POLSKA AKADEMIA NAUK
INSTYTUT MASZYN PRZEPŁYWOWYCH

PRACE INSTYTUTU MASZYN PRZEPŁYWOWYCH

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

70-72

WARSZAWA–POZNAŃ 1976

PAŃSTWOWE WYDAWNICTWO NAUKOWE

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

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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

PAŃSTWOWE WYDAWNICTWO NAUKOWE – ODDZIAŁ W POZNANIU

Wydanie I. Nakład 630+90 egz. Ark. wyd. 63,25 Ark. druk. 49,25 Papier druk. sat. kl. V. 65 g., 70×100. Oddano do składania 4 VII 1975 r. Podpisano do druku w czerwcu 1976 r. Druk ukończono w czerwcu 1976 r. Zam. 528/118. H-16/245.
Cena zł 190,–

DRUKARNIA UNIWERSYTETU IM. ADAMA MICKIEWICZA W POZNANIU

III KONFERENCJA NAUKOWA

na temat

TURBINY PAROWE WIELKIEJ MOCY

Gdańsk, 24 - 27 września 1974 r.

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IIIrd SCIENTIFIC CONFERENCE

on

STEAM TURBINES OF GREAT OUTPUT

Gdańsk, September 24 - 27, 1974

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III НАУЧНАЯ КОНФЕРЕНЦИЯ

на тему

ПАРОВЫЕ ТУРБИНЫ БОЛЬШОЙ МОЩНОСТИ

Гданьск, 24 - 27 сентября 1974 г.

PRACE INSTYTUTU MASZYN PRZEPŁYWOWYCH
1976 Zeszyt 70 - 72

FRITZ LEHTHAUS

Federal Republic of Germany*

Transonic Flow in a Turbine Cascade with High Deflection

(Colour-schlieren-film with high-speed-film passages)

Nomenclature

$t(=36$ mm) – pitch length,
$l(=60$ mm) – chord length,
$t/l(=0.6)$ – pitch-chord ratio,
$\beta_s(=70°)$ – stagger angle,
$\theta(=110°)$ – geometric deflection angle,
β – flow angle,
p – static pressure,
w – velocity,
a – sonic velocity,
$M=w/a$ – Mach number,
ν – kinematic viscosity,
$Re=wl/\nu$ – Reynolds number.

Indices

1 – homogeneous inlet flow,
2 – homogeneous outlet flow.

1. Introduction

For some time past it has turned out that transonic flow phenomena are of great importance for the development of advanced turbines in the field of gas turbines for stationary power plants or in aircraft engines as well as in the domain of the last stages in steam turbines with high work output.

Because of the difficulty to describe the complex three-dimensional-flow in the blade rows by a computational method it is a widely used practice in axial-turbomachinery to look at this problem as the coupling of the flow in a meridional plane and another one in a circumferential plane, to study these two flows separately and to adjust them together in an iteration process. By unrolling the circumferential plane, the two-dimensional-cascade-flow problem is defined.

In the DFVLR-AVA institute of fluid mechanics, Göttingen, a small group is working in the field of transonic flow in turbine cascades. The aim is the development or improvement of computational methods for the design problem as well as for the recomputation task and the verification of these methods by experiments [3, 4].

For the experimental work the institute disposes of two test facilities for the investigation of cascades: a windtunnel for straight cascades and a windtunnel for rotating cascades [1, 2]. Rough descriptions of these two facilities and the main fields of research and testing are given in table 1 and 2.

* DFVLR-AVA, Institut für Strömungsmechanik, Göttingen.

Windtunnel for straight cascades

Location: 34 Göttingen, Bunsenstraße 10
(DFVLR-Institut für Strömungsmechanik)

Operational Date: 1955

Short Description of the Facility: The windtunnel operates intermittently with an open circuit. Atmospheric air runs through a dryer, a setling chamber, and the test section into a vacuum vessel (10 000 m^3). The testing time is about 50 seconds.

Test Section: Designed for cascades with an inlet flow angle ($15° < \beta_1 < 165°$) and rectangular cross-section of variable height: 38 cm (max) - 20 cm (min) × 12.5 cm

Velocity: $v_{min} = 10$ m/s; $v_{max} = 800$ m/s continuous variation by a throttling diffusor.

