

19850002480

NASA Technical Memorandum 83797

NASA-TM-83797 19850002480

Observations from Varying the Lift and Drag Inputs to a Noise Prediction Method for Supersonic Helical Tip Speed Propellers

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September 1984

NASA

3 1 1 RN/NASA-TM-83797

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85N10788** ISSUE 1 PAGE 115 CATEGORY 71 RPT#: NASA-TM-83797 E-2295
NAS 1.15:83797 84/09/00 21 PAGES UNCLASSIFIED DOCUMENT

UTTL: Observations from varying the lift and drag inputs to a noise prediction method for supersonic helical tip speed propellers

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

MAJS: /*AIRCRAFT DESIGN/*BLADE TIPS/*DRAG/*JET AIRCRAFT/*LIFT/*NOISE PREDICTION (AIRCRAFT)/*SHOCK WAVES/*SUPERSONIC SPEEDS/*TURBOPROP AIRCRAFT

MINS: / AERODYNAMIC COEFFICIENTS/ AIRCRAFT COMPARTMENTS/ MACH NUMBER/ NOISE REDUCTION/ WIND TUNNEL TESTS

ABA: R.S.F.

ABS: Previous comparisons between calculated and measured supersonic helical tip speed propeller noise show them to have different trends of peak blade passing tone versus helical tip Mach number. It was postulated that improvements in this comparison could be made first by including the drag force terms in the prediction and then by reducing the blade lift terms at the tip to allow the drag forces to dominate the noise prediction. Propeller hub to tip lift distributions were varied, but they did not yield sufficient change in the predicted lift noise to improve the comparison. This result indicates that some basic changes in the theory may be needed. In addition, the noise predicted by the drag forces did not

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OBSERVATIONS FROM VARYING THE LIFT AND DRAG INPUTS TO A NOISE PREDICTION
METHOD FOR SUPERSONIC HELICAL TIP SPEED PROPELLERS

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SUMMARY

Previous comparisons between calculated and measured supersonic helical tip speed propeller noise have shown them to have different trends of peak blade passing tone versus helical tip Mach number. It has been postulated that improvements in this comparison could be made first by including the drag force terms in the prediction and then by reducing the blade lift terms at the tip to allow the drag forces to dominate the noise prediction.

Propeller hub to tip lift distributions were varied in this study, but they did not yield sufficient change in the predicted lift noise to improve the comparison. This result indicates that some basic changes in the theory may be needed. In addition, the noise predicted by the drag forces did not exhibit the same curve shape as the measured data. So even if the drag force terms were to dominate, the trends with helical tip Mach number for theory and experiment would still not be the same.

The effect of the blade shock wave pressure rise was approximated by increasing the drag coefficient at the blade tip. Predictions using this shock wave approximation did have a curve shape similar to the measured data. This result, even though the spatially distributed shock wave was crudely approximated by increased tip drag, indicates that the shock pressure rise probably controls the noise at supersonic tip speed and that the linear prediction method can give the proper noise trend with Mach number. It also suggests that, with the proper spatial representation of the shock, the linear method might be able to predict the noise from supersonic helical tip speed propellers without having to go to an unwieldy nonlinear method.

INTRODUCTION

High-speed turboprops are attractive candidates for future aircraft because of their high propulsive efficiency. However, the propeller noise has been identified as an aircraft cabin environment problem. The noise of three propeller models was measured in the NASA Lewis 8- by 6-Foot Wind Tunnel in 1978 (refs. 1 and 2). Three individual blades are shown in figure 1(a) and a complete propeller, SR-3, is shown in figure 1(b). An existing linear noise model by Farassat (refs. 3 to 5), based on the solution of the Ffowcs Williams - Hawkins equation (ref. 6) was exercised in 1980 to compare with the measured data at the locations shown in figure 2 (ref. 7). Plots from this report, showing the theory-data comparisons for the blade passing tone versus helical tip Mach number, are repeated here in figure 3. As can be seen, the theory and data have different curve shapes. Above Mach 1.0 the theoretical curve continues to rise with Mach number while the wind tunnel data level off.

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A possible method for improving the theoretical curve shape was presented in 1983 (ref. 8). The proposition was advanced that the likely candidates for change were in the aerodynamic input to the theory. The shape of the drag force curve for these blades appeared to match the shape of the experimental noise curve and should, therefore, be included in the aerodynamic inputs. The theory (refs. 3 to 5) already possessed the ability to include drag forces, but none were included in the previous predictions (ref. 7). Reference 8 also indicated that the inclusion of the drag forces in the aerodynamic input would not, by itself, result in the proper curve shape since the theory, using only lift forces, already overpredicted the data. Hence, it would also be necessary to reduce that predicted lift noise. Since the high-velocity tip region of the blade was assumed to be the major noise producer, the combination of including drag forces and reducing lift at the tip was indicated as the most likely change that would improve the theoretical curve shape.

In order to investigate these possible improvements, noise predictions were made, using the existing Farassat theory, for a wide range of the lift and drag force inputs. This report gives the results of these input variations on predictions of the SR-3 propeller noise.

PROCEDURE

The predictions previously performed in reference 7 used Dr. Farassat's computer code and were performed on the NASA Langley computer system. This computer code has been upgraded and reported in reference 9 and has now been made available on the NASA Lewis computer system. This upgraded code was exercised for this study. For inputs of aerodynamic parameters and blade geometry the code yields separate predictions for lift, drag, and thickness noise, as well as the correctly phased sum of these parts at a given receiver location. The thickness noise prediction requires the blade geometry while the lift and drag noise require aerodynamic forces as well. The lift forces can be input either as hub to tip distributions of propeller lift coefficient C_p or as pressures on the blade surfaces. The drag forces are input as shear stresses on each side of a blade section and can be input only when the lift forces have been input as blade surface pressures.

The outputs of this computer code are free-space sound pressure levels and, in reference 7, 6 decibels was added to these levels to compare them with the wall noise measurements. In this study, the trends resulting from the lift and drag variations are of interest and the predictions are the free-space program outputs, without correction, unless otherwise noted.

Comparisons were made of the present predictions and those of reference 7, and the outputs for the same input parameters were essentially the same. Some very minor changes in the code were made by the original authors during the upgrading of the program. The inclusion of propeller blade camber in this new version has resulted in a slight change in the predictions. The change is only a fraction of a decibel and is not considered significant. More information on this computer code and its use can be found in reference 9.

RESULTS AND DISCUSSION

Lift Input Variations

It was proposed in reference 8 that to improve the prediction curve shape the lift noise would need to be reduced and the likely way to do this involved reducing the lift input at the blade tip. Therefore, a number of variations were performed in the lift input parameters with the goal of determining whether the lift noise could be reduced.

The design condition of the SR-3 propeller, helical tip Mach number of 1.14 (tunnel axial Mach number of 0.8) and advance ratio of 3.06, was chosen as the base condition for the lift variations. The lift forces for this base configuration are input, as in reference 7, as hub to tip variations in the propeller lift coefficient C_p . The base case C_p distribution is shown in figure 4(a). The prediction of the blade passing frequency tone due to lift forces at the four measuring locations (fig. 2) is shown in figure 4(b). The noise predictions presented here are for the lift noise only and do not include thickness noise. The peak noise, which occurs at the 110° position, was dominated by the lift contribution and, when corrected by adding 6 decibels to account for pressure doubling at the wall, compares with the previous prediction of figure 3(c).

