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**INCIDENCE LOSS FOR  
A CORE TURBINE ROTOR BLADE  
IN A TWO-DIMENSIONAL CASCADE**

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# INCIDENCE LOSS FOR A CORE TURBINE ROTOR BLADE IN A

## TWO-DIMENSIONAL CASCADE

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### SUMMARY

The effect of incidence angle on the aerodynamic performance of an uncooled core turbine rotor blade was investigated experimentally in a two-dimensional cascade. The cascade test covered a range of incidence angles from  $-15^{\circ}$  to  $15^{\circ}$  in 5-degree increments and a range of pressure ratios corresponding to ideal exit critical velocity ratios of 0.6 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 shape of the inlet portion of the blade-surface velocity distribution changed significantly at large incidence angles. This effect was confined to the first 30 percent of the blade axial chord. At an ideal exit critical velocity ratio of 0.7, kinetic energy loss for all nonzero incidence angles was higher than it was for zero incidence. The highest loss occurred at a positive incidence of  $15^{\circ}$ .

The results of two methods of estimating incidence loss were compared to the measured loss. Estimated losses based on the assumption that the normal component of the inlet velocity is lost were generally too high. Losses estimated according to the method of Ainley and Mathieson were in generally good agreement with the measured loss.

### INTRODUCTION

The NASA Lewis Research Center has been involved in investigations of the performance of turbine blading for advanced aircraft engines. The high-bypass-ratio turbofan is one of these advanced engines. This engine has a multistage fan drive turbine and a high-speed, high-pressure, high-temperature core engine. The core engine turbine is characterized by short blade heights (high hub-tip radius ratio) and comprehensive cooling to cope with very high turbine inlet temperatures. The complicated and difficult to manufacture cooling provisions make it desirable to use constant-section, untwisted

blades in a core engine turbine. A constant-section, untwisted blade is feasible because of the high hub-tip radius ratio.

However, the use of a constant-section, untwisted blade can result in lower turbine efficiency. In a recent investigation at Lewis, a half-size scale-model core turbine was tested with both constant-section untwisted rotor blades and twisted blades designed for free-vortex flow. The results of this investigation were reported by Szanca (ref. 1). The efficiency of the turbine with the untwisted blades was about 1 percent lower than the efficiency of the turbine with the more conventional twisted blades. Other results of this investigation indicated that the turbine with the twisted rotor blades operated with a much smaller range of incidence angles than did the turbine with the untwisted rotor blades. The difference in turbine performance was attributed to the large difference in incidence encountered by the two types of rotor blading.

The methods of estimating loss due to rotor incidence fall into two general categories. The first of these is based on the assumption that the component of rotor inlet velocity normal to the design angle represents a loss. References 2 to 4 present variations of this method. The second method is based on correlations of cascade data. Ainley and Mathieson (ref. 5) is a good example. However, the blunt-leading-edge blades used in core engine turbines may be less sensitive to incidence than these methods would predict.

Accordingly, a representative core turbine rotor blade was tested in a two-dimensional cascade to determine the effect of incidence on loss. This blade was a full-size version of the constant-section untwisted rotor blade used in the investigation of reference 1.

The cascade test covered a range of incidence angles from  $-15^{\circ}$  to  $15^{\circ}$  in 5-degree increments. The principal measurements were blade-surface static pressures and cross-channel surveys of exit total pressure, static pressure, and flow angle. These data were taken over a range of ideal exit critical velocity ratios from 0.6 to 0.95 for each incidence angle. The results of the investigation include blade-surface velocity distribution and overall performance in terms of weight flow and loss for the range of incidence angles and exit velocity ratios investigated. The measured losses are also compared with two common methods of predicting incidence loss.

