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113

Selected papers from the International Conference on *Turbines of Large Output* devoted to 100th Anniversary of Prof. Robert Szewalski Birthday, Gdańsk, September 22-24, 2003

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GDAŃSK 2003

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Transactions of the Institute of Fluid-Flow Machinery have primarily been established to publish papers from four disciplines represented at the Institute of Fluid-Flow Machinery of Polish Academy of Sciences, such as:

- Liquid flows in hydraulic machinery including exploitation problems,
- Gas and liquid flows with heat transport, particularly two-phase flows,
- Various aspects of development of plasma and laser engineering,
- Solid mechanics, machine mechanics including exploitation problems.

The periodical, where originally were published papers describing the research conducted at the Institute, has now appeared to be the place for publication of works by authors both from Poland and abroad. A traditional scope of topics has been preserved.

Only original and written in English works are published, which represent both theoretical and applied sciences. All papers are reviewed by two independent referees.

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No. 113, 2003, 3-4

Editorial

These Special Issues of the *Transactions of Fluid-Flow Machinery*, Nos. 113 and 114 contain selected papers from the International Conference on *Turbines of Large Output* devoted to commemorate 100$^{\text{th}}$ Birthday Anniversary of Prof. Robert Szewalski. The conference was held in Gdańsk, Poland on September 22-24, 2003.

The Conference is a continuation of previous conferences held at the Institute of Fluid-Flow Machinery PAS in former years dedicated to technology of steam turbines. Series of conferences bearing the same name took place in the years 1962, 1965, 1968, 1993. In 1997 organised has been a conference on steam turbines and related topics, but with a slightly amended title – *Problems of Fluid-Flow Machinery.* At present at the Institute of Fluid Flow Machinery there are conduced research of fundamental character encompassing both the issues related to steam turbines and fundamentals of power engineering.

Organisers of the present conference have returned to the traditional name, i.e. Conference on *Turbines of Large Output* to mark the respect to the memory of Professor Robert Szewalski (1903-1993), the founder and a director of the Institute of Fluid-Flow Machinery for several years, and initiator of the conference series devoted to the problems of steam turbines.

The Editors are very grateful to the referees of the papers presented in this issue of the *Transactions of Fluid-Flow Machinery*: J. Badur, W. Batko, E. S. Burka, J.T. Cieśliński, P. Doerffer, A. Gardzilewicz, B. Grochal, J. Kiciński, G. Kosman, T. Król, J. Krzyżanowski, J. Mikielewicz, A. Neyman, W. Ostachowicz, R. Puzyrewski, R Rządkowski, J. Świrydczuk, M. Trela, T. Uhl and Z. Walczyk.

We appreciate cordially the manifested authors interest in our conference. Special thanks are conveyed to Ms 'Maya' Bagińska, for her fruitful editorial help related to directing the papers to reviewers and correspondence with the authors of contributions.

Prof. Jarosław Mikielewicz
Editor-in-Chief

Dr Edward Śliwicki
Managing Editor

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

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KRZYSZTOF KOSOWSKI* and ROBERT STĘPIEŃ

Theoretical investigations into flows in rotor blade shroud clearance

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Abstract

Asymmetrical shroud clearance, resulting from rotor-stator eccentricity, causes so called aerodynamic forces, which in turn lead to self-excited vibrations of rotor systems. Numerical investigations were carried out to show how CFD code can cope with determination of the pressure field in a rotor blade tip gap. Calculations of flows on the whole turbine stage circumference were performed in order to investigate the aerodynamic forces generated above the shroud due to asymmetrical pressure field caused by rotor-stator eccentricity. The 3D calculations of axial turbine of impulse type were performed using CFD code Fluent. Different types of shroud geometry were considered. The Multiple Reference Frame method and the Sliding Mesh method were applied and some of the results were compared with the experimental data. Both the techniques appeared to give results similar to those obtained in the experiments. The experimental investigations into the pressure field in the shroud clearance were performed on a one-stage air model turbine. The calculations and measurements of pressure distribution were carried out for different rotor speeds and different turbine load.

