NASA-TM-83407

NASA Technical Memorandum 83467

A Possible Explanation for the Present Difference Between Linear Noise Theory and Experimental Data for Supersonic Helical Tip Speed Propellers

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November 1983

DISPLAY 52/2/1

84N14874*# ISSUE 5 PAGE 742 CATEGORY 71 RPT#: NASA-TM-83467 E-1781
NAS 1.15:83467 83/11/00 18 PAGES UNCLASSIFIED DOCUMENT

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CORP: National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio. AVAIL.NTIS SAP: HC A02/MF A01

MAJS: /*BLADE TIPS/*HIGH SPEED/*NOISE REDUCTION/*PROPELLERS/*TURBOPROP AIRCRAFT

MINS: / AERODYNAMIC CONFIGURATIONS/ DRAG/ FLOW VELOCITY/ MACH NUMBER/ PERFORMANCE TESTS/ PREDICTION ANALYSIS TECHNIQUES

ABA: Author

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A POSSIBLE EXPLANATION FOR THE PRESENT DIFFERENCE BETWEEN LINEAR NOISE THEORY AND EXPERIMENTAL DATA FOR SUPERSONIC HELICAL TIP SPEED PROPELLERS

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E-1781

SUMMARY

High speed turboprops are attractive candidates for future aircraft because of their high propulsive efficiency. However, the noise of their propellers may create a cabin environment problem for the aircraft powered by these propellers. The noise of some propeller models has been measured, and predictions of the noise using a method based on the Ffowcs Williams - Hawkings equation have been made. The predictions and data agree well at lower helical tip Mach numbers but deviate above Mach 1.0. This paper investigates some possible reasons why the theory does not predict the data and focuses on improvement of the aerodynamic inputs as the most likely remedy. In particular, it is proposed that an increase in the drag and a decrease in the lift near the tip of the blade, where the majority of the noise is generated, is warranted in the input to the theory.

INTRODUCTION

The noise of three model propellers was measured in the NASA Lewis 8-by-6-foot wind tunnel in 1978 (refs. 1 and 2). Pictures of the three individual blades and of a complete propeller model are shown in the wind tunnel in figure 1. An existing linear noise model by Farassat (refs. 3 to 5), based on the solution of the Ffowcs Williams - Hawkings equation (ref. 6), was exercised to compare with the measured data (reported in 1980, ref. 7). Plots showing the theory-data comparisons for the blade passing tone versus helical tip Mach number are repeated herein (fig. 2). As can be seen, the theory and data compare well for all three propellers at the lower helical tip Mach numbers, but above Mach 1.0 the theoretical curve continues to rise with Mach number, while the wind tunnel data level off. When reference 7 was published, it was not clear whether the theory or the data were incorrect, since the data taken in the wind tunnel might have been contaminated by reflections from the acoustically hard wind tunnel walls; however, it is not likely that reverberations would lead to measurements that were too low as figure 2 suggests. As part of the test program on these propeller models, one of them, SR-3, was flown on the NASA Dryden Jetstar airplane, and noise data were taken with fuselage mounted microphones. A comparison of the wind tunnel and the airplane data (ref. 8; see fig. 3) revealed very good agreement. Thereby, the suspicion of error shifts to the theoretical noise model.

The purpose of this study was to investigate the input parameters to the linear noise model and to explore what might bring the theory and data into better agreement.

ANALYSIS

Ffowcs Williams - Hawkings Equation

The noise prediction method of reference 7 was developed by Farassat (refs. 3 to 5). The starting point of this analysis is the Ffowcs Williams - Hawkings equation (ref. 6). The formulation of the equation (without the quadrupole term) that was used by Farassat is

$$\frac{1}{C^2}\frac{\partial^2 P'}{\partial t^2} - \nabla^2 P' = \frac{\partial}{\partial t}\left[\rho_o V_N \left|\nabla f\right| \delta(f)\right] - \frac{\partial}{\partial x_i}\left[L_i \left|\nabla f\right| \delta(f)\right] \tag{1}$$

where C is the speed of sound, ρ_O is the density in the undisturbed medium, P' is the acoustic pressure, and V_N is the local velocity normal to the surface of the blade. The blade is described by $f(x,t) = 0$. The local force on the fluid (per unit area) at the surface of the blade is denoted by L_i, and $\delta(f)$ is the Dirac delta function. The first term on the right of the equation represents the volume displacement effect and is usually referred to as the thickness term. The second term represents the force exerted on the air and is usually referred to as the loading term. The two terms on the right hand side of the equation are inputs to the equation.

