Improvement in Turbine Blade Aerodynamic Force in the Tip Region*

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An attempt to increase the turbine blade aerodynamic force was made by installing boundary layer fences on the endwalls of a linear turbine rotor cascade. The height and location of the fences were varied to optimize these parameters. Static pressures measured on the passage surface correlated well with surface secondary flow patterns visualized by the oil flow method. The fences favorably attenuated local unloadings in the tip region of the suction surface associated with the endwall crossflow and the passage vortex three-dimensional separation, but unfavorably inhibited a passage-vortex-induced local loading also on the suction surface. The fences were most effective when their height was one-third of the inlet endwall boundary layer thickness and located half a blade pitch away from the blades. The optimum fences then reduced the tangential force defect to 60 percent of the unfenced blading value.

Key Words: Fluid Force, Pressure Distribution, Secondary Flow, Turbine Cascade, Boundary Layer Fence, Separation, Force Defect Thickness

1. Introduction

When a shear flow is deflected, the streamwise component of vorticity is "generated" as a result of stretching of the vortex filaments⁽¹⁾. This vorticity component induces secondary flow, which is usually defined as the flow motion normal to a primary flow direction. Secondary flow, in spite of the terminology, is of considerable magnitude in turbine blade passages, since the inlet flows to the passages have intensive shears within hub and casing boundary layers and are subject to large deflections through the passages. The flow is then highly three-dimensional in the endwall regions, including horseshoe vortices round the blade leading edges, corner vortices at the blade/endwall junction corners, blade-to-blade crossflows on the endwalls, and trailing vortices shed from the blades^{(2),(3)}.

Without the secondary flow, changes in static pressures across the endwall boundary layer would be negligibly small according to the boundary layer theory⁽⁴⁾, consequently a unit-span blade element in the layer would acquire as much aerodynamic force as that outside the layer. Many experiments^{(5)~(9)} on turbine cascades, however, revealed that the blade static pressures in the tip region differ markedly from those around midspan. These results indicate that the secondary flow causes a blade force defect in the tip region. The force defect increasingly affects the turbine aerodynamic performance with a decreasing passage aspect ratio, as does the secondary loss in total pressure. An improvement in the force defect is the object of the present study.

Figure 1 gives a perspective view of oil flow patterns on the endwall and the blade suction surface of a linear turbine rotor cascade⁽³⁾. (Note that one blade is removed for the photography.) On the endwall, the horseshoe vortex leaves behind a separation bubble zone of higher powder concentration wrapping around the blade leading edge. Owing to the prevailing cross-passage pressure gradient, the suction side branch of this zone impinges upon the suction surface,

* Received 9th October, 1989. Paper No. 88-1082A

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while the pressure-side branch impinges upon the suction surface of the neighboring blade. The endwall limiting streamlines downstream of the horseshoe vortex separation zone are almost in the pitchwise direction, thus indicating the existence of a strong crossflow on the endwall toward the suction surface.

It was shown by the present authors^{(10),(11)} that boundary layer fences installed on the passage-confining surfaces were capable of reducing the secondary loss. Figure 2 shows an oil flow visualization result for the optimum endwall fences that minimized the secondary loss: the fences are 1/3 of the inlet boundary layer thickness in height from the endwall surfaces and located half a blade pitch away from the blades. The pressure-side branch of the horseshoe vortex separation bubble is terminated at the fence, without reaching the suction surface of the neighbor-

ing blade. The endwall limiting streamlines between the fence and the blade suction surface are then directed more axially, so the endwall crossflow is weakened as compared with the unfenced (normal blading) case. Furthermore, the passage vortex three-dimensional separation on the suction surface is reduced in size in comparison with the normal blading case. These fence effects on the secondary flow pose the following questions: (1) Are the endwall fences capable of increasing the blade aerodynamic force in the tip region? (2) If the fences are effective, what is the optimum combination of their height and location at which the blade force is maximized? In other words, does such an optimum fence condition coincide with that at which the secondary loss was minimized? The present paper settles these points.