Keywords: Turbines; Aerodynamic forces, CFD

1 Introduction

Rotor-stator eccentricity or rotor-stator misalignment change the distribution of the stage clearances, which influences the fluid parameters in flow channels and alters the pressure distribution in radial gaps. This affects the leakage losses and, as a result, the turbine stage efficiency as well. On the other hand, the asymmetrical clearance distribution above the blade shroud (and in glands) creates

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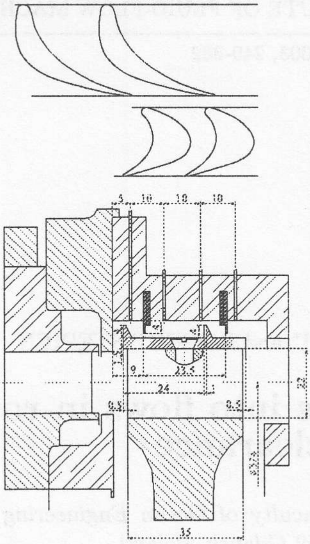


Data

Nominal axial clearance	2.0mm
Nominal radial clearance	0.5mm

Stator

Mean diameter	374 mm
Nozzle height	19 mm
Nominal nozzle chord	74 mm
Nominal nozzle pitch	41.9 mm
Number of nozzles	28
Nozzle stagger angle	39°42'
Nozzle exit angle	9°42'

Rotor

Mean diameter	374 mm
Blade height	22 mm
Blade chord	37.2 mm
Blade pitch	30.9 mm
Number of blades	38
Blade stagger angle	74°30'
Blade exit angle	14°50'

Figure 1. Turbine flow part.

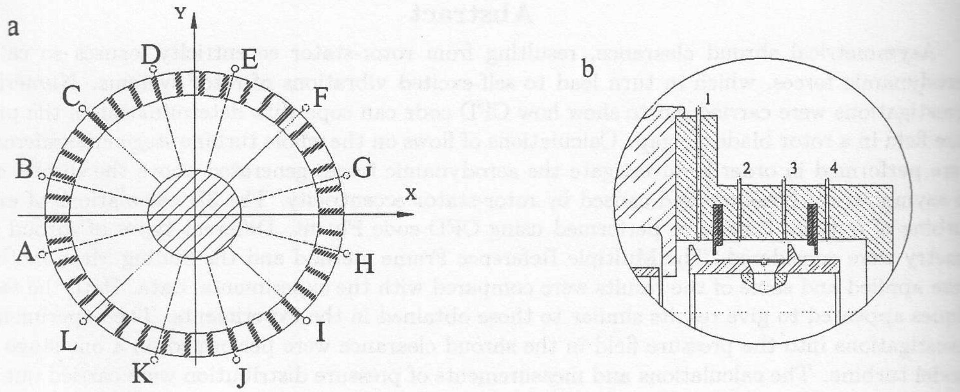
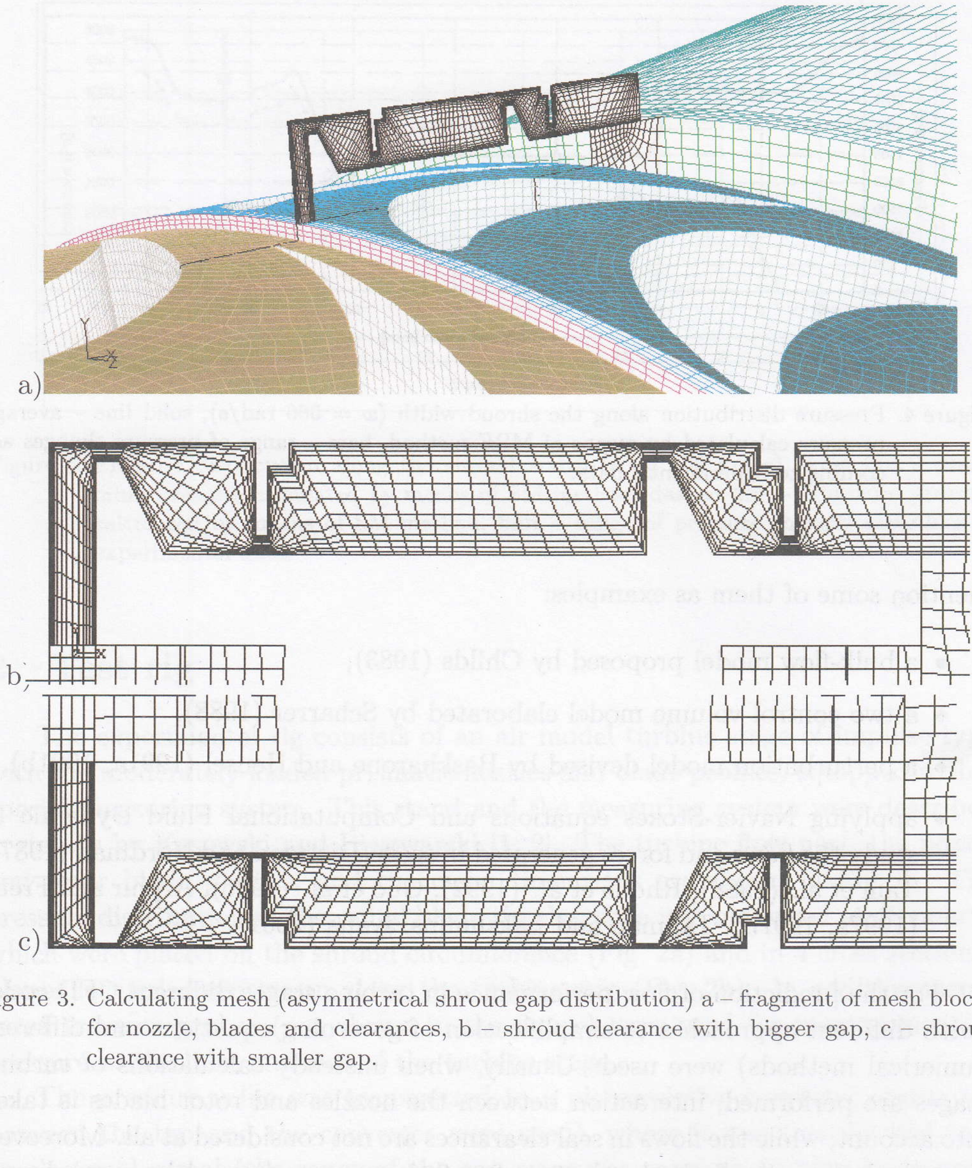


