ARTICLE NO. 78-245R

Axial Compressor Blade Optimization in the Low Reynolds Number Regime

William B. Roberts*
Nielsen Engineering & Research, Inc., Mountain View, Calif.

Original and previously published experimental data are presented in this study of axial compressor blade optimization for use in the subcritical Reynolds number region. Three methods of increasing cascade performance at these low R_c are presented, discussed, and compared: 1) the use of sharp, leading-edge profiles, 2) trip wires or roughness elements, and 3) high freestream turbulence. The original data were collected in the VKI C-1 cascade wind tunnel; during these tests, blade chord Reynolds number was varied from 250,000 down to ~17,000. Each technique demonstrated an increase in low R_c performance for certain profiles, with the sharp, leading-edge profile as the potential optimum. Axial compressors or pumps that must operate for a significant amount of their design life under low Reynolds number conditions might benefit substantially from these methods.

Nomenclature

c	= blade chord
Cp	= pressure coefficient
D	= diffusion factor
dw	= trip wire diameter
g	= pitch (blade spacing)
i	= incidence
L_s	= macroscale of the turbulence
M	= Mach number
P	= static pressure
Po	= total pressure
q	= dynamic pressure
R_c	= Reynolds number based on chord
Tu	= turbulence intensity
t	= maximum blade thickness
U	= flow velocity
x	= distance along the chord line
α	= angle of attack
β_1	= cascade inlet flow angle
β_2	= cascade outlet flow angle
$\hat{\beta}_1$	$= \pi/2 - \beta_1$ (Figs. 7 and 12)
$\hat{\beta}$	$= \pi/2 - \beta_2$ (Figs. 7 and 12)
β_s	$= \gamma + \pi/4$ (Figs. 7 and 12)
γ	= cascade stagger angle
δ^*	= boundary-layer displacement thickness
ζ_{VI}	= total head loss coefficient (Figs. 7 and 12)
θ	= flow deflection angle, $\beta_1 - \beta_2$
ϕ	= camber
ω_1	= total pressure loss coefficient

Subscripts

w	= at the trip wire location
1	= upstream
2	= downstream

Presented as Paper 78-245 at the AIAA 16th Aerospace Sciences Meeting, Huntsville, Ala., Jan. 16-18, 1978; submitted Feb. 13, 1978; revision received May 20, 1979.

Index categories: Airbreathing Propulsion; Aerodynamics; Boundary-Layer Stability and Transition.

*Project Engineer. Member AIAA.

Introduction

VARIOUS recent papers have shown the effect that low Reynolds number can have on the operating characteristics of axial flow compressors or pumps.[1-4] When the Reynolds number based on blade chord R_c falls below a critical value, the aerodynamic performance of conventional blades starts to decrease rapidly (Fig. 1). This performance degradation is caused by the growth of laminar separation bubbles, usually on the blade suction surface. For axial compressors or pumps that must operate for significant periods under these conditions, it would be beneficial to develop methods that would increase axial cascade performance at subcritical R_c. Anything that could shorten or suppress the laminar separation bubbles would increase performance. Three methods for doing this are examined in this study: 1) the use of sharp, leading-edge profiles, 2) trip wires or roughness elements, and 3) high freestream turbulence.

Sharp, Leading-Edge Profiles

Reference 5 reports experimental work done on double-circular-arc, blunt-trailing-edge blades (DCA-BTE) of 8 cm chord in cascade (Fig. 2). These profiles had a low camber of 10 deg and were 10% thick at the trailing edge. Initially, it was thought that such a blade would minimize losses at low R_c due to the mild deceleration that would allow a laminar boundary layer to extend to the trailing edge. After the publication of Ref. 5 a further set of experiments was done using this profile with the chord reduced to 2.5 cm. Testing was performed in the von Kármán Institute (VKI) C-1 low-speed cascade wind tunnel,[6] which allowed testing down to $R_c = 17{,}000$.† The data from the short-chord DCA-BTE blades were combined with selected data from previous testing[5] to produce Fig. 3. Together, these experiments give performance data for the DCA-BTE profile from $R_c = 240{,}000$ down to 17,000. Over this entire range, the performance is virtually independent of Reynolds number. The blade surface velocity distributions for incidence greater than 3 deg in Ref. 5 have shown a region of

†All testing reported herein was carried out in this tunnel under two-dimensional conditions (achieved using sidewall suction) and Mach number less than 0.2. Intensity of turbulence, Tu_1, at the cascade inlet was ~0.48% over the range of tunnel speed and the macroscale of the turbulence L_s (measured transverse to the inlet velocity vector) was measured as 15 mm. This leads to a tunnel turbulence factor, $\mathrm{TF} = Tu(c/L_s)^{1/5}$ of ~0.006. See Ref. 2 for a more complete description of the turbulence properties of the C-1 tunnel.