A number of trial cases were performed with the lift coefficient multiplied everywhere by the same constant. This resulted in the same decibel change at all of the measurement locations that equaled 20 times the logarithm to the base ten of the constant. Since this variation in C_p results directly in a change in the power the propeller imparts to the air, this results, as it should, in the noise varying as $20 \log_{10}$ of the ratio of the power for the two cases.

The next variations were performed to determine if reductions in the tip lift could reduce the peak lift noise as needed to allow the drag noise to dominate and improve the predicted noise curve shape. In the first case tried, the lift on the outer 10 percent of the propeller was reduced to one-half of the original base-case lift. The resulting lift distribution can be seen in figure 5(a). This did not involve any resmoothing of the lift-radius curve and this hypothetical case had the same blade geometry. The reduction in tip lift resulted in a power reduction and cases were run with and without correcting for constant power. The predicted blade passing tone noise for these cases is plotted in figure 5(b). The square symbols represent the uncorrected cases and the triangles the corrected. For the uncorrected case noise reductions were achieved, relative to the base case, at forward angles, but only a small reduction, less than 1 decibel, was achieved at the peak noise angle (110°).

Adjusting the power to be the same as the originally measured power provides a better basis for comparison. In figure 5(a), the corrected curve of lift coefficient versus fractional tip radius is shown for a one-half tip lift case. In order to bring the power back to the original value, all of the lift coefficients are multiplied by a common factor. The predicted blade passing tone noise for this case is also shown in figure 5(b). Noise reductions are observed again in the front with only a slight reduction at the peak. The reductions measured here are less, as expected, than those for the case without power correction.

A case with a further reduction in tip lift is shown in figure 6 where the lift over the outer 10 percent of the blade has been reduced to zero (fig. 6(a)). Again, cases were run with and without adjusting to achieve constant propeller power. The noise reductions can be seen in figure 6(b). For the uncorrected case, large noise reductions were again observed at forward angles, but very little reduction occurred at the peak. Even before bringing the power back to the original measured level, the reductions at the peak are much less than needed to achieve a curve shape similar to the data.

The same procedure was employed to adjust the power for the zero-tip-lift case. The power-corrected noise shown in figure 6(b) is again lower in the front, but here the noise at the peak has slightly increased. This is probably the result of increasing the C_p 's at other positions to balance the power lost by reducing the tip C_p .

The lift noise in the front appears to be controlled by the lift at the propeller tip as shown by the significant reductions that were obtained at the 77° position. If this holds in practice, the forward noise may be controllable by varying the tip conditions for a propeller. This might be particularly effective for a rear-mounted pusher propeller to reduce the forward-radiated noise that would go into the cabin. For the purpose of this study, contrary to what was needed to improve the theoretical curve shape, the tip lift does not control the lift component of the blade passing tone at the peak.

To further investigate possibilities for reducing the peak lift noise, a case was run with the C_p in the high- C_p region of the blade reduced by one-half. This was the region from 0.75 to 0.9 tip radius and figure 7 shows the results of this variation. As can be seen in figure 7(b), a reduction of approximately 4 decibels occurred for the uncorrected power case at the peak. Little or no reduction occurred at forward angles, and this further emphasizes the role of the tip in controlling the forward noise. The noise reduction at and aft of peak is, of course, partly the result of the total propeller power being reduced.

A further variation, where the power was brought back up to the original level, is also shown in figure 7(b). All of the C_p values were multiplied by a constant to bring the total power back up from the lower level resulting from the reduced C_p 's in the 0.75 to 0.9 tip radius region. The blade passing tone noise from this constant-power case is shown in figure 7(b). Here the peak has been reduced a couple of decibels, but not nearly enough to improve the noise curve variation with Mach number. The forward noise has been raised as a result of the power adjustment because the lift at the tip was increased to partially balance out the reduced-lift region from 0.75 to 0.9 tip radius.

In general, it does not appear that reducing the tip lift can result in the computer code predicting enough less lift noise at the peak angle so that the drag noise can dominate. In fact, it does not appear that any reasonable change in the C_p distribution from hub to tip can result in a sufficient reduction in the lift noise to allow the predicted peak blade passing tone - helical tip Mach number curve to have the same shape as the data. It appears that some basic change in the lift noise prediction procedure may be necessary to improve the predictions.

Drag Input Variations

The intent of this drag input section is to determine if the predicted drag noise curve shape is really similar to the measured data as postulated in reference 8. This was accomplished by using a representative drag curve shape as indicated in the following discussion.

As mentioned previously, the ability to input shear stresses (drag) to the program depends on the lift forces being expressed as surface pressures. Since only the C_p distributions were available at the time of this study and no equivalent set of blade pressures was available, the lift and drag calculations could not be performed simultaneously. For these calculations of the drag noise, the lift forces (blade surface pressures) were set to zero and only the drag noise was calculated.

The computer code accepts inputs of drag forces as skin friction (viscous shear) stresses acting on the upper and lower blade surfaces (σ_{upper} and σ_{lower}) at each spanwise location. The sum of these two stresses multiplied by the blade section area is equal to the drag for that section.

$$\sigma_{\text{upper}} + \sigma_{\text{lower}} = \frac{D}{S}$$

where D is the drag and S the surface area of the section. For this exercise the shear stresses were assumed to be equal on each side of the blades.

$$\sigma_{\text{upper}} = \sigma_{\text{lower}} = \frac{D}{2S}$$

The drag of each section can be expressed as

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

where C_D is the section drag coefficient, ρ is the fluid density, V is the relative velocity at the leading edge of the blade section, and S is the section area. Inserting this relation gives

$$\sigma_{\text{upper}} = \sigma_{\text{lower}} = \frac{1}{4} \rho V^2 C_D$$

The SR-3 propeller blades have a NACA 16 series profile over the outer 75 percent of the blade span and a 65 series section inboard. For the purposes of this study, the blade was represented everywhere by a NACA 16 series profile, and a plot of the drag coefficient versus Mach number curve is found in figure 8. This is the same curve used in reference 8.

The drag coefficient curve shape was programmed into the computer by using the incoming relative velocity to a blade section to calculate the Mach number. For ease of programming, the drag coefficient shape was approximated by three straight lines: a horizontal line with a constant value of 0.0065 for Mach numbers below 0.9, a sloping line from a Mach number of 0.9 to a Mach number

of 1.0 ($C_D = 0.0065$ at 0.9, $C_D = 0.030$ at 1.0), and a horizontal line with a constant C_D of 0.030 for Mach numbers greater than 1.0. At each spanwise section the program calculates an incoming relative Mach number and then uses the drag coefficient obtained from this curve at that section.

The drag noise calculations were performed for the axial Mach numbers where data were taken, $M = 0.6, 0.7, 0.75, 0.8, \text{ and } 0.85$ (fig. 2). The positions were chosen to be the same as shown in figure 2, plus an additional position at the 100° angle, which was located on the tunnel centerline. The wind tunnel where the data were taken operates at different densities at different Mach numbers and these different densities were used in the predictions.

