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An Evaluation of a Simplified Near Field Noise Model for Supersonic Helical Tip Speed Propellers

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AN EVALUATION OF A SIMPLIFIED NEAR FIELD NOISE MODEL FOR SUPERSONIC HELICAL TIP SPEED PROPELLERS

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SUMMARY

The noise generated by supersonic helical tip speed propellers may create a cabin environment problem for turboprop airplanes under cruise conditions. Therefore, work has been undertaken to measure the noise of these propellers and to determine noise models to be used for predictions. The existing propeller noise models are versatile and complex, but require large computational times. The intent in this report was to evaluate a simplified noise model that could be used to obtain quick noise estimates for these propellers. This simplified noise model compared favorably with a complex model for a straight-bladed propeller and for swept propeller blades when the propeller sweep was properly considered. The simplified model can thus be used as an approximation to the complex model. Comparisons of either the complex or simplified noise models with the available noise data are not good for supersonic propeller helical tip speeds. By adjusting various constants in the simplified model, the noise estimates can be brought into the same range as the data at the propeller design point but the variation of the model with helical tip Mach number remains different than the data.

INTRODUCTION

The noise generated by supersonic helical tip speed propellers is a factor in the public acceptance of advanced turboprop airplanes. The noise may present a cabin environment problem for turboprop airplanes under cruise conditions. Therefore, work has been undertaken to measure the noise of these propellers and to develop noise models to be used for predictions.

The noise of three supersonic helical tip speed propellers has been measured in the NASA Lewis 8-by-6-foot wind tunnel and reported in references 1 and 2. A photograph of the three individual blades is shown in figure 1(a) and a photo of one of the eight-bladed propellers is shown in figure 1(b). The three blades have been designated SR-2, SR-1M, and SR-3. The SR-2 blade is similar to a conventional straight propeller blade but with a long chord and a relatively low thickness-to-chord ratio at the tip. The SR-1M blade has some sweep built into the outboard section. This sweep was primarily aerodynamic for the purpose of reducing losses on the blade. The mid-chord tip sweep, when measured on the helix formed by the advancing blade, is 23°. The SR-3 blade was an attempt to incorporate sweep both for aerodynamics and noise control. The midchord tip sweep, measured on the helix of the advancing SR-3 blade, was 34°. A comparative listing of these three propellers is found in table I.

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A number of theoretical noise prediction models, for these types of propellers, have also been developed. The most recent of these are the models of Farassat (refs. 3 to 5) and Hanson (refs. 6 and 7). These noise models represent a significant extension of propeller noise prediction into the transonic and supersonic helical tip speed regions. In a previous paper, reference 8, the Farassat model was used to predict the noise from the three tested propellers for comparison with the tunnel data. Farassat's noise model is a complicated calculation based on the Ffowcs Williams-Hankings equation (ref. 9). This model yields the directivity, spectra and wave shapes of the noise and it can make predictions throughout the entire speed range, from subsonic to supersonic speeds. As a result of the many capabilities and the calculational complexity of this model, the computational time is relatively large and detailed blade aerodynamic information is required as input. Because a need exists for a quicker estimate of noise, the present report evaluates a simplified noise model based on sonic boom overpressures. The predictions of this model are compared with those of the Farassat model and with wind tunnel noise data.

SIMPLIFIED NOISE MODEL

The simplified noise model chosen for this evaluation was previously used in reference 10. This model, based on the sonic boom overpressure generated by a body in supersonic flight, comes directly from a NASA contract report by the Boeing Airplane Company, reference 11, which used the overpressure expressions published in reference 12.

This noise model calculates the sonic boom intensity striking the airplane fuselage. The supersonic region of the propeller blade is considered as a body of revolution of an equivalent diameter. The model then uses the average helical Mach number of the supersonic region in the calculation of the volume and lift components of noise. These components are then added together in a root mean square manner and an overall sound pressure level is calculated, accounting for the time the overpressure is felt on the cabin wall. This method does not predict a spectrum or a directivity but only predicts the maximum sound pressure level on the cabin wall. The model also only calculates the noise from the supersonic sections of the blade.

The equations used, taken from reference 11, are presented below and a symbol list is included in the appendix. A more detailed description of this method can be found in reference 10 or 11.

SONIC BOOM EQUATIONS

The overpressure equations are presented below. The volume component of the overpressure is (ref. 11),

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

The lift component of the overpressure is,

$$\Delta P_L = K_R K_L \sqrt{P_g W} \frac{\left(M^2 - 1\right)^{3/8}}{M h^{3/4} \ell_W^{1/4}} \tag{2}$$

(Equation (2) was misprinted in ref. 10 with an extra d multiplying the equation. Although it was misprinted, it was used in the correct form in ref. 10).
Because these equations were originally formulated for the flyover of a supersonic airplane, some parameter interpretation is required. In equation (1), the pressure at altitude (P_a) and at the observer (P_g) are the same for the supersonic propeller, and h is the distance to the fuselage. Because the Mach number M of the flow over the propeller blades varies along the span, an average over the supersonic portion of the blade was used in the model, as given by the following equation.

$$M = \frac{M_{ht} + 1}{2} \tag{3}$$

The helical tip Mach number M_{ht} is

$$M_{ht} = \sqrt{\left(\frac{V_T}{a_o}\right)^2 + M_N^2} \tag{4}$$

The equivalent diameter (d) of the body of revolution is determined from

$$d = 2\sqrt{\frac{(r_t - r_s)(C)\frac{t}{C}}{\pi}} \tag{5}$$

where r_t is the tip radius and r_s is the radius at which the helical Mach number is 1.0. C is the chord of the propeller and t/c is the thickness to chord ratio. 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 the portion of the total propeller thrust generated by the supersonic region of each blade. Then

$$W = \frac{\tau}{B}\left(\frac{r_t - r_s}{r_t - r_h}\right) \tag{6}$$

where uniform loading from hub to tip is assumed and where τ is the total thrust, B is the number of blades and r_h is the hub radius.

