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POLISH ACADEMY OF SCIENCES

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Aims and Scope

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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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

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Managing Editor

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Modeling of flow with periodic wakes

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Abstract

The flow through blade channels in turbomachinery is unsteady due to wakes from the blade rings placed upstream. The squirrel cage is one of the most spread generators for modeling the unsteady flow with wakes. By means of this kind of wake generator it is possible to investigate the influence of wakes on the development of boundary layer in the presence of transition under conditions typical for turbomachines.

The aim of this paper is to compare the features of the external flow behind the squirrel cage generators and structure of boundary layers on the flat plates in installations used at IFFM, Gdańsk, and IET, Kiev.

Keywords: Laminar-turbulent transition; Wakes influence

Nomenclature

D	–	diameter of squirrel cage
d	–	diameter of rods
f	–	frequency
R	–	radius of squirrel cage
U	–	velocity
u	–	longitudinal velocity fluctuation
x	–	distance from the leading edge of the plate
x_o	–	distance from the rod of squirrel cage to the leading edge of the plate
$X = x + x_o$		
y	–	normal coordinate
Y	–	spreading of wake over the plate surface
δ	–	boundary layer thickness

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Subscripts

e – external flow
o – onflow condition

1 Introduction

The flow entering the blade passages in turbomachines is highly unsteady as it contains airfoils wakes, secondary flow generated by upstream stator with a few vortices e.g. horse shoe vortex, blade tip leakage and finally it contains turbulence. This combination of periodic and random disturbances has very strong impact on earlier boundary layer transition and significant enhancement to the overall level of heat transfer. These complex flows occur in both stator and rotor blade passages due to variety of viscous and inviscid flow mechanisms. Viscous effects in form of boundary layer and wakes generate flow three-dimensionalities on all passages surface of both stator and rotor. Inviscid effects, which are present for any three-dimensional airfoil geometry, are more important for the rotating frame of reference, i.e. for rotor where they produce additional three-dimensionalities. However, due to lack of understanding of these unsteady effects, most turbine designs are at present time still based on steady flow analysis. In order to allow further optimization at the performance of turbomachines it is therefore very important to understand and to be able to predict the unsteady flow effects. The importance of wake passing to the aerodynamics and heat transfer of a downstream turbomachinery blades has motivated a great deal of research projects in recent years.

Because of the above mentioned complexity of the flow in turbomachines the modeling of wake in wind tunnel and the investigation of its influence on the boundary layer on a flat plate is needed. It is necessary to note that between different types of wake generators the squirrel cage is the most popular. That is why this type of generator is used in experimental investigations of wake influence on transient boundary layer carried out in the framework of cooperation between the Institute of Fluid-Flow Machinery (IFFM), Gdańsk, and Institute of Engineering Thermophysics (IET), Kiev.

2 Aim of the paper

This paper is aimed at the comparison of characteristics of hydrodynamic structure of external flow and transitional boundary layer for two different installations with squirrel cages. The special attention is paid to some differences and similarities in both constructions and measurement results in two cases of modeling flow with periodic unsteadiness.

3 Brief description of experimental installations

In Figures 1, 2 the experiment arrangements of IFFM and IET are shown.

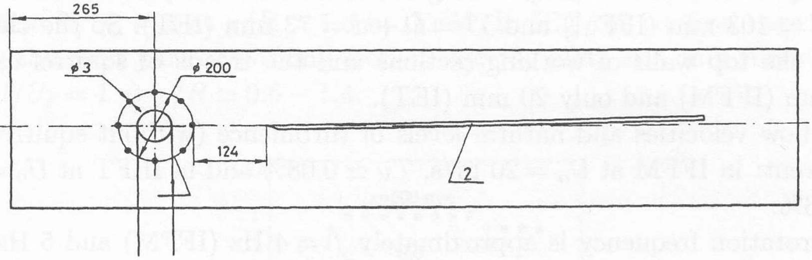

Figure 1. Squirrel cage wake generator and flat plate arrangement in the IFFM, Gdansk.

