

PHYSICAL MODELING THE UNSTEADY FLOW WITH WAKES

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The flow through blade channels in turbomachinery is unsteady due to wake from the blade rings placed upstream. The hesitating cylinder and squirrel cage are the most spread generators for modeling the unsteady flow with wakes. This paper is aimed at the comparison of characteristics of hydrodynamic structure of external flow for two different wake generators. The special attention is focused on development of the methods for dividing of the total longitudinal pulsation into turbulent and nonstationary components and averaging of hydrodynamic external flow characteristics with periodic nonstationarity by replacement of such a flow with shearless equivalent.

Keywords: Wakes, hesitating cylinder, squirrel cage generator, external flow structure, turbulent and nonstationary components.

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. 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 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 there are different types of wake generators. For example, authors [1-3] used squirrel cage as wake generator. In [4] measurements of wake-affected heat transfer distributions on a flat plate are made by use of a wake generator that consists of a rotating disk and several types of circular cylinders attached on the disk rim. Hesitating cylinders were used for modeling flow with periodic unsteadiness in many works, in particular in the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences [5] and Institute of Engineering Thermophysics (IET), Kiev [6]. Thus, as the literature review showed, the most popular wake generators are the hesitating cylinder and squirrel cage. That is why these types of generator are used in present experimental investigations for modeling the unsteady flow with wake.

1. Experimental technique

Experiments were carried out in the working part of the T-5 IET NASU open circuit aerodynamic tunnel with 90x120x800 mm³ dimensions when velocity of an external flow was 9 m/s. A flat plate (2) was mounted in working section (1) asymmetrically at $h=90$ mm from top wall (Fig.1). In order to eliminate separation at the leading edge of the plate the interceptor (5) at a height of 60 mm was installed on the top wall at the end of working section.

For generating periodic unsteady wakes single hesitating at $f = 4.4$ Hz cylinder $d = 3$ mm was located upstream of the plate at $x = -15$ mm. The amplitude of cylinder motion was 20 mm from the axis of the leading edge of the plate. The detailed information about this wake generator is presented in [6].

The squirrel cage (3) with $D = 70$ mm in the axis of cylinders (4) was installed at the entrance into working part and consisted of 6 cylinders ($d = 3$ mm, $N = 6$) (Fig.1). The axis of rotation of the generator was located upstream of the plate at $x = -50$ mm and $y = 35$ mm from the axis of the leading edge of the plate. Speed of generator rotation was $n = 50$ rev / min, which corresponded to the frequency of rotation of the cylinder $f = 5$ Hz.

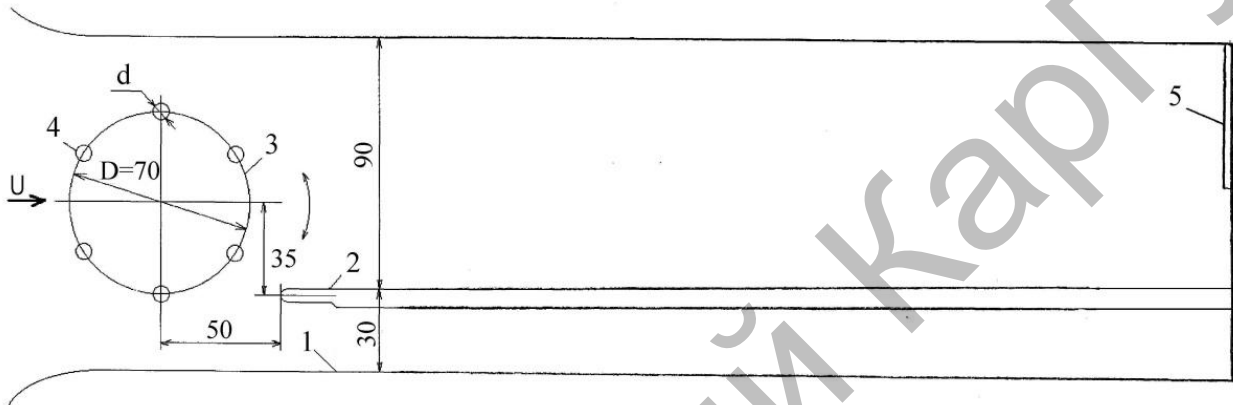


Fig.1. Sketch of the experimental installation

Steady wakes were produced by the same still squirrel cage which is situated in positions 1, 2 and 3 (Fig.2 a, b, c). Positions 2 and 3 correspond to squirrel cage turns $\pm 90^\circ$ and 15° clockwise relative to position 1.