In the overpressure equations, K_L and K_V are two shape factor constants and K_R is a reflection factor to account for the fuselage wall reflection. For the model it is assumed that $K_L = 0.7$, $K_V = 0.8$, and $K_R = 2.0$ (which represents a doubling of pressure at the fuselage wall).

TOTAL OVERPRESSURE

The total overpressure is the combination of the lift and volume overpressures

$$\Delta P = \sqrt{\Delta P_V^2 + \Delta P_L^2} \tag{7}$$

The overall sound pressure level is calculated from the total overpressure as follows:

$$OASPL_{overpressure} = 20 \log_{10}\left[\frac{\Delta P}{P_{ref}} \times K_{NF}\right] \tag{8}$$

(The near-field correction term K_{NF} was assumed by Boeing to be 0.75 as indicated in ref. 11.)

The rms overall sound pressure level is calculated by including the length of time the shock from each blade is present at a point on the fuselage (ref. 11),

$$OASPL_{rms} = OASPL_{overpressure} + 20 \log_{10}\left(\frac{T*}{T}\right)^{1/2} \qquad (9)$$

where the time between each blade passage is,

$$T = \frac{\pi D}{BV_T} \qquad (10)$$

and the shock duration is

$$T* = \frac{C}{M_{ht}a_o} \qquad (11)$$

STRAIGHT-BLADED PROPELLER

The simplified noise theory described in the previous section was formulated for a straight-bladed propeller without sweep. Therefore, the first comparisons are undertaken for the straight-bladed, SR-2 propeller. As previously mentioned, the simplified model yields only an overall sound pressure level at the maximum noise position on the fuselage. From reference 8, figure 12, it was seen that both the Farassat model and the wind tunnel data for the three propellers were dominated by the blade passage tone. Therefore, the predicted overall sound pressure levels from the simplified model will be compared with the maximum blade passage tone values for both the Farassat model and the wind tunnel data previously published in reference 8, figure 3.

Model Comparison

The first comparison undertaken is between the calculations from the simplified model and those from the model presented by Farassat. This comparison is shown in figure 2. The comparison is performed for the same test points as in reference 8 for later comparison with experimental data. As can be observed in figure 2, the simplified model predicts less noise than the values predicted by the Farassat model, although the shapes of the two curves are the same. It can also be observed that the simplified model can only be used for a Mach number greater than one, so only the three upper points are predicted.

As was noted with respect to equation (8), Boeing applied an arbitrary factor to the original overpressure equations of reference 12 to account for the fact that the fuselage was apparently in the near field of the propeller while the overpressure equations were developed for the far field. The near field correction, KNF in equation (8), was assumed by Boeing to be 0.75. This near field correction factor does not appear to be necessary and is artificially lowering the noise calculation. When this factor is removed, that is, set equal to one, the simplified model yields the predictions shown in figure 3. As observed from the figure, this single modification, removal of the near field correction, brings the simplified model in close agreement with the Farassat model. This close agreement is very beneficial because it suggests that quick, equally accurate predictions of supersonic propeller noise can be made without having to use the more time consuming complicated theory. Because of this close agreement, all of tne subsequent calculations with the simplified model will be made with the near field correction removed, that is, $K_{NF} = 1.0$.

Comparison with Data

Although it has been shown that the simplified model can be adjusted to be approximately the same as Farassat's model for the straight-bladed propeller, it should be noted that neither model matches the data taken in the wind tunnel. This was shown in reference 8 for the Farassat model and is shown here with both the Farassat and the simplified model ($K_{NF} = 1.0$) plotted in figure 4. It should also be noted here that the data were taken in a wind tunnel which did not have acoustically treated walls. Therefore, it is possible that the tunnel data may be responsible for part of the difference between theory and data.

In order to get an indication of the reason the simplified model fails to predict the data, the prediction was broken down into components. Figure 5 is a plot showing the noise due to the lift and volume components of the simplified model in comparison with the wind tunnel data. From this plot it can be seen that the lift component significantly overpredicts the data at the higher Mach numbers (1.14 and 1.21) and that the volume component slightly overpredicts the data at these points. Referring to the Boeing contractor report (ref. 11) it can be seen that the lift and volume component coefficients, K_L and K_V, were both chosen by Boeing to be higher than those expected for a supersonic aircraft. Therefore, lowering these coefficients might bring the predictions more in line with the data.

Figure 6 shows tha original predictions with $K_L = 0.7$, and $K_V = 0.8$, and a new set of predictions where K_L has been lowered to 0.3 and K_V to 0.5. As can be seen on this figure, the lowering of these coefficients brings the prediction closer to the data, with the design point, $M_{ht} = 1.14$, being exactly predicted. In effect, this has lowered the prediction to the level of the data. However, the shape of the predicted curve shows a stronger dependence on helical tip Mach number than does the data. It would appear then, that the modified simple model can be adjusted to give an approximation to the level of wind tunnel noise data at the design point, $M_{ht} = 1.14$, but that the variation with Mach number is not the same as the data. (The Farassat model, in addition to not matching the level, also does not have the same variation with Mach number as the data.)