For this study it was initially assumed that the Ffowcs Williams - Hawkings equation can be used at low supersonic helical tip Mach numbers and further that Farassat's solution to this equation is correct. If either of these assumptions is incorrect, then a different theory or solution would be required. The possibility of this theory being incorrect is discussed in reference 9, which approached the problem using shock waves, in reference 10, which investigated the effect of nonlinear terms in equation (1), and in reference 11, which used a nonlinear approximation to an equation from reference 12. This study was conducted to investigate what might be changed in the use of this existing theory, based on the Ffowcs Williams - Hawkings equation, to bring the theoretical results more in line with the data. The main thrust here lies with the possiblity of error in the inputs to this equation and with where an improvement could most likely be made.

Inputs to Equation

The inputs to the thickness term, the first term on right hand side of equation (1), are the actual coordinates of the blade surface. Since these are existing blades, the physical dimensions of the blades are easily confirmed, and this is not a likely source of error. The actual position of the blades in space as a result of blade bending, etc., may be a source of error but, in general, the thickness noise is probably not a likely area for error. However, the aerodynamic forces on the air due to the blades, which are input to the equation (ref. 7) are not as well known. These aerodynamic loads were based on two-dimensional strip theory and may be in error, particularly near the tip where the flow is highly three-dimensional and where the majority of the noise is probably generated. The loading noise is then the term most suspect and in need of further investigation.

Gutin Formulation

Since the loading noise is under consideration, a simplification can be achieved by using an earlier formulation of propeller noise that considers only loading noise. In particular, the propeller noise formulation of Gutin (ref. 13) will be used to illustrate the propeller loading noise and its components. In the Gutin formulation the propeller exerts two forces on the air, a thrust force and a torque force. Gutin considered these forces to act in one plane, as opposed to the Farassat model, which also allows the forces to be distributed along the chord of the propeller. The general character of the solution should probably not be greatly affected by this difference, so that inferences drawn from these two models should be similar.

The Gutin model uses a spanwise integration, of the forces to determine the sound pressure. This integration, shown below, is equation (9) of reference 13 with some changes in symbols to make the notation in this report consistent.

$$P = \frac{m\,\omega_1}{2\pi c r}\left|\int_0^{R_0}\left(-\frac{dT}{dR}\,e^{-i\epsilon_m}\cos\theta + \frac{nc}{\omega_1 R^2}\frac{dM_T}{dR}\,e^{-i\eta_m}\right)J_{mn}\left(\frac{m\omega_1}{c}R\sin\theta\right)\,dR\right| \tag{2}$$

where P is the sound pressure, m is the harmonic number, ω_1 is the circular frequency of the fundamental tone, c is the speed of sound, r is the distance to the observer, R is the distance along the blade span from 0 to R_0, R_0 is the outer radius of the propeller, T is the thrust force, θ is the angle from the propeller axis to the observer, n is the number of propeller blades, M_T is the torque, and ϵ_m and η_m are phase angles in the Fourier decomposition of the thrust and torque noise contributions, respectively.

The aerodynamic inputs to this model are then the thrust T and torque M_T distributions from hub to tip for the propeller. The thrust and torque terms in equation (2) show that in the forward arc the two terms act in opposition (opposite sign); while in the rear arc the cosine term changes sign, and the thrust and torque contributions combine to give the peak noise. The resulting two-lobed directivity pattern has a forward peak and minimum and a larger rearward peak. (See Gutin, ref. 13.) The pattern has been observed previously (refs. 8 and 14). A plot of the sideline blade-passage tone directivity for the SR-3 propeller from reference 14 is repeated here in figure 4. The peaks and the minimum have been shifted downstream in the tunnel by the high axial Mach number, which is not included in the Gutin theory. This similarity between the predicted and measured shapes lends further credibility to the belief that the Gutin analysis provides the proper trends for the thrust and torque terms.

The Gutin analysis was derived for propellers where the airfoil chord was in the plane of rotation. For this blade setting the airfoil lift was along the axis of the propeller, and the drag was in the rotational direction (fig. 5(a)). Therefore, the section thrust was derived from the lift force, and the torque from the drag force multiplied by the radius of the section under consideration. Under these conditions it would have been possible to look separately at the effects of thrust and torque, to see how the trends of the equation compared with the data, and thereby to infer whether the lift or the drag was the most likely aerodynamic parameter needing to be changed. Generally, however, the propeller airfoils are set at some angle β with respect to the propeller plane of rotation (fig. 5(b)). This angle varies along the span of the blade so that each hub to tip airfoil section has a different angle. The thrust and torque terms, therefore, contain components of both the airfoil lift and drag, and the amount of each component varies along the span. Consequently, it is necessary to look at both the lift and drag terms to determine which is most likely in need of change.

