Reduction of VTOL Operational Noise through Flight Trajectory Management

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The concept of altering the flight path of VTOL aircraft to reduce ground noise levels in areas adjacent to the landing site is explored. Two classes of VTOL aircraft are considered: prop-rotor and lift-fan concepts. One theoretical performance and acoustic model from each class is developed and then mathematically flown to yield representative two-dimensional takeoff and landing flight profiles. When proposed noise abatement profiles are compared with minimum time and fuel trajectories, significant decreases in the peak noise level are calculated at measuring points located directly beneath the flight path. However, there is a performance penalty associated with these proposed noise abatement procedures; time and consumed fuel both increase. When the areas encompassed by a chosen annoyance level are calculated, they are found to depend on the specified level of annoyance. In general, high annoyance areas are reduced at the expense of the lower annoyance areas.

Introduction

IN this era of increasing ecological concern, decisions as to whether VTOL aircraft should be used to directly serve the transportation needs of communities will be significantly influenced by the aircrafts' acoustic acceptability. The noise produced by a VTOL aircraft operating from airports located close to the population centers must be minimized to the point where it is acceptable to the neighboring community it is to serve. Realizing this, government agencies as well as the aircraft industry have been involved in numerous programs to reduce the noise at its source through proper aircraft design. Assuming, however, that everything possible has been done in this respect, there still remains an important factor which can help achieve an acceptable community noise level; namely, flight trajectory management of the VTOL aircraft in the terminal area.

The effectiveness of reducing noise exposure through flight path control has been demonstrated both analytically[1,2] and experimentally[3] for CTOL transport aircraft. For instance, it is shown in Ref. 3 by actual acoustical measurements of the CV-990 aircraft flying a pattern established in Ref. 1, that a reduction of the ground noise level by about 6 EPNdB in both takeoff and landing operations can be achieved. More recently, the two-segment landing approach has been suggested as a means of reducing the annoyance of CTOL aircraft. During the first segment, a 6°-glide slope is maintained at low-power settings with wheels and flaps retracted. At approximately 1½ miles from the airport, flaps and wheels are lowered and power is increased to sustain a 3° descent to touchdown. This relatively simple operational maneuver substantially reduces approach noise. Lower power settings and larger distances between the aircraft and listener resulting from steeper approaches both reduce the noise impact area.

The use of flight trajectory management to reduce the noise of helicopters has also been demonstrated. Flight tests performed with a 10,000-lb class Bell helicopter[4] indicated that ground noise reductions from 8 PNdB at 100-ft altitude to 5 PNdB at 3000-ft altitude were possible at selected measuring locations. Most of this noise reduction was realized by using flight path control to avoid regions of blade slap during landing approach. The technique of experimentally altering the flight path to reduce helicopter annoyance has also been investigated abroad. For instance, large reductions in ground noise were achieved on Mi-8 through flight path control.[5]

These experimental attempts at flight path control of helicopters in the terminal area for the purpose of noise reduction are encouraging. They demonstrate that some annoyance reduction is possible for VTOL aircraft. In this paper, the over-all concept of altering the flight path of VTOL aircraft to reduce ground noise levels in areas adjacent to the landing site is investigated in more general terms. Theoretical acoustic-performance models are used to assess the noise-performance tradeoffs associated with terminal flight path control. Two classes of VTOL configurations are analytically represented: 1) prop-rotor and 2) lift-fan aircraft.

It is an accepted fact that the absolute noise levels of VTOL aircraft within each class can vary significantly depending upon design considerations, i.e., tip speed, disk loading, etc. However, the gross features of each class also tend to categorize the aircraft acoustically. Thus the prop-rotor aircraft's acoustical spectrum tends to emphasize low and mid frequency ranges while lift-fan VTOL aircraft characteristically emit higher frequency noise. In this acoustic-performance assessment, only one specific design from each class of VTOL's has been assumed to be representative of that class. Furthermore, both configurations have not been designed to be quiet—a point which should be kept in mind when examining figures of the absolute noise levels appearing in the technical discussion.

Prop-Rotor Aircraft

The first class of VTOL aircraft which is considered derives its lift in hovering flight from unshrouded rotary wings. The helicopter, compound helicopters, tilt-rotor aircraft, and tilt-wing aircraft all belong to this low to medium disk loading class. Only one member of this family of aircraft has been explored in detail—the tilt-rotor aircraft. Although the detailed acoustic and performance characteristics of different configurations vary, the gross

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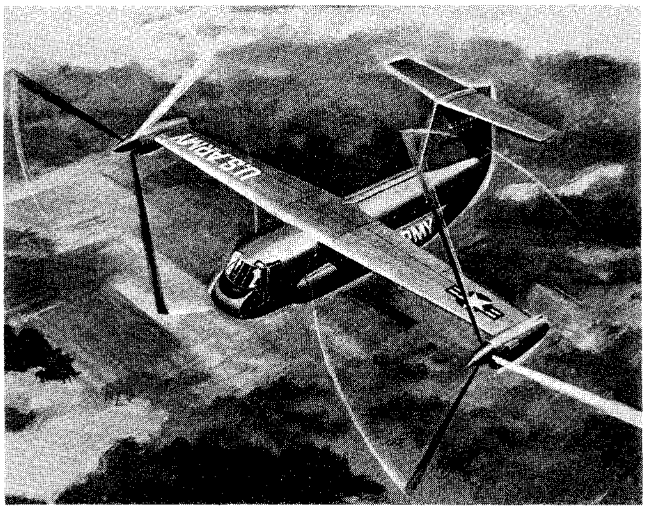
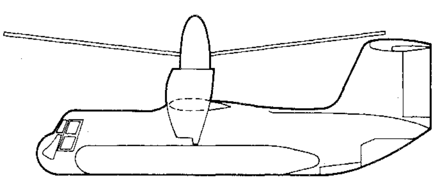


Fig. 1 An artist's conception of the Vertol 160 tilt-rotor aircraft.

benefits of flight trajectory management are illustrated by theoretically exploring the noise-performance tradeoffs of this one configuration. The tilt-rotor aircraft has been primarily designed for the transport mission. It is similar in its basic concept to the Bell XV-3 tilt-rotor aircraft which has undergone extensive flight testing. The basic configuration is depicted in Fig. 1, while its basic characteristics are listed in Fig. 2.

Performance Characteristics

The tilt-rotor concept is based on the highly variable geometry of its configuration: rotor axes vary their inclination with respect to the wing chord through an angle somewhat larger than 90°; trailing edge flaps can be deflected through 90°; rotor blades receive collective and cyclic control inputs; conventional airplane controls can be deflected through large angles, etc. In addition, the aircraft as a whole may vary its attitude with respect to the flight path. In view of this, obtaining an accurate assessment of the performance of a tilt-rotor aircraft in transitioning flight is a formidable task by itself. Fortunately, the main interest of this paper is the evaluation of the gross aspects of tilt-rotor performance. Therefore, a simplified mathematical model based on the momentum theory has been developed. However, necessary refinements were made in order to account for the profile power and the in-plane rotor forces resulting from the blade profile drag. This model permits assessment of the performance tradeoffs which are possible through flight trajectory management. A complete derivation of the governing equations along with several graphs describing tilt-rotor performance are given in Ref. 6.



