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POSSIBILITIES AND PROBLEMS OF ACHIEVING COMMUNITY
NOISE ACCEPTANCE OF VTOL

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POSSIBILITIES & PROBLEMS OF ACHIEVING COMMUNITY NOISE ACCEPTANCE OF VTOL

(Through Design & Flight Trajectory Management)

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Abstract

Two methods of decreasing the acoustical annoyance of VTOL aircraft to the surrounding community are reviewed; reducing the noise at the source through aircraft design, and managing the flight path in the terminal area. Advanced rotorcraft and lift-fan aircraft are discussed in this context with emphasis placed upon understanding the noise performance tradeoffs of rotary-wing designs. A method of evaluating total community annoyance is proposed which accounts for the population distribution within the acoustically affected areas and the ambient noise levels of the community. The resulting methodology is applied to two hypothetical VTOL ports located in existing urban communities, assuming present and 1980 levels of technology.

## Introduction

In view of the increasing awareness of the population to noise pollution, reduction of aircraft noise annoyance to an acceptable level becomes one of the necessary conditions for the acceptability of aircraft operations close to populated areas. In particular, reducing the subjective acoustical annoyance of VTOL aircraft to the surrounding community should become the common objective of aircraft manufacturers, airport planners, potential aircraft operators and the community itself if the latter is to benefit from all the possible advantages of VTOL service.

Rotary-wing aircraft as represented by helicopters and tilt-rotors, and lift-fan configurations may be cited as design concepts that appear to be potentially the most suitable for large-scale VTOL short-haul operations. The helicopter, which is the only VTOL transport that is presently in commercial service, has a relatively high direct operating cost. The tilt-rotor aircraft offers the promise of lower direct operating costs and low noise levels in cruising flight. It is currently under development in the United States and could enter regular commercial service in the 1980s. The transport size lift-fan aircraft may become operational at an even later date. It promises excellent riding qualities, low direct operating costs, and relatively quiet cruising flight.

All of these configurations are candidates for the short-haul market. However, just what is a representative short-haul market? A market analysis expert would undoubtedly like to link CTOL airports, city centers and outlying suburbs into one transportation system. Such a large network of high and medium density operations would probably lower the cost and insure a succesful operation. However, if the acoustical signature of the chosen VTOL aircraft is not acceptable to the neighboring communities, only limited VTOL service may be possible which could make the entire operation unprofitable. It is, therefore, of utmost importance to attempt to establish whether the present level of design and operational technology would make those potentially suitable VTOL aircraft acceptable to a wide range of communities, including residential ones, or whether new technological strides would be required in order to achieve this objective.

There are three basic avenues toward the goal of establishing acceptable outdoor acoustical environments: (1) reduction of noise level at its source through proper design of VTOL aircraft, (2) improvement in the acoustical exposure of the community through management of the terminal flight trajectories, and (3) location of VTOL ports near noise insensitive areas.* All of the above approaches have their particular problems and induce various "penalties" which must be weighed together with the operational advantages of a short-haul VTOL system.

The first two approaches, which are the concern of VTOL designers and operators, are reviewed in this paper. Estimates of acceptable community noise levels for VTOL aircraft are initially made through a literature review. Then both methods (design and flight trajectory management) of achieving those levels, as well as the associated weight and performance tradeoffs, are discussed for prop-rotor and lift-fan VTOL concepts, with more emphasis placed upon underscoring the possibilities and problems of the rotary-wing aircraft.

Community acceptance of a proposed VTOL short-haul operation is further investigated by assuming present and 1980 levels of technology, and evaluating noise annoyance for two suburban communities in the San Francisco Bay area. The importance of locating VTOL ports near noise insensitive areas is highlighted by the choice of two character-

*Possible additional improvements through noise absorption and reflections by special acoustical barriers will not be considered here.

istically different communities. Background noise levels, local population densities, and the intrusive nature of VTOL sound are estimated for chosen airport locations in each case. The total number of people exposed to specified differences between VTOL-generated and background noise levels is then evaluated to determine the likelihood of community acceptance.

Review of Noise Standards

Figure 1, based on a presentation by Cortright[1] of NASA, shows the noise standards projected for transport aviation in general.

An equivalent perceived noise level (EPNL) of slightly above 85 EPNdB* for compound helicopters in 1980 and 85 EPNdB for the tilt-rotor in 1985 is projected. The predicted trend for prop-rotor VTOL aircraft in general is supported by the Boeing Model 347 - an example of an advanced helicopter of the 45,000-pound gross weight class. These figures, as well as studies undertaken by the Noise Subcommittee of the American Helicopter Society[2], indicate that an annoyance level of approximately 95 PNdB at 500 feet represents the acoustic state-of-the-art of current advanced rotary wing VTOL transports. It should be noted however, that for small helicopters (2000 - 3000-pound gross weight class), much lower perceived noise levels have been demonstrated. For example, the Hughes quiet version of the OH-6A model[3] exhibits a PNL of about 80 PNdB in hover at a distance of 150 feet, corresponding to a reduction of about 14 PNdB from the standard production aircraft.

For the lift-fan aircraft, Cortright shows 95 EPNdB as a goal for 1985.

As to the subjective reaction to noise, surveys of noise annoyance conducted in Los Angeles and London, and reported in Ref 4 seem to indicate that the PNL levels below 85 PNdB would be acceptable for the outdoor noise standards. However, Richards' Noise Acceptance Curve[5] (also shown in Fig 1) suggests that the PNL noise level of about 85 PNdB (corresponding to the upper noise limit of heavy city traffic) would probably be accepted only by about 30 percent of the population exposed to that noise level. Joint DOT-NASA Civil Aviation Research and Development Policy Study[6] recommends 80 EPNdB for VTOL aircraft at the airport boundaries achieved through both noise reduction at the source and flight trajectory management.

It has been recognized that in addition to the absolute PNL or EPNL values, which may become intolerable, a relative elevation of the noise level above that of the background also represents a very important criterion of the acoustic tolerance. Fig 2, based on recently published studies[7],

*For the rotary-wing type aircraft where there is usually no need for the pure-tone corrections, the PNL may be assumed as equivalent to the EPNL for the case of hover of 15-second duration, which may be considered as representative for short-haul operations.

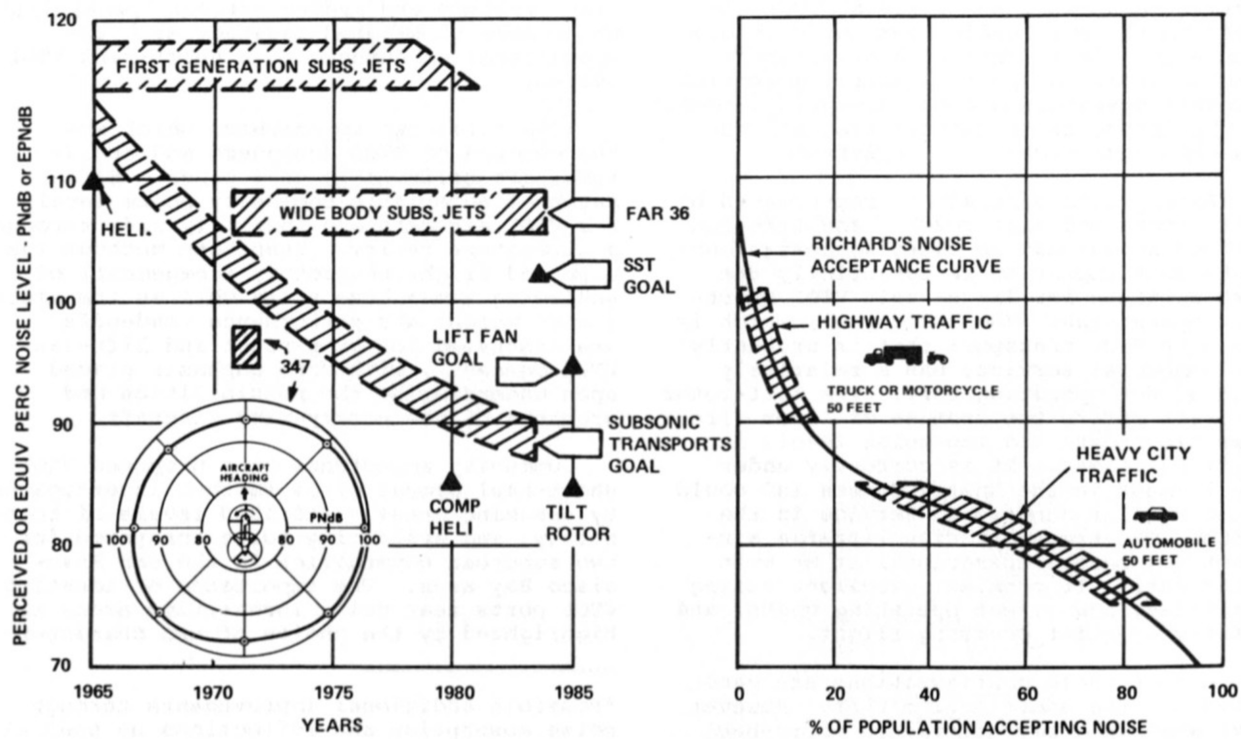


Figure 1. Aircraft Noise Trends

indicates that the percentage of people who are annoyed is almost a linear function of the difference between the intrusive and background noise levels. It also suggests that EPNLs which may be acceptable to a basically noisy downtown or industrial area would not be tolerated in quiet suburban residential neighborhoods. This obviously implies that it may be more difficult to bring VTOL service to these residential districts.

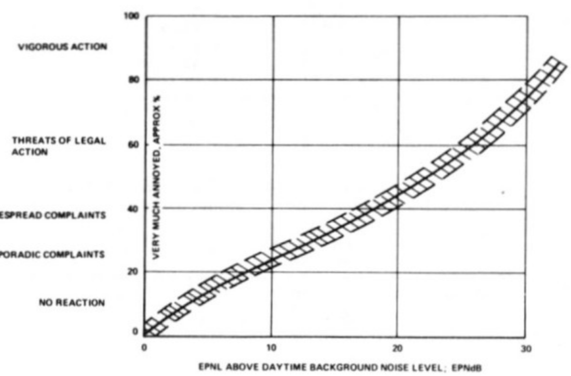


Figure 2. Noise Acceptance, based on Background EPNL

Finally, recognizing that a still more refined approach than that provided by the PNL or EPNL scale may be needed to truly reflect subjective reaction to noise generated by different types of VTOL aircraft, NASA-Langley sponsored a special study by Boeing's Vertol Division[8]. In this study, subjective reaction to a simulated outdoor noise of a transport tandem helicopter (GW = 46,300 lbs) and a tilt-wing aircraft (GW = 71,700 lbs) was registered by subjects engaged in work and leisure activities under typical indoor conditions. Individual reaction to the noise level experienced indoors, when the two considered aircraft were generating various PNL outdoors, was registered on a scale from 1 to 9, where 1 represented the most favorable and 9, the most unfavorable reaction. Results of these tests conducted by Sternfeld, Hinterkeuser and Hackman are summarized in Fig 3. A glance at this figure will indicate that in spite of the differences associated with the noise characteristics of the helicopter and that of the tilt-wing, an outdoor PNL of up to about 85 PNdB could be considered as an acceptable upper limit by people enclosed in a typical housing structure and engaged in work requiring mental concentration.