Variation of Lift and Drag with Mach Number

The procedure is to examine the variation of the lift and drag with helical tip Mach number and compare their behaviors with that of the noise data. To do this, we first examine the lift and drag curves for the particular airfoil sections used in the manufacture of these propellers. Over the outer 75 percent of these blades, a NACA 16 series airfoil is used. Since the most noise is generated at the larger radii (the Bessel function in equation (2) is larger at larger radii), it is assumed that the 16 series airfoil can be used to represent the propeller for noise purposes. The three propellers shown in figure 1 have low camber, and the thickness generally varies from 5 percent thick in-board to 2 percent thick at the tip. The propeller blades were operated at low section angles of attack, and the noise data (fig. 2) were taken at constant advance ratio, so that this angle remains constant with helical tip Mach number. A series of infinite aspect ratio NACA 16 series airfoils has been tested and plots of the lift and drag coefficients (profile) have been compiled (ref. 15). Plots for an NACA 16-004 airfoil at a 2° angle of attack have been chosen from that work as the most appropriate for this investigation and are repeated here in figure 6. The basic similarity of the 16 series family of curves and the transonic similarity rules (refs. 16 and 17) indicate that this NACA 16-004 airfoil will be a good approximation over the entire outer range of the blade (5 to 2 percent thick) at least to the accuracy needed for the comparisons with the noise measured in decibels.

As can be seen from figure 6(a), the lift coefficient is fairly flat, with a magnitude between 0.2 and 0.3 over the Mach number range indicated, and does not exhibit the curve shape of the noise data (fig. 2). On the other hand the profile drag coefficient at a lift coefficient of 0.2 (fig. 6(b)) follows a typical drag rise curve (exhibited by most airfoils) and is very similar in shape to the noise curve of figure 2. This similarity is a strong indication that the drag force inputs to the theory may be in error. To further investigate this possibility, a comparison of the measured noise and the noise increase expected from this drag rise was undertaken.

Drag Rise Variation with Mach Number and Comparison with Noise

The drag on an airfoil section can be calculated from the drag coefficient of figure 6(b) by the formula

$$D = \frac{1}{2}\rho V^2 C_D S \tag{3}$$

where ρ is the density, V the free-stream velocity, C_D the drag coefficient, and S is the section area. From equation (2), if it is assumed for now that thrust and torque are dominated by the drag, it follows that the pressure should be proportional to the drag (approximately) and that the noise variation is

$$dB = 20 \log \frac{C_D M^2}{C_{D,ref} M^2_{ref}} \tag{4}$$

where M is the free-stream Mach number and where constant density is assumed. To determine the shape of the curve with respect to Mach number, a reference Mach number of 0.85 was chosen. This resulted in the curve of figure 7. The shape is very similar to that of the propeller noise. It should be noted here that the Bessel function in equation (2) is also Mach number dependent and that the inclusion of this term could modify the shape of the noise curve somewhat since only the variation of the drag term with Mach number is plotted here. If the inclusion of this term results in a large change in curve shape, it might indicate that some modification to the theory or solution may be needed.

To compare the variation of the drag (fig. 7) with the noise data (fig. 2), it is assumed that the helical tip Mach number is the representative Mach number to be used. This is equivalent to saying that most of the noise is generated at the tip. In addition, since the wind tunnel operates at different densities for different axial Mach numbers, the noise data need to be adjusted to constant conditions. This was done previously (ref. 8) for the SR-3 propeller data and has been done here for the data from all three propeller models. Finally, in order to compare the drag curve variation with the noise, the curves were matched at the design condition (helical tip Mach number of 1.14). This matching was in level only, and no changes were made in the Mach number axis. It should be noted here that the SR-3 propeller noise level at design was significantly lower than the other two propellers as a result of a tailored sweep built into the blades to provide noise cancellation from the various hub to tip blade sections. The sweep was based on a solution of equation (1) and is roughly equivalent to adjusting ϵ_m and η_m in equation (2) to obtain phase cancellation. Even with the cancellation brought about by tailoring ϵ_m and η_m for the various hub to tip sections, the basic drag curve would still apply at each section. Thus, the Mach number variation of the calculated drag noise in the solution would probably remain the same. Therefore, figure 7 is also used in comparing with the noise data of SR-3 with only an adjustment in level. With these adjustments made, figure 8 compares the variation of the drag noise (eq. (4)) and the noise data, with helical tip Mach number. As can be seen the calculated drag curve shape agrees very well with the noise curve for all three propeller models. This agreement is especially good for the SR-3 propeller which had the tailored sweep to provide noise cancellation. The good agreement points toward the drag as a strong candidate for the cause of the curve shape observed in the data.

