NASA TECHNICAL MEMORANDUM

NASA TM-73816

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A PARAMETRIC INVESTIGATION OF AN EXISTING SUPERSONIC RELATIVE TIP SPEED PROPELLER NOISE MODEL

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November 1977

1. Report No. NASA TM-73816	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A PARAMETRIC INVESTIGATION OF AN EXISTING SUPERSONIC RELATIVE TIP SPEED PROPELLER NOISE MODEL		5. Report Date November 1977
		6. Performing Organization Code
7. Author(s) James H. Dittmar		8. Performing Organization Report No. E-9405
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		10. Work Unit No.
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Memorandum
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

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17. Key Words (Suggested by Author(s))		18. Distribution Statement	
Propeller noise Noise Supersonic tip speed		Unclassified - unlimited STAR Category 71	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price*

* For sale by the National Technical Information Service, Springfield, Virginia 22161

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SUMMARY

A high tip speed turboprop is being considered as a future energy conservative airplane. The high tip speed of the propeller combined with the cruise speed of the airplane may result in supersonic relative flow on the propeller tips. These supersonic blade sections could generate noise that is a cabin environment problem. An existing supersonic propeller noise model was parametrically investigated to identify and evaluate the noise reduction variables. Both independent and interdependent parameter variations (constant propeller thrust) were performed. The noise reductions indicated by the independent investigation varied from sizable in the case of reducing Mach number to minimal for adjusting the thickness and loading distributions. The noise reduction possibilities of decreasing relative Mach number were further investigated during the interdependent variations. The interdependent investigation indicated that significant noise reductions could be achieved by increasing the propeller diameter and/or increasing the number of propeller blades while maintaining a constant propeller thrust.

INTRODUCTION

One of the candidate engines for a future energy conservative airplane is a high tip speed turboprop. The high tip speed of the propeller, combined with the high subsonic cruise Mach number of the airplane, results in supersonic relative velocities over the outer portions of the propeller blades. During airplane cruise these supersonic blade sections could generate significant noise that might become a cabin environment noise problem. As a starting point toward reducing the noise of these propellers an attempt is being made to identify profitable noise reduction variables.

A number of models exist for the prediction of high tip speed propeller noise. Hanson, ref. 1, has performed a detailed analysis using the linearized acoustic wave equation which neglects non-linear source effects such as attached shocks. Farassat, ref. 2, also used the linearized acoustic wave equation but only included the thickness noise term and not the loading term. The Boeing Airplane Company, ref. 3, predicts the propeller noise based on existing supersonic aircraft flyover noise. The parametric investigation which is undertaken in this report uses the third model, ref. 3, to evaluate the noise produced by the supersonic portions of the propeller.

The following noise model section discusses the basic equations used in reference 3 and their use in this report. This is followed by sections showing results for both independent and interdependent (constant propeller thrust) parametric investigations and the parameter values that would lead to low noise designs.

NOISE MODEL

Basic Equations

The supersonic tip speed noise model for this investigation was taken directly from reference 3. This model involves the calculation of a sonic boom overpressure that is strictly applicable only for a Supersonic Transport (SST) in steady level flight, as in figure 1(a). The fuselage noise propeller case, for which this prediction is used, is shown in figure 1(b) (a three-bladed propeller is shown for ease of illustration). A discussion of some of the differences that exist between the supersonic flyover type of calculation and the actual propeller case is undertaken. As can be seen in the two parts of figure 1, geometric differences exist between the two cases. The flyover case has the plane passing directly overhead at a constant altitude with supersonic axial velocity relative to the observer. The propeller case has the blade approaching and retreating from the fuselage in a circumferential path with the blade at an angle to the fuselage and although the blade is supersonic with respect to the air, the blade is moving at subsonic speeds with respect to the fuselage. In addition to the geometric differences seen in figure 1 the body shapes for the two cases are different. The shape taken for the flyover model is a body of revolution where the wings and fuselage of the plane are lumped together to give an equivalent diameter. However, the supersonic tip section of the propeller would have a shock pattern more like that of a two dimensional airfoil. Because of the differences that exist between the flyover model and the propeller case, the propeller noise values computed by the flyover method may not be exact. However, the trends of a parametric variation about a base case, which are presented in this report, should probably be accurate.

The noise model used for this investigation calculates the boom intensity striking the airplane fuselage generated by the volume and lift components and adds them together in a root mean square method. Then an rms overall sound pressure level is calculated from the overpressure that accounts for the fraction of time that the overpressure is striking a point on the cabin wall. The equations used, taken from ref. 3, are presented below and a symbol list is included in the Appendix.