In light of the above inputs, it appears that by taking present advanced transport helicopters (PNL of about 95 PNdB at 500 feet) as representative baseline aircraft, a reduction of noise at the source (in hover) of the rotary-wing VTOL by at least 10 PNdB and preferably by 15 PNdB will be required. Achievement of acceptable community noise levels for close-to-population-center operations by lift-fan VTOL aircraft will require much larger PNL reductions from the presently demonstrated values. The resulting penalties for both types of aircraft can now be ascertained with these goals in mind.

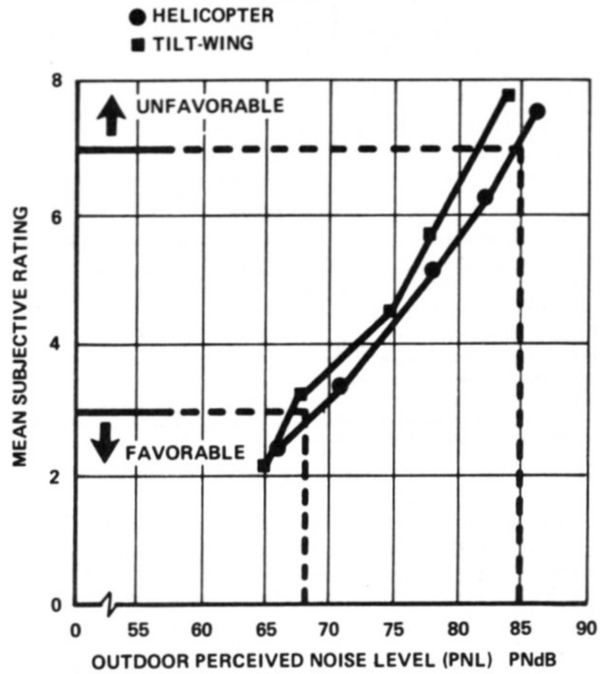


Figure 3. Psychoacoustical Scaling of Subjective Responses

Noise Reduction at the Source

Variation of the Direct Operating Cost (DOC) per seat mile with the noise level[9,10] appears, at first sight, as an attractive overall criterion for evaluating the penalties associated with the improvement of acoustic characteristics of VTOL transports. However, it does not permit a more direct step-by-step insight into the influence of various design parameters and approaches; thus, it is more difficult to scrutinize. For this reason, penalties associated with noise reduction will be expressed here as relative variations (with respect to the baseline aircraft) of weight and/or performance parameters associated with a given decrease ($-\Delta N$) in the perceived noise level.

If it were possible to have a simple closed-form expression relating various design and other parameters of the aircraft to the PNL level at a given distance, it would be much easier to evaluate the acoustic importance of various changes in those parameters and estimate the associated tradeoffs. Unfortunately, there is no such universal formula as yet. For this reason, it is necessary to look separately at the most offensive components of noise at the source and to review possible means of combating them.

Rotary-Wing VTOL

It has been generally accepted[11 12 13] that for the turbine-powered rotary-wing aircraft, sources of the most annoying sound can be listed in the order shown in Table I.

| | NOISE ORIGIN | POSSIBLE MEANS OF NOISE REDUCTION |
|---|---|---|
| 1 | BLADE SLAP (HOVER AND FORWARD FLIGHT) | $V_t\downarrow$; $DL\downarrow$; BT; $BN\uparrow$; RC; AS; $c_{\ell_x}\downarrow$; $\psi$ |
| 2 | TAIL ROTOR ROTATIONAL NOISE | $V_t\downarrow$; BT; $BN\uparrow$; $\bar{c}_\ell\downarrow$; AS; $DL\downarrow$ |
| 3 | MAIN ROTOR BROADBAND (VORTEX) AND ROTATIONAL NOISE | $V_t\downarrow$; $\bar{c}_\ell\downarrow$; $BN\uparrow$; $DL\downarrow$; AS |
| 4 | TURBINE ENGINE NOISE | Basic Engine Design (elimination of inlet guide vanes, etc). Acoustical treatment of inlet and engine enclosure. |
| 5 | TRANSMISSION NOISE | Minimizing dynamic responses and acoustical treatment of enclosures. |

SYMBOLS:

Increase: $\uparrow$ Decrease: $\downarrow$ Tipspeed: $V_t$

Average and Section Lift Coefficients: $\bar{c}_\ell$; $c_{\ell_x}$

Blade Tip (Geometry, Air Mass Injection, Spoilers): BT

Blade Geometry (Planform and Twist): BG

Blade Airfoil Section: AS Number of Blades: BN Disc Loading: DL

Rotor(s) Configuration (Unequal Radii of Blades, Vertical Separation of Blade Tip-Path Planes): RC

Unequal Azimuth Indexing, and Position of Rotors : $\psi$

TABLE I

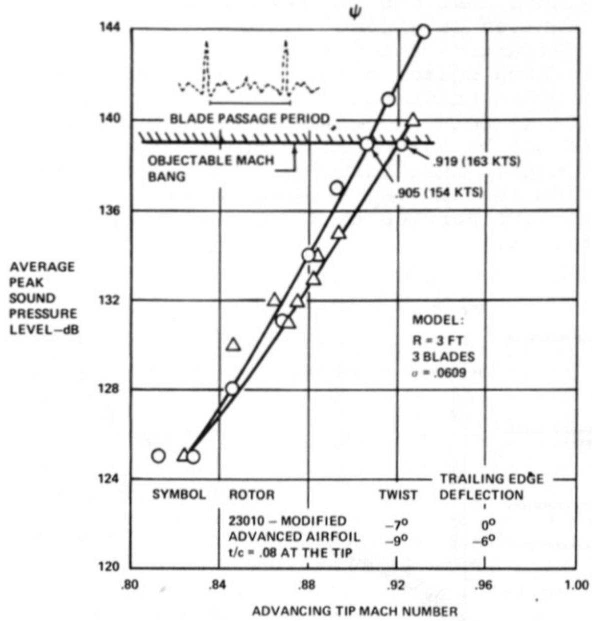


Figure 4. Example of the Influence of Airfoil Section on High-Speed Bang

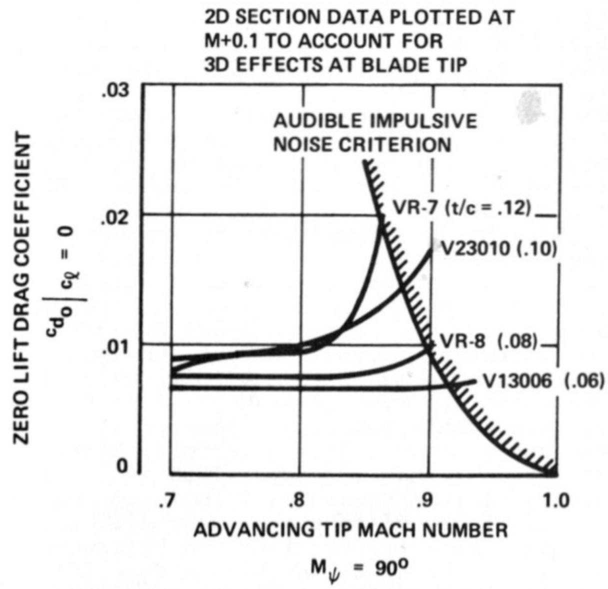


Figure 5. High-Speed Impulsive Noise Criterion

Because of space limitation, prime attention will be concentrated on items (1 and 3) referring to the lifting rotors with the understanding that some of the following discussion may be applicable to the tail rotors as well. It should be noted, however, that once the main rotor(s) noise has been reduced to a low level, then engine noise may become a predominant factor in determining the PNL of the aircraft.

Several possible ways of reducing the noise level of rotary-wing VTOL aircraft are also indicated in Table I. A more detailed discussion of the relative effectiveness of these approaches and the associated tradeoffs is conducted below.

Blade Slap. With its characteristic acoustic signature, blade slap (Fig 4) can occur in many regimes of flight.

In high-speed forward flight, blade slap is usually due to the compressibility phenomena occurring on the advancing blade of the helicopter rotor. Boeing studies[14] indicate that in this case, the impulsive noise can be attributed to the rapid drag rise of the advancing blade tip, coupled with Doppler effect. Reduction of the resultant advancing tip Mach number (reduction of tip speed) and selection of a suitable blade airfoil (low thickness ratio and favorable pressure distribution, etc.) as well as proper blade loading (through twist and planform) in the blade tip area are known means of eliminating or reducing the high-speed blade slap. Fig 4, from wind-tunnel model tests illustrates this point, while Fig 5 shows a relationship between the zero lift drag coefficient and resultant Mach number of the tip, establishing the permissible impulsive noise boundary. In this respect, both Figs 4 and 5 seem to indicate that $M_{\psi=90°} \approx .92$ represents a practical limit, even for thin (t/c = 6%) low drag airfoil sections. In principle, properly swept blade tips can increase the above limit. However, the flight tests performed so far (with the Boeing 347 helicopter) have resulted in only nominal gains.

Hence, by accepting $M_{\psi=90°} \approx .92$ as a limit, the acoustically permissible boundary for maximum flight velocity vs tip speed can be established (Fig 6). In this figure, another boundary representing typical upper limits for operational advance ratios ($.38 \leq \mu \leq .40$) of conventional helicopters is also shown.

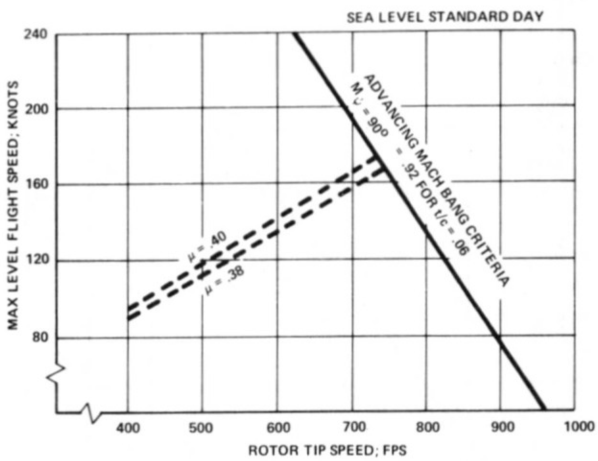


Figure 6. High-Speed Bang and Advance Ratio Limits for Conventional Helicopters

It can be seen that in order to satisfy both boundaries and at the same time attain flight speeds suitable for transport operations (V $\geq$ 160 knots), the corresponding tip speed should be about 700 to 730 fps. In general, similar performance limitations must be applied to all conventional helicopters to avoid high-speed bang. As to the weight penalties associated with these limitations, they can probably be minimized if proper solutions are incorporated during the early design stages of the rotor system.