Nomenclature

C_p : pressure coefficient, $(p - p_1)/\frac{1}{2}\rho U^2$

C_Y : coefficient of pitchwise component of unit-span blade force, $Y/\frac{1}{2}\rho U^2 l$

h : blade span

h_f : height of fence

l : blade chord length

l_x : blade axial chord length

p : static pressure

T_u : longitudinal turbulence intensity

t : blade pitch

U : free-stream velocity

u : velocity component in the free-stream direction

x, y, z : axial, pitchwise, and spanwise coordinates (see Fig. 4)

Y : pitchwise component of unit-span blade force (in the negative y direction)

y_f : distance between fence and blade (see Fig. 4)

δ : boundary layer thickness

Δ : force defect thickness

ρ : air density

Subscripts

0: blade tip

1: upstream of cascade

m : midspan

2. Apparatus and Method

A low-speed cascade wind tunnel was used for the experiment (Fig. 3). The fan-driven airflow passed through a diffuser, a honeycomb and screen set, and a nozzle of two-dimensional contraction. The flow entered the linear cascade of 11 turbine rotor blades at a large incidence (10.5 degrees) and was deflected nominally by 90 degrees through the cascade. The

Fig. 1 Oil streak pattern on the passage surface in normal blading

Fig. 2 Oil streak pattern on the passage surface equipped with endwall boundary layer fences ($y_f/t=0.5$, $h_f/\delta_1=1/3$)

shape of the blade suction surface was a parabola, and the contour of the blade pressure surface was such that the flow area within the blade passage linearly converged downstream. Blading details are summarized in Table 1.

The fences attached to both the endwalls, $z=0, h$, were of uniform size and shape; their thickness was 0.5 mm, their height constant along their chords. As shown in Fig. 4, the fences were normal to the endwalls, and their leading and trailing edges were on the cascade inlet and outlet planes, respectively. The camber line and the stagger angle of the fences were the same as those of the blades.

The endwall and the middle blade were instrumented with static pressure taps 1 mm in diameter, as indicated by 1e to 58e on the endwall and 1b to 26b on the blade surface in Fig. 4. Though not shown in the figure, the endwall had an additional pitchwise row of 6 taps 1 mm in diameter for measuring the mean inlet static pressure 0.95-blade-chord lengths upstream of the cascade inlet plane. The plane of blade tappings was parallel to the endwall. Spanwise displacements of the tapped blade, which pierced both the endwalls with the piercing sections externally sealed, allowed measurements of blade static pressures at 26(chordwise) by 13(spanwise) different

points on the surface.

A hot-wire traverse was carried out 1-blade-chord length upstream of the cascade inlet plane to give spanwise distributions of the inlet flow velocities and longitudinal turbulence intensities. As seen in Fig. 5, the inlet flow had turbulent boundary layers on the endwalls and a potential core around midspan. The boundary layer thickness on the lower endwall $z=0$ was 29.3 mm, which occupied approximately 30 percent of the lower half span $0 \leq z \leq h/2$. Some integrated boundary layer parameters are shown in Table 2 for the lower half-span. The boundary layer data in another half-span were almost the same as above.

The endwall and blade surface static-pressure

Fig. 4 Working section with coordinate system

Fig. 3 Cascade wind tunnel and data acquisition system

Fig. 5 Spanwise distributions of flow velocities and turbulence intensities at inlet to the cascade

measurements were taken for 6 different blade-to-fence distances $y_f = 20, 30, 40, 50, 60, 70$ mm and for 3 different fence heights $h_f = 5, 10, 20$ mm in addition to the measurements in the normal blading case. The pressures at the taps were fed into a semiconducting transducer through a computer-controlled scanning valve, and were recorded and analyzed by computer (Fig. 3).

