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SOME METHODS FOR DIAGNOSTICS OF WAKE-INDUCED LAMINAR-TURBULENT TRANSITION

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Abstract. To create a reliable engineering method for calculating local heat transfer of turbine blades, information about the flow regime on the blade surface is necessary. The presence of a wake-induced laminar-turbulent transition on the surface of the blade requires the development of methods for its diagnostics. The object of the study is blade surface under the influence of unsteady periodic wakes from upstream blade rows. The research method is physical modeling of a wake-induced transition initiated by steady wakes behind a still and periodic unsteady wake behind an oscillating cylinder. The article considers some methods for determining the coordinates and extent of a wake-induced transition region. Reliable diagnostics of such a transition is possible only with the help of a combination of developed methods. The presented experimental data allow us to predict the location of a wake-induced transition and the intensification of heat transfer in the preceding pseudolaminar boundary layer, that is, to control the process of such a transition.

Keywords: wake-induced laminar-turbulent transition, diagnostics of transition coordinates, still and oscillating cylinders.

1. Introduction

The main streamlined surface of thermal power equipment considered in this paper is the turbine blade. Laminar, transitional, and turbulent boundary layers (BLs), as well as separation zones, can coexist on the surface of a turbine blade. One of the primary tasks in turbomachine design is the development of a reliable engineering method for calculating local heat transfer of turbine blades. This method includes both the development of flow regime diagnostic methods and the consideration of the fact that the working fluid in the flow path of turbomachines is highly turbulent. The overall degree of flow turbulence in the gas turbine flow path is determined by both the initial turbulence as it passes through the compressor and combustion chamber, and the flow conditions through the blade cascades of the preceding stages. Such type of flow is formed due to the appearance of stationary and moving wakes behind the trailing edges of the previous rows of blades. These wakes have a significant impact on the development of BL on the blade surface and must be taken into account when calculating the thermal and aerodynamic state of the rotor and stator elements.

Under the influence of unsteady periodic wakes of the upstream blade rows, a transition occurs on the surface of the blades, which is called wake-induced laminar-turbulent transition. In the wake-induced transition, the first stages of the natural transition process are bypassed and the forming turbulent spots immediately merge into turbulent streaks, which then grow and spread downstream. Between these turbulent streaks another type of transition (natural or bypass) may occur. Thus, the transition in gas turbines can occur as multiple transition modes at different distances on the same surface at the same time [1].

The development of improved methods for calculating the intensity of transport processes occurring in the presence of a wake-induced transition requires information about the coordinates and length of this region. The current situation stimulated the continuation of the research started at the IET NASU on the development of new and modification of existing diagnostic methods for the laminar-turbulent transition (LTT). As the results of this work have shown, the methods of diagnosing a bypass transition occurring under conditions of increased turbulence of the external flow can also be successfully used for a wake-induced transition.

2. Analysis of recent research and publications

In recent years, many works devoted to the study of wake-induced transitions have appeared. These works considered various cases of the development of a transition initiated by wakes behind both stationary and moving obstacles; however, the problems of diagnosing such a transition were practically not studied in these works. In particular, review [2] examines models for calculating various types of transitions typical for turbine blade surfaces, including the wake-induced transition. The authors of paper [3] presented the results of calculations using the LES method for the flow around a low-pressure turbine rotor blade with periodically occurring flow wakes. An experimental study of the wake-induced transition using boundary layer flow visualization over a 30P30N multi-element airfoil allows us to detect the formation and subsequent development of Λ -vortices [4]. Paper [5] presents the results of experimental and numerical studies of a low-pressure turbine blade cascade, conducted to analyze wake interaction effects on boundary layer transition. The authors noted that under steady-state conditions, a substantial separated flow occurred on the suction side. Under the influence of the wake generator, this separated flow was reduced, decreasing profile pressure losses by 50%. The influence of the frequency of passage of vortex wakes on the development of transient processes in the boundary layer was considered in [6]. A squirrel cage was used as a wake generator. In experiments, a clear relationship was established: the longitudinal position of the point where the boundary layer becomes fully turbulent shifts upstream with increasing wake vortex frequency. Several papers have been devoted to the experimental study of the transition caused by the wake of a circular cylinder located near the wall using flow visualization techniques [7, 8]. In [9], the flow around a cylinder near a flat wall is numerically investigated for small gap values. Because of the wake-induced transition study, three dynamic vortex motion processes associated with different hairpin vortex generation mechanisms were discovered [9]. These results are consistent with previous data presented in papers [10, 11]. In all the studies cited, methods for diagnosing wake-induced transitions were not considered.