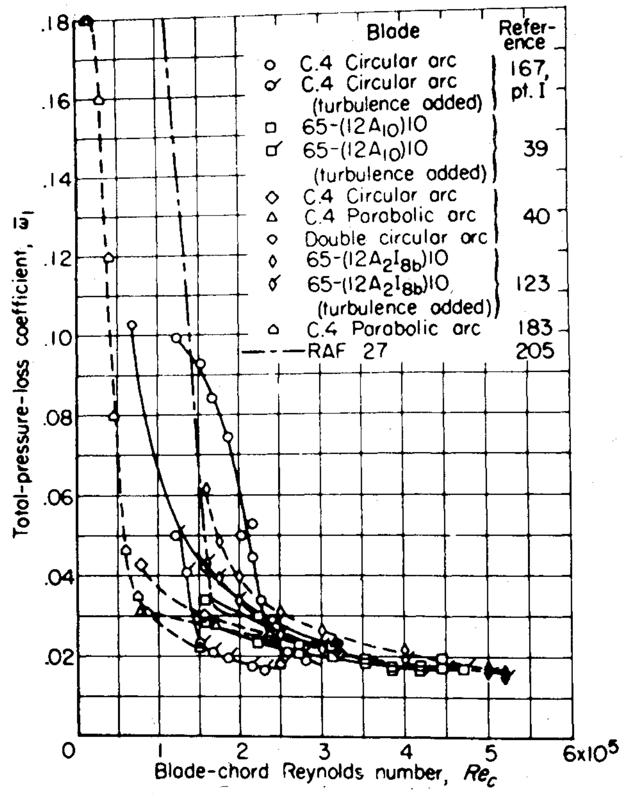


Fig. 1 Total pressure loss coefficient as a function of R_c near low loss angle of attack (taken from Ref. 21, p. 206; the cited references are those of Ref. 21).

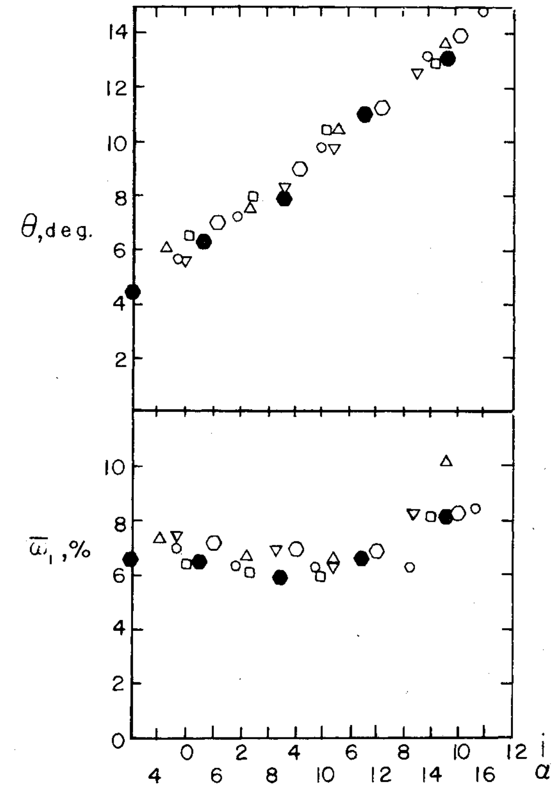


Fig. 3 Performance of 10% thick, 10 deg camber, DCA-BTE blades in cascade over a range of R_c: $g/c=1.2$, $\beta_1=60$ deg (data for $R_c \geq 5\times10^4$ from Ref. 5).

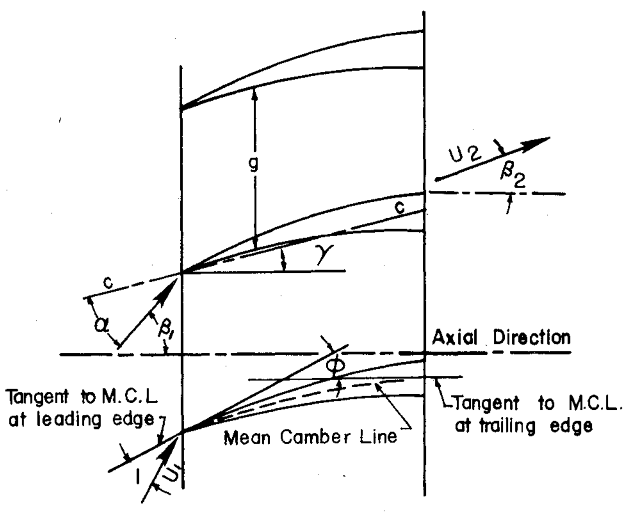


Fig. 2 Schematic of DCA-BTE blades in cascade (showing cascade geometry).

appreciable deceleration near the leading edge for all R_c (an example is given in Fig. 4). A flow visualization using titanium-diozide in oil indicated that there was a separation bubble at the leading edge. Subsequently, a boundary-layer calculation[16] using the measured velocity distributions indicated that a laminar boundary layer could not sustain the velocity gradient given by the experimental results (i.e., calculated separation occurred before observed reattachment). This, in turn, indicates that the reattaching boundary layer was turbulent. (Unfortunately, hot-wire probes and carriages of proper size were not available to measure the turbulence intensity of the reattaching shear layer.)

An attempt was made to reduce the losses due to the blunt trailing edge by fitting a splitter plate to the short-chord DCA-BTE blade. Research done at the National Physics Laboratory (NPL) in Britain[7,8] with blunt trailing-edge airfoils has shown that a drag reduction results from the use of a splitter plate of proper length on the blunt trailing edge (length equal to the trailing-edge thickness). Figure 3 shows no performance improvement for a test at $R=17{,}000$. Perhaps this is due to the very low Reynolds number; that of the NPL experiments was orders of magnitude higher. This could affect the size of the wake vortices and their shedding frequency.

