Effects of Noise Reduction on Characteristics of a Tilt-Rotor Aircraft

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The reduction of far-field acoustic signature through modification of tip speed, number of blades, disk loading, and rotor blade area was examined using a tilt-rotor aircraft as a baseline configuration. Of those design parameters, tip speed appeared as the most important. Next, preliminary design of two aircraft was carried out, postulating the following hover noise reduction at 500 ft when compared to the baseline aircraft: a) original PNL_0 less 10 PNdB, and b) original $OASPL_0$ less 10 dB. These acoustic requirements resulted in weight and performance penalties; the most important were an increase in gross weight of about 25% with a loss in maximum relative productivity of 33% for a), and a weight increase of 6% with a loss in relative productivity of 28% for b). Finally, PNL and EPNL aspects of terminal operation were compared for the baseline and quieter configurations.

Introduction

MILITARY and civilian desire for improvement of VTOL acoustic signatures will probably be reflected in aircraft design and certification criteria. The FAA has already established noise certification criteria for jet and turbofan-powered airplanes, and recently it proposed regulations for propeller-driven airplanes of less than 12,500 lb gross weight. The FAA also plans to establish noise standards for new type-certificated helicopters in the near future. With respect to military requirements, the U.S. Army specified the desired maximum acoustic signature in hover and cruise for the UTTAS helicopter.

This paper, based on Ref. 1, reviews techniques available in current technology for changing the rotorcraft far-field acoustic signature by modifying the design of the aircraft. The study of acoustic characteristics considered both the perceived noise level (PNL) and the overall sound pressure level (OASPL) aspects. This double approach was intended to emphasize the relationship existing between PNL and annoyance on one hand, and OASPL and some facets of detection on the other. This latter is caused by the fact that OASPL is governed by the first lower harmonics of main rotor rotational noise, and it appears that detection of the nonbanging rotor is also influenced by the same harmonics.

Aircraft Selection

The Boeing Vertol Model 222 tilt-rotor (Fig. 1) was selected as the baseline configuration, and a constant design gross weight of 12,000 lb was assumed. The effects of aircraft design parameter modification on acoustic characteristics, performance, and weight were studied first.

Selection of the tilt-rotor flight research aircraft as the baseline reference for noise tradeoff investigations was made for the following reasons: a) this configuration, having potentially greater relative productivity than the helicopter, may be more attractive as a VTOL transport; b) the Model 222 represents a new design which has undergone considerable engineering development; and c) the rotor has been manufactured and tested in the Ames full-scale wind tunnel. Thus, the tradeoff slopes reflect the results of substantiated testing and are not based solely on paper studies. This is an important factor in establishing credibility in the weight and performance trends.

As a follow-up to these design trade studies, two aircraft were designed for the same mission as the baseline aircraft, but with two different acoustic signature criteria: one with the OASPL reduced by 10 dB and another with a PNL 10 PNdB lower than the baseline machine. In general appearance, the new designs are similar to the baseline aircraft depicted in Fig. 1. The resulting weight and performance penalties were established on the basis of comparison with the baseline configuration. Furthermore, PNL and OASPL aspects were compared in both hovering and complete terminal operations (take-offs and landings). In this way, a more complete picture is obtained of "cost" in weight and performance for a reduction of either PNL or OASPL of tilt-rotor aircraft from its present level. The trends and conclusions developed in this study should be applicable to other configurations based on the rotary-wing concept, and to helicopters in particular.

Evaluation of Design Parameters

Upon a review of published and unpublished methods of rotor noise abatement, it was concluded[1] that the following represent the major avenues of technology governing the reduction of rotor noise: a) decreased tip speed V_t, b) increased number of blades, c) reduced disk loading W/A, d) increased rotor blade area.

The effect of tip speed on rotational noise shown in Fig. 2 is comprised of rotor whirl tower data[2-4] plus previously unpublished Boeing Vertol Co. measurements. Trends of

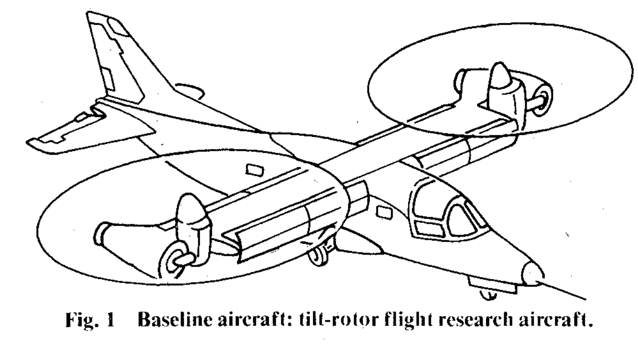

Fig. 1 Baseline aircraft: tilt-rotor flight research aircraft.

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Index categories: VTOL Aircraft Design; Aircraft Noise, Aerodynamics (including Sonic Boom).

