Experimental studies of laminar-turbulent transition on a body of revolution

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Abstract. The focus of the present paper is hydrodynamic stability and transition to turbulence on an axisymmetric body. The objective is to trace the evolution of perturbed flow close to the surface of experimental model with increase of the angle of attack starting with zero incidence. In what follows, we briefly summarize our wind-tunnel data on this topic which were obtained at low subsonic velocities through hot-wire measurements and flow visualization. As is found, in conditions of laminar boundary-layer separation and flow instability, even small variations of the body incidence may have a profound effect on the flow pattern.

1. Motivation
A subject of long-term studies in subsonic fluid dynamics is the spatio-temporal structure of unstable flow on bodies of revolution. An axisymmetric configuration at zero angle-of-attack of the body represents a canonical one which was examined in recent decades. As a result, a lot of research data have been obtained which clarify the mean and nonstationary flow characteristics in conditions of the hydrodynamic instability initiating the growth of velocity perturbations, vortex formation, and transition to turbulence, see e.g. [1−10].

Indeed, an idea about the axial symmetry is appropriate and really helpful at investigation of the instability phenomena. However, at a non-zero angle of attack the flow becomes three-dimensional [11] so that the determination of its quantitative characteristics both in experiments and calculations becomes much more complicated. In this context, an issue is how large the deviation of the body position from zero incidence should be to make the axisymmetric approximation to the unstable flow no longer valid. This is the point which we are interested in here most of all. Note that in the present experimental configuration we deal with laminar boundary-layer separation from the body surface. One expects, similar flow behavior on bodies of revolution is typical of quiet environmental conditions and fairly low Reynolds numbers.

2. Experimental arrangement
The experimental runs were performed in the subsonic T-324 wind tunnel of ITAM SB RAS which is a low-turbulent closed-circuit facility. The closed test section of the tunnel is of 4-m length with a square cross section of 1 × 1 m², the free-stream turbulence level making Tu ≤ 0.04%. The test model sketched in figure 1 represented an axisymmetric body, 1140-mm in length and of 100-mm midsection radius. During the experiments the model was installed at different angles of attack α ranging from 0 to 20° with an accuracy of 0.1°.

Quantitative data on the flow pattern over the body of revolution were obtained through hot-wire measurements using an AN 1003 constant-temperature anemometer from A.A. Lab Systems Ltd and a...
one-wire probe which was calibrated in the free stream against a Pitot-static tube. The probe was positioned in the measurement region by an automated 3D traversing mechanism. The hot-wire readings were digitized by a 14-bit analog-to-digital converter and further processed on a PC in MATLAB environment. Besides, visualization of the mean near-wall flow was carried out using a mixture of a titanium dioxide powder with kerosene which was applied onto the axisymmetric body.

**Figure 1.** Experimental model, dimensions are in millimeters.

The data were acquired at the Reynolds number $Re_r = U_0 r/\nu$ ranging from 63000 to 126000 where $U_0$ is the oncoming flow velocity varying from 10 to 20 m/s and $r$ is the midsection radius of the experimental model. In what follows, $x$ is the streamwise coordinate measured from the nose of axisymmetric body and $y$ is the radial distance from the wall.

3. Wind-tunnel results

Naturally, at zero angle of attack an axisymmetric flow over the model is observed. In the present experimental conditions the laminar boundary-layer separates in the aft part of the body. The mean-velocity contours plotted in figure 2(a) demonstrate a local region of flow separation which is prone to instability. The streamwise growth of velocity perturbations in the separated shear layer results in the laminar-turbulent transition. High amplitudes of the disturbances making about 10 to 15 percent of $U_0$ in the downstream sections of the measurement domain are typical of the near-wall turbulence, see figure 2(b). In more detail, the stability characteristics of the present axisymmetric flow were reported in [12]. In particular, the behavior of small-amplitude oscillations was found to be in a quantitative agreement with that of the instability waves at laminar boundary-layer separation in plane configurations.

**Figure 2.** Mean-velocity contours with the step of 1 m/s (a) and the maximum rms amplitude of velocity perturbations integrated over the frequency spectrum up to 500 Hz (b); $Re_r = 63000$, $\alpha = 0$. 
The axial symmetry of the mean flow breaks down when passing from zero angle of attack to a small incidence of several degrees [13]. In this case, laminar flow separation still occurs on the windward side of the body while the boundary layer is attached to the surface on the leeward side, see figure 3. Because of much different stability characteristics of the attached flow and of the separated boundary layer, a pronounced azimuthal nonuniformity of the amplifying velocity perturbations is generated. One can observe in figure 4 that at the angles of attack $\alpha = 2^\circ$ and $4^\circ$ the amplitudes of laminar flow disturbances on the windward and leeward sides of the body in some cross sections differ by an order of magnitude.