From the evidence presented by the velocity distribution, flow visualizations, and boundary-layer calculations, one can conclude that the performance demonstrated by the DCA-BTE cascade is due primarily to the sharp leading edge acting as a tripping device, rather than the low camber and blunt trailing edge. Similar velocity distributions to those shown in Fig. 4 were noted by Gault[9] on thin wedge airfoil sections. Gault found turbulent flow up to the leading edge where the Reynolds number based on distance was very small. These experiments tend to confirm the hypothesis that the sharp leading edge is acting as a tripping mechanism.

To futher test validity of this concept, a test was made on a cascade of NASA 65-12 (A_{10})10 blades "reversed" (i.e., with the trailing edge forward). These blades were machined from steel and polished and had a sharp trailing edge. Test results for this cascade geometry are shown in Fig. 5 for a range of R_c. In Fig. 6, these results are compared with those of the conventional (i.e., unreversed) cascade geometry giving the same deflection. It can be seen that below a Reynolds number of 160,000, the performance of the conventional cascade starts to deteriorate rapidly, while that for the cascade of reversed profiles is constant down to the lowest Reynolds number tested.

A comparison of Fig. 5 with Fig. 3 shows that the loss level for the reversed profiles is lower than those of the DCA-BTE.

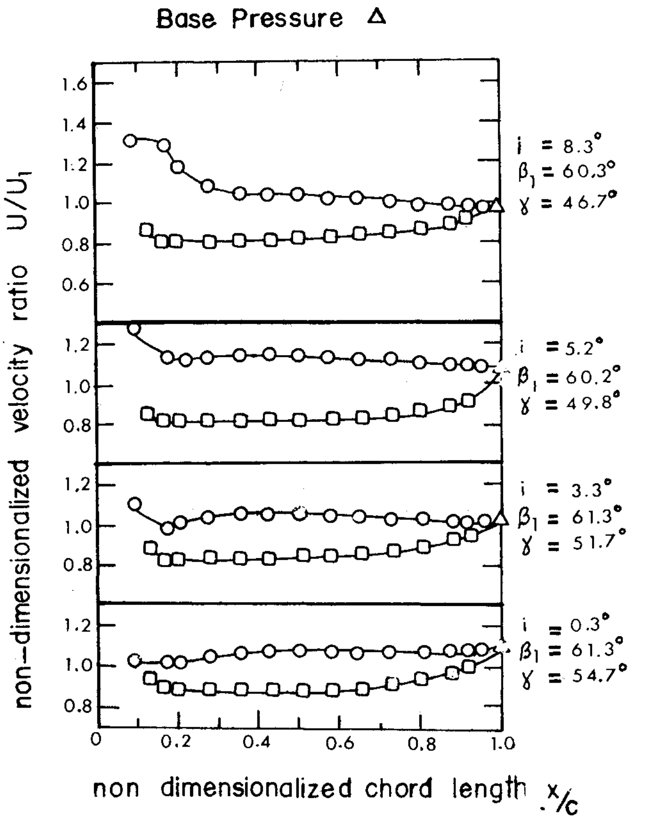


Fig. 4 Nondimensional blade surface velocity for 10% thick, 10 deg camber, DCA-BTE blades in cascade: $R_c = 50{,}000$, $g/c = 1.2$.

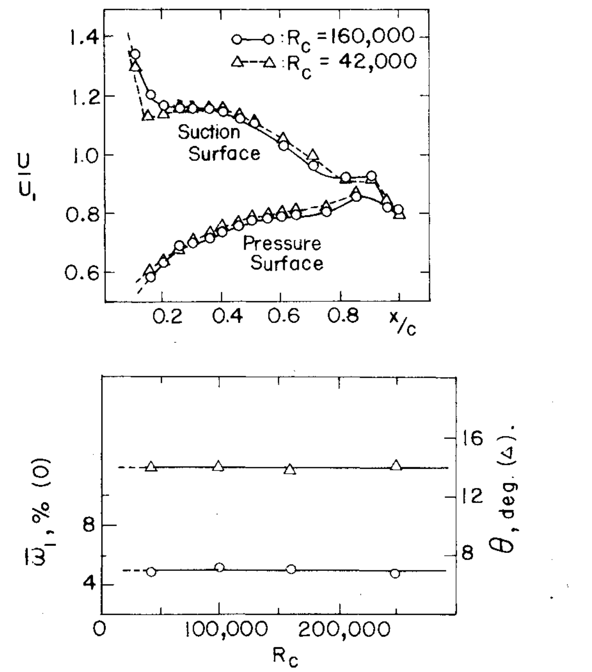


Fig. 5 Cascade performance with R_c and normalized velocity distributions for NACA 65-12 (A_{10}) 10 profiles "reversed": $g/c = 1.2$, $\beta_1 = 60$ deg, $\alpha = 19.2$ deg, T.F. $\simeq 0.006$.

