P O L S K A   A K A D E M I A   N A U K

INSTYTUT MASZYN PRZEPŁYWOWYCH

PRACE

INSTYTUTU MASZYN PRZEPŁYWOWYCH

TRANSACTIONS

OF THE INSTITUTE OF FLUID-FLOW MACHINERY

92

WARSZAWA—POZNAŃ 1990

P A Ń S T W O W E   W Y D A W N I C T W O   N A U K O W E

PRACE INSTYTUTU MASZYN PRZEPŁYWOWYCH

poświęcone są publikacjom naukowym z zakresu teorii i badań doświadczalnych w dziedzinie mechaniki i termodynamiki przepływów, ze szczególnym uwzględnieniem problematyki maszyn przepływowych

*

THE TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

exist for the publication of theoretical and experimental investigations of all aspects of the mechanics and thermodynamics of fluid-flow with special reference to fluid-flow machinery

REDAKCJA–EDITORIAL OFFICE

Instytut Maszyn Przepływowych PAN
ul. Gen. Józefa Fiszera 14, 80-952 Gdańsk, skr. pocztowa 621, tel. 41-12-71

ISBN 83-01-10189-X
ISSN 0079-3205

PAŃSTWOWE WYDAWNICTWO NAUKOWE — ODDZIAŁ W POZNANIU

Ark. wyd. 17,75. Ark. druk. 13. Papier druk. sat. kl. III, 70 g, 70 × 100 cm
Oddano do składania w lipcu 1989 r. Podpisano do druku w listopadzie 1990 r.
Druk ukończono w grudniu 1990 r. Zam. nr 1079/89

Zakłady Graficzne im. KEN w Bydgoszczy

PRACE INSTYTUTU MASZYN PRZEPŁYWOWYCH

1990 Zeszyt 92

KRZYSZTOF MAJKA

Koszalin*)

Blade Defect Force Investigation in a Compressor Cascade

The paper presents an experimental study of the blade defect forces in a compressor cascade end-wall boundary layer. The experiments were aimed at improving the general understanding of the end-wall flow field and experimentally verifying the concepts and assumptions underlying the turbomachine integral boundary layer theory.

Notation

C — blade chord,
C_p — pressure coefficient,
C_L — lift coefficient,
f — blade force,
F — blade defect force,
g — tip clearance width,
H — shape factor δ^*/θ, blade height,
i — blade incidence,
p — pressure measured at the blade,
p_a — atmospheric pressure (exit pressure of cascade),
p_0 — upstream total pressure,
w — boundary layer velocity,
W — free stream velocity,
x, y, z — coordinate system corresponding to axial, tangential (pitchwise) and normal to the end-wall directions, respectively,
x' — chordwise direction,
y' — perpendicular to chordwise direction,
δ — physical boundary layer thickness,
δ^* — displacement thickness $\delta^* = \int_0^\infty (1-w/W)\,dz$,
θ — momentum thickness $\theta = \int_0^\infty (1-w/W)w/W\,dz$,
ε_f — most probable fractional error associated with blade force measurements,
ε — uncertainty parameter of Ref. [2],
λ — stagger angle,
τ — shear stress,
ϱ — density.

Subscripts:
1 — cascade inlet,
2 — cascade outlet,
f — force,
$H/2$ — mid-span position,
m — mean, w — wall.

Superscripts: —— pitch averaged.

1. Introduction

The casing and hub boundary layers in turbomachines are important because:
— they determine the flow blockage — the information on this is needed for design,

*) Zakład Termomechaniki i Chłodnictwa, Wyższa Szkoła Inżynierska, Koszalin

— they are the location of the greatest aerodynamic losses at the blade ends,

— they have an influence on the working range of the machine eg. stall point.