Figure 2. Location of pressure measurement points.

aerodynamic forces and moments acting on the turbine rotor. The distribution of pressure in the seal gaps plays an important role in the generation of so called "pressure forces", which may lead to self-excited rotor vibrations of aerodynamic type. These forces may be estimated primarily as a function of the shroud type, shroud dimensions, radial and axial clearances, and stage output. The resultant vector of "pressure force" is influenced by the rotor displacement (rotor-stator radial and axial displacement as well as rotor-stator misalignment) and by the swirl velocity of the leakage flow in the tip gap. The measurements of flows in



a) b) c)

Figure 3. Calculating mesh (asymmetrical shroud gap distribution) a – fragment of mesh blocks for nozzle, blades and clearances, b – shroud clearance with bigger gap, c – shroud clearance with smaller gap.

seals and experimental investigations into fluid forces were performed by Scharrer (1988), Chids and Scharrer (1988), Kanaki and Kawakami (1988), Morrison et al. (1991), Kanemori and Iwatsubo (1992, 1994), Song and Martinez-Sanches (1997), Marquette et al. (1997), Soto and Childs (1999) and Darden et al. (1999). The unsteady behaviour of the flow field in a nonaxisysmetric tip blade clearance was observed and described by Graf et al. (1998), Xiao et al. (2001), McCarter et al. (2001), Pfau et al. (2001) and Wallis et al. (2001). On the other hand various theoretical models have been elaborated to describe the fluid motion in seals and to determine the aerodynamic forces generated in a shroud clearance. We can

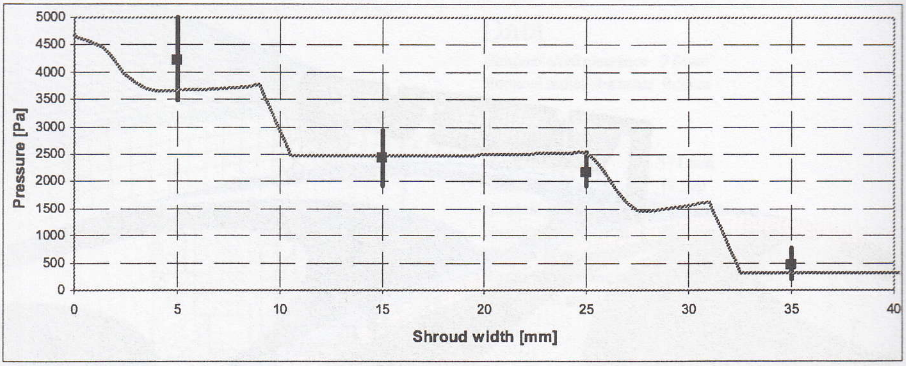


Figure 4. Pressure distribution along the shroud width (ω = 566 rad/s), solid line – average pressure calculated by means of MRF method, bars – range of pressure changes according to experimental data.