Stagnation Pressure: $p_0 = \text{const.} \approx 1.0$ bar

Stagnation Temperature: $T_0 = \text{const.} \approx 300°K$

Reynolds Number based on 1 m Length: 0.8 to $1.6 \cdot 10^7$ 1/m

Typical Model Size: Blade span 12.5 cm; blade chord length: 6 cm

Proved Measurement Techniques:

Force Measurements: None
Pressure Measurements: Wake-flow-measurements, pressure distribution measurements on fixed cascades, unsteady pressure measurements on oscillating cascades (Traversing probes, multimanometer, pressure transducer)
Other Measurements: Colour schlieren system and High-Frequency-Camera (max. 10 000 pictures/s)

Measurement Recording and Computation: Data recording, EDP in computing center.

Special Equipment: Suction of boundary layer in front of the cascade (presently not in operation)

Main Fields of Research and Testing: Straight turbine cascades in sub-, trans- and supersonic flow (max. Mach number of the downstream flow: $M_2 < 2.5$)

Table 2

Windtunnel for rotating cascades

Location: 34 Göttingen, Bunsenstraße 10
(DFVLR-Institut für Strömungsmechanik)

Operational Date: 1972

Short Description of the Facility: Closed circuit, independent variation of Mach and Reynolds number. Power of the 4-stage radial compressor: 1000 kW (max 1500 kW). The test wheel can be driven or braked with a power generator of 500 kW (max 700 kW).

Test Section: Medium cascade diameter: 52 cm, blade height 2.5 to 5.5 cm, ratio of inner to outer diameter: 0.91 to 0.81.

Velocity: Max 800 m/s, continuously changeable.

Stagnation Pressure: $p_{0\ min}=0.05$ bar to $p_{0max}=1.5$ bar

Stagnation Temperature: $T_0=300°K$ to $370°K$

Reynolds Number based on 1 m Length (Relative System):

Air:	$Re \leqslant 1.2 \cdot 10^7$ 1/m
Freon 12:	$Re \leqslant 6 \cdot 10^7$ 1/m

Typical Model Size: Blade span: 5.5 cm (max)
blade height: 5.5 cm (max)

Proved Measurement Techniques:

Force Measurements:	Force measurements by torque meter
Pressure Measurements:	Probes, pressure transducers, Scanivalve
Other Measurement equipments:	Temperature measurements, schlieren system

Measurement Recording and Computation: Data recording, EDP in computing center.

Special Equipment:

The facility can be operated with dry air or Freon 12.
Investigation possible with stator cascades up- and/or down-stream of the rotating cascade.

Main Fields of Research and Testing:

Annular or rotating turbine cascades in sub-, trans-, and supersonic flows. (max. relative Mach number of the downstream flow $M_2 \leqslant 2.5$)

Expecially the arrangement in the test section for straight cascades allows to contribute in a relative simple way to the results of the other measurements by optical means and so to improve the understanding of the physical behaviour of the flow [5].

This short report is only to give an introduction to the film "Transonic flow in a turbine cascade with high deflection", which represents an example for the visualisation of the two-dimensional flow field by colour-schlieren-technique.

2. Flow-visualisation by Schlieren-Technique

Figure 1 gives a scheme of the schlieren-optic-arrangement used for flow visualisation in the test facility for straight cascades.

Dry atmospheric air flows through the test section with a straight turbine cascade and through a subsequent adjustable rotational throttling diffusor into a vacuum vessel.

The optical system shown in this figure allows to choose as a light source a continuously burning xenon-lamp or a spark flash stabilized by argon with a flash duration of about twenty nanoseconds. An image of the choosen light source with a subsequent double-slit

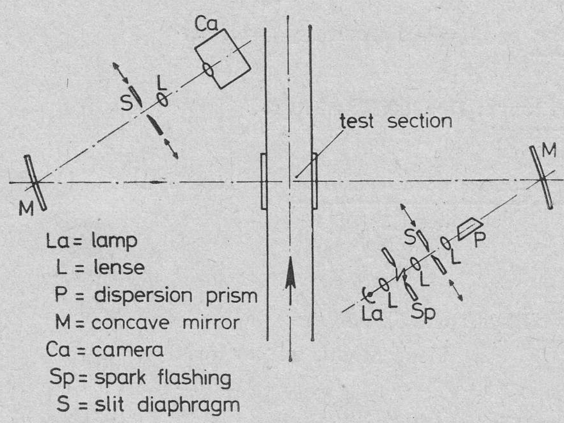

Fig. 1. Arrangement of schlieren-optics.

diaphragm for the adjustment of the light efficiency is projected by a system of achromatic lenses into the focusing plane of a concave mirror. By adaption of a dispersion prism just behind this image of the light source a colour schlieren system is obtained.

