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TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

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Flow field behind the wake generator

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Abstract

The investigation of the non-stationary flow behind the wake generator is presented. The mean velocity and rms velocity fluctuations are measured. The coordinates of points where the wakes from the windward side of the generator are intercepted by the wakes (rods) from the leeward of the generator are determined. The co-ordinates of these points depend on the diameter of the generator, the velocity of the oncoming flow and the frequency of rotation, i.e. the Strouhal number of the generator. The results of calculation are compared with the measurements and a good compatibility has been obtained. At the points of the wake cutting an increased fluctuations level is measured. The results of these investigations can be used in the study of the boundary layer transition induced by wakes with the influence of the wake cutting effect. This phenomenon is known in the turbomachinery as the so called clocking effect where they generate regions of enhanced turbulence level.

Keywords: Wake generator; Ineterception of wakes

Nomenclature

$c = 2\pi Rf$	–	velocity of rod in the wake generator
d	–	diameter of the wake generator
f	–	frequency of the wake generation revolution
L	–	lift
$R = d/2$	–	radius of the wake generator
t_0	–	initial value of time
t_1, t_2	–	sought times in Eq. (3.6)
$T = 1/f$	–	period of the wake gener revolution
U	–	local mean velocity
U_0	–	velocity of the oncoming flow
U_c	–	resultant velocity oncoming the rod in the wake generator
u'	–	velocity fluctuation
(x, y)	–	coordinates
$\dot{x}, \dot{y}$	–	components of velocity of the rod in the wake generator

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α – angle of flow oncoming the rod
δ – boundary layer thickness
Γ – velocity circulation
ρ – fluid density

Subscripts

$i = 0 \div 7$ – number of subsequent rod in the wake generator

1 Introduction

Wakes of the consecutive blade-rings are responsible for significant unsteady flow in fluid-flow machinery. The unsteady flow can be noted in form of mean velocity defect and higher level of turbulence. These periodical variations of velocity have a substantial influence on the boundary layer of the blade which results, primarily, in premature laminar-turbulent transition, and thereby causing an increase in the profile friction losses. This is one of the numerous indications which decide about the effect of the wake on the flow in the machine.

In multistage machines the wakes are often cut by successive blade rings. The cross-cuts are characterized by the much greater mean velocity fluctuation profiles than in an individual wake. The paper by Arndt, 1991, presents the investigation results related to the non-stationary flow in a five stage low-pressure turbine. The author points out a number of significantly different levels of turbulence at various regions of circumference which indicates the occurrence of a non-homogenous circumferential flow at outlet of a stator guide ring.

Very often under conditions of model tests, e.g. in a wind tunnel, advantage is taken of a drum with rods around the periphery (called also the squirrel cage) as a generator to produce the wakes, for instance used by Pfeil et al, 1983, Juszyna and Wierciński, 1994, Wierciński, 1999. Making use of the squirrel cage for the generation of wakes, Juszyna and Wierciński, 1994, have noted for the first time a dependence of the frequency of the generator rotations at the constant oncoming flow velocity, upon the amplitude of velocity fluctuation in the boundary layer, Fig.1.

They both have suggested that the rise in the velocity fluctuations in the boundary layer is due to the inflow of wake cuttings onto the leading edge of the plate.

By changing both the air velocity onflowing the flat plate and the rotation frequency of the wake generator, the authors of the paper have succeeded in obtaining amplified velocity fluctuation in the boundary layer. The effect of the generator rotation frequency on velocity fluctuation in the boundary layer is shown in Fig. 1, where the velocity fluctuations at a distance $x = 112$ mm from the leading edge and the oncoming flow velocity $U = 17.3$ m/s at the height

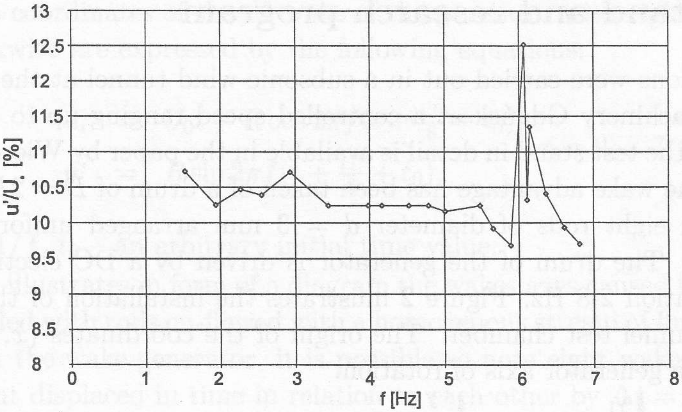

Figure 1. Effect of the generator frequency on the velocity fluctuations in the boundary layer.