The identification of the drag input as most likely to be in error is consistent with the performance data of reference 18. Here, a comparison of the measured design point efficiency of these three propellers (fig. 14 of ref. 18) with the predicted efficiencies (fig. 13 of ref. 18) shows that all three propellers are less efficient than expected from the two-dimensional aerodynamics analysis. (It may be that a three-dimensional analysis might also fail to predict performance because of unpredicted phenomena such as separation, etc.) This difference in predicted and measured efficiencies is attributed in reference 18 to compressibility losses (drag rise). It is probable that some portion of these unexpected losses would result in more drag noise. The same general noise curve shape is found for helicopter noise (ref. 19), and this also is expected because the helicopter airfoils exhibit a similar drag curve shape.

The simple addition of more drag and, therefore, more drag noise, into the solution of equation (1) would probably not result in a curve shape matching the data because the loading noise prediction alone exceeds the data. Therefore, it would be necessary for the lift noise to decrease under the conditions for which the drag noise becomes dominant. This would be equivalent to saying that the noise controlling tip region of the propellers produces less lift as well as more drag than expected.

If the lift to drag ratio of about 10, shown for the infinite aspect ratio wing of figure 6, holds valid near the propeller tip, the lift noise would dominate over the drag noise. However, it is probable that the major noise producing region of the blade near the propeller tip produces less lift and more drag than that indicated by figure 6.

A wing of finite aspect ratio exhibits a lower lift coefficient and a greater drag coefficient as the result of tip effects. These tip effects are primarily the result of air moving from the pressure surface of the wing to the suction surface around the tip, thereby creating a vortex (ref. 20). The general trend for an airfoil with reduced aspect ratio is to have an increase in drag, referred to as induced drag, and a reduction in the effective angle of attack which results in less lift. An example of this can be seen in figure 9, which was redrawn from reference 21 (figs. 2 and 3) and was based on work reported in reference 22. As can be seen, as the aspect ratio of a wing decreases, the lift coefficient also decreases for lift coefficients greater than zero (fig. 9(a)). For example, at a 4° angle of attack the lift coefficient is more than cut in half, from 0.65 (point A) to 0.28 (point B), when the aspect ratio is reduced from 7 to 1. The increase in drag with decreasing aspect ratio can be seen in figure 9(b). For example, in going between points corresponding to the previous example, the drag coefficient has increased from roughly 0.025 to 0.035. This illustrates the general trend for the overall airfoil loss of lift and increase in drag as a result of the tip effect of a finite aspect ratio wing. As the aspect ratio becomes smaller, the tip sections represent a larger portion of the airfoil and the effect on the overall airfoil performance becomes larger. At the tip sections, where the effect occurs, there is of course a larger percentage change than for the airfoil as a whole. At the very tip of the blade the airflow from the pressure to suction surface of the blade may effectively destroy the lift and result in a local lift to drag ratio of less than one.

The tip section of the propeller blade is believed to be the major noise producing region of the blade, so with the increased drag and decreased lift indicated for the tip, the dominance by the drag noise becomes possible. These increases in drag and decreases in lift at the tip, although locally large, would probably not have a major effect on the overall performance of the propeller since the portion of the span would be small. The small differences in predicted and measured efficiencies mentioned earlier may be the result of the propeller tip effects mentioned here.

Since the predictions using equation (1) from reference 7 did not show the thickness noise to be dominant at the rearward peak noise angle, a change in the thickness term would probably not be necessary to bring the predicted and experimental curves together. The most likely changes required to bring the theory in better agreement with the data are to increase the tip drag and reduce the tip lift inputs to the theory so that the drag noise is more dominant in the theoretical solution. This, of course, should not be done arbitrarily. An improved three-dimensional aerodynamic theory with viscous effects should be developed. Until this is available empirical methods will probably have to be used.

CONCLUDING REMARKS

The noise predicted by linear noise theory deviates from the turboprop experimental data at helical tip Mach numbers above one. In looking in general at linear noise theory, it appears that the inputs to the theory and, in particular, the inputs to the loading noise portion of the theory are most likely in error. This loading noise consists of thrust and torque terms which are the result of lift and drag on the airfoils. The shapes of the lift and drag inputs were compared with the data, and the shape of the calculated drag term closely fit the data from the three tested propellers. This thereby points to the drag term as the likely cause for the deviation between theory and experiment. Since the present theory, controlled by the loading terms (thrust and torque), overpredicts the data, a simple increase in the drag term would probably not result in a curve shape matching the data. Therefore, it would also be necessary to reduce the predicted lift noise. This would be equivalent to saying that the major noise producing tip region of the blade had both less lift and more drag than predicted by the two-dimensional strip analysis used as input to the noise theory. This is consistent with the fact that the measured design point efficiencies of these blades were less than predicted by this two-dimensional strip analysis. The paper has advanced the proposition that, if this theory is useable to predict the data, the aerodynamic inputs to the theory need to be improved. In particular, a good candidate for change is to increase tip drag and reduce tip lift so that the drag noise dominates the theoretical solution above sonic helical tip Mach numbers.