Banging in hover and low-speed regimes of flight is probably caused by interaction of the tip or rolled-up vortices from the preceding blades with the oncoming blades. Consequently, two potentially feasible ways of attacking this problem appear: (1) modification of the structure of the vortex itself, and (2) enlargement of the dimensional separation between the vortices and the blades.

The first of these objectives is usually approached through special blade tip design: geometric shape, spoilers, tangential blowing (direction opposite to the vortex circulation) and axial injection (aft, along the vortex axis)(Fig 7).

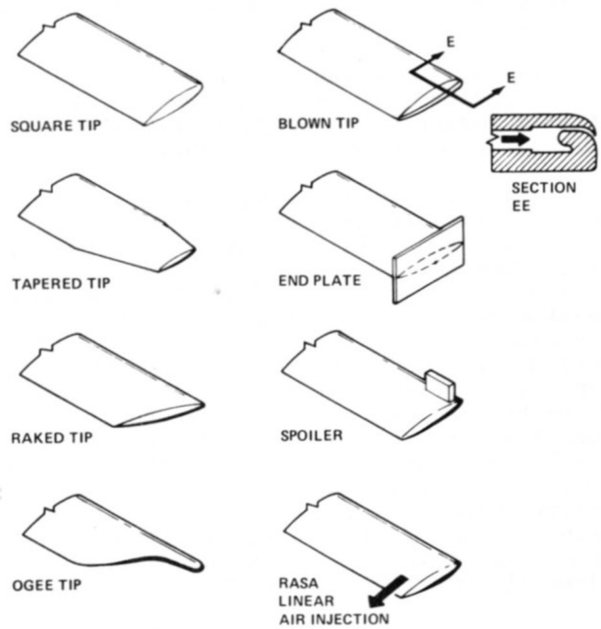


Figure 7. Examples of Various Blade Tips

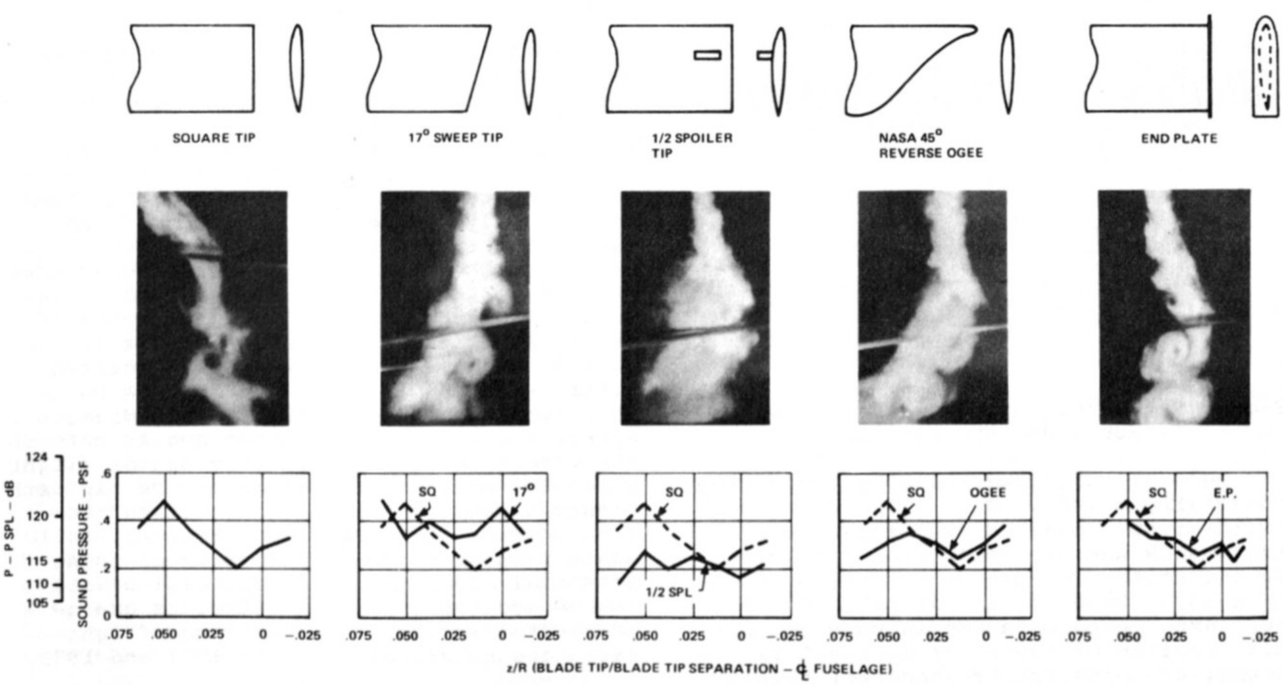


Figure 8. Comparison of Shed Vortex and Noise Level for Several Tip Configurations

Several investigators[15 16 17] show that, indeed, the structure of the vortex itself can be significantly modified by some of those means and maximum tangential velocity occurring in the vortex can be considerably reduced. For instance, Rorke, Moffitt and Ward[16] indicate that for the ogee tip, average maximum tangential velocity ($V_\theta$) amounts to only 25% of that of the square tip. Monnerie and Tognet[17] found that similar results can be obtained by tangential blowing while even simply tapered tips reduce $V_\theta$ to about 70 percent of the square tip value.

Smoke visualization, shown in Fig 8 (from Boeing's wind-tunnel studies on a tandem helicopter model), graphically illustrates the above-discussed subject.

This figure also suggests that a spoiler located at the blade tip may be quite effective in changing the vortex structure. Unfortunately, as far as noise reduction through tip shapes is concerned, Boeing tests are inconclusive. This may be partially due to the fact that measurements were performed on a tandem configuration and apparently, the blade tip position of the lower rotor with respect to the disc of the upper one (z/R parameter in Fig 9) appears to be of about the same importance as the structure of the vortex. Nevertheless, it seems that such a radical suppression of the vortex structure as in the case of the spoiler produces some general reduction of the SPL (Fig 8).

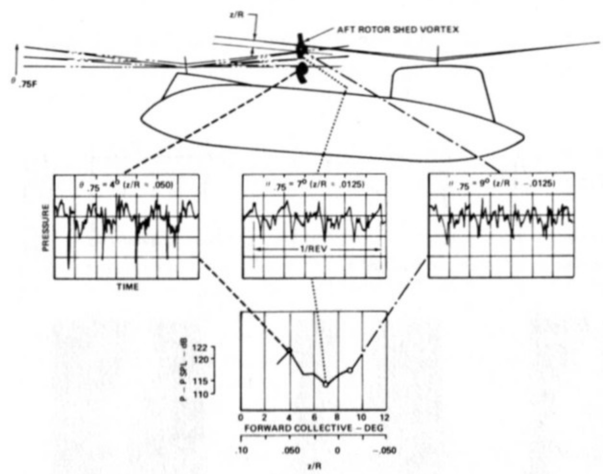


Figure 9. Effect of Vertical Separation on Sound Pressure Level

However, the power penalty, amounting to $\Delta RP/RP_o \approx 74\%$ at $\overline{c}_{\ell h} \approx .33$ (where $RP_o$ is the rotor power for the square blade tip) makes use of the spoiler, at least in its primitive form, not very practical (Fig 10). However, use of retractable spoilers, being extended in some particular regimes of flight (e.g., partial power, or autorotative descents) should not be completely ruled out.

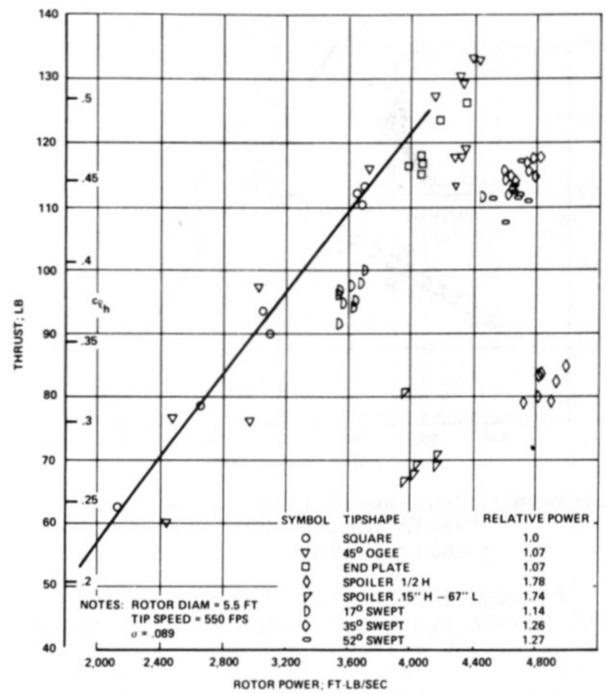


Figure 10. Thrust vs Power for Several Blade Tips

The NASA, Langley-developed ogee tip presently appears as one of the more practical approaches. However, power penalties associated with this concept appear somewhat contradictory. Fixed-wing tests reported in Ref 16 indicate that aerodynamic characteristics of blades with ogee tips should be superior to those with rectangular ones, while Boeing model rotor tests show a low, but still noticeable, power penalty of $\Delta RP/RP_o \approx$ 7-8% at $\overline{c}_{\ell h} \approx .46$ (Fig 10).

In addition to the tip speed reduction and special blade tips, there are other means of suppressing blade slap (see Table I). An increase of the number of blades (at constant thrust) is one method which should be, in principle, beneficial. It would reduce the spanwise blade loading and consequently, reduce the strength of the tip vortices. However, the increased blade number might contribute to smaller distances between vortices and blades. For this reason, new ways of dimensional separation of the tip vortices and oncoming blades in various regimes of flight of the isolated rotor are being investigated by NASA Langley. They include different blade diameters within the same rotor; uneven angles between the blades, either permanently set or flight variable; unequal elevations of the tip path planes of two sets of blades (within the same rotor); etc. (Fig 11). However, full-scale results of the application of those potential means of noise suppression will not be available for some time, as appropriate full-scale wind tunnel and flight tests are scheduled for late 1972 and 1973.

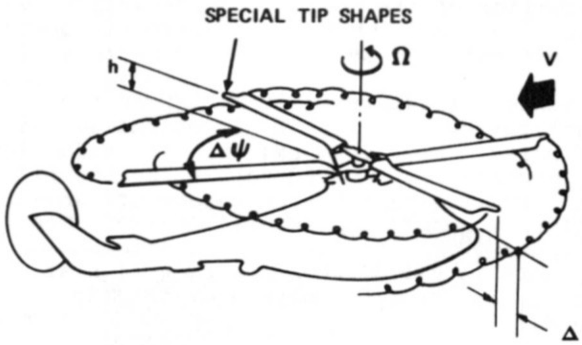


Figure 11. NASA, Langley's Proposed Variable-Geometry Rotor for Control of Noise Due to Blade-Vortex Interaction

Application of some of the above discussed means of combating blade slap may result in structural weight and performance penalties. For instance, aerodynamically active blade tips, flight variable azimuth indexing of blades, enlarged vertical separation of tip path planes in the case of tandem helicopters (e.g., Boeing 347) etc., would increase structural weight and in the case of blown blade tips, some power expenditure would be required. However, if the problem of blade slap is faced during the formulation of aircraft concepts and proper steps are taken during the early design stages, the use of previously discussed methods (with the exception of $V_t$ reduction which will be discussed later) should not result in any noticeable weight and performance penalties.