mention some of them as examples:

- a bulk-flow model proposed by Childs (1983),
- a two control volume model elaborated by Scharrer (1988),
- a perturbation model devised by Baskharone and Hensel (1991a, 1991b),
- applying Navier-Stokes equations and Computational Fluid Dynamic to study the flows and forces generated in seals (Diettzen and Nordman (1987), Tam et al. (1988), Rhode et al. (1992), Guo et al. (1996), Arghir and Frêne (1997a, 1997b), Tallman and Lakshminarayana (2001).

For the prediction of flow performance in turbine stages different CFD codes (with different approaches to simplification of governing equations and different numerical methods) were used. Usually, when unsteady calculations of turbine stages are performed, interaction between the nozzles and rotor blades is taken into account, while the flows in seal clearances are not considered at all. Moreover, the calculations are limited only to a few flow passages formed by a number of blades. The calculations of flows on the whole stage circumference are very rare, although they seem to be necessary for the proper determination of aerodynamic forces generated as a result of the asymmetrical pressure field above the shroud and non-uniform cascade flows due to rotor-stator eccentricity or rotor-stator misalignment. Taking into account that the pressure (or velocity) field fluctuates, is not smooth and is not stable in the whole flow part of the turbine (in flow channels and gaps), it is very important to check how CFD code can cope with determining the pressure field in a rotor blade shroud clearance.

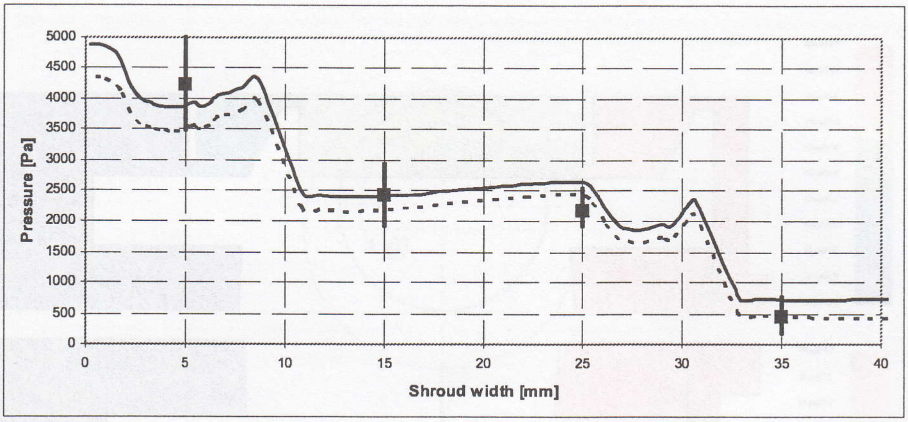


Figure 5. Pressure distribution along the shroud width (ω = 566 rad/s), solid line – maximum pressure calculated by means of SM method, dashed line – minimum pressure calculated by means of SM method, bars – range of pressure changes according to experimental data.

2 Test rig

The experimental rig consists of an air model turbine stage of impulse type with the moderately loaded prismatic nozzles and blade profiles, equipped with a special measuring system. This stand and the measuring system were described in details by Kosowski and Piwowarski [1, 2]. The turbine flow part, the nozzle and rotor blade profiles, and the main dimensions are shown in Fig. 1. The pressure distribution in the radial blade tip clearance was measured at 48 points, which were placed on the shroud circumference (Fig. 2a) and in 4 cross sectional planes located downstream along the turbine axis (Fig. 2b). In addition, some extra traverse probes (not shown in the figure) were used for measurement of pressure at the inlet and exit of the turbine stage.

The pressure value was transmitted to a piezoresistive converter (tubes in-between the tap and the converter were used), where it was transformed into an electrical signal (the range of the converter was equal to 10 kPa, its natural frequency – about 1 kHz). This signal was amplified and transmitted to a PC extension card. Measurements of pressure were usually performed with sampling time equal to 0.0002 s, which is relatively short compared to the pressure pulsation period equal to 0.025 s – 0.1 s. The recorded pressure signals were filtered and time-averaged by numerical methods. The continuous pressure distribution in the shroud clearance was obtained by means of the cubic-spline method. Changes of static pressure across a stator pitch and the location of measurement points were taken into account when the averaged pressure distribution was determined.