## SYMBOLS

a	distance along axial chord from leading edge, cm
$C_a$	blade axial chord, cm
$\bar{e}_3$	kinetic energy loss coefficient, $1 - (V_3/V_{id,3})^2$
i	incidence angle, deg
2	

P	absolute pressure, $\text{N/cm}^2$
S	blade spacing, cm
V	velocity, m/sec
w	flow rate per unit blade span, $\text{kg}/(\text{sec})(\text{cm})$
$\alpha$	flow angle, deg
$\delta$	ratio of inlet total pressure to U.S. standard sea-level atmospheric pressure, $P_1'/10.132 \text{ N/cm}^2$
$\sqrt{\theta}_{\text{cr}}$	ratio of inlet critical velocity to critical velocity of U.S. standard sea-level air, $V_{\text{cr}, 1}/310.6 \text{ m/sec}$

Subscripts:

cr	flow conditions at Mach 1
id	ideal or isentropic process
1	station at blade inlet
2	station at blade exit survey plane
3	station at blade exit where flow conditions are assumed uniform

Superscripts:

'	total state conditions
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## APPARATUS AND PROCEDURE

### Blades and Cascade Tunnel

The shape and relative position of the test blades in the cascade are shown in figure 1. The blade coordinates, the velocity diagrams relative to the blade, and the location of the instrumentation are also shown in this figure. These blades are thick and have blunt leading edges to accommodate cooling air. The blade profiles used in the cascade test were full-size versions of the rotor blade mean radius profiles used in the turbine investigation of reference 1.

The blades were tested in a two-dimensional cascade of eight blades. This cascade had a blade span of 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 the exhaust control valve into the laboratory exhaust system. Boundary-layer suction slots on the inlet end walls a short distance upstream of the blade leading edges were used to remove the inlet boundary layer.

The blades were tested over a range of inlet-total- to exit-static-pressure ratios corresponding to ideal exit critical velocity ratios of about 0.6 to 0.95 and over a range of incidence angles from  $-15^{\circ}$  to  $15^{\circ}$  in 5-degree increments. The incidence angle was varied by changing the angle of the cascade tunnel inlet sidewalls. These walls are shown set at the design angle (zero incidence) in figure 2.

### Instrumentation

The two blades that formed the center channel in the eight-blade cascade were instrumented at midspan with static-pressure taps. The location of these taps is shown in figure 1. The cascade tunnel also had wall static-pressure taps in the exit section. These taps were used to set the exit static pressure. The blade surface and wall static pressures were measured with mercury-filled manometers. The pressure data were recorded by photographing the manometer board.

The blade-to-blade variations of exit total pressure, static pressure, and flow angle were surveyed simultaneously with the rake shown in figure 3. The total pressure was measured with a simple square-ended probe. The static pressure was measured with a wedge probe that had an included angle of  $15^{\circ}$ . The angle probe was a two-tube type with the tube ends cut at  $45^{\circ}$ . The probe measures a differential pressure which is related to flow angle. Strain-gage transducers were used to measure these pressures.

The survey rake was installed in the cascade with the rake stem parallel to the blade trailing edges. The sensing elements of the rake were aligned with the design flow angle and fixed. This angle was not changed during the surveys. The sensing elements were located at the mid-span region of the blade with the element tips at the survey plane, station 2 in figure 1. Station 2 was 18.5 percent of the blade axial chord axially downstream of the blade trailing edges. The rake was traversed tangentially over a distance of about two blade spaces behind the blades bounding the center channel of the eight-blade cascade. The traverse speed was about 2.5 centimeters per minute. An actuator-driven potentiometer was used to provide a signal proportional to rake position. The output signals of the three pressure transducers and the rake position potentiometer were recorded on magnetic tape. The recording rate was 20 words per second.

### Data Reduction

Blade-surface static pressures were taken from the photographs of the manometer board. These data were used to calculate the blade-surface velocity ratios. A computer was used to reduce the blade exit survey data recorded on magnetic tape. These flow angle and pressure data were used to calculate the velocity, mass flow, and tan-

gential and axial components of momentum as a function of rake position. These quantities were then integrated numerically over a distance equal to one blade space to obtain overall values at the plane of the rake, station 2. The continuity and conservation of momentum and energy relations were then used to calculate the flow angle, velocity, and pressures at a hypothetical location where the flow conditions were assumed to be uniform. This location is designated station 3. For these calculations, a constant-area process and conservation of the tangential component of momentum were assumed between stations 2 and 3. The details of these calculations are given in reference 6.

