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Incidence Loss for Fan Turbine Rotor Blade in Two-Dimensional Cascade

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Scientific and Technical
Information Branch

Summary

The effect of incidence angle on the aerodynamic performance of a fan turbine rotor blade was investigated experimentally in a two-dimensional cascade. The test covered a range of incidence angles from $-15°$ to $10°$ and exit ideal critical velocity ratios from 0.75 to 0.95. The principal measurements were blade-surface static pressures and cross-channel surveys of exit total pressure, static pressure, and flow angle. Flow adjacent to the surface was examined using a visualization technique.

The shape of the inlet portion of the blade-surface velocity distribution changed significantly at large incidence angles. At the design exit velocity ratio of 0.877, the kinetic energy loss coefficient was lowest at 0° incidence and amounted to 0.027. This loss coefficient varied from 0.038 at $-15°$ incidence to 0.044 at 7° incidence. At higher values of positive incidence, losses increased dramatically to nearly 0.150 at 10° incidence.

Incidence losses for the subject fan turbine blade with sharp leading edges were markedly higher than the losses from a reference core turbine blade having blunt leading edges.

Introduction

The trend in commercial turbofan engines toward higher bypass ratios has resulted in higher turbine inlet temperatures and pressures and lower flows than in the previous generation of engines. Consequently, there is now a marked difference in the geometry of the core and fan turbines. The core turbine has low aspect ratios and thick blades with blunt leading edges to accommodate cooling. The fan turbine has higher aspect ratios and, since little or no cooling is required, the blading can be thin with sharp leading edges.

Radial variation in work and flow is commonly used to accommodate high loading and to minimize secondary flow losses in both turbines. This results in a radial variation in exit flow angle which can lead to incidence losses in succeeding blade rows if they are not designed to accept the variation in the flow field. The methods available in the literature for estimating incidence loss fall into two general categories. The first of these is based on the assumption that the component of blade inlet flow velocity normal to the minimum loss flow vector is lost. References 1 to 3 utilize variations of this method. The second is based on correlations of cascade data. Ainley and Mathieson (ref. 4) is a good example.

Typical core and fan turbine blades have been tested at Lewis Research Center in a two-dimensional cascade to determine the effect of incidence on loss. Both tests were for a range of incidence angles and exit Mach numbers. The results of the core turbine blade test were reported in reference 5. The relative loss of that blade (the ratio of kinetic energy loss with incidence to kinetic energy loss without incidence) was 1.17 at $-15°$ incidence and 1.22 at 15° incidence. These results agree fairly well with the method of Ainley and Mathieson. Losses calculated assuming that the normal component of inlet velocity was lost were much higher. The relative insensitivity of this blade to loss with incidence was attributed to its blunt leading edge.

This report presents the results of a fan turbine blade test. The blade selected for test was from the first stage of a 4½ stage fan turbine designed by an engine company and tested at Lewis Research Center (refs. 6 to 8). The 25-percent span section of this blade was selected for test because the operating conditions were judged to be the most severe. The test blade was 2× scale to facilitate pressure tap installation. The blade was tested in the same cascade as the core turbine blade of reference 5. The test covered a range of incidence angles from $-15°$ to $10°$ and exit ideal critical velocity ratios from 0.75 to 0.95. The principal measurements were blade-surface static pressure and cross-channel surveys of exit total pressure, static pressure, and flow angle. The results include blade-surface velocity distribution and overall performance in terms of kinetic energy loss coefficients for the incidence angles and exit velocity ratios investigated. The losses are also compared to the results of the core turbine blade of reference 5 and with two common methods of predicting incidence loss.

Symbols

a	distance along axial chord from leading edge, cm
C_a	blade axial chord, cm
e	kinetic energy loss coefficient, $1-(V/V_{id})^2$
Δe_{V_1}	loss coefficient due to variation in inlet velocity
i	incidence angle, deg from design flow angle
S	blade spacing, cm
V	velocity, m/sec
β	flow angle, deg

Subscripts:

cr	flow condition at Mach 1
i	incidence angle
id	ideal or isentropic process
1	station at blade inlet
2	station at blade exit survey plane
3	station downstream of survey, where mixing is complete and flow conditions are uniform

Apparatus and Procedure

Blades and Cascade Tunnel

The blade configuration tested was the 25-percent span section of the first-stage rotor of a 4½ stage fan turbine (described in ref. 6). The velocity diagrams for this section (predicted by the three-dimensional design program in ref. 6) are presented in figure 1 for reference. The test configuration was 2× size to facilitate pressure tap installation. The profile coordinates, flow channel, and instrumentation locations are shown in figure 1.