In recent years a considerable progress has been made in the development of the integral prediction methods for such boundary layers. Those methods are reviewed for example in references [1, 2, 3]. They are based on pitch-averaged axial and tangential or circumferential integral momentum equations and partly on auxiliary equations resulting from certain analytic approximations and simplifying physical assumptions. A momentum integral equation can be obtained in the form

$$\frac{d}{dx}(W_x^2\theta_x)+W_x\delta_x^*\frac{d\overline{W}_x}{dx}=D_x+\frac{\overline{\tau}_{wx}}{\varrho} \tag{1}$$

in the axial direction with similar equations for the tangential or circumferential direction. The term D_x is a term that includes forces due to:

— difference between the blade force in the boundary layer and the force outside it, called the blade defect force,

— apparent stresses that are the consequence of the circumferential averaging of a flow that has variations due to wakes and blade-to-blade velocity variations. To calculate the boundary layer we need information about D_x and a better understanding of the way the force vector varies in the boundary layer. Blade defect force is composed of pressure forces and blade surface shear stresses. The effect of the shear stresses can be taken into account through an appropriate drag coefficient for the boundary layer region. The contribution of the pressure to the blade force is significantly larger than that due to the shear forces. This paper deals mainly with the force defect due to the pressures.

The recently proposed models [3, 5] for the blade defect force calculations seem to be insufficiently accurate. It is felt that exploration of the earlier tip clearance flow models as those of [4, 6] may bring a better insight into the problem. The earlier models are based on the concept that a part of the blade-bound circulation is shed off at the blade tip and a part projected across the tip clearance. Assuming hence the existence of a fictitious blade surface extended over the real one within the tip clearance, it is possible now to consider that a part of lift is carried with the help of that surface through the tip clearance and projected onto the end-wall. The experimental details supporting such model as well as other concepts underlying the turbomachine integral boundary layer theory are discussed below.

2. Experimental details

The experiments were conducted in a low speed cascade wind tunnel of an open cycle configuration exhausting to atmosphere at the exit to the test section. The cascade blades were of 10C4 30C50 profile. They had a chord of 300 mm and were placed at a stagger of 36° at a space-to-chord ratio of 0.633. Three of the centre blades were provided with a simple mechanism allowing them to slide spanwise through slots cut in one of the side walls. The clearance gap between the blade tips and the other cascade end-wall could be varied and precisely adjusted to the required value by a feeler gauge. The central blade was equipped with a large number of pressure taps to enable the chordwise pressure distribution to be measured at the series of stations along the span. The measuring stations were placed particularly close in the tip clearance region. Moreover, the static pressure taps were distributed on the end-wall opposite to the blade tips to measure the wall pressure distribution within the blade passage as well as around the centre blade contour projected at the end-wall to determine the so called lift retained at the wall accordingly to [4, 6].

The results were ploted in the form of a nondimensional pressure coefficient C_p defined as

$$C_p\left(\frac{x'}{C}\right) = \frac{p - p_a}{p_0 - p_a}$$

and presented in two types of graphs. One had the form of C_p distribution along the blade chord (x' axis) and the other one showed the C_p distribution along the blade height, taken as perpendicular to the chord (y' axis). This two-fold presentation of the pressure coefficient C_p allowed to infer the $f_{y'}$ and $f_{x'}$ blade force components. This was accomplished by calculation of the areas enclosed by the C_p curves from both types of graphs. The examples of spanwise variation of the blade force components normalised in respect to their mid-span value are given in Fig. 1. On the same graphs the components of force retained at the wall (jumped across tip clearance) are also marked. The latter were inferred from the static pressure measurements gained by the taps located around the profile contour projected on the end-wall. Knowing the blade force components $f_{y'}$ and $f_{x'}$ the blade force direction was calculated as

$$\alpha_f = \text{arctg}(f_{y'}/f_{x'}). \tag{3}$$

The experiments were run at various blade incidences and for different tip clearances. The inlet velocity far upstream, measured at a distance of 1.2 m from the cascade and treated as the reference velocity, was equal to $W = 34.5$ m/s. This corresponded to the inlet Reynolds number $Re_c = 6.72 \cdot 10^5$ based on the blade chord. The other inlet boundary layer characteristics were as follows: $\delta = 52.5$ mm, $\delta^* = 3.86$ mm, $\theta = 2.79$ mm and $H = 1.38$. The uncertainty intervals associated with the blade force measurements were estimated as $\varepsilon_f = 4.0\%$.

