Cone nose-tip roughness effect on the transition at M=5, 6, 8

Y V Gromyko, D A Bountin, P A Polivanov and A A Maslov
Khristianovich Institute of Theoretical and Applied Mechanics SB RAS
4/1 Institutskaya Street, Novosibirsk 630090, Russia,
E-mail: yurkonsk@gmail.com

Abstract. The article presents data on the effect of distributed and isolated roughness on the blunt nose of the cone on the laminar-turbulent transition position. The experiments were performed at M=4.95, 5.95, 7.95, stagnation temperature $T_0=361–465$ K and stagnation pressure $P_0=2–72$ atm. The unit Reynolds number varied in the range $Re_1=(4.2–69.7)\times10^6$ m$^{-1}$. The study was carried out in the boundary layer of cones with a half-angle of 7º with different zones of applying isolated and distributed roughness of the blunt nose $R=5$ mm. For all types of roughnesses, the effective values of Reynolds numbers are obtained, at which the transition occurs immediately after the roughness area.

1. Introduction
The presence of roughness can have a significant effect on the distribution of heat flux on the surface of hypersonic aircraft, which is mainly due to the displacement of the transition region [1]. High thermal loads can cause changes in surface roughness during flight due to ablation of heat-shielding material, surface erosion. The appearance of roughness on the nose is most likely because usually thermal load is maximum in this area. Moreover, the occurrence of the transition on the nose part can lead to turbulization of the boundary layer on the entire surface of the aircraft [2, 3].

$Re_{kk}$ is most often taken as a criterion for predicting the transition caused by roughness. The Reynolds number $Re_{kk} = \rho_k U_{kk} / \mu_k$ is calculated based on the roughness height $k$ and the flow parameters at the height $k$ for the laminar boundary layer on the corresponding smooth surface [4]. It is known that roughness induces a transition to turbulence if the $Re_{kk}$ exceeds a certain value, which can vary within certain limits depending on the type and shape of the roughness: from about 200 (distributed roughness) to 900 (isolated roughness). For the case when the roughness is located on the nose part, the key role in the laminar-turbulent transition is played by the region of the sound line ($\Theta \approx 45$, Fig. 1), that was obtained in [5]. Numerical simulation shows that for the blunt nose the maximum value of $Re_{kk}$ is in the region $\Theta \approx 45$ from the spreading point that was shown in our previous work [3]. At the same time, it was found in the experiments [3] that the most critical location of the roughness is near the conjugation area of the spherical and conical parts of the model ($\Theta \approx 90$). This was experimentally studied in more detail for different radii of blunting [6] and similar results were obtained. This paper presents data on the effect of the roughness area on the position of the laminar-turbulent transition, depending on the Mach number.
2. Experimental equipment

The experiments were conducted in a hypersonic wind tunnel "Tranzit-M" of ITAM SB RAS [7] when the number $M = 4.95, 5.95$ and $7.9$, the stagnation temperature $T_0 = 361 – 465$ K and the stagnation pressure $P_0 = 2 – 72$ atm. The unit Reynolds number varied in the range $Re_1 = (4.1–58.1) \times 10^6$ m$^{-1}$. The diameter of the exit section of the nozzle was 300 mm, and air was used as the working gas.

The study of the influence of roughness on the laminar-turbulent transition of the boundary layer was carried out on a cone model with a half-solution angle of $7^\circ$ with replaceable noses. The model was made of polyacetal to perform thermal field measurements by IR-camera and equipped with high-frequency surface pressure sensors PCB 132A31 (see Fig.1a). Eight of pressure sensors were installed along generatrix of the cone and the 9th sensor was located symmetrically to the eighth one on the opposite side to control the angle of attack. The model was installed in the working part of the wind tunnel at zero angle of attack, along the axis of the nozzle. The distance from the trailing edge of the model to the nozzle exit was 543 mm.