A cascade of nine blades was tested. Blade length was 10.16 centimeters. Figure 2 shows the cascade tunnel installed in the test cell. In operation, room air was drawn through the cascade tunnel, the blading, and an exhaust control valve into the laboratory exhaust system. Suction slots on the tunnel side (blade end) walls just upstream from the blades were used to remove the boundary layer. The incidence angle was set by positioning the top and bottom walls of the tunnel inlet at the desired free stream flow angle.

The blades were tested over a range of incidence angles from $-15°$ to $10°$ and exit ideal critical velocity ratios from 0.75 to 0.95.

Instrumentation

Surface static pressure taps were installed at midspan on the suction and pressure surfaces of the center blade of the cascade. The location of these taps is indicated in figure 1.

The total pressure, static pressure, and flow angle of the flow leaving the center blade of the cascade were surveyed with the combination probe shown in figure 3. The survey was made in the tangential direction, 1.27 centimeters downstream from the blade trailing edge, and at midspan at a speed of approximately 2.5 centimeters per minute. The probe senses total pressure with a square-ended 0.051-centimeter-diameter tube, static pressure with a 15° included angle wedge, and flow angle with two tubes cut at 45°. Pressure and angle corrections were determined in a calibration facility over a range of flow velocities and flow angles.

The three probe sensors and the probe position sensor were sampled every 0.01 centimeter of the survey. The temperature and pressure of the room air entering the tunnel were sampled every tenth survey sampling and averaged.

Data Reduction

Cascade inlet total pressure was used with blade-surface static pressure to calculate an ideal blade-surface critical velocity ratio $(V/V_{cr})_{id}$ at each pressure tap location. Survey probe readings were corrected as indicated by calibration. At the cascade exit, station 2, mass flow, axial and tangential momentum, and static pressure were integrated across the center blade wake for a distance of one blade pitch. The continuity and conservation of momentum and energy relations were then used to calculate flow angle, velocity, and pressure at a hypothetical location where these flow conditions are uniform. This location was designated station 3. For

Blade coordinates

x	Y_L	Y_u
0.000	1.222	1.222
.010	-----	1.250
.140	1.181	-----
.188	1.252	1.643
.376	1.445	1.969
.564	1.565	2.230
.752	1.638	2.438
.940	1.679	2.598
1.128	1.697	2.718
1.316	1.694	2.797
1.504	1.674	2.837
1.692	1.636	2.845
1.880	1.580	2.812
2.068	1.511	2.746
2.256	1.425	2.639
2.444	1.323	2.492
2.632	1.201	2.299
2.820	1.064	2.055
3.008	.902	1.750
3.196	.714	1.379
3.384	.488	.955
3.572	.206	.493
3.688	-.015	-----
3.757	-----	.013
3.760	0.000	0.000

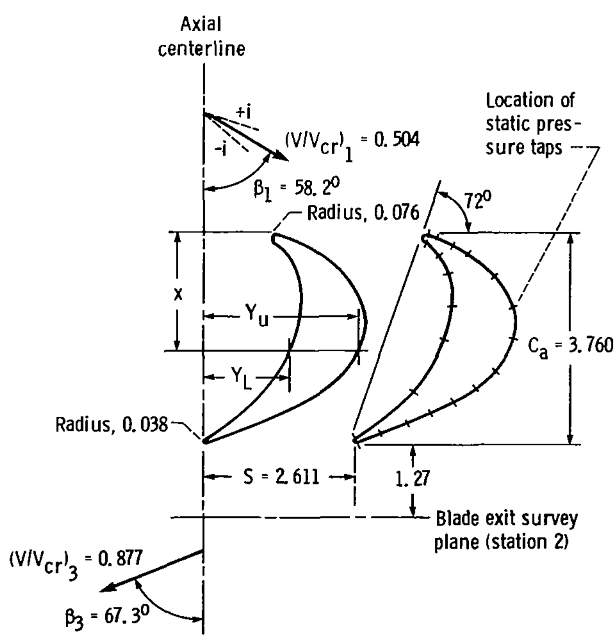


Figure 1. - Rotor blade geometry. (All linear dimensions are in cm.)