3. Experimental results

Estimation of blade forces using the technique described in the previous section shows considerable differences in their character caused by the presence of the tip clearance. When there is no tip clearance the magnitude of the blade forces falls towards the end-wall (Fig. 1). As a tip clearance is introduced a local rise of blade force can be seen near the blade tip. The position of this kink-like rise is very close to the line where the rolled up leakage vortex leaves the blade suction surface. This

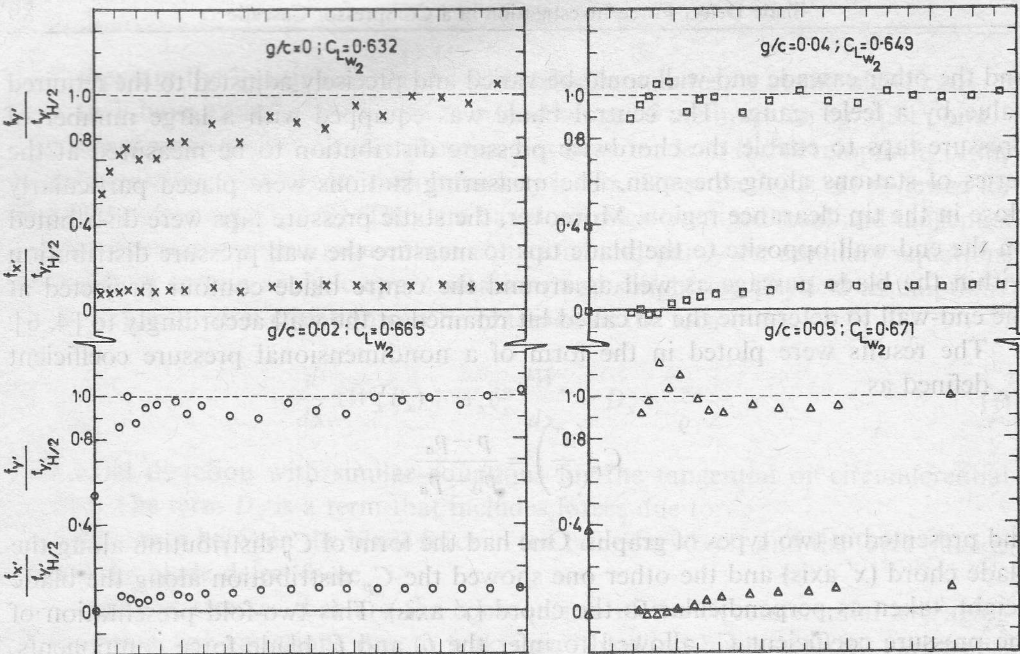

Fig. 1. Spanwise variation of the blade force; $i = +1°$, $g/C = 0, 2, 4, 5\%$

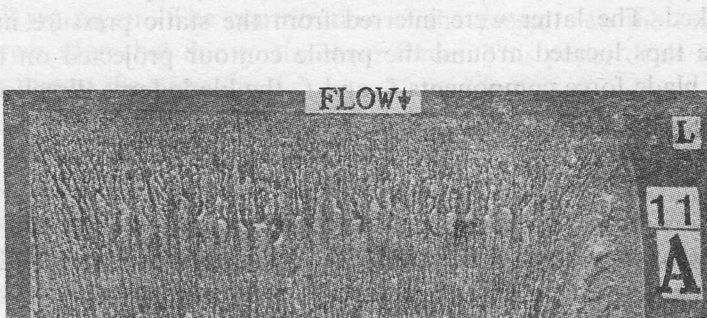

Fig. 2. Surface film traces on the suction blade surface; $i = +4°$, $g/C = 2\%$
L — blade leading edge, T — blade trailing edge, t — tip clearance

