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ANALYTICAL INVESTIGATION OF BLADE EFFICIENCY FOR TWO-DIMENSIONAL SUPERSONIC TURBINE ROTOR BLADE SECTIONS

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16. Abstract

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SUMMARY

An analysis was conducted to determine the blade efficiency for two-dimensional, supersonic rotor blade sections designed to produce vortex flow within the blade passage. Boundary layer characteristics were calculated and used to obtain the conditions downstream of the rotor blades after the flow had mixed to a uniform state. The boundary layer calculations were also used to give some indication as to whether flow separation would occur.

Subsonic and supersonic aftermixing axial Mach number solutions were obtained when the free-stream axial Mach number at the rotor exit (before mixing) was supersonic. The subsonic solution corresponds to mixing plus oblique shock losses, whereas the supersonic solution corresponds to shockless mixing. The effect of the lower- and upper-blade-surface Mach numbers on both blade efficiency and boundary layer separation were investigated. In addition, the effects of inlet flow angle and inlet Mach number on blade efficiencies were obtained.

The analysis indicated that either decreasing the lower-blade-surface Mach number or increasing the upper-blade-surface Mach number resulted in higher rotor blade efficiencies and also increased tendency for boundary layer separation. For this reason, the optimum blade performance would be expected to occur for rotor blades designed so that flow separation is imminent or has occurred slightly on both surfaces.

The rotor blade efficiency for the supersonic solution was found to be higher than for the subsonic solution because of the absence of shock losses in the supersonic solution. For the supersonic solution, it was found that the aftermixing flow angle deflects towards the axial direction resulting in further flow expansion on mixing. This results in higher aftermixing Mach numbers and higher total- to static-pressure ratios for the supersonic solution than for the subsonic solution.

Decreasing the inlet flow angle results in lower rotor blade efficiencies for the subsonic solution because of increased oblique shock losses. For the supersonic solution, little effect was noted. Increasing the inlet Mach number results in a significant decrease in efficiency.

INTRODUCTION

Supersonic turbines have potential application in turbopump and open-cycle auxiliary power systems (ref. 1) where high-energy fluids are used and high pressure ratios are available. This has resulted in a need for design procedures applicable to this type of turbine. The relatively small amount of experimental data on the overall performance of supersonic turbines (refs. 2 to 4) does not contain sufficient information to assess the individual performance of either the stator or the rotor. Because of this, both are usually designed by theoretical methods.

Supersonic stators and rotors can be designed by the method of characteristics as applied to the isentropic flow of a perfect gas. Computer programs for the design of two-dimensional supersonic nozzles and rotor blades have been reported in references 5 and 6, respectively. The design of blading by these procedures must then be supplemented by a knowledge of the loss characteristics of both the stator and the rotor. The efficiency of supersonic stators with sharp-edge throats were studied analytically in reference 7. Boundary layer characteristics were calculated (in ref. 7) and used to obtain the conditions downstream of the stators after the flow had mixed to a uniform state.

The purpose of this report is to study analytically the blade efficiency for supersonic rotor blades designed for conditions applicable to auxiliary space power systems. The rotor blades are designed so as to produce vortex flow within the blade passage. To obtain a theoretical estimate of the efficiency, the following calculations are required: (1) isentropic design of the supersonic rotor blades, (2) calculation of the boundary layer characteristics (momentum and displacement thicknesses) for the blades, and (3) determination of the losses due to mixing downstream of the rotor. The isentropic rotor blade design is obtained from the computer program of reference 6. The boundary layer parameters are calculated (assuming the flow entering the rotor is turbulent) by the computer program described in reference 8. For turbulent flow, the program uses the method given by Sasman and Cresci in reference 9. Finally, the aftermixing losses are found by the procedure given by Stewart (ref. 10) for turbomachine blades.

The blade efficiency for two-dimensional supersonic impulse rotor blades were primarily investigated for an inlet Mach number of 2.5. The effect of the lower- and upper-surface Mach number levels on both blade efficiency and boundary layer separation were studied. In addition, the effects of inlet flow angle and inlet Mach number on blade efficiency were obtained.

SYMBOLS

C   blade chord, ft; m

G blade spacing, ft; m

H_i incompressible form factor, displacement thickness divided by momentum thickness

M Mach number

p pressure, psia; N/m^2 abs

Re Reynolds number, $\rho_0'' V_0' C / \mu_0$

u tangential direction

V velocity, ft/sec; m/sec

x axial direction

α relative flow angle measured from axial direction, deg

η rotor blade efficiency, $\left(V_2'/V_{2,id}'\right)^2$

μ_0 viscosity based on relative total inlet temperature, lb/(ft)(sec); kg/(m)(sec)

ν Prandtl-Meyer angle, angle through which flow must turn in expanding from Mach 1 to given Mach number, deg

ρ density, lb/ft^3; kg/m^3

σ blade solidity, C/G

Subscripts:

id ideal

in inlet to rotor

l lower surface of blade

out outlet of rotor

u upper surface of blade

0 station at rotor inlet

1 station at rotor exit

2 station downstream of rotor

Superscripts:

' conditions relative to rotor

'' total relative conditions

METHOD OF ANALYSIS

The calculation of the blade efficiency for two-dimensional supersonic rotor blades designed to produce vortex flow within the blade passage is described herein. The rotor blades were designed for conditions applicable to an auxiliary space power system similar to that described in reference 1.

The rotor blade efficiencies were obtained by first designing a series of loss-free passages for given values of lower- and upper-surface Mach numbers. The boundary layer characteristics (momentum and displacement thicknesses) for the ideal passages were then obtained and the passage corrected to include the effect of the displacement thickness. Since the final blade profile must have equal outlet and inlet spacing (for constant mean diameter turbine), this requires that the ideal passage be designed so that the outlet spacing is less than the inlet spacing. This is discussed further in the section Rotor Blade Description and Design. The exit Mach number, flow angle, pressure ratio, and kinetic energy loss were calculated assuming that the flow mixes to uniform conditions downstream of the rotor. In addition, the boundary layer characteristics were used to give some indication as to whether flow separation would occur in the rotor.

The efficiencies obtained in this analysis are for two-dimensional blade rows. In an actual design, three-dimensional effects would have to be included. A method of estimating three-dimensional efficiency from two-dimensional efficiency has been described in reference 11.

Rotor Blade Description and Design

The design of the loss-free (isentropic) blade passage is based on establishing vortex flow within the blade passage by a procedure analogous to that given in reference 6. A typical passage, designed by the method of characteristics, is shown in figure 1. The passage consists essentially of three major parts: (1) inlet transition arcs, (2) circular arcs, and (3) outlet transition arcs. The inlet transition arcs (lower and upper) are required to convert the assumed uniform parallel flow at the passage inlet into vortex flow. The concentric circular arcs turn and maintain the vortex flow conditions. The outlet transition arcs reconvert the vortex flow into uniform parallel flow at the passage exit. Straight-line segments parallel to the inlet and outlet flow direction complete the passage.