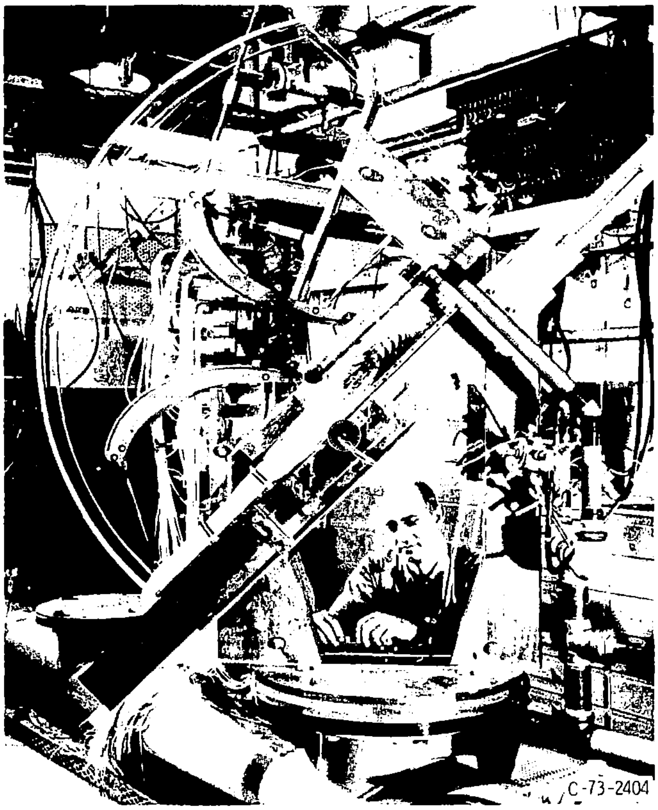


Figure 2. - Cascade tunnel.

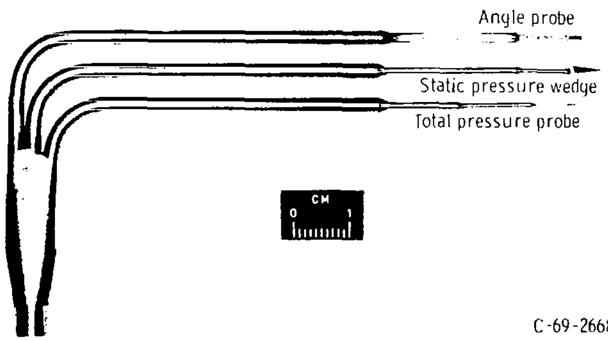


Figure 3. - Combination exit survey probe.

these calculations, a constant area process and conservation of the tangential component of momentum were assumed between the survey station 2 and station 3. The details of these calculations are given in reference 9.

Flow Visualization

A visualization technique was used to examine flow adjacent to the blades and endwalls. This involved coating the surfaces with a fluid containing particles of a material which fluoresces under ultraviolet light and thus indicates the pattern of the adjacent flow. The coating was applied to all surfaces of the center blade and to both endwalls in the adjacent areas. Fluorescence patterns were photographed.

Results and Discussion

In this section, the overall performance of the fan turbine rotor blade as determined in a two-dimensional cascade is presented for a range of incidence angles from −15° to 10° and exit velocity ratios from 0.75 to 0.95. Also, the losses due to incidence are compared with the results obtained from a previous core turbine blade test and the estimated losses from two prediction methods.

Blade Surface Velocity Distribution

The variation in predicted and experimental velocity distributions on the blade surface is shown in figure 4 for a 0° blade inlet incidence angle. The solid-line variation was taken from the design report (ref. 6). The design blade shape was then used as input to the in-house prediction code TSONIC (ref. 10) and resulted in the dashed curve of figure 4. The experimental points shown were determined from static pressure measurements obtained at the design exit critical velocity ratio of 0.877. The results show that the cascade operated with surface loading very close to design at design exit velocity ratio and 0° incidence. The surface velocity distribution and blade loading are typical of a reaction (accelerating) blade row.