Figures 9 and 10 show the results of these drag noise predictions. Figure 9 shows the drag blade passing tone directivities corresponding to Mach numbers of 0.6 to 0.85; figure 10 shows the variation of the predicted peak blade passing tone drag noise plotted versus helical tip Mach number. Also on this plot for shape comparison is the peak measured noise on the tunnel wall. This measured curve has been reduced by 6 decibels to make comparison with the free-field prediction. As can be seen, the drag noise curve does not have the same shape as the measured curve and is lower in value. To emphasize the shape difference, the predicted curve has been translated in level to match the measured curve at the $M = 0.7$ ($M_H = 1.0$) condition, resulting in the dashed line. Although the predicted curve does start to flatten out, it does so at a higher Mach number than the data and the curve does not possess the same shape as the measured data.

In general the prediction resulting from the drag coefficient curve does not have the same curve shape as the measured data. It is possible that, because of being out of phase, the drag noise could act in opposition to the lift noise to result in a lower noise prediction than the lift noise by itself. Because of the low levels of the drag noise the effect would be small and it would be extremely fortuitous if the summation had a curve shape matching the data. The general outcome of this drag noise study is that the inclusion of the normal section drag forces is not likely to improve the theoretical curve shape.

Shock Drag

A number of papers have discussed possible improvements to the Ffowcs Williams - Hawkins approach for noise predictions of supersonic-tip-speed propellers. Improvements or differences in approach were discussed in reference 10, which approached the problem by using shock waves; in reference 11, which investigated the effect of addition of nonlinear terms to the Ffowcs Williams - Hawkins (FW-H) equation; in reference 12, which used a nonlinear approximation to an equation from reference 13; and in reference 14, which pointed out the omission of the shock wave in the existing noise solutions and suggested a possible way of incorporating the shock wave. The first three of these approaches abandoned the basic linear approach of the Farassat solution in an attempt to achieve a better theory-data comparison. The intent here is to not completely abandon the linear method but to approximate the pressure rise of the nonlinear shock wave with aerodynamic inputs into the linear Farassat noise model.

A number of shadowgraphs of the SR-3 propeller blade operating at a supersonic condition have been reported in reference 15. A reprint of one of these is shown in figure 11. As can be seen from this photograph the SR-3 blade exhibits a trailing-edge shock structure. This type of shock appears to be formed from a number of weaker pressure waves over the outer 5 to 10 percent of the propeller blade that then coalesce into the shock wave that in turn extends out beyond the blade tip. To accurately model this shock pressure rise as a noise source, even in the context of the linear noise theory, the pressure rise should be distributed in the space outboard of the propeller tip. At present the computer program is not configured to do this and so, as an approximation, the forces resulting from this shock pressure rise are modeled as though they existed on the outer portion of the blade. This then means that the level of the forces to be applied on the outer blade surfaces is much larger than would be normally expected there since the forces actually represent the sum of the pressure rises that exist over the much larger off-blade region. Although this approximation would likely yield a somewhat different directivity than the spatially distributed forces, it was hoped that the level of the peak and the variation of the peak level with Mach number would show the same trends for the approximation as for the actual spatial distribution.

The shock pressure rise was approximated by adding a large drag at the propeller tip. The outer 5 percent of the blade was given a drag coefficient much higher than the coefficient previously determined from figure 8 for the airfoil alone. The drag coefficients for the other sections of the blade were left as they were in the drag input variation section. The intent here was to see if this approach would result in a curve shape looking like the data curve. Since it was not known what level of drag coefficient would match the summed pressure rises of the distributed shock, a number of cases were run at the $M = 0.85$, $M_H = 1.21$ condition to obtain a drag coefficient that would cause the prediction to match the data. (The 6-dB pressure doubling on the tunnel wall was accounted for in the matching.) In effect the predictions and data have thereby been normalized at $M = 0.85$, $M_H = 1.21$. This resulted from a drag coefficient approximately 5.5 times the drag coefficient normally indicated for this section. Since this represents the total spatially distributed shock pressure rise, this level does not seem unreasonable. This drag coefficient is held constant for all of the helical tip Mach numbers. Since the drag is a function of the velocity as well as the drag coefficient, the drag force and the predicted drag noise vary with helical tip Mach number.

The noise predicted for this approximation of the shock wave is shown in figures 12 and 13. The directivities are shown in figure 12 and the normalized plot of peak blade passing tone versus helical tip Mach number in figure 13. As can be seen in figure 13 the predicted trend with helical tip Mach number is very similar to the data curve shape. The predicted curve bends over at approximately the same Mach number as the data and even bends over a little more than the data with the $M = 0.85$, $M_H = 1.21$ point slightly below the $M = 0.8$, $M_H = 1.14$ point. The predicted point at $M = 0.6$, $M_H = 0.86$ is lower than the data, but this is reasonable since the noise is probably not dominated by the drag noise from the shock rise but is probably controlled by the lift noise at this subsonic tip speed condition.

The curve shape agreement achieved by this drag noise approximation to the shock pressure rise indicates, as did reference 10 previously, that the shock controls the noise curve shape. (This noise curve shape would, of course, also occur if a genuine tip drag increase of this magnitude were present.) The

results, with even this crude approximation to the shock pressure rise, show that the linear prediction method can give the proper noise trends. It may also be possible that the linear method, with the proper spatial representation, might be able to accurately predict the noise from these propellers, sparing one from having to resort to an unwieldy nonlinear method.

CONCLUDING REMARKS

It was proposed in a previous paper (ref. 8) that to improve the predictions of a linear high-speed propeller noise method (ref. 3), the aerodynamic inputs to the theory were the ones most likely to change. In particular it was proposed to reduce the propeller lift terms at the tip to reduce the peak noise so the drag noise could dominate and then to include these in the prediction. Variations of the radial distribution of the section lift coefficients (lift variation) were input to an existing linear noise computer code for predicting propeller noise (ref. 9). The first variations reduced the tip lift and led to reductions in the forward-radiated noise but only small reductions at the peak. The reductions achieved in the front suggest that unloading the tip might be useful in reducing the cabin noise of a rear-mounted pusher propeller. From the small size of the peak noise reductions it does not appear that changes in the tip lift can result in the noise reductions necessary to allow the peak noise to be dominated by conventional drag noise. Other variations of the midspan lift also did not result in enough lift noise reduction, and it does not appear that any reasonable change in the spanwise lift distribution can result in a sufficient lift noise reduction to allow a better predicted curve shape. From these lift variations it now appears that some change in the lift noise portion of the theory may be necessary to improve the predictions.