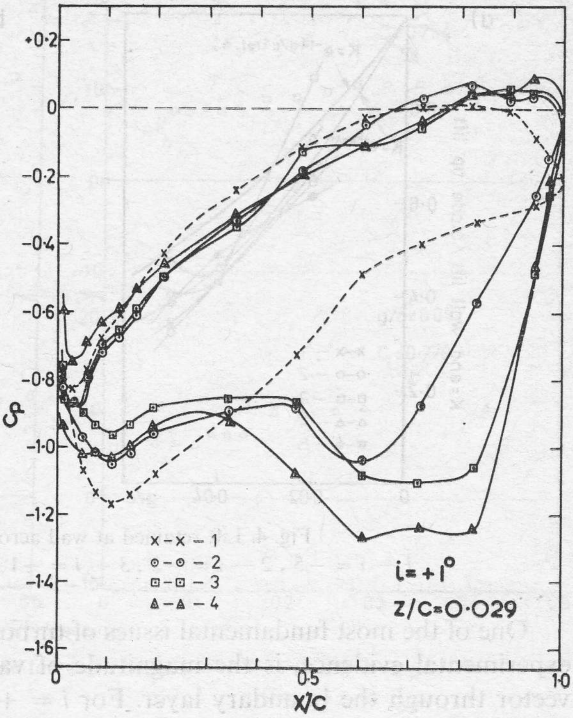

Fig. 3. Spanwise blade pressure distribution, *1* — $g/C = 0\%$, *2* — $g/C = 2\%$, *3* $g/C = 4\%$, *4* $g/C = 5\%$

line is seen very close to the blade edge in the photograph of Fig. 2. At this location the chordwise pressure distributions (for instance Fig. 3) show very large suction pressures resulting in a high local lift. Such kinks of high blade force are especially well marked at higher tip clearances and are present over the whole range of blade incidences investigated.

There is an experimental evidence to adopt in tip clearance flow models the idea of blade force projected across the tip (lift retained at the wall). In Fig. 1 it is seen that forces (f_y component) measured at the blade tip are no less than 80% of their midspan value and that the size of tip clearance does not affect them much. A so called lift retained at the wall [4,6] and evaluated as described in previous section still remains at a level of around 40% of the midspan value. Smaller tip clearances tend to retain a bigger lift at the end-wall. In Fig. 4a the lift retained at the end-wall is presented as a fraction of the blade tip value and in Fig. 4b the same results are plotted with respect to the midspan value. It is felt that the latter presentation may be more useful from the designer's point of view. The midspan lift is certainly a more precisely defined parameter than the lift at the blade tip. Fig. 4b suggests that in the case of $g/C = 4\%$ the end-wall lift is insensitive to the blade incidence. An expression for the lift retained at the wall, in the same form as proposed in [4], was correlated with the present experimental results and is given in Fig. 4b. The numerical values of the curve fitting the present results are different from that given in [4]. The curve equation will, however, also fit the results of [4] for smaller tip clearances which is the range of real importance.

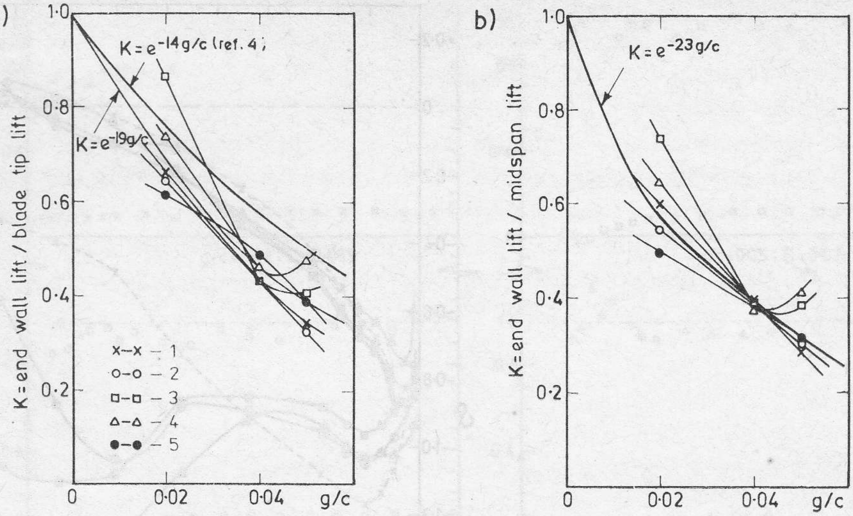

Fig. 4. Lift retained at wall across the tip clearance
1 — $i = -5°$, *2* — $i = -2°$, *3* — $i = +1°$, *4* — $i = +4°$, *5* — $i = +7°$

One of the most fundamental issues of turbomachine boundary layers, still lacking experimental evidence, is the magnitude of variation of the direction of the blade vector through the boundary layer. For $i = +7°$ (Fig. 5) the blade force outside of the boundary layer is inclined to the y' axis at an angle of about 10 degrees. This angle decreases as the blade incidence becomes smaller and is almost perpendicular to the chord at $i = -5°$ (Fig. 6). The above values are independent of the tip clearance magnitude.