$y/\delta = 0.25$ in the boundary layer are presented versus the generator frequency (in its clockwise rotation). It is evident that for the generator rotation frequency $f = 6.05$ Hz there occurs the maximum velocity fluctuations, where u'/U_0 is approximately 25% larger than the values in the proximity of this frequency. This phenomenon attracted our greater interest in the velocity field downstream the rotating wake generator. Thus the aim of the paper is to investigate the unsteady velocity field behind the generator of the wakes in the form of a drum with eight rods around its periphery. The interest is related not only to the theoretical shape of the wake axis and the coordinates of their cuttings but also the measurements of the velocity field behind the wake generator. Under the velocity fluctuations the whole disturbance is understood without differentiating between the group mean velocity defect and stochastic turbulent fluctuations, so we do not differentiate between the large velocity fluctuations, caused by periodic motion of rods, and the smaller stochastic fluctuations. The measurements of the time mean velocity and the velocity fluctuations flowing freely downstream the wake generator are aimed at a better understanding of the type of turbulence induced by the wakes in the boundary layer on a flat plate and in particular to get to know the cutting effect of the wakes on the laminar-turbulent transition within the boundary layer. This is likely to make it possible to study the phenomenon known as the clocking effect (the intersection of wakes) and its interaction with that flat plate boundary layer. In literature, regarding the investigation of the laminar-turbulent transition induced by wakes, the effect of the wakes cutting on the boundary layer has been neglected though the action of the wakes caused on both the windward and the leeward side of the wake generator on the boundary layer was evident (Schröder, 1985).

2 Test stand and research program

Investigations were carried out in a subsonic wind tunnel at the Institute of Fluid-Flow Machinery Gdańsk at a controlled speed ranging up to 100 m/s. A description of the test stand in detail is available in the paper by Wierciński, 1991. To generate the wake advantage has been taken of a drum of $D = 2R = 200$ mm provided with eight rods of diameter $d = 3$ mm arranged uniformly around the periphery. The drum of the generator is driven by a DC electric motor of controlled rotation 2-8 Hz. Figure 2 illustrates the installation of the generator in the wind tunnel test chamber. The origin of the coordinates (x, y) has been assumed in the generator axis of rotation.

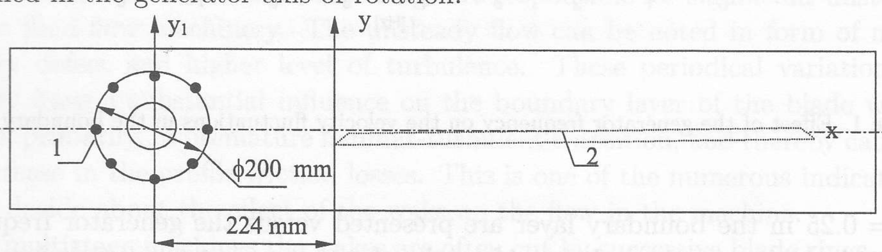

Figure 2. Position of the generator in the wind tunnel test chamber, 1 – generator, 2 – denotation of the hypothetical position of the flat plate.

The measurements of the mean velocity and the flow fluctuations have been carried out using a single-fibre hot-wire probe and the DISA 55M01 measuring bridge. The sensitive part of the element is the 8 μm thick tungsten wire of 1.25 mm length.

The measurements of the mean velocity and fluctuations of the axial velocity component downstream the rotating drum were made for 13 distances from the drum axis $x = 336$ to 846 mm with the distance difference $\Delta x = 25$ mm and for the following three oncoming velocities $U_0 = 10$, 15 and 20 m/s, and two rotation frequencies as $f = 4$ and 6 Hz both counter- and clockwise. The set of x, y coordinates is illustrated in Fig. 2 with additionally marked position of the flat plate which was used in the cited investigation of the induced boundary layer.

3 Wake field downstream the generator

3.1 Shape of the wake axis

The shape of the wake axis following a single rod rotating with the generator at frequency f around the circumference of radius R with a homogeneous flow around it of velocity U_0 can be described as a sum of translatory motion along axis x and the rotation of rod around the circumference.

The axis coordinates of the i^{th} wake of the generator with eight rods rotating counterclockwise are expressed by the following equations:

$$\begin{aligned} x_i &= U_0 t + R\cos 2\pi f(t + \tfrac{iT}{8} + t_0), \\ y_i &= R\sin 2\pi f(t + \tfrac{iT}{8} + t_0), \end{aligned} \qquad i = 0 \ldots 7 \tag{1}$$

where $T = 1/f$, t_0 – an arbitrary initial time value.

Figure 3 illustrates in form of a diagram the wakes axes caused by the rotating drum provided with rods on-flowed with a homogenous stream of fluid. As a result downstream the wake generator, it is possible to note eight wakes, in principle, identical, but displaced in time in relation to each other by $\Delta t = iT/8$, or along axis x by $\Delta x = iUT/8$, where $i = 0 \div 7$. In addition on the lee side, each rod cuts the wakes of the remaining rods, Fig. 3.

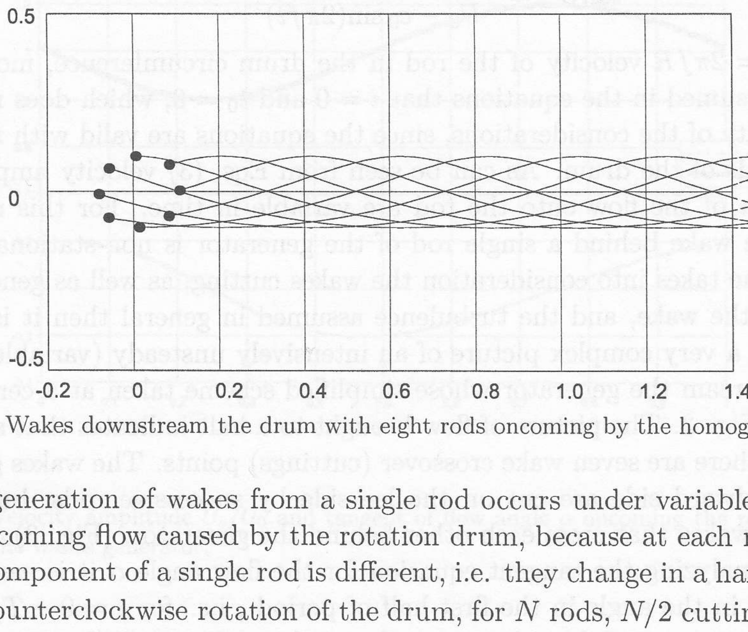

Figure 3. Wakes downstream the drum with eight rods oncoming by the homogeneous flow.