SWEPT-BLADED PROPELLER

As previously mentioned, the simplified noise model was formulated for a straight-bladed propeller without sweep. The purpose of the following discussion is to determine how well the model works when applied to swept propeller blades and to adjust the model if it does not compare favorably. The simplified theory with the near field correction removed, $K_{NF} = 1.0$, is used in this section.

Model Comparison

Again, the first comparisons undertaken are those between the simplified model predictions ($K_L = 0.7$, $K_V = 0.8$) and the Farassat model predictions generated in reference 8. Figure 7 shows the Farassat model and the simplified model values on the same plots. Part (a) is for SR-1M and part (b) is for SR-3. As can be observed from this figure, the simplified model slightly overpredicts the Farassat values for the SR-1M propeller, which has 23^o of tipsweep, and significantly overpredicts for the SR-3 propeller, which has 34^o of tipsweep.

Shock production on a swept leading edge is a function of the normal component of the incoming Mach number. Therefore, this normal component may be used in calculations of M for the overpressure equations. The normal Mach number, M_W, for a two-dimensional, infinite aspect ratio, no taper, swept wing, is the free stream Mach number, M_f, multiplied by the cosine of the sweep angle, Λ, that is,

$$M_w = M_f \cos \Lambda \tag{12}$$

If this modification is applied to the SR-1M and SR-3 propellers, the helical tip Mach number, M_{ht}, would be multiplied by the cosine of the blade sweep angle which is 0.921 for SR-1M and 0.829 for SR-3. In the case of the SR-3 propeller, this results in effective values of the tip Mach number less than or equal to unity and equations

(1) and (2) do not apply. The results for SR-1M are shown in figure 8, again as a function of the helical tip Mach number, not the normal component. The modification results in predicted noise levels significantly below those from the Farassat theory which suggests that the modification based on the cosine of the sweep angle is too large and should not be used.

A more detailed look at the wing sweep effects indicates that the infinite wing sweep adjustment does not apply directly for the tip region of a finite aspect ratio wing. The effect of the tip is to lower the effective sweep in the tip area, resulting in a larger effective normal Mach number than the blade sweep would yield. For example, this results in shock waves appearing at the tips of finite aspect ratio wings at lower Mach numbers than expected; however, the exact amount of the effect is not well defined. In the aerodynamic design of a swept wing the tip effect is often not very critical because the majority of the wing operates as expected. The tip effect is then treated as some, usually small, correction to the overall wing performance. On the other hand, for a supersonic propeller, the tip region is where the vast majority of the noise is generated and the effect is very important for our calculations. However, an attempt to quantify this tip effect was not successful. A general formula for the amount of this effect, the eduction of effective sweep near the tip, was not found during a search of the literature.

An effective sweep angle, equal to 80 percent of the true blade sweep angle, was found to give reasonable good agreement with the Farassat theory. The cosines of the effective sweep angles were 0.95 for SR-1M and a 0.89 for SR-3. Figure 9 compares the predictions from the simplified model using 80 percent of the true sweep with the Farassat model. It can be seen from this figure that when the same 80 percent effective sweep criterion was applied to both SR-1M and SR-3, the simplified model gave results fairly close to those of the Farassat model. This then indicates that the simplified model can be used on these swept blades as an approximation to the Farassat model if an effective sweep angle equal to 80 percent of the actual blade sweep angle is used.

Comparison with Data

As before, with the SR-2 propeller, both the simplified model and the Farassat model overpredict the data for the two swept propellers at the higher Mach numbers. This can be seen in figure 10 where both models are plotted on the same scale as the data. (Here the simplified model uses the effective sweep angle presented in the previous paragraph.)

If the same corrections to the simplified model are used here as were used for the SR-2 data comparison, namely, K_L changed to 0.3 and K_V to 0.5, the model predictions are lowered to the levels of the data as seen in figure 11. As before, with the SR-2 data comparison, the simplified model matches the data at the $M_{ht} = 1.14$ point, but the model variation with Mach number is significantly larger than is the data variation. This leaves the $M_{ht} = 1.21$ predictions for SR-1M and SR-3 much higher than the data. The use of the same coefficients, $K_L = 0.3$ and $K_V = 0.5$, on all three propellers generally gives the same results. This indicates that with these coefficients, the simplified model preductions can be lowered to match the data at the design point, $M_{ht} = 1.14$, but the dependence of the model results on Mach number is greater than the dependence of the data.

CONCLUDING REMARKS

The evaluation of a simplified noise model for supersonic tip speed propellers was undertaken in this report. The simplified noise model was compared with a more com-licated noise model (Farassat, references 3 to 5) and with wind tunnel noise data for one straight-bladed propeller, SR-2 and two swept-bladed propellers, SR-1M and SR-3. After the removal of an unnecessary near field correction, K_{NF}, in the original model, the simplified noise model was in close agreement with the more complicated Farassat model for the straight SR-2 propeller. The application of the simplified model to the swept propellers gave results higher than those of the Farassat theory. When a sweep adjustment was applied to the helical tip Mach number for the swept blades, the simplified model then yielded results close to those of the Farassat model. This sweep adjustment consisted of using an effective tip sweep angle of 80 percent of the blade sweep angle and then multiplying the helical tip Mach number by the cosine of this effective sweep angle. The simplified noise model, using the effective sweep when applied to swept blades, appears to be usable as a means of obtaining a quick estimate to the more complicated Farassat predictions.

