ISSN 0021-8944, Journal of Applied Mechanics and Technical Physics, 2024, Vol. 65, No. 1, pp. 61–65. © *Pleiades Publishing, Ltd., 2024.*
Russian Text © *L.R. Gareev, O.O. Ivanov, V.V. Vedeneev, D.A. Ashurov.*

EFFECT OF THE AMPLITUDE OF A STATIONARY PERTURBATION ON ITS NON-MODAL GROWTH IN A LAMINAR SUBMERGED JET

L. R. Gareev[a,*], **O. O. Ivanov**[a], **V. V. Vedeneev**[a], **and D. A. Ashurov**[a]

UDC 532.5.013.4

Abstract: This paper touches upon the effect of an amplitude of a deflector introduced into a laminar jet flow on the linear change coefficient of the radial component of a stationary perturbation. Methods for introducing and measuring the perturbations are described. It is shown that a decrease in the deflector amplitude has no effect on the flow pattern, cannot prevent an algebraic growth mechanism, and causes a proportional decrease in the radial component of the stationary velocity perturbation. Turbulence is established after reaching some radial expansion value that is independent of the initial perturbation amplitude.

Keywords: non-modal growth of perturbations, submerged jet, laminar-turbulent transition.

DOI: 10.1134/S0021894424010073

INTRODUCTION

There are two main ways for perturbation growth in near-wall flows: a modal mechanism and an algebraic (non-modal) mechanism. The latter ensures a bypass transition to turbulence [1, 2] and leads to the emergence of longitudinal vortex structures, causing the mixing of fluid layers and the turbulization of the main flow. It is shown in [3, 4] that there are longitudinal vortices formed in the laminar section in jet flows and in near-wall flows. These longitudinal vortices are also called streaky structures. Such structures were modeled in the form of stationary perturbations arising behind roughness elements located at the nozzle exit in [5]. Their visualization and the study of their effect on Kelvin–Helmholtz billows were carried out in [6].

However, despite the large number of works devoted to the study of coherent structures arising in submerged jets, the transition to turbulence in a laminar jet flow by a non-modal mechanism remains understudied as the first theoretical investigations of optimal perturbations in jet flows have been published relatively recently [7, 8]. The first known experimental study of the non-modal mechanism of perturbation growth in a jet flow was described in [9]. The present work is its continuation.

Stationary perturbations in submerged jets [7, 8] and in boundary layers [10] increase kinetic energy most significantly through a non-modal mechanism. Therefore, it is proposed to place thin wave-like structures (deflectors) into the laminar jet flow considered in this work. As shown in [9], they initiate the algebraic (non-modal) mechanism of perturbation growth. In contrast to the modal mechanism [11], the algebraic mechanism is characterized by a linear (rather than exponential) increase in the longitudinal component of the downstream velocity perturbation and the formation of longitudinal vortices, which changes the laminar-turbulent transition scenario [9]. A similar process occurs in boundary layers [12].

[a]Institute of Mechanics of the Lomonosov Moscow State University, Moscow, Russia; *gareev.lr@yandex.ru, ivanov@imec.msu.ru, vasily.vedeneev@mail.ru, denis.ashurov@icloud.com. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 65, No. 1, pp. 70–74, January–February, 2024. Original article submitted June 2, 2023; revision submitted September 7, 2023; accepted for publication September 25, 2023.

*Corresponding author.