3. Results and Discussion

3.1 Pressure distribution on passage surface

The static pressures measured on the passage surface are contour-plotted with full lines of constant $4C_p + 17$ in Figs. 6 and 7. Note that in these figures, the suction and pressure surfaces are viewed in the pitchwise direction. The broken lines and the two-dot chain lines superimposed respectively denote three-dimensional separation lines and stagnation streamlines observed in the oil flow visualizations and are as follows: $S1_p, S2_p$ =primary and secondary separation lines of the horseshoe vortex pressure-side leg. $S1_s, S2_s$ =primary and secondary separation lines of the horseshoe vortex suction-side leg. $S5, S3_s$ =primary and secondary separation lines of the suction-side corner vortex. $S6, S7$ =primary and secondary separation lines of the pressure-side corner vortex. $S4$ =separation line of the passage vortex. $S5_r, S3_r$ =primary and secondary separation lines of the fence corner vortex. $R1$ =stagnation streamline.

3.1.1 Normal blading On the pressure surface in the normal blading case, the bottom of Fig. 6, the static pressures near the endwall are slightly lower than those at midspan owing to the influence of the horseshoe vortex.

The contour lines on the endwall, the middle of Fig. 6, exhibit an intensive blade-to-blade pressure gradient. Nevertheless, as has been frequently observed⁽⁵⁾⁻⁽⁹⁾, the point of minimum pressure is not located at the intersection of the suction surface and the endwall, but is displaced away from the suction surface as seen from closed contour line 8 in the throat region. The present simultaneous plot of isobars and separation lines reveals that the minimum pressure occurs on the immediate midpitch side of the corner vortex primary separation line, $S5$.

The displacement of the minimum pressure point is caused by the following two effects. First, the

Fig. 6 Static-pressure contours on the passage surface in normal blading

Table 2 Inlet boundary layer data

Thickness/blade span	0.147
Displacement thickness/blade span	0.0201
Momentum thickness/blade span	0.0146
Shape factor (displacement/momentum)	1.38

Fig. 7 Static-pressure contours on the passage surface, with endwall boundary layer fences ($y_f/t=0.5$, $h_f/\delta_1=1/3$)

impingement of the endwall crossflow upon the blade suction surface causes the static pressures at the endwall/suction surface intersection to increase. In fact, the displaced minimum-pressure region extends upstream along line S5 up to the pressure-side branch of the horseshoe vortex separation bubble, thus indicating the increases in static pressures toward the intersection. Secondly, the passage vortex, or the horseshoe vortex pressure-side leg, imposes its own low static pressures upon the endwall. This is evidenced by endwall contour lines 12 to 17: each line bulges slightly in the negative y direction immediately downstream of line S2_p owing to the low pressures imposed by the leg, and this low-pressure zone joins the displaced minimum-pressure region at the throat.

The static pressures on the suction surface are plotted at the top of Fig. 6. The pressures deviate markedly from the midspan values as the endwall is approached. The most significant deviations are:

- (i) a pressure rise in the leading edge region,
- (ii) a pressure rise at around 50 percent axial chord, and
- (iii) a pressure drop at around 65 percent axial chord and $0.6\delta_1$ away from the endwall.

The first higher-pressure region extends from the leading edge up to where the suction-side branch of the horseshoe vortex separation bubble meets the suction surface, while the second higher-pressure region is located where the pressure-side branch of the bubble meets the suction surface. The third lower-pressure region is ascribed to the passage vortex^{(5),(12)}, since it is on the immediate endwall side of the passage vortex separation line, S4, and extends downstream along this line. The passage vortex three-dimensional separation accompanies a zone of relatively high pressures on the immediate midspan side of the lower-pressure region, as seen from isobars 7 to 9 bulging upstream along the separation line S2_s.

The above results indicate that in the normal blading case, the secondary flow causes the blade to become unloaded by reducing pressures on the concave surface and by simultaneously increasing pressures on the convex surface. It is interesting, however, to observe that the passage vortex can increase the blade tangential force by locally reducing the suction surface pressures.