Figure 5 shows the change in surface velocity at incidence angles of −15°, 0°, 7°, and 10°. The effect on blade loading for incidence angles of −15°, 0°, and 7° is

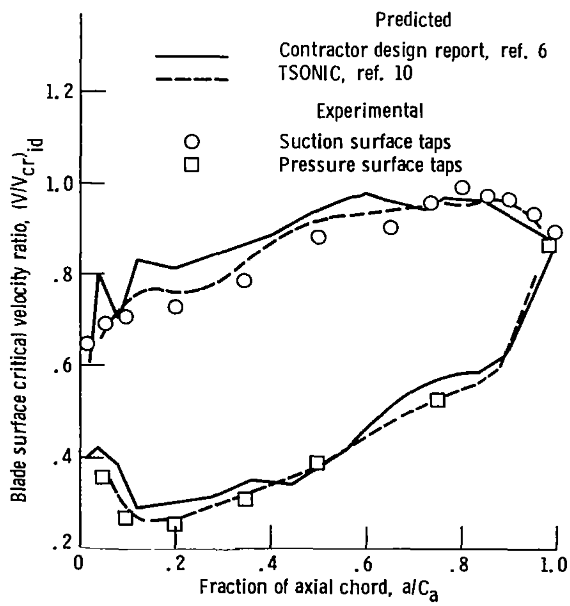


Figure 4. - Comparison of predicted and experimental blade surface velocities at design exit velocity ratio.

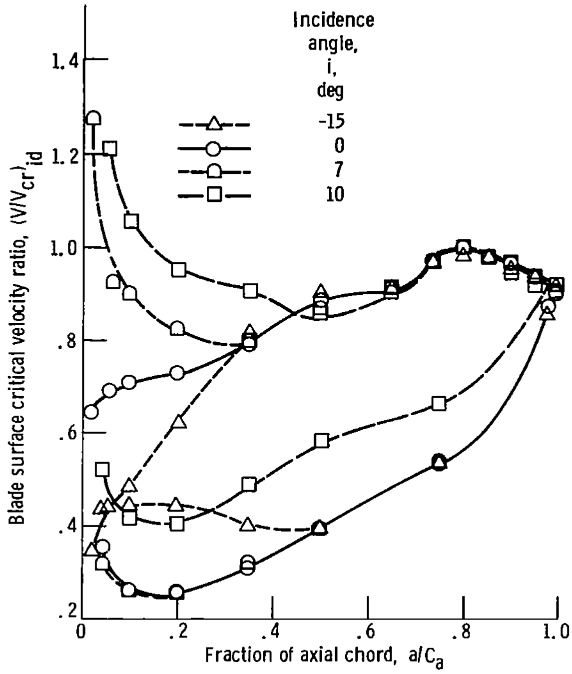


Figure 5. - Comparison of blade surface velocities at approximately design exit velocity ratio for incidence angles of -15°, 0°, 7°, and 10°.

considerable for the first 40 percent of axial chord and is caused by both changes in incidence angle and blade inlet velocity. The blade inlet velocity changed because of the method of varying cascade incidence angles. In the cascade test, incidence angle was varied by changing the angle of the wooden tunnel inlet walls (see fig. 2). This caused an increase in inlet velocity with increasing incidence angle. The effect of the change in inlet velocity on loss is discussed further in the section on kinetic energy losses.

At a 10° incidence angle, figure 5 indicates that the velocity level along the entire pressure surface of the blade was higher than design. The results obtained at a 10° incidence angle are therefore felt to be questionable because of probable flow separation.

Figure 5 shows that positive incidence resulted in increased loading and rapid diffusion on the leading portion of the suction surface due to both an increase in inlet velocity and required additional turning. Negative incidence resulted in decreased loading on the inlet portion of the blade. In fact, for the −15° distribution shown, a negative (opposite to rotation) force existed over the front 5 percent of the blade. The latter 60 percent of the blade was largely unaffected by incidence change. Very similar results were obtained for the core turbine of reference 5. Incidence loss effects were thus caused by local flow changes near the leading-edge region of the blades, as would be expected.