Several methods for diagnosing a wake-induced transition are discussed in the article [12]. The purpose of this paper is to conduct a more detailed study of methods for diagnosing a wake-induced transition initiated by steady wakes behind a still and periodic unsteady wake behind oscillating cylinders.

3. Materials and research methods

The electro calorimetric method was used to study heat transfer. DISA-55M hot-wire system was used to measure the parameters of the internal structure of the dynamic and thermal boundary layers and external flow. Experimental investigations of a flat plate heat and momentum transfer processes in the presence of unsteady flows were carried out in the T-5 wind tunnel of the IET NASU using various wake generators (a still and oscillating cylinders).

The experimental setup diagram of a still and oscillating cylinder (1) with a frequency of 4.4 Hz, as well as a limiting plate (2) in the working section (3) of the T-5 wind tunnel is shown in Fig. 1. In contrast to the case described in paper [12], this study examined the diagnostics of a wake-induced transition in two cases of a still cylinder and an oscillating cylinder. The still cylinder was installed at distances equal to both the amplitude ($y_c=20$ mm) and the mid-span of the oscillation ($y_c=10$ mm). The study of heat and momentum transfer processes on a flat plate in the presence of a wake-induced transition was carried out at an external flow velocity $U \approx 9$ m/s.

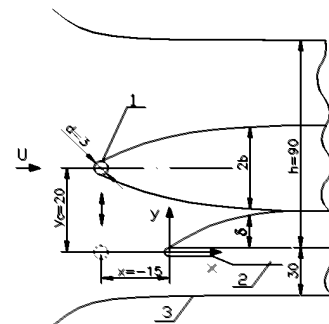


Fig.1. Experimental setup diagram

A total of 4 series of experiments were conducted: in the absence of a cylinder (natural LTT at $Tu = 0.2-0.4\%$) (series 1), with two installations of a still cylinder ($y_c = 20$ and 10 mm) (series 2 and 3), and with an oscillating cylinder (series 4).

4. Results and discussion

We will consider the main methods for diagnosing a wake-induced transition using the example of determining the coordinates of transition for the cases of a still and an oscillating cylinder. This study was based on an analysis of distributions of local heat transfer and friction coefficients and the characteristics of dynamic and thermal boundary layers, which are developing along the length of the plate.

1. The traditional method of determining the start and end of the transition by the minimum and maximum points in the distributions of heat transfer and friction coefficients along the length of the plate is unsuitable in case of an oscillating cylinder due to their smoothed nature (Fig. 2a, 2b, symbol 6).