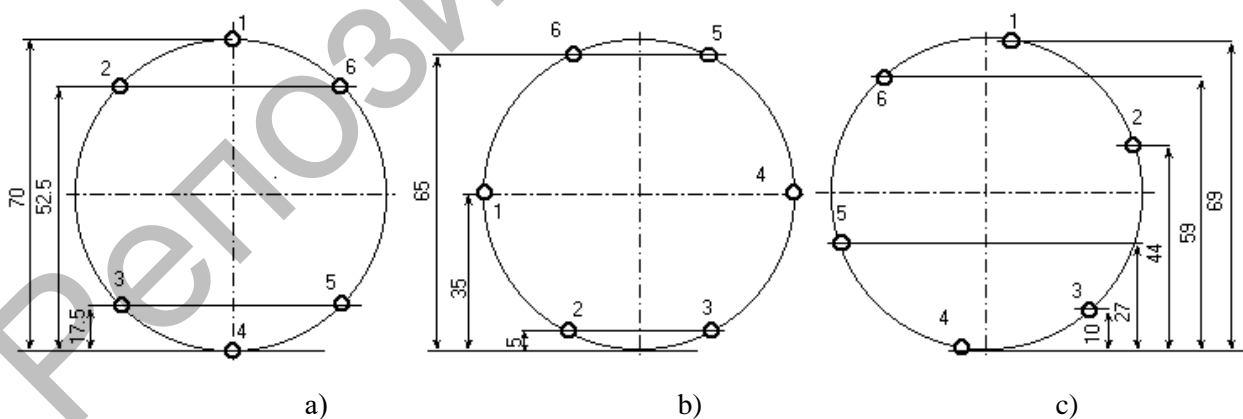


Fig.2. Schemes for installing still squirrel cage.

The parameters of the internal structure of the external flow were measured by DISA-55M hot-wire system. It is necessary to remark that in periodically disturbed flow total turbulence intensity was measured including periodic and turbulent fluctuating components.

2. Results and discussion

2.1. Improvement of measuring technique

Measurements of the periodically disturbed flow structure required improvements in the technique for processing experimental data. For this purpose, the following methods were developed: dividing of the total longitudinal pulsation into turbulent and nonstationary components and averaging of hydrodynamic external flow characteristics with periodic nonstationarity.

For dividing total fluctuations (u'_e) into turbulent (u'_t) and nonstationary (u'_n) components the additional measurements after still wake generator were conducted. The method of dividing was based on two following assumptions: 1. rotation does not substantially influence on turbulent component; 2. energies of disturbances of different nature are not correlated i.e. $\overline{u_e'^2} = \overline{u_t'^2} + \overline{u_n'^2}$.

It is known that wakes change the uniformity of the velocity distribution because of the presence of defect and generate a nonuniform turbulence field in the free-stream ($y > \delta$). To describe such external flow, it is necessary to average the indicated hydrodynamic characteristics. When implementing this procedure, the most important is the selection of the averaging region.

As shown in [6], in cases of still and hesitating cylinder the interaction between shearing motion in the wake and boundary layer leads to formation the region with the uniform field of the velocity $U_e = \text{const}$. In this case the value U_e is taking as a velocity of free-stream at forming of boundary layer. In work [5] similar results that wakes do not change the uniformity of the velocity distribution, but generate a non-uniform turbulence field with maximal level up to 5% were obtained.

The distributions of mean in time velocities behind a squirrel cage demonstrate the presence of the narrow shearless core broadening down flow as well as the zone of shear flow on the periphery of squirrel cage. The common tendency is weakening of velocity defect with x growth. For estimating the characteristics of shear external flow behind rotating squirrel cage its replacement by shearless equivalent was made. For this purpose in the every cross section the distributions of velocity and fluctuations were averaged in the range of $y = D + d$ what corresponded the width of wakes spreading.

2.2. Distributions of longitudinal fluctuations in external flow

Distributions of longitudinal fluctuations in the free-stream ($y > \delta$) after still (Fig.3a) and hesitating cylinder (Fig.3b) showed that total intensity of longitudinal fluctuations in case of hesitating cylinder is higher than for still one.