Sonic boom equations. - The overpressure equations are presented below. The volume component of the overpressure is (ref. 3),

$$\Delta P_V = \frac{\sqrt{P_a P_g}}{h^{3/4}} K_R (M^2 - 1)^{1/8} \frac{d}{(l_B)^{1/4}} K_V \tag{1}$$

The lift component of the overpressure is,

$$\Delta P_L = \frac{\sqrt{P_a P_g}}{P_A^{1/2} h^{3/4}} K_R \frac{(M^2 - 1)^{3/8}}{M} W^{1/2} \frac{d}{(l_W)^{1/4}} K_L \tag{2}$$

<u>Total overpressure</u>. - The total overpressure is the combination of the two overpressures

$$\Delta P = \sqrt{\Delta P_V^2 + \Delta P_L^2} \tag{3}$$

The overall sound pressure level is calculated from the total overpressure (the quantity K_{NF} in the following equation is the near to far field correction term discussed in the text of ref. 3)

$$OASPL_{overpressure} = 20 \log_{10}\left[\frac{\Delta P}{P_{ref}} \times K_{NF}\right] \tag{4}$$

The rms overall sound pressure level is calculated by including the length of time the shock from each blade is present on the fuselage.

$$OASPL_{rms} = OASPL_{overpressure} + 20 \log_{10}\left(\frac{T^*}{T}\right)^{1/2} \tag{5}$$

where the time between each blade passage is

$$T = \frac{\pi D}{BV_T} \tag{6}$$

and the shock duration is

$$T^* = \frac{C}{M_{ht} a_o} \tag{7}$$

Application of Equations and Base Case

As these equations were formulated for an SST flyover some parameter interpretation is required. Starting with equation (1), the pressure at altitude (P_a) and at the observer (P_g) are the same for the supersonic propeller. For the base case, about which the parametric investigation is conducted, the altitude is taken as 10 973 meters (36 000 ft) where the pressure is 22 695 N/m^2 (474 psf). A compilation of all of the base case parameters is found in Table I.

The distance of the propeller tip from the fuselage wall (h) is taken as eight tenths (0.8) of the propeller diameter for the base case. The propeller diameter is 6.10 meters (20 ft) for the base case and h is 4.88 meters (16 ft).

Since the Mach number M of the flow over the propeller blades varies along the span an average is used in the equations. The average helical Mach number (vector sum of axial Mach number M_N and rotational Mach number M_t) for the supersonic region of the propeller blade tip given by

$$M = \frac{M_{ht} + 1}{2} \tag{8}$$

was used. The helical tip Mach number M_{ht} is

$$M_{ht} = \sqrt{\left(\frac{V_T}{a_o}\right)^2 + M_N^2} \tag{9}$$

where V_T is the tip speed of the propeller (taken as 244 m/sec (800 ft/sec)) for the base case

a_o is the speed of sound at altitude (297 m/sec (973 ft/sec) for base case)

M_N is the airplane Mach number ($M_N = 0.8$ for base case)

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The equivalent diameter (d) is determined from

$$d = 2\sqrt{\frac{(r_t - r_s)(C)\frac{t}{C}}{\pi}} \tag{10}$$

where r_t is the tip radius and r_s is the radius at which the helical Mach number is 1.0. The chord (C) of the base case propeller is 0.762 m (2.5 ft). The thickness to chord ratio (t/C) is 0.02 and the tip radius (r_t) is 3.05 m (10 ft) for the base case. The effective lengths l_B and l_W are both taken as the chord of the airfoil (C).

In equation (2) the wing loading (W) is taken as the portion of the total propeller thrust generated by the supersonic region of the blade. Then

$$W = \frac{\tau}{B}\left(\frac{r_t - r_s}{r_t - r_h}\right) \tag{11}$$

where uniform loading from hub to tip τ/B is assumed and where τ is the total thrust (33 953 N (7633 lb for base case)), B is the number of blades (8 for the base case) and r_h is the hub radius (0.46 m (1.5 ft) for the base case).

In the overpressure equations K_L and K_V are two shape factor constants depending on the chordwise loading and thickness distributions and K_R is a reflection factor to account for the fuselage wall reflection. For the base case K_L is 0.7, K_V is 0.8, and K_R is 2.0 (which represents a doubling of pressure at the fuselage wall). The near to far field correction term K_{NF} is taken as 0.75 for the base case.