## RESULTS AND DISCUSSION

In this section, the overall performance of the core turbine rotor blade as determined in a two-dimensional cascade is presented for the range of incidence angles and exit velocity ratios investigated. Also, the loss due to incidence is compared with two common methods of estimating incidence loss.

### Overall Performance

Blade-surface velocity distribution. - Blade-surface velocity ratios for incidence angles of  $0^\circ$ ,  $-15^\circ$ , and  $15^\circ$  are plotted against the fraction of axial chord in figure 4. These velocity ratios were calculated from blade-surface static-pressure measurements. The data shown are for an ideal exit critical velocity ratio near design.

The velocity distribution for zero incidence is typical for a reaction (accelerating) blade row. The velocity distributions for large positive or negative incidence angles are radically different, but on the inlet section of the blade only. Incidence affects the blade-surface velocities only to about 30 percent of axial chord. For large positive incidence ( $15^\circ$  and  $10^\circ$ ), there is a rapid diffusion from very high velocities on the suction surface near the leading edge. For large negative incidence ( $-15^\circ$  and  $-10^\circ$ ), the velocity on the pressure surface near the leading edge is higher than it is on the suction surface. That is, there is a negative tangential force, opposing blade rotation, on the first 7 to 8 percent of the axial chord. For incidence angles of  $-5^\circ$  and  $5^\circ$ , the velocity distributions were similar to those at zero incidence. The velocities near the leading edge were higher or lower than for zero incidence depending on whether the incidence was positive or negative, respectively. But there were no velocity peaks and large diffusions or regions of negative tangential force.

The area enclosed between the pressure- and suction-surface velocity curves shown in figure 4 is an indication of the blade loading. In figure 4, the loading for positive incidence is much higher than it is for negative incidence. This occurs because the flow

is turned more and the inlet velocity is higher for positive incidence than it is for negative incidence.

In the cascade test, incidence angle was varied by changing the angle of the tunnel inlet walls. This caused an increase in inlet velocity with incidence angle. This change in inlet velocity affects both blade loading and loss and is discussed further in the section on the comparison of losses. The cascade test simulates turbine operation at off-design speed or pressure ratio where incidence changes are caused by changes in the velocity diagrams.

In the turbine test of reference 1, however, differences in incidence angles occurred because the blade geometry was different. The velocity diagrams were essentially the same for the twisted and untwisted blades. Thus, the blade loading at a given radius must also be the same even though the incidence angles were much different for the two types of blades.

Because of these differences, no direct comparison of blade loading between the turbine test of reference 1 and the cascade tests can be made. Qualitatively, however, the shape of the blade-surface velocity distribution on an untwisted blade in a turbine, such as in reference 1, would be similar to those shown in figure 4. But the level of the velocity over the first 30 percent of the axial chord would be different, depending on the level of the inlet velocity.

Equivalent weight flow. - Data for all incidence angles investigated are plotted against ideal exit critical velocity ratio in figure 5(a). The curve is drawn through the data for zero incidence. The equivalent flows for other incidence angles vary approximately  $\pm 1$  percent from this curve. There is no consistent significant difference in flow with incidence angle for exit velocity ratios to about 0.8. At higher velocity ratios the equivalent flows for incidence angles of  $10^\circ$  and  $15^\circ$  begin to fall off. There were some other anomalies in these data, and they are discussed later in the section Kinetic energy loss.

The design exit critical velocity ratio, 0.749, occurred at an ideal value of 0.765. The inlet velocity ratio, calculated from continuity, at this point and for zero incidence was 0.391. The design value was 0.395. Thus, the cascade was operating at close to design reaction and flow.

Kinetic energy loss. - The kinetic energy loss coefficient for all incidence angles investigated is plotted against the ideal exit critical velocity ratio in figure 5(b). The solid curve is drawn through the data for zero incidence. Loss data for incidence angles from  $-15^\circ$  to  $5^\circ$  group closely around this curve. The losses for these incidence angles are generally somewhat higher than the loss for zero incidence. The losses for incidence angles from  $-15^\circ$  to  $5^\circ$  increase gradually from an ideal exit critical velocity ratio of 0.7 to 0.95, where suction-surface separation occurred. Separation was determined by total-pressure surveys in the wake. In figure 5(b) suction-surface separation is indicated by a very rapid rise in loss with exit velocity ratio. Separation for



all incidence angles occurred at an ideal critical velocity ratio of about 0.95. Separation was preceded by the occurrence of supersonic velocities on the suction surface near the trailing edge in all cases.