Kinetic Energy Loss Coefficients

The variation in measured kinetic energy loss coefficients for the exit velocity ratios and incidence angles tested is shown in figure 6. For each incidence

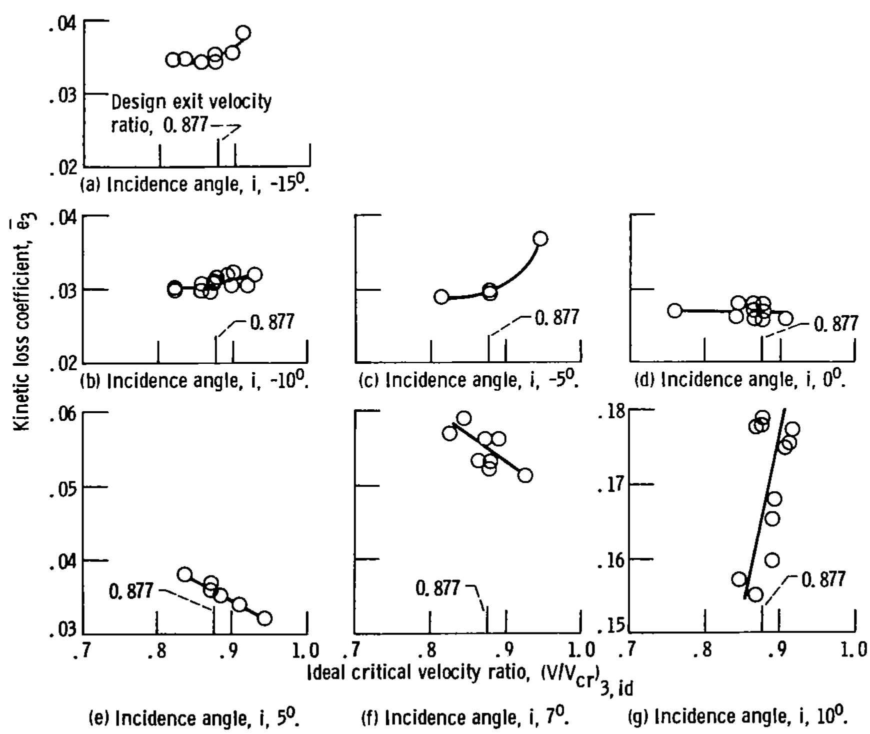


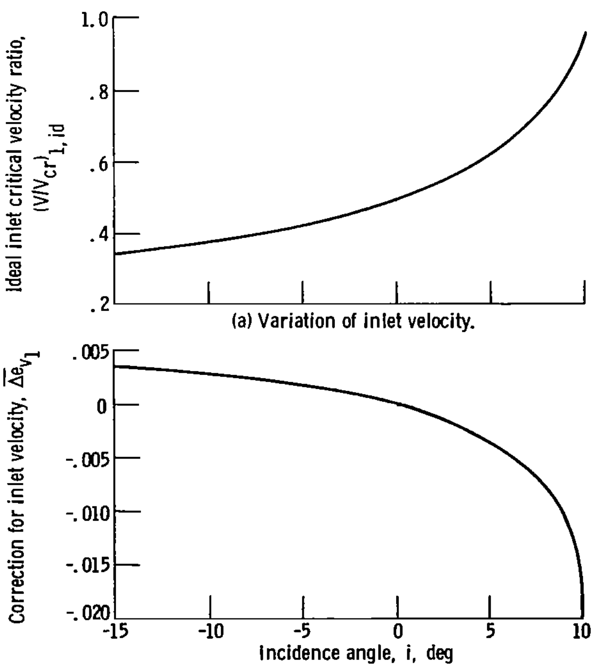
Figure 6. - Overall loss as function of incidence angle and critical velocity ratio.

angle tested, the design exit velocity ratio of 0.877 is indicated by a tick mark. The lowest losses occur at 0° incidence (fig. 6(d)). The scatter in loss coefficient data at 0° incidence ranges from 0.026 to 0.028. An averaging curve was drawn through the data at a constant value of 0.027 over the range of exit velocity ratios tested. There is a large scatter of data at 10° incidence, ranging from a loss coefficient of about 0.15 to 0.18. However, at this level of positive incidence, the loss curve is nearly vertical. Figure 6 indicates a decrease in loss with velocity ratio at incidence angles of 5° and 7°. The reason for this is not known, but additional tests showed the data to be repeatable.

The measured loss differences of figure 6 include both the effect of incidence angle and also the effect of the change in inlet velocity resulting from moving the inlet walls to vary incidence. In order to isolate and show the effect of incidence angle on loss, values were taken from figure 6 at the design exit velocity ratio of 0.877 (indicated by tick marks on the figure) and corrected for inlet velocity. The corrections were made as follows. The variation in ideal inlet velocity with incidence change was calculated from continuity and is shown as figure 7(a). Inlet velocity increased with increasing incidence angle. The loss corrections were then made by assuming that frictional loss within a blade row is proportional to the average kinetic energy across the blade row (ref. 11). The loss proportionality factor was determined from the data at 0° incidence and applied to other incidence angles. The resulting loss corrections are shown in figure 7(b). These corrections are then added to the measured data from figure 6. The correction is less than −0.005 at incidence angles less than 6° and increases sharply to almost −0.020 at a 10° incidence.

