Journal of Applied Mechanics and Technical Physics, Vol. 45, No. 2, pp. 286–291, 2004

EFFECT OF POROUS COATINGS ON STABILITY OF HYPERSONIC BOUNDARY LAYERS

A. N. Shiplyuk, E. V. Burov, A. A. Maslov, and V. M. Fomin

UDC 532.526

The influence of ultrasound-absorbing coatings on stability of hypersonic boundary layers is considered. Two types of coatings were used in experiments: felt-metal with a random porous microstructure and a sheet perforated by blind cylindrical microchannels. The experiments were performed in a wind tunnel at a Mach number $M = 5.95$ on sharp cones with a 7° apex half-angle. Evolution of natural disturbances and artificially induced wave packets in the boundary layer was studied with the help of hot-wire anemometry. Spatial characteristics of artificial disturbances were obtained. It is demonstrated that such coatings exert a stabilizing effect on second-mode disturbances.

Key words: *hypersonic flows, boundary layer, laminar–turbulent transition, stability, ultrasound-absorbing coatings.*

Introduction. Keen interest in methods for hypersonic boundary-layer control is now observed, which is inspired by the development of promising flying vehicles with a hypersonic cruising velocity. The laminar–turbulent transition leads to a significant increase in drag and strong local heating of the flying vehicle [1, 2]. The problem of extending the laminar flow region is one of the most important in design of hypersonic flying vehicles.

If the incoming flow perturbations are small (which is typical of actual flight conditions) and there are no roughness elements, the initial stage of the laminar–turbulent transition can be considered as a result of excitation of various unstable modes [3, 4]. Disturbances of the first and second modes are dominating in two-dimensional hypersonic flows. The first mode corresponds to the Tollmien–Schlichting waves whose instability is caused by viscous effects at low Mach numbers. These disturbances can be stabilized by surface cooling, suction, or a favorable pressure gradient. Cooling of the wall, which is a natural process on the surface of a hypersonic flying vehicle, appreciably stabilizes the first mode [5] but simultaneously destabilizes the second mode [6].

The second mode results from viscous instability existing due to the presence of a supersonic mean flow relative to the phase velocity of disturbances. This mode refers to the family of acoustic modes propagating in the waveguide between the wall and sonic line [7]. For thermally insulated surfaces, the growth rate of the second mode for Mach numbers $\mathrm{M} > 4$ becomes greater than that of the first mode. On cooled surfaces, the second mode can prevail even for lower Mach numbers [7, 8]. Since most hypersonic flying vehicles have a flat shape with a sharp leading edge and local Mach numbers are high ($\mathrm{M}_e > 6$), the second mode here is a dominating instability of the boundary layer.

In high-velocity flows, the second mode is associated with disturbances of a comparatively high frequency corresponding to the ultrasonic range. Malmuth et al. [9] were the first to propose and Fedorov et al. [10] developed the concept of passive control of the boundary-layer state with the help of ultrasound-absorbing coatings (UAC). It was shown that the surface with a porous microstructure can quench oscillations of the second and higher modes of disturbances.

This concept gained the first qualitative support in the experiments of Rasheed et al. [11]. The experiments were performed on a sharp cone 1 m long with an apex half-angle of 7°. One side of the cone was solid, and the other side was porous (perforated by blind cylindrical holes: up to 100 holes per 1 mm^2). The experiments were performed

Institute of Theoretical and Applied Mechanics, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 45, No. 2, pp. 169–176, March–April, 2004. Original article submitted November 19, 2003.