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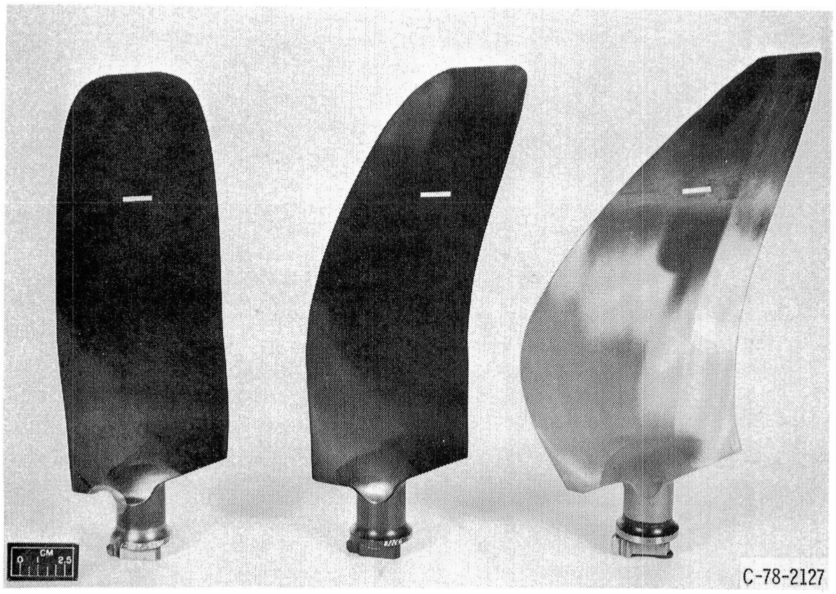
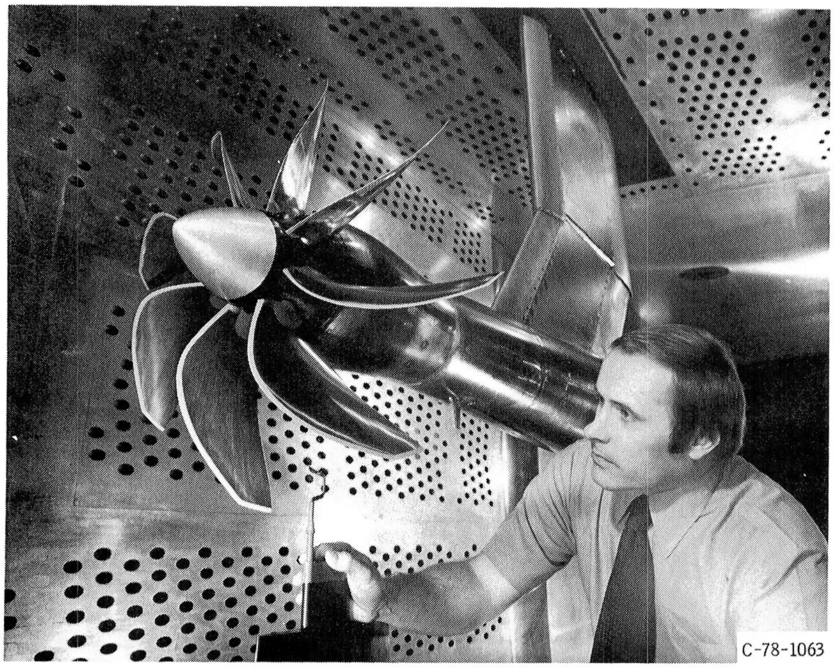


(a) Propeller blades.



(b) Sr-3 model propeller.

Figure 1.

