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Effect of Incidence Angle on Wake Characteristics of High Deflection Turbine Rotor Linear Cascade

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ABSTRACT

The wake characteristics of a high deflection turbine rotor linear cascade at three incidences (one at zero incidence and one each at above and below zero incidence) are presented. Flow properties across the wake at various axial distances downstream the blade trailing edge were measured with a small five hole probe. The wakes are asymmetrical about the wake centre near the trailing edge, due to differential growth of the boundary layers on the pressure and suction surfaces of the blade. The total velocity defect at all incidences is represented by the Gaussian function given by $e^{-0.693\eta^2}$. Static pressure in the wake increases towards the wake centre. Location of maximum static pressure is different from that of minimum stagnation pressure and occurs always on the suction side. The total velocity defect is maximum at negative incidence and minimum at zero incidence.

INTRODUCTION

Wakes are a major source of losses, inefficiency, unsteady flows and noise in turbomachinery. The inlet flow to a blade row is non-uniform due to the wakes of the preceeding blade row. This gives rise to unsteady flows when a rotating blade row cuts into the wake of the preceeding stationary blade row or vice versa. Noise and vibrations are generated. Hence detailed investigations on turbomachinery wakes are necessary for their understanding and modeling.

Although there is a substantial work done on compressor wakes, (both cascades and rotors), there is very little information available on turbine wakes. Sitaram et al (1986) measured wake characteristics of a high deflection turbine rotor linear cascade at zero incidence. In the present investigation, wake characteristics of the same cascade are measured at postive and negative incidences and compared with those at zero incidence.

EXPERIMENTAL FACILITY, TECHNIQUE AND ACCURACY

The low speed cascade tunnel CT1 of Thermal Turbomachines Laboratory at the Indian Institute of Technology, Madras is used in the present investigation. A detailed description of the tunnel is given by Govardhan (1984). The test section is rectangular channel of constant span of 400 mm with provision for varying the height from 200 mm to 430 mm and for varying the incidence angle. A schematic view of the cascade tunnel is shown in figure 1.

The details of the cascade used in the present investigation are given below:

Inlet blade angle	α_{1b} =	57.5°
Exit blade angle	α_{2b} =	-62.5°
Design turning angle	ε =	120°
Stagger angle	γ =	12.5°
Blade height	h =	400 mm
Blade chord	ch =	90 mm
Axial chord	e=	88 mm
Aspect ratio	AR =	4.4
Space-chord ratio	S/ch =	0.35
Number of blades	Z =	13
Trailing edge thickness/ chord t_{te}/ch	=	0.05
Maximum thickness/ chord t_{max}/ch	=	0.38
Position of maximum thickness X/e	=	0.42

A schematic of the cascade is shown in figure 2. The wake was surveyed at a Reynolds number (based on the chord and exit total velocity) of 2.7×10^5 and exit Mach number of 0.15. The inlet turbulence was about 1% . The wake was measured with a small five--hole probe (diameter=3.7 mm). The probe was used in the non-nulling mode suggested by Treaster and Yocum (1978). This probe was mounted in a traverse mechanism, which provides automatic motions in the cascade pitchwise and spanwise directions and rotation about the probe support. In addition axial motion was manually possibe. The probe was used to measure wakes at the axial stations given in table 1. The wake was measured at the cascade mid span, where the flow was two-dimensional. The probe measurements were subjected to many sources of errors, such as velocity or pressure gradients, wall vicinity, turbulence etc. A detailed description of these sources of errors and estimates of their magnitude for five-hole probes and other pressure probes were given by Sitaram et al (1981). For the present investigation, the following experimental accuracies are estimated.

Axial position of the probe	:	± 0.2 mm
Pitchwise position of the probe	:	± 0.01 mm
Flow and spanwise angles	:	± 1°
Stagnation land static pressures	:	± 1% of settling chamber pressure.

EXPERIMENTAL RESULTS AND INTERPRETATION

The experimental results are presented and interpreted here. Due to lack of space, only total velocity, static and stagnation pressures are presented. All the tabulated data are available from the authors.

Blade static pressures: Blade static pressures at various axial stations at the three incidences are shown in figure 3. They follow same trend at all incidences. Lift coeficient at positive incidence is more than that at zero and negative incidences.