At exit velocity ratios less than design, the losses for large positive incidence angles,  $10^\circ$  and  $15^\circ$ , are significantly higher than the losses for the other incidence angles. This result was expected since the losses for large positive incidence angles are generally considered to be higher than the losses for other incidence angles. In this case, however, the losses for incidence angles of  $10^\circ$  and  $15^\circ$  did not increase with exit velocity ratio as they did for the other incidence angles investigated. This resulted in a region at higher than design exit velocity ratio where the losses for incidence angles of  $10^\circ$  and  $15^\circ$  were actually lower than for incidence angles from  $-15^\circ$  to  $5^\circ$ . Cascade operation in this region, which includes one data point for  $15^\circ$  and four data points for  $10^\circ$ , was characterized by a much higher noise level than for the other data. This high noise level is an indication that there was a higher level of turbulence in the cascade tunnel for these five data points than for all the other data points.

The inlet Reynold's number based on inlet conditions and the blade chord was in the transition region, and also the inlet turbulence level was low. These conditions can combine with Mach number effects to cause the cascade to operate with very different blade boundary layers (ref. 7). Because of the differences in cascade operation the flow and loss data for incidence angles of  $10^\circ$  and  $15^\circ$  for exit velocity ratios greater than 0.8 may not be comparable to the other flow and loss data presented in figure 5.

### Comparison of Experimental and Predicted Loss

Kinetic energy losses are compared to two common methods of estimating incidence loss. Data and calculations are for an ideal exit critical velocity ratio of 0.7. This exit velocity ratio was chosen to avoid the differences in results that are caused by the dissimilar cascade operation discussed in the previous section.

The measured losses for incidence angles from  $-15^\circ$  to  $15^\circ$  are shown in figure 6(a). The losses for all nonzero incidence angles are higher than the loss for zero incidence. The loss for an incidence angle of  $15^\circ$  is significantly higher than the loss for zero incidence.

Incidence angle was varied by changing the angle of the cascade tunnel inlet side-walls. This procedure changed the inlet flow area. And, since the weight flow was virtually independent of incidence angle, the inlet velocity varied with incidence. The variation in inlet velocity with incidence angle is shown in figure 6(b). This curve was determined from continuity. As discussed previously, this variation in inlet velocity affects both loss and blade loading and is not representative of the turbine test of reference 1. For these reasons, the losses are compared relative to the loss and inlet

velocity for zero incidence.

The dashed curve in figure 6(a) is the estimated variation in loss caused by the change in inlet velocity only. This loss was calculated by assuming that loss is proportional to the average kinetic energy across the blade row (ref. 8). Measured and estimated incidence loss are compared in figure 6(c). The losses are shown relative to the measured loss at zero incidence using the curve shown in figure 6(a) as a datum.

The estimated losses, calculated by assuming that the component of inlet velocity normal to the design angle is lost, were generally much too high. This procedure seems to be valid only for small incidence angles in the range of  $-5^{\circ}$  to  $5^{\circ}$ . The losses calculated according to the method of Ainley and Mathieson (ref. 5) are in generally good agreement with the measured losses.

The blades tested had a fairly high reaction and very blunt leading edges. Incidence losses are lower for reaction blading than they are for impulse blading. Blunt leading edges probably also reduce the sensitivity of the blade to the effects of incidence. The effect of reaction is considered in the method or reference 5. And this is probably the reason for the much better correlation of the experimental results with this method. Predicting incidence losses by assuming that the normal component of the inlet velocity is lost may be a method more applicable to impulse blading. Impulse blades, in addition to having little or no reaction, also usually have sharp leading edges.