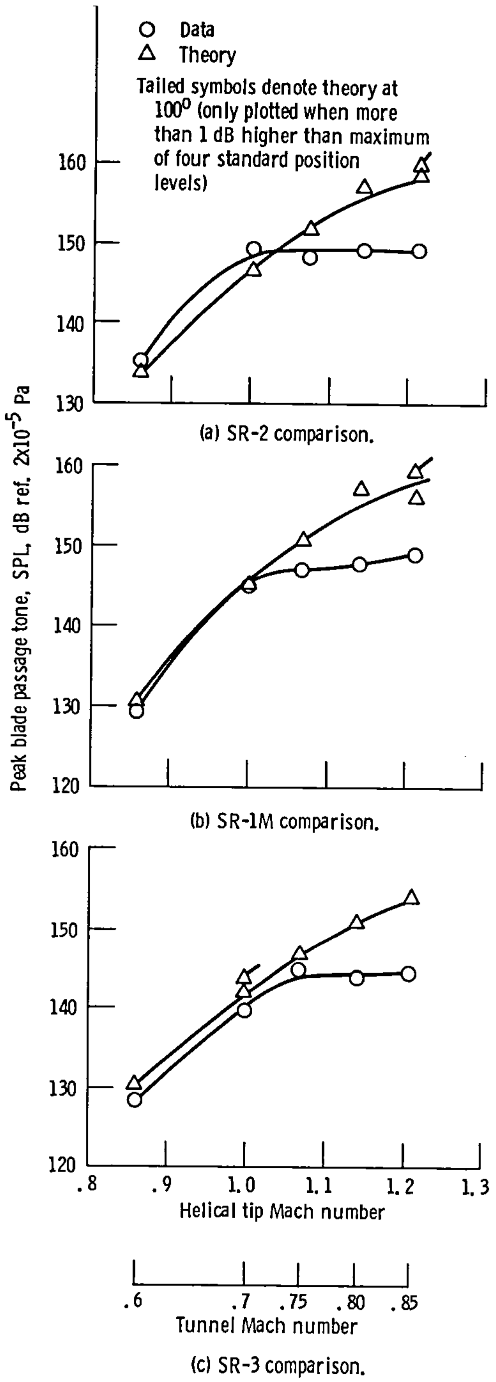


Figure 2. - Peak blade passage tone variation with helical tip Mach number.

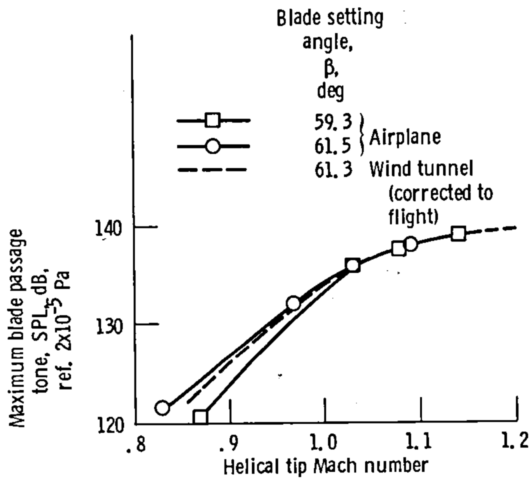


Figure 3. - Comparison of maximum blade passage tones from the wind tunnel and flight tests.

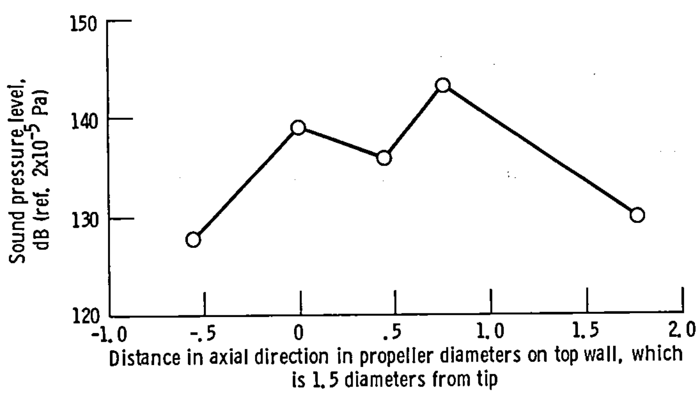
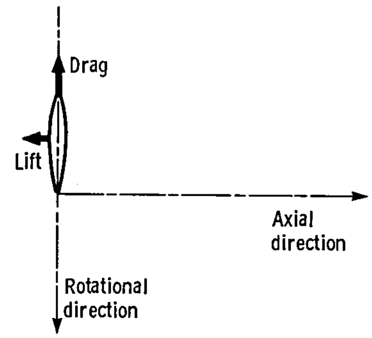
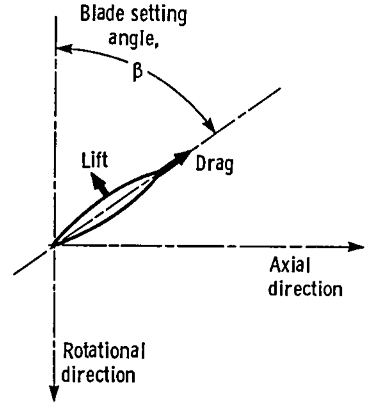


Figure 4. - SR-3 sideline directivity of blade passing tone at a tunnel Mach number of 0.80.