Total velocity profiles: Distribution of total velocity across the wake and at various downstream stations is normalized by the free stream total velocity at that particular axial statioon (Fig.4). As the free stream total velocity is slightly different on suction and pressure sides, probably due to minor difference in adjacent blades and their arrangements, the total velocity in each side is normalized by the free stream total velocity of that side. The distance across the wake is normalized by the blade spacing. Slightly more than half spacing is covered on either side of the wake. The pitchwise station, where the stagnation pressure is minimum at each axial station is taken as wake centre (y=0) at that axial station. This criterion, rather than minimum total velocity criterion, is chosen, because the error, due to the large gradients present in the wake centre, in the stagnation pressure measurements is less than the corresponding error in the total velocity measurements.

The total velocity profiles at all incidences are asymmetrical about the wake centre indicating differential growth of the boundary layers on the two surfaces of the blade. At far downstream stations the wake tends to become symmetrical because of wake spreading and mixing with free-stream as well as interchange of momentum and energy on either side of the wake.

At both positive and negative incidences, the wake defect is more than that at zero incidence at all axial positions. At negative incidence, the wake defect is more than that at positive incidence.

Stagnation pressure profiles: Distribution of stagnation pressure across the wake and at all axial stations is shown in figure 5. The stagnation pressures are normalised by the free stream stagnation pressure on the corresponding side of the wake center. The stagnations pressure profiles are asymmetrical about the wake centre due to the differential growth of boundary layers on the two surfaces of the blade. But this asymmetry is less compared to that of the total velocity.

The defect in stagnation pressure at negative incidence is more than that at positve and zero incidences at all axial stations. For example, the defect in stagnation pressure at Z=0.055 is 0.5, 0.34 and 0.25 at negative, positive and zero incidence respectively.

Static pressure profiles: Distribution of static pressure across the wake and at all axial stations is shown in figure 6. The static pressures are normalised by the free stream stagnation pressure on the corresponding side of the wake centre. The static pressure increases towards the wake center at all axial stations. The increase is as much as 35% of free stream stagnation pressure at the axial station nearest to the trailing edge. Similar increases are reported for the wake of compressor rotors (Ravindranth and Lakshminarayana, 1980 and Thompkins and Kerrebrock, 1975). The static pressure profiles are also asymmetric about the wake centre, due to the differential growth of boundary layer on the two surfaces of the blade. At downstream axial stations, the static pressure becomes uniform across the wake. It is also noted that the maximum static pressure occurs at a pitchwise location different from that of the minimum stagnation pressure, at all incidences. The difference in these locations is as much as 20% of blade spacing. The maximum static pressure always occurs in the suction side of the wake.

Similarty of total velocity profiles: Experimental evidence of similarly of velocity profiles was presented for the wakes of compressor cascades and rotors by Raj and Lakshminarayana (1973) and Ravindranath and Lakshninarayana (1980) respectively. The deflection is relatively small for these cases. In this section velocity similarity is examined for a large deflection turbine rotor cascade at non-zero incidences. The velocity defect is normalised by the maximum velocity defect. The non-dimensionalising factor for the pitchwise distance is the wake width at half the maximum velocity defect. Corresponding half wake width for the pressure and suction sides are taken respectively. Using this method, similarity was examined for the total velocity profiles and is shown in figure 7. It is interesting to note that the similarity exists for a heavily loaded turbine rotor linear cascade at all the three incidences. The normalized wake defect follows the Gaussian distribution, given by $e^{-0.693\eta^2}$.

Axial variation of wake width: Variation of wake width along the axial direction is shown in figure 8 at all incidences. Wake width is taken as the sum of half wake widths on the pressure and suction sides of the blade. At all incidences, the wake width increases rapidly near the trailing edge. At negative incidence, the wake width remains more or less constant beyound Z = 0.085. At positive incidence, the wake width increases rapidly compared to that at zero incidence.

Axial variation of maximum total velocity defect: Variation of maximum total velocity defect along the axial direction at all incidences is also shown in figure 8. The maximum velocity defects is normalized by the free stream total velocity. As the free stream total velocity is slightly different on both sides of the wake centre, average of free stream total velocities on the pressure and suction sides is taken. At all incidences, the maximum velocity defect decreases rapidly near the trailing edge and slowly away from it. The velocity defect is maximum at negative incidence, and minimum at zero incidence. Beyond Z = 0.114, velocity defects at the three incidences are more or less equal and remain fairly constant with the axial distance.

CONCLUSIONS

Wake characteristics of a high deflection turbine rotor linear cascade at three incidences are reported in the present investigation. From this investigation, the following major conclusions are drawn.