The generation of wakes from a single rod occurs under variable conditions of the oncoming flow caused by the rotation drum, because at each moment the motion component of a single rod is different, i.e. they change in a harmonic way.

For counterclockwise rotation of the drum, for N rods, $N/2$ cuttings are situated under axis x, while $N/2 - 1$ over x. Of course, in case of eight rods, as in the situation under investigation, three cuttings are over axis x, and four successive ones below it, Fig. 3. At any arbitrary measuring cross section downstream the generator, the wake points (sections), which occur in time while the rod moves on the windward side of generator, take a longer way than the wake points of the same rods generated in time when the rod travels on the lee side. That is why at any arbitrary measuring cross-section downstream the generator, defects of velocity including wake sections created on the generator windward side should be smaller than the velocity defects, i.e. wakes caused on the lee side. This can be clearly seen in Fig. 6.

3.2 Instantaneous flow velocities acting on the rod in the generator

By differentiating Eq. (1) it is possible to obtain the components of the instantaneous oncoming flow velocity acting on the i^{th} rod:

$$\begin{aligned} \dot{x}_i &= \tfrac{dx_i}{dt} = U_0 - 2\pi f R \sin 2\pi f(t + \tfrac{iT}{8} + t_0), \\ \dot{y}_i &= \tfrac{dy_i}{dt} = 2\pi f R \cos 2\pi f(t + \tfrac{iT}{8} + t_0). \end{aligned} \tag{2}$$

Making use of the above equations one can calculate the instantaneous amplitude of velocity U_c and tangent of the angle of the oncoming flow acting on the rod:

$$\begin{aligned} U_c^2 &= U_0^2 - 2U_0 c_0 \sin(2\pi f t) + c_0^2, \\ \tan\alpha &= \frac{c_0 \cos(2\pi f t)}{U_0 - c_0 \sin(2\pi f t)}, \end{aligned} \tag{3}$$

where: $c_0 = 2\pi f R$ velocity of the rod in the drum circumference, moreover, it has been assumed in the equations that $i = 0$ and $t_0 = 0$, which does not lessen the generality of the considerations, since the equations are valid with respect to all eight rods of the drum. As can be seen from Eqs. (3) velocity amplitude U_c and angle α of the flow onto the rod are variable in time. For this reason, in general, the wake behind a single rod of the generator is non-stationary. If, in addition, one takes into consideration the wakes cutting, as well as generation of vortices in the wake, and the turbulence assumed in general then it is possible to arrive at a very complex picture of an intensively unsteady (variable in time) flow downstream the generator whose simplified scheme taken at a certain time is given in Fig. 3. The picture of flow brought to a halt indicates that along axis $x = UT/8$ there are seven wake crossover (cuttings) points. The wakes generated on the windward side are cut on the lee side by successive rods, building up network of wakes that cross each other behind the generator, (Fig. 3).

When analyzing the tangent equation for the flow angle α it is easy to note a difference in the angle in the first half of period , i.e. for $t = 0 \div T/2$, where $T = 1/f$, in respect of the other part of period i.e. for $t = T/2 \div T$, that is on account of the denominator value. The difference is also seen in Fig. 3, where the shape of the wake axes in the area above the x axis is different from the shape of the wake axis below. However, the difference is more striking in Fig. 4. where variation of the velocity amplitude U_c/U and the α angle of flow onto the rod for $c_0/U_0 = 0.2$ with respect to a full rotation period of generator $t/T = 0$ up to 1.

It is possible to note that the wake cuts axis x alternately at angle $\alpha = \pm\arctan(\frac{c_0}{U_0})$ since for $ft = 0, \frac{1}{2}, 1, \frac{3}{2}, 2$, etc., the value of sin $2\pi f t = 0$, and at the same time $\cos 2\pi f t = \pm 1$. It is worthy of taking into consideration two cases, when $\sin 2 \sin f t \to \pm 1$ i.e. for $\frac{t}{T} = \pm\frac{1}{4} + k$, $k = 0, 1, 2$, etc., in this way the denominator will tend towards $U_0 \pm c_0$, at this time the numerator will aim at zero since $\cos 2\pi f t \to 0$, and thus angle α tends to zero, but at a variable rate because of the denominator behaviour mentioned before. Moreover, it is possible to point out the antisymmetry of angle α in relation to $t/T = 0.25$ and 0.75, namely $\alpha(0.25\ t/T) = \alpha(0.25 + t/T)$ and like $\alpha(0.25 - t/T) = -\alpha(0.75 + t/T)$.