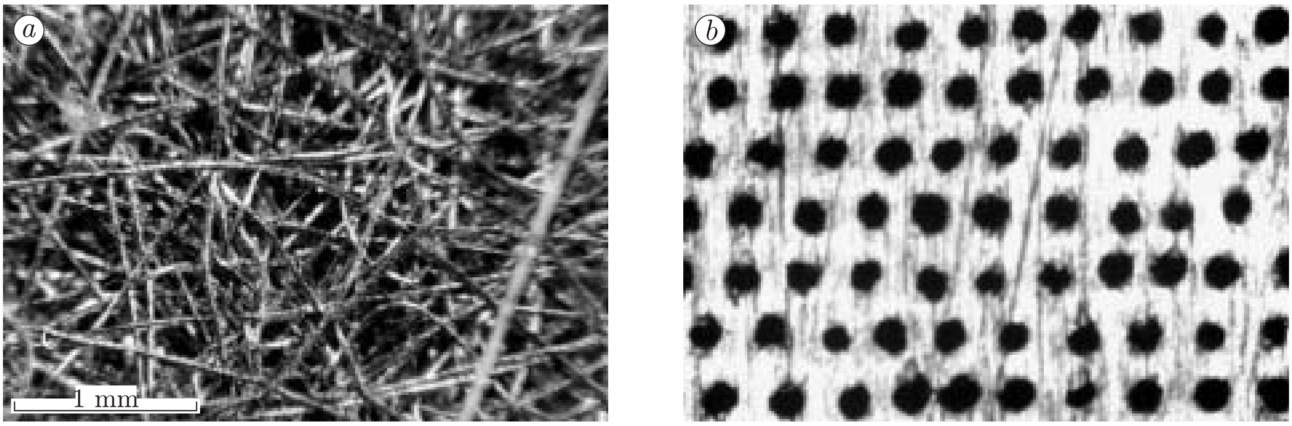

Fig. 1. Porous coatings: felt-metal (a) and perforated sheet (b).

with variations of the total enthalpy of the incoming flow 4.18 MJ/kg $\leqslant H_0 \leqslant$ 13.34 MJ/kg and free-stream Mach number $4.59 \leqslant \mathrm{M}_\infty \leqslant 6.4$. In most regimes, the boundary layer on the porous surface was laminar along the entire model, whereas the transition on the solid surface was observed at half length of the cone. Thus, it was shown that a porous coating significantly delays the laminar–turbulent transition. Since boundary-layer disturbances were not measured (only the transition location was measured), the experiments did not give clear evidence of stabilization of second-mode disturbances by the porous surface. To predict the properties of ultra-sound-absorbing coatings and estimate their efficiency, one needs detailed information on the structure and evolution of disturbances in the boundary layer on such surfaces. Stabilization of second-mode disturbances was confirmed for porous coatings with a random microstructure [12].

The objective of the present work was an experimental study of boundary-layer stability on a UAC with a regular microstructure. The data for random porosity are presented for comparison.

1. Experimental Equipment. The experiments were performed in a T-326 hypersonic wind tunnel based at the Institute of Theoretical and Applied Mechanics of the Siberian Division of the Russian Academy of Sciences [13]. T-326 is a blowdown facility with gas holders, a set of contoured nozzles, and a one-stage perforated ejector. The test section of T-326 is a free-jet chamber. The nozzle-exit diameter is 200 mm. The test duration is determined by the operation regime and reaches 30 min for $\mathrm{M} \approx 6$.

The experiments were performed at $\mathrm{M}_\infty = 5.95$. The nonuniformity of the Mach number field in the flow core is 0.7%. The magnitude of mass-flow fluctuations under the present test conditions (about 1%) is typical of this class of wind tunnels.

The flow parameters in the plenum chamber of the wind tunnel (stagnation pressure P_0 and stagnation temperature T_0) during the experiments were measured and maintained constant by the control system within 0.1% and 0.25%, respectively.

Hot-wire probes were moved by a coordinate gear with accuracy of 0.01 mm; the models were rotated around the longitudinal axis by a rotating mechanism with rotation accuracy of 0.1°.

Two types of the porous surface (with random and regular microstructures) were used in the experiments. The first was felt-metal; its porous layer consisted of pressed thin wires made of stainless steel 30 μm in diameter, which were randomly connected with each other and with the substrate (Fig. 1a). The coating thickness was 0.75 mm, and the mean porosity was $\phi \approx 0.75$. To ensure coating integrity, the felt layer was applied onto a solid substrate: stainless steel sheet 0.245 mm thick. The second type of the considered surface was a perforated stainless steel sheet 0.45 mm thick (Fig. 1b). Perforation was made by laser drilling. The pores were cylindrical orifices 50 μm in diameter, the distance between the holes was 100 μm, the open area was 20%, and the total number of orifices was approximately $3.35 \cdot 10^6$. The parameters of this porous coating were similar to characteristics of the coating used in the experiments of [11].

The models in the experiments were sharp cones 0.5 m long with an apex half-angle of 7°. The layout of the model is shown in Fig. 2. Half of the cone surface between its generatrices was covered by an ultrasound-absorbing material; the remaining part was solid. On the model with the felt-metal coating, the latter began at a distance $L = 186$ mm from the cone tip; for the model with the perforated sheet coating, it began at a distance $L = 182$ mm (see Fig. 2). The model was mounted at zero incidence. The mounting error was smaller than 0.05°.