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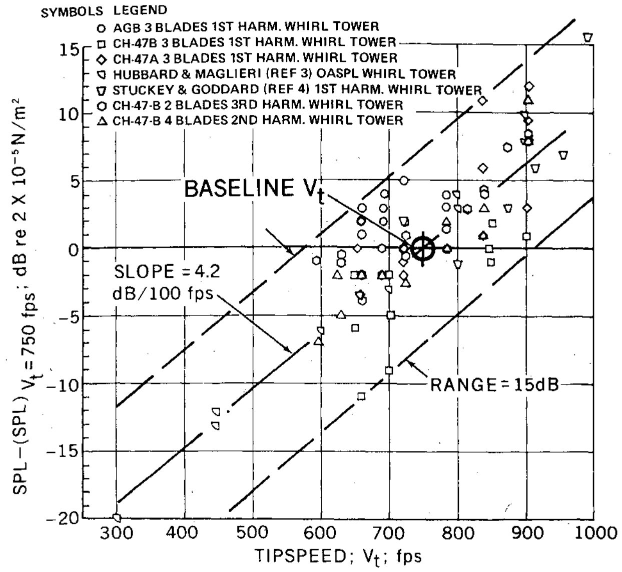

Fig. 2 Effect of tip speed on rotational noise.

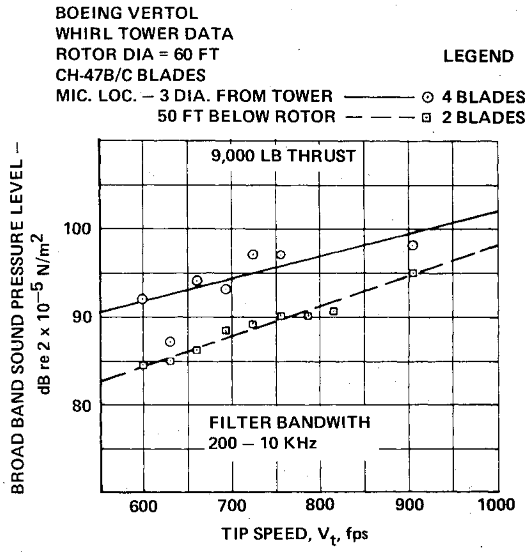

Fig. 3 Effect of tip speed on broadband noise.

specific sets of low harmonic rotational noise data at constant thrust display variations of from 3 to 6 dB in sound pressure level per 100 fps change in tip speed. Grouped together, they show a 4.2 dB/100 fps slope with a scatter band of approximately ±7.5 dB. The higher harmonic sound pressure levels do not follow a consistent trend with variations in tip speed. However, the OASPL of rotary-wing aircraft is usually determined by the first three harmonics of rotational noise.

The effect of tip speed on rotor broadband noise is shown in Fig. 3. The broadband noise represents the major component of the perceived noise level of the aircraft. Similar to rotational noise, this noise component decreases with decreasing tip speed. However, the average of the slopes (about 3 dB/100 fps) shown in this figure is lower than the trend of 4.2 dB/100 fps established for the low harmonics of rotational noise. It may be expected, hence, that PNL will be less sensitive than OASPL to variations in tip speed.

The effect of number of blades on broadband noise, although showing an orderly grouping, cannot be clearly determined for V_t and total thrust T constant on the basis of Fig. 3 or other available whirl-tower data. This is caused by the fact that changes in the number of blades have associated changes in rotor solidity and thus do not permit isolation of the influence of each parameter separately.

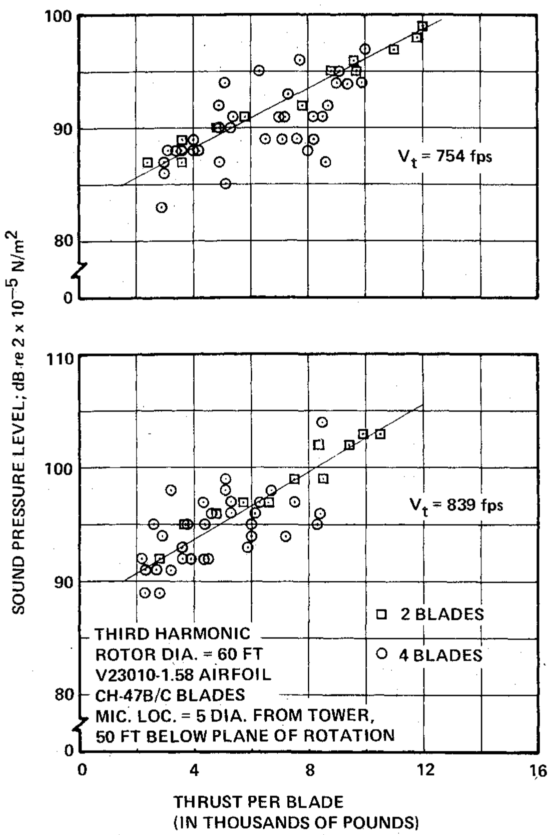

Fig. 4 Effect of thrust-per-blade on rotational noise.