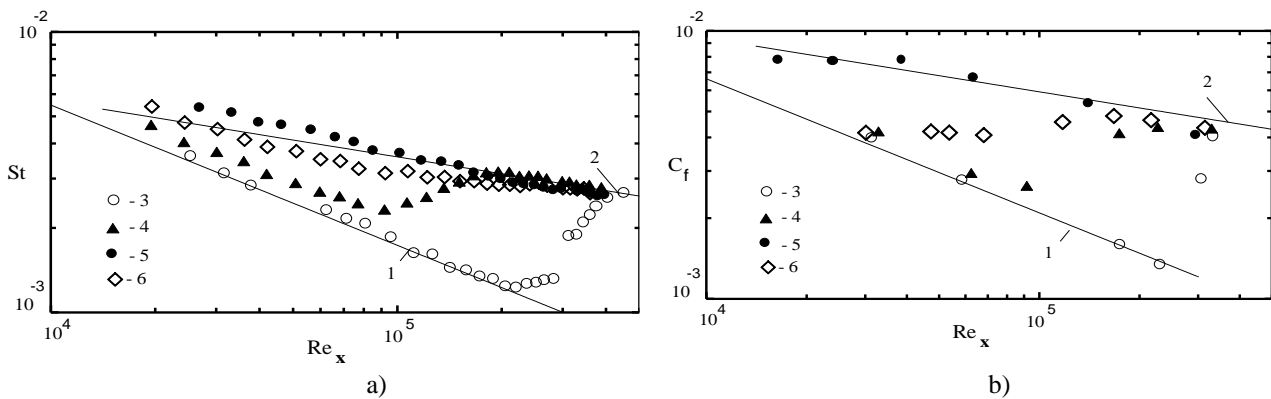


Fig.2. Distributions of local heat transfer (a) and friction coefficients (b):

1 – $St_0 = 0.55 \cdot Re_x^{-0.5}$ (a); $C_{f0} = 0.664 \cdot Re_x^{-0.5}$ (b); 2 – $St_0 = 0.036 \cdot Re_x^{-0.2}$ (a); $C_{f0} = 0.0595 \cdot Re_x^{-0.2}$ (b); 3 – in the absence of a cylinder; 4 - $y_c = 20$ mm; 5 - $y_c = 10$ mm; 6 – an oscillating cylinder

In the absence of a cylinder (series 1, symbol 3 in Fig. 2), the start and end of the LTT region, corresponding to the minimum and maximum of these distributions, are $Re_{x_{st}} = 2 \cdot 10^5$ and $Re_{x_{end}} = 4.5 \cdot 10^5$. The length of the natural transition region was $Re_{x_{end}}/Re_{x_{st}} = 2.25$ (where $Re_{x_{st}}$ and $Re_{x_{end}}$ are the coordinates of the start and end of the LTT, respectively). In series 4 (Fig. 2a, symbol 6), under the influence of an oscillating cylinder, the distribution of local heat transfer coefficients was non-monotonic, and the experimental points were located between series 2 ($y_c = 20$ mm) and 3 ($y_c = 10$ mm). The intensification of heat transfer in the pre-transitional pseudolaminar BL in series 4 reached $\sim 40\%$ at $Re_x = 6 \cdot 10^4$. The distribution of friction coefficients in series 4 (Fig. 2b, symbol 6) also has a smoothed character and is located between series 2 and 3. The intensification of friction in the pre-transitional BL changes from 1.09 in the first measuring section to 1.5 at $Re_x = 6 \cdot 10^4$. Thus, the intensification of heat transfer at $Re_x = const$ in the pre-transitional BL exceeds the increase in friction for both a still ($y_c = 20$ mm) and an oscillating cylinder. The reasons for the increase in heat transfer, which outpaces friction, are associated with changes in the internal structure of the pre-transitional BL (primarily with a high degree of correlation between velocity and temperature fluctuations).

As shown by the results of experimental studies of the external flow turbulence when installing a still ($y_c = 20$ mm, series 2) and an oscillating cylinder (series 4), given in [12], added by additional experiments at $y_c = 10$ mm (series 3), the degree of turbulence of the external flow gradually increased in series 2, 4, and in series 3 was maximum. Thus, the analysis of the obtained distributions of local heat transfer coefficients along the plate length shows that with increasing turbulence of the external flow caused by the cylinder location (series 1, 2, 4 and 3, respectively), an increase in the heat transfer coefficients in the pre-transition pseudolaminar BL is observed. In the third series, with the cylinder positioned at $y_c = 10$ mm (symbol 5 in Fig. 2a), the effect of the wake led to a monotonic change in the heat transfer coefficients along the plate length, resulting in a «upper» approach to the turbulent BL characteristics. Such variations of St don't permit to predict the «upper» transition origin and to diagnose the location of its start and end. It should be noted that the distribution of heat transfer coefficients in Fig. 2a of this article coincides with the corresponding distributions in Fig. 2 in the

work [12] for the cases of without cylinder, for installations of a still cylinder $y_c=20$ mm and an oscillating cylinder.