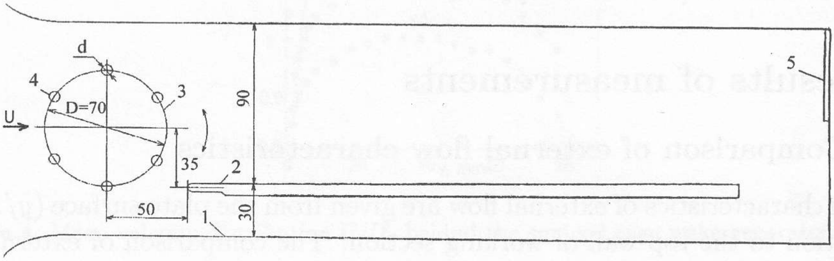

Figure 2. Squirrel cage wake generator and flat plate arrangement in the IET, Kiev

The IFFM wind tunnel of a closed circuit has the working section of dimensions $0.60 \times 0.46 \times 1.5\,\mathrm{m}^3$. The IET wind tunnel of an open circuit has the working section of dimensions $0.12 \times 0.12 \times 0.7\,\mathrm{m}^3$.

The flat plate in the IFFM wind tunnel (2, Fig. 1) is placed in the center of the working section at the incidence angle of -2.5° to avoid the flow separation at its leading edge. This positioning of the plate produces acceleration in the free stream along the plate ($dU/dx = 5.5$ 1/sec). In IET (Fig. 2) the flat plate is placed asymmetrically at the distance of 30 mm from the bottom of working section 1, to the plate surface 2. For avoiding separation and ensuring the zero pressure gradient along the plate an interceptor 5 with length of 60 mm is used. Shapes of leading edge of the flat plates are different: in IFFM it was cut slantwise at 30° then made rounded off by a radius of 2 mm, in IET – it was rounded off by a radius of 1.5 mm.

The diameters D of the squirrel cages and their locations relatively to the plates are also different. In IFFM at $D = 200$ mm the axis of rotation coincides with the horizontal axis of the leading edge of the plate. In IET at $D = 70$ mm the distance between axes of rotation and leading edge of the plate is 35 mm. At the same rod diameters of $d = 3$ mm in both installations the distances from the nearest rod to the leading edges of plates are following: in IFFM $x_o = 124$ mm; in IET $x_o = 15$ mm. The spreading of wakes over the plate surface is $Y = D/2 + d = 103$ mm (IFFM) and $Y = D + d = 73$ mm (IET). So the clearances between the top walls of working sections and the treads of squirrel cages are ~ 128 mm (IFFM) and only 20 mm (IET).

The flow velocities and natural levels of turbulence (without squirrel cages) are different: in IFFM at $U_o = 20$ m/s, $Tu \simeq 0.08\%$ and in IEFT at $U_o = 9$ m/s $Tu \simeq 0.3\%$.

The rotation frequency is approximately $f = 4$ Hz (IFFM) and 5 Hz (IET), when the quantity of rods is 8 and 6 correspondingly.

Measurements are carried out by means of hot-wire technique using DISA-55M System. The total longitudinal fluctuations are measured without division into turbulent and periodic components.

4 Results of measurements

4.1 Comparison of external flow characteristics

The characteristics of external flow are given from the plate surface ($y/R = 0$) in direction to the top wall of working section. The comparison of external flow characteristics is conducted at the different distances x along the plates.

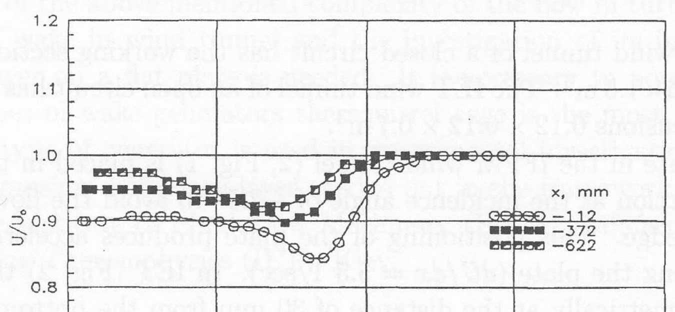

Figure 3. Mean velocity distribution U/U_o behind the squirrel cage wake generator in IFFM.