In the absence of the tip clearance the direction of the blade force across the boundary layer was found to be constant for all blade incidences investigated. In the experiments the boundary layer at the cascade inlet was collateral but inside the blade passage it was heavily skewed. This implies that the direction of the blade force vector does not seem to be directly related to the skewing of the boundary layer.

As a tip clearance is introduced the local blade force vector within the boundary layer tends to rotate backwards towards the blade trailing edge. The angle between the blade force vector outside the boundary layer and at the end-wall itself was found to be equal to about 10 degrees in the case $g/C = 4\%$ and 5% and decreasing with tip clearance decrease (Fig. 5 and 6). The direction of the blade force vector does not seem to change much across the boundary layer, the change being negligible at the zero tip clearance and limited to a maximum of 10° at 5% tip clearance.

In practical turbomachine boundary layer calculations the blade force effects are incorporated in the form of defect forces and it is also thought that the defect forces control the development of the equilibrium boundary layer state in multistage machines. The present experiments showed that within the boundary layer the local defect forces varied significantly in magnitude and sign depending on their spanwise position and tip clearance (see blade force variation of Fig. 1). However, the direction

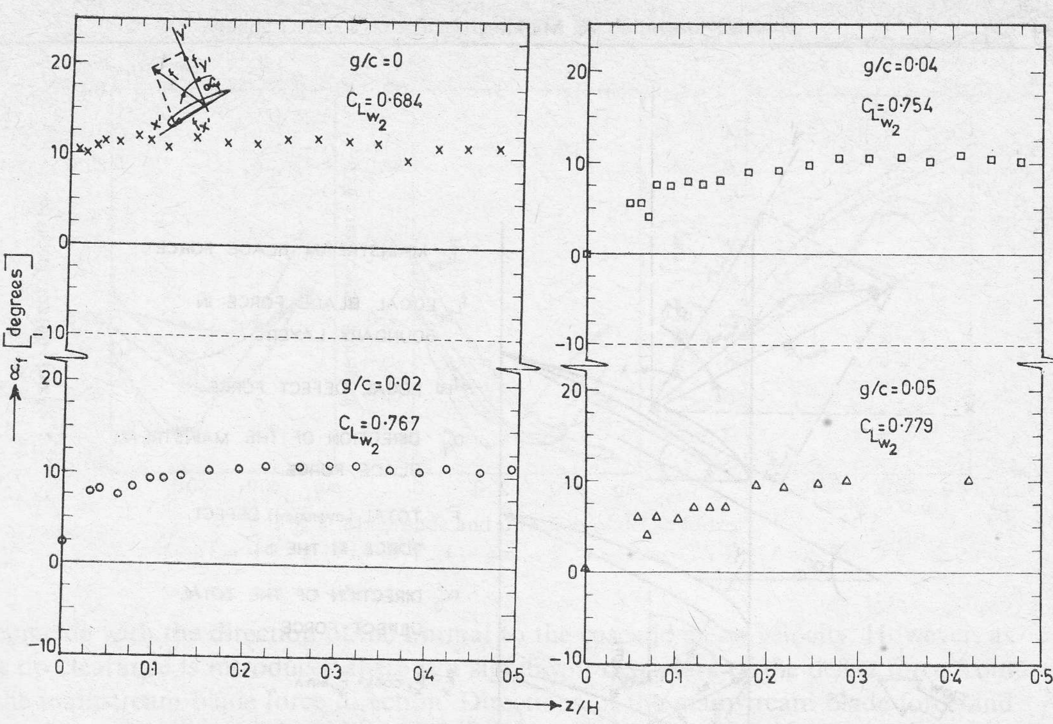

Fig. 5. Spanwise variation of the blade force direction; $i = +7°$, $g/C = 0, 2, 4, 5\%$