CHARACTERISTICS

NUMBER OF BLADES PER ROTOR	3
ROTOR DIAMETER, ft	55
DISK LOADING, lb/ft^2	9.7
TIP SPEED, ft/sec	750
WING SPAN, ft	67.8
WING LOADING, lb/ft^2	80
ASPECT RATIO	7.9
DESIGN TAKEOFF WEIGHT, lb	46,200
PAYLOAD, lb	12,000
NUMBER OF ENGINES	2
MAXIMUM RATED HP STATIC AT S.L. STD.	4,450 HP/ENGINE

Fig. 2 Tilt-rotor performance characteristics.

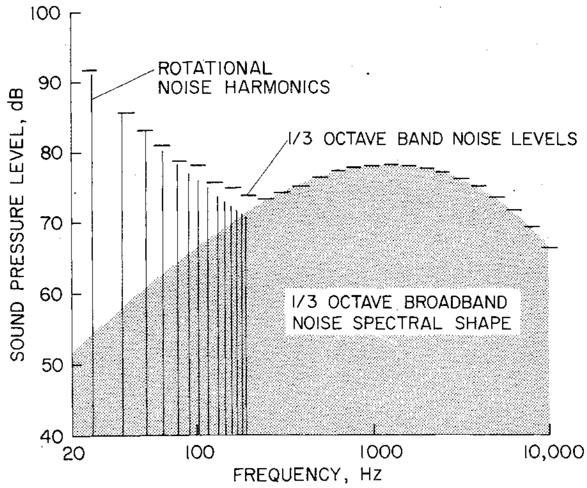


Fig. 3 A representative one-third octave band analysis of a tilt-rotor aircraft.

Practical considerations necessitate the enforcement of additional performance constraints throughout the flight envelope. Some of the more important auxiliary constraints that were enforced are: 1) accelerations parallel and perpendicular to the flight path were constrained to $\pm 0.2g$ and $\pm 0.25g$, respectively; 2) the flap deflection angle and attitude angle of the aircraft were programmed to be a function of the aircraft's performance state; 3) pitching rate limits and a touchdown velocity limit were enforced; and 4) a minimum permissible applied power was assumed to maintain controllability of the aircraft in all regimes of flight.

Acoustic Characteristics

The noise generated by a prop-rotor VTOL aircraft is typically classified by its generation mechanism. For a VTOL aircraft driven by turboshaft engines, sound which is generated by aerodynamic forces often dominates in the far acoustic field. This aerodynamic sound includes various types of noise which are commonly classified as rotational noise, broadband noise, and blade slap (if it occurs).

The two classifications of sound which are considered in this paper are rotational and broadband noise. They are diagramatically illustrated in Fig. 3. The lower frequency discrete sound is commonly called rotational noise. It is directly related to the blade passage frequency and the airloads experienced on the rotor blade. A rather comprehensive theory[7] was developed to predict the rotational noise of helicopter rotors in forward flight. This same theory was adapted to the prediction of rotational noise of the tilt-rotor aircraft. In essence, the basic theory predicts the sound that is produced by a rotor and is related to an analytical representation of the rotor's harmonic blade loading. By introducing a parameter that reflects the operating state of the rotor and by correlating this parameter to the higher harmonic data obtained from wind-tunnel experiments of a rotor in nonaxial flight,[6] a rotational noise prediction analysis was developed for the tilt-rotor aircraft. The important aspect of this analysis is that the resulting rotational noise theory does reflect the influence of the proximity of the tip vortex in the generation of noise. When a rotor blade is operating near the tip vortex of a preceding blade, higher harmonic aerodynamic blade loading is predicted, resulting in higher harmonic rotational noise. Although the impulsive nature of the blade slap phenomena resulting from pure vortex-blade interactions is not quantitatively represented by this analysis, the importance of the rotor's operating state in the generation of rotational noise is emphasized. Similarly, in the airplane configuration, large helical wake angles insure that the dominant noise source arises from only the steady component of aerodynamic forces. Under these operating conditions, rotational noise contains very little acoustical energy at the higher rotational harmonic frequencies.

Broadband noise, on the other hand, consists of a continuous spectrum (Fig. 3) of noise which is characteristic of acoustic sources which are random in nature. These are primarily dipole acoustic sources resulting from the random force fluctuations on the rotor blades and generally contain their acoustic energy at higher frequencies. In this analysis, an empirical equation has been used to predict the broadband noise spectrum of the tilt-rotor aircraft. It has been corrected for directivity and forward speed effects. A complete discussion of the details of this empirical equation is presented in Ref. 6.

Fortunately for the aircraft designer and builder, operator, and user, the sound generated by the aircraft is rapidly reduced in several ways: by spatial and atmospheric effects and by absorption due to vegetation. Spatial effects include the effect of directivity which is included in the governing point source acoustic model of the tilt-rotor aircraft. In addition, sound pressure levels are decreased 6 dB per doubling of distance between the source and observer. Furthermore, atmospheric effects also decrease the sound pressure level at the higher harmonic frequencies. Both of these effects are included in the basic tilt-rotor acoustic model. Because of the complexity of the problem, no attempt was made to include the effect of the terrain, atmospheric temperature, or wind gradients on the propagation characteristics of the sound.

A subjective measure of the noise has also been included in this analysis to assess the acoustic benefits of some flight profiles with respect to the others. The subjective measure chosen to describe the acoustic properties of the aircraft is the Perceived Noise Level (PNdB).[8] It incorporates the effects of noise amplitude and frequency, an observer's nonlinear hearing response and the concept of an annoyance criterion in a single rating scheme.

Noise-Performance Tradeoffs

To assess the potential benefits of altering the flight path to optimize performance and/or minimize noise, the previously described mathematical model of the tilt-rotor aircraft was flown along selected takeoff and landing trajectories. The trajectories were chosen to minimize one of three quantities of interest: time, fuel to climb or descend from a given altitude and velocity conditions, and noise measured at selected ground locations. Because the noise generated by the tilt-rotor aircraft flying above 3000-ft altitude is not of primary importance, all takeoff and landing trajectories considered did not emphasize flight above that altitude. Also, the performance equations were somewhat simplified by flying a kinematic performance model which treated vertical ($\pm 0.2g$) and horizontal ($\pm 0.25g$) accelerations as constraints.

The intricacies of how optimization techniques were applied to this problem formulation as well as very detailed time histories of the performance and acoustic variables of interest are presented in Ref. 6. In this paper, only an over-all assessment of the results is intended. However,

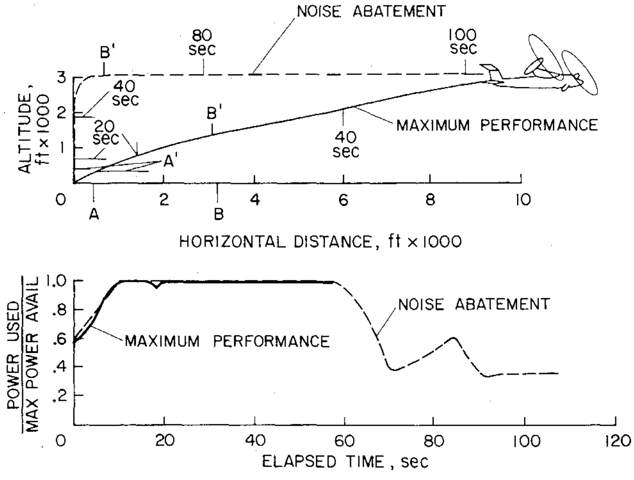


Fig. 4 Tilt-rotor maximum performance and proposed noise abatement takeoff profiles and applied power time histories.

some of the more subtle implications of the noise-performance tradeoffs can be graphically illustrated by comparing two representative flight profiles: a maximum performance takeoff and a noise abatement takeoff.

