Numerical study of the influence of a single roughness element on development of disturbances in a hypersonic boundary layer on a blunted cone

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Abstract. A supersonic \(M_c=5.95\) flow around a blunted cone with a cylindrically shaped single roughness element located in the bluntness region is considered. Numerical simulations are performed by means of solving the unsteady three-dimensional Navier-Stokes equations with a computational module that takes into account the action of external acoustic waves on the flow. Numerical data are obtained for the mean flow characteristics and evolution of disturbances formed in the wake behind the roughness element. It is shown that intense interaction of steady streamwise vortices occurs behind the single roughness element \((Re_k=4880, k/\delta=3.95)\) on the cone with a bluntness radius of \(5\) mm. This interaction is accompanied by formation of three-dimensional finger-shaped structures in the azimuthal direction, which testifies to the initial stage of the laminar-turbulent transition.

1. Introduction
At supersonic velocities, the leading edges of flying vehicles experience the action of high temperatures, which leads to ablation and formation of roughness elements on the vehicle surface. Changes in the body shape and surface structure of the ablating material affect significantly the laminar-turbulent transition (LTT) position.

Surface roughness usually initiates a premature LTT [1-3], whereas nose bluntness leads to downstream shifting of the LTT [4]. Thus, the presence of roughness on the blunted nose part of a flying vehicle produces an ambiguous effect: the stabilizing influence of nose bluntness competes with the destabilizing influence of roughness.

It was shown in [5] that a single three-dimensional roughness element submerged into the boundary layer on a smooth titanium hemisphere in hypersonic free flight at \(Re_k\sim1000\) can induce a laminar-turbulent transition. The Reynolds number \(Re_k\) is based on the roughness element height \(k\) and boundary layer flow parameters at \(y=\delta\). At the moment, there are no unified criteria for roughness-induced transition prediction, but the ratio of the roughness height to the boundary layer thickness \(k/\delta\) and Reynolds number \(Re_k\) are the most popular LTT criteria.

2. Numerical simulation of a supersonic flow around a blunted cone with a single roughness element in the nose bluntness region
The present study is based on the results of numerical simulations of a three-dimensional unsteady flow around a blunted cone (the bluntness radius is \(R=5\) mm) with an apex half-angle of \(7^\circ\), which has a single roughness element in the blunted region (Fig. 1). The cone length from the junction of the blunted and conical parts to the end of the cone model is \(95\) mm. We consider a sector with an angle of...
60° in the plane \((y,z)\) of the Cartesian coordinate system. The roughness element is a cylinder with diameter \(d = 0.3\) mm and height \(k = 0.6\) mm. The roughness element is aligned normal to the bluntness surface at angle \(\theta = 90°\), i.e., in the supersonic flow region behind the sonic line. The size and position of the roughness element were chosen to fit the experiments performed in the Transit-M wind tunnel based at the Khrisianovich Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences. The following flow parameters were used: Mach number \(M_\infty = 5.95\), unit Reynolds number \(Re_1 = 38 \times 10^6\) m\(^{-1}\), and free-stream temperature \(T_\infty = 45.67\) K.

The computational domain (Fig. 2) in the normal direction consisted of three subdomains: shock wave, boundary layer, and flow between them. The upper boundary of the computational domain was equidistant to the shock wave position; a prismatic sublayer including the shock wave was constructed from the upper boundary of the computational domain. The near-wall region height was chosen in such a way that it included the boundary layer over the entire cone length. This subdomain was also covered with an irregular prismatic mesh, which was refined toward the cone surface. An irregular tetrahedral mesh was generated between these two subdomains. The total number of cells was up to 13.3 million.

**Figure 1.** Pressure distribution over the surface of a blunted cone \((R = 5\) mm\) with a single roughness element.

**Figure 2.** Fragment of the computational mesh in the \(xy\) plane \((z = 0)\) in the region of the roughness element on the cone surface.

Numerical simulations of the supersonic flow around the cone were performed by means of solving a system of three-dimensional unsteady Navier-Stokes equations by using the ANSYS Fluent software package. The Navier-Stokes equations were integrated with the use of a density-based solver and explicit scheme of the second order in space with the Roe-FDS method of splitting of convective fluxes and explicit Runge-Kutta method in time. The following boundary conditions were imposed: free-stream parameters on the upper boundary of the computational domain, outflow conditions on the exit boundary, no-slip condition and constant temperature \(T_w = 293\) K on the cone surface, and symmetry condition on the side boundaries of the sector of the computational domain. Air was considered as an ideal gas with the ratio of specific heats \(\gamma = 1.4\) and Prandtl number \(Pr = 0.72\); the dynamic viscosity was calculated by the Sutherland formula.

The computations were performed on computational clusters (up to 16 processors) of the Information-Computational Center of the Novosibirsk State University and Siberian Supercomputer Center.
3. Results

3.1. Laminar base flow
A steady flow was first calculated by an implicit method. Figure 3 shows the streamlines and isosurfaces of streamwise vorticity. Such visualization of the flow demonstrates that the presence of a cylindrical roughness element leads to local distortions of the steady flow field near the roughness element and formation of a horseshoe vortex structure ahead of it. The central streamlines turn around the roughness element and pass to the periphery. Two separation regions are formed near the roughness element: immediately ahead of the roughness element and in the wake behind it (see the dashed green curves). The structures formed behind the roughness element are the pairs of counter-rotating streamwise vortices (see the screwing of the streamlines in the wake). Similar patterns were observed near single roughness elements on the bodies of various shapes: flat plate [6, 7], capsule [8], and cone with a bluntness radius of 9 mm [9].