Broadband and Rotational Noise. Broadband and rotational noise of the main rotor(s) becomes the most important source of subjective annoyance in the configurations without tail rotors (tilt-rotors, tandems, etc.) once the blade slap has been eliminated.

In a physical sense, rotational noise and blade slap have much in common. In both cases, there is an element of interaction between wake vortices and the blade. Thus, blade slap (in other than high-speed regimes of flight) may be considered as a particular case of strong manifestation of that interaction. For this reason, many of the means suggested for blade slap suppression, especially through modification of the vortex structure and wake geometry (e.g., special blade tips, increase of the number of blades, etc.) could also be beneficial for the reduction of rotational noise. This explains why some shapes of blade tips (e.g., tapered) may contribute to the reduction of rotational noise[18]. However, because of the low rotational frequencies that may be anticipated in rotary-wing aircraft of transport size, the broadband noise appears to be an important contributor to the rotor PNL. In spite of the fact that there is evidence that some of the components of the so-called broadband noise are really high harmonics of rotational noise, the traditional concept of the broadband noise will be used here since it provides convenient relationships for establishing noise - structural weight tradeoffs.

The works of Davidson and Hargest[19], Ollerhead & Lowson[11], Leverton[12 13], etc., can be cited as attempts to develop relatively simple formulae for the overall sound pressure level (OASPL) associated with broadband noise.

For those cases where there is no appreciable shift in the frequencies spectrum, variation in OASPL can be considered as equivalent to that of the PNL ($OASPL - OASPL_o \approx PNL - PNL_o \equiv \Delta N$, where the subscript o refers to the baseline aircraft), thus providing a convenient way for investigating noise reduction at the source.

Some of the formulae for OASPL were recently checked by Boeing's Vertol Division against actual noise measurements of a helicopter rotor on a tower[20]. The OASPL prediction, based on Davidson & Hargest's formula, provided the closest approximation of the test data, and hence, it is used here to establish simple analytical relationships between noise reduction and various structural weight tradeoffs (Appendix 1). This formula, rewritten in terms of tip speed ($V_t$), thrust (T) and average blade lift coefficient in hover ($\overline{c}_{\ell h}$) for OASPL at 180 feet becomes as follows:

$$N_{180} = 40 \log V_t + 10 \log T + 10 \log \overline{c}_{\ell h} \rho - 24.3 \qquad (1)$$

It can be seen from eq (1) that at T = const., reduction of tip speed represents a much more effective means of decreasing the OASPL than reduction of $\overline{c}_{\ell h}$ (i.e., increasing the blade area, while $V_t$ remains constant). It should be remembered, however, that even in the case of noise abatement by decreasing $V_t$, the $\overline{c}_{\ell h}$ = const condition imposes modification of the total blade area ($A_b$) from that of the baseline aircraft ($A_{bo}$) in the following way:

$$A_b = A_{bo}(V_{to}/V_t)^2.$$

Fig 12 shows ratios of the new tip speed ($V_t$) to that of the baseline aircraft ($V_{to}$) that would be required to decrease the OASPL (at a selected distance) by a given dB value, when $T = T_o$ and $\overline{c}_{\ell h} = \overline{c}_{\ell h_o}$. The effectiveness of noise reduction through the $\overline{c}_{\ell h}$ decrease is also illustrated in Fig 12 by showing the ($A_b/A_{bo}$) ratios required for a given variation in OASPL (in dB), while $T = T_o$ and $V_t = V_{to}$. It can be clearly seen from this figure that indeed, the tip speed reduction approach appears as a more effective way of decreasing the OASPL.

By combining the statistical trend formulae for structural weight of the rotor/propeller and dynamic system assemblies with eq (1), simple analytical relationships can be developed between noise reduction ($-\Delta N$) through a decrease of $V_t$ and $\overline{c}_{\ell h}$ and corresponding structural weight increases. These relationships, developed in Appendix 1, are plotted in Fig 12. The resulting curves estimate the new structural weight of the rotor/propeller ($W_R/W_{R_o}$) and dynamic system assemblies ($W_{DR}/W_{DR_o}$) related to those of the baseline aircraft when the OASPL is reduced by a certain number of dB. A glance at Fig 12 will indicate that noise reduction through the tip speed decrease carries much lower structural weight penalties than those associated with a $\overline{c}_{\ell h}$ reduction (increase in the blade area, while $V_t = V_{t_o}$ and $T = T_o$).

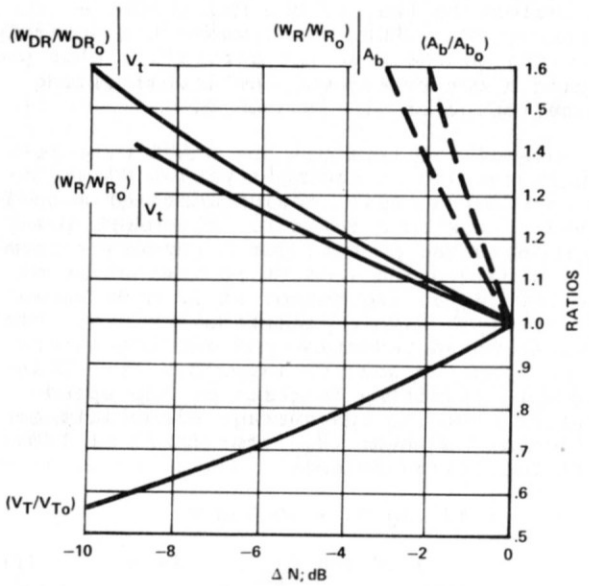


Figure 12. Noise Reduction through Blade Tip Speed Decrease (at constant $\overline{c}_{\ell h}$) and Blade Area Increase (at constant $V_t$)

Discussion

Various means of noise reduction at the source of the rotor/propeller have been discussed in the preceding sections. They all represent some ingredients of the art of practicing rotary-wing acousticians. Unfortunately, thorough understanding of the basic mechanisms of many of the sources of rotary-wing noise is still lacking. Therefore, discrete acoustical benefits resulting from proposed design changes can not be quantified and only general recommendations can be made. In fact, when acousticians are asked a direct question: "By how many dB can the noise of a given baseline aircraft be reduced through application of one, or more, of those special means?", then with the single exception of tip speed, the answer is, at least, evasive. Even noise reduction through a decrease of $\overline{c}_{\ell h}$ is somewhat controversial. For instance, acoustical benefits indicated for lower $\overline{c}_{\ell h}$ by eq (1) are contradicted by the formulae of Leverton that almost equally well-predicted the OASPL reported in Ref 20. When it comes to a quantitative evaluation of the possible acoustical benefits resulting from various blade tips, etc., the estimate may be even more uncertain.

Hence, it appears that as far as the quantitative estimate of structural weight and performance tradeoffs vs noise reduction is concerned, tip speed remains as one of the very important design parameters whose influence can be properly estimated. Consequently, in this discussion, prime emphasis is placed on noise reduction at the source through lowering of the tip speed.

Weight tradeoffs (Fig 13) were prepared in order to give some idea regarding the trends of noise reduction. In this figure, ratios of the new weight empty ($W_E/W_{E_o}$), hovering gross weight ($W_h/W_{h_o}$) and useful load ($W_U/W_{U_o}$) to those of the baseline aircraft are shown vs OASPL reduction, which is assumed to be equivalent to the PNL decrease at the source. Trends in $W_E/W_{E_o}$, shown in this figure were prepared on the basis of $W_R/W_{R_o}$ and $W_{DR}/W_{DR_o}$ from Fig 12 and the relative weight of the rotor propeller system within the limits of $.09 \leq W_R/W \leq .11$, and that of the drive system, $.085 \leq W_{DR}/W \leq .115$. It was further assumed that weight empty to gross weight ratios are within the following limits: $.52 \leq W_E/W \leq .62$. As a result of all of these assumptions, the upper limit of the $W_E/W_{E_o}$ trend graph corresponds to the higher values of the rotor and dynamic system and the lower $W_E/W$ ratios, and the lower to the opposite assumed limits. It can be seen from this plot that even neglecting further structural weight expenditures due to silencing of the powerplants, etc., the weight empty cost of reducing the source noise level in hover by 10 dB may be quite considerable. One point from actual experience[3] (normalized to a constant installed power) along with other design studies[4], support this general trend. As far as useful load ratios ($W_U/W_{U_o}$) are concerned, here some of the weight losses are recovered due to an increase in the hovering gross weight ratios at $HP_h = HP_{h_o}$. For the helicopter configurations, there is also a performance penalty. The $\overline{c}_{\ell h} = \overline{c}_{\ell h_o}$ condition would lead to "overblading" of the rotor for the forward flight condition where, due to the tip speed ratio limitations ($\mu_t \leq .38$ to $.40$, shown in Fig 6), operation at higher $V_t$ values than in hover would be required. Assuming that power available remains the same as that for the baseline aircraft, maximum speed ($V_{max}/V_{max_o}$) would be as shown in Fig 13. Tolerance of higher than $\mu = .4$ tip speed ratios, which is not very likely for pure helicopters, makes $V_{max}/V_{max_o}$ ratios more favorable. All of these inputs when reflected into direct operating cost (DOC) would indicate the trend shown in Fig 13 for the relative increase of cost per air mile of pure helicopters (lower limit for 15, and upper limit for a 100-statute mile stage length).

Looking at the practical aspects of implementation of the above discussed

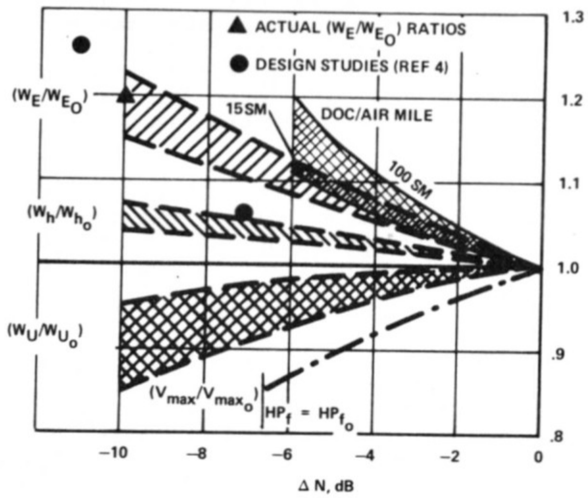


Figure 13. Weights, $V_{max}$ and DOC Trends with Noise Reduction by Lowering $V_t$

general trends, it should be noted that the current advanced state-of-the-art transport class rotary-wing aircraft (as represented, for instance, by the Boeing 347) have a tip speed in hover of $V_{t_O} \approx 690$ fps. Fig 12 implies that in order to reduce PNL at the source by about 10 PNdB, the tip speed should come down to $V_t = .57 \times 690 = 400$ fps, while in high speed cruise, a $V_t = 700$ fps, or slightly higher (Fig 6) may be required. This would lead to a two-speed transmission. Furthermore, structural weight trends, as used in the weight trade-off estimates (Fig 12), may not be reliable. Because of the very low $V_t$, they may be outside of the statistical inputs on which the trends were based.