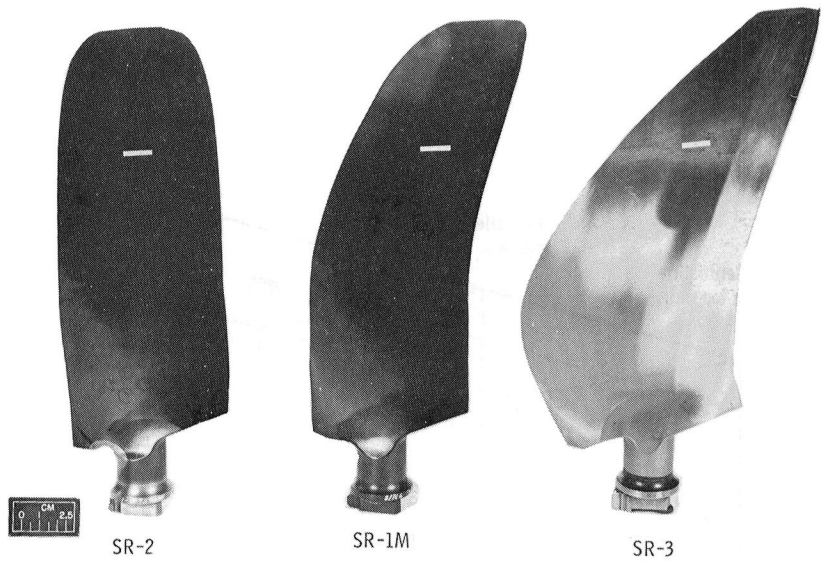
The drag forces were input to the computer as separate cases to determine if the predicted drag noise would have the same peak noise versus helical tip Mach number curve shape as the data. Although the predicted drag noise curve did start to bend over as the data curve does, it was at a higher Mach number. In general the predicted drag curve shape did not match the data curve shape.

Reference 10 indicated that the blade shock wave may control the noise and also account for the peak blade passing tone versus helical tip Mach number curve shape. To explore this possibility, in the context of this computer program, an approximation to the blade shock wave pressure rise was input as an increase in the drag coefficient at the blade tip. This did result in a curve shape (peak noise versus helical tip Mach number) that looked very similar to the data curve. This result, even with the spatially distributed shock wave being crudely approximated by increased tip drag, indicates that the shock pressure rise may indeed control the noise and that the linear prediction method can give the proper noise trends. It may also indicate that, with the proper spatial representation of the shock, the linear method might be able to accurately predict the noise from supersonic helical tip speed propellers without having to go to an unwieldy nonlinear method.

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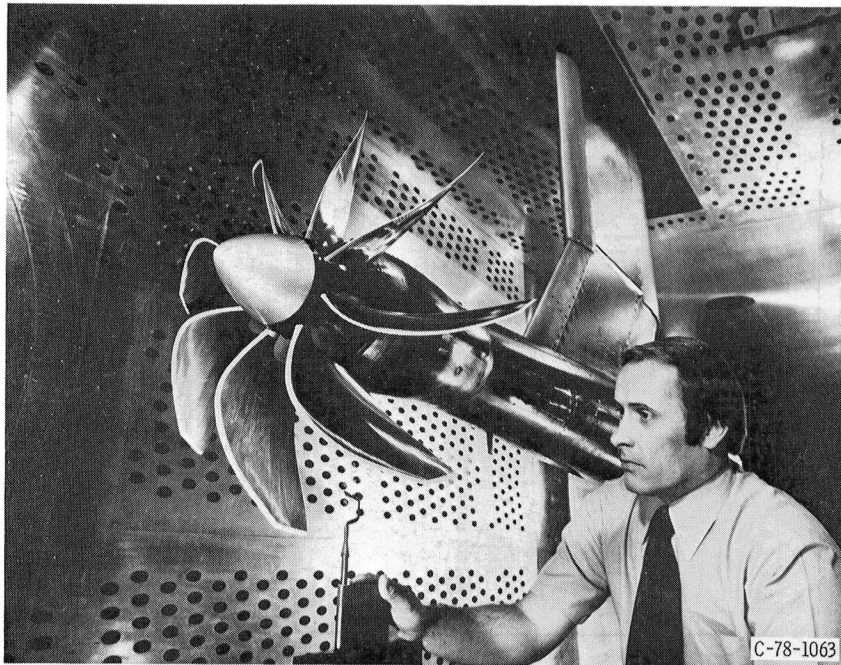
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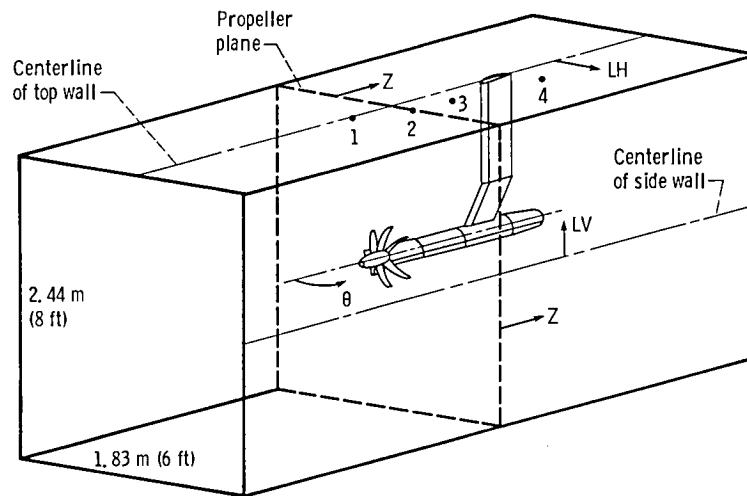
(a) Propeller blades.



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(b) SR-3 model propeller.

Figure 1. - Propeller blades and model.



POSITIONS	TRANSDUCER POSITIONS, cm (in.)			
	1	2	3	4
Z	-27.7 (-10.9)	0.953 (0.375)	45.2 (17.8)	104.4 (41.1)
LH	2.54 (1.0)	10.2 (4.0)	7.62 (3.0)	31.5 (12.4)
LV	121.9 (48.0)	121.9 (48.0)	121.9 (48.0)	121.9 (48.0)
NOMINAL ANGLE, θ , deg	77	90	110	130

Figure 2. - Pressure transducer positions.