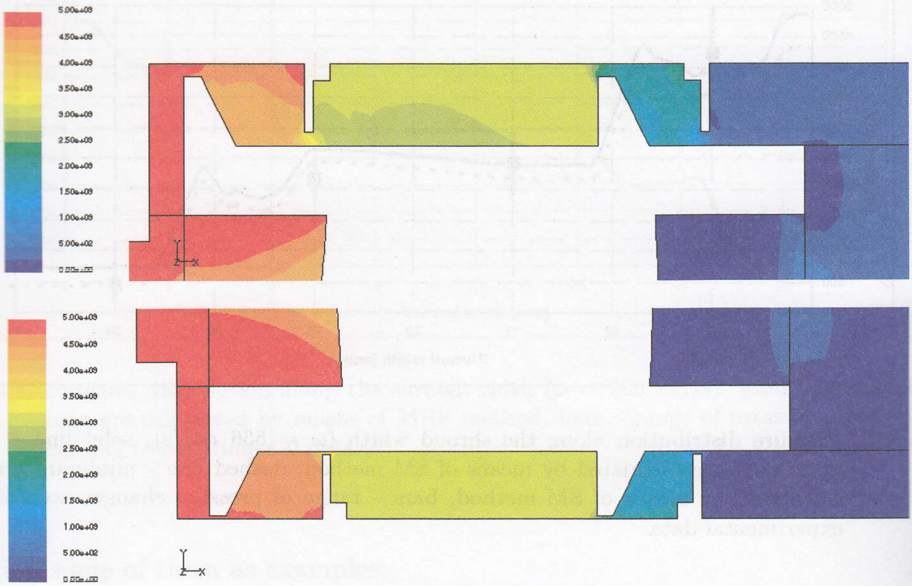


Figure 6. Pressure distribution (average values) in shroud clearance for different radial gaps.

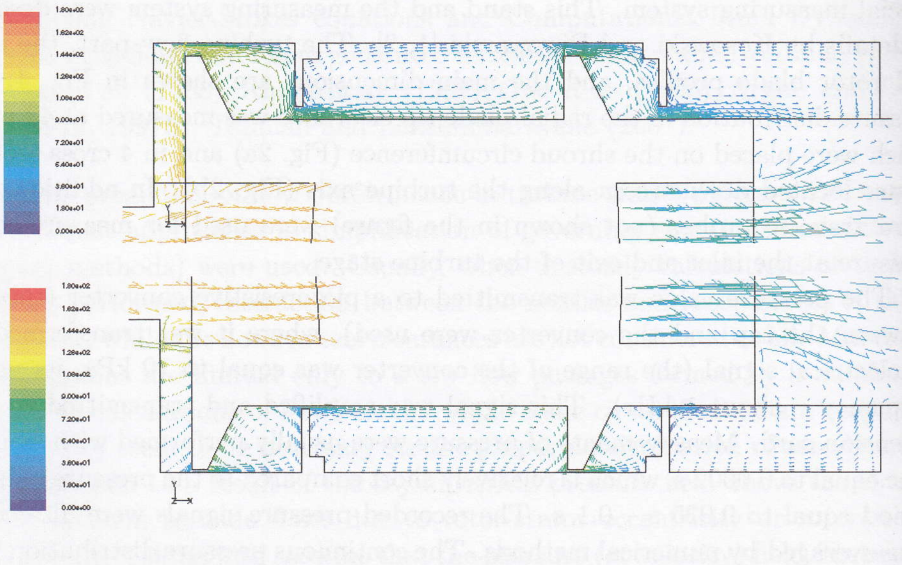


Figure 7. Velocity vectors in shroud clearance for different radial gaps.