Therefore at the point where two wakes cross each other, the axes of the wakes cut themselves at angle. So the angle of crossing 2α is also different for each of $N-1$ points. All the properties mentioned above are illustrated in Fig. 4 where the amplitude variation U_0 is marked with thick line, while the $\tan(\alpha)$ variation is in a fine line.

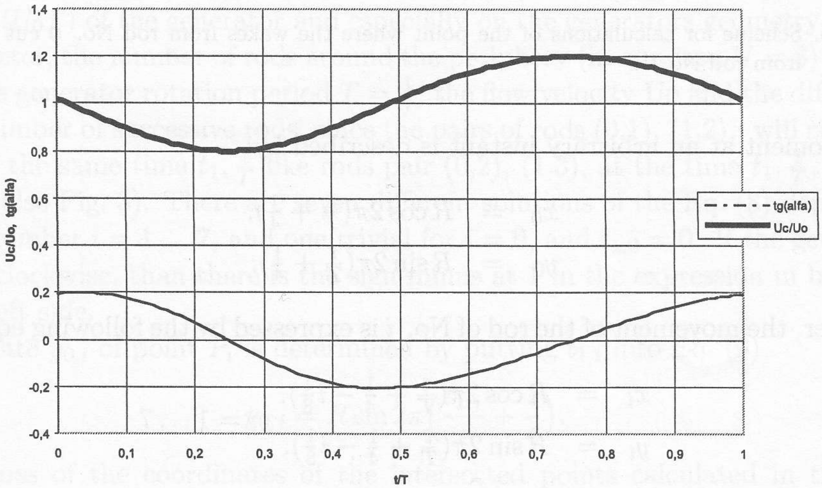

Figure 4. Velocity amplitude U_c/U_0 and tangent of flow angle α oncoming the rod rotating in the wakes generator.

3.3 Determination of coordinates of points at which the wakes intercept

Let us now concentrate our attention on the determination of the coordinates of points where the wakes from the windward side are intercepted the rods on the leeward side of the generator. Figure 5 will help in such consideration. It is assumed that at an instant $t = 0$ the rod No. 0 is situated at the top point, i.e. it moves from the lee side to the generator windward side. Its movement from

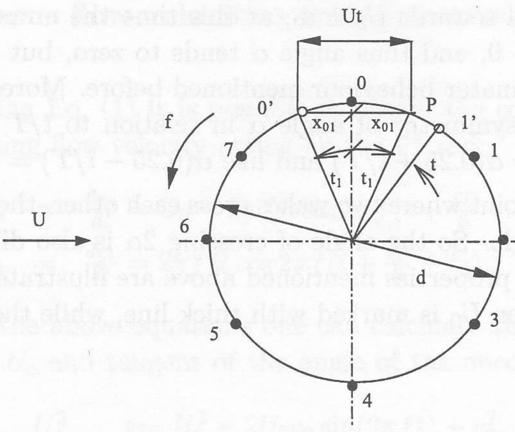

Figure 5. Scheme for calculations of the point where the wakes from rod No. 0 cut the wales from rod No. 1.

that moment at an arbitrary instant is described by:

$$\begin{aligned} x_0 &= R\cos 2\pi(\tfrac{t}{T} + \tfrac{1}{4}), \\ y_0 &= R\sin 2\pi(\tfrac{t}{T} + \tfrac{1}{4}). \end{aligned} \tag{4}$$

However, the movement of the rod of No. i is expressed by the following equations:

$$\begin{aligned} x_i &= R\cos 2\pi(\tfrac{t}{T} + \tfrac{1}{4} - i\tfrac{1}{8}), \\ y_i &= R\sin 2\pi(\tfrac{t}{T} + \tfrac{1}{4} - i\tfrac{1}{8}). \end{aligned} \qquad i = 1 \ldots 7 \tag{5}$$

For the purpose of intercepting rod No. 1 with the wake from rod No. 0 at point P, it is necessary to fulfill the following conditions:

$$\begin{aligned} &2x_{01} = 2R\cos 2\pi(\tfrac{t_1}{T} + \tfrac{1}{4}) = Ut_2, \\ &\tfrac{2t_1}{T} + \tfrac{t_2}{T} = \tfrac{1}{8}. \end{aligned} \tag{6}$$

The first of the Eqs. (6) indicates that the wake from point O' of coordinate $-x_{01}$ should come over a distance of $2x_{01}$ to point P at velocity U in time t_2. It should be added that the rod No. 0 needed time t_1 to cover the section of arch OO', whereas at this time the rod 1 was at position 1'. In other words, the wake point O' requires time t_2 to reach point P which is also aimed at by the rod No. 1 from position 1' in time t_2.

The second equation ascertains that the time to transfer from the rod 0 to rod 1, at the same point in circumference, is $T/8$ and that time is equal to the double sum of time t_1 and time t_2.