It is seen from figure 1, that the ideal passage has an outlet spacing G_{out} less than the inlet spacing G_{in}. This is done purposely. It will be required that the corrected passage (i.e., the passage corrected by the boundary layer displacement thicknesses) have equal outlet and inlet spacing (see fig. 2). This is possible only if for the ideal passage G_{out} is less than G_{in}. For an ideal passage designed for impulse conditions

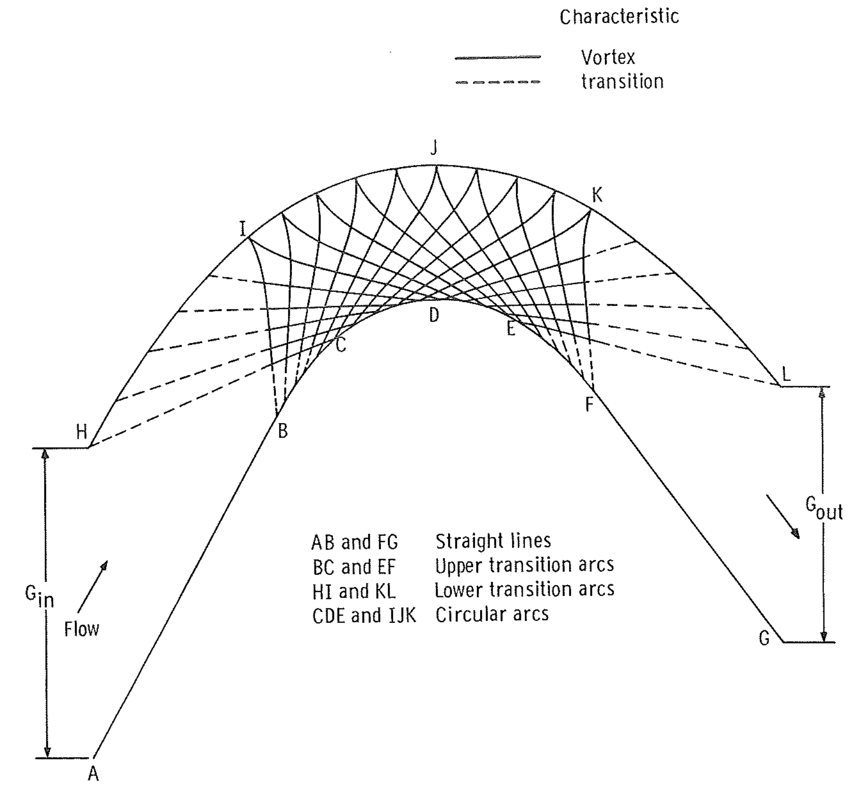


Figure 1. - Design of ideal supersonic flow passage by method of characteristics.

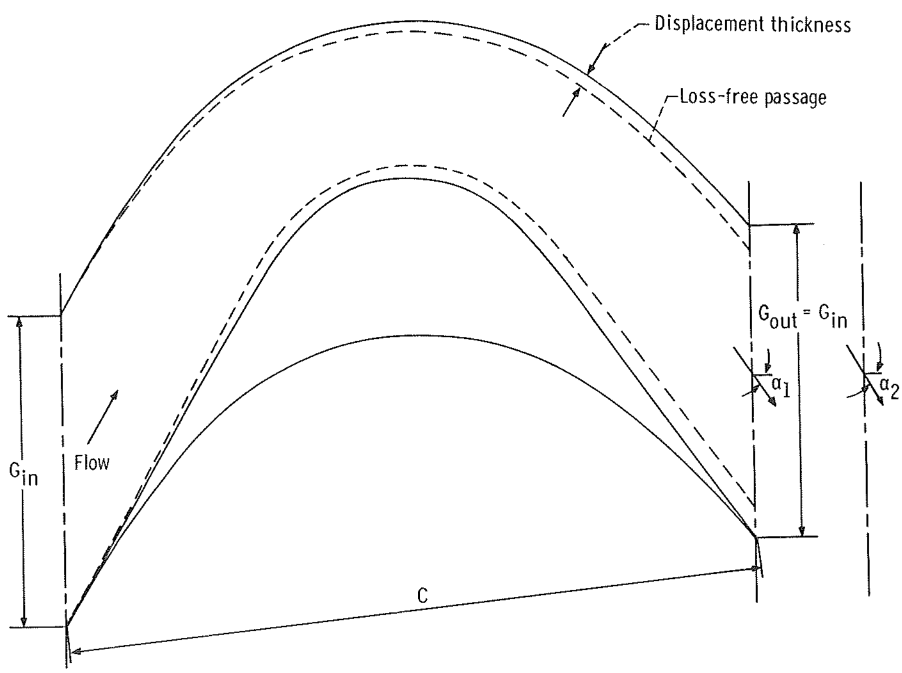


Figure 2. - Design of supersonic rotor blade section.

(equal inlet and outlet Mach numbers) this is accomplished by having less circular turning for the outlet portion of the passage. That is, the outlet circular arcs JK and DE (fig. 1) are less than the corresponding inlet circular arcs IJ and CD. An iterative procedure is required to find out just how much less to make JK and DE. This was done automatically using a modified version of the computer program described in reference 6.

For the low flow rate open-cycle auxiliary space power systems of current interest (ref. 1), the flow through the turbine is likely to be laminar. The calculation of laminar boundary layer parameters in strong adverse pressure gradients, as exist in the rotor passage, does not appear to be possible with existing theory because of boundary layer separation. In order to get an estimation of the losses in the rotor, the boundary layer characteristics for the ideal passages were calculated assuming the flow is turbulent. If the flow is actually laminar, the larger friction losses occurring would result in lower efficiencies than presented herein. However, the effect of the design variable on blade efficiency would be expected to follow similar trends.

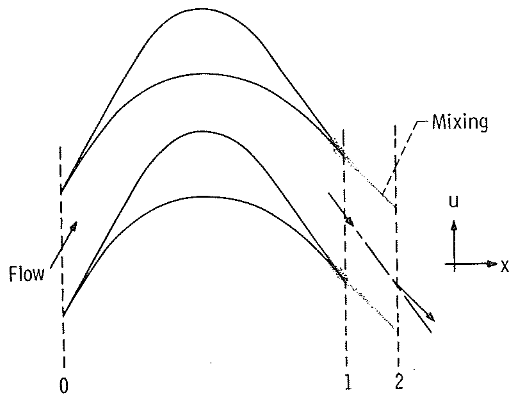
The boundary layer parameters were obtained using the computer program described in reference 8. For turbulent flow, the program uses the compressible boundary layer theory given in reference 9. In this method, the boundary layer parameters are obtained by simultaneous solutions of the transformed momentum and moment-of-momentum integral equations. The final blade passage is obtained by adding the displacement thicknesses to the loss-free passage coordinates. Figure 2 shows a typical blade section designed by this procedure. The dashed line represents the loss-free passage. The displacement and momentum thicknesses at the blade exit (station 1, fig. 2) were used to calculate the conditions downstream of the blades.

Blade Efficiency

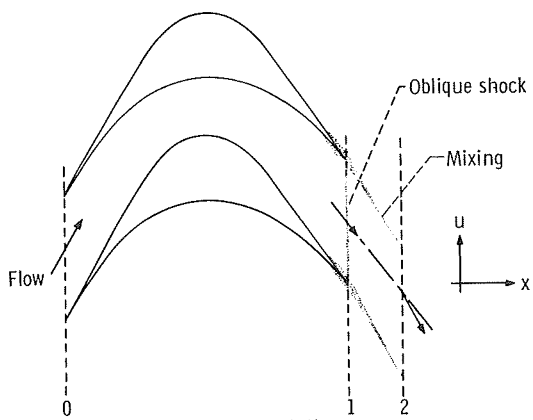
The calculation of the losses due to mixing downstream of turbomachine blade rows has been described in terms of boundary layer characteristics in reference 10. In this loss model, the flow sufficiently downstream of the blade row is assumed to be uniform and parallel. Application of the continuity, momentum, and energy equations between stations 1 and 2 (fig. 2) results in the determination of the aftermixing Mach number, flow angle, pressure ratio, and kinetic energy loss (or efficiency). The rotor blade efficiency η is defined herein as

$$\eta = \left(\frac{V_2'}{V_{2,id}'}\right)^2 \qquad (1)$$

where V_2' is the aftermixing relative velocity and $V_{2,id}'$ is the ideal relative velocity at



(a) Supersonic solution.