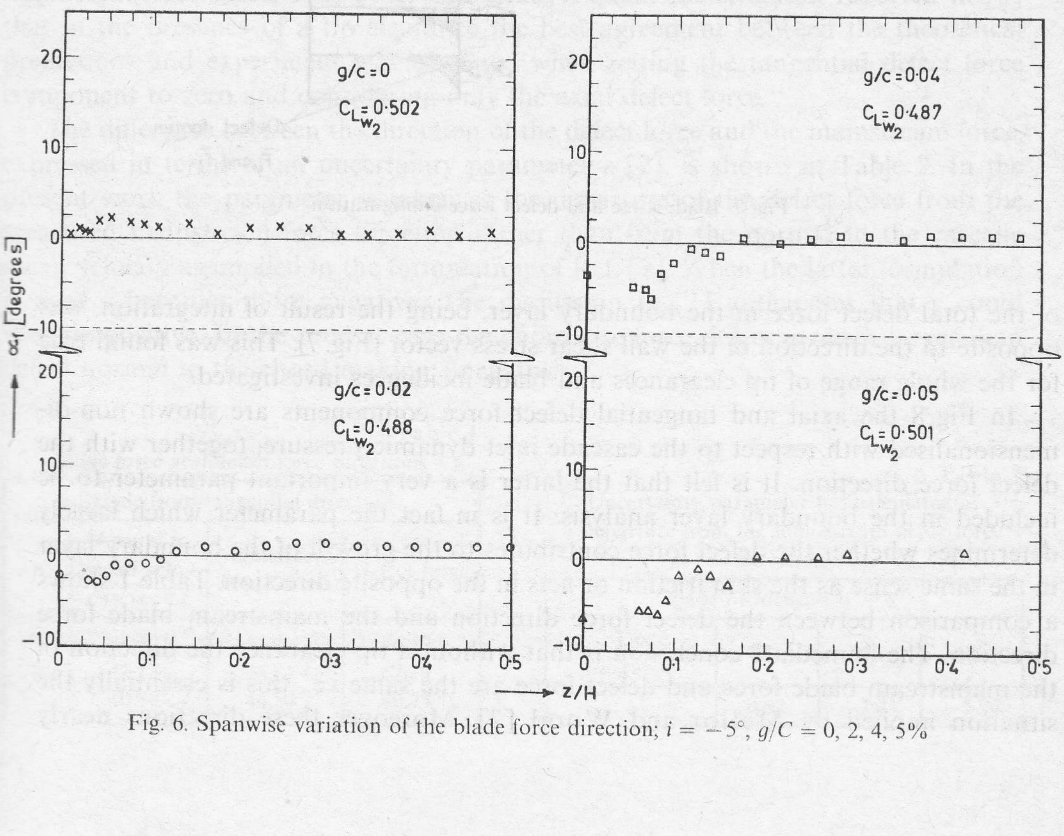

Fig. 6. Spanwise variation of the blade force direction; $i = -5°$, $g/C = 0, 2, 4, 5\%$