Thus it is possible to obtain a set of two equations with two unknowns t_1 and t_2. To determine, in a general way, the intersection coordinates where rod No. $i = 1 \dots 7$ and the wakes from rod 0 cross each other, the second condition in Eq. (2) will have the form of

$$\frac{2t_{1,j}}{T} + \frac{t_{2,j}}{T} = i\frac{1}{8} \quad i = 1 \dots 7. \tag{7}$$

The substitution of Eq. (7) in formula (6) provides an equation for the sought value t_1/T,

$$\frac{D}{UT}\cos 2\pi\Big(\frac{t_{1,j}}{T} + \frac{1}{4}\Big) = i\frac{1}{8} \quad 2\frac{t_{1,j}}{T}. \tag{8}$$

The above equation is a transcendental function that can be solved numerically. It is easy to notice that the value of time $t_{1,i}$ depends on the Strouhal number $\mathrm{St} = D/(U_0T)$ of the generator and especially on the generators geometry i.e. on its diameter, the number of rods around the periphery (in our case $N = 8$) as well as on the generator rotation period $T = \frac{1}{f}$, the flow velocity Uo and the difference in the number of successive rods, since the pairs of rods (0,1), (1,2), will cut each other at the same time $t_1, \frac{1}{T}$ like rods pair (0,2), (1,3), at the time $t_1, \frac{2}{T}$, and so on, (see also Fig. 3). There are seven different solutions of the Eq. (8) depending on the number $i = 1 \dots 7$, and one trivial for $i = 0$, and $t_{1,0} = 0$. If the generator rotates clockwise, than there is the sign minus at 1 in the expression in brackets on the left side.
Coordinate $y_{0,i}$ of point P_i is determined by putting $t_{1,i}$ into Eq. (9)

$$y_{0,j} = R\sin 2\pi\Big(\frac{t_{1,j}}{T} + \frac{1}{4}\Big). \tag{9}$$

The values of the coordinates of the intersected points calculated in the way presented above will be compared later in this paper together with an experiment.

Taking advantage of the values calculated for $t_{1,j}$ and putting them into the second formula of Eq. (3) it is possible to find the angle of inclination α of the wake at this point, and using property of antisymmetry mentioned above that is $\alpha(0.25 - \frac{t}{T}) = -\alpha(0.25 \pm \frac{t}{T})$ and similarly $\alpha(0.75 - \frac{t}{T}) = -\alpha(0.75 + \frac{t}{T})$ and then calculate appropriately angle 2α at which two wakes cut each other at the point of their intersection.

4 Measurement results of the unsteady velocity field behind the wakes generator

4.1 Velocity fluctuations in time behind the wake generator

The presentation of the measuring results will begin with the velocity fluctuations registered at two points $\frac{y}{R} = 0.06$ and -0.18 of one measurement cross-section $x = 112$ mm for $U_0 = 15$ m/s and $f = 6$ Hz. Figures 6 and 7 are illustrating two different, in relation to each other, positions of wakes from the rods of the drum.

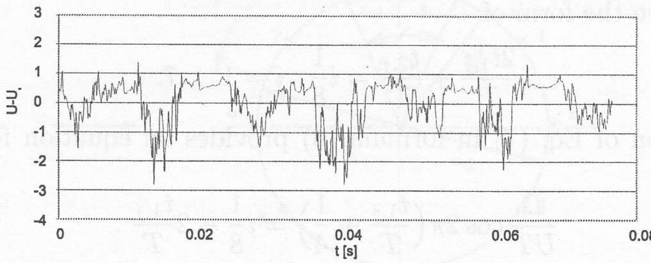

Figure 6. Velocity fluctuations downstream the generator for $x = 112$ mm and $y/R = 0.06$ and $U = 15$ m/s and for $f = 6$ Hz

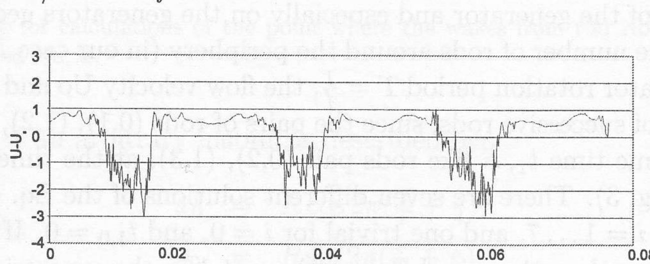

Figure 7. Velocity fluctuations downstream the generator for $x = 112$ mm, $y/R = -0.18$ and $U = 15$ m/s for $f = 6$ Hz.

In Fig. 6 one can clearly see that the wakes are alternately weaker and stronger. The weaker wakes i.e. of a minor velocity defect have their origin on the generator windward side, whereas the stronger ones i.e. of greater velocity defect – on the lee side. The total number of seven wakes are seen where four of them are weaker and alternately three wakes are of stronger velocity defect. Figure 6 reveals the position of y/R when the wakes on the lee side are located in the center between the wakes from the generator windward direction. On the other hand, Fig. 7 shows only three wakes, since the position y/R is registered when the rod on the lee side intercepts the wake on the windward side. That is why only three and not seven wake are registered. The point here is the interception of wakes by a pair of rods (1,4), (2,5), (3,6), etc, (see also Fig. 3 showing the wakes cutting arrangement).

4.2 Profiles of mean velocity

Analyzing the velocity field behind the wakes of rotating generator it is worthwhile noting the mutual relationships between the oncoming flow velocity U_0 and the rod velocity $c_0 = 2\pi R f$ around the periphery of the drum. With respect to the generator clockwise uniform motion, the axial component x of the rod velocity changes linearly from value c_0 to $-c_0$, for $y = R$ up to $-R$. When the drum rotation frequency $f = 4$ Hz then velocity c_0 will be equal to 2.51 m/s, whereas for $f = 6$ Hz it will amount to 3.77 m/s. Thus, in the case of a clockwise motion of the generator the axial component of the rod velocity in relation to the flow at a point $y/R = -1$ will be the rod velocity $U_0 + c_0$, while at a point $y/R = 1$ it will be the difference between both velocities $U_0 - c_0$.