The comparisons of the simplified noise model with the wind tunnel data were not good. This is the same result as found previously for the Farassat model at the higher Mach numbers tested. When the same adjustments to the lift and volume shape factor constants in the simplified theory were applied to all three propeller predictions, the noise model results and the experimental data agreed well at the propeller design point. However, the variation of the predictions with Mach number were not the same as the data variation, so the predictions at other Mach numbers were not correct.

APPENDIX - SYMBOLS

a_o	speed of sound at altitude, length/time
B	number of blades
C	blade chord, length
D	propeller diameter, length
d	equivalent diameter of supersonic region of blade (eq. (5)), length
h	distance of propeller tip from fuselage wall, length
K_L	lift shape factor constant
K_{NF}	near-field correction constant
K_R	reflection constant
K_V	volume shape factor constant
ℓ_B	effective body length, length
ℓ_W	effective wing length, length
M	average helical Mach number
M_f	wing freestream Mach number
M_{ht}	helical tip Mach number
M_N	airplane Mach number
M_w	wing normal Mach number
N	rotational propeller 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. (10))
T^*	shock duration (eq. (11))
t	blade thickness, length
V_T	propeller tip speed, length/time
W	loading in supersonic region of propeller, force
ΔP	total overpressure (eq. (7)), 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
τ	propeller thrust, force
Λ	sweep angle

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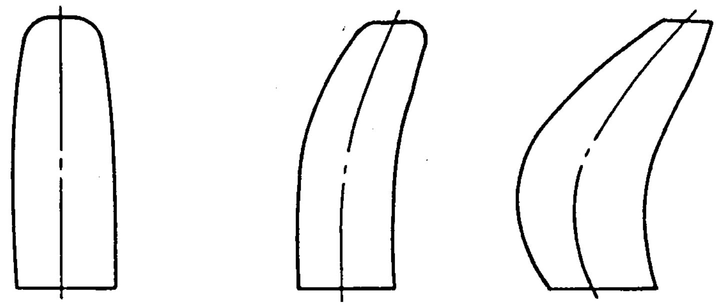
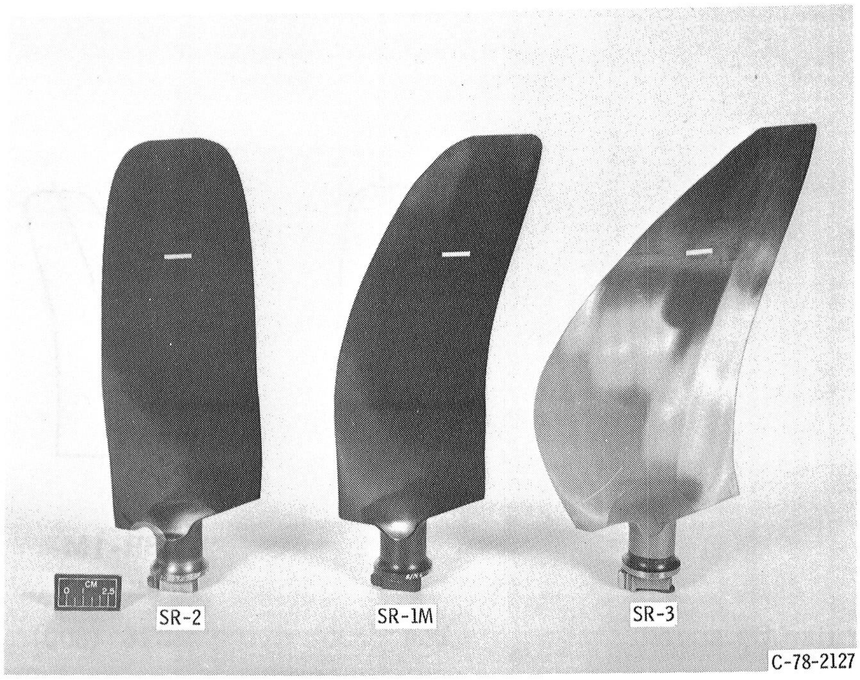
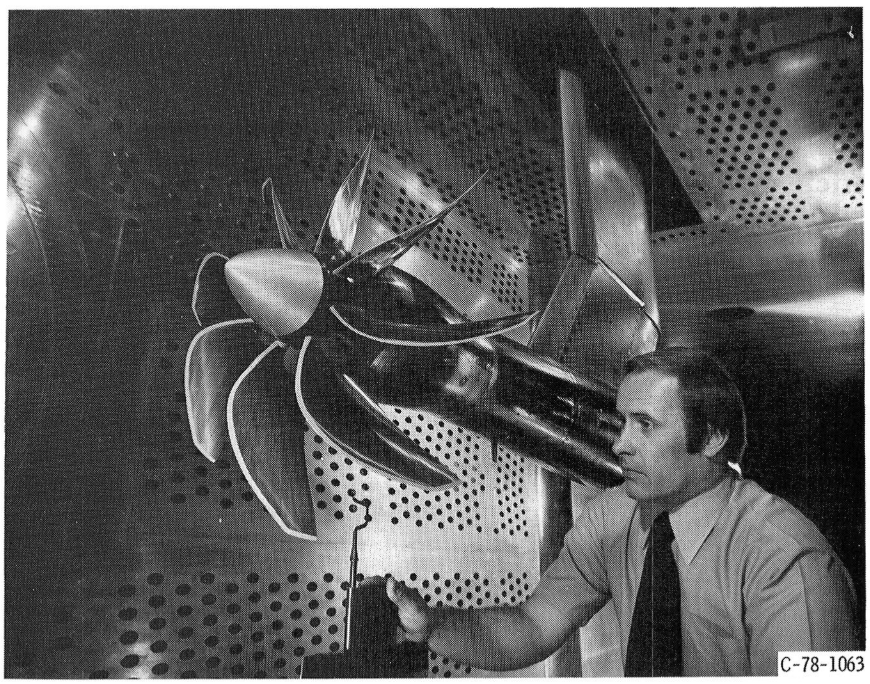
TABLE I. - COMPARISON OF PROPELLERS