2. A common method for diagnosing LTT is to determine the start and end of the transition as minimum and maximum points in the dynamic pressure distribution. To implement this method, the total pressure nozzle is moved in the direction of flow at a fixed distance close to the plate surface, which is usually chosen to correspond to the displacement thickness of the laminar BL at the start of the transition region.

3. Less commonly used is the hot-wire anemometer method for determining the transition region. In this method, the hot-wire anemometer probe is also moved along the flow at a fixed distance from the surface. The coordinates of the start and end of the transition can be determined by changes in voltage proportional to the time-averaged velocity or temperature, as well as its longitudinal fluctuations over a wide or fixed frequency band. This method, compared to the previous one, has a number of advantages: the ability to visually observe the nature of disturbances at a given point with low inertia of the measuring system.

4. Diagnostics of the wake-induced transition can be carried out using the temperature distribution on the plate surface or changes in temperature difference: $\Delta t = A \cdot x^n$. Figure 3 clearly shows a break in the temperature difference distribution at $x_{st} \approx 140$ mm, indicating the start of a wake-induced transition. In the pre-transition region, $n = 0.28$, and in the transition region, $n=0.13$. Diagnosing the end of a wake-induced transition based on this temperature difference distribution is difficult.

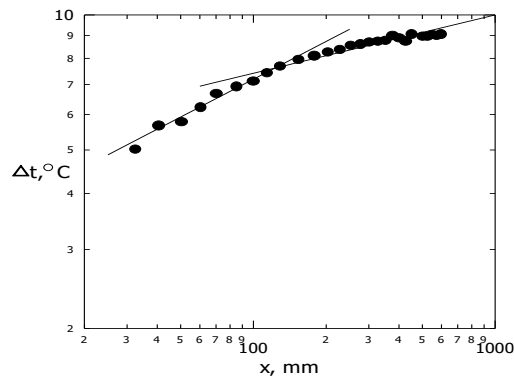


Fig. 3. Distribution of temperature difference along the length of the plate with an oscillating cylinder

5. Determination of the start and end of a wake-induced transition based on the deformation of the velocity profiles in wall law coordinates (Fig.4a).