Figure 8 depicts the mean velocity profiles $U/U_0 = f(y/R)$ crosswise the stream for various distances x behind the wakes generator, where $R = 0.1$ m is the generator radius for the oncoming flow velocity $U_o = 20$ m/s and rotational frequency of generator $f = 6$ Hz for various distances of x with respect to the measuring section behind the generator for its clockwise motion. Within the profiles it is possible to distinguish three regions of different amplitude of mean velocity defect ΔU: the first one for $-1.15 < y/R < -0.5$, the second one for $-0.5 < y/R < 0.75$ and finally the third one for $0.75 < y/R < 1.1$. The amplitude of mean velocity defect is remarkably strong in the first region, while in the second region it is much weaker, and in the third it is again stronger but not so strong as in the first region. In the first region the maximum of the velocity defect amplitude is about $\Delta U/U_0 = 0.15$, while in the third region it is equal to $\Delta U/U_0 = 0.08$. In the second region of $-0.5 < y/R < 0.75$ the mean velocity defect amounts approximately to $\Delta U/U_0 = 0.05$ and rises moderately between these two utmost points.

It is easy to notice that the amplitude of the mean velocity defect is much stronger in the region where the velocity of the rod is opposite to the oncoming velocity than in the region where they agree.

Of course, the velocity defect declines along with the rise of distance x, and thus with regard to the first region the minimum velocity defect at distance $x = 112$ mm reaches $\Delta U/U_0 = 0.15$ whereas at a distance $x = 622$ mm it amounts to $\Delta U/U_0 = 0.11$. Similar values of velocity defect decrease can be noted in the remaining two regions.

The profiles of the mean velocity related to the generator counterclockwise motion is a mirror image of the profiles shown in Fig. 8 with respect to axis $y/R = 0$.

4.3 Profiles of velocity fluctuations

Figure 9 presents the velocity fluctuations profiles of $u'/U = f(y/R)$ for the oncoming flow velocity of $U_0 = 15$ m/s and the rotational frequency of the wake generator when $f = 6$ Hz for clockwise motion of the generator and for numerous measuring cross sections, where U is local mean velocity at a given testing point. As for the mean velocity profiles shown in Fig. 8, there is a mirror symmetry

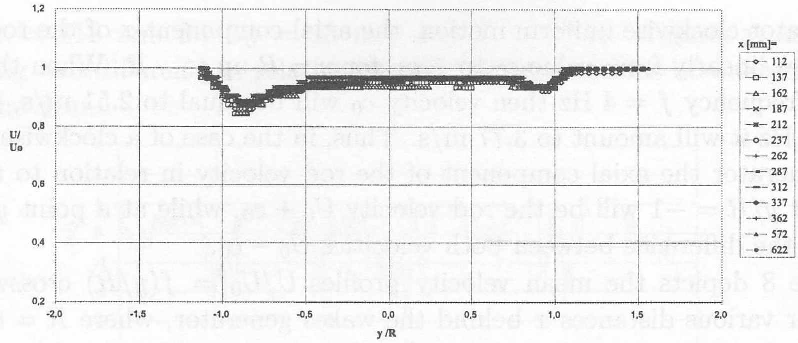

Figure 8. Mean velocity profile U/U_0 at variable distance behind the wake generator for $U_0 = 20$ m/s and $f = 6$ Hz when the motion is clockwise.

related to the drum axis of $y = 0$ for velocity fluctuations profiles of a generator rotating clockwise and counterclockwise.

In this figure it is possible to distinguish eight peaks, seven of which are caused by cutting the wake from the windward side by the rods on the lee side of the generator and the eight peak for $y/R = 1$ (or -1) created as a result of cutting across its own wake from the rod (trivial solution of Eq. (8)).

The difference between the adjacent maximum and minimum velocity fluctuation is $\Delta(u'/U) \approx 2\%$ (percentage points) and the problem is interesting because the interception of wakes consequently yields a higher root mean square value of the velocity fluctuations than two independent wakes.

Assuming that a single wake is a step function of duration Δt and the amplitude of this step is equal to U_s, then for two independent wakes the root mean square value would amount to $2\Delta t U_s/T$, where T is a certain cyclic wake period. At the cross-cut point of two wakes the assumed amplitude should be $2U_s$ and the duration also amounts to Δt. For this reason the quadratic mean of the velocity fluctuations should be equal to $2\Delta t U_s/T$. Thus the root mean square of fluctuations caused by the wakes generator ought to be the same in every part of the cross section. Therefore one should expect that a more complex process occurs here than just simple addition of separate wakes.

From the diagram in Fig. 9 it is evident that with the increase of distance x behind the wake generator the values of the fluctuations velocity decrease. For $x = 112$ mm the largest value of u'/U is 7.6 % while for $x = 622$ mm the largest value of u'/U is only 4.5%.