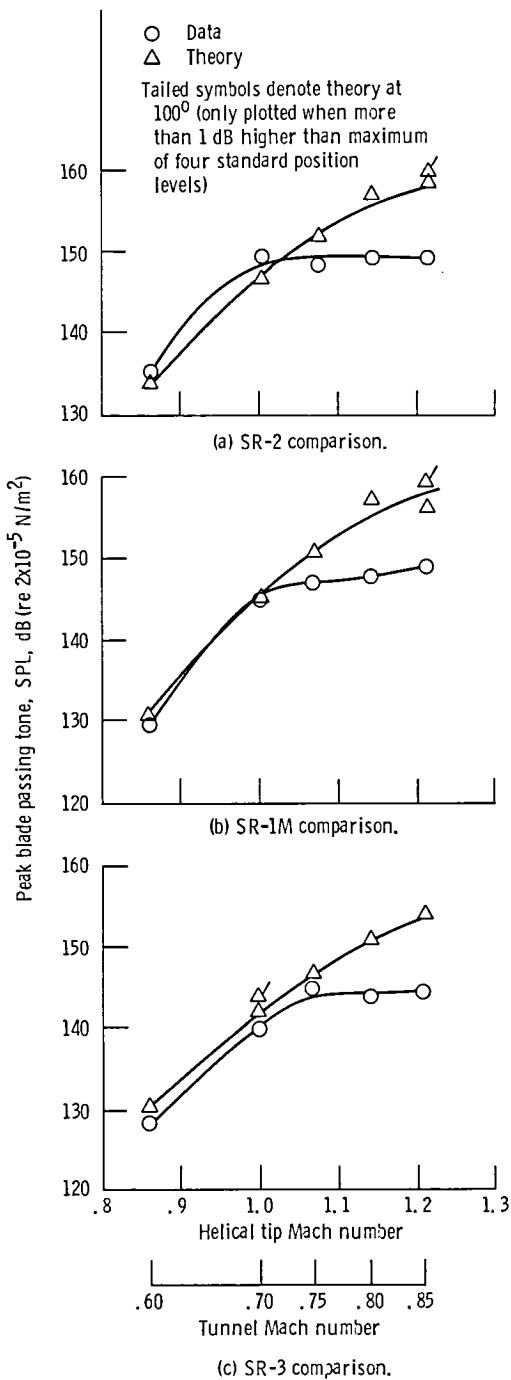
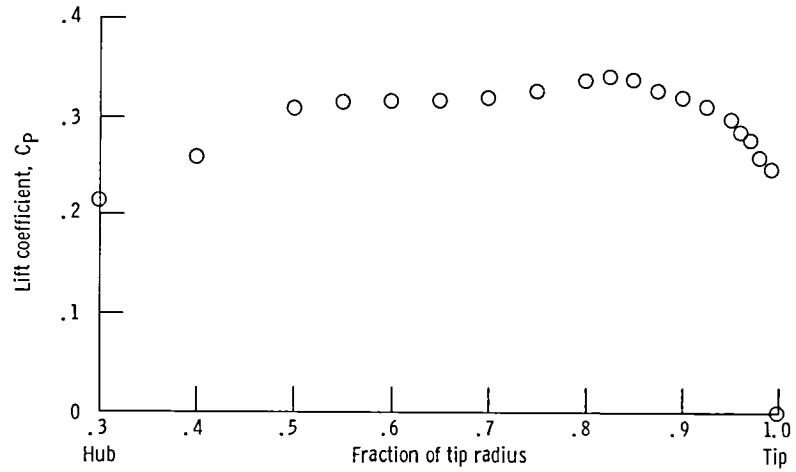
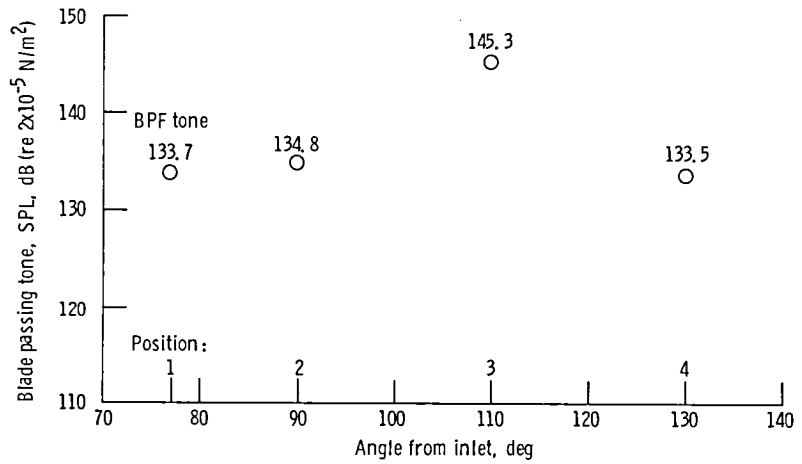


Figure 3. - Peak blade passing tone variation with helical tip Mach number.

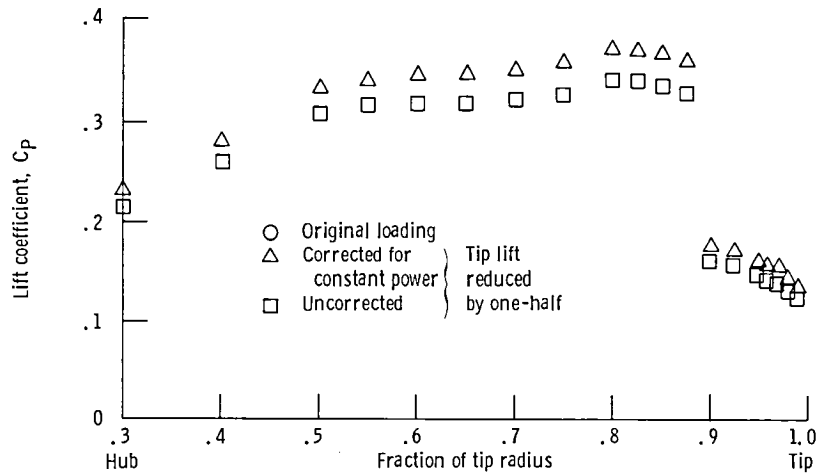


(a) Variation of lift coefficient with spanwise position.

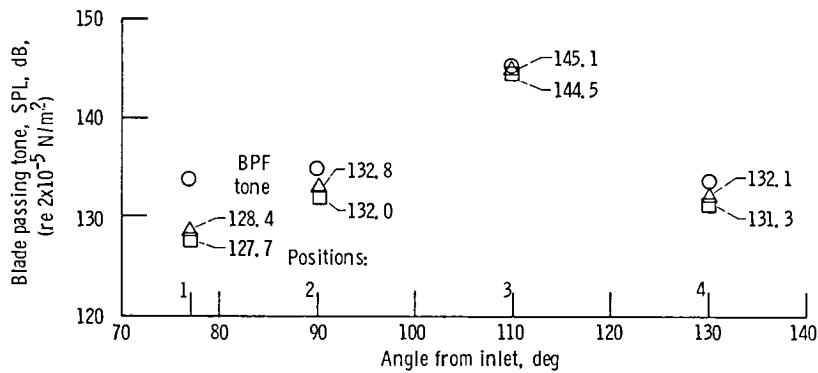


(b) Variation of lift noise blade passing tone with angle from inlet.

Figure 4. - SR-3 propeller at $M_H = 1.14$ with standard lift distribution.

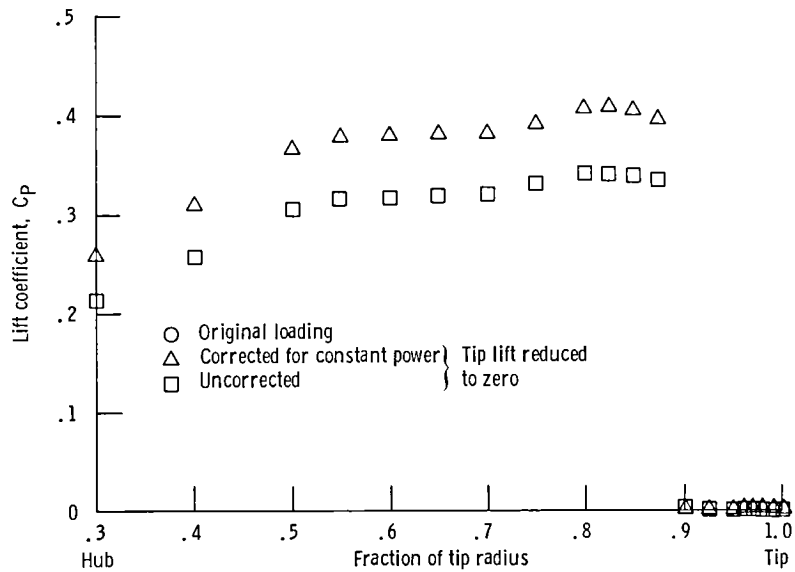


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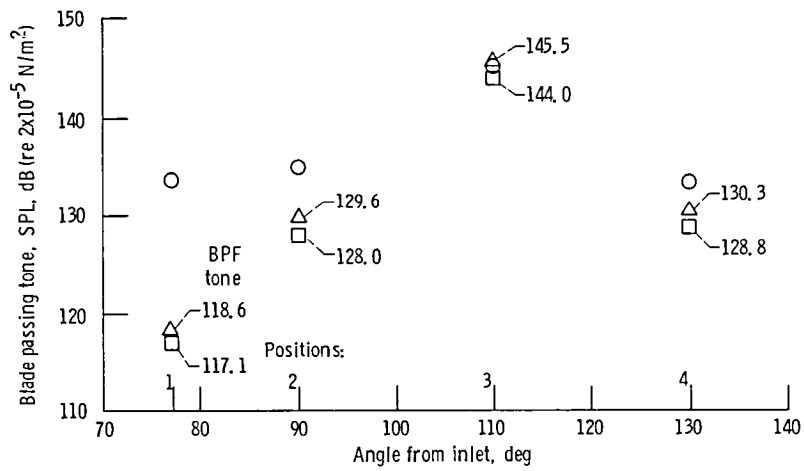


(b) Variation of lift noise blade passing tone with angle from inlet.