Distributions of longitudinal fluctuations in the free-stream after still squirrel cage (Fig.4) at $x=50$ mm depend on its position. In position 1 (as shown in Fig.2a), when the near wakes behind the cylinders 6 and 5 coincide with far wakes behind the cylinders 2 and 3 (Fig. 4, designation 1), maximum of longitudinal fluctuations $u'_{\max} / U_e = 11\%$ at $x=50$ mm is observed. When the still squirrel cage is installed in positions 2 and 3 (Fig. 2b and 2c), the amplitude of the maxima in the wakes behind the cylinders is higher than in the previous case ($u'_{\max} / U_e = 13\%$ and 12-16% at $x=50$ mm respectively, Fig. 4, designations 2 and 3). The amplitude of the maxima of longitudinal fluctuations decreases along the plate and reaches 4.5% and $\sim 4\%$ in the section $x=600$ mm for positions 1, 2 and 3 respectively.

Thus, the distributions of longitudinal fluctuations in the last sections of the plate are practically independent of the positions of still squirrel cage. A characteristic feature of the distribution of longitudinal fluctuations of the external flow behind still squirrel cage is a significant difference in the amplitudes of the maximum and minimum. At $x=50$ mm u'_{\max} / u'_{\min} reaches $\sim 17, 12$ и 5 for positions 1, 2 and 3 respectively. Along the plate, this ratio decreased to 1.5-1.1.

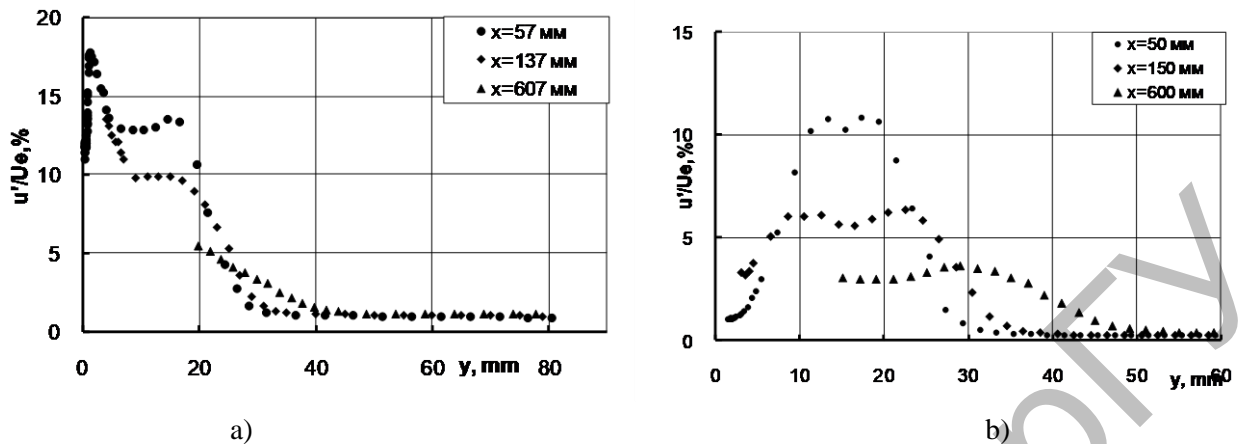


Fig.3. Distributions of longitudinal fluctuations in the free-stream after still (a) and hesitating cylinder (b)

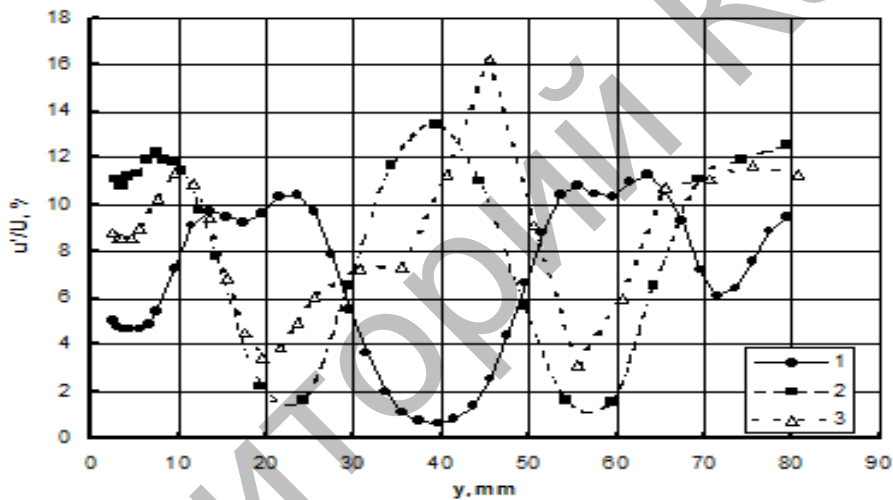


Fig.4. Distributions of longitudinal fluctuations in the free-stream after still squirrel cage in positions 1, 2 and 3 ($x= 50$ mm)