RESULTS AND DISCUSSION

Independent Variation of Parameters

Some of the parameters in the overpressure equations were varied to observe their effect on overall sound pressure level. These parameters were varied independent of any of the other parameters in the equations to observe their possible importance as noise reduction variables. This independent variation is probably not possible in all of the cases because of the interdependence of the parameters in basic propeller aerodynamics. The intent here is to identify the parameter variations that can give significant noise reduction. In a later section the interdependence of some of the parameters will be considered. The variations are typically taken about the base case which yielded a calculated overall sound pressure level of 149.5 decibels (ref 2×10^{-5} N/m^2).

Helical tip Mach number. - The helical tip Mach number is a combination of the axial velocity of the airplane and the rotational tip speed of the propeller. The helical Mach number as defined by equations (8) and (9) appears specifically in the pressure equations (1) and (2) and therefore a variation in this parameter should have a direct effect on the noise. Since the helical Mach number is a combination of two velocities the parametric investigation involved varying each of these separately to obtain the Mach number variation. The separate variation is necessary because the radius at which the blade becomes sonic (r_s) will be different depending on whether the axial or rotational Mach number is varied. This different radius will affect the amount of thrust in the supersonic region and in turn affect the noise. Figure 2(a) shows the noise variation with Mach number where the axial velocity was varied and figure 2(b) shows the variation with Mach number where the tip speed was varied. As can be observed the two curves have the same general shape with only some slight differences in level. The importance of these variations is the large number of decibels of noise reduction that are possible by lowering the helical Mach number. This noise reduction could be accomplished by slowing down the airplane (i.e., a 0.7 Mach number airplane as opposed to the 0.8 Mach number of the base case) and/or by lowering the propeller tip speed.

The present equations do not directly address the relative Mach number reduction that might be achieved by sweeping the propeller blades. Rohrbach and Metzger, ref. 4, and Hanson, ref. 1, have shown the noise reduction benefits of proper blade sweep in their noise model. This noise reduction scheme is recognized but a parametric investigation was not undertaken as this quantity is not directly addressed in the equations.

Distance from fuselage. - A noise reduction is possible by increasing the distance from the propeller tip to the fuselage. Figure 3 is a plot of noise with a variation of distance from the fuselage measured in propeller diamaters. The base propeller is 4.88 m (16 ft) from the fuselage and has a spacing to diameter ratio (h/D) of 0.8. As can be observed from figure 3 some noise reduction can be achieved by moving the propeller outboard from the fuselage. It should be noted however that a tradeoff would exist between the weight added to the airplane as a result of moving the engine outboard and the weight of noise reduction material required in the airplane fuselage to achieve the same noise reduction.

Diameter. - The variation of noise with a diameter change only is shown in figure 4. It should be noted that this variation is made at a constant propeller tip to fuselage distance $h = 4.88$ m (16 ft). Here it is seen that some small noise reduction could be obtained by increasing the diameter by itself without change to any of the other parameters. The noise reduction appears to come through the time term in equation (5) where the overpressure from the larger diameter blade is present for proportionately less time during a revolution. It should again be noted that some weight tradeoff is needed between the extra landing gear size, etc. that would be needed to accommodate a larger propeller and the weight of fuselage treatment material.

Airfoil thickness. - The overpressure terms in the noise evaluation are directly affected by the volume of the airfoil. Therefore a noise reduction was expected with decreasing thickness. This reduction is shown in figure 5. Some significant reductions can be obtained in going from a 10 percent thick airfoil to a 2 percent thick airfoil. However, since the base case propeller was 2 percent thick, which is about as thin as possible, no further noise reduction is likely.

Shape factors. - Two shape factor constants K_V and K_L are present in the overpressure equations. These constants could be changed by varying the chordwise thickness and loading distributions of the airfoil. A reasonable range for these constants is assumed to be from 0.5 to 0.8 (ref. 3). A noise plot of these variations is shown in figure 6. As can be observed only a few decibels of noise reduction are available over the entire range of these parameters. When actual aerodynamic constraints are put on these variables they appear to be very unlikely sources of noise reduction.