This indicates that the rounded trailing edge helps to decrease the trailing edge dump loss and leads to the proposition that the best profile for low R_c is one with a sharp leading and trailing edge, such as a double-circular arc.‡ However, at supercritical R_c, the sharp, leading-edge blades might have a smaller range of operation than those with a more rounded leading edge.

‡No such blades were available for testing at the time the present data were taken.

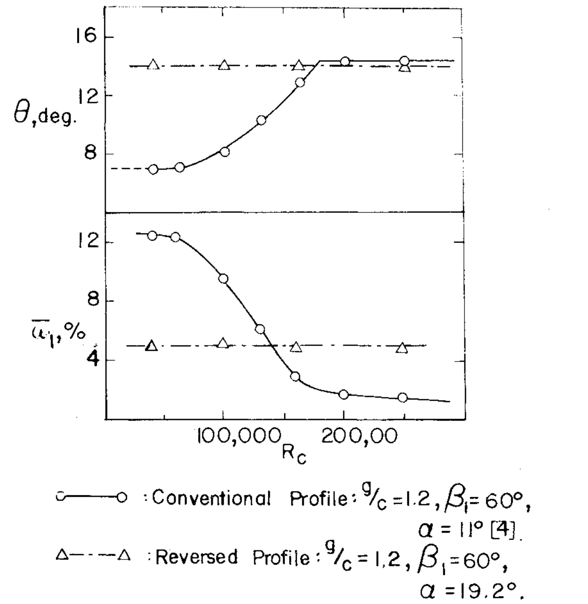


Fig. 6 Performance comparison between conventional and "reversed" NACA 65-12 (A_{10}) 10 profiles in cascade near minimum loss angle of attack over a range of R_c.

Trip Wires or Roughness Elements

It is not always possible to use a sharp, leading-edge profile in the subcritical Reynolds number regime. Often mechanical considerations, such as the possibility of particle ingestion, force the use of a more rounded leading edge. In this case, the suction surface boundary layer must be forced to transition to avoid a great deterioration of performance at subscritical R_c. One method of achieving premature transition is to trip the laminar boundary layer with a roughness element. (A review of the effect of a cylindrical roughness element on flat plate laminar boundary layer can be found in Ref. 10.)

Dryden[11] has shown that there is a negligible effect on the position of flat plate transition if

$$dw/\delta_w^* \leq 0.1 \tag{1}$$

where dw is the diameter of the trip wire and δ_w^* is the boundary-layer displacement thickness at the location of the trip (in the absence of the trip wire). As the size of the wire increases with respect to the displacement thickness, the transition point moves closer to the trip wire until at

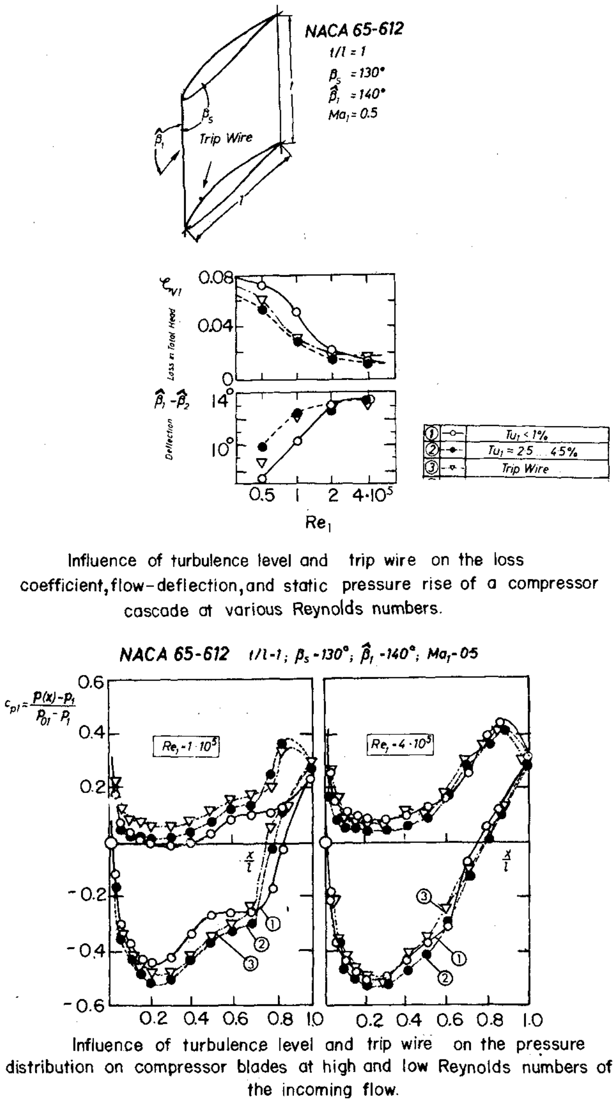
$$R_{dw} = \frac{U_w \cdot dw}{\nu} \geq 900 \tag{2}$$

The transition occurs immediately after the trip [Eq. (2) is due to Kraemer[12]].§

Klebanoff and Tidstrom[13] have demonstrated the mechanics by which a two-dimensional roughness element induces transition: the boundary-layer velocity profiles downstream of the element have points of inflection which are highly unstable and, therefore, amplify any disturbance already present.