The distributions of total velocity fluctuations behind rotating squirrel cage differ by peaks (Fig.5), amplitude of which decreases down flow. Mechanism of peaks origin is connected with the interaction of wakes after rotating cylinders what causes the growth of energy of disturbances in points of intersections of wakes. The number of peaks corresponds to $(N-1)$, i.e. there are 5 peaks at $N=6$. Along the plate peaks degenerated, and their amplitude decreased from $u'_{max}/U_e = 17-18\%$ at $x=50$ mm to 5% at $x=600$ mm. In this case the ratio u'_{max}/u'_{min} decreased along the plate from 1.4 at $x=50$ mm to 1.2 at $x=600$ mm.

Comparison of the relations u'_{max}/u'_{min} in the external flow behind the still and rotating squirrel cage made it possible to determine that the rotation of the cage leads to a smoother distribution of longitudinal velocity fluctuations.

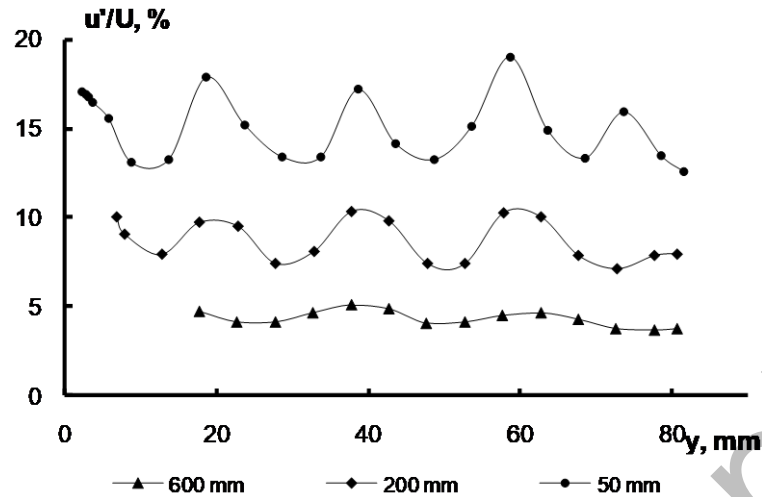


Fig.5. Total velocity fluctuations after rotating squirrel cage.

2.3. Characteristics of shearless equivalent flow

After averaging of hydrodynamic external flow characteristics with periodic nonstationarity by the method of shearless equivalent flow described above it is possible to obtain the distributions of velocity U_e and total velocity fluctuation u'_e . The values of the calculated fluctuations u'_e/U_e in each section along the plate are shown in Fig. 6. The extraction from the total energy of longitudinal fluctuations of an equivalent flow $\overline{u'_e{}^2}$ the turbulent $\overline{u'_t{}^2}$ and nonstationary $\overline{u'_n{}^2}$ energy was carried out on the basis of the uncorrelatedness of the latter, i.e.: $u'_n = \sqrt{\overline{u'_e{}^2} - \overline{u'_t{}^2}}$. Turbulent fluctuation u'_t was calculated on the basis of the distribution of longitudinal fluctuations in the external flow when a still generator was installed.

As seen from Fig.6, the fluctuations of turbulent component $u'_t/U_e = f(x)$ changed from 8.9% to 3.6% and nonstationary components $u'_n/U_e = f(x)$ from 12% to 2.3% along the plate (at $x=50$ mm and $x=600$ mm respectively). Thus the fluctuations of turbulent component measured after still squirrel cage changed slower than calculated fluctuations of nonstationary component. Immediately near the squirrel cage the nonstationarity was dominating, however down flow the turbulent component became prevailing. The observed fact is important from a practical point of view, because allows controlling the intensity of the transport processes using separately the parameters of nonstationarity (frequency, amplitude) or turbulence.