	SR-2	SR-1M	SR-3
Design cruise tip speed, m/sec (ft/sec)	244 (800)	244 (800)	244 (800)
Design cruise power loading, kW/m^2 (shp/ft^2)	301 (37.5)	301 (37.5)	301 (37.5)
Number of blades	8	8	8
Tip sweep angle, mid chord, deg	0	23	34
Design efficiency, percent	77	79	81
Nominal diameter, D, cm (in.)	62.2 (24.5)	62.2 (24.5)	62.2 (24.5)



(a) INDIVIDUAL BLADES.



(b) PROPELLER SR-3 IN TUNNEL.

Figure 1. - Propeller blades.

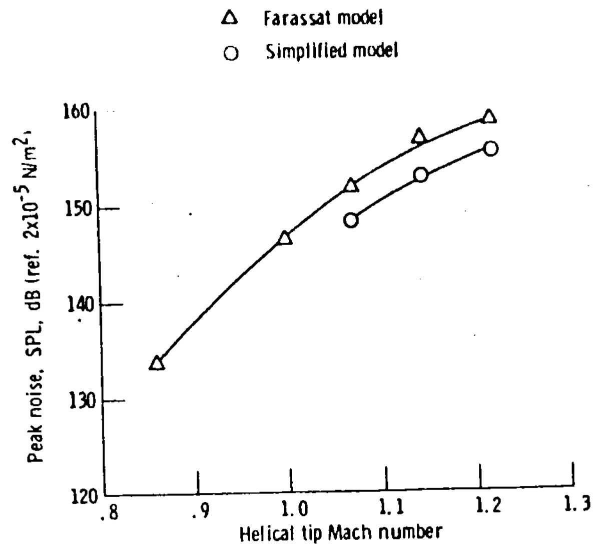


Figure 2. - Model comparison for SR-2 propeller.

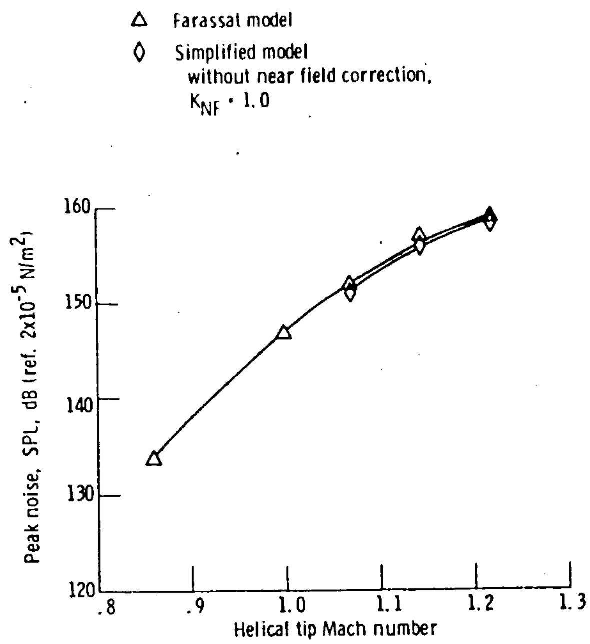


Figure 3. - Simplified model without near field correction compared with Farassat model for SR-2 propeller.

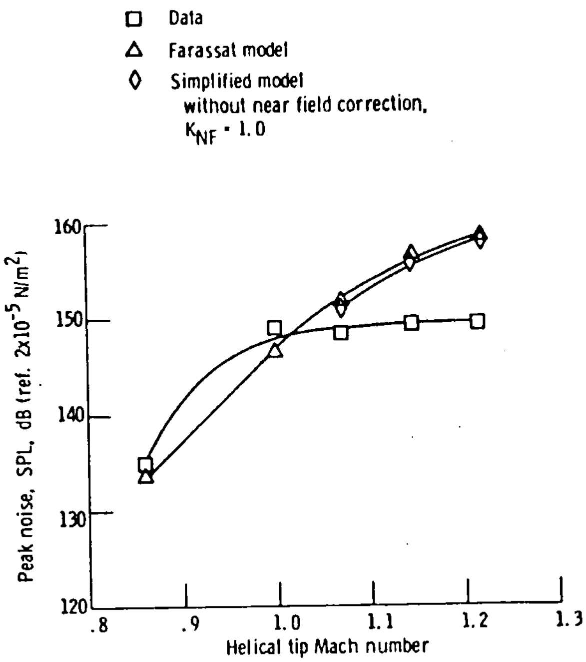


Figure 4. - Models compared with SR-2 propeller data.