Specific Interdependent Variation

A number of the noise reduction parameters that were independently varied in the previous section cannot in actuality be changed without changing other parameters. The intent here is to more thoroughly investigate how to accomplish one of the previous parametric investigations where some of the more obvious aerodynamic constraints are included. The reduction in helical tip Mach number appears to have the largest potential for reducing the noise from the propeller and is therefore the one considered here. Since the cruise design Mach number of the airplane is probably not a likely candidate for change only a reduction in the propeller tip speed is included in this discussion. (If a change in cruise Mach number is possible, the noise reduction available from this change can be seen from the independent variation presented in fig. 2(a).)

In the following discussion the propeller tip speed is parametrically varied while maintaining the aerodynamic performance. The thrust of a propeller can be expressed as,

$$\tau = \rho N^2 D^4 C_{T_B} B \qquad \text{from ref. 5} \tag{12}$$

where ρ is the density, N the rotational speed, D the propeller diameter, C_{TB} the thrust coefficient for a blade and B is the number of blades. When N^2D^2 is replaced by V_T^2/π^2, there results

$$\tau = \frac{\rho}{\pi^2} C_{TB} V_T^2 D^2 B \tag{13}$$

where V_T is the tip speed. It can be seen that in order to maintain the same thrust while varying the tip speed some of the other terms in equation (13) must be varied. The two most obvious are the propeller diameter and the number of blades.

<u>Variation of V_T by changing propeller diameter</u>. - An increase in the propeller diameter enables the same thrust to be produced at a lower tip speed. In this particular variation the product of the tip speed and the propeller diameter is held constant which results in a constant thrust. Plots of the noise reduction with this increasing diameter are seen in figure 7. One of the plots is taken at a constant distance and the other at a constant h/D. As can be observed in this figure an increase in the diameter, with its reduction in velocity, brings significant noise reductions. For example, an increase in the diameter from 6.10 m (20 ft) the base diameter to 7.32 m (24 ft) yields a noise reduction of more than 6 decibels at a constant distance and more than 7 decibels at a constant h/D.

It should be noted that increasing the diameter brings with it some additional propulsion system weight and airplane installation problems, neither of which have been considered herein. However, an increase in diameter, with its reduction in velocity, appears to have significant noise reduction potential.

<u>Variation of V_T by changing blade number</u>. - An increase in the number of propeller blades allows a reduction in tip speed by lowering the required thrust per blade. In order to maintain the same thrust, the product of the number of blades and the square of the tip speed is held

constant, as indicated by equation (13). The noise reduction with increasing blade number is seen in figure 8. An increase in the number of blades can result in sizable noise reductions through a decrease in the propeller tip speed. For example, some 6 dB of noise reduction is available by going from the 8 blades of the base case to a 12 bladed propeller. Although some problems might exist in blade mounting, etc., the increase of blade number appears to be a promising method of noise reduction.

CONCLUDING REMARKS

A parametric investigation was performed with an existing noise prediction procedure for supersonic relative tip speed propeller blades. An investigation was first performed wherein the pertinent parameters were varied independent of one another. The parameters which showed noise reduction possibilities are listed below roughly in order of potential: reducing the Helical tip Mach number; increasing the propeller tip to fuselage distance; increasing the propeller diameter; reducing the airfoil thickness and; adjusting the chordwise thickness and loading distributions. The amount of noise reduction possible ranged from sizable in the case of Mach number reduction to minimal for adjusting the thickness and loading distributions. The largest potential method of noise reduction, decreasing Mach number, was further investing by interrelating the quantities through the requirement that constant propeller thrust be maintained. Two parameters, diameter and blade number, were varied to reduce the tip speed and in turn the helical tip Mach number. The investigation using the interrelated quantities indicated that significant noise reductions could be achieved by increasing the propeller diameter and/or increasing the number of propeller blades while maintaining a constant propeller thrust.

APPENDIX - SYMBOLS

a_o	speed of sound at altitude, length/time
B	number of blades
C	blade chord, length
C_{T_B}	thrust coefficient for one blade
D	propeller diameter, length
d	equivalent diameter of supersonic region of blade (eq. (10)), length
h	distance of propeller tip from fuselage wall, length
K_L	lift shape factor constant
K_{NF}	near to far field correction constant
K_R	reflection constant
K_V	volume shape factor constant
l_B	effective body length
l_W	effective wing length
M	average helical Mach number
M_{ht}	helical tip Mach number
M_N	airplane Mach number
N	rotational propelle speed, rev/time
P_a	pressure at altitude, force/(length)^2
P_g	pressure at surface, force/(length)^2
P_{ref}	reference pressure (2×10^{-5} N/m^2)
r_h	propeller hub radius, length
r_s	radius at which helical Mach number is 1, length
r_t	tip radius, length