The variation of corrected overall loss with incidence angle at design exit velocity is shown in figure 8. The overall loss varied from 0.038 at −15° incidence, to 0.027 at 0° incidence, and 0.044 at 7° incidence. At higher values of positive incidence, losses increased dramatically to a value of about 0.145 at 10°.

The most significant result from figure 8 is the extreme sensitivity of loss for this blade to positive incidence angles. This sensitivity stresses the need for an accurate knowledge of the three-dimensional flow field through multistage turbines with sharp leading-edge blade rows. For example, the subject fan turbine blade is the 25-percent span section of the first-stage blade of the 4½ stage fan turbine described in references 6 to 8. The overall efficiency of this turbine was less than design. Unpublished flow angle data were taken behind each stage during the 4½ stage testing. The data taken behind the first-stage blade at the 25-percent span (the profile used for subject study) indicated there would be about 7° of incidence at the inlet of the following blade row. The cumulative effect could have been a significant part of the lower than design efficiency results (ref. 7).



(b) Loss correction.

Figure 7. - Loss correction due to variation in inlet velocity with incidence change at design exit velocity ratio of 0.877.

Flow Along Surfaces

A photograph of the flow pattern adjacent to the rear portion of the suction surface of the fan blade is shown in figure 9. The pattern entering the field of view from

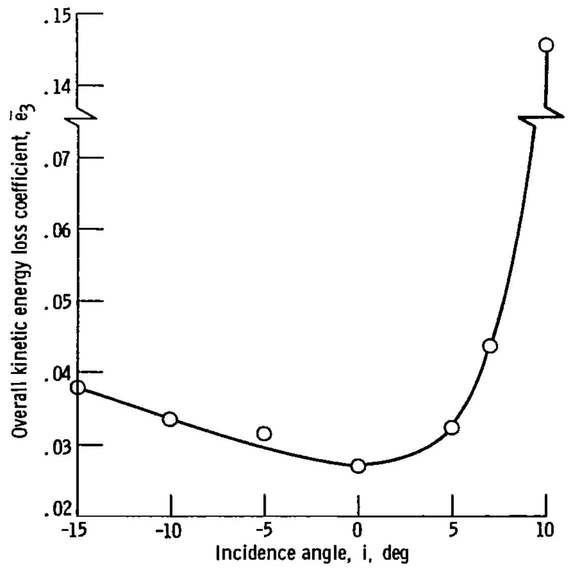


Figure 8. - Effect of incidence angle on loss for subject fan turbine blades at design exit velocity ratio of 0.877.

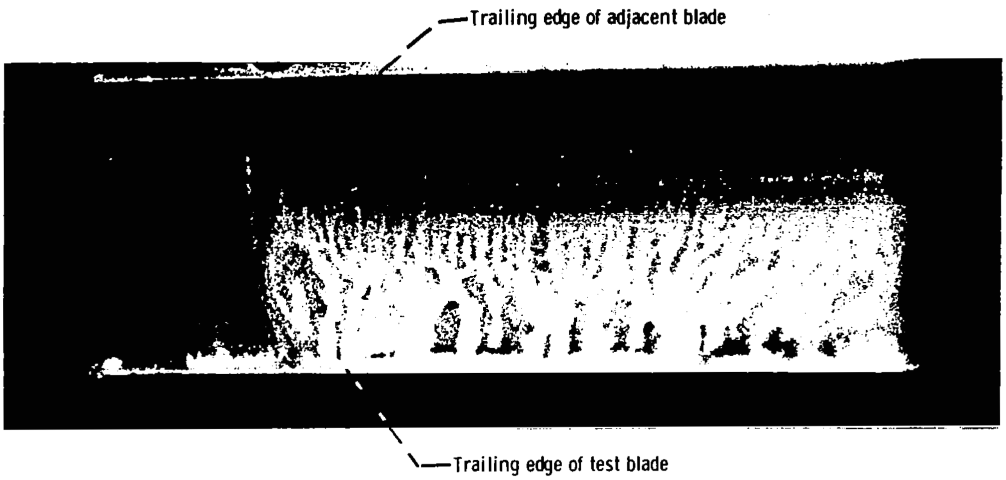


Figure 9. - Flow visualization pattern on aft portion of suction surface at 0^0 incidence and design blade exit flow.