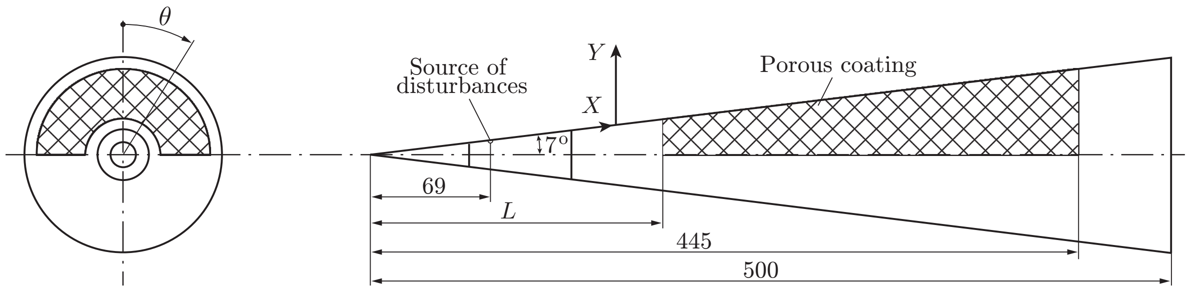

Fig. 2. Layout of the model.

The mean and fluctuating characteristics of the boundary layer were measured by a constant-current hot-wire anemometer. The hot-wire anemometer used allows one to measure fluctuations in a frequency band up to 500 kHz. The measurements were performed by a single-wire probe made of tungsten wire 1 mm long and 5 μm in diameter. Wire overheating $a_w = (r_w - r_e)/r_e$, where r_w and r_e are the resistances of the heated and cold wire, respectively, was chosen to be 0.5. Thus, the probe was mainly sensitive to mass-flow fluctuations.

The influence of porous coatings on boundary-layer stability was studied by considering the development of natural disturbances in the boundary layer. Detailed characteristics of the second-mode disturbances were obtained by the method of artificial wave packets: disturbances with controlled amplitude and phase were introduced into the boundary layer. The main advantage of this method is synchronization of measurements in terms of the phase of the introduced disturbances, hence, the possibility of obtaining the disturbance-phase value at an arbitrary point. The spatial distributions of mass-flow fluctuations were measured by a hot-wire anemometer and were subjected to the Fourier analysis, which allowed obtaining the wave characteristics of fluctuations. The method was developed for investigating stability of compressed flows [14] and successfully used to study stability at hypersonic velocities [15]. The disturbances were introduced into the flow by a high-voltage periodic electric discharge initiated in the chamber located inside the model. The discharge was ignited by a high-voltage generator producing voltage pulses up to 2000 V with a duration of approximately 1 μsec and repetition frequency up to 400 kHz. The discharge device was located in the nose part of the model at a distance of 69 mm from the model tip. The disturbances penetrated into the boundary layer through an orifice 0.4 mm in diameter in the cone surface.

To determine the amplitude (A) and phase (Φ) of controlled disturbances, the following discrete Fourier transform was used:

$$A(X,Y,\theta)\,\mathrm{e}^{i\Phi(X,Y,\theta)} = \frac{2}{N}\sum_{j=1}^{N} m_n(X,Y,\theta,t_j)\,\mathrm{e}^{-i\omega t_j}\,.$$

Here, N is the number of samples in the time realization, ω is the frequency of introducing controlled disturbances, and $m_n(X,Y,\theta,t_j)$ is the digital oscillogram of mass-flow fluctuations.

The artificial wave packet was presented as a set of simple waves. For this purpose, the transverse wave spectra were calculated:

$$SA(x,\beta)\,\mathrm{e}^{iSF(x,\beta)} = \int_{-\theta_0}^{\theta_0} A(x,\theta)\,\mathrm{e}^{i\Phi(x,\theta)}\,\mathrm{e}^{-i\beta\theta}\,d\theta$$

(SA and SF are the amplitude and phase spectra in terms of the transverse wavenumber β).

The measurement scheme used allowed us to simultaneously obtain characteristics of both artificial and natural disturbances.