## SUMMARY OF RESULTS

The aerodynamic performance of an uncooled core turbine rotor blade was investigated experimentally in a two-dimensional cascade. The blade was tested over a range of incidence angles and ideal exit critical velocity ratios. The results of this investigation are summarized as follows:

1. The shape of the blade-surface velocity distribution changed significantly with incidence angle. For large positive incidence ( $10^{\circ}$  and  $15^{\circ}$ ), there was a rapid diffusion from very high velocities on the suction surface near the leading edge. For large negative incidence ( $-10^{\circ}$  and  $-15^{\circ}$ ), the velocity on the pressure surface was higher than it was on the suction surface, resulting in a negative blade tangential force on the first 7 to 8 percent of the axial chord. Incidence effects were confined to the first 30 percent of the axial chord. The rest of the blade was unaffected.

2. At an ideal exit critical velocity ratio of 0.7 the kinetic energy loss for all non-zero incidence angles was higher than it was for zero incidence. The highest loss occurred at the largest positive incidence angle investigated,  $15^{\circ}$ .

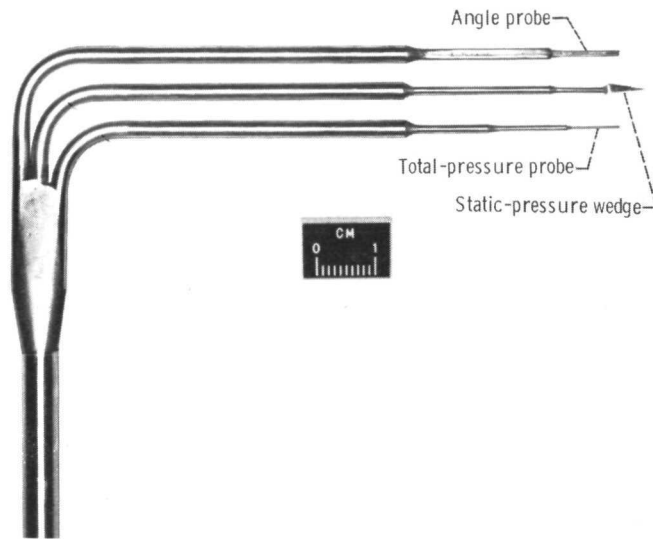
3. The results of two methods of estimating incidence loss were compared to the measured loss. Estimated losses based on the assumption that the normal component of the inlet velocity is lost were generally too high. Losses estimated according to the method of Ainley and Mathieson were in generally good agreement with the measured loss.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, January 28, 1974,  
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Figure 3. - Combination exit survey probe.