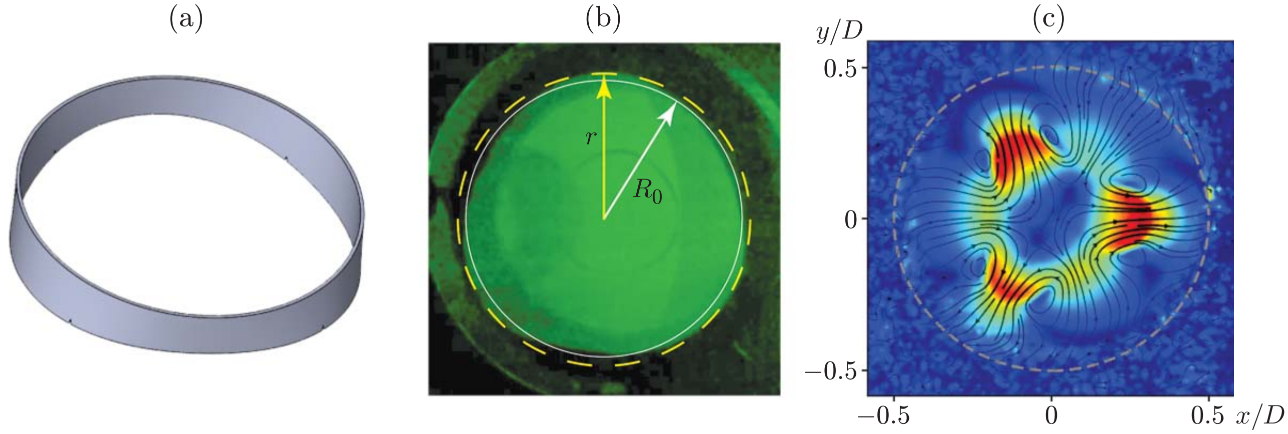

Fig. 1. 3D model of a deflector with $n = 3$ and $\varepsilon = 0.05$ (a), the visualization results of the cross section of the flow subjected to a stationary deformation by the deflector (b), and the distribution of the transverse velocity perturbation component experimentally obtained by the PIV method at a distance from the outlet section equal to the jet diameter (c).

The linear stability theory is used to describe the perturbation growth mechanisms under the assumption that the perturbations under consideration are small. Experiments with deflectors with relative deviations of outlet shapes from a circle ($\varepsilon = 0.05$; 0.10) are described in [9]. It is shown that the laws of growth of longitudinal and transverse velocity perturbation components correspond to the laws obtained theoretically for optimal perturbations. Now the question is what minimal perturbations should be introduced into the jet in order to initiate the algebraic mechanism. To answer this question, the azimuthal number is set to $n = 3$ (the nature of the perturbation growth is the same for different values of $n > 1$ [9]: paired counter-rotating longitudinal vortices are observed on the transverse section), and the value of ε is varied. Another phenomenon studied here is the dependence of the transverse perturbation amplitude at which the transition to turbulence on the magnitude of the initial perturbation introduced by the deflector.

1. EXPERIMENTAL APPARATUS AND THE METHOD OF INTRODUCING STATIONARY PERTURBATIONS

A laminar axisymmetric air jet is considered. The apparatus that generates this jet is a short diffuser with deturbulizing metal grids. Jet diameter $D = 0.12$ m, axial velocity $U_c = 1.5$ m/s, and Reynolds number $\mathrm{Re} = 5400$ (calculated using the average velocity and the diameter). The jet generator is described in detail in [13].

Stationary perturbations are introduced into the jet using thin wave-like deflectors with a height $h = D/12$ and a thickness of $0.005D$. Its inlet section is a circle with a diameter $d = D/2$, its the outlet section is a sinusoidally deformed circle of the same diameter with the azimuthal number of deviations from the circle $n = 3$, and the relative amplitude of this deviation $\varepsilon = 0$; 0.01; ...; 0.09; 0.10.

The nature of the change in the radial velocity perturbation component u_r introduced by these deflectors is determined using two methods: laser sheet visualization and particle image velocimetry (PIV) measurements. This paper presents the results obtained only by the former method. Figure 1 shows a 3D model of the deflector, the visualized transverse section of the flow, the distribution of the transverse velocity perturbation component $u_{tr} = \sqrt{u_r^2 + u_\theta^2}$, taken from [9], and streamlines.

2. VISUALIZATION OF THE FLOW CROSS SECTION

Experiments on the visualization of the flow cross section are similar to those described in [9]. The flow moving from top to bottom is seeded with small particles of glycerol (a continuous laser is used to create a laser sheet), and a portable web camera is located below the plane of the laser sheet at a distance equal to $3D$. The laser

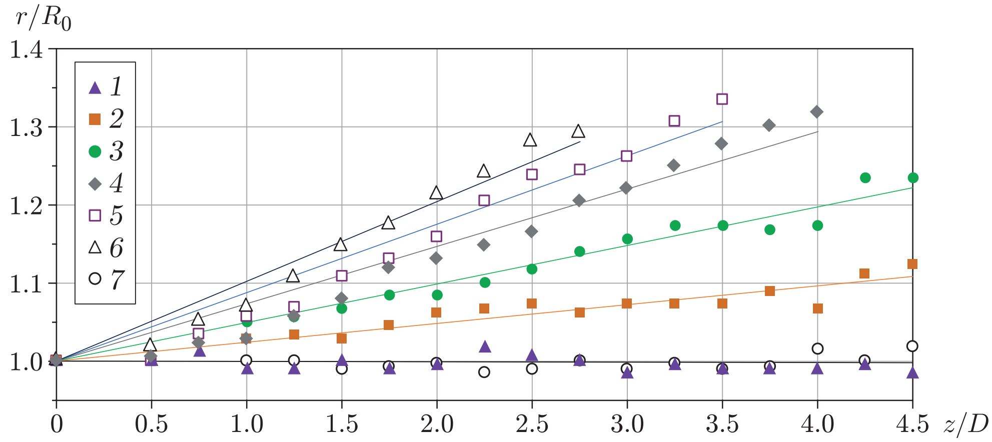

Fig. 2. r/R_0 versus z/D at different values of ε: (*1*) $\varepsilon = 0$, (*2*) $\varepsilon = 0.02$, (*3*) $\varepsilon = 0.04$, (*4*) $\varepsilon = 0.06$, (*5*) $\varepsilon = 0.08$, (*6*) $\varepsilon = 0.10$, and (*7*) no deflector.