upstream is typical of the pattern also seen on the forward portions of the pressure and suction surfaces. It is characterized by fine, uniformly spaced chordwise lines which indicate that the adjacent flow has high velocity and is strongly oriented parallel to the tunnel walls. Just downstream of the physical throat the pattern changes. The fluid is clustered in thick globs with little overall orientation, characteristic of very low velocity flow. Evidently, the high velocity strongly oriented main flow has moved from the surface. The pattern change occurs where the flow velocity indicated by the blade surface static pressures is nearly sonic. Possibly a weak shock wave at this point on the blade surface triggers a flow change.

The flow pattern on the suction surface front and rear and the pressure surface front did not change over the range of incidence angles from $-10°$ to $10°$ and blade exit flow rates from design to 110 percent of design. The possibility that the high loss at 10° incidence is due to separation of the flow from the forward position of the suction surface was not supported by the flow visualization results which showed no flow irregularity at 10° incidence and no change in the flow pattern between 10° incidence and the lower loss incidences of 5° and 0°.

Comparison of Results with Core Turbine Blade

The variation of incidence loss (i.e., the difference between loss with incidence and loss at zero incidence) with incidence angle for the fan turbine blade and the core turbine blade of reference 5 is shown in figure 10. Sketches of the two blades as tested in cascades with the dimensions of the leading edge are also shown in this figure.

The most significant difference in the performance of these two blades is the relative insensitivity of the blunt leading edge core turbine blade to positive incidence.

Incidence loss increases slowly with positive incidence for the core turbine blade to a value of 0.008 at 15°. For the fan turbine blade, incidence loss increases very rapidly with positive incidence, as previously discussed. At 7° the loss is 0.017. Both blades performed well with negative incidence. Both blades also have an incidence loss at $-5°$ which is higher than the curves drawn through the data. This seems to indicate that there may be a step increase in loss at small negative incidence angles. The possiblity that this loss increase might be due to separation of flow from the pressure surface near the leading edge is not supported by the flow visualization results which showed no flow irregularity and no change in the pattern.

The incidence loss of both blades is compared with two common methods of predicting incidence loss in figure 11. These methods are (1) assuming that the component

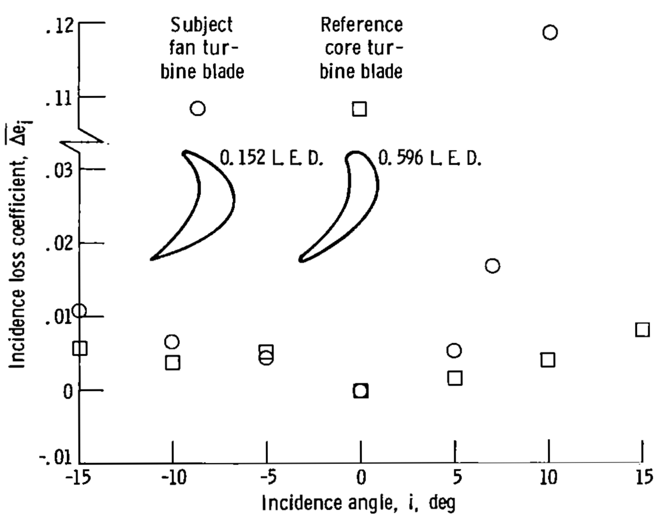
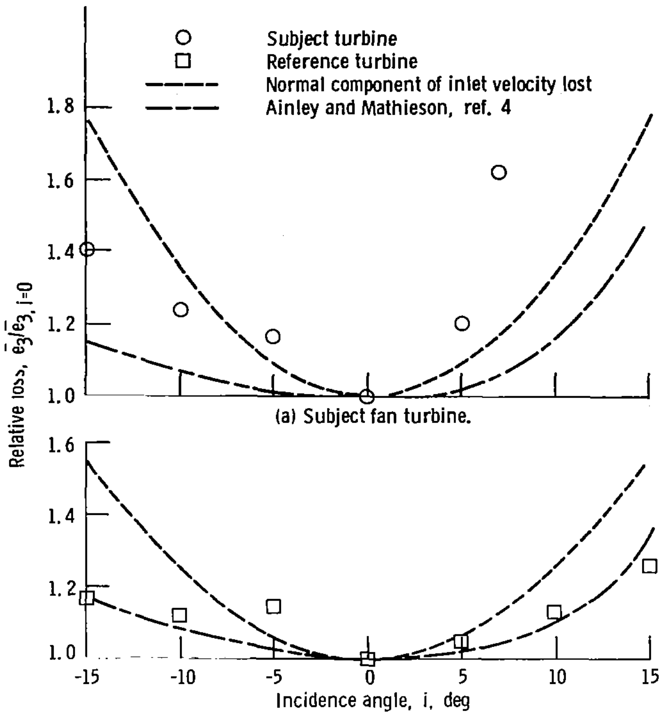