The effect of number of blades on rotational noise appears to be more clearly defined. The sound pressure level collapses into a trend line which becomes a function of the thrust per blade (Fig. 4). The data shown in this figure are for the third harmonic of rotational noise, the lowest recorded frequency during this test. No published data are available on variation in disk loading alone.

The influence of the blade area on rotational noise is generally not considered in the simplified analytical models (e.g., the theory of Lowson[5]). With respect to the influence of blade area on the broadband noise level, there is some disagreement among investigators of the rotor acoustic problems. Again, there are no reliable test data related to the single parameter variation.

Design Tradeoffs

Design tradeoffs associated with tip-speed variation were used to illustrate the sensitivity of aircraft component weights and performance at a constant design gross weight. When determining acoustic chracteristics, established analytical techniques[6] for broadband and rotational noise were incorporated into a computer program.[7] The performance was calculated[8] for the typical transport mission shown in Fig. 5.

Figure 6a shows that the acoustic trend for OASPL falls within the data range shown in Fig. 2, while the PNL trend is similar to that indicated by the character of the broadband noise in Fig. 3.

The effect of tip speed on maximum cruise speed, as constrained by the transmission limit, is shown in the upper half of Fig. 6b. It can be seen here that the reduction of V_t from 750 fps to 550 fps reduces the maximum cruise speed from 305 to 292 kns. Similarly, the 0.99 best range speed changes from 258 to 247 kns.

While the engine weight remains practically unchanged, the weights of the other major subsystems i.e., airframe, transmission, and rotors increase substantially with decreasing tip speed (Fig. 6c). As a result, the weight-empty to gross-weight ratio increases from 0.77 at $V_t = 750$ fps to 0.83 at V_t

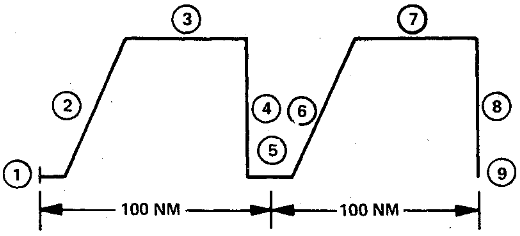

Fig. 5 Mission profile.

$=550$ fps. Consequently, the payload for the 100 nmi radius decreases from the original value of 1300 lb to 1000 lb at $V_t=650$ fps, and further drops to 480 lb when the tip speed is lowered to $V_t=550$ fps. There is practically no change in the slope of payload vs range, since both the geometry and the gross weight remain the same. Of all the important parameters, only propulsive efficiency changes slightly.

Tradeoff studies[1] similar to those previously discussed for tip speed were performed for the number of blades at constant area per blade, disk loading, blade area, and the number of blades at constant total blade area. A comparison of the tradeoffs in Ref. 1 indicated that tip speed remained as the only parameter having a significant effect on PNL. The number of blades and disk loading, in addition to tip speed, were effective in reducing the OASPL.

Quiet Aircraft Selection

The most effective methods of noise reduction at the source, resulting in the most favorable performance and weight tradeoffs, were applied to the design of two tilt-rotor aircraft with an improved noise signature at 500 ft from the point of hover. For one aircraft, a reduction of PNL by 10 PNdB and for the other, of OASPL by 10 dB from the level of the baseline aircraft were specified.

Additional ground rules used were maintenance of the baseline design point performance, flying qualities, and structural flight envelope. The three parameters shown to be the most effective in changing the rotor signature from the tradeoff studies were a) tip speed V_t at constant rotor thrust coefficient/solidity C_T/σ, b) number of blades at constant solidity ($\sigma=$const), and c) hover disk loading W/A at $C_T/\sigma=$const.

The three rotor parameters were varied, one at a time, in the direction shown to be the most effective. The disk loading of the baseline was reduced to half its original value in two equal steps. The hover tip speed was reduced by 100 fps increments from the baseline. Then, the aforementioned matrix of rotor design was repeated for 4 and 5 blades per rotor. Thus, 27 designs were evaluated. The final selection of an aircraft meeting each noise criterion was made on the basis of minimum design gross weight. This selection process was facilitated by the use of carpet plots similar to the one in Fig. 7 which illustrates the variation of design gross weight as a function of hover tip speed and disk loading for a 4-bladed rotor. Acoustic constraints on aircraft design result in lines of constant PNL and OASPL. This graphical optimization method with noise constraints not only shows the minimum, but also the parameter values about the minimum, thus determining the penalty involved for a nonoptimum design.

The main characteristics of aircraft resulting from design optimization as well as those of the baseline configuration are shown in Table 1. The −10 dB OASPL aircraft has a lower disk loading (5.65 psf), 5 blades per rotor, and a design gross weight of 12,700 lb. The aircraft having a reduced PNL (−10 PNdB) has a disk loading of 6.22 psf, 4 blades per rotor and a design gross weight of 15,045 lb.