In Fig. 3, 4 the measurements of mean in time velocity across the flow behind the wake generator show that at same relative distances $X/Y \simeq 2$ ($x = 112$ mm in IFFM and $x = 100$ mm in IET from the leading edge of the plate) the distributions are characterised by presence of flow core with constant values of velocity $U_e = const$. In IET this core broadens downflow meanwhile in IFFM it becomes narrower. Due to existence of clearance between cage and top wall there is region where $U/U_o = 1$ at $y/R > 1.3$ in IFFM. In IET the squirrel cage occupies actually the most part of working section over the plate and only there is region where $U/U_e = 1$ at $y/R \simeq 0.6 - 1.4$.

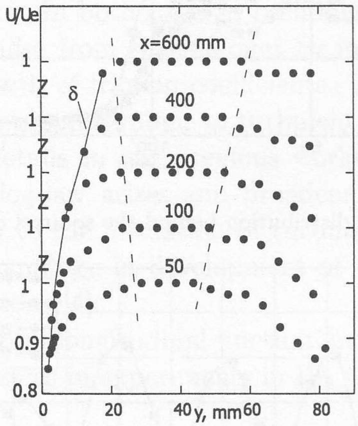

Figure 4. Mean velocity distribution U/U_e behind the squirrel cage wake generator in IET.

In sections pointed above ($X/Y \simeq 2$), in IFFM, the defect of velocity manifests itself in appearance of the minimum in the velocity distribution (at $y/R \simeq 0.8$ $U_{min}/U_o = 0.84$) with consequent recovery of uniformity near the outer edge of the boundary layer (at $y/R < 0.5$ $U_e/U_o = 0.9 = const$). So in IFFM the formation of boundary layer occurs under conditions of shearless external flow ($U_e = const$) despite the presence of velocity unsteadiness induced by wakes. The thickness of boundary layer δ is determined as usually by conditions $U_\delta = 0.99U_e$.

In IET the boundary layer formation occurs in shear flow at $U/U_e = var$. The velocity minimum caused by wake takes place near the outer edge of the boundary layer. Under such conditions the thickness of boundary layer is determined as the extreme point in which the derivative $dU/dy = 0$.

In different sections along the plates the tendency to the uniformity of velocity distributions in flow cores is preserved.

The field of total longitudinal velocity fluctuations is characterized by peaks appearing in external flow as a result of intersections of wakes (Fig. 5, 6). In IFFM the mean level of u'/U_o changes from $\simeq 6\%$ to 3.5% at $x = 112 - 622$ mm (Fig. 5). At the same time in IET it reaches $\simeq 12\%$ and decreases to 4.5% at

$x = 100 - 600$ mm (Fig. 6).

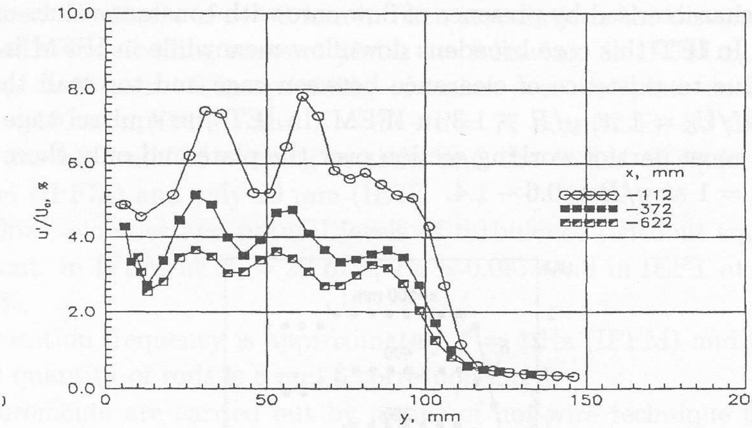

Figure 5. Velocity fluctuation distribution behind the squirrel cage wake generator in IFFM.

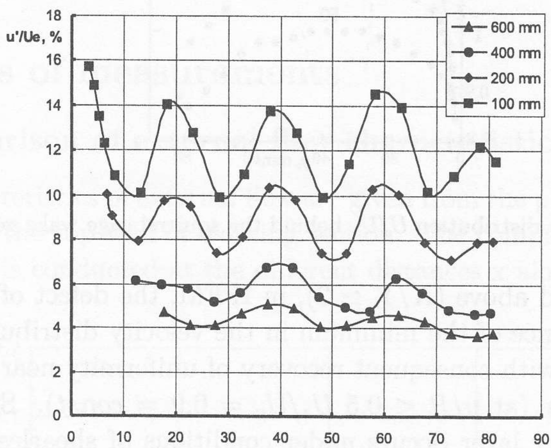

Figure 6. Velocity fluctuation distribution behind the squirrel cage wake generator in IET.