(b) Subsonic solution.

Figure 3. - Representation of different aftermixing solutions.

station 2 obtained by isentropic expansion to the aftermixing static pressure p_2.

Since the free-stream Mach numbers at station 1 are supersonic, two cases are considered for this loss model: (1) supersonic free-stream axial Mach numbers and (2) subsonic free-stream axial Mach numbers. These will now be discussed.

Supersonic free-stream axial Mach numbers. - When the free-stream axial Mach number at the blade exit (station 1, fig. 2) is supersonic, two aftermixing solutions are analytically possible for the loss model of reference 10. One of the solutions results in supersonic aftermixing axial Mach numbers (station 2, fig. 2) and is hereafter referred to as the supersonic solution. The losses for this solution are the result of mixing the nonuniform flow at the blade exit to uniform flow. In the limit, as the boundary layer parameters go to zero this solution corresponds to straight-through flow. No shock losses occur for this solution. The second solution results in subsonic aftermixing axial Mach numbers and will be referred to as the subsonic solution. As the boundary layer parameters go to zero, this solution corresponds to an oblique shock wave occurring across the blade exit plane (station 1). Therefore, with a boundary layer present, the losses are a combination of mixing and shock losses. A schematic representation of these solutions is shown in figures 3(a) and (b).

Subsonic free-stream axial Mach numbers. - When the free-stream axial Mach number at the blade exit is subsonic, only one aftermixing solution is analytically possible for this model. The aftermixing axial Mach number is subsonic, and this solution will again be referred to as the subsonic solution. Only mixing losses occur for this solution.

Boundary Layer Characteristics

As described previously, the boundary layer calculations are needed to correct the ideal passage for the displacement thickness. In addition, the calculations also give an indication if the adverse pressure gradients along the blade surfaces are severe enough to cause flow separation. This type of information is obtained from the value of the incompressible form factor H_i along the blade surfaces. A typical distribution of H_i is shown in figure 4. The corresponding surface Mach number distribution is shown in figure 5. Flow separation usually occurs in the range of H_i from 1.8 to 2.4 (ref. 12). From figure 4 it is seen that separation is possible on both the lower and upper surfaces of the blade. Separation on the lower surface, if it occurs, is probably not as important since the flow would tend to reattach shortly downstream. The maximum value of H_i along either surface usually occurs on the transition arc (points I and F of fig. 4).

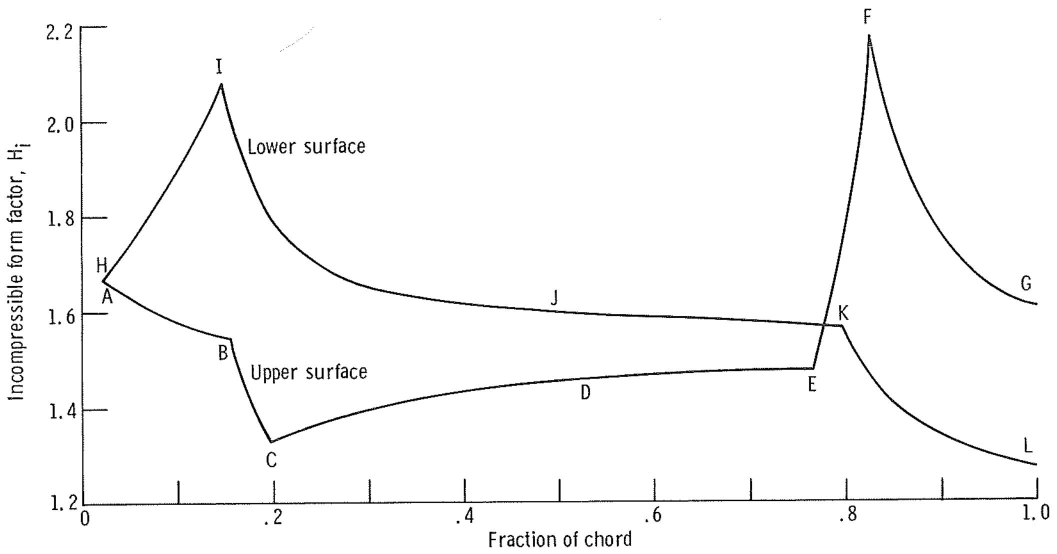


Figure 4. - Typical variation of incompressible form factor with axial distance.

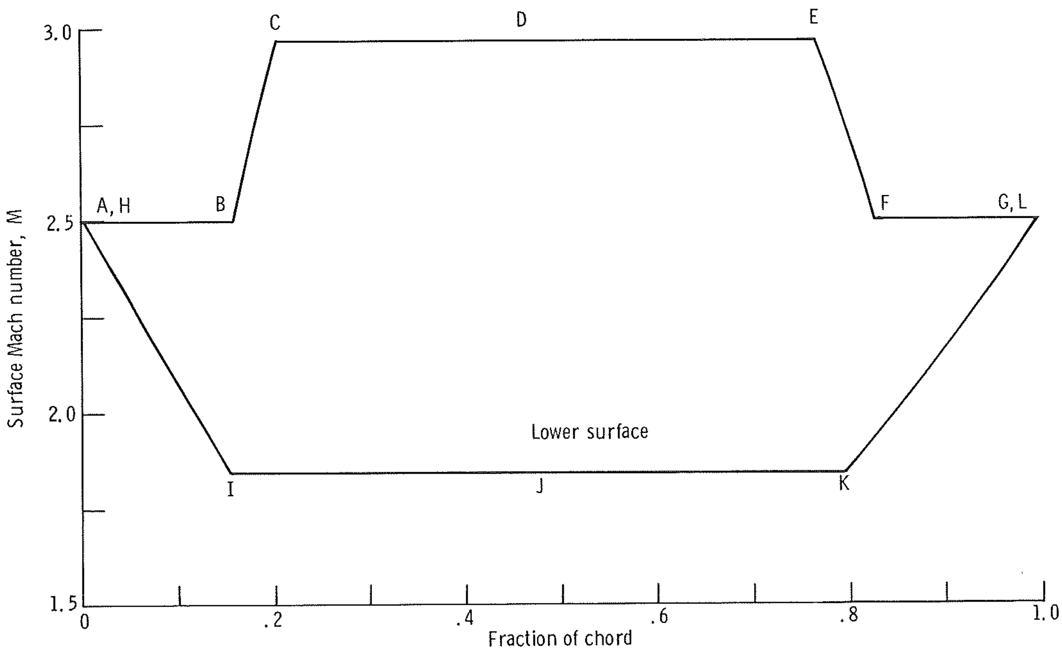


Figure 5. - Typical variation of surface Mach number with axial distance.