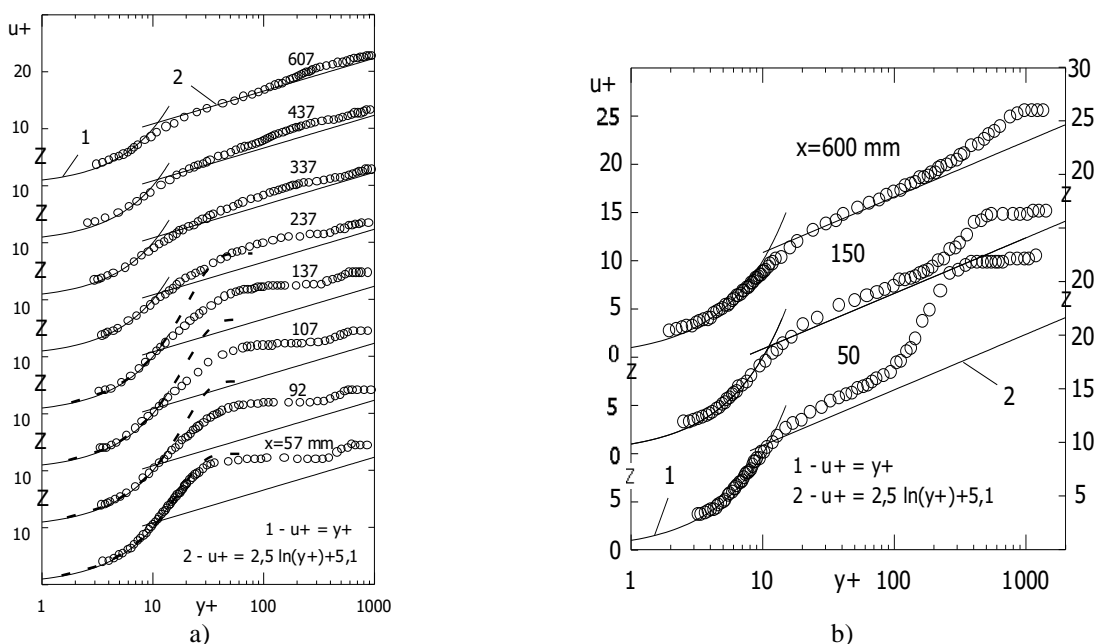


Fig.4. Velocity profiles with an oscillating cylinder (a) and $y_c = 10$ mm (b)

In the first measurement section, at $x = 57$ mm, the velocity profile for an oscillating cylinder practically coincided with the Blasius profile (dashed line in Fig. 4a). In following sections, at $x = 92$ – 137 mm, the velocity distribution in the near-wall region, although different from the Blasius profile, retains its shape. The start of a wake-induced transition is determined by appearance of a flattened portion (an analog of the future region of log-law validity) (Fig.4a, $x = 237$ mm). The end of the transition corresponds to a section in which a velocity profile with a clearly defined region of the logarithmic law is observed (Fig.4a, $x = 437$ mm). This deformation of the velocity profile is characteristic of a bypass transition. The analysis of Fig. 4b shows that when the cylinder is installed at $y_c = 10$ mm, a transitional flow regime is already observed in the section at $x = 50$ mm, which is transformed into a turbulent one, and at $x = 600$ mm the logarithmic law of the velocity distribution occupies the region of $y^+ = 30$ – 120 . This distribution of velocity profiles proves the presence of an «upper» transition in the initial sections of the plate.

6. Diagnostics of a wake-induced transition can be carried out using distributions $\delta/x = f(Re_x)$ and $\delta^{**}/x = f(Re_x)$, where δ^{**} is momentum thickness (Fig.5a, 5b). If we draw two straight lines in these distributions through points lying in the pre-transitional BL and in a wake-induced transition, then their intersection will indicate the coordinate of the start of transition region. The end of the transition cannot be clearly determined using these distributions.