All of this may give some idea regarding practical difficulties that may be associated with $\Delta N = -10$ PNdB in hover. Perhaps reduction of tip speed to $V_t = 500$ fps, corresponding to $\Delta N = -6$ PNdB would be more practical, while the full goal of $\Delta N = -10$ PNdB or even more, could be achieved through some other means which, unfortunately, are not clearly identified as yet.

With respect to the tilt-rotor configuration, all of the previous remarks associated with noise reduction in hover remain basically valid. However, in forward flight, reduction of speed (at $HP_f = HP_{f_O}$) would be nominal (only due to the increase of the gross weight) as propulsive efficiency of the rotor/propeller in this regime of flight should remain practically the same as for the baseline aircraft; providing, of course, that the tip speed in forward flight can be reduced in the same ratio as for the baseline case. This also should lead to a more favorable trend in the relative increase of cost per air-mile.

## Lift-Fan Concepts

There are people, both in Europe and the USA, who believe that direct-lift jet-powered V/STOL concepts have the greatest potential for future short-haul transportation[21]. However, noise problems still remain the Achilles heel of that concept. In this respect, it is frequently claimed that because of the more rapid attenuation of high frequencies with distance, a somewhat higher PNL at short distances (at the source) can be tolerated for the lift-fan VTOL than for rotary-wing aircraft. It should be remembered, however, that this might be true only for those scenarios where the potentially noise-sensitive population is sufficiently far removed from the takeoff and landing points. In this case, appreciable acoustical benefits can be derived from terminal flight trajectory management[22].

Recognizing the basic difficulties of noise reduction of the lift-fan, NASA foresees 95 PNdB at 500 feet as a goal for 1985. In order to achieve this goal, first of all, the fan-pressure ratio must be kept low and probably should not exceed the 1.25 value, while bypass ratio may be as high as 13[23]. This, of course, will tend to increase both size (volume) and weight of the engine. However, a fan-pressure ratio of 1.25 apparently is still not sufficient to achieve the 95 PNdB level at 500 feet. Ref 24 shows 110 PNdB at 500 feet for a 100,000-pound class lift-fan VTOL with twelve 10,000-pound thrust engines having unsuppressed single-stage fans of 1.25 pressure ratio. A further reduction by 15 PNdB is required. In principle, this is possible through suppression of the machinery noise with acoustical treatment of the nacelle. "However, there may be a severe mechanical problem in just finding sufficient area to treat in the small engine nacelle. Because of this, the overall feasibility of 15 PNdB suppression is problematic at this point and needs further study."[24]

As to the evaluation of penalties associated with noise reduction of the lift-fan concept, at present there is not enough trend data to estimate the structural weight and performance tradeoffs. Should the present design goals as stated by NASA be achieved, then the most important characteristics of both integral and remote lift fans would be as shown in Table II (based on Ref 23).

| TYPE / CHARACTERISTICS | INTEGRAL LIFT FAN | REMOTE LIFT FAN |
|---|---|---|
| Noise @ 500, PNdB | 95 | 95 |
| Thrust/Wt Ratio | 12 | 9 |
| Fan Press. Ratio | 1.25 | 1.25 |
| Bypass Ratio | 13 | 10 |
| Hover SFC, lb/hr-lb | .36 | .40 |

TABLE II

## Flight Trajectory Management

By carefully controlling the flight path of a VTOL aircraft near the terminal area, significant reductions in ground measured noise levels are often possible.[22] Although the concept of flight path control to minimize noise is simple, determination and implementation of the required operational procedures for VTOL aircraft is often complicated. Vehicle performance characteristics, area navigation capabilities, and safety considerations all constrain the permissible set of practical flight paths.

In the United States, several airlines are now implementing two-segment landing procedures for CTOL aircraft to reduce the noise levels in the surrounding community. A six-degree glide slope is initially maintained at low power settings with wheels and flaps retracted. At one and one-half miles from the airport, flaps and wheels are lowered and power is increased to sustain a three-degree descent to touchdown. This relatively simple operational maneuver substantially reduces the approach noise at large distances from a conventional airport. Lower power settings and larger distances between the aircraft and listener resulting from steeper approaches both reduce the noise impact area. However, questions have been raised about the safety of such procedures. The higher sink rates and lower power settings leave less room for error and require greater pilot proficiency.

Similar considerations must be kept in mind when novel approach and departure paths are considered for VTOL aircraft. The safety of the resulting operational procedure cannot be sacrificed for noise reductions. Fortunately, new and improved guidance and control schemes are being developed which, in the future will eventually allow implementation of carefully controlled VTOL terminal trajectories. The question of importance is, then, can the noise exposure of a VTOL aircraft be significantly reduced through flight path control and at what cost?


Figure 14. Boeing Model 347

To estimate the potential benefits of flight path control with present day rotary-wing technology, the Boeing 347 was flown in a limited series of approach and departure paths. This helicopter (Fig 14) was designed with noise reduction as a major program objective[25].

The solid curves of Fig 15 illustrate the maximum perceived noise level contours of an almost conventional takeoff of the 347. The helicopter first climbs to 120 feet, then applies power and initiates an approximate 10-degree climbout. Two acoustical characteristics are immediately obvious: the tandem-rotor helicopter does not have a symmetrical noise signature about the flight path; and near-conventional takeoff flight profiles markedly elongate the perceived noise level contours in the direction of the flight path. The first characteristic is easily justified by remembering that the rotors do overlap by 19 percent, thereby creating non-uniform loads in the region of overlap. The second characteristic is predominantly a result of having too low an altitude at the time of noise measurement. If a pure vertical ascent is made to 750 feet altitude followed by a 10-degree climbing segment (the dashed curves in Fig 15), a marked reduction in the total land area encompassed by the 90 PNdB contour results. Although some reduction in land area is realized for the 95 PNdB contour, little or no reduction occurs for noise levels above 100 PNdB. The resulting contours for these cases are generated in near hovering flight and as such are not influenced by flight path control.

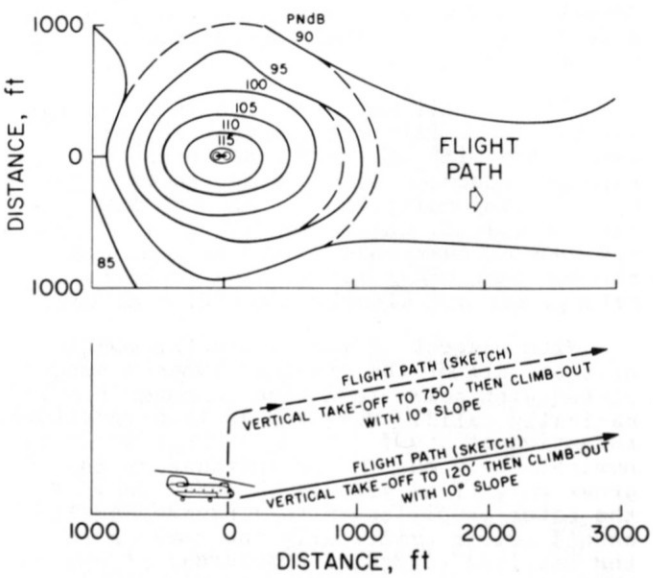


Figure 15. Model 347 Takeoff Flight Profiles and Resulting Noise Exposure

Contrary to one's first intuitive thoughts, landing may often be noisier than takeoff. Although the power settings are lower, the wake of the rotor system in certain descent conditions interacts with the lifting rotors causing high blade loads and hence, additional noise. The solid curves of Fig 16 depict a near-normal 10-degree descent and its corresponding perceived noise level contours. The 95, 100, and 105 PNdB contours all cover more land area than the conventional takeoff patterns shown in Fig 15. The highly elongated character of the resulting perceived noise level contours is believed to be caused by the low approach altitudes of a conventional landing profile. A proposed "noise abatement" landing profile is also illustrated in the same figure. A marked reduction in the 90, 95, and 100 PNdB contours is realized if a near vertical 500-foot descent follows the normal approach procedure.

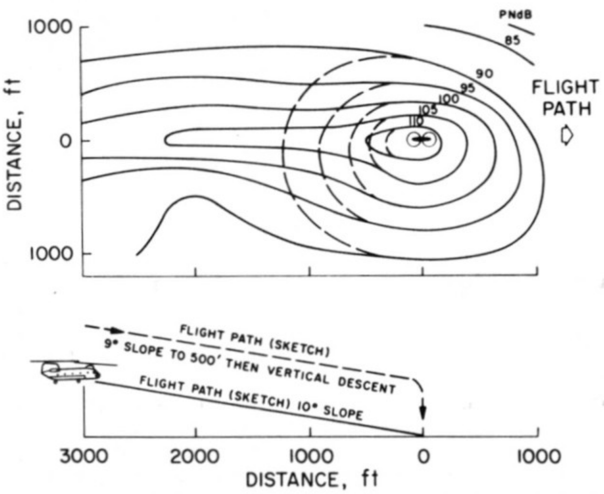


Figure 16. Model 347 Landing Flight Profiles and Resulting Noise Exposure

The actual power and flight path angles for the normal descent case are illustrated in Fig 17. Near zero power was used for nearly 20 seconds as the pilot attempted to steepen his flight path to the desired 10 degrees. Even under this near-autorotation condition, the noise levels did not decrease - but remained high because of rotor wake interaction. Unfortunately, the performance data scatter illustrated in this last figure is representative of the entire flight test program. Large deviations in the actual and desired flight test conditions were not unusual. Therefore, the test results reported can only be viewed as trending information - demonstrating the inherent acoustical benefits of flight path control.

A more detailed estimate of the acoustical advantages of flight management in the terminal area was reported[26] by the present authors and their colleagues. In this study, a theoretical performance and acoustical model of a tilt-rotor aircraft of the 45,000-pound gross weight class was mathematically flown along specified two-dimensional flight paths. The aircraft's trajectory was chosen to minimize the total time or fuel expended to ascend from a specified altitude, or to minimize the noise heard on the ground at selected checkpoints located directly beneath the flight path. It was theoretically shown that at the chosen checkpoint locations, the maximum and the effective perceived noise level could be lowered by as much as 8 EPNdB by controlling the flight path of the VTOL aircraft.