T	time between each blade passage (eq. (6))
T^*	shock duration (eq. (7))
t	blade thickness, length
V_T	propeller tip speed, length/time
W	loading in supersonic region of propeller, force
ΔP	total overpressure (eq. (3)), force/(length)^2
ΔP_L	lift component of overpressure (eq. (2)), force/(length)^2
ΔP_V	volume component of overpressure (eq. (1)), force/(length)^2
ρ	density, mass/(length)^3
τ	propeller thrust, force

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TABLE I. - BASE CASE PARAMETERS

Parameter		Valve	
		Metric	English
P_a	pressure	22 695 N/m^2	474 lb/ft^2 at 36 000 ft
P_g	pressure	22 695 N/m^2	474 lb/ft^2
D	prop diameter	6.10 m	20 ft
h	distance from prop	4.88 m	16 ft
r_h	hub radius	0.46 m	1.5 ft
V_T	tip speed	244 m/sec	800 ft/sec
a_o	speed of sound	297 m/sec	973 ft/sec
M_N	airplane Mach number	0.8	0.8
τ	total thrust	33 953 newtons	7633 lbs
B	number of blades	8	8
K_R	various constants as suggested by ref. 3	2.0	2.0
K_L		0.7	0.7
K_V		0.8	0.8
K_{NF}		0.75	0.75
C	chord	0.762 m	2.5 ft
t/C	thickness to chord	0.02	0.02

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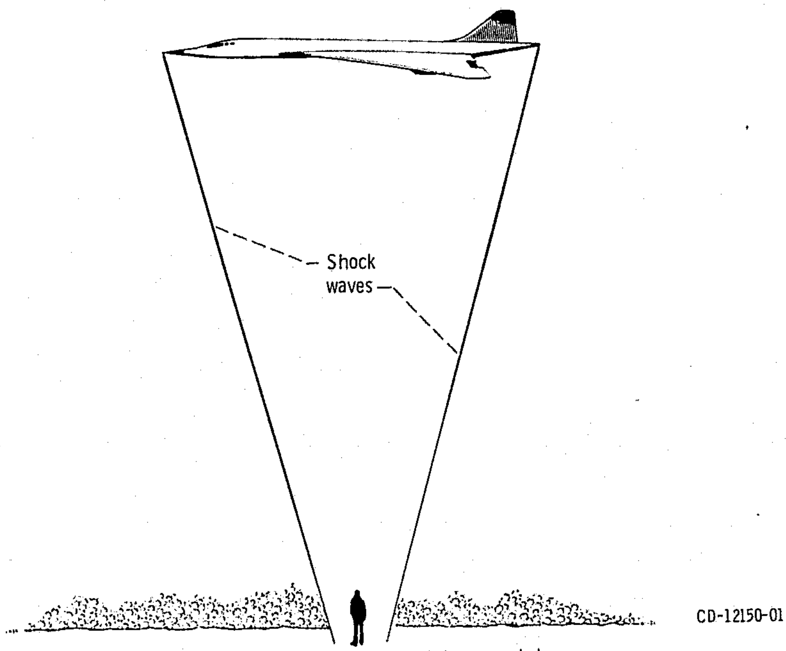
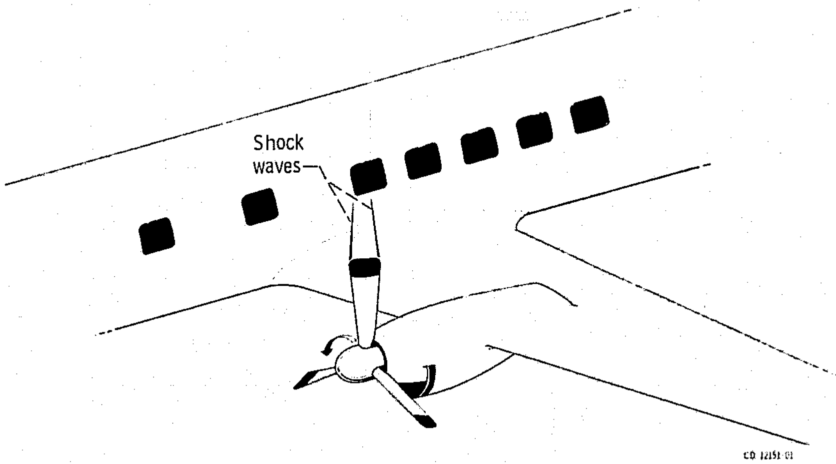
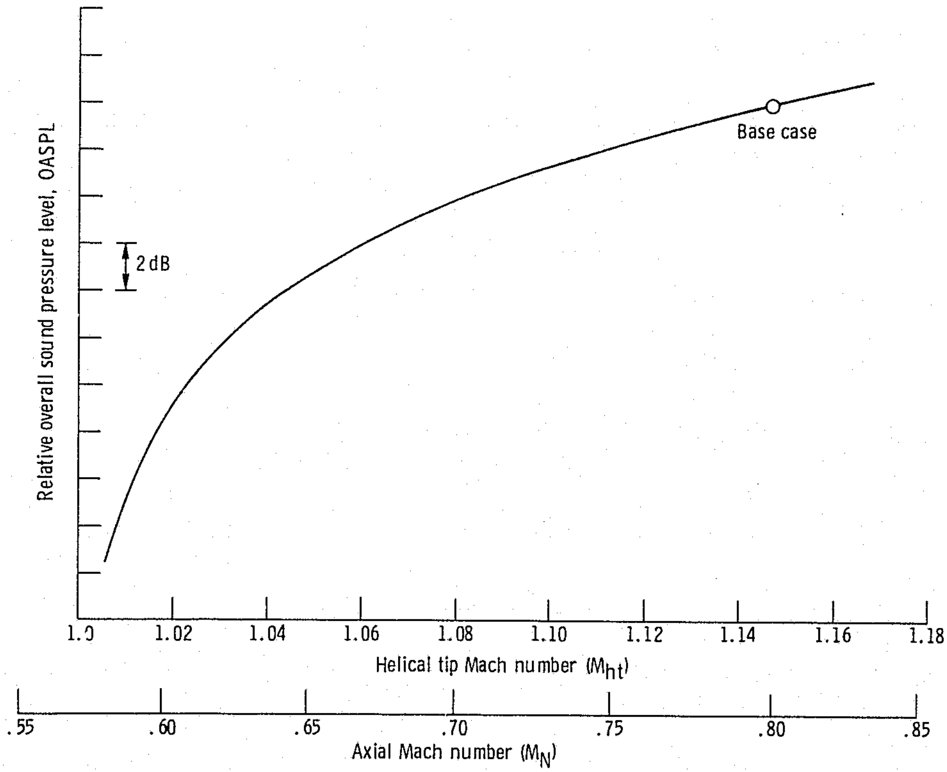