2. Measurement Results. The experiments were performed for the following free-stream parameters: free-stream Mach number $\mathrm{M}_\infty = 5.95$, stagnation pressure $P_0 = 1000$ kPa, stagnation temperature $T_0 = 385$–400 K, unit Reynolds number $\mathrm{Re}_{1\infty} = (11.5$–$12.3) \cdot 10^6$ 1/m, and wall temperature $T_w = (0.80$–$0.84)T_0$.

The hot-wire measurements show that the boundary layer in the measurement region remained laminar both on the solid and porous surfaces. The mean characteristics of the flow (velocity profile, boundary-layer thickness, etc.) were close to each other and to calculations by the boundary-layer theory. Hence, the considered porous coatings do not alter the mean characteristics of the boundary layer. The coating with the random microstructure

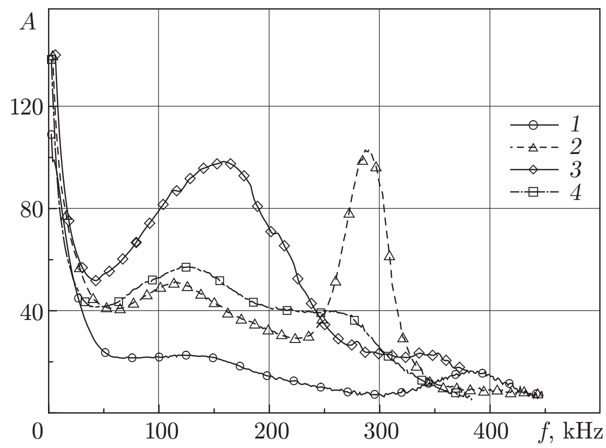

Fig. 3. Amplitude–frequency spectra of mass-flow fluctuations: 1) initial cross section (on the coating surface) for $\mathrm{Re}_{eX} = 2.8 \cdot 10^6$; 2) solid surface for $\mathrm{Re}_{eX} = 4.5 \cdot 10^6$; 3) surface with a random microstructure for $\mathrm{Re}_{eX} = 4.5 \cdot 10^6$; 4) coating with a regular microstructure for $\mathrm{Re}_{eX} = 4.5 \cdot 10^6$.

caused an increase in the level of integral fluctuations by no more than 20% as compared to the solid coating, and the coating with a regular microstructure had no influence on the root-mean-square fluctuations of the mass flow.

The spectra of mass-flow fluctuations were measured at a distance from the model wall Y corresponding to the maximum of fluctuations, in cross sections uniformly distributed along the X axis. The first cross section was located upstream of the leading edge of the coating. Examples of the spectra obtained are shown in Fig. 3 where curve 1 refers to disturbances in the first cross section. An analysis shows that the spectra in the first (upstream) sections are similar for the solid surface and for the UAC-covered sides. This indicates that the level of external disturbances remained constant in measurements on surfaces of different types. The behavior of the spectra downstream of the leading edge of the coating is appreciably different.

On the solid surface (curve 2), the measured spectra of disturbances are typical of hypersonic boundary layers (see, e.g., [16]). In the first measurement cross sections, the second mode is observed at a frequency $f \approx 430$–450 kHz. Its amplitude rapidly increases downstream, whereas the central frequency decreases to 270 kHz in the last cross section. The growth of first-mode disturbances is observed in a wide range of frequencies (50–200 kHz). In the center of the measurement zone ($\mathrm{Re}_{eX} \geqslant 3.42 \cdot 10^6$), the second-mode disturbances become greater than the first-mode disturbances, i.e., the first mode grows slower than the second one.

Strong stabilization of second-mode disturbances occurs on the porous coating with a random microstructure (curve 3 in Fig. 3), and second-mode disturbances are not observed for $\mathrm{Re}_{eX} \geqslant 3.3 \cdot 10^6$ (which corresponds to a distance of 28 mm from the leading edge of the coating). At the same time, strong destabilization of low-frequency first-mode disturbances in the frequency band of 100–200 kHz is observed.

The porous coating with a regular structure also effectively stabilizes the second mode. In the entire range of measurements, the amplitudes of the second mode are smaller than the amplitudes of the first mode. Amplification of the first-mode disturbances actually favors amplifications on the solid side.

Artificial disturbances were generated in the boundary layer with frequencies of 280 and 275 kHz in measurements with random and regular porosity, respectively. In the region of these frequencies, the second mode has the maximum amplitude in natural disturbance spectra measured on the solid side.