At all incidences, flow properties (total velocity static and staganation pressures) are asymmetrical about the wake centre and tend to become symmetrical at axial distance away from the trailing edge. This is due to the asymmetric growth of boundary layer on the pressure and suction surfaces of the blade. The total velocity at all incidences becomes symmetrical and similar when the defect is normalized by its defect at the wake center and the lengths by corresponding wake half width. All the similarity profiles follow the Gaussian function given by $e^{-0.693\eta^2}$.

Static pressure in the wake increase towards the wake centre. Locations of maximum static pressure and minimum stagnation pressure differ at all axial stations. Maximum static pressure always occurs on suction side. The velocity defect is maximum at negative incidence and minimum at zero incidence. The maximum velocity defects decreases rapidly at negative incidence, less rapidly at positive incidence, more slowly at zero incidence. Wake width increases rapidly at positive incidence, less rapidly at zero incidence and remains fairly constant at negative incidence.

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NOMENCLATURE

e	Blade axial chord, m
L	Wake width, normalised by blade spacing, $=L_s+L_p$
L_p, L_s	Wake width on the pressure and suction sides, where the wake defect is one half of the maximum wake defect, (normalised by the blade spacing), respectively
P	Static pressure, N/m^2
P_o	Stagnation pressure, N/m^2
PS	Pressure side
S	Blade spacing, m
SS	Suction side
V	Velocity, m/sec
X	Axial distance from the blade trailing edge, m
Y	Pitchwise distance from wake centre, m
Z	Non-dimensionalised axial distance, X/e
η	Non-dimensionalised pitchwise distance, $= Y/L_p$ or Y/L_s

Subscripts

C	Wake center line
max	Quantity at the wake edge or maximum value

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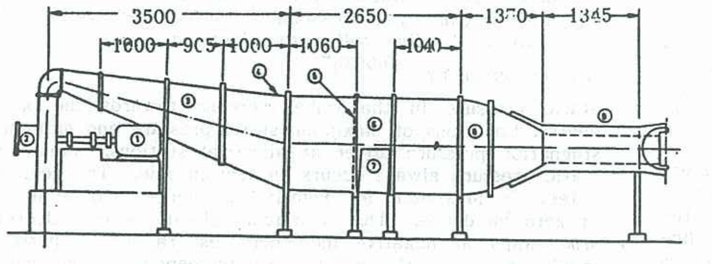
TABLE 1

WAKE MEASUREMENT STATIONS

i	Z 0.028	0.057	0.085	0.114	0.171	0.228	0.341
-5^o	-	x	x	x	x	x	-
0^o	x	x	x	x	x	x	x
5^o	x	x	x	x	x	x	x



1 MOTOR 2 BLOWER 3 DIFFUSER 4 WIRE GAUZE 5 HONEY COMB
6 SETTLING CHAMBER 7 DOOR 8 CONTRACTION 9 TEST SECTION
(ALL DIMENSIONS IN MM)

FIG. 1 LINEAR CASCADE TUNNEL CT1

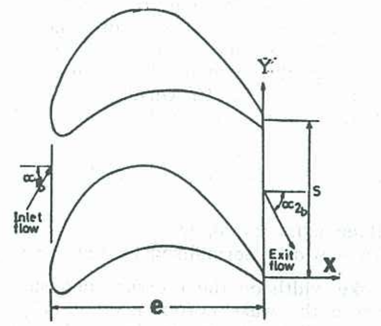


FIG. 2 CASCADE DETAILS.