From the preceding it is clear that Eq. (2) should be satisfied if the trip device is to be effective everywhere downstream. Furthermore, the location of the wire on the

§The numerical values given in Eqs. (1) and (2) are for low-speed flow and could be different for the compressible case.



Influence of turbulence level and trip wire on the loss coefficient, flow-deflection, and static pressure rise of a compressor cascade at various Reynolds numbers.

Influence of turbulence level and trip wire on the pressure distribution on compressor blades at high and low Reynolds numbers of the incoming flow.

Fig. 7 Barsun's data.[14]

blade is important. It should be located at or near the leading-edge suction surface. If the roughness element were much behind the leading edge, the velocity peak could be ahead of the trip for incidence angles greater than zero, and laminar separation could occur. However, with the trip wire at the leading edge, the boundary layer after the roughness element is accelerated for negative incidence angles and this could restabilize the laminar bounday layer.

In 1970 Barsun[14] presented some results using a trip wire on the suction surface of NACA 65-6 (A_{10}) 12 blades in cascade at an inlet Mach number of $M_I = 0.5$. The trip wire was located at 25% of the chord and the diameter-to-chord ratio was $dw/c = 0.001$. The data were taken for R_c between 400,000 and 50,000; results are shown in Fig. 7. A boundary-layer calculation[16] performed by this author (using the pressure distribution given in Fig. 7) for this cascade showed that at the trip wire location $dw/\delta_w^* \simeq 0.8$ for $R_c = 400{,}000$ and ~ 0.4 for $R_c = 100{,}000$ (Tu_I for both $\sim 1\%$). Both values of dw/δ_w^* are well above that given in Eq. (1). However, the approximate values of R_{dw} for the two Reynolds numbers are 500 and 125, respectively $[R_{dw} = U_w \cdot dw/\nu = R_c \; (U_w/U_I) \; (dw/c)]$, significantly below the value given by Eq. (2). For this situation, the transition position will be somewhere downstream of the trip; therefore, the effect on the performance will not be as great as if the wire were larger in diameter. Figure 7 indicates that the trip is not as effective as it could be. Although the performance deterioration with the

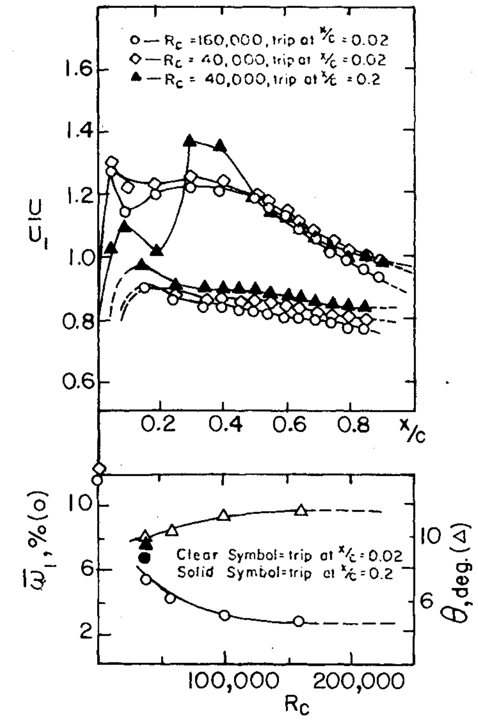


Fig. 8 Cascade performance with R_c and normalized velocity distributions for a NACA 65-12 (A_{10}) 10 profile with a trip wire on the suction surface: $g/c = 1.2$, $\beta_I = 60$ deg, $\alpha = 11$ deg, T.F. $\simeq 0.006$, $dw/c = 0.016$.

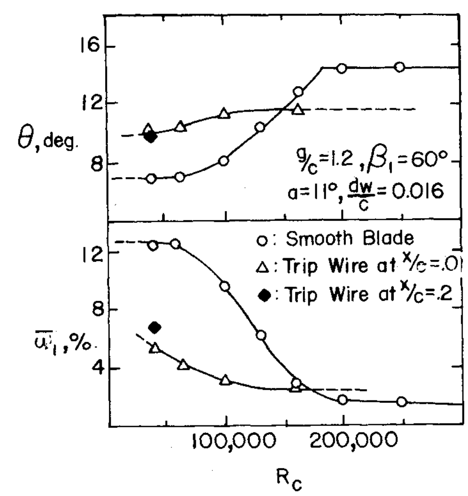


Fig. 9 Performance comparison between two cascades of NACA 65-12 (A_{10}) 10 blades over a range of R_c, one with a trip wire on the suction surface.

trip is somewhat lower than that of the smooth blade, the performance variation shows a similar trend.

Further tests were done by this author in the VKI C-1 cascade tunnel using NACA 65 blades with trip wires. The object of this test series was to determine whether increasing the relative size of the trip would further decrease the amount of performance deterioration over that shown by Fig. 7. For all but one test, the trip wires were located near the leading edge (on the suction surface). In this way the roughness element could affect the downstream laminar boundary layer regardless of the incidence angle (i.e., independent of where the velocity peak occurs). To insure that the roughness element would be effective at the leading edge and everywhere downstream, the relative size of the wire was increased (over that of Fig. 7) to $dw/c = 0.016$. For the blades tested using this wire size, $R_{dw} \geq 900$ until R_c falls below $\sim 45{,}000$. Therefore, even if there is a positive velocity gradient downstream of the roughness, a high degree of instability can be expected.