As shown at Fig.6 the decay law of averaged total fluctuations $u'_e/U_e = f(x)$ was similar to the one after traditional still grids widely used for generation of turbulence in aerodynamic tubes. The decay law of total energy of longitudinal velocity fluctuations of shearless equivalent permits to estimate the transport properties of turbulized flow in the working part of aerodynamic tube. For that it is possible to use the traditional form of decay laws behind stationary generators of turbulence [7]:

$$\frac{U_e^2}{u_e'^2} = A(x + x_0)^m, \quad (1)$$

where the exponent values (m) usually are chosen in the range of $m=1,2-1,4$, while virtual distance (x_0) and coefficient (A) are determined in the results of experimental investigations.

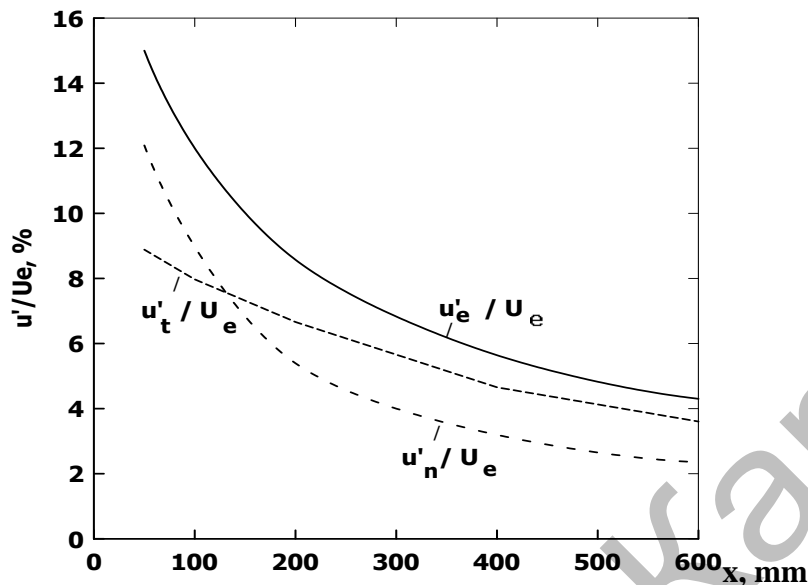


Fig.6. Distribution of components of velocity fluctuations after rotating squirrel cage.

On the base of decay law (1) it is possible to calculate the kinetic energy of fluctuations, their dissipation and characteristic scale as well as to estimate turbulent viscosity of turbulized flow ν_{te} [7] in the frames of “energy – dissipation” turbulence model. Preliminary calculations show that values of the latter change from $\nu_{te} \approx 2.7 \cdot 10^{-3}$ to $\nu_{te} \approx 1.4 \cdot 10^{-3}$ m²/s along the length of working part, i.e. exceed values of molecular viscosity almost into 200 times at $x=50$ mm.

These features of the unsteady flow with wakes must be taken into account in developing numerical methods for calculation of transport processes of the flow in turbomachines on the basis of turbulence models.

Conclusion

Experimental investigations of an external flow in the presence of wakes after still and hesitating cylinder and the still and rotating squirrel cage were carried out.

It has been shown that external flow with periodic nonstationarity is characterised by shearing motion in the wake and nonuniform turbulence field. For estimating the characteristics of such external flow its replacement by shearless equivalent was made and method for dividing total fluctuations into turbulent and nonstationary components was proposed. It was shown that nonstationarity enhances longitudinal velocity pulsations in the external flow, in particular total intensity of longitudinal fluctuations in case of hesitating cylinder is higher than for still one.

Distributions of longitudinal fluctuations in the free-stream after still and rotating squirrel cage are characterised by presence of peaks. The rotation of the squirrel cage leads to a smoother distribution of longitudinal velocity fluctuations. The rate of change for the fluctuations of turbulent and nonstationary components after rotating squirrel cage is different, namely near the squirrel cage the nonstationarity was dominating, however down flow the turbulent component became prevailing. On the basis of the obtained data the kinetic energy of fluctuations, their dissipation and characteristic scale as well as turbulent viscosity of turbulized flow with periodic nonstationarity can be calculated.

Nomenclature

U, u' are velocity, longitudinal velocity fluctuation, m/s,
 x, y are coordinates,

Greek symbols

δ is thicknesses of boundary layer.

ν_{te} is turbulent viscosity of turbulized external flow

Subscripts

e - total,

t - turbulent,

n - nonstationary,

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Article accepted for publication 06.12. 2017