A comparison of the summary weight statements for the baseline aircraft and the two quieter aircraft is presented in Table 2. The maximum relative increases of the component weights are shown in Table 3. These weight increases are

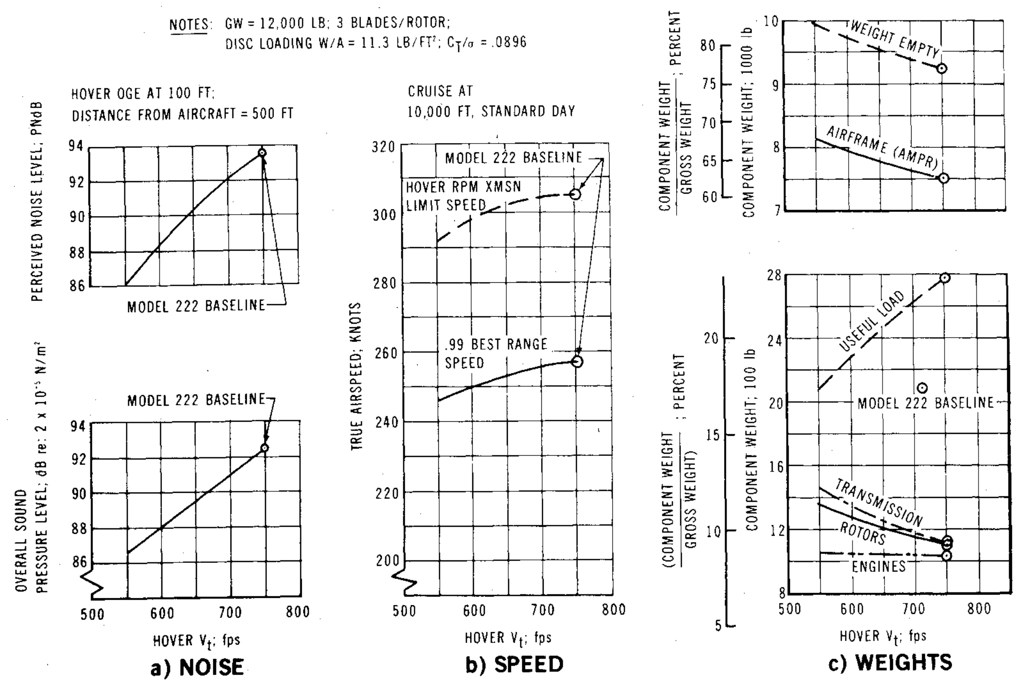

Fig. 6 Effect of V_t on a) noise, b) speed, and c) weights.

Table 1 Tabulation of configuration characteristics

Item	Baseline aircraft	−10 dB OASPL aircraft	−10 PNdB aircraft
Rotor			
Rotor radius; ft	13	18.9	18.8
Number of blades	3	5	4
Hover tip speed; fps	750	660	505
Rotor solidity (σ)	0.1154	0.0746	0.1527
Disk loading; lb/ft^2	11.3	5.65	6.78
Wing			
Wing area; ft^2	200	281.4	308.3
Wing span; ft	33.42	45.3	45.0
Aspect ratio	5.61	7.28	6.57
Taper ratio	1.0	1.0	1.0
Horizontal tail			
Area; ft^2	58.3	85.3	103.0
Span; ft	15.67	19.8	21.8
Aspect ratio	4.22	4.61	4.61
Taper ratio	0.337	0.337	0.337
Tail volume coeff.	1.0	1.0	1.0
Moment arm; ft	20.3	20.3	20.3
Vertical tail			
Area; ft^2	43.3	82.5	89.9
Span; ft	8.12	12.1	12.6
Aspect ratio	1.52	1.77	1.77
Taper ratio	0.329	0.329	0.329
Tail volume coeff.	0.127	0.127	0.127
Moment arm; ft	19.55	19.6	19.6
Number of engines	2	2	2
SHP/engine	1550	1100	1510
XMSN hp limit/rotor	1150	820	1125
Eq. flat plate area; ft^2	6.279	7.404	7.776
Noise in hover @ 500-ft alt.			
PNL @ 500-ft radius	92.5	89.1	82.5
OASPL: @ 500-ft radius	93.6	83.6	79.4
Prop-rotor performance			
Hover figure of merit[a]	0.757	0.796	0.751
Propulsive efficiency[b]	0.770	0.728	0.683

[a] 2500 ft, 93°F.
[b] Cruise at 300 knots, 10,000 ft, std.