Parallel light is crossing the test section with the cascade and focused by a second concave mirror in the plane of a knife edge or a slit diaphragm for black-white or coloured schlieren reproduction respectively. The defraction of the light in the test section causes in the produced picture of the test section a darkening or brightening or – respectively – deviations from the chosen basic colour which are proportional to the density gradients of the flow in one direction. This direction is defined by the direction of the knife edge or – respectively – by the direction of the dispersion prism on one side and of the slit diaphragm on the other side.

For the following film the described colour schlieren system is used with the continuous xenon-lamp as light source and two different cameras, one of conventional type with a pick-up frequency of 25 frames/second and a high-speed-camera with a regulated pick-up frequency of 5000 frames/second.

The central spectral colour yellow-green is chosen as the basic colour associated with zero density gradient in the tested flow field. Flow expansion produces a deviation to yellow and red, compression to green and blue. The four black-white schlieren pictures of this report are taken with the spark flash mentioned above.

3. Contents of the film

Figure 2 gives the geometry of the cascade, which is shown in the film. The profiles have a geometric deflection angle $\theta \approx 110°$. They are composed to a cascade with the stagger angle $\beta_s = 70°$ and the pitch chord ratio $t/l = 0.6$. This cascade was designed for a high-

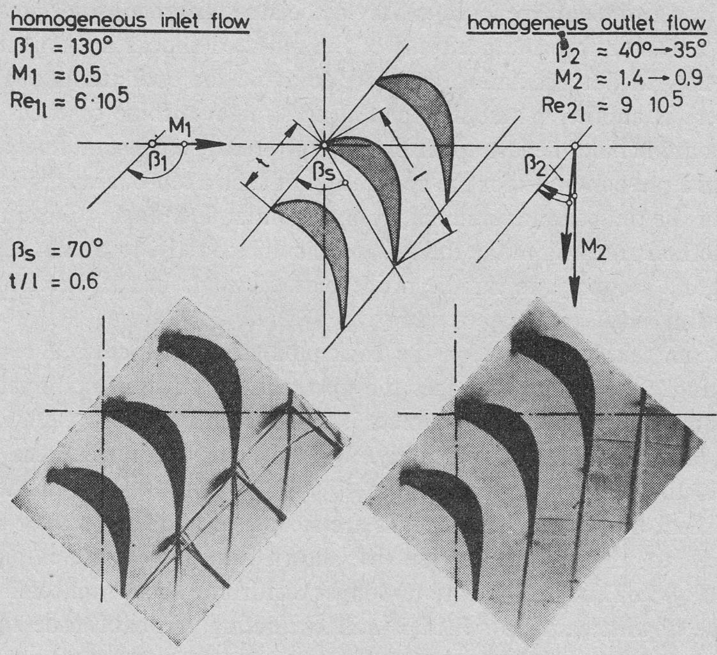

Fig. 2. Transonic 2-D-cascade flow for increasing back pressure

loaded gas turbine rotor blade row, but the geometry of cascades for the inner sections (between the middle and the hub section) of a rotor in one of the last stages of a steam turbine and also the flow conditions in these cascades may be very similar.

3.1. Variation of back pressure

In the first part of the film the changes in the transonic two-dimensional cascade flow field are produced for a fixed inlet flow angle $\beta_1 = 130°$ by increasing the back pressure p_2 continuously.

The schlieren picture on the left side of Fig. 2 represents the flow situation shown in the beginning of the film. The pressure ratio across the cascade is supercritical, the flow is accelerated from subsonic to supersonic velocity. The cascade is "choked", a change of the outlet Mach number $M_2 \approx 1.4$ does not effect the inlet conditions, the "choking" Mach number $M_1 \approx 0.5$ is coupled with the given inlet flow angle $\beta_1 = 130°$. The nozzle-type expansion in the flow channel between two blades is followed by a Prandtl-Meyer expansion around the trailing edge of the upper profile. The last expansion wave with the subsequent right running oblique shock nearly formes one plane with the outlet of the cascade. The reflection of this shock on the suction side of the lower blade is combined with a small separation buble just in front of the trailing edge. The left running trailing edge shock propagates from its origin into the downstream flow field. This shock is reflected by the jet boundary of the last upper profile and therefore disturbes the periodicity of the outlet flow field. This effect, which is due to the finite cascade, was one of the reasons to build a test facility for annular and rotating cascades. In the case shown here these shocks are reflected by a turbulent free jet boundary-associated with a constant pressure boundary condition – and therefore the positions of the reflected shocks are unstable. The whole downstream flow field is oscillating. In order to avoid the oscillations due to the free jet boundary there is another possibility for testing straight turbine cascades by using a jet leading tail-board behind the last upper blade – producing a constant flow angle boundary condition. But a pre-condition for the application of such a tail-board is, of course, a strong dependence of the outlet Mach number from the outlet flow angle. Certain disadvantages of this test method are lying in the following difficulties: fiıstly, to obtain periodicity of the cascade flow and secondly, to handle probe measurements in the downstream flow field of cascades with small pitch-chord ratios.