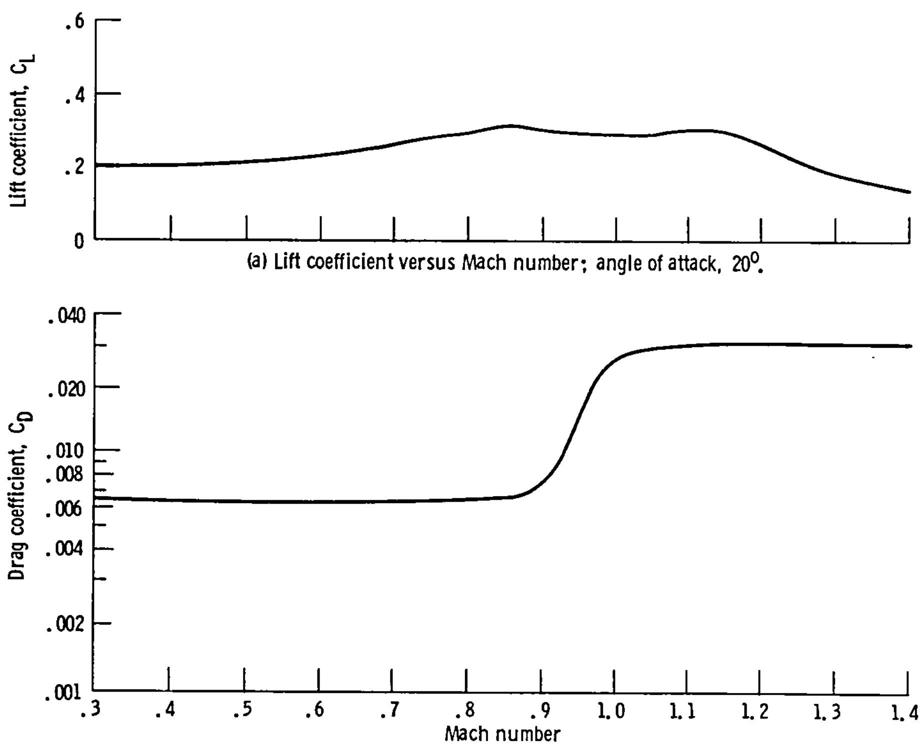


(a) Airfoil in plane of rotation.



(b) Airfoil at setting angle β.

Figure 5. - Airfoil orientation.



(a) Lift coefficient versus Mach number; angle of attack, 20°.

(b) Drag coefficient versus Mach number; lift coefficient, 0.2.

Figure 6. - Airfoil performance characteristics. Airfoil section NACA 16-004; aspect ratio, ∞.

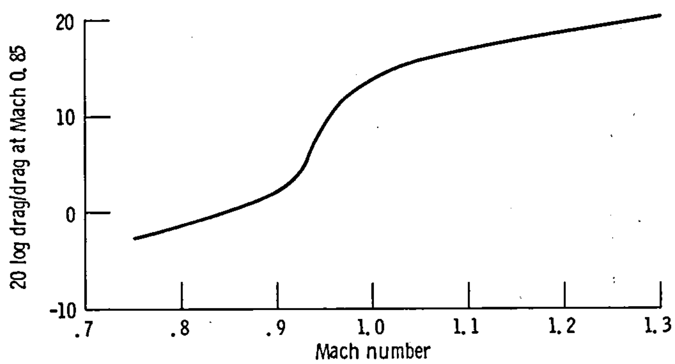


Figure 7. - Variation of drag with Mach number.