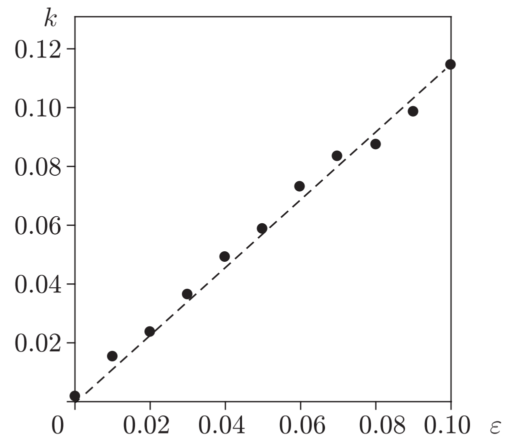

Fig. 3. k versus ε.

and the web camera are attached to a coordinate device and synchronously moved in the vertical direction. The video recording is carried out at distances $z/D = 1.00$; 1.25; ...; 4.25; 4.50 for $\varepsilon \leqslant 0.05$. For $\varepsilon \geqslant 0.06$, the initial and the final measurement are carried out in sections $z/D = 0.50$ and $z/D = 2.75$, respectively. The reason for this is as follows: in the case of large distances, the jet becomes turbulent and its conditional radius is impossible to determine. The video recording is carried out at a frequency of 30 fps. Next, approximately five-second intervals corresponding to some values of ε and z/D are selected. The frames selected in these intervals are averaged by pixel brightness. The averaged frame is used to determine the radius of the circle that circumscribes the cross section (Fig. 1b) and consequently the average radius r of the petal (perturbation). The resulting sets of values of r are nondimensionalized by R_0 at $z/D = 0.5$. The dependences of the resulting values r/R_0 downstream on the z/D coordinate are shown in Fig. 2. It is clear that dependence $r/R_0(z/D)$ is linear in all experiments, including those for $\varepsilon = 0$ and in the absence of a deflector. The experimental points are more accurately approximated by a linear dependence at $\varepsilon \leqslant 0.05$ than at large values of ε. The explanation for this phenomenon is twofold. Firstly, there is a need for a minimum distance at which perturbations are formed and begin to propagate linearly (this distance is shorter for small ε); secondly, there is a greater degree of nonlinearity of the introduced perturbation. The least squares method is applied for each ε to determine the straight line slope coefficient k (a constant increment coefficient that is proportional to the downstream averaged radial component of the velocity perturbation u_r). It can be seen that, as ε becomes larger, the value of k increases almost linearly (Fig. 3). Consequently, the perturbations introduced by the deflectors for different values of ε are similar. Indeed, before the jet flow reaches turbulence at

(a) (b)

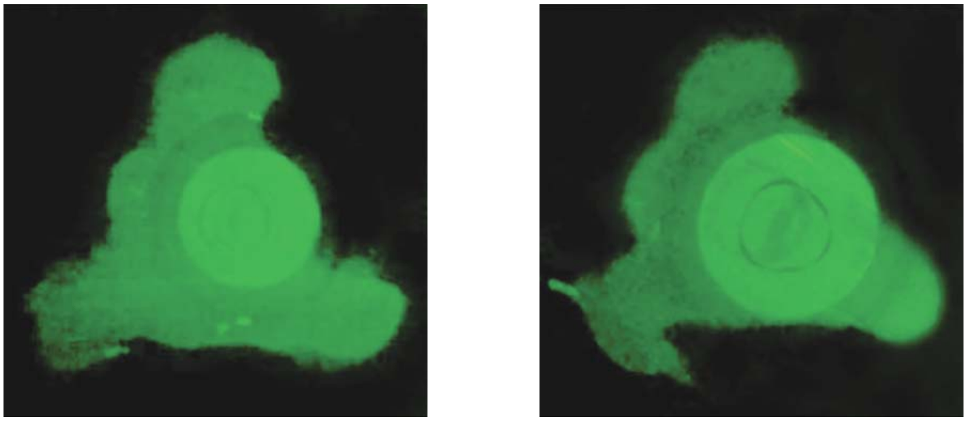

Fig. 4. Visualization of the flow cross section before the transition to turbulence when perturbations are introduced by the deflector ($n = 3$): (a) $\varepsilon = 0.05$, (b) $\varepsilon = 0.10$.