The first profile tested in cascade was the NACA 65-12 (A_{10}) 10 with the trip located at $x/c = 0.02$. Testing was done over a range of R_c from 250,000 down to 40,000. An additional test was run with the trip at $x/c = 0.20$ for the lowest R_c. The results are given in Fig. 8. The effect of the trip on the velocity distribution is clear, with the leading-edge trip location easily distinguished from that of the 20% position.

The velocity distribution on Fig. 8 was calculated from static tap readings and indicates that there is probably a separation zone ahead of the trip wire for the 20% chord position. This separation bubble is analogous to that ahead of a forward facing step. The performance does suffer significantly below $R = 100{,}000$, probably due to decreased tripping effect at the lower Reynolds numbers where the boundary layers are thicker. The test with the trip at the 20% chord location showed a slight decrease in performance when compared to that at the leading edge. Figure 9 also shows the performance of the smooth blade (taken from Ref. 4) to determine the performance increment due to the trip. It shows that below $R_c = 160{,}000$, the cascade performance becomes substantially better for the tripped blade; above $R_c = 160{,}000$, the trip causes higher losses and decreased deflection due to an increased boundary-layer thickness. However, the performance of this cascade with the larger trip wire located at the leading edge demonstrates significantly less deterioration in performance than that of Fig. 7, even though it is more highly loaded.¶ This is probably due to the size and position of the trip wire.

For profiles with lower camber or thickness than that of the NACA 65-12 (A_{10}) 10, the blade aerodynamic loading is less within the cascade operating range (for similar geometry). If loading is lower, it follows that the effect of low R_c should be less, since the boundary layer does not have to overcome such a severe pressure gradient. Consequently, the effect of a trip wire at low R_c should not be as beneficial for these blades as for the thicker or more highly cambered profiles. To demonstrate this, testing over a range of R_c with and without trip wires was conducted for two different profiles in cascade: NACA 65-4 (A_{10}) 10 blades representing a low-cambered, thick profile and NACA 65-8 (A_{10}) 06 representing a medium-cambered, thin profile. For both cascades, the trip wire was positioned near the leading edge and $dw/c = 0.016$. Test results are given in Figs. 10 and 11. They show that the effect of the trip is less beneficial at low R_c. For the NACA 65-4 (A_{10}) 10 blades, there is very little performance gain with the trip even at the lowest R_c tested, while above this, the losses become much higher. For the NACA 65-8 (A_{10}) 06, the performance was constant over the range of Reynolds number tested, which gives a slight improvement over the smooth blade when $R_c < 120{,}000$ at a cost of a slight decrease at higher R_c.

Testing with trip wires at subcritical cascade Reynolds numbers has demonstrated that they can be of substantial benefit for blades of medium to high camber and thickness with a cost of moderately decreased performance at supercritical R_c. The size and location of the trip wire or roughness element on the blade surface is important in determining the level of performance improvement. The shape for any specific situation would be determined experimentally.

Medium- or high-cambered profiles are used near the hub of a rotor where R_c is the lowest. However, for typical tip sections of low camber and thickness, the gain in performance using a trip wire is slight at low R_c. At the higher Reynolds numbers occurring near the tip, the trip wire causes a degradation in performance when compared to smooth blades due to an increased boundary-layer thickness. It is possible that thinner trip wires might improve the low Reynolds number performance of axial blades with less penalty at high R_c. Perhaps a more thorough experimental study might show an optimum trip wire diameter and location as a function of cascade geometry and Reynolds number.

¶A calculation of diffusion factor[15] for both cascades gives $D \simeq 0.34$ for that of Fig. 7 and $\simeq 0.44$ for Fig. 8, thereby indicating the higher aerodynamic loading of the latter.

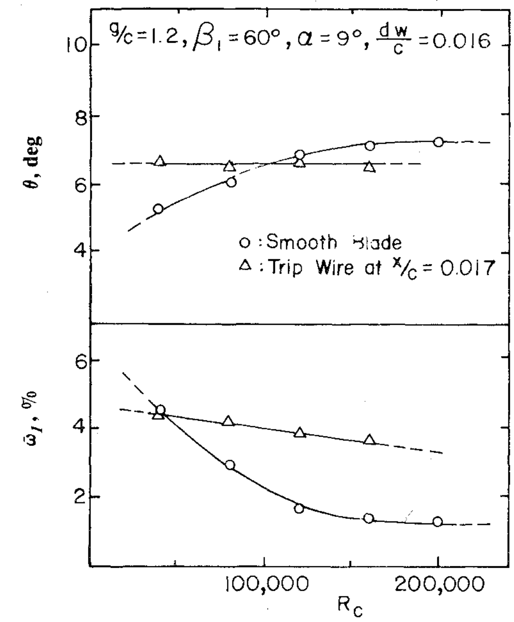


Fig. 10 Performance comparison between two cascades of NACA 65-4 (A_{10}) 10 blades over a range of R_c, one with a trip wire on the suction surface.