RESULTS AND DISCUSSION

The results of the study of the blade efficiency of supersonic rotor blades are presented in this section. The blade efficiencies were primarily investigated for rotor blades designed for an inlet Mach number of 2.5 and inlet flow angle of 70°. The Reynolds number $Re = \rho_0'' V_0' C / \mu_0$ was 35 000, and the specific heat ratio was 1.4. With the aforementioned conditions, specification of the lower- and upper-surface Mach number completely determines the blade shape, solidity, outlet blade angle (since equal outlet and inlet spacings are required), and aftermixing conditions. The effect of the lower- and upper-surface Mach number levels on the rotor blade efficiency and boundary layer characteristics were investigated. In addition, the effects of inlet flow angle and inlet Mach number on blade efficiencies were obtained.

Blade Efficiency and Boundary Layer Characteristics at Mach Number of 2.5

Rotor blade efficiency. - The rotor blade efficiency as a function of lower- and upper-surface Prandtl-Meyer angle (or Mach number) is shown in figures 6 and 7, respectively. As discussed previously, solutions corresponding to subsonic and supersonic aftermixing axial Mach numbers are shown in the figures.

The efficiency for the supersonic solution is higher than for the subsonic solution be-

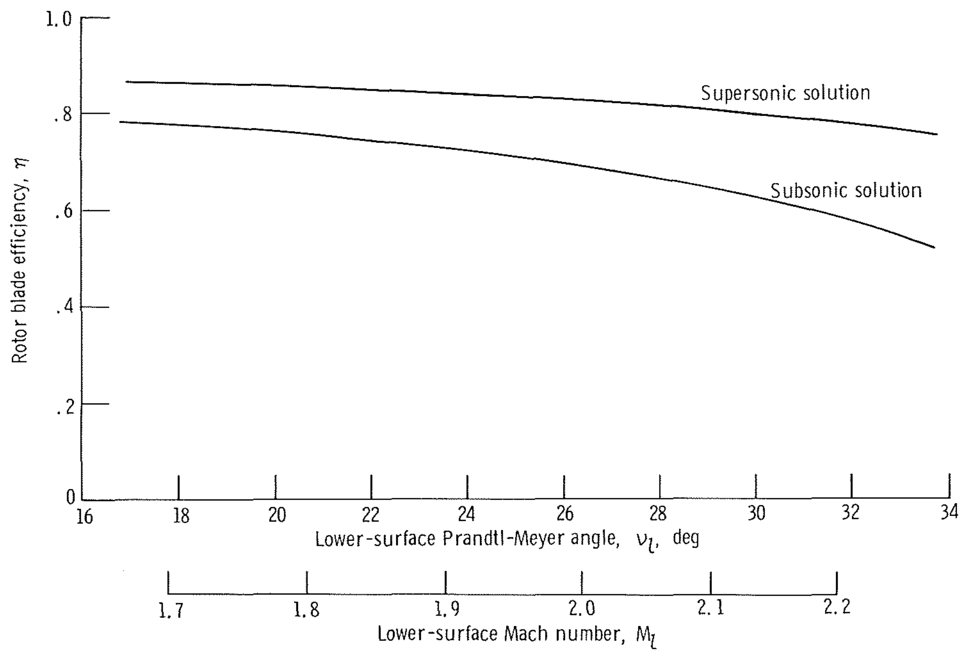


Figure 6. - Effect of lower-surface Prandtl-Meyer angle on rotor blade efficiency for rotor blades designed for inlet Mach number of 2.5 (Upper-surface Prandtl-Meyer angle, 49°).

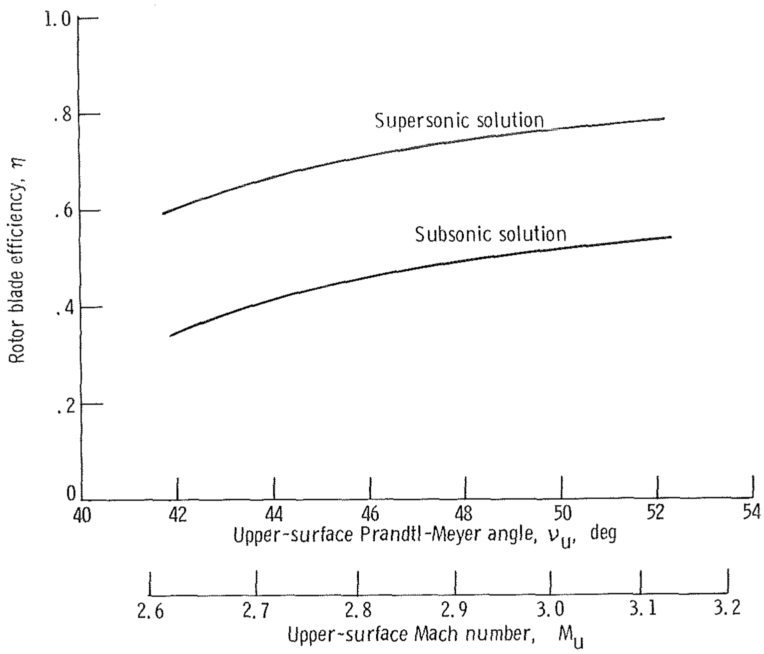


Figure 7. - Effect of upper-surface Prandtl-Meyer angle on rotor blade efficiency for rotor blades designed for inlet Mach number of 2.5 (Lower-surface Prandtl-Meyer angle, 34°).

cause of the absence of shock losses in the supersonic solution. It should be noted that for this loss model, the work output of the turbine would be the same for both the subsonic and supersonic solutions. The rotor blade efficiency is seen to increase when either the lower-surface Prandtl-Meyer angle (or Mach number) decreases or the upper-surface Prandtl-Meyer angle increases. This is to be expected since these changes increase the passage width which results in a smaller percentage of the passage being occupied by the boundary layer. These results assume that boundary layer separation does not occur along the blade surfaces. Flow separation could lower these rotor blade efficiencies significantly.

Boundary layer characteristics. - The effect of lower- and upper-surface Prandtl-Meyer angles on the maximum value of incompressible form factor H_i is shown in figures 8 and 9, respectively. As discussed previously, the boundary layer characteristics of the rotor blades (from a flow separation standpoint) can be represented by the maximum value of H_i on each surface. Flow separation usually occurs in the range of H_i from 1.8 to 2.4. From figures 8 and 9, it is seen that the maximum value of H_i increases when either the lower-surface Prandtl-Meyer angle (or Mach number) decreases or the upper-surface Prandtl-Meyer angle increases. But these same changes in Prandtl-Meyer angle were previously found to increase the rotor efficiency. Therefore, changes in surface Mach number levels that tend to increase blade performance also tend to cause flow separation. A compromise between these opposing tendencies is necessary in an actual design.