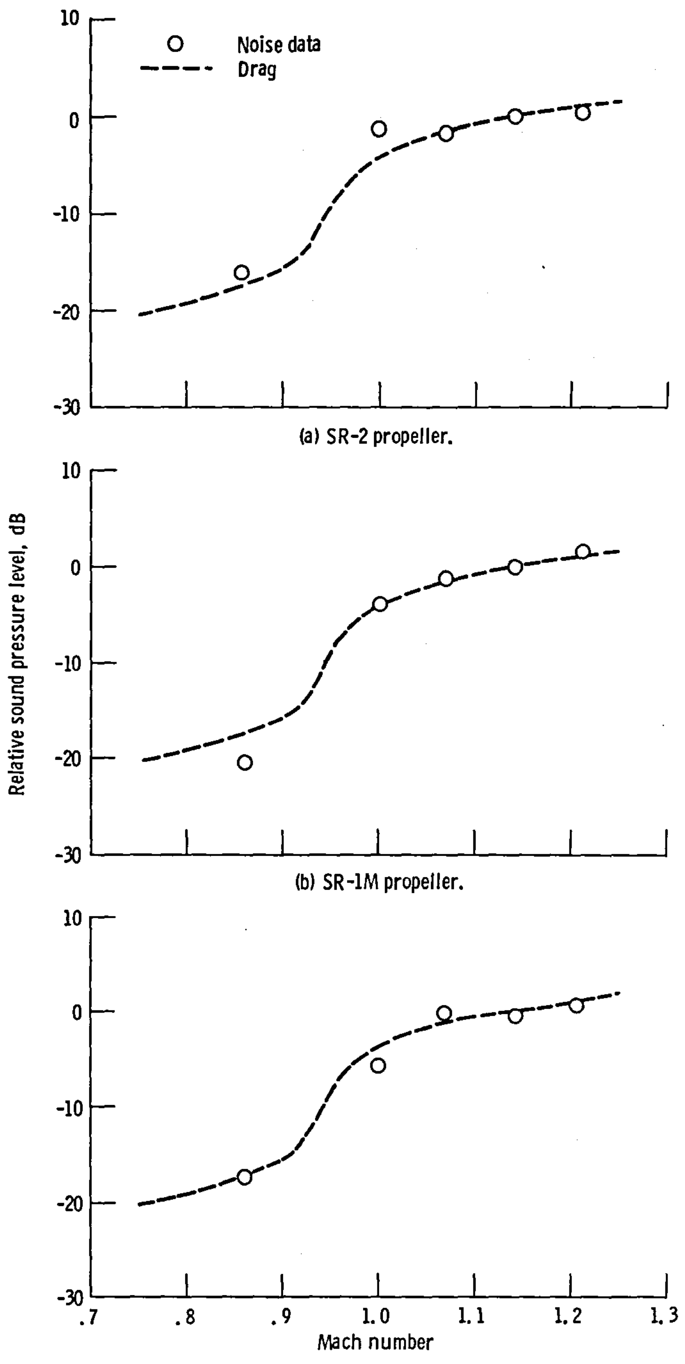
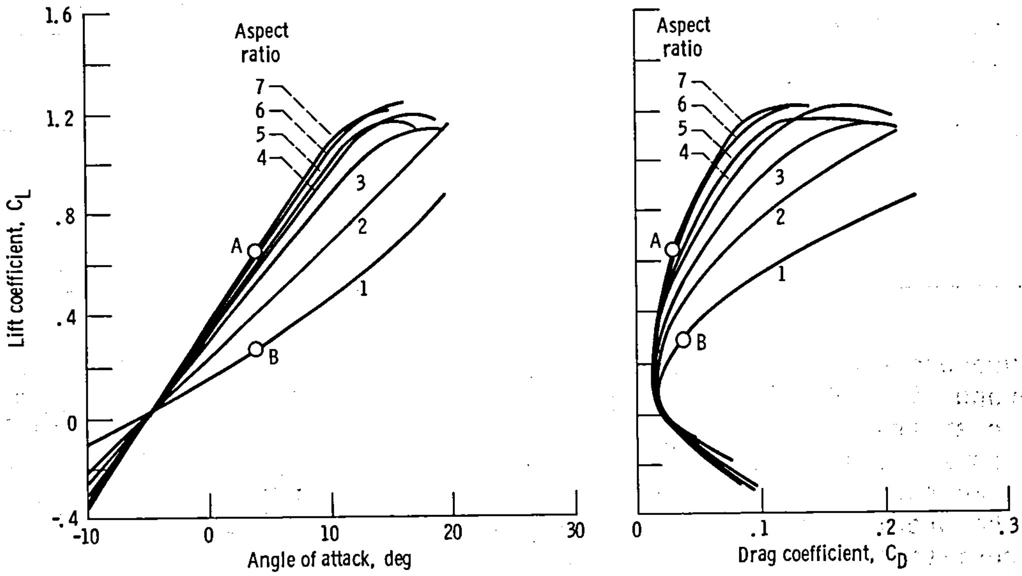


Figure 8. - Comparison of noise and drag variation with Mach number at constant density.



(a) Lift coefficient versus angle of attack.

(b) Lift coefficient versus drag coefficient.

Figure 9. - Variation with aspect ratio.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-83467		

4. Title and Subtitle	
A Possible Explanation for the Present Difference Between Linear Noise Theory and Experimental Data for Supersonic Helical Tip Speed Propellers	5. Report Date November 1983 6. Performing Organization Code 505-31-32
7. Author(s) James H. Dittmar	8. Performing Organization Report No. E-1781 10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	11. Contract or Grant No. 13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	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)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified		

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