The distributed roughness was produced by means of calibrated sand glued to the nose. The sand was applied at a distance of $S = 7.9$ mm ($\Theta \approx 90^\circ$) (see Fig.1b, Fig.2a), and then, if necessary, cleaned to the desired angle $\Theta$. Isolated roughness was made of fishing line to control the diameter of the roughness with high accuracy. The line was inserted into the hole, pre-drilled at the required angle $\Theta$, and then cut to a height $h \approx 500$ mkm (see Fig.2 b, c). The following configurations of isolated and distributed roughness were investigated in the experiments: $S_0 = 5.23$ mm ($\Theta = 60^\circ$); $S_0 = 7.9$ mm ($\Theta = 90^\circ$).

Figure 2. Noses with roughness $R = 5$ mm: a – distributed roughness $\Theta = 90^\circ$; b, c – isolated roughness with height $k = 480$ $\mu$m ($\Theta = 60^\circ$ and $90^\circ$, respectively).
Table 1. Roughness characteristics

| Parameters       | rms, μm | Ra, μm | k, μm |
|------------------|---------|--------|-------|
| Sand, Θ = 90°    | 83      | 67     | -     |
| Sand, Θ = 60°    | 61      | 51     | -     |
| Isolated, Θ = 90°| -       | -      | 459   |
| Isolated, Θ = 60°| -       | -      | 537   |

Two parameters of the distributed roughness were measured: rms – the standard deviation of the recesses or surface convexities from the mean line of the surface, and Ra – the standard characteristic of the roughness, defined as the arithmetic mean deviation of the profile. Roughness was measured by three-dimensional surface structure analyzer Zygo newview 6300 (USA). Measurements were carried out in several places of one nose, and then averaged. The measured characteristics are given in table 1:

Measurements of heat fluxes on the surface of the model were performed using FLIR sc7000 IR-camera with 7300M matrix consisting of 320×256 pixels. The spectral range of the device is 3.7 – 4.8 μm, and the temperature range is 5 – 150 °C. The frame rate in the experiments was 250-300 Hz. During the run, the surface of the model was heated by 1 - 2 degrees. The Cook-Feldereman algorithm [8] was used to find the value of the unsteady heat flux, which allows restoring the heat flux on the model surface from the temperature fields.

To measure pressure fluctuations on the model surface, high-frequency pressure sensors PCB 132A31 were installed in the model. Pressure sensors were used in combination with the PCB Piezotronocs 482C05. Three four-channel L-card E20-10 ADC with sampling rate of 1.67 MHz were used. The experimental data were processed in time intervals, in which the flow parameters could be considered quasi-stationary. The spectral distributions were calculated by averaging over 96 blocks with 29 points in each block in the time interval of 100 – 115 ms from the start of the run.

3. Experimental results

An experimental study was conducted for all types of roughnesses. Effective values of the Reynolds numbers, at which a laminar-turbulent transition occurs immediately after the roughness, were obtained. Fig. 3 shows a graph of effective Reynolds numbers (unit Reynolds number multiplied by the roughness height Ra for distributed roughness, and k for single roughness, see Table 1) for different angles of distributed roughness. It can be seen that for all studied Mach numbers and roughness types, the minimum unit Reynolds number at which the transition took place at the nose of the model corresponds to the angle Θ = 90°. It can be concluded that for bluntness close to spherical, the critical location of the roughness is near the line of conjugation of the spherical and conical

![Figure 3](image)

Figure 3. Dependence of the unit Reynolds number at which the laminar-turbulent transition occurred, multiplied by the height of the roughness (Ra for distributed, k for single roughness) vs. the Mach number of the incoming flow.
parts of the model: $\Theta \approx 90$. It is also important to note a decrease in the effective Reynolds numbers with increasing Mach numbers.

If for the distributed roughness at $\Theta = 90^\circ$, $Re_{kk}$ are close to the literature value ($Re_{kk} \approx 170$, except in the case of $M = 8$, where $Re_{kk} = 120$), then for the isolated roughness $Re_{kk}$ values differ strongly from $\approx 1600 (M = 5.95, \Theta = 90^\circ)$ to $\approx 6000 (M = 5, 5.95, \Theta = 60^\circ)$ and average $Re_{kk} \approx 3000$. This discrepancy may be due to the fact that the literature data are mainly based on the results of flight experiments with small values of roughness, which, as a rule, are within the boundary layer. In current study the height of the roughness was significantly greater than the thickness of the boundary layer.