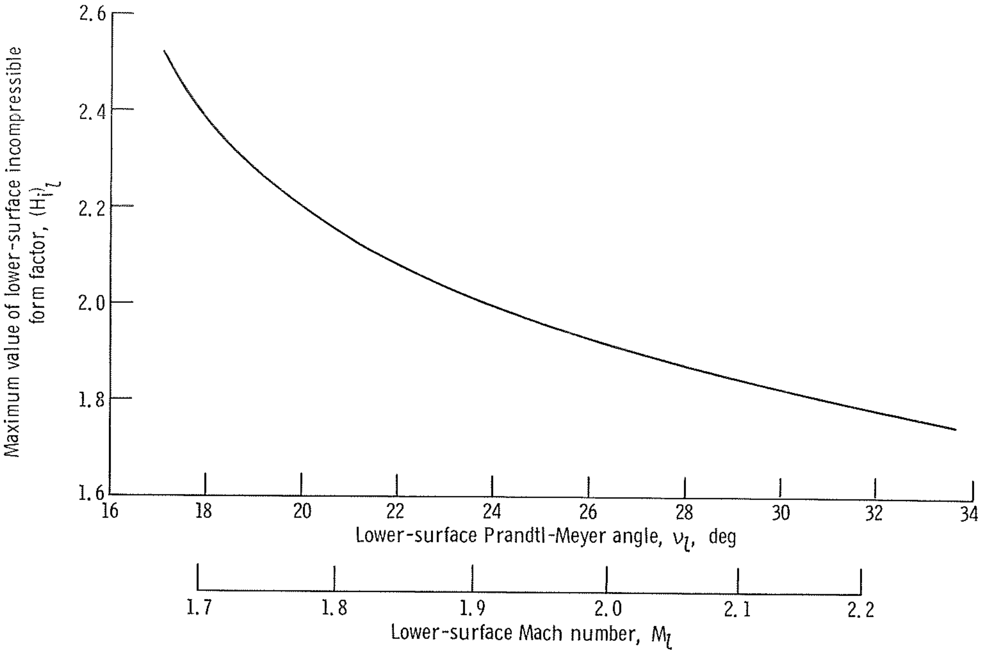


Figure 8. - Effect of lower-surface Prandtl-Meyer angle on maximum value of incompressible form factor on lower surface (Upper-surface Prandtl-Meyer angle, 49°).

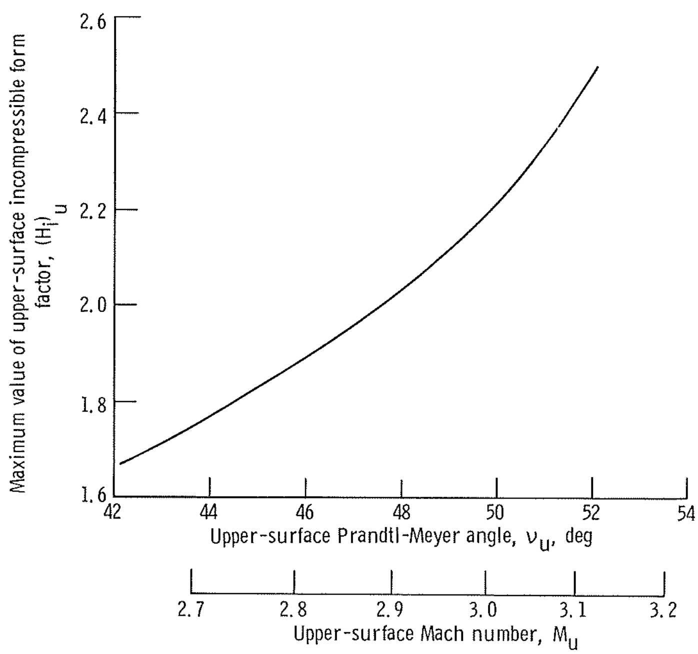


Figure 9. - Effect of upper-surface Prandtl-Meyer angle on maximum value of incompressible form factor on upper-surface (Lower-surface Prandtl-Meyer angle, 34°).

An optimum supersonic rotor blade design would be expected to occur for a blade design in which the lower- and upper-surface Mach numbers are chosen such that flow separation is imminent or has occurred slightly on each surface. For under these conditions, it would be expected that the rotor blade efficiency would be close to its maximum value. A similar result for more conventionally shaped cascade blades was obtained by Schlichting in reference 13.

In an actual blade design, other factors such as blade solidity and supersonic starting would also have to be considered. These have been discussed in reference 14. For completeness, the blade solidity as a function of lower- and upper-surface Prandtl-Meyer angles is shown in figure 10. It is seen from the figure that the solidity decreases

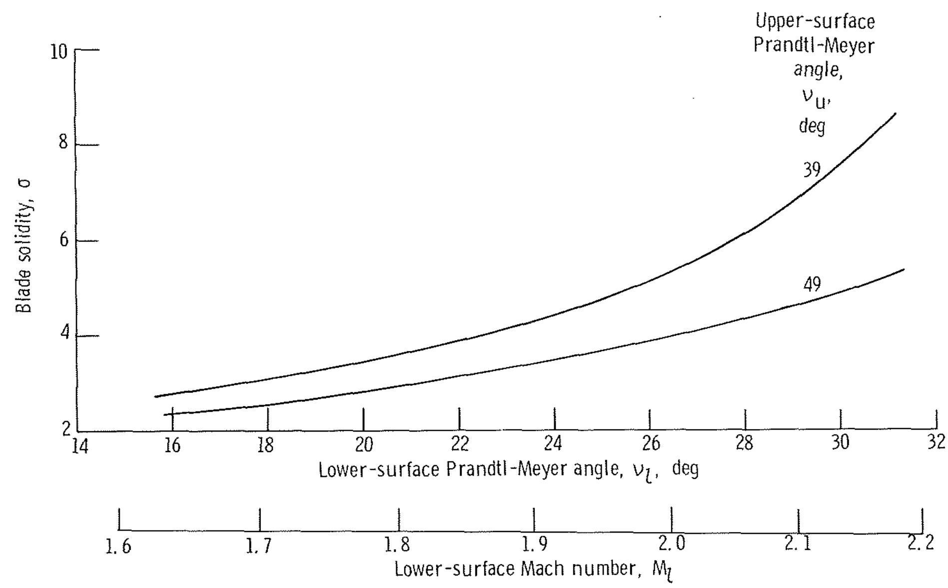
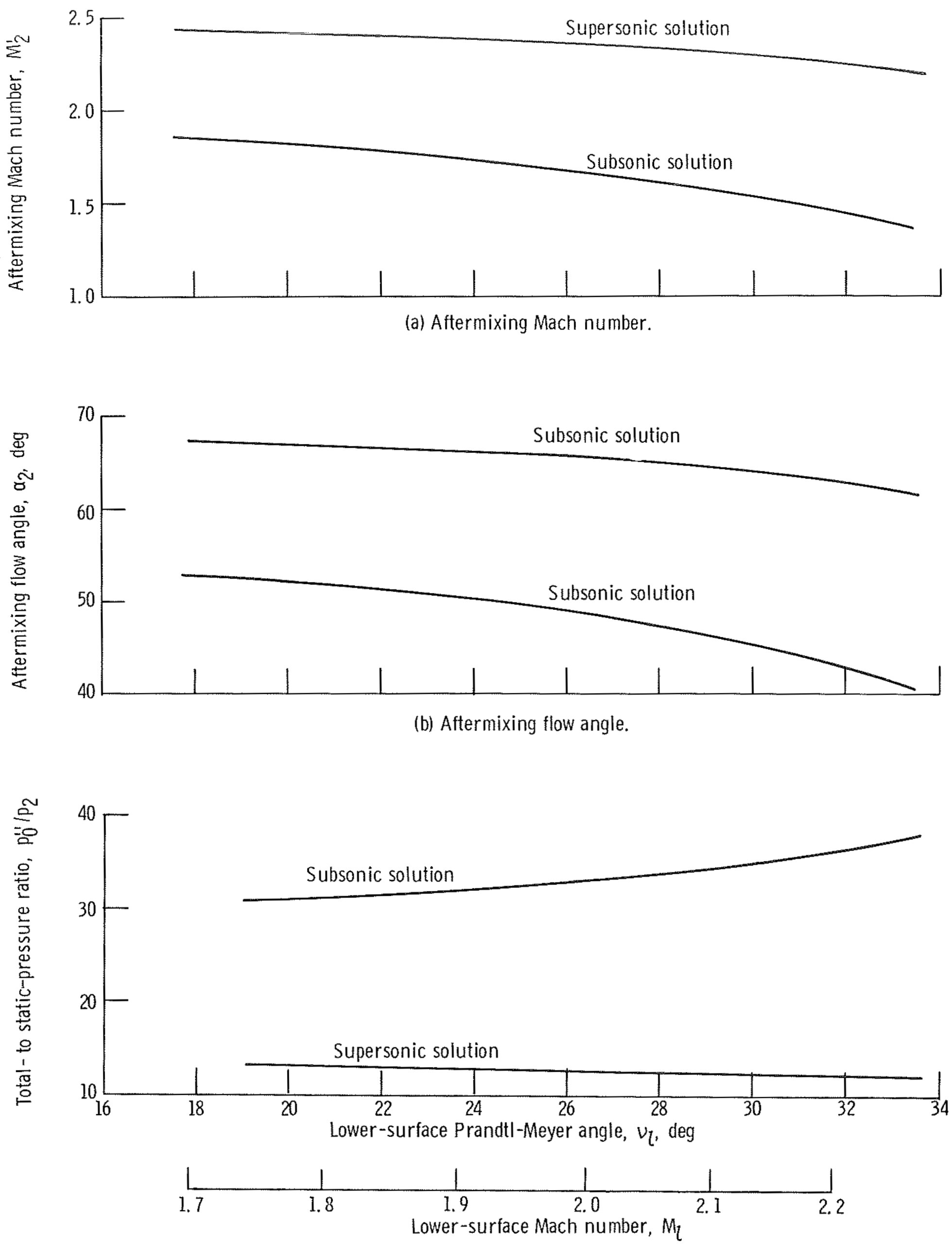