Figure 10. - Comparison of incidence loss between subject fan turbine blade and reference core turbine blade.



(b) Reference core turbine.

Figure 11. - Comparison of experimental data with theory for subject fan and reference core turbine blades.

of inlet velocity normal to the design blade inlet flow vector is lost, and (2) the method of reference 4. In figure 11, the ratio of loss with incidence to loss at 0° incidence is shown for incidence angles from −15° to 15°.

Neither method predicts the performance of the fan turbine blade at off-design incidence very well. Losses calculated according to reference 4 are lower than measured losses at all incidence angles. Losses calculated by assuming the normal component of the inlet velocity is lost are higher than measured losses for negative incidence and lower than measured losses for positive incidence. This method predicted losses which were too high for the core turbine blade at all incidence angles. The method of reference 4, however, predicted losses which agreed very well with the experimental results for the core turbine blade over the range of incidence angles investigated.

Summary of Results

The aerodynamic performance of a fan turbine rotor blade was investigated experimentally in a two-dimensional cascade. The blade was tested over a range of incidence angles from −15° to 10° and exit critical velocity ratios from 0.75 to 0.95. The results of this investigation are summarized as follows:

1. The overall kinetic energy loss of the fan turbine blade tested was very sensitive to positive incidence. The overall loss coefficient varied from 0.038 at −15° incidence, to 0.027 at 0° incidence, to 0.044 at 7° incidence. At higher values of positive incidence, losses increased dramatically to a value of nearly 0.150 at 10° incidence.
2. Incidence losses for the sharp leading-edge fan turbine blades were markedly higher than the losses from a reference core turbine blade having blunt leading edges.
3. Incidence angle had a considerable effect on the blade surface velocity distributions over the first 40 percent of axial chord for negative incidence and positive incidence angles up to 7°. For 10° incidence, the effect was over the entire surface of the blade. Positive incidence resulted in increased loading and rapid diffusion on the leading-edge portion of the suction surface due both to an increase in inlet velocity and to the required additional turning.

Concluding Remarks

The results of this study lead to several observations that can be made relative to the design of multistage fan drive turbines:

1. The extreme sensitivity of loss to positive incidence angles makes it prudent to design the blade to operate at design point with some negative incidence angle at the blade inlet. The amount, which could be as high as 7°, would depend on the confidence in the three-dimensional design code used to predict flow fields and the degree of anticipated off-design turbine operation.
2. The magnitude of the losses involved stresses the need for an accurate knowledge of the three-dimensional flow field through multistage turbines. This is particularly applicable to the present trend toward large radial flow angles and work gradients used to minimize endwall losses and secondary flows.
3. From an incidence loss standpoint, it appears desirable to design both fan and core turbines with relatively blunt leading edges to avoid the bulk of incidence loss problems.

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National Aeronautics and Space Administration
Cleveland, Ohio, March 21, 1983

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15. Supplementary Notes

16. Abstract

The effect of incidence angle on the aerodynamic performance of a fan turbine rotor blade was investigated experimentally in a two-dimensional cascade. The test covered a range of incidence angles from -15° to 10° and exit ideal critical velocity ratios from 0.75 to 0.95. The principal measurements were blade-surface static pressures and cross-channel surveys of exit total pressure, static pressure, and flow angle. Flow adjacent to surfaces was examined using a visualization technique. The results of the investigation include blade-surface velocity distribution and overall kinetic energy loss coefficients for the incidence angles and exit velocity ratios tested. The measured losses are compared with those from a reference core turbine rotor blade and also with two common analytical methods of predicting incidence loss.

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