The maximum performance takeoff flight profile minimizes the time and fuel to climb to 3000 ft. The solid lines of Figs. 4 and 5 depict the time histories of some of the more important performance states as well as the resulting two-dimensional trajectory. Because a simplified performance model has been employed to predict tilt-rotor performance, maximum horizontal and vertical acceleration limits must be enforced at various times throughout the resulting profile. At the time of takeoff, the vertical acceleration constraint of $0.2\,g$ restrains the initial applications of the full power until the maximum applied power limit is intersected (Fig. 4). Maximum power is then applied for the remainder of the trajectory. The horizontal acceleration of $0.25g$ is maintained at its limiting value until the horizontal velocity which corresponds to the tilt-rotor's best rate of climb speed is attained. As horizontal velocity increases, the aircraft makes the transition from the helicopter to the airplane configuration. An additional limit upon the rate of change of the tilt-rotor's attitude with respect to time reduces the applied power slightly during transition for a small time interval. The remainder of the trajectory is flown in the

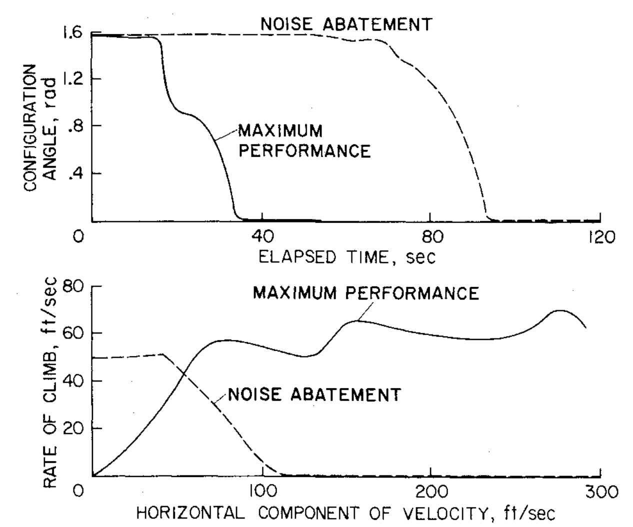


Fig. 5 Tilt-rotor configuration time histories and velocity profiles for maximum performance and proposed noise abatement takeoff trajectories.

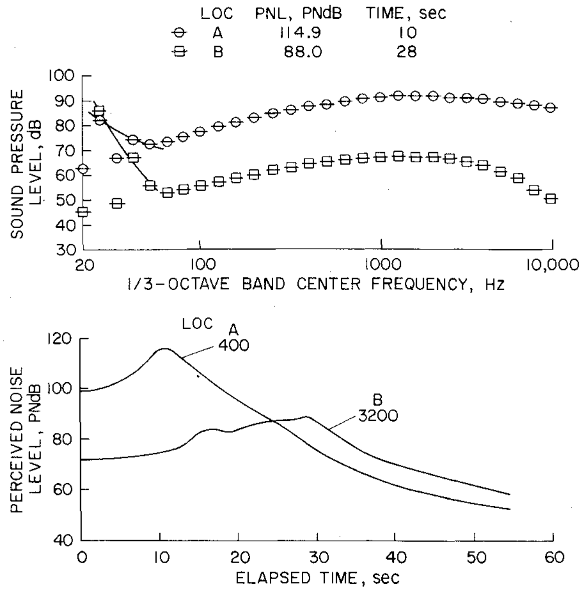


Fig. 6 Tilt-rotor one-third octave band analyses and PNdB time histories for a maximum performance takeoff trajectory.

airplane configuration at the best rate of climb speed with maximum power applied.

Several interesting performance characteristics of the tilt-rotor's climbing transition to forward flight are also illustrated in Fig. 5. The rate of climb vs horizontal velocity curve is remarkably similar to the constant altitude performance curves.[6] However, the kinematic performance which is shown has been further limited by the dynamic performance constraints. For example, the initial vertical acceleration constraint is directly responsible for low rates of climb near the takeoff point.

The second dip in the rate of climb vs horizontal velocity curve is attributable to the significant download on the wing which occurs at moderate forward speeds and high rates of climb. The last dip in the kinematic performance curve occurs in high speed helicopter flight. The power expended to overcome the drag of the tilt-rotor aircraft in the helicopter configuration at high speeds reduces the power which is left to maintain high rates of climb.

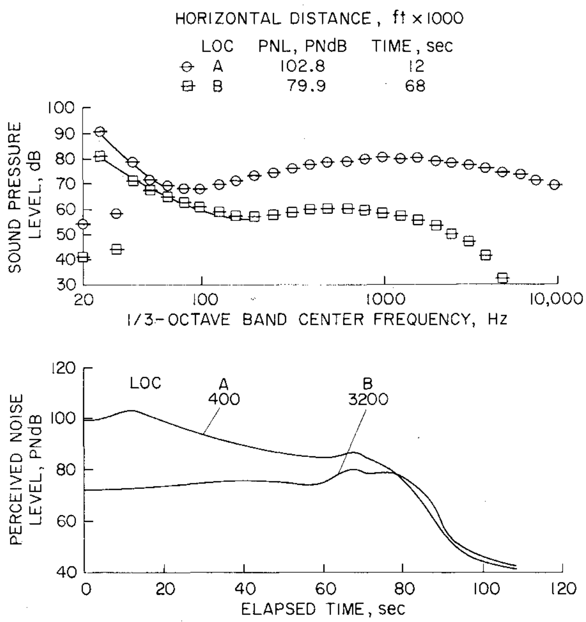


Fig. 7 Tilt-rotor one-third octave band analyses and PNdB time histories for a proposed "Noise Abatement" takeoff trajectory.

Table 1 A comparison of tilt-rotor takeoff trajectories

DESCRIPTION	TIME, sec	FUEL, lb	MAXIMUM PERCEIVED NOISE LEVEL ~ PNdB: DISTANCE FROM TAKEOFF 400 ft	3200 ft
MAXIMUM PERFORMANCE TAKEOFF	54.2	75.4	114.6	88.2
PROPOSED TAKEOFF NOISE ABATEMENT PROFILE	106.0	143.9	103.2	79.5

The performance characteristics of the proposed noise abatement profile are depicted by the dashed lines in these same figures. The takeoff begins with maximum allowable vertical acceleration. Horizontal acceleration is nulled and the applied power is increased until its limit is attained. Maximum power is then applied, resulting in maximum rate of climb of the tilt-rotor aircraft in the helicopter configuration. This near constant rate of climb is sustained until the terminal altitude is approached (3000 ft). The applied power is then reduced to maintain level flight. At the same time, the tilt-rotor accelerates horizontally at its maximum permissible limit. Conversion to the aircraft configuration occurs as horizontal velocity increases. When the velocity which corresponds to the steady-state, best rate of climb speed is achieved, the tilt-rotor maintains level steady-state flight. The maneuver ends when the aircraft reaches the same down-range position as in the minimum time to climb trajectory.

Some of the important acoustic differences of both trajectories can be illustrated by simultaneously referring to Fig. 4 and the acoustic detail presented in Figs. 6 and 7. Two acoustic measuring locations situated directly below the flight path are shown in Fig. 4. Position *A* was chosen to be 400 ft from the point of takeoff while location *B* is 3200 ft downrange of the same point. The primed letters (*A′*, *B′*) which are shown at specific flight path locations in Fig. 4 illustrate the position of the aircraft where the maximum predicted perceived noise level at each respective measuring location occurs. For example: an observer at location *B* would register the largest value of PNdB when the aircraft is at position *B′*.