![Image](figure3.png)

**Figure 3.** Mean-velocity contours with the step of 1 m/s at the windward (a) and the leeward (b) sides of axisymmetric body; $Re_c = 63000$, $\alpha = 4^\circ$.

![Image](figure4.png)

**Figure 4.** Maximum rms amplitude of velocity perturbations integrated over the frequency spectrum up to 500 Hz at $\alpha = 2^\circ$ (a) and $4^\circ$ (b), $Re_c = 63000$; windward (□) and leeward (■) sides of the experimental model.

Even more distinct transformation of the unstable flow around the model occurs when the angle of attack is further increased and the local boundary layer separation is replaced with the global one. Then, in a fully 3D separated flow the reliability of hot-wire measurements with one-wire probes goes down. Instead, visualization by surface coatings, although providing qualitative data only, is helpful to obtain a panoramic pattern. An example is given in figure 5. At the angles of attack $\alpha = 10^\circ$ and $20^\circ$ the separated flow is featured with a pair of large-scale streamwise vortices originating in the mid-chord (figure 5(a)) and in the upstream (figure 5(b)) sections of the model. Similar vortex behavior of the flow past axisymmetric bodies at incidence was observed in a number of studies, for graphic illustrations see [14].
4. Concluding remarks
The above wind-tunnel results illustrate a variety of flow regimes on a body of revolution at low subsonic velocities. In the present configuration of experimental model, the hydrodynamic events at small angles of attack are dominated by the shear-layer instability of a locally separated boundary layer, while at increasing the body incidence, a globally separated flow with the prevalence of large-scale vortex motion is observed.

The key point of the present consideration is the profound response of the flow pattern to small variations of the angle of attack at its close-to-zero values. The effect is basically due to different stability characteristics of the separated and attached boundary layers in the aft part of the body. As a result, minor deviations of its angular position from zero incidence generate a nonuniformity of the mean flow and, hence, strong variations of the nonstationary velocity component in the azimuthal direction. In this respect, the unstable flow over the body of revolution with laminar boundary-layer separation becomes far from being axisymmetric.

References
[1] Gates E M 1980 Observations of transition on some axisymmetric bodies Laminar-Turbulent Transition ed Eppler R and Fasel H (Berlin: Springer) pp 351-63
[2] Kiya M 1987 Structure of flow in leading-edge separation bubbles Boundary-Layer Separation ed Smith F T and Brown S N (Berlin: Springer) pp 57-71
[3] Sigurdson L W and Roshko A 1988 The structure and control of a turbulent reattaching flow Turbulence Management and Relaminarization ed Liepmann H W and Narasimha R (Berlin: Springer) pp 497-514
[4] Kiya M, Mochizuki O, Tamura H, Nozawa T, Ishikawa R and Kushioka K 1991 Turbulence properties of an axisymmetric separation-and-reattaching flow AIAA J. 29 936-41
[5] Kiya M, Shimizu M, Mochizuki O, Ido Y and Tezuka H 1993 Active forcing of an axisymmetric leading-edge turbulent separation bubble AIAA Paper/93-3245
[6] Michalke A, Kozlov V V and Dovgal A V 1995 Contribution to the instability of laminar separating flows along axisymmetric bodies. Part I: Theory Eur. J. Mech., B/Fluids 14 333-50
[7] Dovgal A V., Kozlov V V and Michalke A 1995 Contribution to the instability of laminar separating flows along axisymmetric bodies. Part II: Experiment and comparison with theory Eur. J. Mech., B/Fluids 14 351-65
[8] Michalke A 1995 Receptivity of axisymmetric boundary layers to excitation by a Dirac point source at the wall Eur. J Mech., B/Fluids 14 373-93
[9] Hammache M, Browand F K and Blackwelder R F 2002 Whole-field velocity measurements around an axisymmetric body with a Stratford-Smith pressure recovery J. Fluid Mech. 461 1-24

[10] Hudy L M, Naguib A and Humphreys W M 2007 Stochastic estimation of a separated-flow field using wall-pressure-array measurements Phys. Fluids 19 024103 1-18

[11] Tobak M and Peake D J 1982 Topology of three-dimensional separated flows Ann. Rev. Fluid Mech. 14 61-85

[12] Dovgal A V, Zanin B Yu and Sorokin A M 2013 Flow instability in the zone of laminar axisymmetric boundary layer separation Fluid Dynamics 48 747-53

[13] Dovgal A V, Zanin B Yu and Sorokin A M 2014 Stability of the laminar flow on the body of revolution at incidence Thermophysics and Aeromechanics 21 401-6

[14] Van Dyke M 1982 An Album of Fluid Motion (Stanford, California: The Parabolic Press)