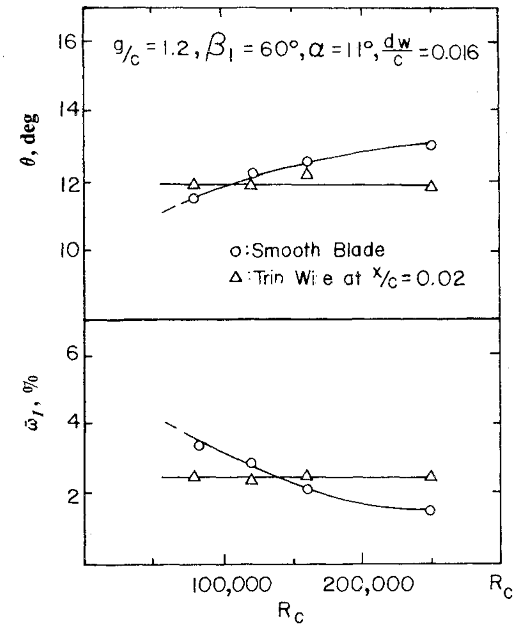
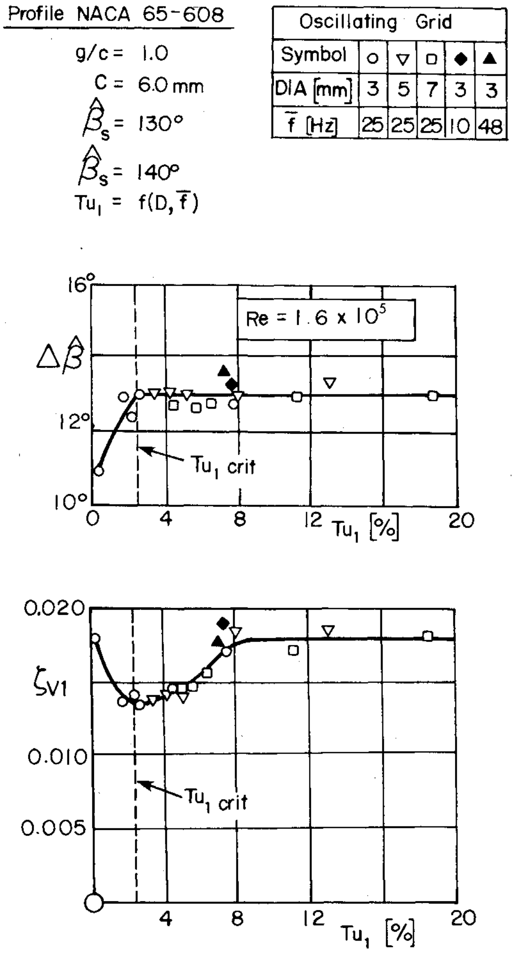


Fig. 11 Performance comparison between two cascades of NACA 65-8 (A_{10}) 06 blades over a range of R_c, one with a trip wire on the suction surface.

High Freestream Turbulence

Figure 7 shows that increased freestream turbulence can aid cascade performance at subcritical R_c. Reference 2 and the work of Evans[17] have shown that the turbulence level of the freestream has a great effect on the position of transition either before or after laminar separation. Depending upon the level, an increase in the freestream turbulence at low R_c can cause the boundary layer to undergo transition before separation or shorten the laminar separation bubble con-



Influence of the turbulence level on the flow loss and flow deflection of compressor casade.

Fig. 12 Data of Schlichting and Das.[18]

siderably. From the standpoint of losses and deflection across the cascade, an increase in freestream turbulence is one of the best solutions in principle, since it involves no physical modification to the blades.

Schlichting and Das[18] have presented experimental results that demonstrate the effect of grid-generated turbulence on cascade performance at low R_c (Fig. 12). The losses go through a minimum at $Tu_I = 2.5\%$ and then start to increase with turbulence (due to increased turbulent dissipation). It follows that for each cascade situation and Reynolds number, there will be a certain value of freestream turbulence that produces a minimum in loss and maximum deflection. This optimum point results from a combination of decreased laminar separation bubble length (and, therefore, loss) and increased loss due to dissipation.

Practical artifical generation of turbulence for low R_c compressor systems requires the use of grids that cause considerable drag. An increase of intensity from a low level to 2.5%, the approximate optimum from Fig. 12, 10-15 cm downstream of a biplanar grid consisting of 0.5 mm wire covering 10% of the inlet area, would cause a total pressure loss of 25% of the dynamic pressure (calculation done using the formulation given in Refs. 19 and 20). In most situations, whether an internal flow system or externally mounted engine, this level of loss is unacceptable. For this reason, the use of grid-generated turbulence to suppress the effect of low R_c cannot be recommended for most situations.

As indicated here and in Refs. 2, 17, and 18, an increase in turbulence can suppress the effects of laminar separation bubbles at low R_c. Often axial pumps or compressors operate in situations where freestream turbulence is relatively high, i.e., >1%. This could be caused by upstream duct interference and/or struts, or, in a multistage machine, by operation in the wake mixing regions of upstream blade rows. For these situations, the critical value of R_c will be much lower than for a cascade with low-turbulence inflow.

Summary

It has been demonstrated that a sharp leading edge would act as a tripping device at an incidence greater than zero. The probable reason for this is that the region of separation immediately downstream of the thin leading edge causes severe destabilization of the shear layer which results in the amplification of any disturbances present. The same process occurs aft of single roughness elements placed on an otherwise smooth surface.

