[6] permit the use of an alleviation factor that is a function of rotor-disk loading. For disk loadings greater than 6 psf, however, this factor is unity. Drees and McGuigan[7] investigated the effect of sine-squared gusts, with the gust velocity experienced by the aircraft assumed to be equal to the gust velocity at the center of the rotor. Gust alleviation factors of about 0.6 were found for the sine-squared gust shapes.

The rapid development of helicopters with higher forward speeds and higher disk loadings, and the addition of wings and auxiliary propulsion in the case of compound helicopters, have made the present methods of determining gust response inadequate. At high speeds and for disk loadings greater than 6 psf, the computed load factors are too high. When, in addition, gusts are superimposed on maneuver loads (as has occasionally been required in certain design studies) an unrealistic design situation is created.

Approach and Scope of the Study

The objective of the study was to investigate the effect of discrete gusts on a great variety of rotary-wing aircraft. The study included pure single-rotor helicopters with tail rotors, tandem and side-by-side helicopters, and compound

Presented as Paper 68-981 at the AIAA 5th Annual Meeting and Technical Display, Philadelphia, October 21–24, 1968; submitted October 14, 1968; revision received November 3, 1969. This study was performed under contract to the U. S. Army Aviation Material Laboratories.

* Chief, Flight Technology Section. Member AIAA.
† Senior Aeromechanics Engineer. Member AIAA.