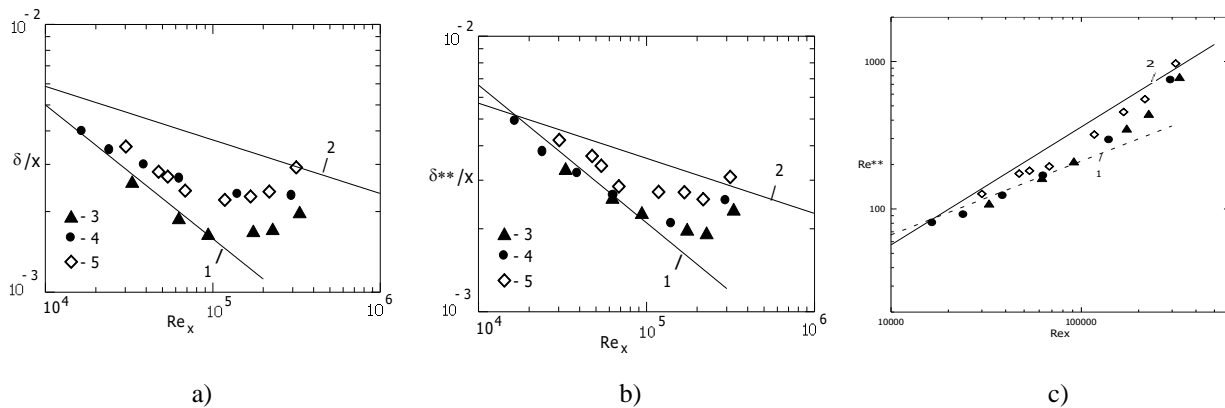


Fig. 5. Distribution of the thickness of the BL (a) and the momentum thickness (b) along the length of the plate: 1 – $\delta/x = 5/Re_x^{-0.5}$ (a), $\delta^{**}/x = 0.664 \cdot Re_x^{-0.5}$ (b); 2 – $\delta/x = 0.37 \cdot Re_x^{-0.2}$ (a); $\delta^{**}/x = 0.036 \cdot Re_x^{-0.2}$ (b) 3 – $y_c = 20$ mm; 4 – $y_c = 10$ mm; 5 – an oscillating cylinder
c) Distribution $Re^{**} = f(Re_x)$ 1 – $Re^{**} = 0.664 \cdot Re_x^{0.5}$; 2 – $Re^{**} = 0.036 \cdot Re_x^{0.8}$

7. A variation of the previous method is the use of a distribution $Re^{**} = f(Re_x)$ constructed in a logarithmic coordinate system (Fig.5c).

8. The end of a wake-induced transition can be clearly determined from the distribution of the shape parameter along the length of the plate $H = f(Re^{**})$ as the coordinate of the beginning of its linear changes in the region of the turbulent BL (Fig. 6). It should be noted that this distribution is often used to determine the start of LTT. Typically, the start of LTT is defined as the point at which the shape parameter begins to deviate from 2.6, characteristic of laminar BL. This method is unsuitable for diagnosing the start of a wake-induced transition due to the decrease in the shape parameter in the pre-transitional BL (Fig. 6).

9. Diagnostics of a wake-induced transition is possible based on the analysis of velocity and temperature fluctuations. During the transition process, the shape of the longitudinal velocity fluctuations profile is transformed from smooth with a rounded top, characteristic of a pseudolaminar BL, into a pointed shape, typical of a turbulent BL (the first wall peak for an oscillating cylinder in Fig. 7). A characteristic feature of these distributions, which distinguishes them from the fluctuation profiles for still cylinders, is the appearance of a second maximum due to the interaction of wakes. The behavior of the first wall maximum for an oscillating cylinder is characterized by: as it approaches to the transition region, it increases, reaching a value $u_m'/U_e = 14$ – 15% , and then decreases and approaches the wall in the turbulent BL. The second maximum occurs closer to the outer edge of the BL and in the initial sections is larger in amplitude than the wall peak. Thus, in particular, in the section $x = 50$ mm the wall peak with a maximum $u_m'/U_e = 12\%$ is located at $y/\delta = 0.2$, and the second maximum $u_m'/U_e = 17.8\%$ – at $y/\delta = 0.6$. In following sections of the plate, the amplitude of the

second maximum decreases, at the start of the transition it becomes comparable in amplitude to the wall maximum ($x = 137$ mm) and then gradually disappears ($x = 607$ mm).

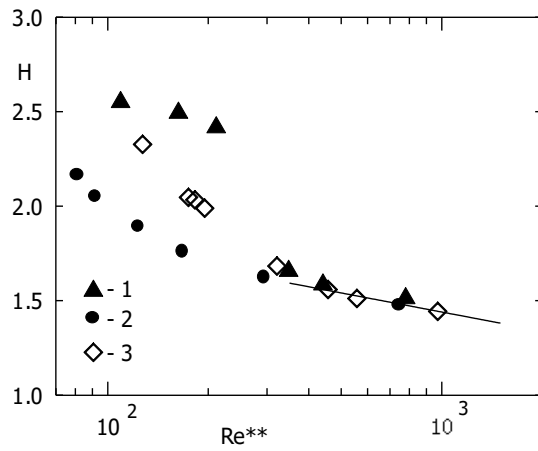


Fig.6. Changing the shape parameter H along the length of the plate: 1 - $y_c = 20$ mm; 2 - $y_c = 10$ mm; 3 – an oscillating cylinder