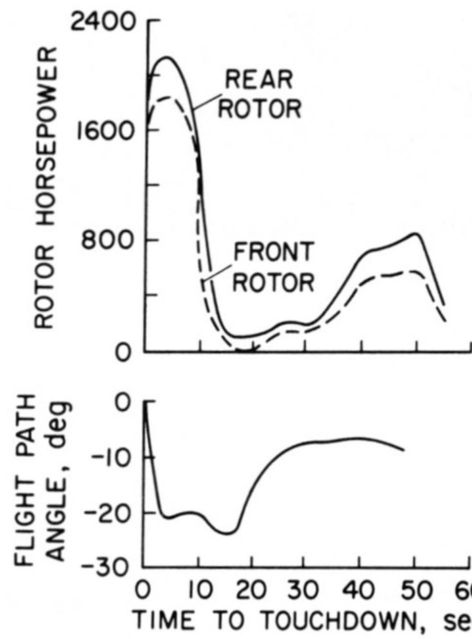


Figure 17. Power and Flight-Path Angle Time Histories in a 10-Degree Descent to Hover

Unfortunately, reducing the noise at selected locations is only part of the overall 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, this same tilt-rotor performance and acoustic model as in Ref 26 was mathematically flown along selected flight paths to generate maximum and effective perceived noise level contours on the ground plane. It should be noted that the tilt-rotor aircraft depicted in Fig 18 was not designed with noise reduction as a primary program objective. As a result, the basic configuration is somewhat noisy (98 PNdB at 500 feet in hover out-of-ground effect). Nevertheless, the flight profiles which are presented demonstrate the relative effectiveness of flight path control in reducing the noise exposure in the terminal area.

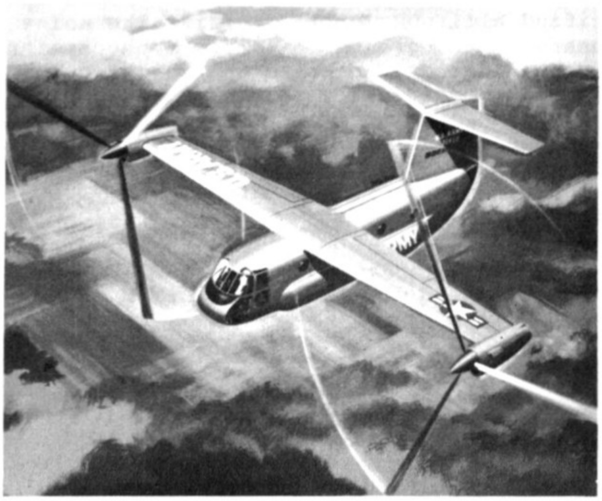

Figure 18. Artist's Concept of a Tilt-Rotor Aircraft

The trajectory which minimizes the time and fuel to attain a prescribed altitude (3,000 feet) which will be called the maximum performance trajectory, is shown in Fig 19, along with several acoustic "footprints". At the time of takeoff, a vertical acceleration constraint of .2g restrains the initial application of full power until the maximum applied power limit is intersected. Maximum power is then applied for the remainder of the trajectory. The horizontal acceleration of .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 transitions from the helicopter to the airplane mode of flight. A constraint upon the tilt-rotor's vertical acceleration reduces the applied power slightly during transition. The remainder of the trajectory is flown in the airplane configuration at the best-rate-of-climb speed with maximum applied power.

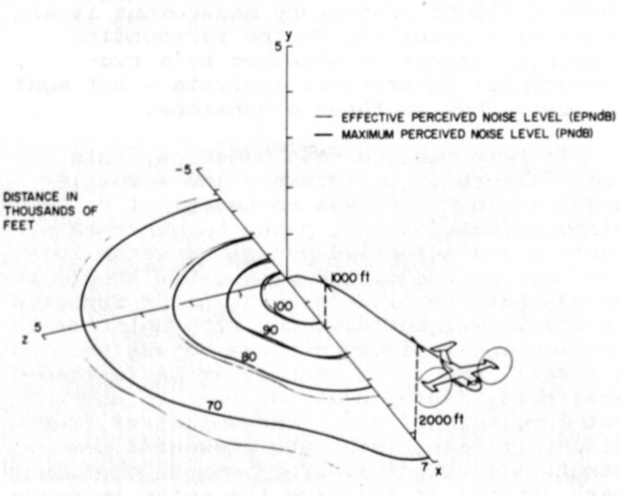


Figure 19. PNdB & EPNdB Contours for a Maximum performance Takeoff

The solid lines in the X-Z plane of Fig 19 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 causes 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 19. 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 8 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 to 30 seconds, a 2 PNdB correction is added to the maximum PNdB value, while for durations of 120 to 240 seconds, a .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 19. 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.

The maximum performance takeoff which has been illustrated in Fig 19 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 comparison purposes, a similar takeoff profile was flown in the helicopter mode of flight (Fig 20). 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 20 by the shaded 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.

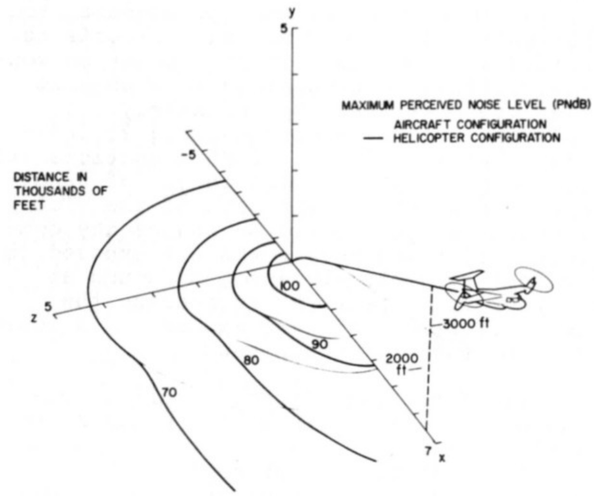


Figure 20. PNdB Comparison - Helicopter Mode Takeoff vs Maximum Per formance Takeoff

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[26]. 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. In Ref 26, it was 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 21 and 22, together with its maximum PNdB and EPNdB contours. The light-colored 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 .2g. At an altitude of 1500 feet, 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.

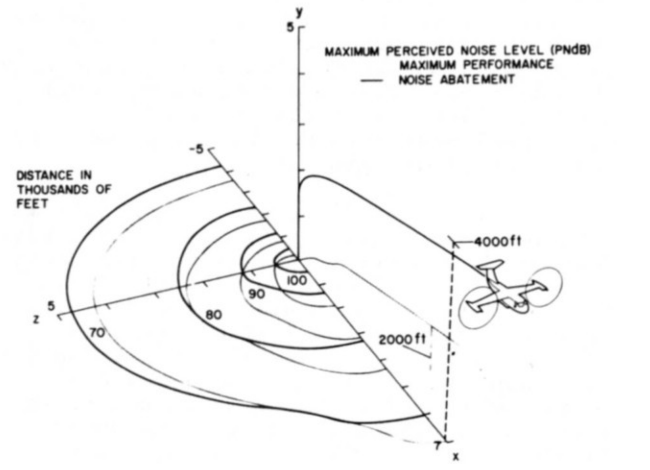


Figure 21. PNdB Comparison - Extended Vertical Ascent Takeoff vs Maximum Performance Takeoff

The maximum perceived noise level contours which are shown in Fig 21 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-percent 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.

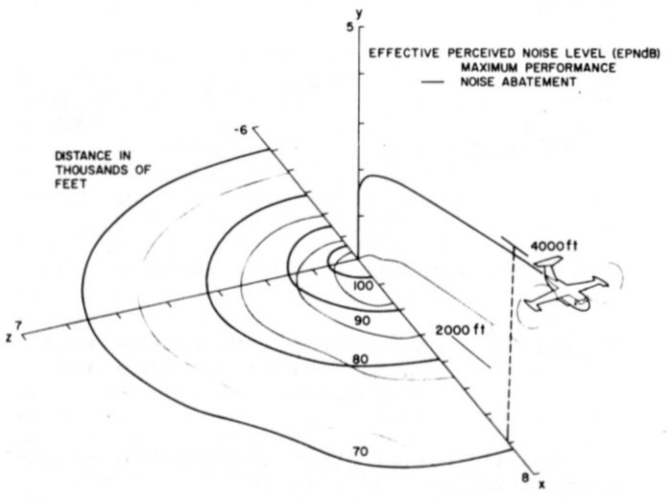


Figure 22. EPNdB Comparison - Extended Vertical Ascent vs Maximum Performance Takeoff.

Fig 22 illustrates the changes in the effective perceived noise level contours which occur when the proposed "noise abatement" trajectory is implemented. Compared with the maximum PNdB contours of Fig 21, less drametic 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 feet tends to reduce the acoustical advantage of this proposed noise abatement flight profile.

The choice of 1500 feet 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. Fig 23 illustrates the effect of initial vertical ascent height on the 80, 90, 95, 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.

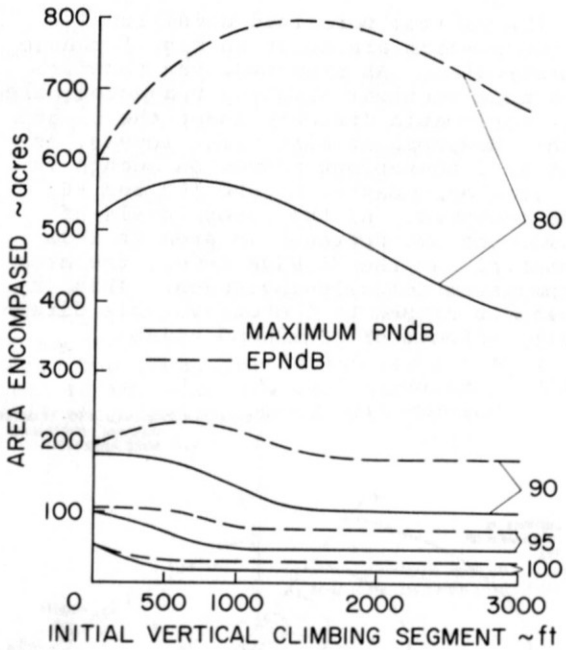


Figure 23. Influence of the Height of Vertical Ascent on PNdB and EPNdB Contour Areas

The annoyance areas encompassed by constant EPNdB contours vs initial ascent height are also plotted in Fig 23. 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 feet might be considered if large reductions in annoyance areas are possible. Unfortunately, at these low initial altitudes, Fig 23 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.

All of the takeoff trajectories considered thus far begin with a maximum vertical acceleration segment which results in a steep initial climb angle. These unconventional takeoff procedures maximize performance if the aircraft initially accelerates at its maximum horizontal rate and tends to minimize the noise footprint area if the aircraft is allowed the luxury of a pure vertical climb. Fig 24 compares a more conventional takeoff flight profile with the maximum performance trajectory.