Figure 6 illustrates the character of the noise which is heard at locations *A* and *B* when a minimum time or fuel trajectory is flown. The relative importance of high frequency broadband noise is immediately obvious. The low-frequency rotational noise drops off very rapidly with increasing frequency. The large inflow through the plane of the rotor in takeoff flight conditions reduces the importance of the higher harmonic rotor airloads, thus reducing the magnitude of higher harmonic rotational noise. The effect of varying the distance between the aircraft and the observer can also be seen in this same figure. Besides the standard reduction of 6 dB with a doubling of distance, a more rapid attenuation of high-frequency noise with distance is observed. A time history of the perceived noise level which is heard at each measuring location is presented in the second half of this same figure for both measuring locations. The initial peak in each of the curves occurs just before the tilt-rotor reaches the point of closest passage to the measuring location. Doppler shift, directivity effects, and transition performance are reflected in these rather complex curves.

Figure 7 illustrates the SPL vs frequency curves and the PNdB time history plots of the proposed noise abatement profile for the same two noise measuring locations. Notice that higher levels of rotational noise are calculated in the pure vertical takeoff as compared to the minimum time to climb case. The higher thrust-to-weight ratios of the helicopter configuration generate a significant

Table 2 A comparison of tilt-rotor landing trajectories

DESCRIPTION	TIME, sec	FUEL, lb	MAXIMUM PERCEIVED NOISE LEVEL ~ PNdB, DISTANCE FROM TAKEOFF 400 ft	3200 ft
MAXIMUM PERFORMANCE LANDING	64.4	26.0	118.5	101.4
PROPOSED LANDING NOISE ABATEMENT PROFILE	99.0	60.0	105.2	82.8

amount of low frequency noise. However, because the higher harmonic airloads which generate this noise still decay rapidly with frequency under these large inflow conditions, the rotational noise quickly becomes less important at higher frequencies. The PNdB time history plots shown in this same figure illustrate the major advantage of flight trajectory management—that of reducing the peak valves of PNdB at measuring locations located directly under the flight path. By initially flying vertically for some period of time, the initial rise in annoyance which occurs during the maximum performance takeoff is reduced significantly.

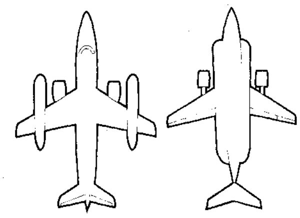
These results can be summarized by referring to Table 1 where the major performance and acoustic parameters of both trajectories are listed. The quietest flight path at both the near and the far measuring locations is seen to be the proposed "noise abatement trajectory." However, the time and fuel expended to achieve the maximum performance terminal conditions are almost doubled, when compared to the minimum time and fuel flight profile. Fortunately, the total fuel consumed in all of the maneuvers is relatively small because of the low disc loading rotors and is probably not a primary operational consideration. However, the time to attain 3000 ft does vary significantly, depending on the flight trajectory management technique.

Similar to takeoff, noise is only a problem to neighboring areas during the last 3000 ft of descent. For this reason, the tradeoffs in noise and performance during descent and landing have only been evaluated below 3000 ft. Table 2 compares two of the several trajectories computed in Ref. 6; a minimum time and fuel trajectory and a proposed noise abatement trajectory from the same initial position in state space.

All of the annoyance levels indicated in Table 2 are higher than those calculated for similar flight profiles during takeoff. Even though the applied power is, on the average, lower during landing than takeoff, high thrust values together with wake-induced higher harmonic airloads generate high acoustic levels at multiples of the fundamental rotational frequency of the rotor. This increase in the level of the higher harmonics of rotational noise substantially increases the subjective annoyance (PNdB) of the aircraft.

Fortunately, Table 2 suggests that flight trajectory management is an effective way of reducing acoustical annoyance at locations directly under the flight path. Significant reductions (up to 10 PNdB) are possible if near vertical terminal approaches are permitted. The cost in performance of achieving this annoyance reduction is estimated to be about a 50% increase in the time of flight and fuel consumed. Because of the tilt-rotor's relatively low disk loading, these net increases in flight time and consumed fuel would probably be secondary considerations for commercial operation of the tilt-rotor VTOL aircraft.

It has been clearly demonstrated in Ref. 4 and in several undocumented flights by one of the present authors that further optimization of descent and landing noise abatement trajectories is indeed possible. For instance, if near autorotational flight is permitted during descent in the UH-1 series helicopter, it is possible to fly "under" the blade vortex interaction condition. Thus blade-vortex interaction is avoided by encouraging the strong tip vortices to pass over the rotor's disk. This substantially reduces the higher harmonic blade loading and thus reduces the net rotational noise. The tilt-rotor model considered in this analysis could not enter this near autorotational condition. The applied power limits, which were chosen for safety, automatically prohibited this type of near autorotational noise abatement trajectory.



CHARACTERISTICS	DO-231C	HS-141	HYPOTHETICAL FAN LIFT
LENGTH, ft	118.8	120.2	65.0
WING SPAN, ft	85.2	75.0	46.5
WING AREA, ft^2	1,290.0	1,060.0	400.0
ASPECT RATIO	5.6	5.3	5.4
DESIGN TAKEOFF WEIGHT, lb	130,000.0	124,200.0	46,200.0
TAKEOFF WING LOADING, lb/ft^2	101.0	117.0	115.0

Fig. 8 Lift-fan performance characteristics.

Lift-Fan Aircraft

The second class of VTOL aircraft which is briefly considered in this paper derives its lift and propulsive force from jet driven fan engines. A very simplified mathematical performance and acoustic model of a hypothetical lift-fan VTOL aircraft is developed which is representative of this class of aircraft. The hypothetical aircraft is assumed to be of the same gross weight as the tilt-rotor used in the previous noise studies (W = 46,200 lb). Furthermore, its basic design parameters (see Fig. 8) are assumed to represent an average of those of the Dornier Do-231C[9] and the Hawker-Siddeley HS-141.[10] The resulting performance and acoustic model is mathematically flown along several takeoff flight profiles to ascertain, in a gross manner, the possible noise abatement advantages available to the lift-fan VTOL aircraft through flight trajectory management.

Performance Characteristics

Figure 8 lists the hypothetical lift-fan mathematical model's basic design parameters. The assumed lift (C_L) and drag (C_D) coefficient values which are shown in Fig. 9 are based on the projected wing area. They were estimated for the entire angle of attack range (measured from the zero lift chord of the aircraft as a whole) from −90° to +90°. This was done for two flap deflection angles shown: $\delta_f = 0°$ and $\delta_f = 20°$. In order to simplify the problem further, it has been assumed that there is no interference between the efflux of the lift and propulsive engines and flow around the frame. In other words, it has been assumed that regardless of the level of thrust, aerodynamic coefficients of the airframe remain the same as estimated for the no-thrust case.