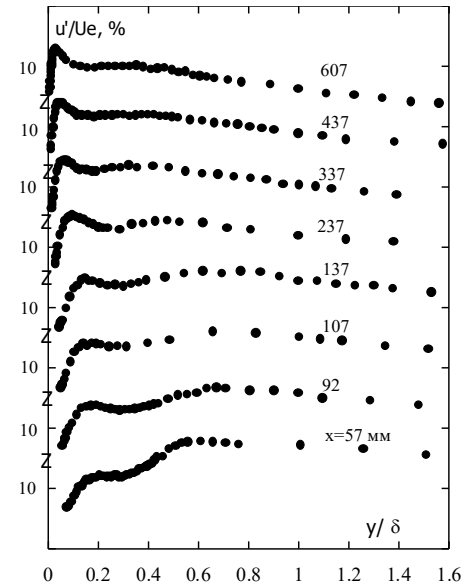


Fig.7. Longitudinal velocity fluctuations profiles with an oscillating cylinder

10. Indicators of the type of BL developing on the surface are the location and amplitude of the longitudinal velocity fluctuations maxima. During the development of the transition, the amplitude of the maximum increases for $y_c = 20$ mm and for an oscillating cylinder (wall peak), reaching a value of $u_m' / U_e = 14-15\%$, decreasing slightly in the turbulent BL (Fig. 8). The maximum values $u_m' / U_e = f(Re^{**})$ in the distribution for an oscillating cylinder are achieved at values Re^{**} smaller than for $y_c = 20$ mm, which confirms the shift of the transition zone upstream in the first case. In addition, which was noted earlier, a distinctive feature of the wake-induced transition, as well as the bypass transition, is the increase in the values of the longitudinal velocity fluctuations maxima in the pre-transition BL with an increase in the external flow turbulence created by the wakes behind the cylinders. The position of the still cylinder at $y_c = 10$ mm turbulizes the external flow so much that the values u_m' / U_e are already maximum in the first measurement section and decrease along the length of the plate during a wake-induced transition process. The amplitude of the second maximum for an oscillating cylinder change is similarly. The observed features of velocity fluctuation profiles are in good agreement with results of investigation presented in [12].

A comparison of all the considered diagnostic methods is presented in the table 1.

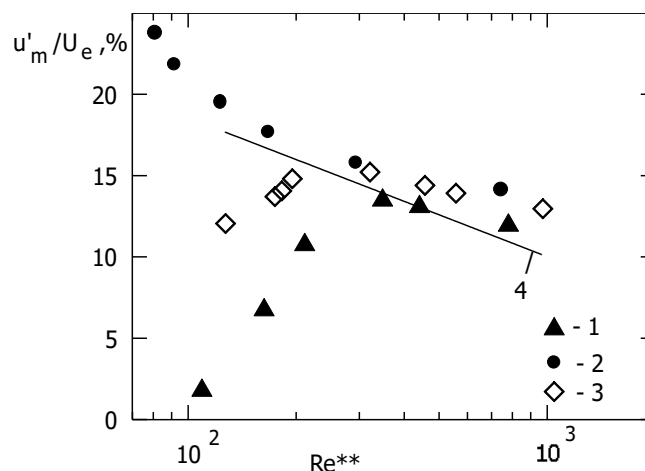


Fig.8. Distributions of the longitudinal velocity fluctuations maxima: 1 - $y_c = 20$ mm; 2 - $y_c = 10$ mm; 3 – wall peak for an oscillating cylinder; 4 – second maximum for an oscillating cylinder