Figure 4 shows examples of the amplitude wave spectra versus the transverse wavenumber β. It is seen that the entire wave packet is within the range $\beta = \pm 0.3$ rad/deg, which approximately corresponds to the range of inclination of the wave vector $\pm 12°$. The maximum amplitude is observed for $\beta = 0$. The dimensionless longitudinal phase velocity $C_x = 0.9$ remains almost unchanged with increasing X coordinate and coincides for porous and solid surfaces. These characteristics show that the wave packet consists mainly from the second-mode disturbances for all coatings under study.

The development of natural and artificial disturbances on the solid and porous surfaces is shown in Fig. 5. The amplitudes of artificial disturbances correspond to $\beta = 0$. The amplitudes of artificial and natural disturbances almost coincide. Hence, natural disturbances at this frequency above ultrasound-absorbing surfaces are predomi-

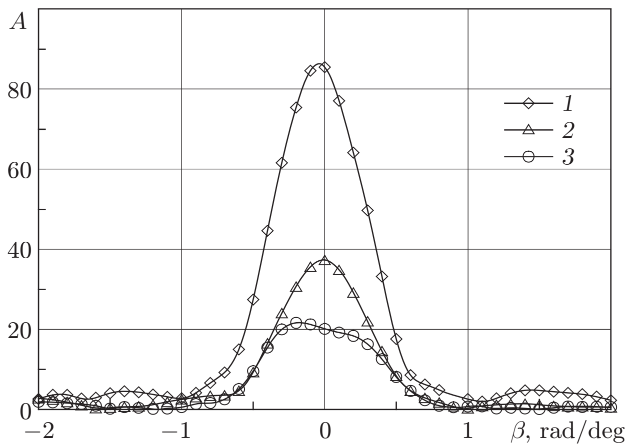

Fig. 4. Distribution of the amplitude of mass-flow fluctuations in the wave packet versus the wavenumber for $\mathrm{Re}_{eX} = 4.5 \cdot 10^6$: 1) solid surface; 2) coating with a random microstructure; 3) coating with a regular microstructure.

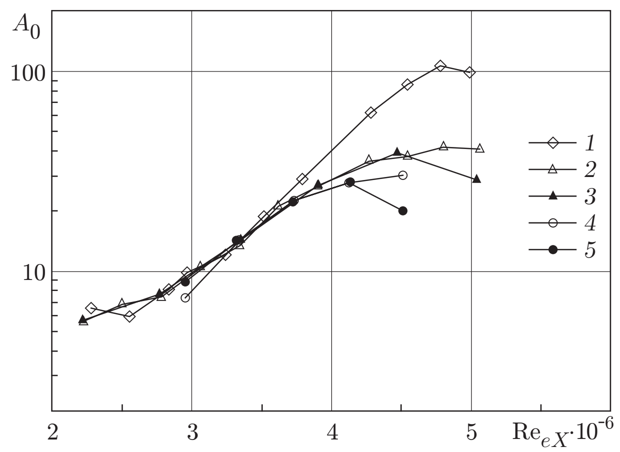

Fig. 5. Downstream evolution of the second-mode disturbances for $f = 275$ kHz: 1) solid surface (natural disturbances); 2, 3) surface with a regular microstructure [natural (2) and artificial (3) disturbances]; 4, 5) surface with a random microstructure [natural (4) and artificial (5) disturbances].

nantly two-dimensional waves of the second mode, as well as on the solid side [16]. It is well seen that the use of porous coatings leads to a significant decrease in the amplitude growth: the maximum amplitude is approximately three times smaller than that on the solid wall. The coating with a regular microstructure stabilizes the second mode almost as effectively as the coating with a random microstructure.

Conclusions. Complex studies of stability of hypersonic boundary layers on cones 0.5 m long with an apex half-angle of 7° with different types of porous coatings (felt-metal and a sheet perforated by blind holes) were performed for a free-stream Mach number M = 5.95. The development of artificial and natural disturbances in the boundary layer was analyzed.

The measurements of the mean profiles and integral root-mean-square mass-flow fluctuations showed that the boundary layer was laminar on the solid and porous surfaces in all measurement cross sections. It was found that the porous coating did not affect the mean flow.

The first (low frequencies) and second (high frequencies) modes were observed under natural conditions in the boundary layer. An analysis of natural disturbance spectra showed that the second mode dominated on the solid side. It was shown that ultrasound-absorbing coatings stabilized the second mode of disturbances, but elevated roughness destabilized the first mode of disturbances (in the case of a felt-type coating). If the roughness was insignificant (regular type of porosity), its influence on the first mode was also insignificant.