Furthermore, it has been assumed that the thrust of the propulsive engines, whose installed value was taken as $(T_{pr}/W)_{ins}$ = 0.4, can be deflected through 90° all the

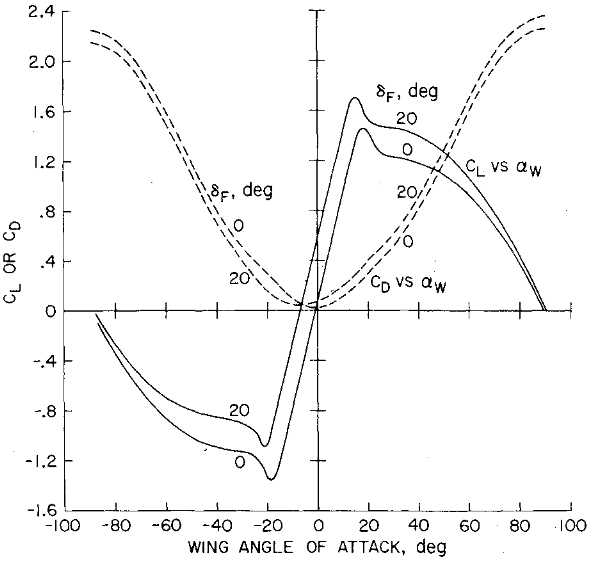


Fig. 9 Lift and drag coefficients for a theoretical model of a lift-fan aircraft.

way to the vertical position for takeoffs and landings. It was also assumed that the thrust of the lift-fans can be rotated +30° from the vertical.‡ In this way, the resultant thrust acting on the aircraft was considered as a single force passing through the c.g. and capable of being tilted from 60° to 90° with no reduction in its magnitude.

Two operational constraints were imposed on the aerodynamic mathematical model: 1) accelerations in the ground frame of reference were limited (as in the case of the tilt-rotor) to $\pm 0.25g$ in the horizontal and $\pm 0.2g$ in the vertical direction, and 2) the position of the fuselage remained horizontal during the initial phase of vertical takeoff.

In preliminary investigations, three levels of the total installed thrust were considered: $(T/W)_{\text{ins}}$ = 1.1, 1.25, and 1.4. By assuming that the specific fuel consumption was constant (0.36 lb/lb-wt/hr) and imposing a $\pm 0.2g$ constraint on vertical acceleration, the time and fuel required to climb vertically to 3000 ft were calculated. As can be expected, both time to climb and fuel required favored higher thrust-to-weight ratios. In addition, extensive flight simulator studies conducted by Hawker-Siddeley[11] also indicated operational desirability of a high installed thrust-to-weight ratio. Therefore $(T/W)_{\text{ins}}$ = 1.4 was selected for the following trajectory investigations.

Acoustic Characteristics

Because of the many complicating factors in the prediction of lift-fan noise, the theoretical acoustic model of a lift-fan engine has been derived solely from measured experimental data. Data from a fairly high bypass ratio tip-driven lift-fan engine of the 3500 lb class[12] was analytically approximated in the following manner. A total narrow constant bandwidth frequency spectrum of noise was assumed to have the general character as illustrated in Fig. 10. The level ($A1$), slope ($S1$) and fundamental and second harmonic characteristic frequencies were approximated to a given distance (150 ft) from the assumed point source of sound at all azimuth positions. In general, a highly directional sound pattern was noted that was also strongly related to the frequency. A maximum over-all level as well as a slower decay of higher harmonic noise occurs approximately 30° behind the thrusting plane of the fan. Higher levels of noise at the fundamental and second harmonic frequencies were noted in front of the thrusting plane.

Quite a number of additional computations and assumptions had to be made to use this data to represent the powerplant of a lift-fan VTOL aircraft. The data was corrected for Doppler effects. The previously discussed spatial and atmospheric absorption characteristics were applied to the acoustical model in the calculation of sound at ground measuring locations. Fourteen engines of this size and class were assumed to attain the required take-off thrust-to-weight ratio of 1.4 for a 46,200-lb aircraft. It is apparent that these acoustical calculations are overly pessimistic. A rationally designed quiet lift-fan transport would undoubtedly achieve levels of noise and frequency characteristics which would greatly reduce the entire level of noise. However, the intent of this paper is to assess, in a gross manner, the possible relative benefits of flight trajectory management to reduce noise. Although the over-all level of noise is high, the theoretical model which is presented does reflect the lift-fan's over-all acoustic characteristics. Therefore, this first estimate of the potential benefits of flight trajectory management to reduce the noise exposure is thought to be representative of this class of vehicles.

Noise Performance Tradeoffs

Only two specific takeoff trajectories are discussed in this initial assessment of the use of flight trajectory management to reduce lift-fan operational noise. Both trajectories, which are graphically illustrated in Fig. 11, are similar to those discussed in detail for the tilt-rotor aircraft (Fig. 4). They represent two extremes of operation; maximum performance (solid curves) and minimum noise (dashed curves).

Figures 11 and 12 illustrate the major performance differences between both flight profiles. To achieve maximum performance (in this case, minimum consumed fuel), the lift-fan VTOL aircraft is flown to maintain both the vertical and the horizontal accelerations at the maximum permissible limits of 0.2 and $0.25g$, respectively, as long as possible. Figure 11 illustrates the resulting flight profile while Fig. 12 illustrates time histories of the thrust-to-weight ratio and the inclination angle of the resultant thrust vector. In this case, after vertical takeoff, the aircraft goes into an immediate transition to forward speed at the maximum permissible horizontal acceleration, while initially accelerating vertically at the maximum allowable value and then climbing at the rate of climb permissible by the available vertical component of the thrust. As the resultant flight speed becomes higher than 150 fps, the aircraft's attitude angle is gradually increased to reduce the vertical drag and thus assure that the maximum horizontal acceleration of $0.25g$ is maintained. Finally, at an altitude approaching 3000 ft and a flight speed of 260 fps, the aircraft is further rotated to an attitude angle which maximizes the aircraft's steady rate

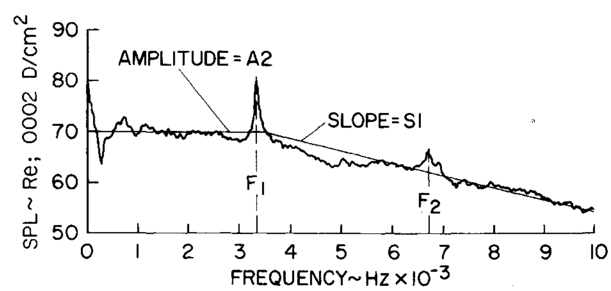


Fig. 10 An example of a constant 20-Hz bandwidth frequency analysis of fan noise.

‡Since only takeoff trajectories are considered, aft inclination of the thrust vector is of no significance.

Table 3 A comparison of lift-fan takeoff trajectories

DESCRIPTION	TIME, sec	FUEL, lb	MAXIMUM PERCEIVED NOISE LEVEL ~ PNdB, DISTANCE FROM TAKEOFF 400 ft	3200 ft
MAXIMUM PERFORMANCE TAKEOFF	40.3	210	130.2	102.0
PROPOSED TAKEOFF NOISE ABATEMENT PROFILE	78.4	376	126.0	94.0

of climb speed. A flap deflection angle of 20° was maintained throughout the maneuver.

The proposed noise abatement trajectory is illustrated (Fig. 11) in parallel with the maximum performance trajectory. The end conditions of both trajectories are similar, thus allowing meaningful noise-performance comparisons. The noise abatement trajectory consists of a vertical climbing segment to 3000-ft altitude followed by a horizontal transition segment at maximum permissible horizontal acceleration ($0.25g$) up to a velocity of 240 fps. Some preliminary studies indicated that the flaps and attitude of the aircraft should be chosen to maintain a C_L = 1.7 during the horizontal acceleration segment.