Figure 10. - Effect of surface Prandtl-Meyer angles on blade solidity.

(number of blades decreases) as the lower-surface Prandtl-Meyer angle decreases or the upper-surface Prandtl-Meyer angle increases. These are the same trends that tend to increase the probability of separation.

Aftermixing characteristics. - The aftermixing conditions for the rotor blades as a function of lower- and upper-surface Prandtl-Meyer angle are shown in figures 11 and 12, respectively. The effect of the surface Prandtl-Meyer angles on the aftermixing Mach number is shown in figures 11(a) and 12(a). The aftermixing Mach number exhibits trends similar to that seen for the rotor efficiency (figs. 6 and 7). The aftermixing Mach number for the supersonic solution is larger than for the subsonic solution because of the absences of shock losses in the subsonic solution.



(c) Rotor total- to static-pressure ratio.

Figure 11. - Effect of lower-surface Prandtl-Meyer angle on aftermixing conditions for rotor blades designed for inlet Mach number of 2.5 (Upper-surface Prandtl-Meyer angle, 49°).

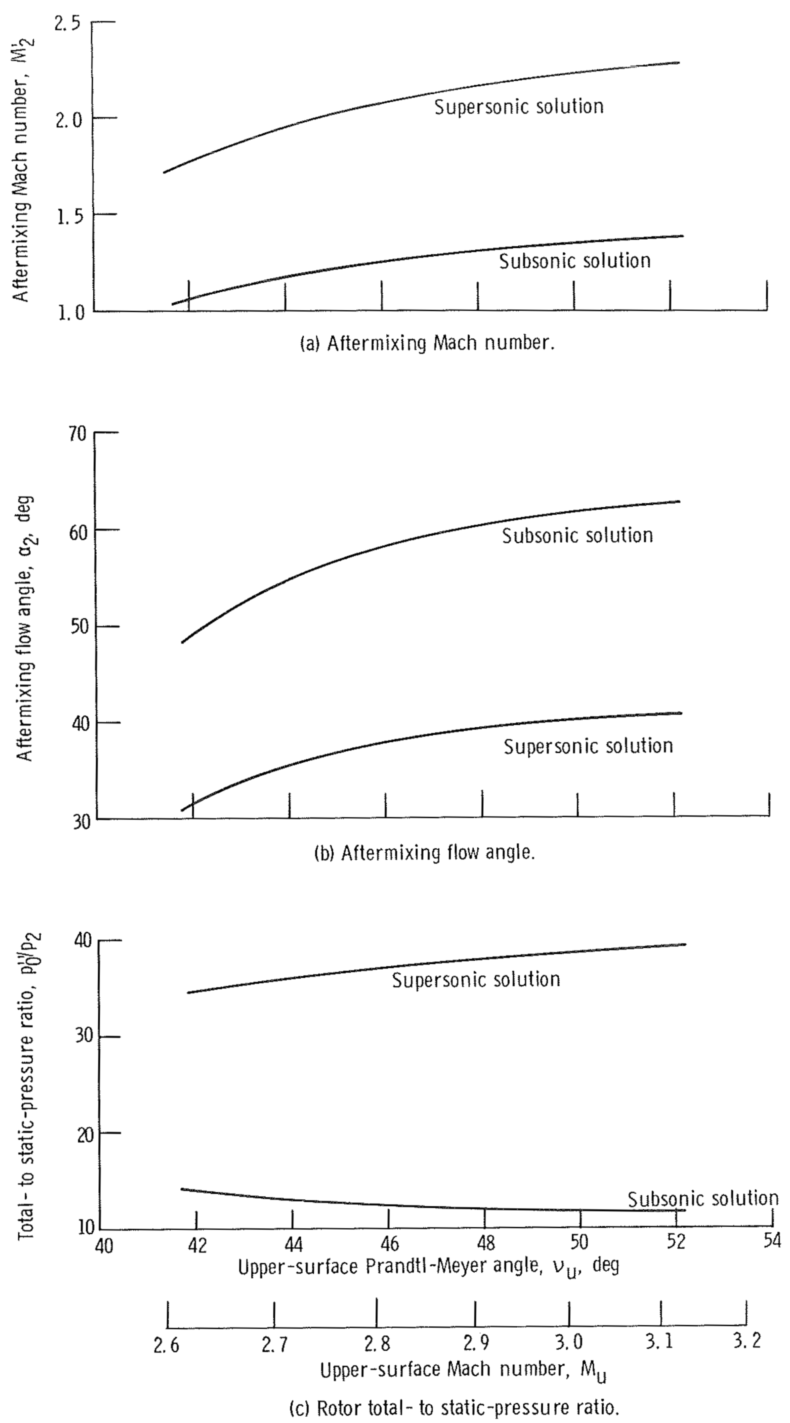


Figure 12. - Effect of upper-surface Prandtl-Meyer angle on aftermixing conditions for rotor blades designed for inlet Mach number of 2.5 (Lower-surface Prandtl-Meyer angle, 34°).