The counter-rotating vortices arise on the sides of the roughness element; one pair of vortices is formed near the top of the roughness element, and the other pair is formed at the base of the roughness element. Via the lifting mechanism, these vortices induce immediate low-momentum motion of the gas from the near-wall region upward beyond the roughness element. As a consequence, there arises a low-velocity band along the axial line of the roughness element, as is shown in Fig. 4a. Gas rotation around the axis of the streamwise vortices is visualized in Fig. 3 by the screwing streamlines in the wake behind the roughness element. The downstream development of the unsteady vortex wakes occurs almost independent of each other, and the vortex intensity decreases (Fig. 4c). It should be noted that the flow parameters and the wake shape change rapidly in the flow because of intense acceleration of the main flow owing to the nose bluntness. As compared to a smooth cone (without...
roughness), the presence of low-velocity bands is associated with strong deformation of the flow, resulting in a potentially unstable wake.

Figure 4. Contours of the streamwise vorticity \( \omega \) and isolines of the streamwise velocity component for \( x = 0.5 \) mm (a), \( x = 4 \) mm (b), and \( x = 40 \) mm (c). The velocity levels are plotted with an interval of 42 m/s.

It is known that velocity profiles with inflection points are unstable and characterize the tendency to the transition to turbulence. Figure 5 shows the profiles of the streamwise velocity component \( U_x \) in two cross sections \( x = \text{const} \) at \( z = 0 \) for the smooth and rough cones. It is seen that the presence of the roughness element leads to changes in the velocity profiles near the roughness element itself, namely, to the emergence of inflections of the profiles.

Figure 5. Profiles of the streamwise velocity component \( U_x \) in four cross sections \( x = 0.5 \) mm (a) and \( x = 4 \) mm (b) at \( z = 0 \) for a smooth blunted cone (1) and a cone with a single roughness element \( k=0.6 \) mm, \( d=0.3 \) mm (2): \( R=5 \) mm, \( \text{Re}_1=37.8 \times 10^6 \) m\(^{-1} \), \( M_{\infty}=5.95 \), \( P_0=26.5 \) Pa, and \( T_0=369 \) K.

3.2 Generation of disturbances

The experiments on the blunted (\( R=5 \) mm) cone with a single roughness element showed that the LTT is observed directly on the blunted part of the cone. Under wind tunnel test conditions, the unsteady flow computations revealed that the structures formed in the mean flow are stable and do not induce the emergence of growing disturbances capable of LTT initiation. A possible reason is the presence of external unsteady disturbances, which are always present in experiments. Therefore, we simulated the evolution of disturbances arising due to external fast acoustic perturbations with amplitudes \( \Delta = 0.3p_\infty \) and frequencies \( f=50, 110, 170, 230, 310, \) and 350 kHz propagating in the flow.

Figure 6a shows the static pressure distribution on the cone surface. It is seen that this distribution differs from the pressure field in the steady flow (see Fig. 1): enhancement of pressure in the downstream direction induced by unsteady perturbations is observed near the streamwise vortex structures behind the roughness element. Figure 6b shows the isosurface of the Q-criterion [9] with the contours of the transverse velocity component. It is seen that interaction of the steady vortex structures and unsteady perturbations of the external flow leads to formation of three-dimensional finger-shaped
structures in the azimuthal direction, which apparently testifies to the initial stage of the laminar-turbulent transition.

Figure 6. Static pressure distribution over the cone surface with a single roughness element under the action of a superposition of fast acoustic waves at $t=0.374$ ms (a) and isosurfaces of the Q-criterion for $Q=2 \times 10^9$ with the colour-marked $U_y$ velocity component (b): $A=0.3 \rho_c$, $f=50$, 110, 170, 230, 310, and 350 kHz; $R=5$ mm, $Re_1=37.8 \times 10^6$ m$^{-1}$, $M_\infty=5.95$, $P_0=26.5$ Pa, $T_0=369$ K, $k=0.6$ mm, and $d=0.3$ mm.

Figure 7 shows the experimental data on the heat flux obtained in the Transit-M wind tunnel (Bountin D.A., Maslov A.A., Gromyko Yu.V. Report 2017 on the project of the Russian Science Foundation No. 14-11-00490). It is clearly seen that there is a wake with an elevated heat flux behind the roughness element; the intensity of this heat flux corresponds to a turbulent flow. This fact shows that the LTT is observed immediately behind the roughness element.

Figure 7. Experimental data on the heat flux: $R=5$ mm, $Re_1=37.8 \times 10^6$ m$^{-1}$, $M_\infty=5.95$, $P_0=26.5$ Pa, $T_0=369$ K, $k=0.6$ mm, and $d=0.3$ mm

4. Conclusion

A supersonic ($M_\infty=5.95$) flow around a blunted cone with a single roughness element shaped as a cylinder 0.3 mm in diameter and 0.6 mm high located in the blunted region under the action of external acoustic waves is numerically simulated.

It is demonstrated that the presence of a single roughness element leads to local distortions of the steady flow field near the roughness element: formation of a horseshoe vortex structure ahead of it and a pair of counter-rotating streamwise vortices in the wake behind the roughness element.

Under the flow conditions with $Re_1=4880$ and $k/\delta=3.95$, the action of external acoustic waves initiates intense interaction of the vortex structures immediately behind the roughness element, which is accompanied by formation of three-dimensional finger-shaped oscillations in the flow field in the azimuthal direction and generalization of the disturbed state of the boundary layer, resulting in the laminar-turbulent transition.
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