A one-third octave band analysis of the resulting noise signature at the time of maximum PNdB is illustrated in Figs. 13 and 14 at the two measuring locations indicated in Fig. 11. A comparison of both spectral plots reveals that at the time of peak PNdB, the sound emitted by flying either the minimum fuel or the noise abatement trajectory is characteristically the same. The importance of high-frequency noise is clearly shown in both figures. However, as noted in Ref. 13, part of this general trend of rising, then falling amplitude levels with increasing frequency is a result of the conversion to a one-third octave band analysis. In any case, the rapid attenuation characteristics of the higher frequency sound with distance from the source are clearly illustrated in both figures.

The major differences between both trajectories are illustrated in the PNdB time history plots of Figs. 13 and 14. The minimum fuel takeoff trajectory of the lift-fan aircraft exhibits a rising, then falling PNdB time history which is quite similar in character to the PNdB time history of the maximum performance trajectory of the tilt-rotor aircraft, with the peak occurring just before the aircraft passes directly over the measuring location. However, unlike the tilt-rotor acoustic profile, only a small increase in annoyance level is registered because the maximum performance takeoff trajectory is already quite steep. For the lift-fan aircraft, a near vertical takeoff trajectory is seen to completely eliminate the initial rise in annoyance level at the first measuring location (Fig. 14).

Table 3 summarizes the potential benefits of takeoff flight trajectory management to reduce lift-fan VTOL operational noise. The proposed takeoff noise abatement trajectory does significantly reduce the noise heard at

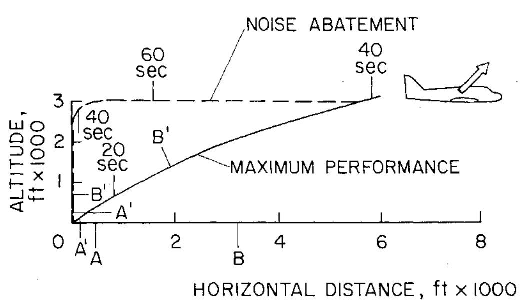


Fig. 11 Lift-fan maximum performance and proposed noise abatement takeoff profiles.

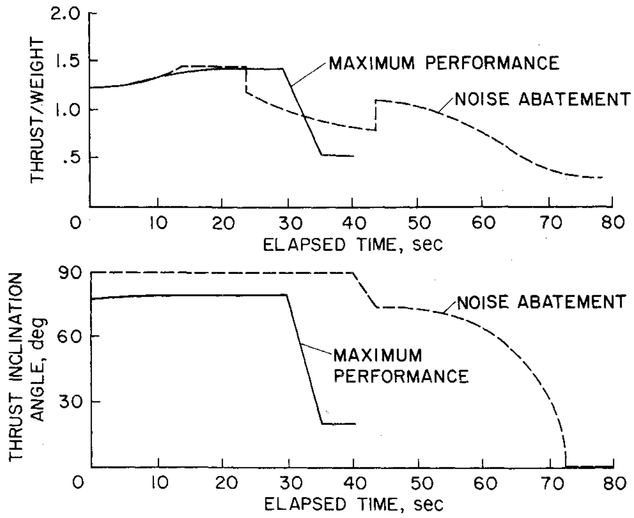


Fig. 12 Lift-fan thrust to weight and thrust inclination angle time histories.

each measuring location. Unfortunately, the reductions in annoyance are not as large as those obtained by altering the takeoff flight profile of the tilt-rotor aircraft. Because the maximum performance trajectory of the lift-fan aircraft is much steeper than the tilt-rotor's maximum performance trajectory, further increases in flight path angle of the lift-fan aircraft to near vertical do not radically increase the distance from the point of maximum annoyance to any given measuring location and thus do not cause large reductions in annoyance. Furthermore, the performance costs (as measured in time and fuel consumed) to achieve this noise reduction are almost twice the near-optimal climbing performance of the aircraft. Because the disk loading of the lift-fan aircraft is high, the extra fuel used as a result of flying the proposed noise abatement profile may significantly reduce the range payload capability of the vehicle.

These results suggest that the maximum performance takeoff trajectory of the lift-fan aircraft may already exhibit some of the benefits of flight trajectory management to reduce noise. Further steepening of the flight path for

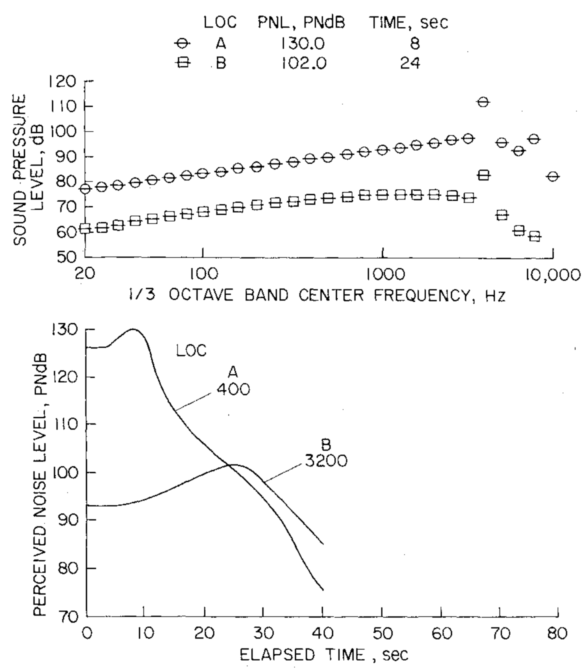


Fig. 13 Lift-fan one-third octave band analyses and PNdB time histories for a maximum performance takeoff trajectory.

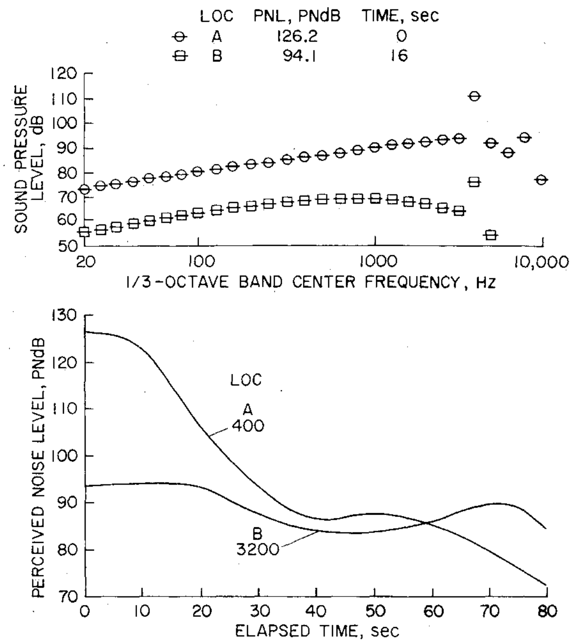


Fig. 14 Lift-fan one-third octave band analyses and PNdB time histories for a proposed "Noise Abatement" takeoff trajectory.

noise reduction will be successful but costly. However, these results also imply that shallowing the flight path to more conventional takeoff flight profiles will decrease performance and will definitely increase the ground annoyance level directly under the flight path.

Flight Trajectory Management to Reduce Acoustical Annoyance Areas

Unfortunately, reducing the noise at selected locations beneath the flight path is only part of the overall VTOL noise problem. It is quite conceivable that the noise heard at other measuring points located to the side of the flight path may increase in level and/or duration as a result of flying "noise abatement" flight paths. Therefore, the question of whether flight trajectory management is an asset or a liability to the surrounding community cannot be answered by a two-dimensional theoretical analysis, but must be approached in three dimensions.