The experimental work presented here indicates that an airfoil shape with both a thin leading and trailing edge, such as a DCA profile, should be an optimum shape for continuous operation at low Reynolds number. For operations combining both low Reynolds number and abrasive conditions (not necessarily at the same time), the conventional profile with some appropriate roughness element or surface at the leading edge provides a reasonable solution. In a situation where an axial compressor or pump is occasionally operating at low R_c, the blade thickness and camber should be kept as low as possible to give the required amount of flow deflection, necessary mechanical strength, and to minimize the losses.

An increase of performance through the first blade rows can be realized at low Reynolds numbers by increasing the freestream turbulence up to a certain level. However, the overall decrease in system efficiency due to the drag of the required grid could be greater than the benefit derived.

Acknowledgment

The author wishes to thank the von Kármán Institute, the University of Notre Dame, and the National Aeronautics and Space Administration for their support during the preparation of this paper.

References

[1] Heidelberg, L. J. and Ball, C. L., "Effect of Reynolds Number on Overall Performance of a 3.7 Inch-Diameter Six-Stage Axial Flow Compressor," NASA TN D-6628, Feb. 1972.

[2] Roberts, W. B., "The Effect of Reynolds Number and Laminar Separation on Axial Cascade Performance," ASME Paper 74-GT-68, *Journal of Engineering for Power, Transactions of ASME*, Series A, Vol. 97, April 1976, p. 261.

[3] Walker, G. J., "Observations of Separated Laminar Flow on Axial Compressor Blading," ASME Paper 75-GT-63, March 1975.

[4] Roberts, W. B., "The Experimental Cascade Performance of NACA Compressor Profiles at Low Reynolds Number," ASME Technical Brief, *Journal of Engineering for Power, Transactions of ASME*, Series A, Vol. 97, July 1975, p. 453.

[5] Papailiou, K. P. and Roberts, W. B., "On the Behavior of Bladings in the Small Reynolds Number Regime," ASME Publication 70-WA/GT-11, Dec. 1970.

[6] "Experimental Facilities at VKI," von Kármán Institute for Fluid Dynamics, TM 11, 2nd ed., 1967.

[7] Nash, J. F., "Quincey, V. G., and Callinan, J., "Experiments on Two-Dimensional Base Flows at Subsonic and Transonic Speeds," National Physics Laboratory Aero. Rept. 1070, ARC 25070, Jan. 1963.

[8] Nash, J. F., "A Discussion of Two-Dimensional Turbulent Base Flows," National Physics Laboratory Aero. Rept. 1162, ARC 27175, July 1965.

[9] Gault, D. E., "An Investigation at Low Speed of the Flow Over a Simulated Flat Plate at Small Angles-of-Attack Using Pitot-Static and Hot-Wire Probes," NACA TN-3876, 1957.

[10] Schlichting, H., *Boundary Layer Theory*, 4th ed., McGraw-Hill Book Co., Inc., New York, Ch. XVII g, 1960.

[11] Dryden, H. L., "Review of Published Data on the Effect of Roughness on Transition from Laminar to Turbulent Flow," *Journal of the Aeronautical Sciences*, Vol. 20, July 1953, pp. 477-482.

[12] Kraemer, K., "Uber die Wirkung von Stolperdrahten auf den Grenzschichtumschlag" ("Concerning the Effect of Lashing Wires on the Boundary-Layer Transition"), ZFW9, 1961, pp. 20-27.

[13] Klebanoff, P. S. and Tidstrom, K. D., "Mechanism by Which a Two-Dimensional Roughness Element Induces Boundary Layer Transition," *The Physics of Fluids*, Vol. 15, July 1972.

[14] Barsun, K., "Discussion During Session 2," *Internal Aerodynamics (Turbomachinery)*, Institute of Mechanical Engineers, London, 1979, p. 41.

[15] Lieblein, S., Schwenk, F. C., and Broderick, R. L., "Diffusion Factor for Estimating Losses and Limiting Blade Loading in Axial-Flow Compressor Blade Elements," NACA RM E53D01, 1953.

[16] LeFoll, J., "A Theory of the Representation of Boundary Layers on a Plane," *Proceedings of Seminar on Advanced Problems in Turbomachinery*, von Kármán Institute, Oct. 1965.

[17] Evans, B. J., "Effects of the Free-Stream Turbulence on Blade Performance in a Compressor Cascade," Cambridge University, Engineering Dept. Turbo/TR 26, 1971.

[18] Schlichting, H. and Das, A., "On the Influence of Turbulence Level on the Aerodynamic Losses of Axial Turbomachines," from *Flow Research on Blading*, pp. 243-268, L. S. Dzung, Ed., Elsevier Publishing Co., 1970.

[19] Frenkiel, F. N., "The Decay of Isotropic Turbulence," *Transactions of ASME*, Vol. 70, 1948, p. 311.

[20] Idelcik, I. E., "Momento Des Pertes De Charge" (Memorandum on Discharge Loss), Collection du Centre de Recherchers et D'Essais de Chatou, Eyrolles, Paris, 1960.

[21] *Aerodynamic Design of Axial Flow Compressors*, NASA SP-36, 1965.