Table 2 Summary weight statement comparison

Components	Baseline aircraft		−10 dB OASPL A/C		−10 PNdB PNL A/C	
Rotor group		1100		1211		1743
Wing group		800		1402		1416
Tail group		213		305		361
Body group		1211		1274		1282
Alighting gear		590		623		737
Flight controls		1183		1262		1623
Engine section		400		400		400
Propulsion group		2533		2387		3405
Engines	(1026)		(718)		(988)	
Powerplant subsyst.	(200)		(200)		(200)	
Fuel system	(200)		(200)		(200)	
Drive system	(1107)		(1269)		(2017)	
Instr. & navigation		108		108		108
Electrical group		305		305		305
Electronics group		230		230		230
Furn. & equipment		439		439		439
Personnel accom.	(299)		(299)		(299)	
Misc. equipment	(63)		(63)		(63)	
Furnishings	(35)		(35)		(35)	
Emergency equip.	(42)		(42)		(42)	
Aircond. & deicing		108		108		108
Auxiliary gear		10		10		10
Weight empty; lb		9230		10064		12167
Fixed useful load		400		400		400
crew (2)	(360)		(360)		(360)	
Trapped liquids	(40)		(40)		(40)	
Fuel		1072		945		1180
Cargo and/or passengers/troops		1298		1298		1298
Gross weight; lbs		12000		12707		15045

offset by decreases in engine weights (30% for the −10 dB OASPL aircraft and 4% for the −10 PNdB aircraft), and mission fuel (13% for the −10 dB OASPL aircraft). By contrast, mission fuel for the −10 PNdB aircraft increased by 11%.

Resultant Performance

Performance estimates for the baseline aircraft and the two designs with acoustic constraints were made in the following areas: a) rotor hover performance (Ref. 1, Fig. 4-6), b) level flight power required (Fig. 8), c) mission payload (Ref. 1, Fig. 6-6), and d) mission productivity as a function of range (Fig. 9).

The hover design figure-of-merit *FM* for the three aircraft and their propulsive efficiencies η_{pr} are shown in Table 1. It can be seen that for cruise at 300 kns at 10,000 ft, the drop in η_{pr} of the quieter aircraft is much greater than the corresponding variation in *FM*. This decrease in propulsive efficiency is caused by the higher propeller advance ratio of the acoustically improved configurations, and the less favorable blade twist compromise between hover and cruise requirements.

Power required curves for the three aircraft are given in Fig. 8. In this figure, an unusual phenomenon for the −10 PNdB aircraft is the increase in power required in the 80-kn speed range corresponding to $V/V_t \approx 0.20$, with a nacelle angle of about 45°. Differences in parasite drag, wing span loading, rotor-area to wing-area ratio, and hover disk loading cannot, by themselves, account for the magnitude of this power rise. This phenomenon can be attributed to the occurrence of blade stall associated with the low tip speed $V_t = 505$ fps.

To alleviate this problem, the following design approaches can be taken: a) lower the C_T/σ, b) decrease wing loading, and/or c) incorporate sophisticated high-lift devices on the wing. All of these alternatives would still further penalize aircraft performance and weight. Taking the simplest approach for the two quiet aircraft, only wing loading was reduced with respect to that of the baseline (Table 1). This obviously was not enough to achieve a conversion speed sufficiently low to eliminate the power-required hump associated with rotor stall (Fig. 8). A more detailed study is needed to determine the optimum design of the wing and rotor in the conversion flight regime.

The payload vs mission radius comparison (Ref. 1, Fig. 6-6) illustrates that as a result of the common ground rules adopted in this study, the capabilities of all three aircraft are similar. However, the relative mission block productivity ($V_{block} \times$ payload/wt empty, of the noise constrained designs) in Fig. 9, is lower than that of the baseline aircraft (−10 PNdB by 33%, and the −10 dB OASPL by 28%).

Resulting Acoustic Signatures

Hover

Sound absorptive linings were installed in the engine inlets of the two noise constrained designs. Thus, the rotor spectrum becomes the major influence in determining either OASPL or PNL. The acoustic spectra in hovering out-of-ground effect (OGE), reflecting inlet treatment and rotor design changes,

Table 3 Component weight variation from the baseline

Component	Increase in component weight (%) −10 dB OASPL Aircraft	−10 PNdB Aircraft
Rotor	11	58
Wing	75	77
Empennage	43	70
Flight controls & drive system	15	82.5

Table 4 Peak PNL & EPNL at 800-ft location

A/C data	Baseline	−10dB OASPL	−10 PNdB
Takeoff			
Peak PNL; $PNdB_{max}$	98	94	87.5
$10 \log (\Delta t/15)$	−.62	−.15	.14
EPNL; EPNdB[a]	97.38	93.85	87.64
Landing			
Peak PNL; $PNdB_{max}$	106.5	104.0	100.5
$10 \log (\Delta t/15)$	−.97	−1.98	−2.2
EPNL; EPNdB[a]	105.53	102.02	98.30

[a] $EPNdB = PNdB_{max} + 10 \log (\Delta t/15)$.