Figure 5. - SR-3 propeller at $M_{tip} = 1.14$, loading at outer 10 percent reduced by one-half.

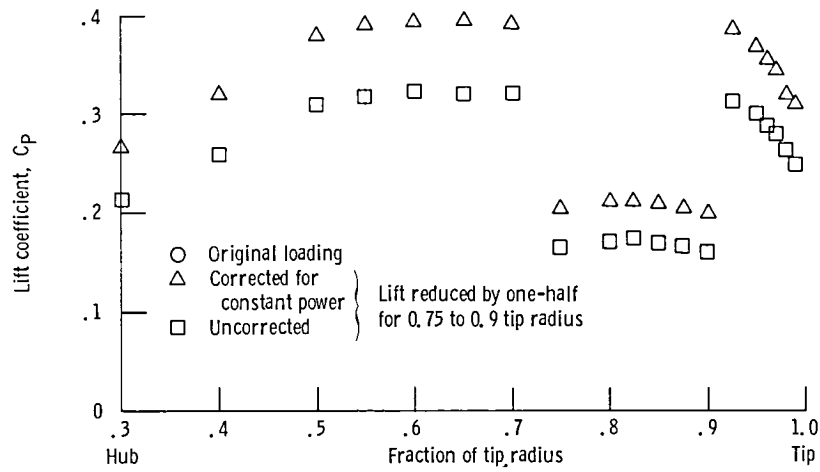


(a) Variation of lift coefficient with spanwise position.

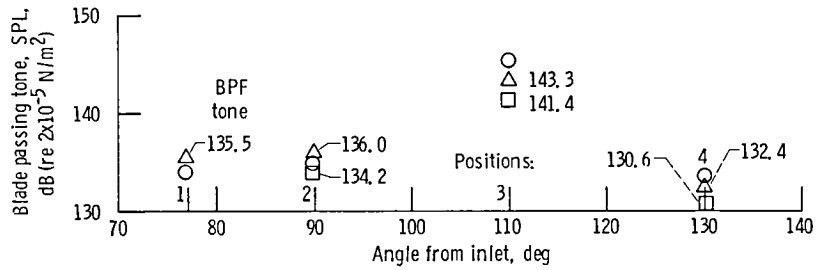


(b) Variation of lift noise blade passing tone with angle from inlet.

Figure 6. - SR-3 propeller at $M_{T1} = 1.14$, loading at outer 10 percent reduced to zero.



(a) Variation of lift coefficient with spanwise position.



(b) Variation of lift noise blade passing tone with angle from inlet.

Figure 7. - SR-3 propeller at $M_H = 1.14$, loading reduced by one-half for 0.75 to 0.9 tip radius.

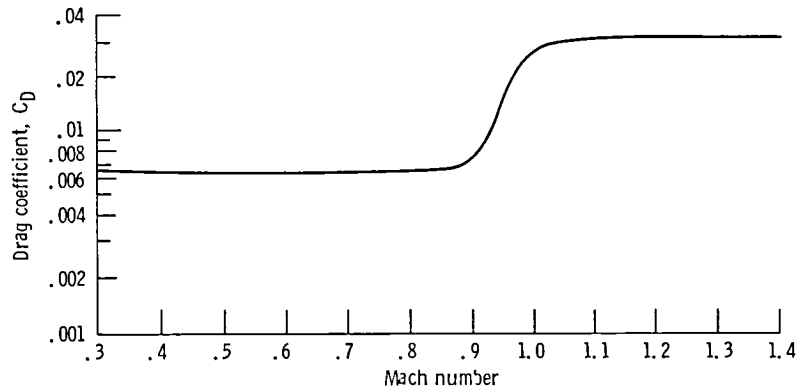


Figure 8. - Airfoil performance characteristics. Airfoil section NACA 16-004; aspect ratio, ∞ . Drag coefficient versus Mach number; lift coefficient, 0.2.