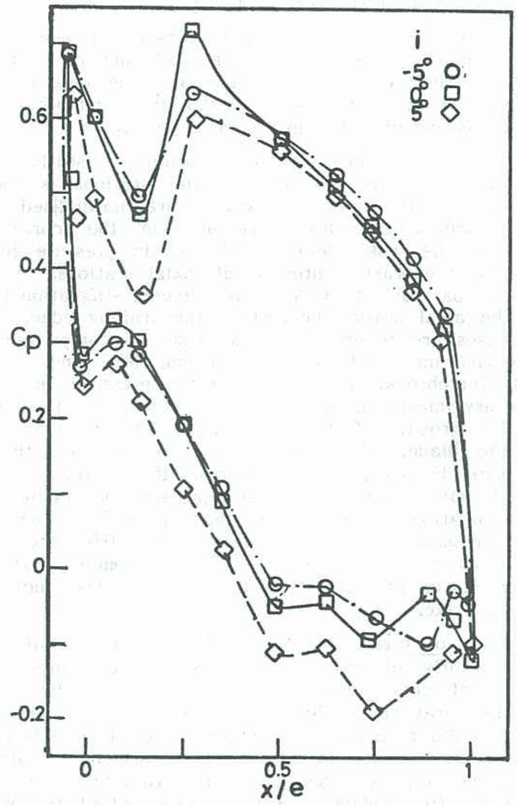


FIG. 3 BLADE STATIC PRESSURE DISTRIBUTION

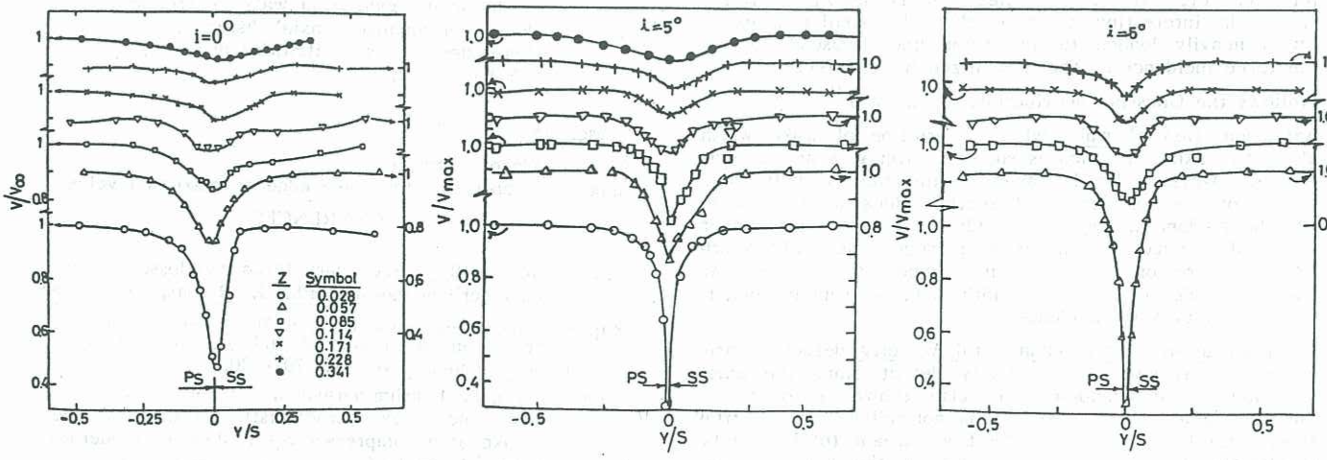


FIG. 4. TOTAL VELOCITY PROFILES

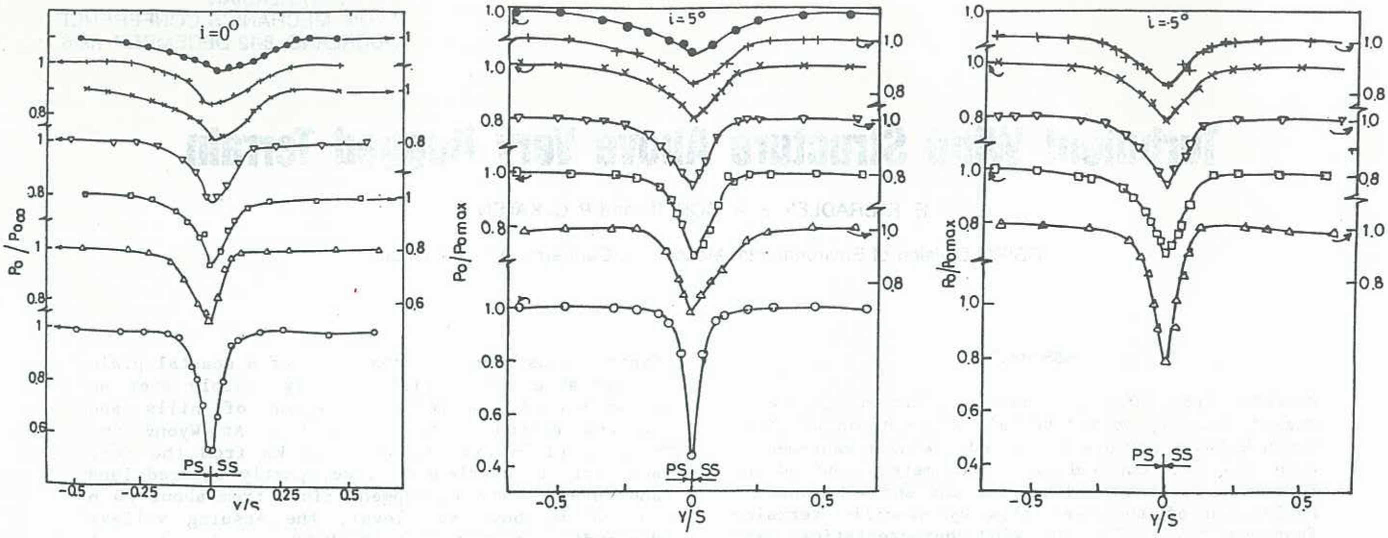


FIG. 5. STAGNATION PRESSURE PROFILES (FOR LEGEND SEE FIG. 4)