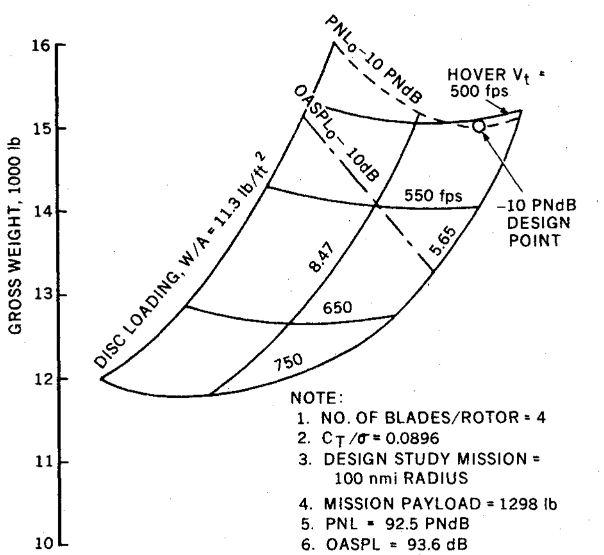

Fig. 7 Carpet plot for 4-bladed rotor.

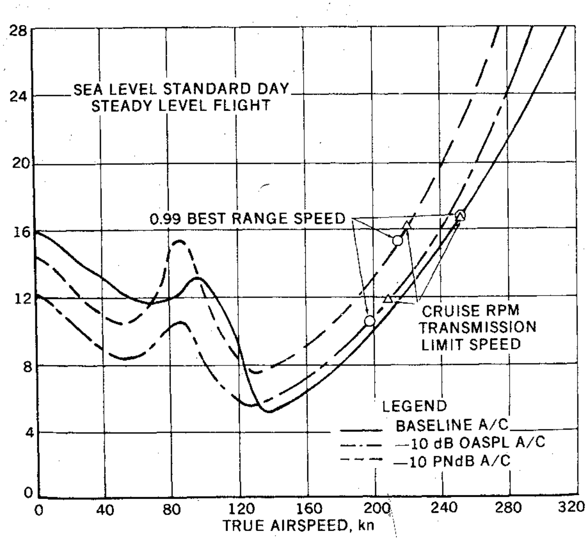

Fig. 8 Effect of noise reduction on power required.

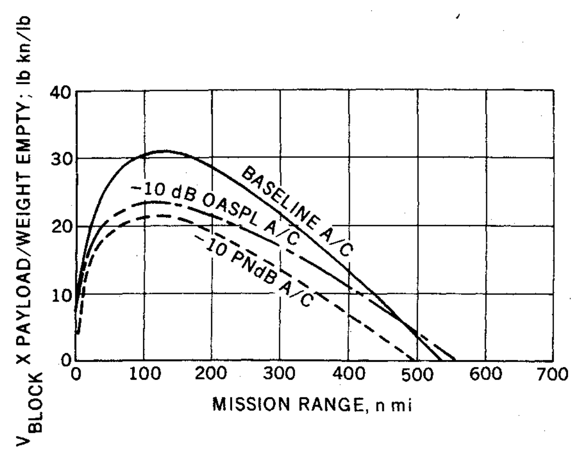

Fig. 9 Comparison of mission relative productivity.

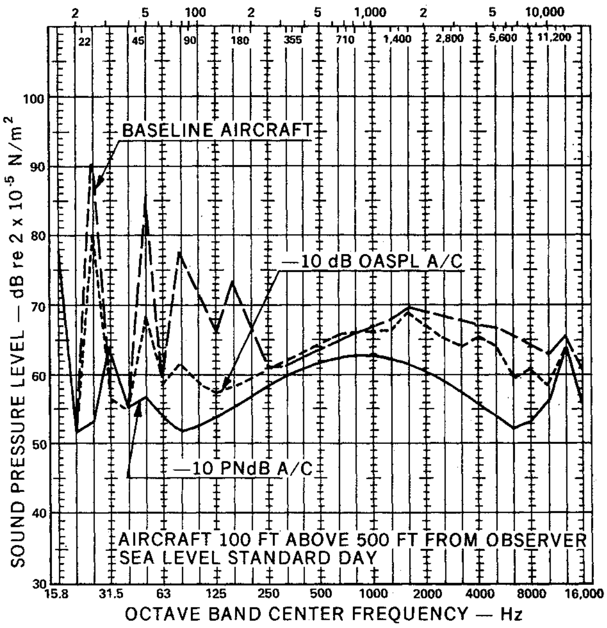

Fig. 10 OGE hover acoustic spectra.

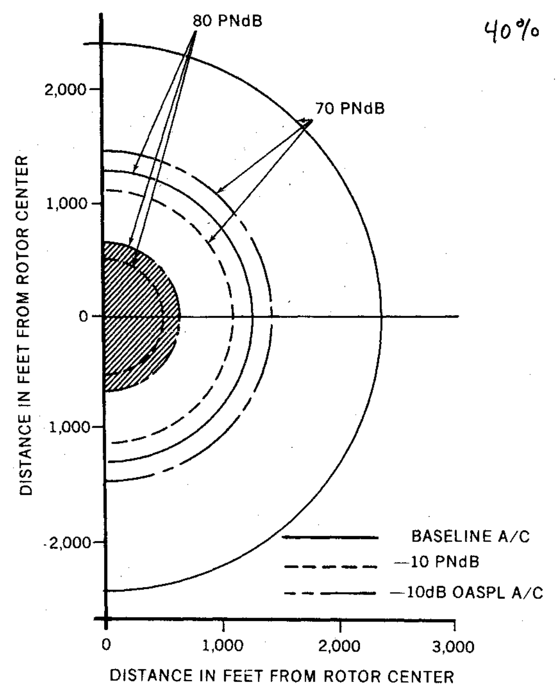

Fig. 11 A comparison of hovering acoustic footprints, OGE.