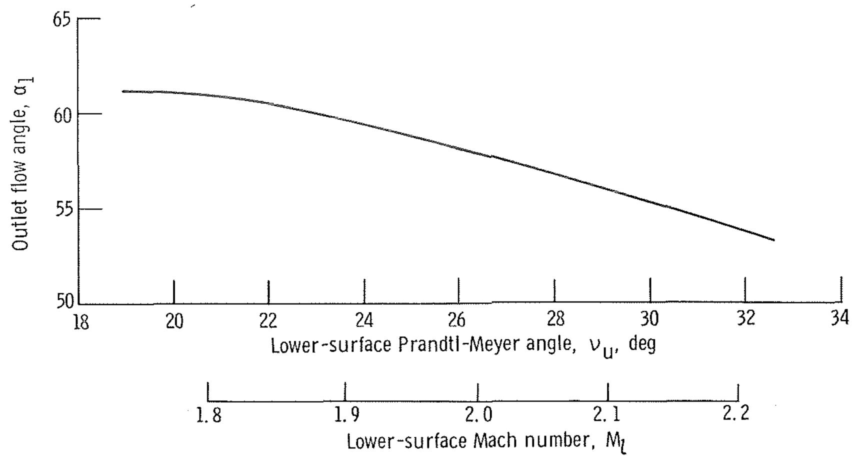


Figure 13. - Effect of lower-surface Prandtl-Meyer angle on rotor outlet flow angle for rotor blades designed for inlet Mach number of 2.5 (Upper-surface Prandtl-Meyer angle, 49°).

The aftermixing flow angles as a function of lower- and upper-surface Prandtl-Meyer angles are shown in figures 11(b) and 12(b), respectively. The corresponding blade outlet flow angles before mixing (station 1, fig. 2) are shown in figures 13 and 14. From these figures it is seen that the flow deflects away from the axial direction for the subsonic solution and deflects towards the axial direction for the supersonic solution. The deflection of the flow towards the axial direction results in further flow expansion.

The rotor total- to static-pressure ratios p_0''/p_2 as a function lower- and upper-surface Prandtl-Meyer angles are shown in figures 11(c) and 12(c), respectively. For the supersonic solution the flow expansion results in lower aftermixing static pressures

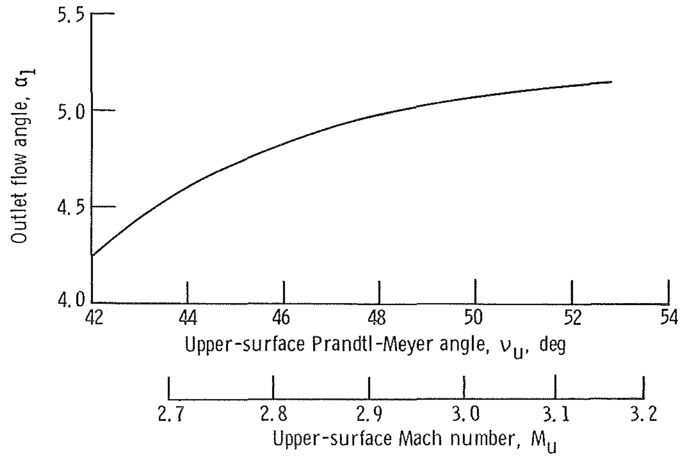


Figure 14. - Effect of upper-surface Prandtl-Meyer angle on rotor outlet flow angle for rotor blades designed for inlet Mach number of 2.5 (Lower-surface Prandtl-Meyer angle, 34°).

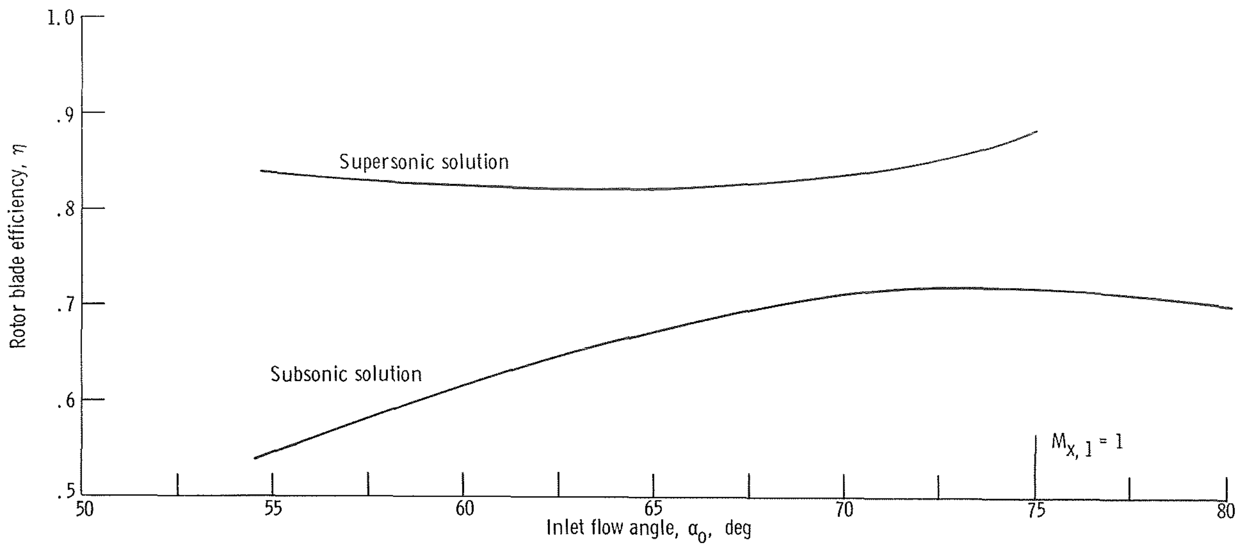


Figure 15. - Effect of inlet flow angle on rotor blade efficiency for rotor blades designed for inlet Mach number of 2.5 (Lower- and upper-surface Prandtl-Meyer angles, 25° and 49°, respectively.

p_2 than occur for the subsonic solution. Therefore, the total- to static-pressure ratio is higher for the supersonic solution than for the subsonic solution.

Effect of inlet flow angle on efficiency. - The effect of inlet flow angle on rotor blade efficiency is shown in figure 15. The lower- and upper-surface Prandtl-Meyer angles are kept constant at values of 25° and 49°, respectively. For the subsonic solution, decreasing the inlet flow angle results in a decrease in efficiency. This occurs because decreasing the inlet flow angle causes the outlet flow angle (station 1) to decrease, which results in larger oblique shock losses. For the supersonic solution, the inlet flow angle has a small effect on efficiency. The slight increase in efficiency for high inlet angle is due to the decreased mixing losses which occur as the axial Mach number approaches one.

Effect of Inlet Mach Number on Rotor Blade Efficiency

The effect of rotor inlet Prandtl-Meyer angle (or Mach number) on rotor blade efficiency is shown in figure 16 for rotor blades designed for an inlet flow angle of 70° and Reynolds number of 35 000. The maximum value of the lower- and upper-surface incompressible form factor was kept constant at a value of 2.0. As expected, increasing the inlet Mach number level results in a significant decrease in efficiency. For the subsonic solution, larger losses occur because the strength of the oblique shock increases as the Mach number at the rotor exit (station 1) increases.