To help resolve this question, the tilt-rotor performance and acoustic model was mathematically flown along selected flight paths to generate maximum and effective

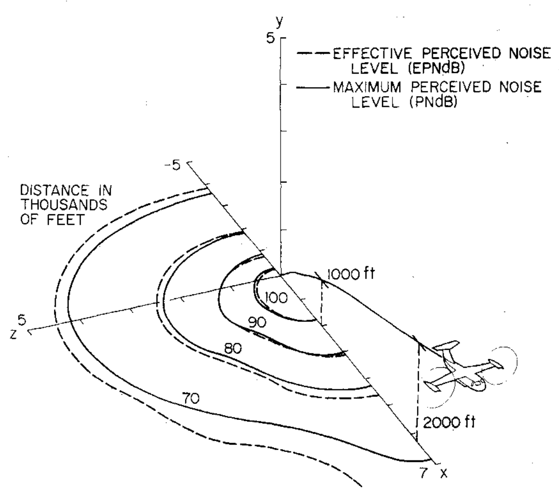


Fig. 15 PNdB and EPNdB contours for a maximum performance takeoff.

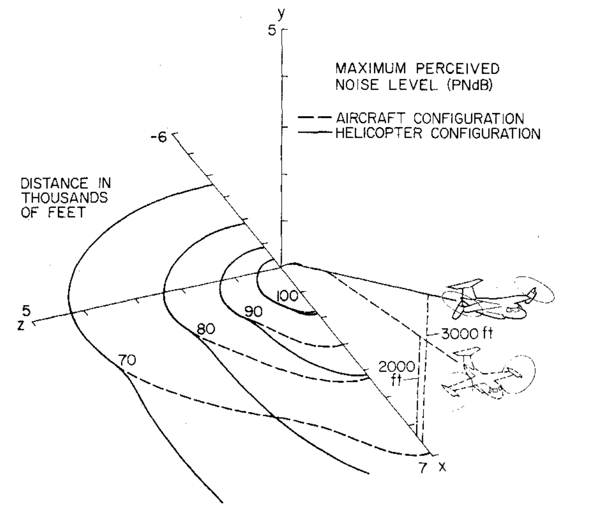


Fig. 16 PNdB comparison—helicopter mode takeoff vs maximum performance takeoff.

perceived noise level contours on the ground plane. Only takeoff flight profiles were considered in this initial assessment. The minimum time/minimum fuel takeoff flight profile, which is diagrammatically shown in Figs. 4 and 15, is chosen as a reference case with which to compare the effectiveness of proposed noise abatement trajectories.

The solid lines in the X-Z plane of Fig. 15 depict the constant maximum perceived noise level contours (PNdB). Because the theoretical acoustical model generates symmetrical contours about the projected flight path, only one-half of the resulting pattern is shown. Notice that applying maximum power and accelerating at the permissible limits cause an initially large climb angle which results in noise contours which are distinctly different from those generated by CTOL aircraft. The downrange maximum PNdB lobes are substantially shortened because of the increased altitude at the time of fly-by and because of an early transition to the airplane configuration.

The effective perceived noise level (EPNdB) contours are also shown in Fig. 15. The EPNdB subjective measure of annoyance penalizes sounds of long duration, thus resulting in an EPNL higher than the maximum perceived noise level, while short duration sounds lead to an EPNL lower than the maximum PNL. However, the curves shown do not utilize the standard linear jet EPNdB energy correction for duration, but employ the results of Ref. 14 for VTOL aircraft.§ The relative effect of changing the duration of a sound upon its subjectively rated annoyance is allowed to decrease exponentially with increasing duration. For example, for duration intervals of 15–30 sec, a 2 PNdB correction is added to the maximum PNdB value, while for durations of 120–240 sec, a 0.75 PNdB correction is required. The relative change in total annoyance area resulting from subjective duration corrections is evaluated by comparing the constant EPNdB and PNdB contours shown in Fig. 15. Because the lower noise levels (80, 70) occur for long periods of time, the net area encompassed by these contours increases substantially. However, the very high subjective (100, 95) contours are of short duration, thereby causing a decrease in the total area encircled by these contours.

§Reference 14 also concludes that PNdB as a subjective measure of annoyance of rotary-wing or propeller driven aircraft is 3 to 4 PNdB too conservative. This result has not been incorporated in the present analysis. As a result, the footprints shown are thought to be subjectively optimistic.

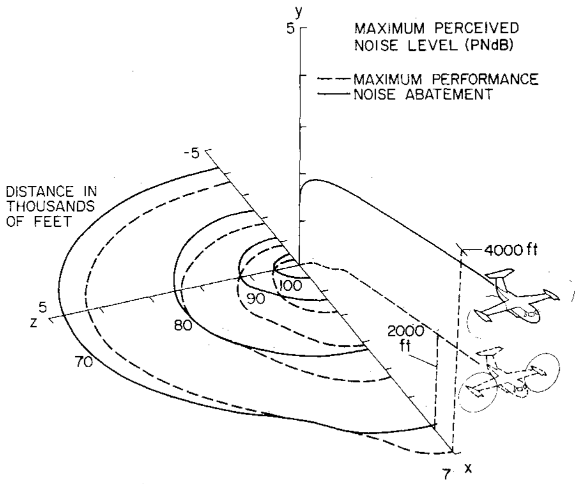


Fig. 17 PNdB comparison—extended vertical ascent takeoff vs maximum performance takeoff.

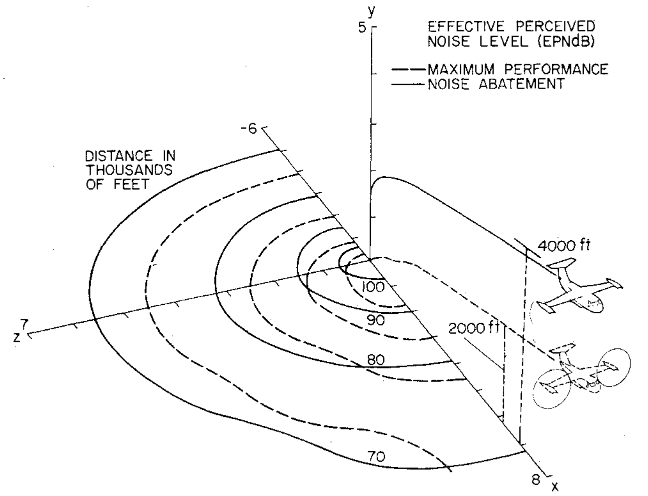


Fig. 18 EPNdB comparison—extended vertical ascent vs maximum performance takeoff.

The maximum performance takeoff which has been illustrated in Fig. 15 has one distinct acoustic advantage—early conversion to the airplane configuration. The low thrust and power levels associated with the airplane mode of flight are indicative of efficient takeoff performance and result in relatively low noise levels. For purposes of comparison, a similar takeoff profile was flown in the helicopter mode of flight (Fig. 16). The tilt-rotor accelerated at the allowable limits until the maximum power and the best rate of climb speed constraints were encountered in the helicopter configuration. The aircraft then maintained this configuration, yielding a steep flight profile. Substantial increases resulted in the areas encompassed by the constant maximum PNdB contours over those generated by the pure maximum performance takeoff flight profile (also illustrated in Fig. 16 by the dashed curves). Because the thrust levels required to maintain steady flight in the helicopter configuration are high, the resulting noise footprint areas are large in spite of an increased minimum distance between the observer and the aircraft at the time of fly-by. Thus, early transition to the airplane configuration can be concluded to be an effective means of reducing the takeoff noise "footprint" areas.