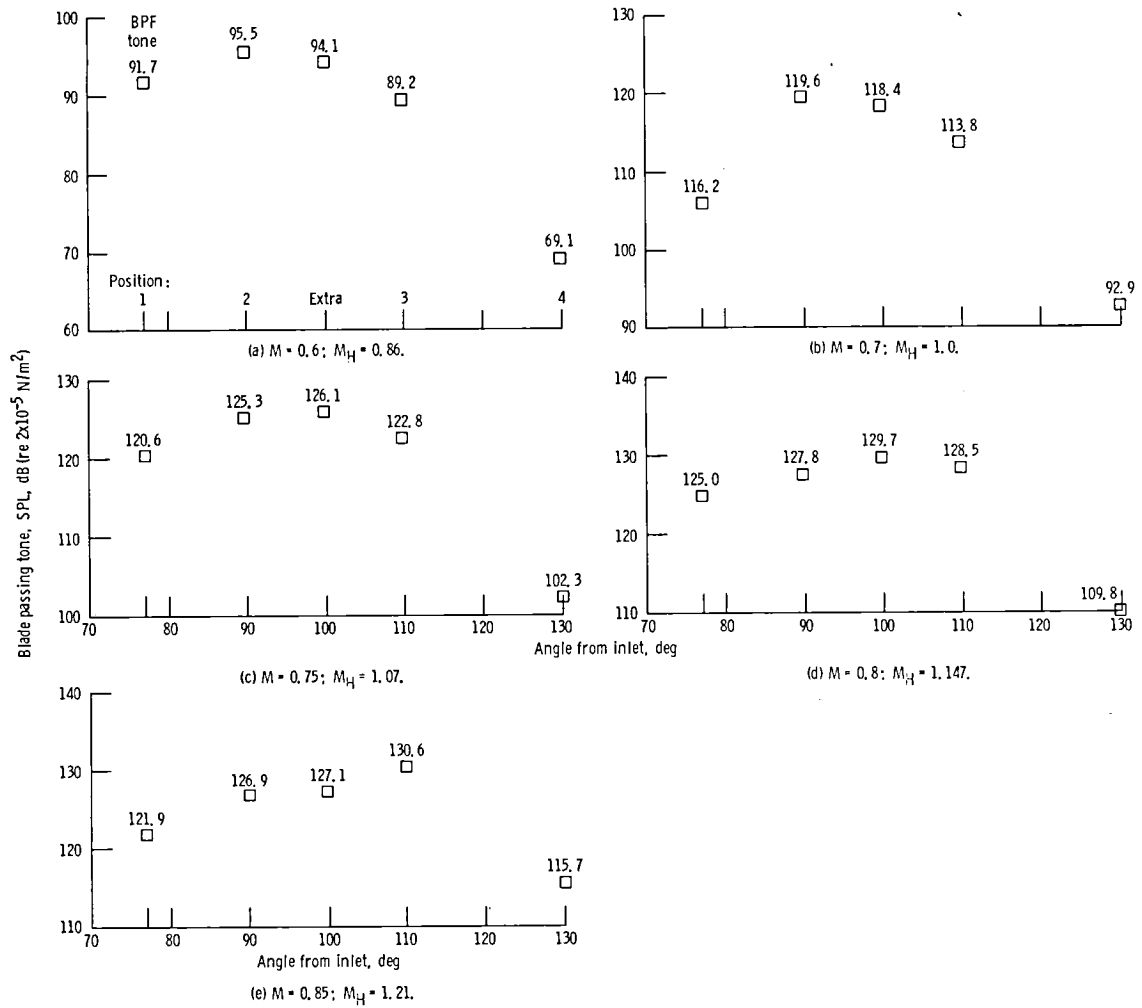


Figure 9. - Variation of drag noise blade passing tone with angle from inlet.

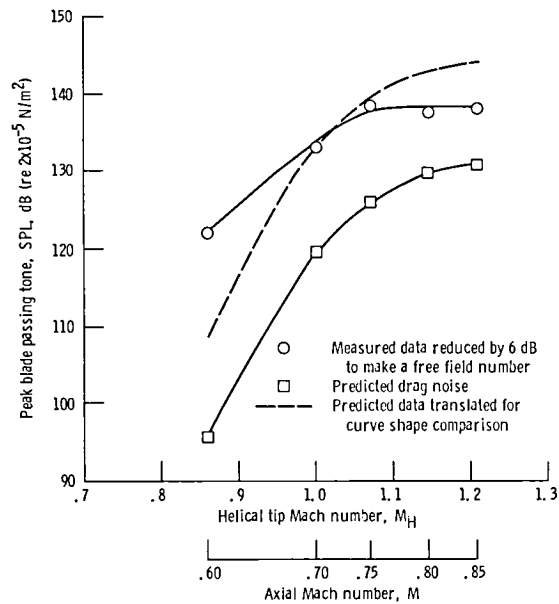


Figure 10. - Variation of peak drag noise blade passing tone with Mach number.

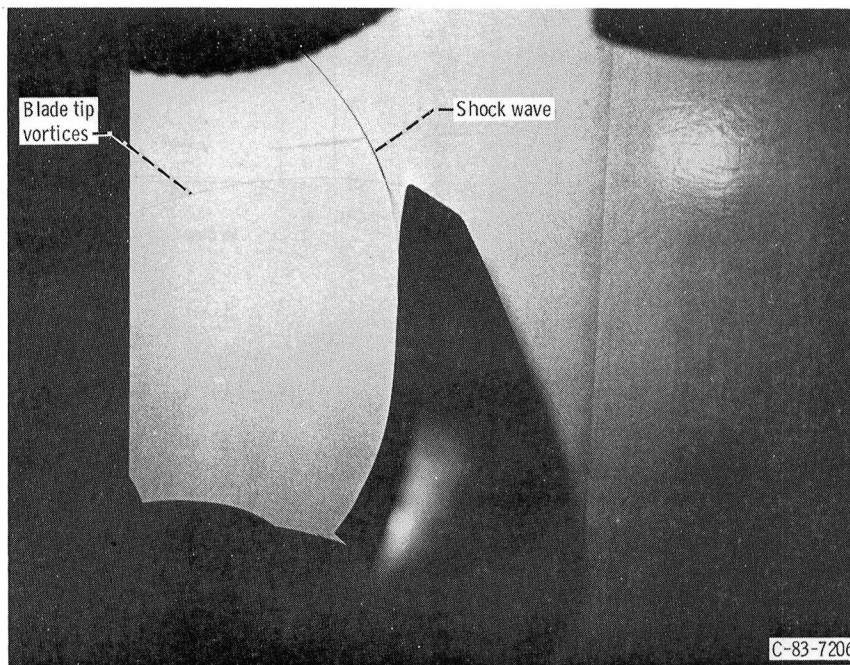


Figure 11. - SR-3 shadowgraph.

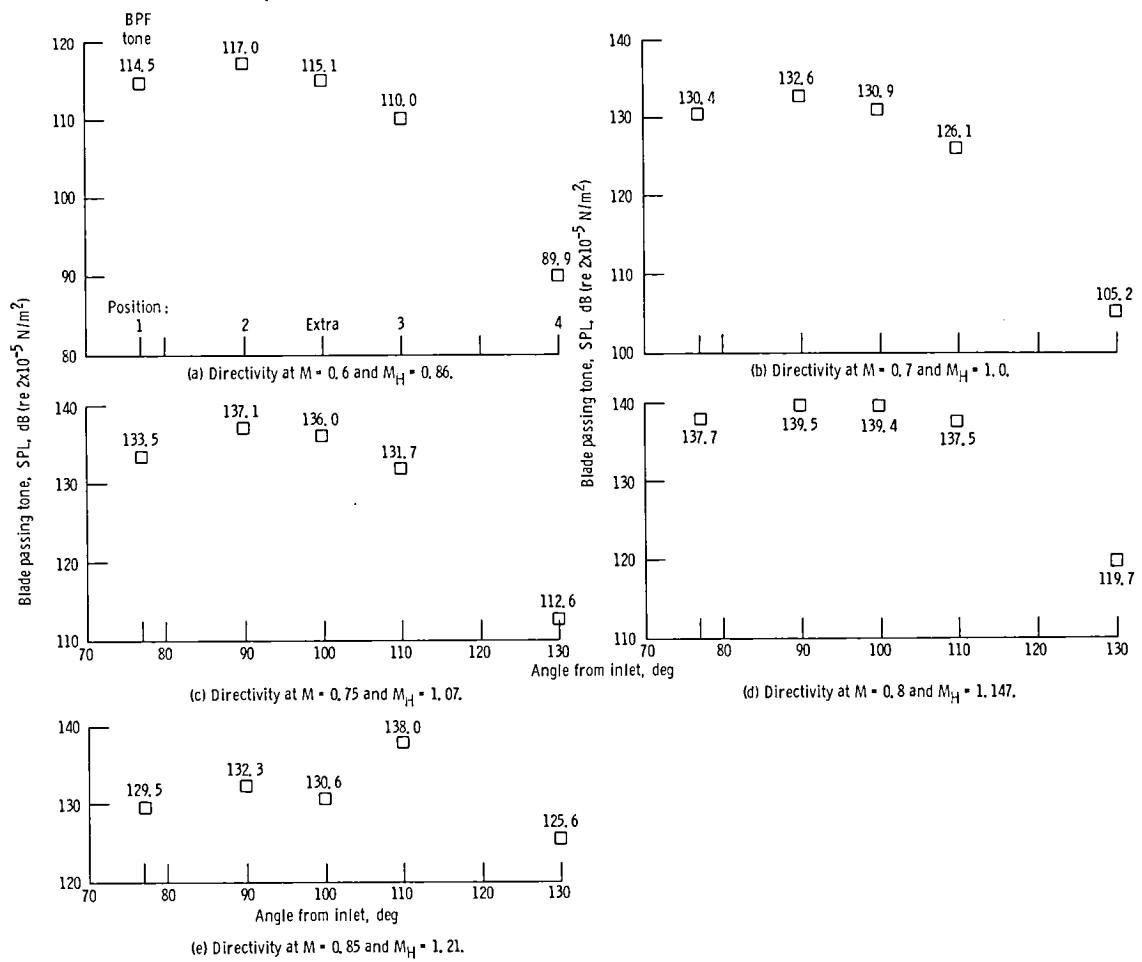


Figure 12. - Noise predicted from drag force simulation of shock pressure rise.