Starting from this flow situation the back pressure p_2 is increased continuously.Due to the "choking" of the flow passages the upstream Mach number remains constant at $M_1 \approx 0.5$ as long as the outlet Mach number is higher than unity, $M_2 \gtrapprox 1.0$, while the downstream flow pattern changes significantly. With decreasing downstream Mach number from $M_2 \approx 1.4$ to 0.9 and flow angle from $\beta_2 \approx 40°$ to 35° the Prandtl-Meyer expansion fan is diminished, the trailing edge shocks are steepened and finally there are only shock waves normal to the flow direction as shown on the schlieren-picture on the right side of Fig. 2. Though there are no longer disturbing shocks reflected by the free jet boundary, the downstream flow field is still oscillating, probably due to this unstable boundary.

But another source, that disturbes the stationary flow, may be an unsteady separation process at the trailing edge of the blades and additional reinforcement in presence of shocks by the interaction between these shocks and the instationary wake flows.

This process of the continuous increase of the back pressure p_2 or, respectively, of the continuous decrease of the outlet Mach number M_2 is filmed with a conventional camera for 25 frames/second pick-up-frequency. The process is interrupted for $M_2 \approx 1.4$, 1.1 and 0.9 in order to show for these Mach numbers the local nonstationary effects, mentioned abo ve,by the presentation of three high-speed-film-sections taken with a pick-up-frequency of 5000 frames/second.

3.2. Variation of the inlet flow angle

Figure 3 represents an impression of the second part of the film. The changes in the flow field are produced, for constant back pressure p_2, by increasing the inlet flow angle from $\beta_1 = 130°$ by steps of 3 respectively 5 degrees to $\beta_1 = 160°$. This increase of β_1 is realized by turning the cascade with respect to the inlet flow direction, which remains always horizontally for the spectator.

The flow situation, shown in the beginning of this film-section and represented by the schlieren picture on the left side of this figure, is the same as in the beginning of the first