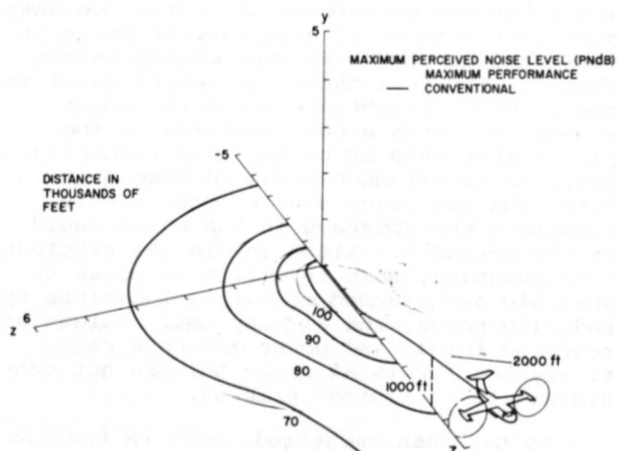


Figure 24. PNdB Comparison - Conventional Takeoff vs Maximum Performance Takeoff

Initially, the tilt-rotor accelerates horizontally at its maximum allowable limit (.25g) until the speed for best rate of climb in the helicopter mode is attained. Maximum pwoer is then gradually applied as the aircraft continues to accelerate horizontally while simultaneously transitioning to the airplane mode of flight. Accelerating horizontally at low altitudes prevents lateral spreading along the flight path, but extends the maximum PNdB contours in the direction of takeoff. The noise footprint areas encompassed by these trajectories increase slightly; the major effect, however, is simply elongation of the contours.

Fig 25 illustrates a typical decelerating descending landing overlayed upon the conventional takeoff flight profile of Fig 24. The tilt-rotor decelerates at minimum allowable power while simultaneously converting to the helicopter configuration. At near zero terminal altitude, the aircraft is flared in the helicopter mode and decelerates to hover. An increase in the landing noise footprint areas occurs when compared with those generated by a conventional takeoff (shaded curves). Even though the applied power is, on the average, lower during landing, high thrust values together with wake induced harmonic airloads generate high acoustic levels. (A more detailed discussion of tilt-rotor acoustic and performance characteristics during descent is presented in Ref 26).

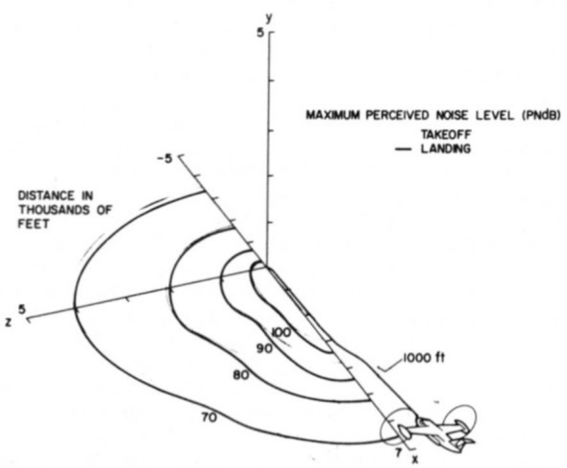


Figure 25. Comparison of Typical Landing with that of Conventional Takeoff (Fig 24)

The overall benefits of flight path control to reduce noise have been illustrated by these few examples. It should be noted that because rotary-wing aircraft appear to offer the quietest forms of VTOL in the immediate future, they have been exclusively treated in this section of the paper. This does not imply that flight trajectory management is not effective in reducing the annoyance areas of lift-fan VTOL aircraft. In fact, the opposite is generally true (Ref 22). The characteristically high frequency lift-fan acoustic spectrums attenuate rapidly with distance. Thus, lift-fan VTOL aircraft benefit substantially from the techniques of flight path control.

## Community Acceptance

It is now well recognized that the "promise" of widespread commercial VTOL flight is dependent upon many factors in addition to the technical and economic feasibility of the operational system. One of these factors - community acceptance by the non-using public - is also one of the most difficult to quantitatively define. However, from many years of CTOL experience, it is known that community acceptance is strongly related to the acoustical annoyance of the surrounding population. Thus, a necessary condition for acceptability is quiet flight operation.

Many advocates of commercial VTOL transportation envision a "commute" market with major cities and municipalities at the hubs of a series of spoke-like feeder lines to the surrounding communities. Major cities and airports located within the range of this short-haul system would also be tied into the proposed network affording the paying passenger tremendous flexibility and rapid movement to his destination. At least four classes of VTOL ports have been proposed to implement such a service; the terminal located at a major CTOL or STOL port, the city-center VTOL port, the newly established operation at an existing light-plane airport, and possible operation from a VTOL port located within the residential community.

The first two classes of terminals are now in operation in many large cities. Helicopter service is available from city center to surrounding CTOL ports. With further projected noise reductions on existing rotary-wing VTOL's, it is probably fair to assume that these types of VTOL ports will be able to achieve community acceptance. Two mitigating factors help in this situation: (1) the overall background noise levels in the downtown city and at the CTOL airport is already quite high, and (2) a large percentage of the public that benefits from the VTOL system also judges the final acceptance of the intruding sound.

However, the situation is quite different for the third and fourth classes of VTOL ports. Because of much lower background noise levels and less involvement with the convenience of VTOL flight, the adjacent communities are much less likely to accept disturbing intrusions. To illustrate these observations, two representative hypothetical VTOL ports of the third and fourth classes were arbitrarily chosen by the authors. Localized population distributions[27] and background noise level distributions were determined for each location at one time of the day. Noise abatement and maximum performance takeoffs were then theoretically flown and the number of people annoyed, together with their relative annoyance level, was predicted.

A sketch of a hypothetical VTOL port located at the San Carlos, California, light-plane airport is shown in Fig. 26. Because the San Francisco Bay borders the airport on the east and the Bayshore Freeway forms the western border, much of the noise resulting from existing aircraft operations is distributed over unpopulated areas.

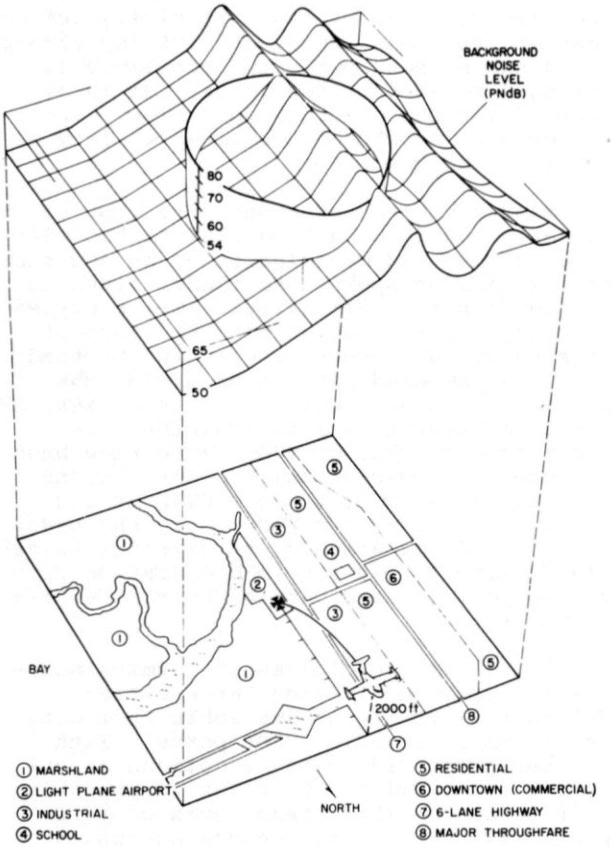


Figure 26. Scenario of V-port Location at a Light Plane Airport (San Carlos)

The town of San Carlos, with a total population of about 35,000, is located west of the airport on the opposite side of the Bayshore Freeway. The town itself lies along El Camino Real, which is also a busy thoroughfare. Industrial and some residential areas lie between the freeway and the town with the majority of the residential areas lying west of the town in the nearby hills.

Superimposed upon the geographical features of interest are the background noise level contours of the surrounding community (Fig 26). The indicated levels (PNdB) were estimated at chosen locations by adding 13 dB to measured levels of background noise obtained from a hand-held dB-A meter. As expected, the background noise of the adjacent community reaches its highest levels over the major traffic arteries and decreases to low levels over residential and uninhabited areas.

It was indicated previously (Fig 2) that one person's reaction to intruding noise can be correlated with the difference between the noise level of the intruding sound and that of the background noise. The authors of Ref 7 conclude that the duration-corrected "energy equivalent noise level" is a good measure of the effective intruding sound level. Because this paper is concerned with VTOL aircraft annoyance, the previously discussed modified EPNdB scale has been used to represent duration corrected annoyance levels in lieu of the "energy equivalent noise level." By employing this subjective measure, the offensiveness of the noise is now related to the difference between the EPNdB of the intruding sound and the background PNdB levels at each ground location. For example, in Fig 26 the relative annoyance of those areas lying below the 80 EPNdB contour is found by noting the difference between that contour and its projected intersection with the background PNdB annoyance levels.

An estimate of the total number of people who experience similar levels of annoyance is found by first calculating the difference between the intruding and background annoyance levels at a matrix of points throughout the neighboring community. The total number of people at constant difference levels is then added.

Fig 27 illustrates the results of this procedure for the town of San Carlos. The two upper curves represent the results of flying the hypothetical tilt-rotor aircraft along a maximum performance and a proposed noise-abatement trajectory (1500 feet). Notice that the suggested noise abatement profile actually annoys more people and at higher levels of relative annoyance than the maximum performance takeoff. The initial vertical climb of the noise abatement profile spreads the intruding noise to the residential land area west of the Bayshore Freeway - which has a relatively low background noise level. However, the shallower flight path and the rapid conversion to airplane flight of the maximum performance regime, confine the intruding noise to a more narrow but elongated region already experiencing high background noise levels.

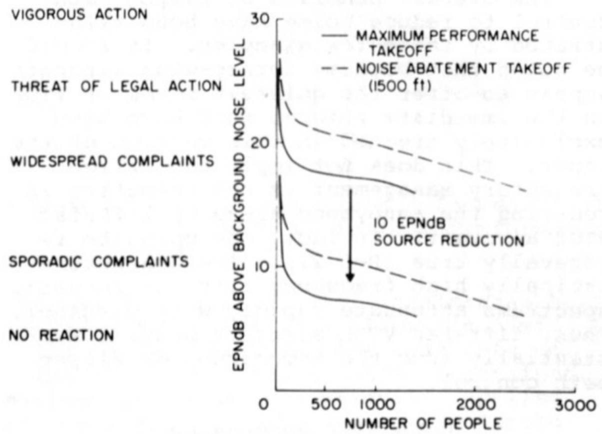


Figure 27. Acoustical Annoyance Profile of San Carlcs

Therefore, for this scenario, tilt-rotor trajectories based on acceleration or deceleration at their maximum permissible rates, while flying near the ground offer the greatest annoyance reduction potential.

As illustrated in Fig 27, too many people in the San Carlos area would experience large differences between takeoff and background noise levels if commercial operation of present technology tilt-rotor aircraft were allowed. However, with advanced technology tilt-rotor aircraft which incorporate at least a 10 PNdB noise reduction at the source, no significant adverse community reaction is predicted. To most people living in the area, the noise generated by these aircraft would probably be quite acceptable.