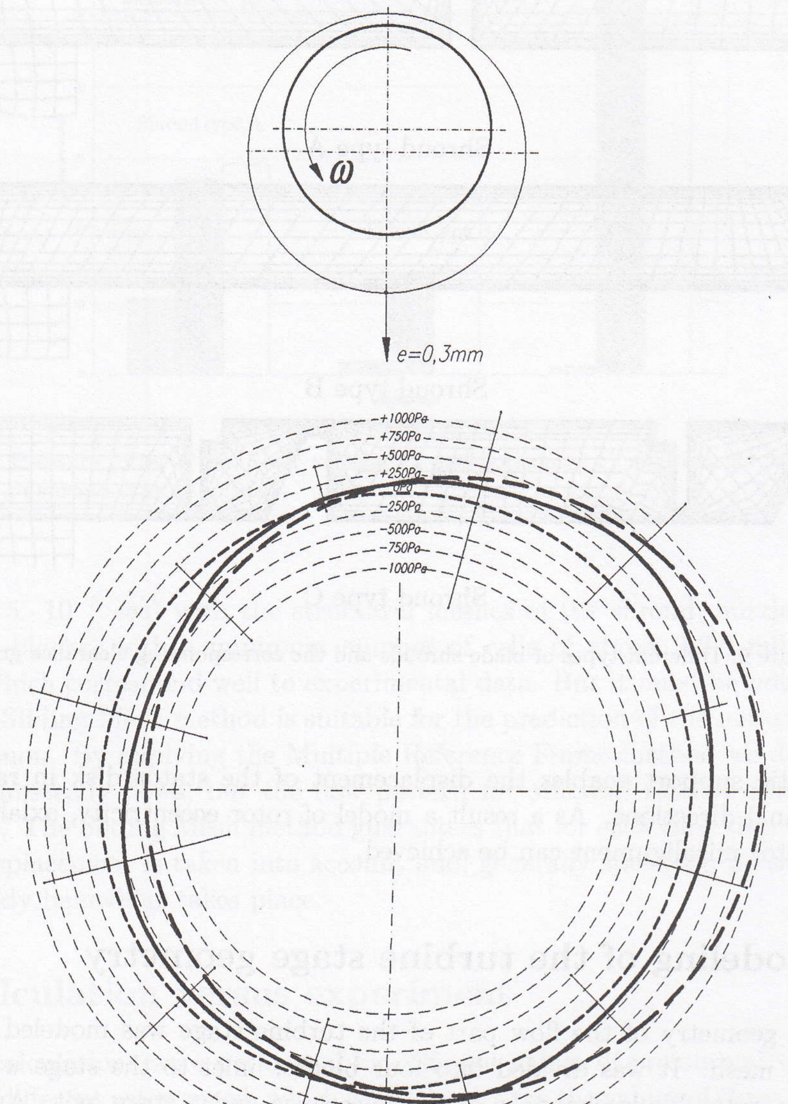


Figure 8. Changes of pressure distribution (average values) on the shroud circumference at the shroud gap inlet (in the first control plane) caused by eccentricity when the stator is moved down ($\omega = 566$ rad/s), solid line – experiment, doted line – calculations.

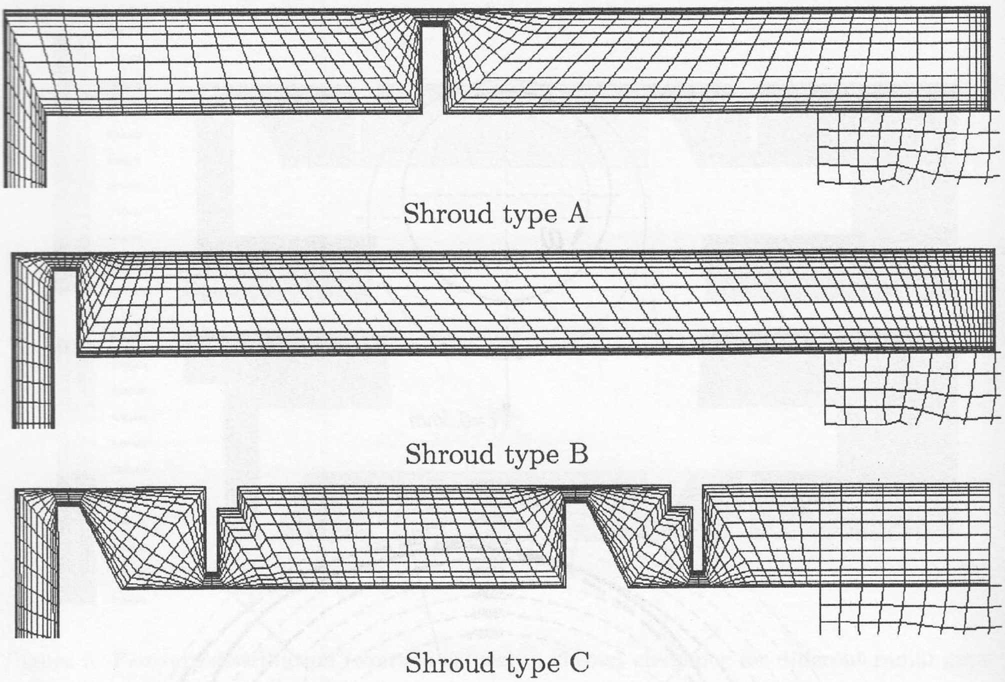


Figure 9. Different types of blade shrouds and the corresponding clearance grids.