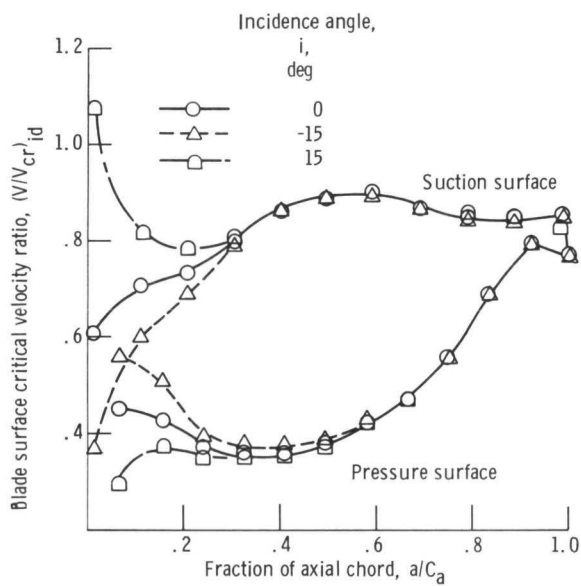
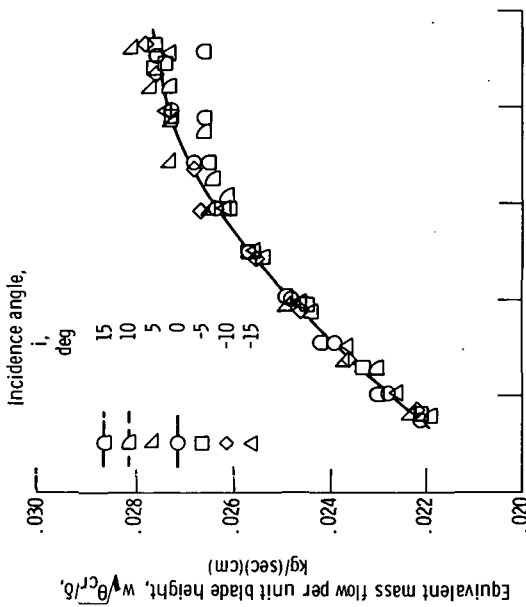
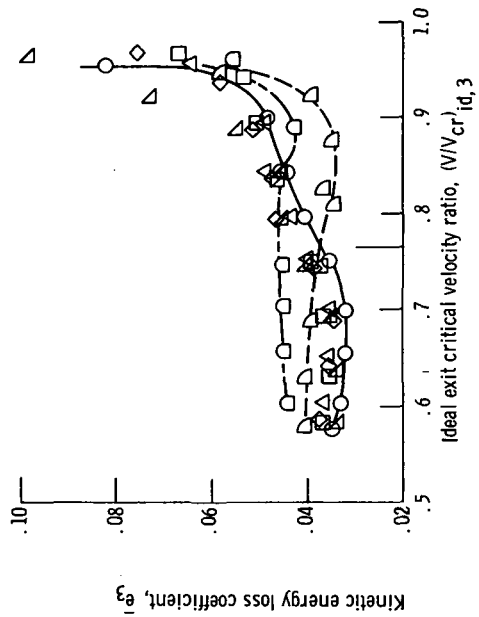


Figure 4. - Comparison of blade surface velocities at approximately design exit velocity ratio for incidence angles of  $0^\circ$ ,  $-15^\circ$ , and  $15^\circ$ .

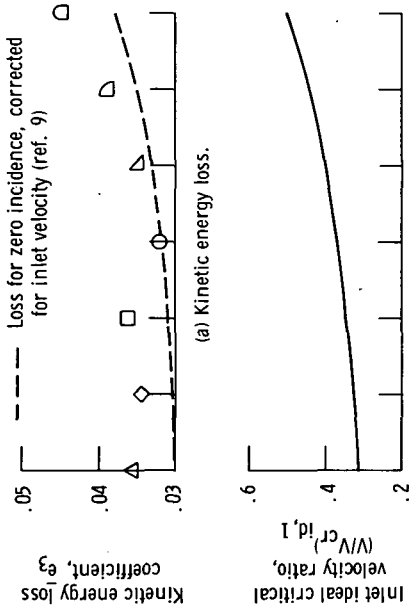


(a) Equivalent weight flow.

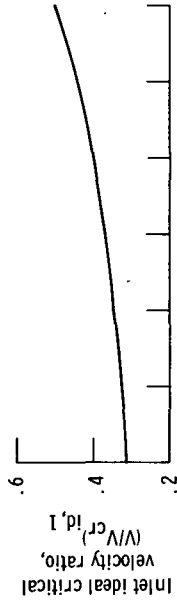


(b) Kinetic energy loss coefficient.

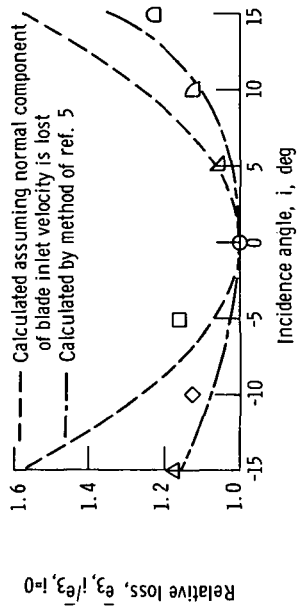
Figure 5. - Overall performance of core turbine rotor blades with incidence angle and ideal critical velocity ratio.



(a) Kinetic energy loss.



(b) Inlet ideal critical velocity ratio.



(c) Relative loss comparison.

Figure 6. - Comparison of loss with incidence. Ideal critical velocity ratio,  $(V/V_{cr})_{id,3} \sim 0.07$ .



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