One can note that the height of the peaks across the flow for different y/R are not equal. In the region where axial component of the rods velocity is directed against the flow direction i.e. in the region $y/R < 0$ for the generator operating clockwise and $y/R > 0$ for the wakes generator operating counterclockwise the

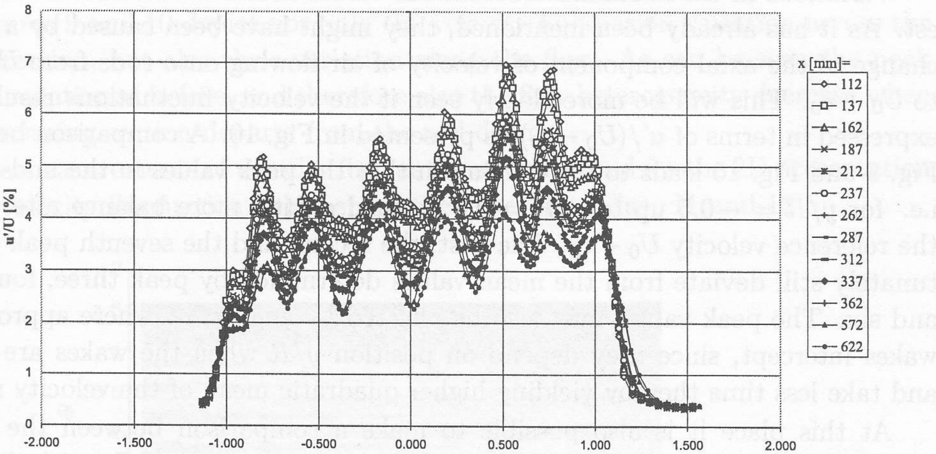

Figure 9. Velocity fluctuations profiles for the generator counterclockwise motion, $U_0 = 15$ m/s, $f = 6$ Hz.

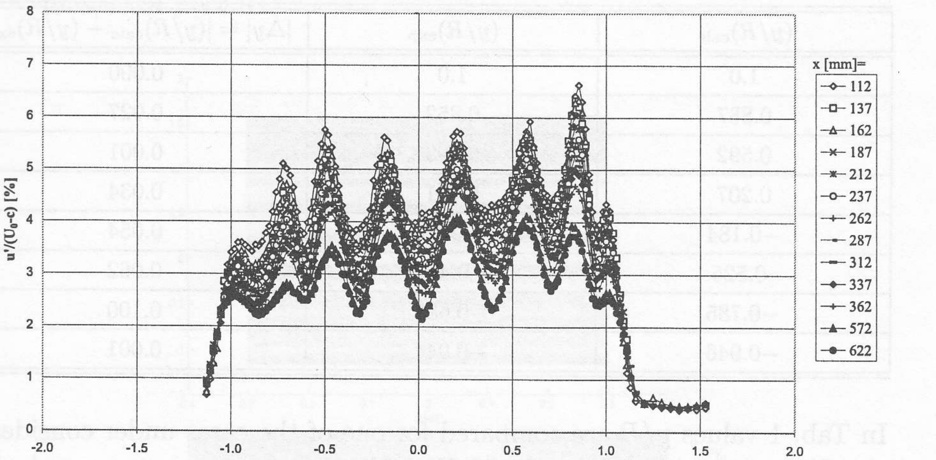

Figure 10. Velocity fluctuations fluctuations with the wakes generator related to velocity $U_0 - c_0$ for generator operating counterclockwise, when $U_0 = 15$ m/s, $f = 6$ Hz.

velocity fluctuations are higher than in the region where the axial component of the rod velocity agreed with the flow direction.

Variations in the maximum fluctuations values across the stream strike interest. As it has already been mentioned, they might have been caused by a linear change of the axial component of velocity of air flowing onto rods from $U_0 - c_0$ to $U_0 + c_0$. This will be more clearly seen if the velocity fluctuations results are expressed in terms of $u'/(U_0 - c_0)$ as presented in Fig. 10. A comparison between Fig. 9 and Fig. 10 leads to the conclusion that the peak values in the mid-range, i.e. for $y/R = -0.5$ up to $y/R = 0.6$ reached a little more balance after using the reference velocity $U_0 - c_0$. The first, the second and the seventh peak unfortunately still deviate from the mean values determined by peak three, four, five and six. The peak values may also be affected by angles 2α, where appropriate wakes intercept, since they depend on position y/R when the wakes are wider and take less time thereby yielding higher quadratic mean of the velocity signal.

At this place it is also possible to make a comparison between the peaks resulting from the interception of wakes determined experimentally with the ones obtained from calculation by solving the transcendental Eq. 8 and employing the solution in Eq. (9).

Table 1. Comparison of the calculated and measured y/R coordinates of wake interception points of the generator rotating at a mean velocity of $U_0 = 15$ m/s and drum rotation frequency $f = 6$ Hz for the counterclockwise motion

$(y/R)_{\text{calc}}$	$(y/R)_{\text{exp}}$	$\|\Delta y\| = \|(y/R)_{\text{calc}} - (y/R)_{\text{exp}}\|$
1.0	1.0	0.000
0.887	0.852	0.027
0.592	0.593	0.001
0.207	0.241	0.034
−0.184	−0.13	0.054
-0.525	−0.463	0.062
−0.785	−0.685	0.100
−0.946	−0.944	0.001

In Tab. 1 values y/R are compared for one of the cases under consideration, i.e. for $U_0 = 15$ m/s, and for $f = 6$ Hz. The discrepancy between calculations and the experiment i.e. $|\Delta y| = |(y/R)_{\text{calc}} - (y/R)_{\text{exp}}|$ is 0.001 up to 0.1, and it can be regarded as insignificant taking into account a possible strain of the bars fixed to the drum during the generator rotation. The largest divergence between the experiment and the calculation refers to peak six and amounts to $\Delta(y/R) = 0.1$. Similarly, the results of coordinates of the intersection points have been obtained for the remaining velocities flowing onto the generator and its rotational frequency values. The comparison with calculation is also as good as in the case shown above.