The elastic support enables the displacement of the stator disk in radial and longitudinal directions. As a result a model of rotor eccentricity, axial gap and rotor-stator misalignment can be achieved.

3 Modeling of the turbine stage geometry

The geometry of the flow part of the turbine stage was modeled by a calculating mesh. It was divided into four blocks: inlet to the stage with nozzle channels, rotor blade channels, shroud clearance and a stage exit. An example of the mesh of the turbine flow part (see Fig. 1) is presented in Fig. 3. In all calculated variants the rotor passages were modeled by the moving mesh and the rotor blades were treated as a "moving wall". All the other meshes were assumed to be stationary. Meshes of different types and configurations were used for calculations. The structural meshes were built with hexahedral cells, while the meshes made in the unstructured way consisted mainly of pyramid cells. Calculations were performed by applying Fluent CFD code, using the $\kappa - \varepsilon$ turbulence model. The Frozen Rotor method and Sliding Mesh method (with time step

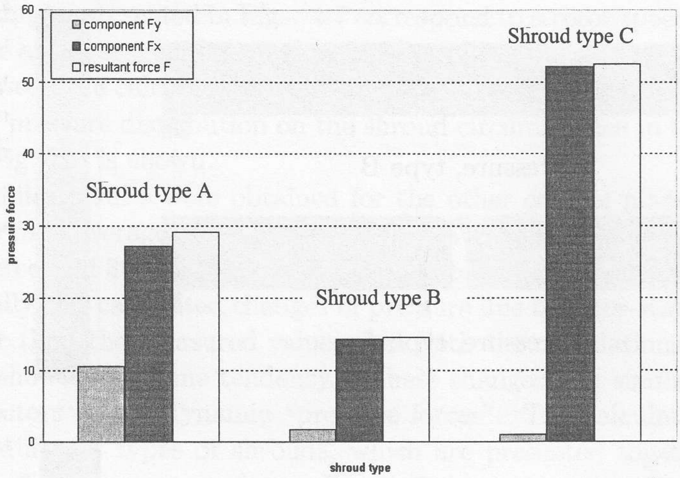


Figure 10. Pressure forces F and their vertical F_y and horizontal F_x components as a function of shroud type (Fig. 9).

equal to $5 \cdot 10^{-5}$ sec) with the structural meshes of the shroud, nozzles, blades and exit blocks, with a minimum number of cells of about 2-2.5 million gave results which correspond well to experimental data. But it must be noticed that only the Sliding Mesh method is suitable for the prediction of the non-stationary phenomenon. By applying the Multiple Reference Frame method we do not determine unsteady flows, but the flow pattern for different relative rotor/stator positions. The Sliding Mesh method guarantees that for each time step the effect of the displacement is taken into account and, generally speaking, no avera ging of unsteady behaviour takes place.

4 Calculation versus experiment

The calculations were performed for different values of pressure at the stage inlet and different rotor speed, which were identical as the values of these parameters measured during the experiments. The nominal value of radial clearance was equal to 0.5 mm and by changing the rotor-stator eccentricity by 0.3 mm in vertical direction a nonsymmetrical radial gap distribution was obtained. According to the results of our calculations, the Sliding Mesh and Multiple Reference methods gave the very similar results of average values of the pressure distribution or the velocity field in the shroud clearance. The results obtained by these methods correspond well to the values of the pressure at the measuring points recorded during the experiment. This conclusion may by confirmed by data presented