In studying by the method of artificial disturbances, it was found that the dominating component of the wave packet was a two-dimensional wave whose amplification practically corresponded to amplification of natural disturbances of the same frequency. This confirms that natural disturbances of the high-frequency band are predominantly two-dimensional waves that refer to the second mode of instability. It was shown that the coatings considered significantly reduced the wave-packet growth: the maximum amplitude on the porous side was approximately three and four times smaller (for coatings with regular and random microstructure, respectively) than on the solid side.

We can conclude that passive control of the boundary layer by ultrasound-absorbing coatings can stabilize the boundary layer and increase the region of the laminar flow around hypersonic flying vehicles. In this case, felt-metal seems to be a rather promising material from the viewpoint of manufacturability, since one can expect that excitation of the first mode is suppressed on the cold wall of a hypersonic flying vehicle, because the typical value of the temperature factor is 0.2–0.3.

This work was supported by the Russian Foundation for Fundamental Research (Grant No. 02-01-00141) and EOARD (Grant No. 2172).

REFERENCES

1. T. C. Lin, W. R. Grabowsky, and K. E. Yelmgren, "The search for optimum configurations for re-entry vehicles," *J. Spacecraft Rockets*, **21**, No. 2, 142–149 (1984).
2. P. V. Tartabini, R. A. Lepsch, J. J. Korte, and K. E. Wurster, "A multidisciplinary performance analysis of a lifting-body single-stage-to-orbit vehicle," AIAA Paper No. 2000-1045 (2000).
3. M. R. Malik, T. A. Zang, and D. M. Bushnell, "Boundary layer transition in hypersonic flows," AIAA Paper No. 90-5232 (1990).
4. E. Reshotko, "Boundary layer instability, transition and control," AIAA Paper No. 94-0001 (1994).
5. V. I. Lysenko and A. A. Maslov, "The effect of cooling on supersonic boundary-layer stability," *J. Fluid Mech.*, **147**, 38–52 (1984).
6. M. R. Malik, "Prediction and control of transition in supersonic and hypersonic boundary layers," *AIAA J.*, **27**, No. 11, 1487–1493 (1989).
7. L. M. Mack, "Boundary-layer stability theory. Special course on stability and transition of laminar flow," AGARD Report No. 709 (1984), pp. 3-1–3-81.
8. R. Kimmel, A. Demetriades, and J. Donaldson, "Space–time correlation measurements in a hypersonic transitional boundary layer," AIAA Paper No. 95-2292 (1995).
9. N. D. Malmuth, A. V. Fedorov, V. Shalaev, et al., "Problems in high speed flow prediction relevant to control," AIAA Paper No. 98-2695 (1998).
10. A. V. Fedorov, N. D. Malmuth, A. Rasheed, and H. G. Hornung, "Stabilization of hypersonic boundary layers by porous coatings," *AIAA J.*, **39**, No. 4, 605–610 (2001).
11. A. Rasheed, H. G. Hornung, A. V. Fedorov, and N. D. Malmuth, "Experiments on passive hypervelocity boundary layer control using a porous surface," AIAA Paper No. 2001-0274 (2001).
12. A. Fedorov, A. Shiplyuk, A. Maslov, et al., "Stabilization of a hypersonic boundary layer using an ultrasonically absorptive coating," *J. Fluid Mech.*, **479**, 99–124 (2003).
13. V. D. Grigor'ev, G. P. Klemenkov, A. I. Pirogov, and N. V. Yakovleva, "Hypersonic wind tunnel T-326 of ITAM. Methodical study of velocity and temperature fields," Report No. 1129, Inst. Theor. Appl. Mech., Sib. Div., Acad. of Sci. of the USSR, Novosibirsk (1980).
14. A. A. Maslov, A. D. Kosinov, and S. G. Shevelkov, "Experiments on the stability of supersonic laminar boundary layers," *J. Fluid Mech.*, **219**, 621–633 (1990).
15. A. A. Maslov, A. A. Sidorenko, and A. N. Shiplyuk, "Application of artificial disturbances to study stability of a hypersonic boundary layer," *Teplofiz. Aéromekh.*, **4**, No. 4, 429–433 (1997).
16. K. F. Stetson and R. G. Kimmel, "Example of second-mode instability dominance at a Mach number of 5.2," *AIAA J.*, **30**, No. 12, 2974–2976 (1992).