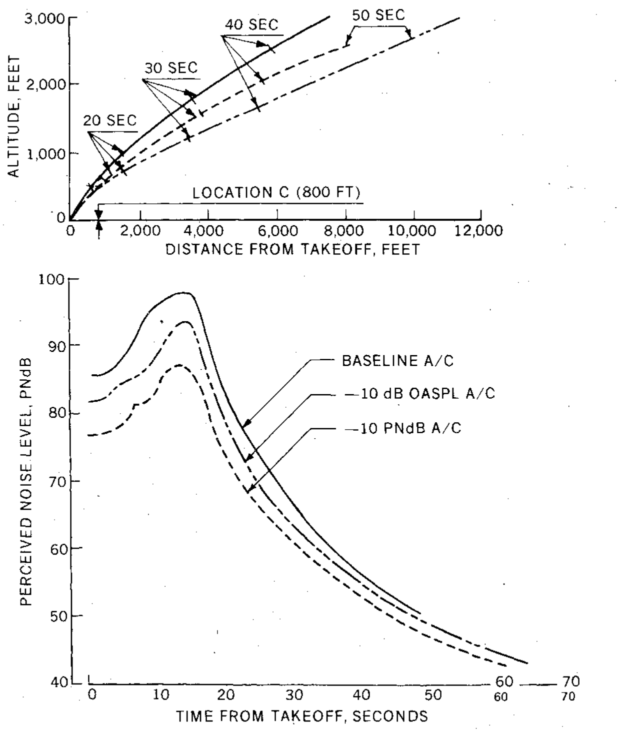

Fig. 12 Takeoff trajectories and PNL time histories at 800-ft location.

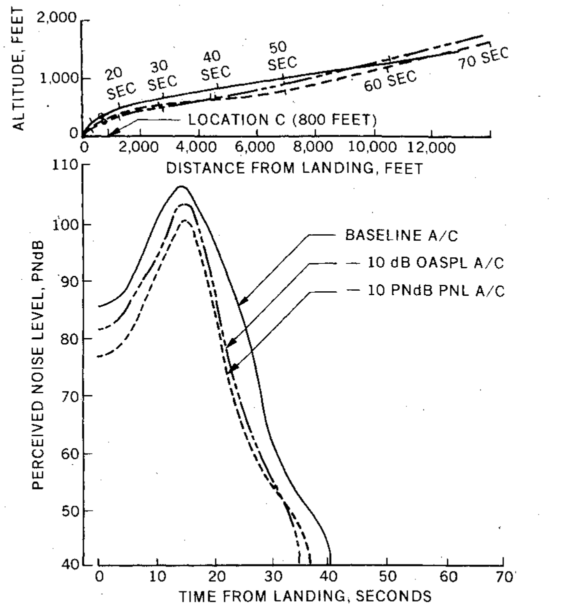

Fig. 13 Landing trajectories and PNL time histories at 800-ft location.

are shown in Fig. 10. As a result, the acoustic footprints also change from that of the baseline aircraft (Fig. 11). For instance, the 80 PNdB footprint area of the −10 PNdB aircraft is reduced to 15% of the baseline value.

Trajectories and PNL Time Histories

Performance and acoustic characteristics in the forward flight phase of terminal operation are more important than in hover. In this respect, the tilt-rotor configuration may have an acoustic advantage over a pure helicopter. After vertical takeoff, the rotor thrust and tip speed can be decreased as the wing begins to provide lift thus reducing the aircraft noise signature.[1] Similar acoustic advantages can be realized in landing.

The peak and duration of the PNL time histories are dependent on the far-field acoustic signature in forward flight and the aircraft flight trajectories (Figs. 12 and 13). It should be noted that the takeoff trajectories (Fig. 12) are quite different, because the rate of climb of the three compared aircraft varied considerably. By contrast, the differences between landing trajectories (Fig. 13) are small because all three aircraft are constrained by a rate of sink in the approach.

In spite of the fact that during takeoff the baseline aircraft exhibits the steepest trajectory (thus increasing the distance between an observer on the ground and the aircraft), the peak levels of the noise constrained designs are lower than that of the baseline. For example, for an observer located 800 ft from the takeoff point, the difference from the baseline is −4 PNdB for the −10 dB OASPL, and −10.5 PNdB for the −10 PNdB aircraft, respectively (Table 4). As shown in Fig. 12, the duration of these peak values Δt, when measured at −10 PNdB from the peak of PNL, are as follows: $\Delta t = 13$ sec for the baseline, $\Delta t = 14.5$ sec for the −10 dB OASPL aircraft, and $\Delta t = 15.5$ sec for the −10 PNdB aircraft. The equivalent perceived noise level (EPNL) was calculated, using the −10 PNdB points (on both sides of the peak), showing that the EPNL levels are quite similar to those of the PNL (Table 4). During landing, the noise constrained configurations exhibit trends in both peak PNL (Fig. 13) and EPNL (Table 4) similar to those in takeoff. However, in this case, the differences between the new designs and the baseline are not as large.