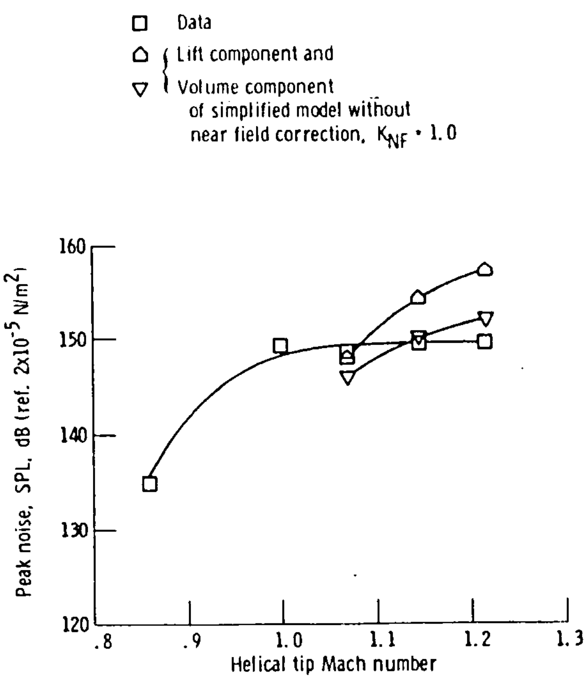


Figure 5. - Lift and volume components of simplified model prediction for SR-2 propeller.

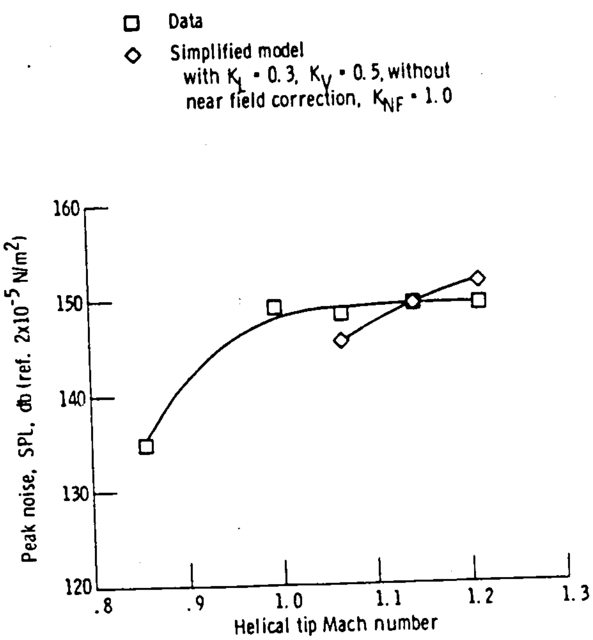
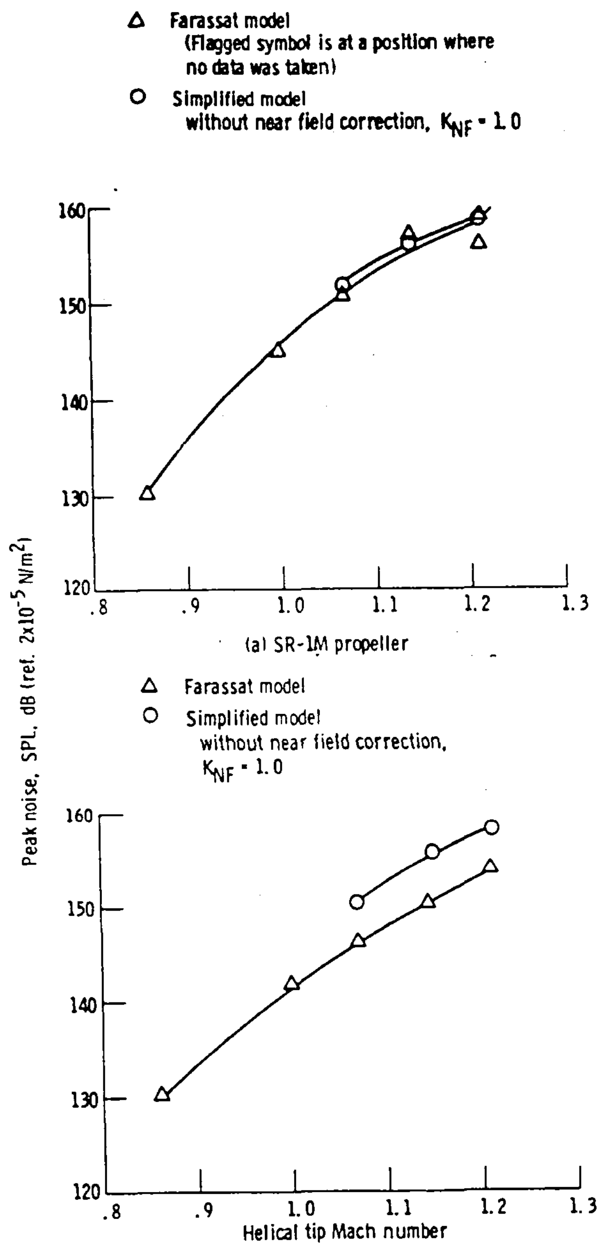


Figure 6. - Simplified model with adjusted lift and volume coefficients compared to SR-2 data.