Reducing the applied power does not, in general, reduce the noise "footprint" areas for the tilt-rotor aircraft. Because most of the terminal area takeoff noise is generated in the helicopter configuration when the required thrust is nearly equal to the aircraft weight, reducing the power primarily causes a net reduction in the permissible rate of climb. The resulting decrease in altitude attained more than outweighs the lower source noise levels, causing a net increase in the noise heard on the ground.[6] Although in the airplane configuration, some reduction in noise is possible at selected measuring locations by reducing power, the already small values of required thrust and power generate relatively low levels of noise and are not considered to be a major problem.

It has been suggested, both in the U.S. and Europe, that near-vertical takeoffs would reduce the noise "footprint" areas around proposed VTOL ports. It has been shown that significant reductions in noise levels can be obtained at points located directly under the projected flight path. One such "noise abatement" trajectory is illustrated in Figs. 17 and 18, together with its maximum PNdB and EPNdB contours. The dashed lines in these same figures represent the reference case—a maximum performance takeoff. The trajectory consists of an initial pure vertical climbing segment at maximum power subject to a vertical acceleration constraint of $0.2g$. At an altitude of 1500 ft, the aircraft commences a maximum performance takeoff, thus converting as quickly as possible to the airplane configuration while simultaneously maintaining its maximum rate of climb.

The maximum perceived noise level contours which are shown in Fig. 17 change dramatically. As expected, the benefits of a pure vertical climbing trajectory are most noticeable directly under the flight path. However, at high noise levels, as much as a 50% reduction occurs in the area encompassed by the 100 and 90 PNdB contours. At the lower levels of noise, the net decrease in area is less dramatic. At the 70 PNdB level, the area encompassed actually increases. This increase is caused by the unfavorable directivity effects of broadband noise.

Figure 18 illustrates the changes in the effective perceived noise level contours which occur when the proposed "noise abatement" trajectory is implemented. Compared with maximum PNdB contours of Fig. 17, less dramatic area reductions are shown. The 100 and 90 EPNdB contours still decrease, but the area encompassed by the 80 EPNdB contour increases. The extended duration of the noise levels resulting from the additional time spent climbing vertically to 1500 ft tends to reduce the acoustical advantage of this proposed noise abatement flight profile.

The choice of 1500 ft for an initial vertical ascent height was quite arbitrary. Further reductions in some annoyance areas are realized if longer pure vertical climbing segments are permitted. Figure 19 illustrates the effect of

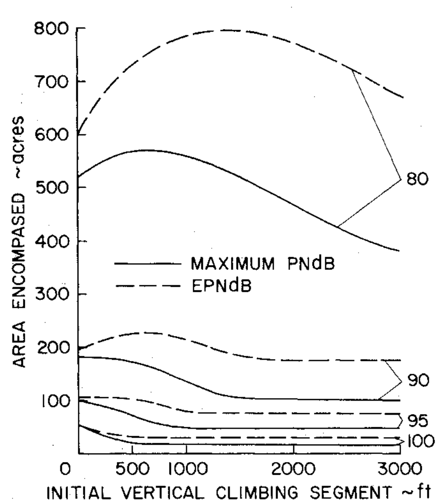


Fig. 19 Influence of the height of vertical ascent on PNdB and EPNdB contour areas.

initial vertical ascent height on the 80, 90, 95, and 100 annoyance areas. In general, the acreage encompassed by all of the maximum perceived noise level contours decreases to some asymptotic value with increasing height, except for an initial area increase in the lower noise levels at small vertical ascent heights.

The annoyance areas encompassed by constant EPNdB contours vs initial ascent height are also plotted in Fig. 19. Unfortunately, many of the gains obtained through the proposed "noise abatement" profiles are mitigated somewhat when the maximum annoyance levels are corrected for duration. The additional time which is required in the helicopter mode of flight to attain the desired height of the initial pure vertical climb trajectory increases the effective annoyance of the noise abatement profile.

It is highly unlikely that long vertical takeoff segments will be implemented in the near future. The control, safety, and guidance problems are, at present, too difficult. However, vertical takeoffs to altitudes of 500 to 1000 ft might be considered if large reductions in annoyance areas were possible. Unfortunately, at these low initial altitudes, Fig. 19 indicates that significant EPNdB reductions are only possible at the high levels of annoyance. Thus, the flight path of the VTOL aircraft can be altered to reduce the complaints of those people who are exposed to the most subjectively annoying sound at the probable expense of increasing the number of people who are exposed to a lower level of subjective annoyance.

Concluding Remarks

Controlling the flight path of VTOL aircraft in the terminal area can be an effective means of reducing operational noise. Very substantial annoyance reductions are possible at measuring locations directly beneath the flight path. By managing two-dimensional flight paths, up to a 10 $PNdB_{max}$ reduction at specific ground measuring locations is possible on takeoff and landing for a tilt-rotor aircraft flying a suggested noise abatement trajectory as compared with a performance optimal trajectory. Similar reductions in annoyance were shown feasible for a representative model of a fan-lift VTOL aircraft.

The enlargement of the distance from the measuring point to the noise source appears to cause most of the direct benefits of flight path control. The larger distances reduce noise through spherical spreading (6 dB per doubling of distance) and rapid attenuation of high-frequency sound with distance. Lift-fan aircraft benefit the most from the latter effect because of their characteristically high-frequency acoustic spectrum.

The cost, in terms of performance, of flying the proposed noise abatement trajectories can be significant. Near vertical takeoffs and landings incur as much as a 100% increase in landing and takeoff time of flight. However, because the prop-rotor class of VTOL aircraft has characteristically low disk-loadings, these aircraft consume less fuel than the higher disk-loading lift fan aircraft when maneuvering in near-hovering flight. As a result, the additional fuel required to perform noise abatement trajectories for the prop-rotor class of aircraft is small when compared with the total fuel load. A more critical assessment of the lift-fan noise performance tradeoffs is warranted. The higher disk loadings of these aircraft make them less efficient hovering vehicles and as a result, they use larger amounts of fuel when flying "noise abatement" trajectories.

The decreasing exponential time duration correction to the maximum PNdB levels does remove the ambiguity introduced by applying the linear jet time duration correction to VTOL aircraft. Duration corrections are accounted for in a logical and systematic manner and give credibility to hovering annoyance contours. However, some uncertainty as to the absolute subjective annoyance levels for rotary-wing VTOL aircraft still exists. The establishment of a true measure of rotary-wing annoyance awaits further research.

Flight trajectory management can be used to reduce the annoyance level areas encompassed by VTOL operations. However, the total land area encompassed by any one level of annoyance may increase or decrease, depending upon the specified level of annoyance. In general, high annoyance areas are reduced at the expense of an increase in lower annoyance level areas.

The ultimate determination of acceptability of VTOL parts to neighboring surburban communities cannot be answered in a study such as this. It is dependent upon many additional factors in addition to the absolute subjective annoyance evaluation of one VTOL profile. Population distribution and ambient noise levels of the surrounding area as a function of the time of day are known to be of importance in predicting community reaction to acoustic annoyance. The frequency of the proposed VTOL service should also be included in the evaluation of the ultimate acceptability of the VTOL system. In any case, it is obvious that the aircraft itself should be designed to be as quiet as is economically feasible. This will help reduce the annoyance area contours in the most effective manner. After this has been accomplished, some additional annoyance area reduction is possible through flight path control in the terminal area.

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