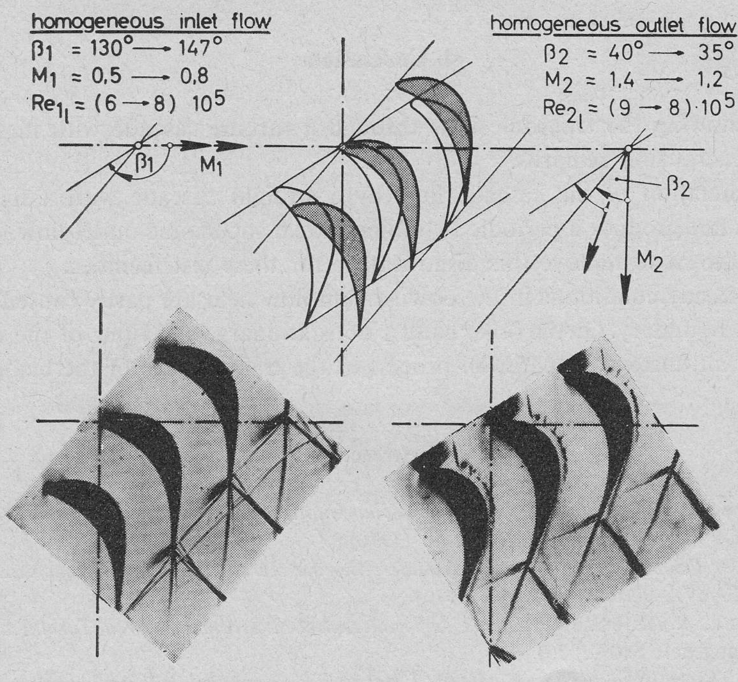

Fig. 3. Transonic 2-DX-cascade flow for increasing inlet flow angle

part and as it is described in the preceding chapter. The flow is attached to the profile surface over the entire pressure side and the suction side except for a small separation bubble in the shock-boundary layer interference region. The picture shows the stagnation point at the leading edge of each profile and the acceleration of the flow around the nose in direction to the suction surface. Knowing from pressure distribution calculations and measurements that sonic velocity is reached on the suction side already in this region and on the pressure side near the trailing edge, it is easy to imagine roughly the curved shape of the sonic line. According to the curvature of the sonic line a recompression zone exists in the middle region of the suction side. Then the flows is again expanded due to the expansion waves propagating from the Prandtl-Meyer-fan at the trailing edge of the upper profile.

Increasing the inlet flow angle, the inlet Mach number M_1 increases, too, due to the decreasing throat-inlet-area-ratio. The accelerating and the following decelerating pressure gradients on the contour of the leading edge of the blade are locally steepened until there are small supersonic pockets ended by normal shocks. Increasing the inlet flow angle further, the flow separates on the suction surface. The schlieren picture on the right side of figure 3 gives an example for an inlet angle $\beta_1 = 147°$. The separation of the flow on the suction side, which is combined with a λ-shock at the separation point, is almost a total one and shows a series of small expansion fans and normal shocks at its boundary. Due to the additional losses, the outlet Mach number decreases.

The film ends with an inlet air angle $\beta_1 = 160°$ which is totally out of the operational range of this cascade.

4. Conclusion

The film showing the transonic flow through a turbine cascade with high deflection allows two generalizing remarks.

– The simulation of the cascade flow by a straight cascade with a finite number of blades does not produce a periodic two-dimensional supersonic outlet flow. No realistic possibility is known to remove this disadvantage for these test facilities.

– The unsteady conditions in the downstream flow field are partly caused by the turbulent free jet boundary. On the other hand a nonstationary behaviour of the outlet flows is imposed by an unsteady separation process at the trailing edge of the blades.

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Przepływ przydźwiękowy w palisadzie turbiny, o dużym odchyleniu

Streszczenie

Referat zawiera opis przepływu przydźwiękowego w palisadzie turbiny, dokonany na podstawie filmu.

Film przedstawia wizualizację pola przepływu w dwuwymiarowej palisadzie silnie odchylających profilów turbinowych, przy użyciu metody Schlierena w kolorze. Warunki nominalne pracy takiej palisady charakteryzują się dużymi poddźwiękowymi wartościami liczby Macha na wlocie i umiarkowanymi naddźwiękowymi wartościami liczby Macha na wylocie.

W pierwszej części filmu wywoływano zmiany pola przepływu zwiększając w sposób płynny przeciwciśnienie. Na skutek dławienia przepływu w kanałach międzyłopatkowych, parametry na wlocie do palisady, liczba Macha i kierunek przepływu, zostają niezmienne tak długo, jak długo liczba Macha na wylocie jest większa od jedności. W tej części filmu pokazano trzy serie zdjęć wykonanych kamerą szybkobieżną (o prędkości 5000 klatek na sekundę), przedstawiające lokalne efekty niestacjonarne w polu przepływu.

W drugiej części, przy stałym przeciwciśnieniu, wywoływano zmiany w polu przepływu drogą skokowego zmieniania kierunku przepływu na wlocie, od warunków nominalnych aż do całkowitego oderwania przepływu na podciśnieniowych stronach profilów.

Околозвуковое течение в сильно отклоняющей турбинной решетке

Резюме

Фильм представляет визуализацию поля течения в двухразмерной сильно отклоняющей решетке турбинных профилей, достигнутую цветным методом полос. Расчетные условия работы такой решетки характеризуются большими околозвуковыми значениями числа Маха на входе и умеренными сверхзвуковыми значениями числа Маха на выходе.

В первой части фильма показаны изменения поля течения, происходящие ввиду плавного увеличивания противодавления. В результате торможения течения в межлопаточных каналах, параметры на входе в решетку, число Маха и направление течения остаются неизменными так долго, пока число Маха на выходе имеет значение больше единицы. В этой части фильма показаны три фрагмента, снятых быстрой камерой (со скоростью 5000 клеток в секунду), представляющих локальные нестационарные эффекты в поле течения.

Во второй части фильма представлены изменения в поле течения, вызываемые при постоянном противодавлении путем скачкообразного изменения направления течения на входе от расчетных условий для данной решетки до полной сепарации течения на вакуумных сторонах профилей.