(a) Flyover basc - relationship of SST shock to ground observer.
Figure 1. - Schematic of the extrapolation of the flyover noise model to the turboprop.



(b) Propeller case - relationship of propeller shock to fuselage.
Figure 1. - Concluded.



(a) Variation with axial Mach number (tip speed constant).

Figure 2. - Variation of noise with helical tip Mach number.

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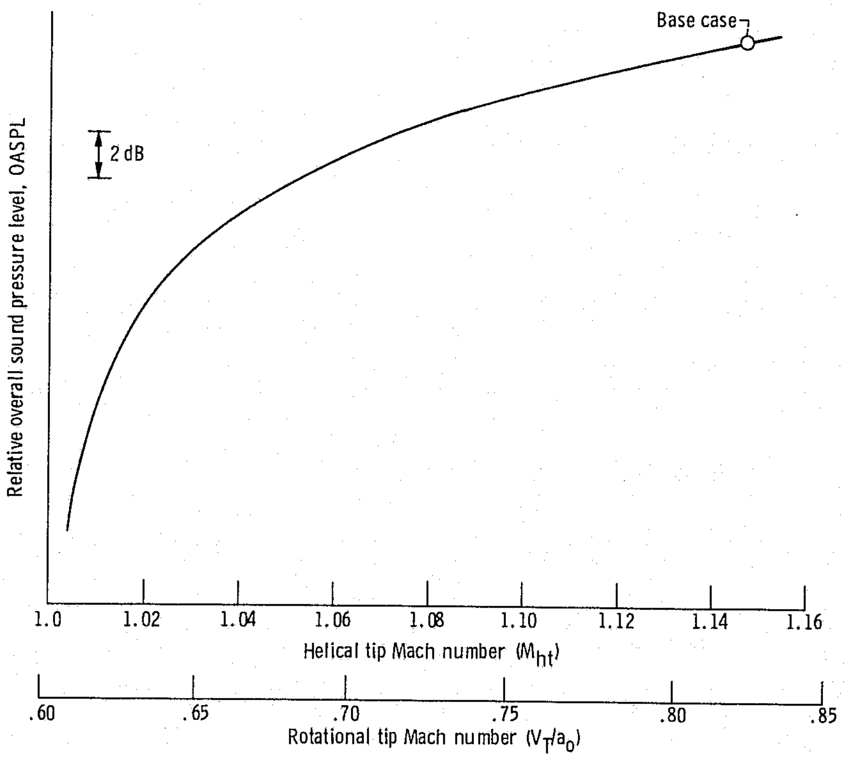