Discussion

Growth in dimensions of the noise constrained aircraft, in comparison with the baseline, is shown in Fig. 14. The aircraft designed to meet the OASPL requirements is lighter and has a lower disk loading than the PNL aircraft. This resulted from the emphasis being placed on two different rotor noise com-

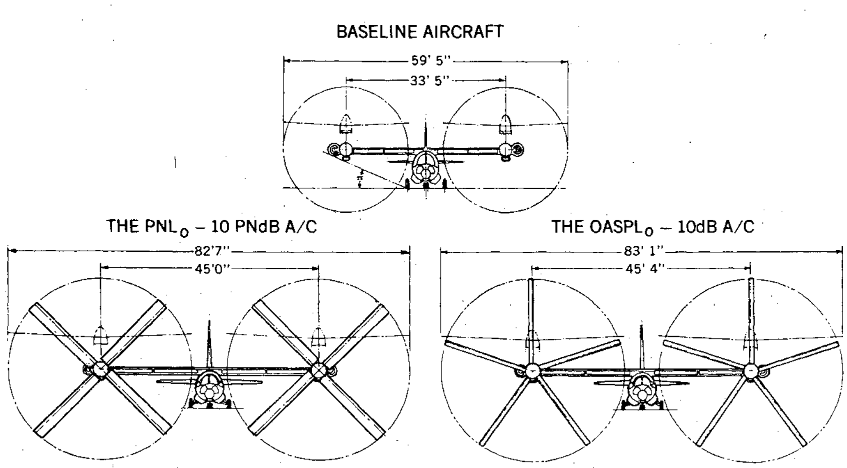

Fig. 14 Comparison of aircraft dimensions.

ponents: rotational in the first case, and broadband in the second.

Rotational noise is a function of rotor blade span loading and tip speed. Of those two parameters, reduced spanwise loading can be accomplished through an increase in blade number and lower disk loading without encountering large drive system weight penalties associated with tip speed reduction. Thus, in comparison with the baseline configuration, the tip speed of the −10 dB OASPL aircraft was reduced by only 90 fps (from $V_t = 750$ fps to 660 fps), while the number of blades was increased from 3 to 5, and the disk loading was lowered to half the baseline value.

By contrast, the perceived noise level of rotary-wing aircraft without tail rotors is primarily a function of broadband noise. Here, tip speed was shown to be the most significant parameter influencing this rotor noise characteristic. Consequently, the PNL constrained aircraft has a tip speed of $V_t = 505$ fps, which is 155 fps lower than that of its OASPL counterpart. It should be noted that a 500 fps rotor hovering tip speed probably represents the lowest current practical value for this type of aircraft. Reduction of the disk loading in this design was primarily used as a means of lowering the hovering installed power required to meet the established performance requirements. In turn, the lower power installed contributed to a reduction in weight empty and hovering fuel which, to some extent, offset the weight increases resulting from the reduction in tip speed. Nevertheless, the weight empty of the −10 PNdB was 31%, and gross weight 25% higher than that of the baseline configuration, while for the −10 dB OASPL machine, the figures were 9 and 6%, respectively.

The changes required to improve the rotor acoustic signature also contributed to the modification of overall aircraft performance. As a result of their reduced disk loadings, the quieter designs have the advantage of lower hovering power required. However, the best range speed of the quieter aircraft is below that of the baseline configuration (215 kns for the −10 PNdB aircraft and 195 kns for the −10 dB OASPL vs 250 kns for the baseline, Fig. 8).

In spite of the fact that hover represents only a portion of the takeoff and landing cycles, the noise levels in complete terminal operations appear to follow the hovering trend. It can be seen from Table 4 that the differences between both PNL_{max} and EPNL for the two quieter designs and the baseline aircraft are approximately the same as those in hover (see bottom of Table 1). Thus, determination of noise design requirements for hovering may represent a simple method for establishing a valid criterion for noise characteristics for complete terminal operations of VTOL aircraft.

Conclusions

Choice of criteria for at-the-source noise reduction (PNL vs OASPL) has a significant effect on resulting vehicle design. Reduction of rotor tip speed remains the most powerful means for decreasing the PNL level. Increase in the number of blades, combined with a lower disk loading as well as a reduction in tip speed, is important in the OASPL case. As a result, weight and performance penalties for aircraft designed to PNL criteria are higher than for the OASPL. After some level of noise reduction is reached through variation of rotor design parameters, acoustic treatment of the powerplant is required. Noise design requirements in hover may represent a valid criterion for the whole terminal operation.

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