(b) SR-3 propeller.

Figure 7. - Noise model comparison.

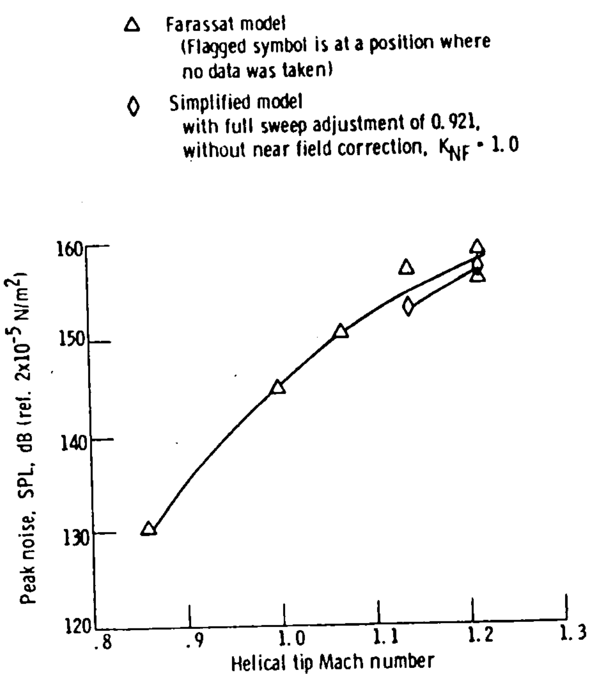


Figure 8. - Noise model comparison with full sweep adjustment applied to the simplified model for the SR-1M propeller.

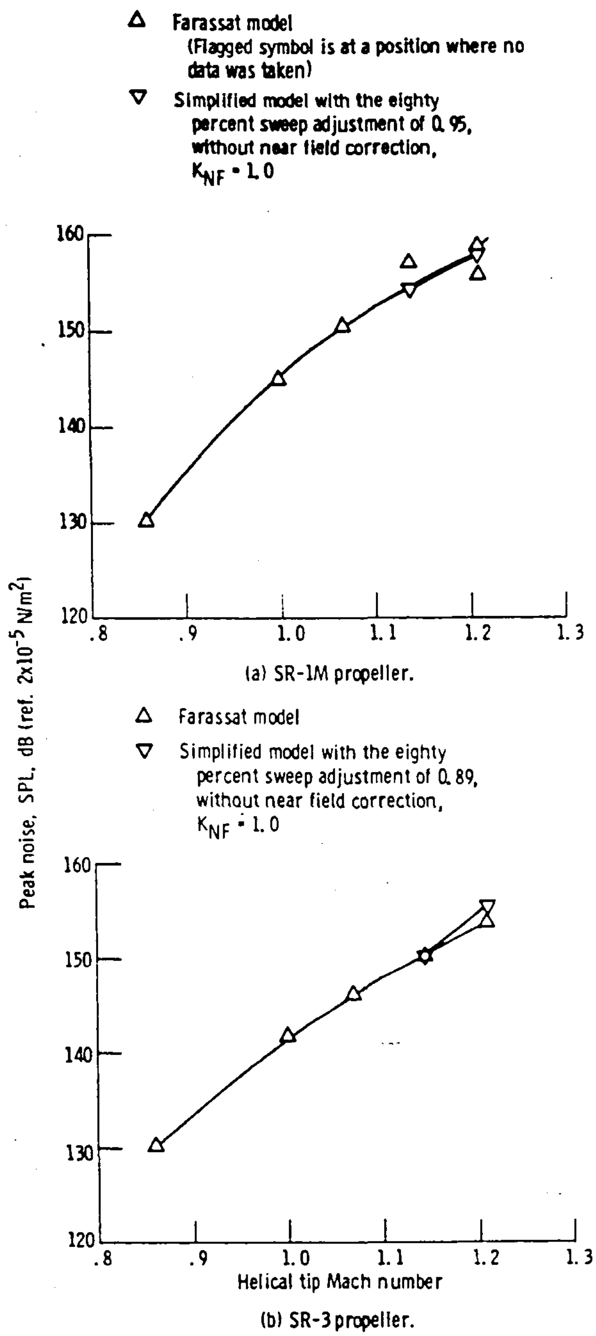
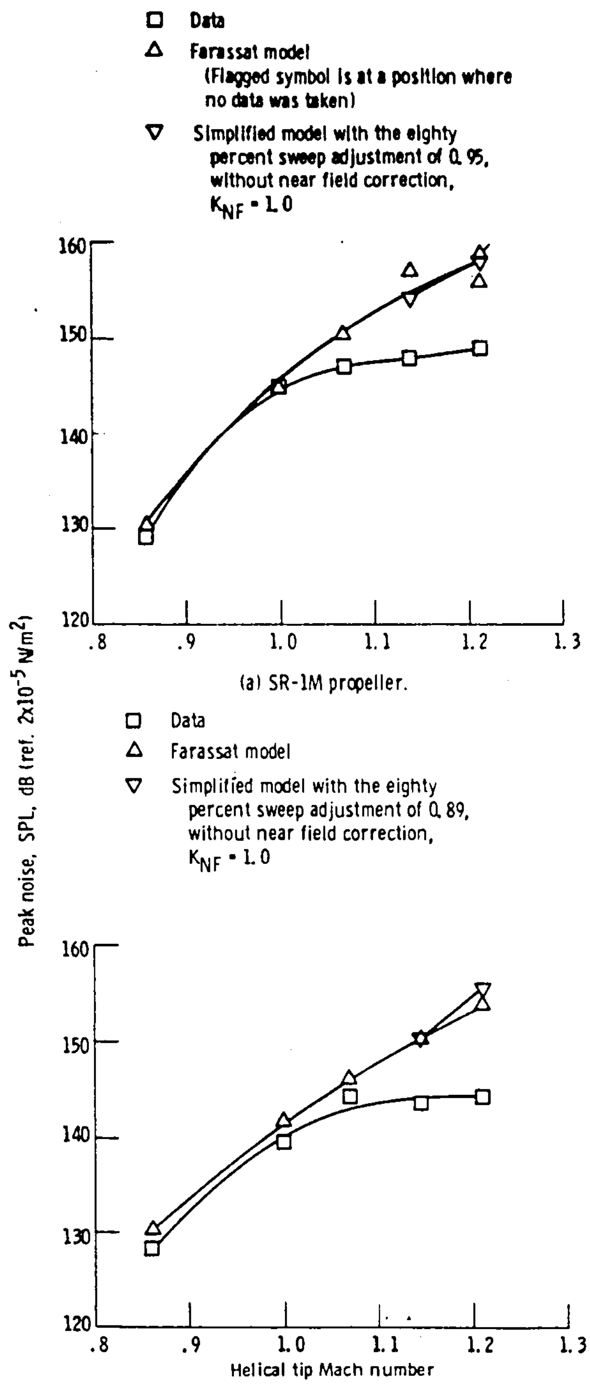