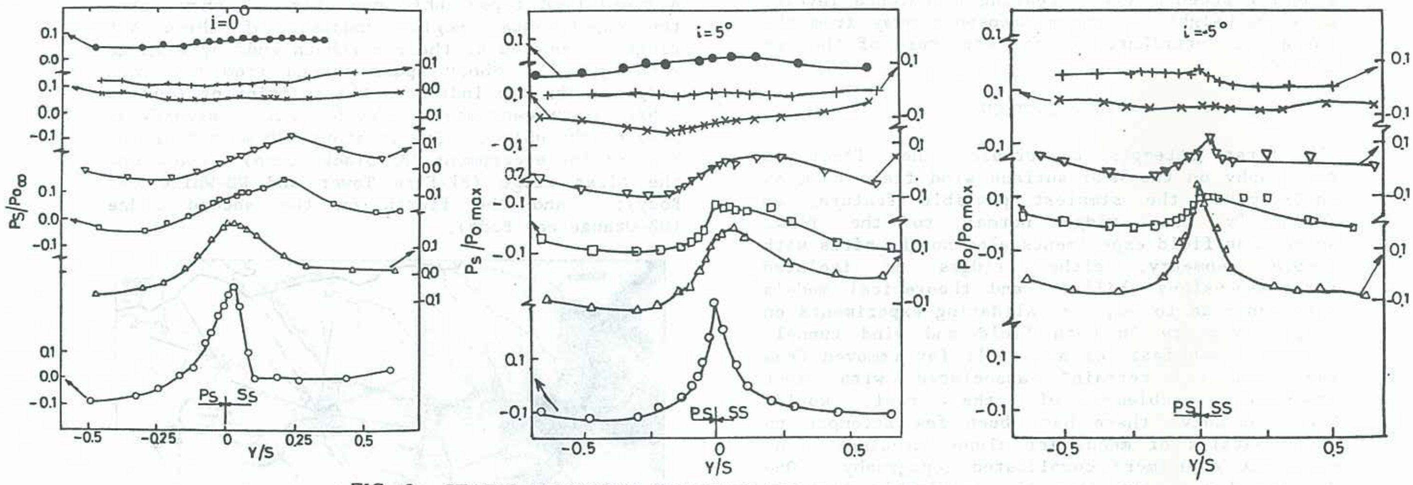


FIG. 6. STATIC PRESSURE PROFILES (FOR LEGEND SEE FIG. 4)

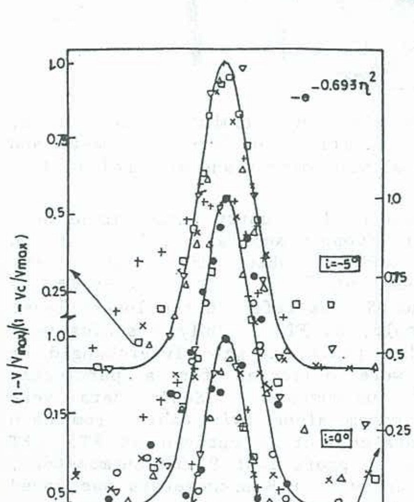


FIG. 7. TOTAL VELOCITY SIMILARITY (FOR LEGEND SEE FIG. 4)

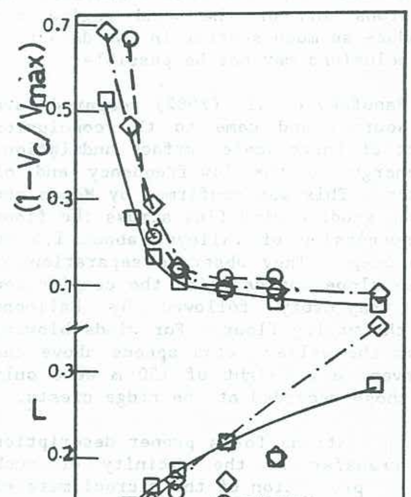


FIG. 8. AXIAL VARIATION OF WAKE WIDTH AND TOTAL VELOCITY DEFECT (FOR LEGEND SEE FIG. 3)