3.1.2 Fenced cascade In Fig. 7, the fences $(1/3)\delta_1$ -high are placed half a blade pitch away from the blades. The static pressures on the blade pressure surface, shown at the bottom, are hardly influenced by the fences installed, as seen from a comparison with Fig. 6. On the endwall (the middle of Fig. 7), the point of minimum static pressure in the throat region is no longer displaced from the suction surface. Rather, the

point is located on the endwall/suction surface intersection as in potential flows⁽⁵⁾. The static pressures in the vicinity of the intersection are thus considerably lower than those in the normal blading case. As seen in the top of Fig. 7, the two local pressure rises, (i) and (ii), on the suction surface have been attenuated, with the latter attenuation being more noticeable. The local pressure drop (iii), caused by the passage vortex, has disappeared. The local pressure rise associated with the passage vortex three-dimensional separation has accordingly become quite small. As a result, there is an improved spanwise uniformity in the suction surface pressures.

These effects of the fences are due to the facts that the fence traps the horseshoe vortex pressure-side leg to prevent the leg from affecting the suction surface flow and that the fence simultaneously attenuates the fence-to-blade endwall crossflow, as seen in Fig. 2. The attenuated crossflow rolls up into a passage vortex near the blade suction surface. This additional passage vortex is too weak⁽¹¹⁾ to bring about any noticeable local pressure drop on the blade suction surface.

3.2 Axial-chordwise blade pressure distribution

The blade surface static pressures in the tip region and at midspan in the normal blading case are shown in Fig. 8 as a function of axial distance. At the spanwise location of $2/3$ of the inlet boundary layer thickness, i.e., at $z/h=0.1$, the forward portion of the blade becomes unloaded in comparison with the midspan. Conversely, the rear portion becomes more loaded than the midspan owing to the passage-vortex-induced local pressure drops on the suction surface. At the $(1/3)\delta_1$ spanwise location ($z/h=0.05$), the forward portion is further unloaded, while the rear portion has the same amount of loading as the corresponding midspan value. At the tip ($z=0$), the blade becomes markedly unloaded over the entire chord

Fig. 8 Axial-chordwise distributions of blade static pressures in normal blading

length.

When the $(1/3)\delta_1$ -high fences are installed midway down the blade passage, Fig. 9, the suction surface static pressures within the inlet boundary layer thickness are considerably reduced, and the pressure surface ones are slightly increased. These effects favor the blade tangential force. Unfavorably, however, the passage-vortex-induced local loading is no longer present in Fig. 9, since the fence installed has isolated the horseshoe vortex pressure-side leg from the blade suction surface.

3.3 Blade tangential force

The static pressures measured on the blade surface were axial-chordwise integrated to evaluate the blade tangential force coefficient per unit span.

$$C_v = \frac{l_x}{l} \oint C_p d\left(\frac{x}{l_x}\right). \quad (1)$$

In carrying out the integration, the C_p at the trailing edge was assumed to be independent of the spanwise distance and equal to the mean value of endwall C_p measured at downstream taps 51e to 58e (Fig. 4), as shown by dashed lines in Figs. 8 and 9. The results are shown in Fig. 10 for different fence locations y_f with the fence height h_f fixed to $(1/3)\delta_1$, including the unfenced case. In the unfenced case, force coefficients C_v at around $z=0.20h (=1.3\delta_1)$ are somewhat smaller than those at midspan as a result of the suction surface local pressure rises along the passage vortex three-dimensional separation line. The force reaches a local maximum at $z=0.13h (=0.8\delta_1)$ owing to the passage-vortex-induced local pressure drops on the suction surface. As the endwall is more closely approached, the force rapidly decreases mainly because of the local pressure rises on the suction surface. The minimum force at the tip is 32 percent weaker than the midspan value.

As fence distance y_f/t increases from zero (the unfenced case) to 0.7, the forces increase in the first

Fig. 9 Axial-chordwise distributions of blade static pressures, with endwall boundary layer fences ($y_f/t = 0.5$, $h_f/\delta_1 = 1/3$)

span section $0 \leq z/\delta_1 \leq 0.5$, but decrease in the second section $0.5 \leq z/\delta_1 \leq 1.2$, and again slightly increase in the third section $1.2 \leq z/\delta_1$. The spanwise distribution of the forces then becomes increasingly uniform. When the fences are nearest the blade suction surface ($y_f/t=0.7$) in particular, the tangential force at the tip is only 12 percent smaller than the midspan force.