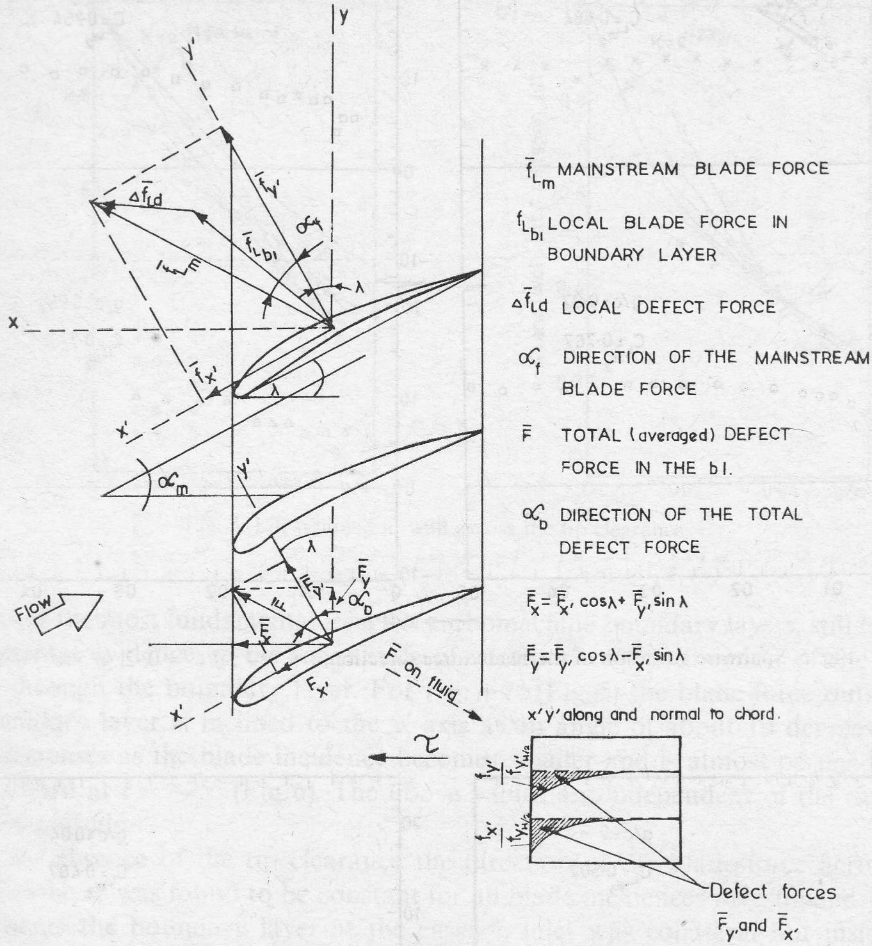

Fig. 7. Blade force and defect force configuration

of the total defect force in the boundary layer, being the result of integration, was opposite to the direction of the wall shear stress vector (Fig. 7). This was found true for the whole range of tip clearances and blade incidences investigated.

In Fig. 8 the axial and tangential defect force components are shown non-dimensionalised with respect to the cascade inlet dynamic pressure, together with the defect force direction. It is felt that the latter is a very important parameter to be included in the boundary layer analysis. It is in fact the parameter which largely determines whether the defect force contributes to the growth of the boundary layer in the same sense as the skin friction or acts in the opposite direction. Table 1 shows a comparison between the defect force direction and the mainstream blade force direction. The immediate conclusion is that without a tip clearance the direction of the mainstream blade force and defect force are the same i.e., this is essentially the situation implied by Mellor and Wood [2]. Moreover these directions nearly

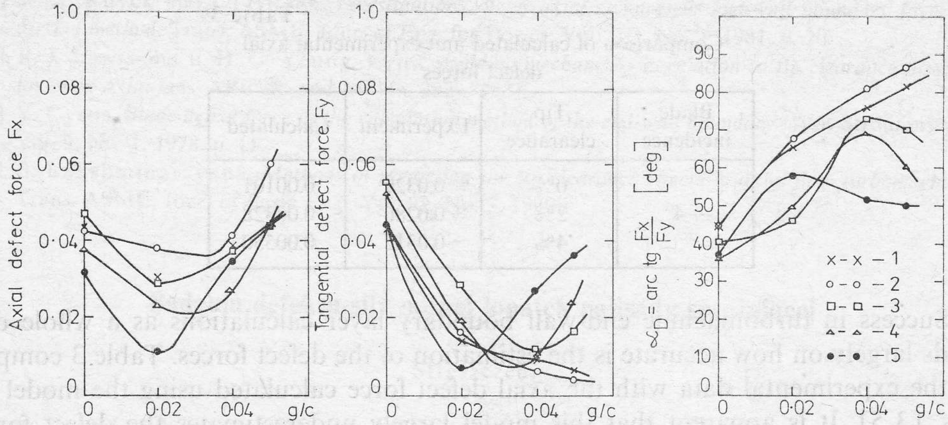

Fig. 8. Magnitude and direction of defect forces
1 — $i = +7°$, *2* — $i = +4°$, *3* — $i = +1°$, *4* — $i = -2°$, *5* — $i = -5°$

coincide with the direction of the normal to the cascade mean velocity. However, as a tip clearance is introduced there is a significant departure of the defect force from the mainstream blade force direction. Directions of the mainstream blade force and the mean cascade velocity seem to be insensitive to the tip clearance (Tab. 1). From Fig. 7 it may be deduced that large values of the defect force angle mean that the defect force vector rotates towards the axial direction and its tangential component significantly decreases. This observation may explain the situation reported in [3] that in the presence of a tip clearance the best agreement between the theoretical predictions and experiment was obtained when setting the tangential defect force component to zero and considering only the axial defect force.

The difference between the direction of the defect force and the mainstream force, expressed in terms of an uncertainty parameter ε [2], is shown in Table 2. In the present work the parameter is taken as the departure of the defect force from the measured mainstream force direction rather than from the normal to the cascade mean velocity as implied in the formulation of Ref. [2]. When the latter formulation is used ε becomes more negative. The discussion of [2] anticipates that ε could become positive. In the present case the chordwise force defect is much larger than defect normal to the chord making ε negative.