(b) Variation with propeller tip speed (axial Mach number constant).

Figure 2. - Concluded.

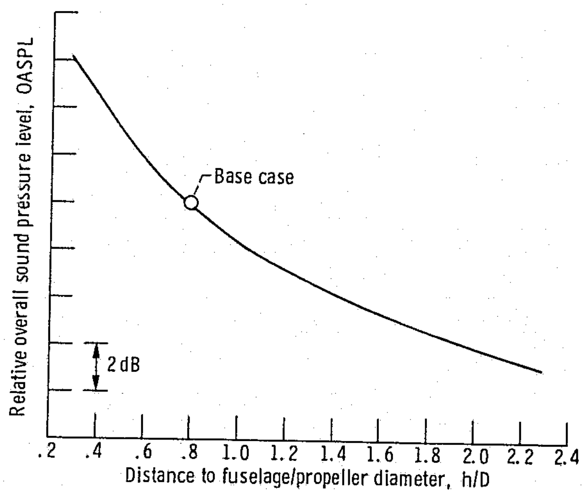

Figure 3. - Variation of noise with distance from fuselage (diameter constant).

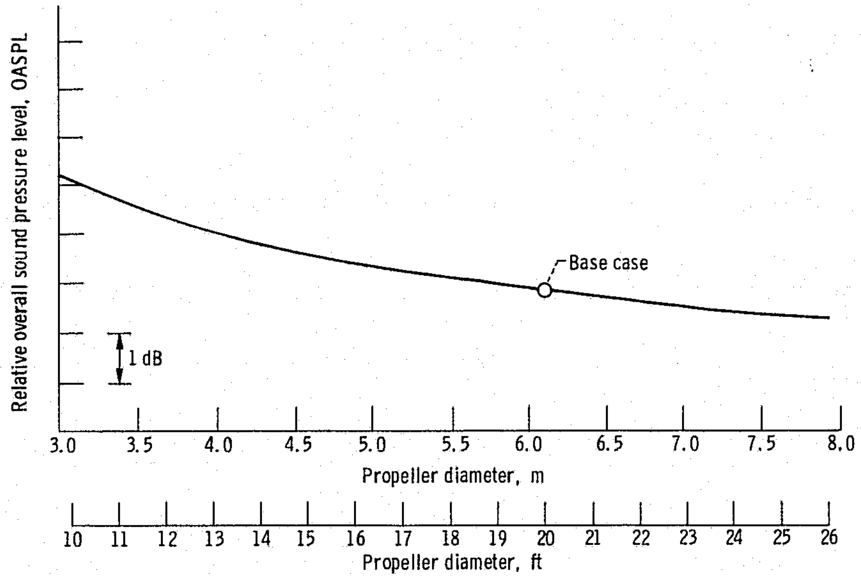

Figure 4. - Variation of noise with propeller diameter (h is a constant).

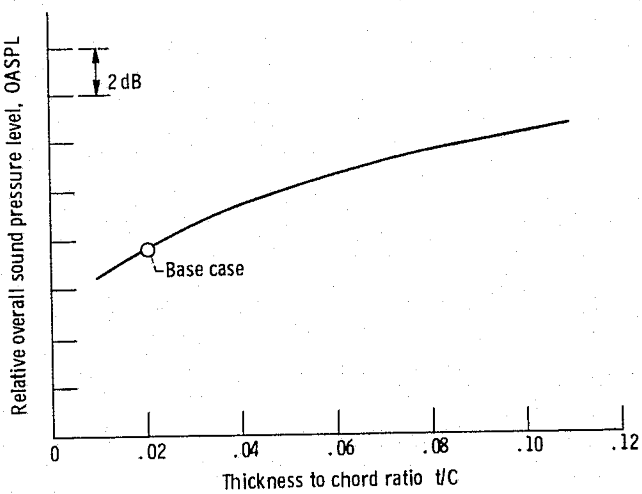

Figure 5. - Variation of noise with airfoil thickness (chord constant).