Influence of the fence height is shown in Fig. 11, where the spanwise distributions of the forces are presented for different fence heights h_f , with the fence location fixed to $y_f/t=0.5$. It is seen in the figure that the midway fences of any height increase C_T in the first and third sections of span, and decrease C_T in the second section. In Fig. 10, the forces in the first and second sections change monotonously with the fence location. In Fig. 11, in contrast, there is no monotonous change with the fence height.

The defects of the tangential forces in the tip

Fig. 10 Spanwise distributions of tangential force coefficients per unit span for different pitchwise locations of $(1/3)\delta_1$ -high fences

Fig. 11 Spanwise distributions of tangential force coefficients per unit span for different heights of midway-installed fences

region are $Y_m - Y$. A spanwise integration of these defects gives force defect thickness

$$\Delta = \int_0^{h/2} \left(1 - \frac{Y}{Y_m}\right) dz. \quad (2)$$

The thickness represents a spanwise extent of a zero-force region when a stepwise force distribution is assumed, as shown in Fig. 12. Figure 13 then shows the force defect thickness, nondimensionalized by the inlet boundary layer thickness, as a function of location and height of the fences (the lower boundary $h_f/\delta_1 = 0$ denotes the normal blading case). It is evident from the figure that the fences decrease the defect thickness, thus increasing the integrated blade force, unless they are high and located close to the blade pressure surface. In particular, installing the $(1/3)\delta_1$ -high fences midway results in the minimum defect thickness, which is 40 percent smaller than the normal blading value. It should be emphasized that this optimum combination of height and location coincides with the combination at which secondary loss, secondary kinetic energy, flow underturning, and thickness of the secondary vorticity region were minimized⁽¹¹⁾.

The increase in the integrated force shown in Fig. 13 obviously results from a compensation such that in Figs. 10 and 11, the improvements achieved in the first and third sections of the span offset the deterioration

Fig. 12 Force defect thickness

Fig. 13 Nondimensional tangential force defect thickness plotted against height and fence location

Fig. 14 Tangential force coefficient at tip plotted against height and fence location

brought about in the second section. The tip force (the force C_τ at $z=0$) represents the forces within the first span section. Figure 14 then shows the tip force, $C_{\tau 0}$, as a function of height and location of the fences. A comparison of this figure with Fig. 13 reveals that $C_{\tau 0}$ depends on y_f and h_f very similarly to the force defect thickness. The only difference is that there is a local minimum value in the force defect thickness as a result of the compensation mentioned above. The good correlation between Δ and $C_{\tau 0}$ indicates that the increase in the integrated blade force is caused mainly by the weakening effect of the pressure rises on the suction surface in the tip region, i. e., by the attenuation of the endwall crossflow impinging upon the suction surface.

4. Conclusions

It has been shown that the boundary layer fences attached to the passage-confining endwalls of the turbine rotor cascade are capable of increasing the tangential component of the aerodynamic force exerted on the blade. The fences are most effective when they are one-third of the inlet boundary layer thickness in height and located half a blade pitch away from the blades, reducing the force defect thickness to 60 percent of the normal blading value. This optimum combination of height and location of the fences coincides with the combination at which the secondary flow and loss were minimized.

On the blade suction surface in the normal blading cascade, there are local rises in static pressures ascribable to the impinging endwall crossflow, local pressure rises associated with the passage vortex three-dimensional separation, and local pressure drops due to the passage vortex. The reduction in the force defect

thickness by the fences results mainly from the weakening of the crossflow-induced local pressure rises, which offsets the weakening of the local pressure drops. The point of minimum static pressure on the endwall in the throat region moves onto the intersection of the suction surface with the endwall when the optimum fences are installed.

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