Table 1

Blade force and defect force directions

g/C	Angle from tangential direction		
	Normal to mean velocity vector	Mainstream blade force	Defect force
0%	41.40°	45.0°	44.40°
2%	41.13°	44.75°	67.29°
4%	40.79°	44.50°	80.74°

Table 2

Uncertainty parameter [2] calculated as a departure from the mainstream blade force direction

Blade incidence $i = +4°$			
Tip clearance	0%	2%	4%
ε	0.02	−1.41	−5.24

Table 3

Comparison of calculated and experimental axial defect forces

Blade incidence	Tip clearance	Experiment	Calculated
+4°	0%	0.0329	0.00101
	2%	0.0286	0.00328
	4%	0.0312	0.00550

Success in turbomachine end-wall boundary layer calculations as a whole depends largely on how accurate is the estimation of the defect forces. Table 3 compares the experimental data with the axial defect force calculated using the model of Refs. [3, 5]. It is apparent that this model largely underestimates the defect force magnitudes.

4. Conclusions

A considerable local rise of blade force was present near the blade tip. Right at the tip itself the local blade force was about 80% of the midspan value. The so called lift retained at the wall remained at a level of around 40% of the midspan value. These estimates were found to be essentially independent of the magnitude of the tip clearance and blade incidence.

The change in direction of the blade force vector across the boundary layer was small. The experiments showed the change being negligible at a zero tip clearance and limited to a maximum of 10° at 5% tip clearance. Without tip clearance the direction of the maximum blade force and that of the total defect force were found to be the same and nearly coincided with the direction of the normal to the cascade mean velocity. In the presence of a tip clearance the mainstream blade force direction and normal to the mean cascade velocity remained the same but the defect force direction differed from them significantly. In the presence of a tip clearance the assumption frequently made in the calculations that the tangential defect force is equal to zero is justified.

Acknowledgment. The author wish to express his gratitude to prof. S. Soundranayagam of the Indian Institute of Science Bangalore for the support and valuable discussions of the results.

Received by the Editor, March 1984.

References

[1] J. H. Horlock and H. J. Perkins, *Annulus wall boundary layers in turbomachines.* AGARDOGRAPH AG-185 1974

[2] G. L. Mellor and G. M. Wood, *An axial compressor end-wall boundary layer theory.* Trans. ASME, Jour. of Basic Eng., Vol. 93, No. 3, 1971, p. 300.

[3] J. De Ruyck and C. Hirsch, *Investigations of an axial compressor end-wall boundary layer prediction method.* Trans. ASME, Jour. of Eng. for Power. Vol. 103, No. 1, 1981, p. 20.
[4] R. J. Lewis and E. H. G. Yeung, *Vortex shedding mechanisms in relation to tip clearance flows and losses in axial fans.* ARC. R. and M, No. 3829, 1977.
[5] V. Cyrus, *Blade defect force in the calculation method of the end-wall boundary layer.* Strojirenstvi 28, Vol. 9, No. 1, 1978, p. 11.
[6] B. Lakshminarayana, *Methods of predicting the tip clearance effects in axial flow turbomachinery.* Trans. ASME, Jour. of Basic Eng., Vol. 92, No. 3, 1970.

Badania defektu siły nośnej łopatek palisady sprężającej

Streszczenie

W pracy przedstawiono badania eksperymentalne defektu siły nośnej łopatek palisady sprężającej występującego w rejonach warstw przyściennych ograniczających wysokość kanałów łopatkowych. Głównym celem badań było uzyskanie lepszego zrozumienia przepływów w tym rejonie oraz eksperymentalna weryfikacja niektórych koncepcji i założeń formujących całkową teorię warstwy przyściennej maszyn przepływowych.

Исследования аэродинамического дефекта рашётки компрессорных лопаток

Резюме

В работе представлены экспериментальные исследования аэродинамического дефекта решётки компрессорных лопаток, появляющегося в районах пограничных слоёв ограничивающих высоты межлопаточных каналов. Основной целью исследований были: достижение лучшего изучения течений в этом районе, а также экспериментальная проверка некоторых идей и предположений формирующих интегральную теорию пограничного слоя проточных машин.