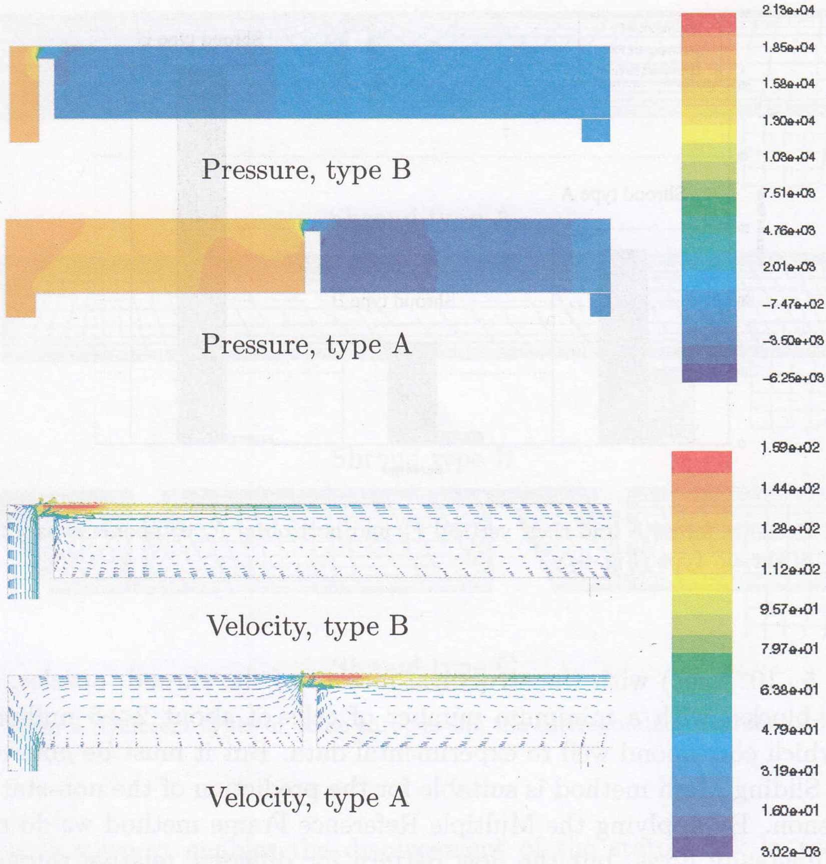


Figure 11. The examples of pressure distribution in shroud clearance and the corresponding velocity vectors for shrouds of types A and B.

in Figs. 4 and 5 for the Multiple Reference and Sliding Mesh methods respectively. The solid line in Fig. 4 shows the calculated mean pressure distributions in the blade shroud clearance while the measured range of pressure pulsations was marked by the means of the bars. In Fig. 5 the range of calculated pressure pulsations is compared with the range of the pressure changes recorded during the experiment. Although the calculated pressure amplitudes are a bit lower than the recorded values, the calculated results fairly correspond to the experimental data, especially in the case of higher rotor speeds (closer to the nominal value of the turbine rotor speed). The pressure distribution and velocity field in the shroud clearance caused by nonsymmetrical clearance is shown in Figs. 6 and 7 respectively.

The examples presented in Figs. 4-7 correspond to a rotor speed of 566 rad/sec and pressure at the stage inlet equal to 20 kPa (above ambient conditions). Comparison between the calculated results and the experimental data is presented in Fig. 8, were pressure distribution on the shroud circumference in the first control plane (see Fig. 2b) is shown.

Very similar results were obtained for the other control planes. Differences between the time-averaged calculated and time-averaged measured values of pressure never exceeded 300 Pa, which is much less than the pressure pulsation amplitudes. Usually, the calculated changes of pressure due to rotor-stator eccentricity were greater than the measured values, but both the calculations and the measurements, showed the same tendency of these changes and similar directions of resultant vectors of aerodynamic "pressure forces". The calculations were performed for different types of shrouds, which are presented together with their grids in Fig. 9. The pressure forces F and their components F_y, F_x in vertical direction and horizontal directions respectively are shown in Fig. 10. The forces presented in Fig. 10 should be read as the relative values expressed in percents of $0.5p \cdot A$, where p and A stand for average pressure in a shroud clearance and area of the shroud respectively.

The examples of pressure distribution in shroud clearance and the corresponding velocity vectors for shrouds of types A and B are presented in Fig. 11. The geometry of blade shroud shows an effect on aerodynamic pressure forces created in the shroud clearance. The most popular and highly recommended due to relatively low (compared with two other examples) leakage losses shroud of type C is characterised by the remarkable highest level of pressure forces. This statement refers fairly to the experimental results presented earlier by Puchaczewski (1993)

5 Conclusion

The investigations showed that CFD codes can cope with determination of the pressure field in a rotor blade shroud clearance in the case with asymmetrical clearance distribution and may be used for determination of aerodynamic forces leading to self-excited vibrations of the turbine rotor systems.

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