$r/R_0 \approx 1.35$, the shapes of the jet boundaries at $\varepsilon = 0.05$, $z/D = 4.5$ and $\varepsilon = 0.1$, $z/D = 2.75$ are approximately the same (Fig. 4). At such a rate of increase in the size of the petals, the transverse vortex motion becomes quite intense, which causes the transition to turbulence downstream.

CONCLUSIONS

It can be concluded from the experiments on visualizing the flow cross section in the presence of stationary perturbations introduced by deflectors with a fixed azimuthal number $n = 3$ and a variable amplitude ε that a decrease in ε does not lead to a change in flow pattern, does not prevent the occurrence of an algebraic growth mechanism, and causes a proportional decrease in the radial velocity perturbation component. Moreover, the transition to turbulence in all cases where they could be detected (for $\varepsilon \geqslant 0.5$) occurs when almost the same level of deformation of the cross section of the jet is reached (but at different distances downstream): the size of the petals reaches a threshold value, followed by the transition to turbulence.

FUNDING

This work was financially supported by the Russian Science Foundation (Grant No. 20-19-00404).

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

1. V. S. Kosorygin, N. F. Polyakov, T. T. Suprun, and E. Ya. Epik, "Effect of Turbulence on Perturbation Structure in a Laminar Boundary Layer," in *Turbulent Near-Wall Flows*. Ed. by S. S. Kutateladze (Kutateladze Institute of Thermophysics of the Siberian Branch of the USSR Academy of Sciences, Novosibirsk, 1984) [in Russian].
2. B. F. Farrell and P. J. Ioannou, "Optimal Excitation of Three-Dimensional Perturbations in Viscous Constant Shear Flow," Phys. Fluids A: Fluid Dynamics **5** (6), 1390–1400 (1993).
3. D. Liepmann and M. Gharib, "The Role of Streamwise Vorticity in the Near-Field Entrainment of Round Jets," J. Fluid Mech. **245**, 643–668 (1992).

4. C. G. Ball, H. Fellouah, and A. Pollard, "The Flow Field in Turbulent Round Free Jets," Progr. Aerospace Sci. **50**, 1–26 (2012).
5. V. V. Kozlov, G. R. Grek, L. L. Lofdahl, et al., "Role of Localized Streamwise Structures in the Process of Transition to Turbulence in Boundary Layers and Jets (Review)," Prikl. Mekh. Tekh. Fiz. **43** (2), 62–76 (2002) [J. Appl. Mech. Tech. Phys. **43** (2), 224–236 (2002); DOI: 10.1023/A:1014745424327].
6. M. V. Litvinenko, V. V. Kozlov, G. V. Kozlov, and G. R. Grek, "Effect of Streamwise Streaky Structures on Turbulization of a Circular Jet," Prikl. Mekh. Tekh. Fiz. **45** (3), 50–60 (2004) [J. Appl. Mech. Tech. Phys. **45** (3), 349–357 (2004); DOI: 10.1023/B:JAMT.0000025016.11554.5b].
7. S. Boronin, J. Healey, and S. Sazhin, "Non-Modal Stability of Round Viscous Jets," J. Fluid Mech. **716**, 96–119 (2013).
8. J. I. Jiménez-González, P. Brancher, and C. Martínez-Bazán, "Modal and Non-Modal Evolution of Perturbations for Parallel Round Jets," Phys. Fluids **27**, 044105 (2015).
9. O. O. Ivanov, D. A. Ashurov, L. R. Gareev, and V. V. Vedeneev, "Non-Modal Perturbation Growth in a Laminar Jet: An Experimental Study," J. Fluid Mech. **963**, A8 (2023).
10. A. Tumin and E. Reshotko, "Spatial Theory of Optimal Disturbances in Boundary Layers," Phys. Fluids **13** (7), 2097–2104 (2001).
11. L. Gareev, J. Zayko, A. Chicherina, et al., "Experimental Validation of Inviscid Linear Stability Theory Applied to an Axisymmetric Jet," J. Fluid Mech. **934**, A3 (2022).
12. M. Matsubara and P. H. Alfredsson, "Disturbance Growth in Boundary Layers Subjected to Free-Stream Turbulence," J. Fluid Mech. **430**, 149–168 (2001).
13. J. Zayko, S. Teplovodskii, A. Chicherina, et al., "Formation of Free Round Jets With Long Laminar Regions at Large Reynolds Numbers," Phys. Fluids **30**, 043603 (2018).