Table 1. Methods for diagnostics of wake-induced transition

Methods	Advantages	Limitations
Distributions of heat transfer and friction coefficients	Suitable for still cylinder ($y_c=20$ mm)	Unsuitable for still cylinder $y_c = 10$ mm and an oscillating cylinder
Distributions of dynamic pressure near the plate surface	Simplicity and accessibility of the method	Selecting a fixed distance near the plate surface corresponding to the displacement thickness of the laminar boundary layer
Changing the signal of a hot-wire anemometer near the plate surface	The ability to visually observe the nature of disturbances at a given point with low inertia of the measuring system	Selecting a fixed distance near the plate surface corresponding to the displacement thickness of the laminar boundary layer
Temperature distribution on the plate surface	Simplicity of the method. Suitable for diagnosing the start of a wake-induced transition	Diagnosing the end of a wake-induced transition is difficult
Deformation of the velocity profiles in wall law coordinates	Suitable for still cylinder ($y_c=20$ mm) and an oscillating cylinder	Diagnosing the region of a wake-induced transition in the presence of an «upper» transition ($y_c = 10$ mm) is difficult
Distributions $\delta/x = f(Re_x)$, $\delta^{**}/x = f(Re_x)$, $Re^{**} = f(Re_x)$	Suitable for diagnosing the start of a wake-induced transition	The end of the transition cannot be clearly determined
Distribution of the shape parameter	Suitable for diagnosing the end of a wake-induced transition	Unsuitable for diagnosing the start of a wake-induced transition
Analysis of velocity fluctuations distributions including location and amplitude of the longitudinal velocity fluctuations maxima	Suitable for diagnosing the start and end of a wake-induced transition	Diagnosing the region of a wake-induced transition in the presence of an «upper» transition ($y_c = 10$ mm) is difficult

As the presented methods for diagnosing a wake-induced transition have demonstrated, there is no single, reliable way to determine the start and end of the transition region. Some proposed methods reliably determine the start of the transition, while others only determine the end. This may explain the existing discrepancies in the interpretation of the results of various authors on diagnosing a wake-induced transition. Only a combination of the methods described above allows for the diagnosis of such a transition.

5. Conclusion

The presented results were focused on development of new and modification of existing diagnostic methods for a wake-induced transition initiated by wakes behind a still and oscillating cylinders. The special attention was paid to finding the start and end of its region. It is necessary to use a combination of presented methods to reliably determine the coordinates of a wake-induced transition.

Using a combination of developed diagnostic methods, the coordinates of a wake-induced transition were determined for 4 series of experiments:

- with an oscillating cylinder (series 4): $Re_{x_{st}}=8.5 \cdot 10^4$, $Re_{x_{end}}=2.4 \cdot 10^5$, respectively $x_{st} \approx 140$ mm, $x_{end} \approx 400$ mm;
- still cylinder ($y_c=20$ mm) (series 2): $Re_{x_{st}}=9 \cdot 10^4$ and $Re_{x_{end}}/Re_{x_{st}}=2.94$;
- still cylinder ($y_c=10$ mm) (series 3): $Re_{x_{st}}=8.2 \cdot 10^4$, $Re_{x_{end}}/Re_{x_{st}}=2.82$.

Increasing the turbulence of the external flow by installing fixed and moving cylinders leads to the fact that a wake-induced transition region shifts upstream in series 2, 4 and 3. These experimentally established facts make it possible to predict the location of the wake-induced transition and the intensification of heat transfer in the pseudolaminar BL, i.e., to control the process of such type transition using wakes behind the still and oscillating cylinders in the range of these experiments parameters. The experimentally discovered fact that with increasing vortex frequency the start of a wake-induced transition region shifts upstream coincides with the conclusions of the previously cited article [6].

Based on the data obtained in the range of parameters in the present experiments, the possibilities of controlling a wake-induced transition are confirmed:

- its location - from $x_{st} \approx 115$ to 155 mm at $y_c=10$ and 20 mm respectively;

- length - from ($x_{end} - x_{st}$) ~230 to 300 mm at $y_c=10$ and 20 mm respectively;
- intensification of transfer in the preceding pseudolaminar BL - from ~20% ($y_c =20$ mm) to ~90% ($y_c=10$ mm) at $Re_x = 6 \cdot 10^4$.

The need to coordinate the efforts of researchers to unify experimental procedures for determining the coordinates of a wake-induced transition region was emphasized.

Conflict of interest statement

The author declares that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Statement on the use of Artificial Intelligence.

The authors declare that no artificial intelligence tools were used to generate scientific content, results, or conclusions of this article.

Data Availability Statement

The data are available upon reasonable request from the authors.

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