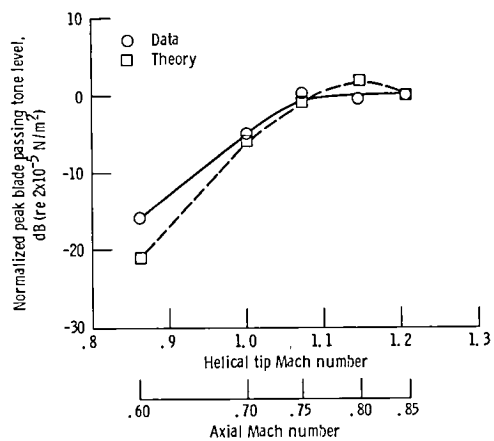
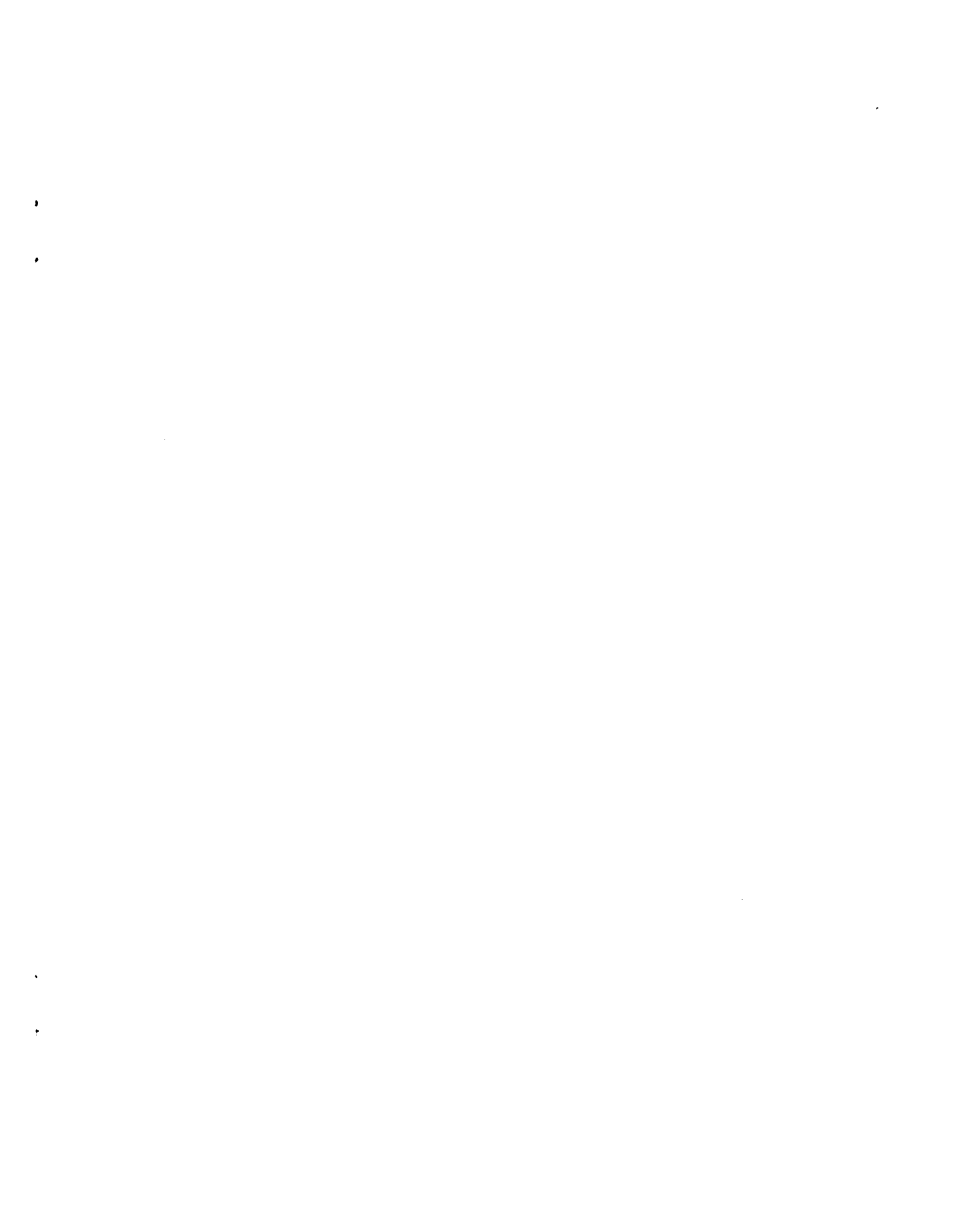


Figure 13. - Variation of normalized shock peak blade passing tone with Mach number.

1. Report No. NASA TM-83797		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Observations From Varying the Lift and Drag Inputs to a Noise Prediction Method for Supersonic Helical Tip Speed Propellers				5. Report Date September 1984	
				6. Performing Organization Code 505-31-32	
7. Author(s) James H. Dittmar				8. Performing Organization Report No. E-2295	
				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 Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546				14. Sponsoring Agency Code	
15. Supplementary Notes					
16. Abstract Previous comparisons between calculated and measured supersonic helical tip speed propeller noise have shown them to have different trends of peak blade passing tone versus helical tip Mach number. It has been postulated that improvements in this comparison could be made first by including the drag force terms in the prediction and then by reducing the blade lift terms at the tip to allow the drag forces to dominate the noise prediction. Propeller hub to tip lift distributions were varied in this study, but they did not yield sufficient change in the predicted lift noise to improve the comparison. This result indicates that some basic changes in the theory may be needed. In addition, the noise predicted by the drag forces did not exhibit the same curve shape as the measured data. So even if the drag force terms were to dominate, the trends with helical tip Mach number for theory and experiment would still not be the same. The effect of the blade shock wave pressure rise was approximated by increasing the drag coefficient at the blade tip. Predictions using this shock wave approximation did have a curve shape similar to the measured data. This result, even though the spatially distributed shock wave was crudely approximated by increased tip drag, indicates that the shock pressure rise probably controls the noise at supersonic tip speed and that the linear prediction method can give the proper noise trend with Mach number. It also suggests that, with the proper spatial representation of the shock, the linear method might be able to predict the noise from supersonic helical tip speed propellers without having to go to an unwieldy nonlinear method.					
17. Key Words (Suggested by Author(s)) Propeller noise Noise Supersonic Tip speed			18. Distribution Statement 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*



National Aeronautics and
Space Administration

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