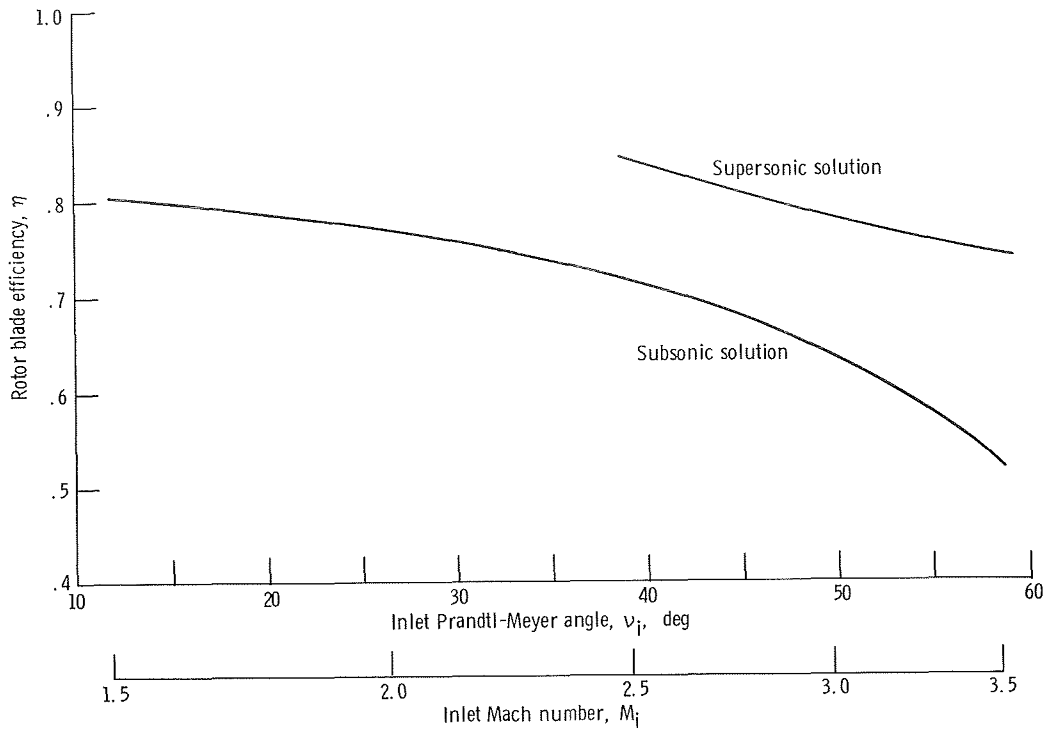


Figure 16. - Effect of inlet Prandtl-Meyer angle on rotor blade efficiency for rotor blades designed for inlet flow angle of 70° (Maximum value of lower- and upper-surface incompressible form factor, 2.0).

SUMMARY OF RESULTS

An analysis was conducted to determine the blade efficiency for two-dimensional supersonic rotor blade sections designed to produce vortex flow within the blade passage. Boundary layer characteristics were calculated and used to obtain the conditions downstream of the rotor blades after the flow had mixed to a uniform state. The boundary layer calculations were also used to give some indication as to whether flow separation could occur in the rotor. Subsonic and supersonic aftermixing axial Mach number solutions were obtained when the free-stream axial Mach number at the rotor exit (before mixing) was supersonic. The subsonic solution corresponds to mixing plus oblique shock losses, whereas the supersonic solution corresponds to shockless mixing. The effect of the lower- and upper-surface Prandtl-Meyer angles (or Mach numbers) on both blade efficiency and boundary layer separation were investigated. In addition, the effect of inlet flow angle and inlet Mach number on blade efficiencies were obtained. The following results were obtained:

1. The rotor blade efficiency increases when either the lower-surface Prandtl-Meyer angle (or Mach number) decreases or the upper-surface Prandtl-Meyer angle increases

(assuming flow separation does not occur). The tendency for boundary layer separation also increases when either the lower-surface Prandtl-Meyer angle decreases or the upper-surface Prandtl-Meyer angle increases. The optimum blade performance would, therefore, be expected to occur for rotor blades designed so that flow separation is imminent or has occurred slightly on both surfaces.

2. The rotor blade efficiency for the supersonic solution is higher than for the subsonic solution, because of the absence of shock losses in the supersonic solution. The aftermixing flow angle deflects away from the axial direction for the subsonic solution, but deflects towards the axial direction for the supersonic solution. The supersonic solution, therefore, represents further flow expansion on mixing which results in higher aftermixing Mach numbers and higher total- to static-pressure ratios than occur for the subsonic solution.

3. Decreasing the inlet flow angle results in lower rotor blade efficiencies for the subsonic solution because of increased oblique shock losses. For the supersonic solution, the inlet flow angle has a small effect on efficiency.

4. Increasing the inlet Mach number results in a significant decrease in efficiency. For the subsonic solution, larger losses occur because the strength of the oblique shock increases as the rotor exit Mach number increases.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 3, 1970,
128-31.

REFERENCES

1. Vanco, Michael R.: Thermodynamic and Turbine Characteristics of Hydrogen-Fueled Open-Cycle Auxiliary Space Power System. NASA TM X-1337, 1967.
2. Moffitt, Thomas P.: Design and Experimental Investigation of a Single-Stage Turbine with a Rotor Entering Relative Mach Number of 2. NACA RM E58F20a, 1958.
3. Moffitt, Thomas P.; and Klag, Frederick W., Jr.: Experimental Investigation of the Partial-Admission Performance Characteristics of a Single-Stage Mach 2 Supersonic Turbine. NASA TM X-80, 1959.
4. Moffitt, Thomas P.; and Klag, Frederick W., Jr.: Experimental Investigation of Partial - And Full - Admission Characteristics of a Two-Stage Velocity-Compounded Turbine. NASA TM X-410, 1960.

5. Vanco, Michael R.; and Goldman, Louis J.: Computer Program for Design of Two-Dimensional Supersonic Nozzle with Sharp-Edged Throat. NASA TM X-1502, 1968.

6. Goldman, Louis J.; and Scullin, Vincent J.: Analytical Investigation of Supersonic Turbomachinery Blading. I - Computer Program for Blading Design. NASA TN D-4421, 1968.

7. Goldman, Louis J.; and Vanco, Michael R.: Analytical Investigation of Two-Dimensional Loss Characteristics of Supersonic Turbine Stator Blades. NASA TM X-1823, 1969.

8. McNally, William D.: Fortran Program for Calculating Compressible Laminar and Turbulent Boundary Layers in Arbitrary Pressure Gradients. NASA TN D-5681, 1970.

9. Sasman, Philip K.; and Cresci, Robert J.: Compressible Turbulent Boundary Layer with Pressure Gradient and Heat Transfer. AIAA J., vol. 4, no. 1, Jan. 1966, pp. 19-25.

10. Stewart, Warner L.: Analysis of Two-Dimensional Compressible-Flow Loss Characteristics Downstream of Turbomachine Blade Rows in Terms of Basic Boundary-Layer Characteristics. NACA TN 3515, 1955.

11. Stewart, Warner L.; Whitney, Warren J.; and Wong, Robert Y.: Use of Mean-Section Boundary-Layer Parameters in Predicting Three-Dimensional Turbine Stator Losses. NACA RM E55L12a, 1956.

12. Schlichting, Hermann (J. Kestin, trans.): Boundary-Layer Theory. Sixth ed., McGraw-Hill Book Co., Inc., 1968.

13. Schlichting, H.: Application of Boundary-Layer Theory in Turbomachinery. J. Basic. Eng., vol. 81, no. 4, Dec. 1959, pp. 543-551.

14. Goldman, Louis J.: Analytical Investigation of Supersonic Turbomachinery Blading. II - Analysis of Impulse Turbine-Blade Sections. NASA TN D-4422, 1968.

NASA-Langley, 1970 —— 1 E-5532

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