In the first turn the difference in values of u'/U_e can be explained by different distances $x + x_o$ between the chosen sections and the squirrel cages. It is useful to note that in both cases the relations of maximum amplitudes to minimum ones do not exceed $\simeq 1.4 - 1.5$ at $x \simeq 100$ mm and 1.2-1.3 at $x \simeq 600$ mm.

Preliminary calculations show that the changes of averaged values of total longitudinal fluctuations after squirrel cages in the flow cores can be described by usual decay laws broadly used for turbulence after grids in stationary flows [1]:

$$\frac{U_e^2}{u'^2} = A(X + X_0)^m,$$

where in the first approximation $m = 1.2$, $A = 4.1$ and 4.6 , $X_o = 117$ and 7.1 mm in IFFM and IET respectively.

4.2 Comparison of boundary layer characteristics

The special experimental methods developed in IET NASU for diagnostics of flow regimes [2] confirmed the existence of pseudolaminar, transitional and turbulent boundary layer on the plate surfaces in both installations.

In IFFM and IET before transition initiated by wakes the pseudolaminar boundary layer takes place. In both cases in pseudolaminar boundary layer profiles of mean velocities differ from Blasius ones by increased gradients near the wall what causes the growth of friction coefficients. Along the plates the transformation of profiles from pseudolaminar to turbulent is similar to that in bypass transition described in details in our previous works [1, 3]. In the process of transition the region of log-law arises and broadens in direction of outer part of the boundary layer up to the formation of turbulent boundary layer. In our opinion there is the full analogy in development of velocity profiles for bypass and wake-induced transitions [4].

The distributions of total longitudinal fluctuations across the boundary layer show the principal differences in experiments in IFFM and IET (Figs. 7, 8).

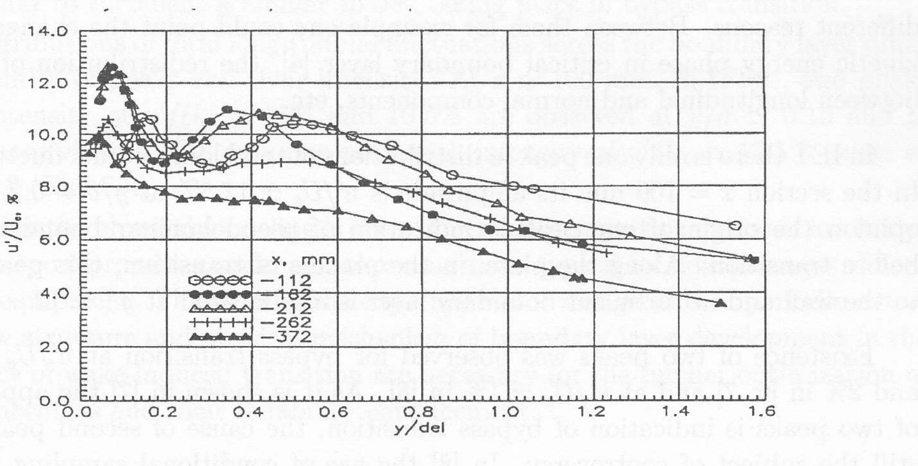

Figure 7. Velocity fluctuation distribution in the boundary layer in IFFM.

In IFFM there are two peaks in distributions of total longitudinal fluctuations. In the section $x = 112$ mm first of them with amplitude of $u'/U_e \simeq 11\%$ is located at $y/\delta = 0.15$. The second peak with amplitude of $u'/U_e \simeq 10\%$ is located at $y/\delta = 0.55$. The latter can be considered as a result of interaction between boundary layer and external flow when turbulence level is not high and

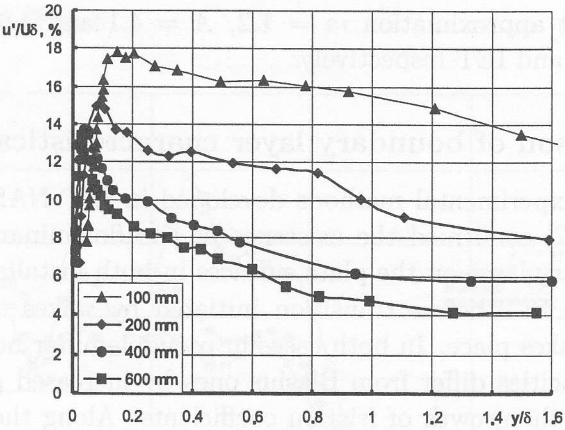

Figure 8. Velocity fluctuation distribution in the boundary layer in IET.