Figures 9 and 10 depict not only the velocity fluctuation variation across the flow direction, but also their variation along the flow. As can be seen the peak values, mentioned before, and therefore also the flow heterogeneity decrease when the measuring section departs from the rod drum.

The measurements of velocity fluctuations can be used for the 2D presentation of the velocity fluctuation field behind the generator, Figs. 11 and 12.

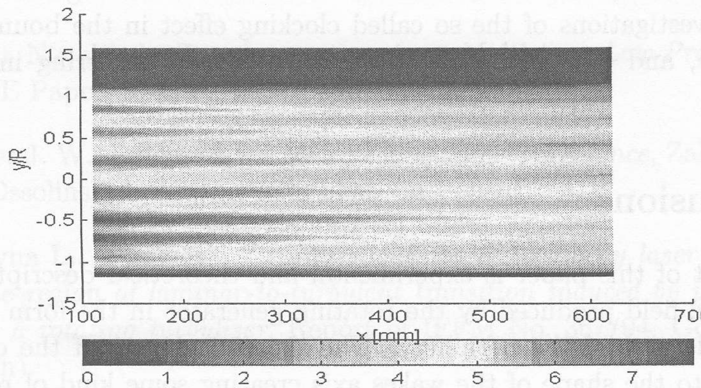

Figure 11. Velocity fluctuations field for the wake generator in clockwise motion when $U_0 = 10$ m/s and $f = 4$ Hz.

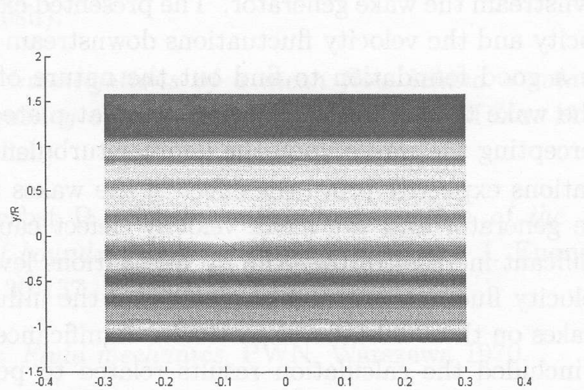

Figure 12. Velocity fluctuations field crosswise the stream for clockwise motion of the wake generator when $U_0 = 10$ m/s and $f = 4$ Hz.

The presentation of a 2D distribution of the velocity fluctuations along and crosswise the flow (Figs. 11 and 12) will become an interesting matter. This affords possibilities for a pictorial demonstration of the velocity fluctuations variation in the field behind the wake generator providing it with the range of the wakes and their intensity. Peak five and six counting from the top, are the most intensive ones, taking into consideration their range and the fluctuation level.

At this place, let us also take the liberty of expressing an opinion that the non-stationary velocity field generated in such a way downstream the rods drum may be used for the investigation of the effect of the wakes interception on the flat plate boundary layer and in particular for analyzing the transition in the boundary layer induced by wakes. Therefore we are of the opinion that such a configuration of wakes and their cross-cuts created behind the generator can be utilized for investigations of the so called clocking effect in the boundary layer of a flat plate, and thus modeling of the phenomenon occurring in fluid-flow machinery.

5 Conclusions

The object of this paper is experimental and theoretical description of the generator wake field produced by the rotating generator in the form of a drum with eight rods around the periphery. The theoretical part of the description has relevance to the shape of the wakes axis creating some kind of regular but asymmetric network with points where the wakes intersect each other making the nodes of network. The experimental part deals with the determination of the velocity field downstream the wake generator. The presented experimental results of the mean velocity and the velocity fluctuations downstream the rotating wake generator create a good foundation to find out the nature of the disturbances brought in by the wake to the boundary layer on a flat plate and in particular the effect of intercepting the wakes upon the laminar-turbulent transition.

The investigations explicitly prove the effect of the wakes in the free stream behind the wake generator and the mean velocity defect caused by the wakes as well as a significant increase of the velocity fluctuations level. The presented results of the velocity fluctuations measurements and the influence of the interception of the wakes on their level are of particular significance. Moreover, there have also been included the calculation results related to point which crosses across the wakes created on the windward side of the wake generator with the wakes on the lee side, and thus it was possible to determine the coordinate point where the wakes intercept, and determine the dependence on the drum diameter, the oncoming flow velocity, and the rotational frequency so the Strouhal number St.

Calculations of the cross-cut coordinate points have been compared with the experimental data and a satisfactory compatibility has been obtained. In view of the above it is suggested to make use of the unsteady velocity field created downstream the wakes generator in investigations of the "clocking effect" known in fluid-flow machinery, which is connected with the wakes from two or more cross-cutting blade rings, and its interaction with the laminar-turbulent transition in the boundary layer and its effects on the losses.

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