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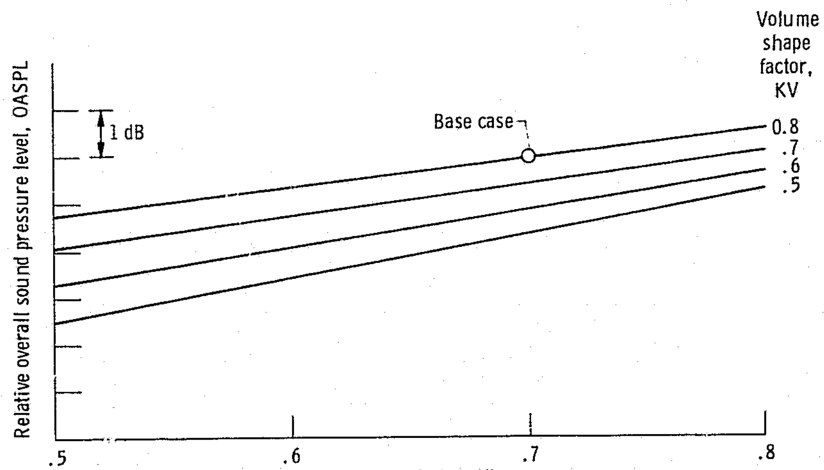

Figure 6. - Variation of noise with shape factors.

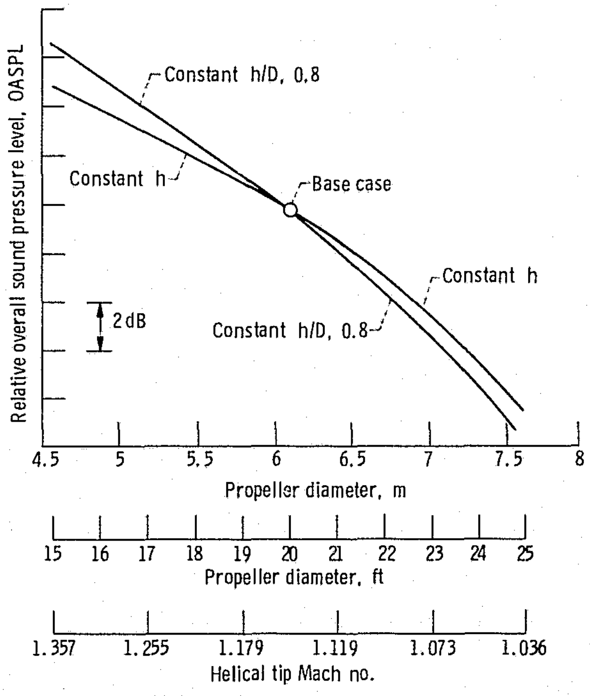

Figure 7. - Reduction of noise through an increase in propeller diameter while maintaining constant thrust.

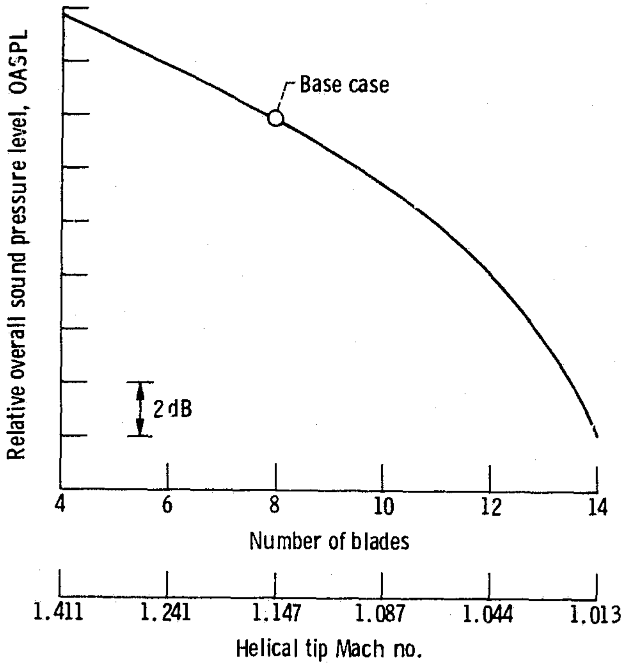

Figure 8. - Reduction of noise through an increase in blade number while maintaining constant thrust.

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