intermittency plays an important role. Along the plate the second peak becomes weaker and gradually disappears, meanwhile the first peaks shifts to the wall and reaches the location typical for turbulent boundary layer. Although the details of peaks mechanism require further understanding; an existence of longitudinal fluctuation minimum between peaks at $y/\delta = 0.3$ may be partly explained by different reasons. Between them for example one could point the change of the kinetic energy phase in critical boundary layer [4], the redistribution of energy between longitudinal and normal components, etc.

In IET there is only one peak in distributions of total longitudinal fluctuations. In the section $x = 100$ mm its amplitude is $u'/U_e \simeq 17.5\%$ at $y/\delta = 0.2$. In our opinion the origin of one peak is indication of pseudolaminar boundary layer before transition. Along the plate, in the process of transition, this peak shifts to the wall and in turbulent boundary layer is also located at $y^+ \simeq 12 - 13$ [5].

Existence of two peaks was observed for bypass transition at $u'/U_e = 0.68$ and 2% in [6, 7] and at $u'/U_e = 1\%$ in [8]. As it is shown in [7] the appearance of two peaks is indication of bypass transition, the cause of second peak being still the subject of controversy. In [8] the use of conditional sampling permits to determine the locations of peaks of longitudinal fluctuation profiles in non-turbulent and turbulent parts separately. In turbulent part peak is located closer to the wall then in non-turbulent one. The combination of peaks with different amplitudes and locations in every part defines the final shape of longitudinal fluctuation profiles in transition. It is necessary to note that in all works of IET [1, 3] devoted to bypass transition the second maximum of longitudinal fluctuations does not take place at $u'/U_e > 3\%$.

5 Summary and conclusions

On the basis of experimental investigations the comparison of external flow structure and some characteristics of boundary layer, developing on the flat plate in the presence of wake-induced transition, is made for installations in IFFM and IET.

It is shown that in both installations behind rotating squirrel cages there are two regions in the distributions of mean time velocities. The flow core located behind the central part of squirrel cage is uniform ($U_e \simeq const$) with following dimensions: $0.3D$ and $0.2D$ at $x \simeq 100$ mm in IFFM and IET, respectively. The remaining part of flow is shear and characterised by velocity defects (for example $\frac{U_e - U_{min}}{U_e} \cong 0.07$ in IFFM and $\frac{U_e - U_{min}}{U_e} \cong 0.13$ in IET at $x = 100$ mm, Figs. 3, 4).

Beyond the boundary layer in distributions of total longitudinal fluctuations there are minima and maxima caused by intersections of wakes. Behind the squirrel cages the levels of averaged fluctuations decrease along the plates at $x \cong 100 - 600$ mm from $\cong 12$ to 4.5% (IET) and from $\cong 6$ to 3.5% (IFFM) and can be described by decay laws for grid turbulence (Figs. 5, 6).

Despite the development of boundary layer happens under different external conditions (in uniform (IFFM) and shear (IET) flows), wake-induced transition takes place in both installations. Transformation of velocity profiles from pseudolaminar to turbulent is similar to one taking place in bypass transition.

Distributions of total longitudinal fluctuations across the boundary layer differ by quantity of peaks and their intensity. At $x \simeq 100$ mm, in IFFM, two peaks with intensity of $u'/U_e \simeq 11\%$ and 10.5% are observed at $y/d \simeq 0.15$ and $\simeq 0.55$, meanwhile in IET only one peak with intensity of $u'/U_\delta \simeq 17.5\%$ exists at y/d=0.2 (Fig. 7, 8).

Today the physical modeling is one of the most perspective methods for studying transport processes under complex conditions typical for flow passages of heat power equipment. That is why the experimental investigations of periodic external flow structure and physical mechanism of boundary layer development in the presence of wake-induced transition are necessary for the further optimization of turbomachines and their reliability enhancement.

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