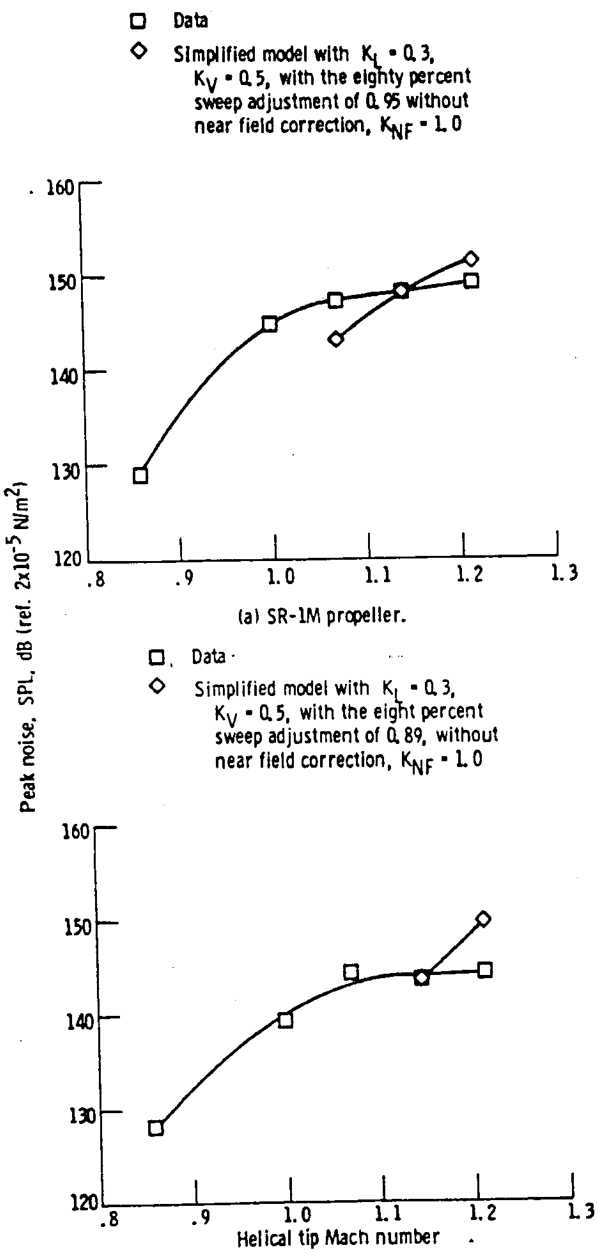
Figure 9. - Noise model comparison with eighty percent sweep adjustment applied to the simplified model.



(a) SR-1M propeller.

(b) SR-3 propeller.

Figure 10. - Comparison of noise models with data from swept propellers.



(a) SR-1M propeller.

(b) SR-3 propeller.

Figure 11. - Comparison of adjusted noise model with data.

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15. Supplementary Notes

16. Abstract

The noise generated by supersonic helical tip speed propellers may create a cabin environment problem for turboprop airplanes under cruise conditions. Therefore, work has been undertaken to measure the noise of these propellers and to determine noise models to be used for predictions. The existing propeller noise models are versatile and complex, but require large computational times. The intent in this report was to evaluate a simplified noise model that could be used to obtain quick noise estimates for these propellers. This simplified noise model compared favorably with a complex model for a straight-bladed propeller and for swept propeller blades when the propeller sweep was properly considered. The simplified model can thus be used as an approximation to the complex model. Comparisons of either the complex or simplified noise models with the available noise data are not good for supersonic propeller helical tip speeds. By adjusting various constants in the simplified model, the noise estimates can be brought into the same range as the data at the propeller design point but the variation of the model with helical tip Mach number remains different than the data.

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