Although it is fairly obvious, this example further emphasizes the beneficial effect of using unpopulated and/or noisy neighboring land to reduce aircraft noise annoyance. Many existing light-plane airports which are close to suburban communities already take advantage of these very factors to maintain current operations. If future VTOL aircraft can meet or only slightly exceed the existing acceptable noise levels at these airports, no adverse community reaction for infrequent commercial service is expected. However, because the number of daily flights also increases annoyance, further reductions in noise will probably be required for an operation involving many flights per day.

A sketch of another hypothetical VTOL port (representing the fourth classification) which is located within the community of Palo Alto, California, is shown in Fig 28. This terminal has been arbitrarily chosen to be located on a vacant lot on the fringe of the Stanford University campus in close proximity to major highways and rail transportation. Its close proximity to the university, the downtown commercial area, and the nearby residential areas make this type of terminal very accessible to commuter traffic. In fact, many people would be within walking distance or bike-riding distance of the suggested VTOL port.

The background noise levels (PNdB) for the same area are illustrated in the upper part of Fig 28. As in the previous illustration, the background noise attains its highest levels over the major traffic arteries and decreases to low levels over residential areas. However, unlike San Carlos, the Palo Alto scenario represents a community with little commercial or unused land to buffer most of the inhabitants from the intrusive noise generated by VTOL flight. Therefore, the noise abatement profile and its resulting acoustic footprints which are illustrated in Fig 28 will annoy and disturb many more people.

Fig 29 defines the magnitude of the resulting problem. Thousands of people would be exposed to very high difference

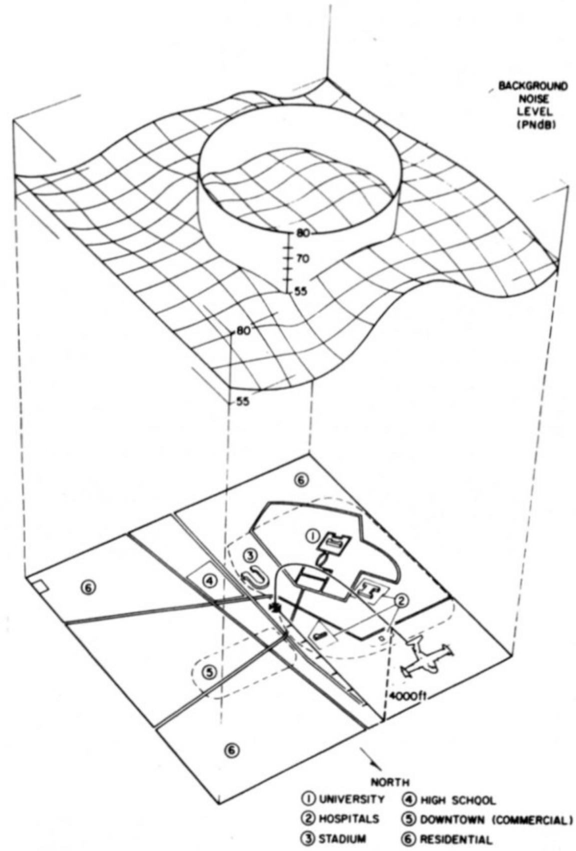


Figure 28. Scenario of V-Port Location Close to a Suburban Downtown Area (Palo Alto)

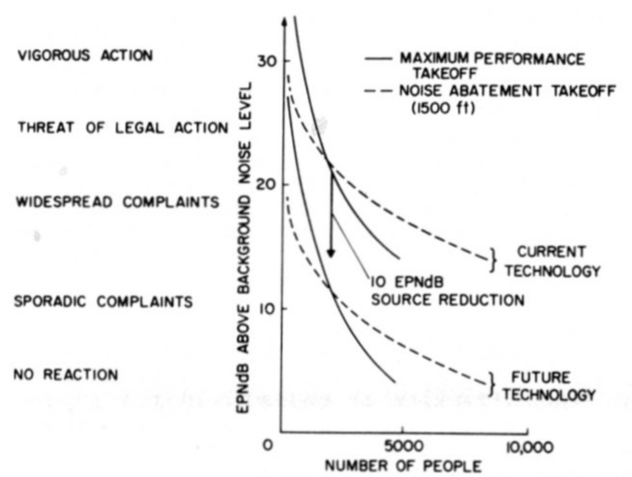


Figure 29. Acoustical Annoyance Profile of Palo Alto

levels of annoyance and would undoubtedly complain bitterly if present technology tilt-rotor VTOL aircraft were flown in this community. Flying a noise-abatement trajectory does reduce the number of people exposed to extremely high difference levels - but not nearly enough and at the expense of increasing the number of people experiencing moderate levels of relative annoyance. Lowering the source of noise through advanced technology is the most effective means of reducing annoyance. Unfortunately, Fig 29 indicates that before we can even begin to talk about community acceptance of this type of airport, noise reductions greater than 10 dB will be required.

## Concluding Remarks

Studies of general trends of acceptable noise level standards, as well as particular investigations of two typical suburban communities, imply that new strides in acoustical technology are needed in order to bring VTOL transport service directly to the residential areas. Reduction of the noise level at the source by more than 10 PNdB from the current state-of-the-art for the rotary-wing and probably by at least twice as much for the lift-fan transport aircraft appears mandatory. Otherwise, the dream of a VTOL port located next to quiet suburban residential areas will remain just a dream.

However, a PNL reduction by even slightly less than 10 PNdB would make rotary-wing VTOL acceptable to such locations as already existing light aircraft ports and major commercial and industrial centers with already high background noise.

Thorough understanding of potential means for reducing noise at the source and their early implementation during concept formulation and preliminary design stages is essential for minimization of the weight and performance penalties. Although some success has been achieved in the partial avoidance of impulsive noise for rotary-wing aircraft, reduction in tip speed offers (at least at present) the only universally accepted means of reducing noise at the source. Unfortunately, lowering the tip speed to reduce the noise of the present state-of-the-art transport VTOL aircraft (45,000-pound weight class) by 10 dB would result in large weight and performance sacrifices. It appears, hence, that the development of new acoustic design methods is needed to achieve truly quiet commercial VTOL transports.

Flight trajectory management can be used to reduce the noise heard at specified measuring locations. The technique is most effective at those locations situated directly under the flight path. However, the total land area encompassed by any one level of annoyance may increase or decrease - depending on the specified level of annoyance. In general, high annoyance areas are reduced at the expense of the lower annoyance level areas.

The relative effectiveness of the noise abatement flight trajectories is dependent upon scenarios of the proposed VTOL ports. Airports that utilize buffer strips which permit high noise levels favor near conventional takeoff and landing techniques. Airports which are completely surrounded by noise-sensitive areas can reduce the area exposed to high noise levels through special flight path control in the terminal area.

Population distribution and ambient noise levels of the surrounding area are of great importance in predicting community reaction to acoustic annoyance. Thus, they represent the necessary elements for development of realistic specifications for V-port location, acoustic characteristics of the aircraft and determination of terminal flight trajectories that together, could lead to VTOL operation acceptable to the community.

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## Appendix I

### Structural Weight Variation with Noise Reduction

Eq (1) from the main text leads to the following dependence of the OASPL variation ($\Delta N$)* in hover with tip speed ($V_t$), when $\overline{c}_{\ell h} = \overline{c}_{\ell h_o}$ and $T = T_o$:

$$\Delta N|_{V_t} = 17.3 \ \ell n(V_t/V_{t_o}) \qquad \text{(I-1)}$$

or

$$V_t/V_{t_o} = e^{.058\Delta N}. \qquad \text{(I-1a)}$$

The $\overline{c}_{\ell h}$ condition implies that

$$A_b = A_{bo}(V_{t_o}/V_t)^2.$$

As to the influence of the $\overline{c}_{\ell h}$ variation on $\Delta N$ through blade area modification, while $T = T_o$ and $V_t = V_{t_o}$, eq (1) leads to the following:

$$\Delta N|_{A_b} = -4.3 \ \ell n(A_b/A_{bo}) \qquad \text{(I-2)}$$

or

$$A_b/A_{b_o} = e^{-.23\Delta N} \qquad \text{(I-2a)}$$

Statistical weight trend formulae developed by Boeing's Vertol Division for the weight of the rotor/propeller assembly ($W_R$) are presented in the following form:

$$W_R = C_1 n[r^{.25}(HP_R/100)(V_t/100)(A_b/10)]^{.67} \qquad \text{(I-3)}$$

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*Sign "-" for decrease and "+" for increase.

where $C_1 \equiv$ statistical correlation constant, $n \equiv$ number of rotor/propellers, $r \equiv$ radial distance to average blade attachment point, $HP_R \equiv$ horsepower transmission limit, $A_b \equiv$ total blade area (per rotor), and $V_t \equiv$ design limit tip speed.

Remembering that $A_b = 6T/\overline{c}_{\ell h}\rho V_t^2$, eq (I-3) becomes:

$$W_R = C_1 n[r^{.25}(HP_R/100)(6T/1000\ \overline{c}_{\ell h}\rho)1/V_t]^{.67}$$

With no change in the design $HP_R$:

$$(W_R/W_{R_o})\,|_{V_t} = (V_{t_o}/V_t)^{.67} \qquad \text{(I-4)}$$

Substituting $V_{t_o}/V_t$ from eq (I-4) into eq (I-1a), a direct relationship between the relative variation(with respect to that of the baseline aircraft) in the rotor/propeller weight and that in the OASPL ($\Delta N$ from the baseline aircraft) is obtained.

$$(W_R/W_{R_o})\,|_{V_t} = e^{-.0386\Delta N} \qquad \text{(I-5)}$$

Similarily, the $W_R/W_{R_o}$ variation with $\Delta N$ through a modification of the total blade area from $A_{b_o}$ to $A_b$ (while $V_t = V_{t_o}$ and $T \approx T_o$)* becomes

$$(W_R/W_{R_o})\,|_{A_b} = e^{-.154\Delta N} \qquad \text{(I-6)}$$

In order to obtain dependence of the variation of the drive system weight ($W_{DR}$) with $-\Delta N$, either through tip speed reduction or total blade area increase, the statistical weight trend formula for $W_{DR}$ is again combined with eqs (I-1a) and (I-2a).

For the drive system weight ($W_{DR}$), an expression was developed at Boeing's Vertol Division under the following form:

$$W_{DR} = C_2(C_3 HP_R/RPM_R)^{.8} \qquad \text{(I-7)}$$

where $C_2$ and $C_3$ are constants determined from the statistical fit and $RPM_R$ is the design RPM (at constant rotor diameter RPM $\sim V_t$) of the rotor propeller, and consequently,

$$(W_{DR}/W_{DR_o})\,|_{V_t} = e^{-.0463\Delta N} \qquad \text{(I-8)}$$

As to the $W_{DR}$ variation with $A_b$ increase, it should be noted that as long as there is no change in the design power limit ($HP_R = HP_{R_o}$ and $V_t = V_{t_o}$), there would be no change in the transmission weight. However, some performance deterioration resulting from the increased profile power (reduction of rate of climb, maximum hovering gross weight, etc.) may be expected.

*If there is no change in the design $HP_R$, higher profile power requirements may cause some decrease in the total thrust. However, the acoustical consequences of this small thrust variation has been neglected.

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