The pressure pulsation spectra on the model wall were obtained by PCB sensors for each run. Examples of spectra for the sensor at $X=100$ mm (on a line of the roughness) are shown in Fig. 4 for Mach numbers 5, 6 and 8. The amplitude spectra normalized to the pressure at the boundary layer edge are presented for cases of distributed roughness with an angle of application of $\Theta = 90^\circ$, $60^\circ$ and a smooth nose for $R = 5$ mm. For all Mach numbers, the unit Reynolds numbers correspond to the case

Figure 4. Spectra of pressure pulsations, $R = 5$ mm, $X = 100$ mm.

a – $M = 5$, b – $M = 6$, c – $M = 8$. 
when the turbulence occurs immediately behind the roughness zone Θ = 90°. It is seen that for all Mach numbers the spectra for the smooth nose coincide well with the spectra for the nose-tip with the roughness with an angle of application Θ = 60° and correspond to the laminar boundary layer. This means that for these Reynolds numbers, the presence of roughness at Θ = 60° does not lead to changes in the conditions for the development of disturbances and does not affect their growth. As the roughness zone increases to Θ = 90°, the flow is rearranged beyond the roughness zone, and the longitudinal vortices decay into two turbulent wedges, which leads to the filling of the spectrum on the spectral distribution. It can be seen from the data that the effective influence of roughness, in which the transition occurs immediately behind the roughness, depends on the Mach number. In this case, for the effective influence of the roughness with the area of application Θ = 90°, a larger unit Reynolds number is required if Mach number increases: for M ≈ 5, Re_1 = 11.7 × 10^6 m^-1 is required, for M = 6, Re_1 = 18.2 × 10^6 m^-1 is required, for M ≈ 8, Re_1 = 24.6 × 10^6 m^-1 is required.

Summary
The experimental study was carried out in the boundary layer of cones with a 7° half-angle with different zones of applying isolated and distributed roughness on blunt nose with R = 5 mm. Effective values of Reynolds numbers have been obtained for all types of roughnesses, in which the laminar-turbulent transition occurs immediately after the roughness.

It is found that the roughness located on the whole nose of the model (up to the line of conjugation of conic and spherical parts of the model Θ ≈ 90°) is the most effective for turbulizing the flow in the boundary layer. This has been confirmed for different types of roughness, different Mach numbers, and different radii of blunting (from 2 to 5 mm, [6]).

The Reynolds number values calculated for the parameters at the roughness height and multiplied by the roughness height (Re_{kk}) for the distributed roughness at Θ = 90° (sand type) were close to those given in the literature: 250 and 170. For an isolated roughness value Re_{kk} was significantly higher (1600-6000) than specified in literature (800).

Acknowledgments
The work is supported by the Program of Fundamental Research of the State Academies of Sciences for 2013–2020 (project AAAA-A17-117030610126-4) and was conducted at the Joint Access Center “Mechanics” of ITAM SB RAS.

References
[1] Boiko A.V., Kirilovskiy S.V., Maslov A.A., Poplavskaya T.V. 2015 J.of Appl. Mech. and Tech. Phys. 56 (5) 761–76
[2] Schneider S.P. 2008 J. Spacecraft and Rockets 45 193–209
[3] Bountin D.A., Gromyko Yu.V., Maslov A.A., Polivanov P.A., Sidorenko A.A. 2016 Thermophysics and Aeromechanics 23 629–38
[4] Reda D.C. 2002 J. of Spacecraft and Rockets 39 (2) 161–7
[5] Batt R.G., Legner H.H 1983 AIAA J. 21 (1) 7–22
[6] Gromyko, Y. V., Bountin, D. A., Polivanov, P. A., & Maslov 2018 Journal of Physics: Conference Series. IOP Publishing 1128 (1) 012012
[7] Fomin V.M., Kharitonov A.M., Maslov A.A., Shiplyuk A.N., Shumskii V.V., Yaroslavtsev M.I., Zvegintsev V.I. 2016 Experimental Methods of Shock Wave Research 9 (Berlin-Heidelberg-New York: Springer-Verlag) 9 pp 315–46
[8] Cook W.J. and Felderman E.J. 1966 AIAA J 4 (3) 561