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Experimental Study of Disturbances in Transitional and Turbulent Hypersonic Boundary Layers

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Nomenclature

c_f = skin-friction coefficient
f = frequency, Hz
k = roughness height
M = Mach number
P_0 = total pressure, kPa
q = heat flux, W/m^2
Re_x = Reynolds number
Re_1 = unit Reynolds number, m^{-1}
T = temperature, K
T_0 = stagnation temperature, K
u = velocity along the cone surface, m/s
u_τ = wall friction velocity, m/s
X = longitudinal coordinate measured along the cone surface, mm
ν = kinematic viscosity, m^2/s
ρ = density, kg/m^3
τ = shear stress, N/m^2

Subscripts

aw = adiabatic wall
e = at the upper boundary-layer edge
tr = transition end
w = on the wall
∞ = freestream

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Introduction

FOR small freestream disturbances and negligible surface roughness, laminar–turbulent transition is due to amplification of unstable modes in the boundary layer [1,2]. The second mode, which is a dominant instability in essentially two-dimensional boundary layers at hypersonic speeds, belongs to the family of trapped acoustic waves of an ultrasonic frequency band. Exploiting this fact, Fedorov and Malmuth [3,4] assumed that an ultrasonically absorptive coating (UAC) can stabilize the second mode and increase the laminar run. Stability analyses [3,4] confirmed that a thin porous layer reduces the second-mode growth rate. Transition measurements [5] on a 5-deg half-angle sharp cone in the GALCIT T-5 shock tunnel showed that UAC of regular structure (equally spaced cylindrical blind microholes) can double the laminar run. The theoretical model was validated by stability measurements on a 7-deg half-angle sharp cone in the Institute of Theoretical and Applied Mechanics (ITAM) T-326 wind tunnel at the freestream Mach number 6 [6]. Similar results were obtained on a sharp cone with a felt-metal coating of regular structure [7]. The nonlinear aspects of the second-mode stabilization by this coating were studied in [8]. Transition measurements [9] in the ITAM AT-303 wind tunnel at Mach 12 showed that the felt-metal coating significantly delays the transition locus.

In this Note, we briefly discuss new experimental data relevant to the felt-metal coating effect on disturbances in transitional and turbulent boundary layers on a sharp cone in the Mach-6 freestream.

Experimental Setup

Experiments are performed in the ITAM Transit-M impulse wind tunnel that is a noisy conventional facility [10]. The run time is approximately 110–200 ms for the Mach-6 experiments discussed hereafter. The model is a 7-deg half-angle sharp cone of $L = 0.5$ m length. The felt-metal coating covers half of the cone surface between the stations $X = 186$ and 445 mm. A detailed description of this model is given in [6]. The cone was tested at zero angle of attack.

All heat-flux data discussed hereafter were obtained using the atomic-layer thermal pile (ALTP) gauges, which are flush mounted at the station $X = 437$ mm on the solid and porous cone surfaces. The ALTP working principle is based on a thermoelectric field generated due to the transverse Seebeck effect [11]. These gauges have small time constant (approximately 1 μs) that allows for measurements of high-frequency (up to 1 MHz) disturbances. The sensor signal is a linear function of the measured heat flux in a wide range (from mW/cm^2 to kW/cm^2). Characteristics of the ALTP gauges and the static and dynamic calibration methods are discussed in [12–14].

Table 1 Table of flow conditions

Run	P_0, kPa	T_0, K	$Re_{1\infty} \times 10^6$, m^{-1}	$Re_{1e} \times 10^6$, m^{-1}
26	748–705	420–435	8.2–7.4	10–9.2
27	992–690	437–485	10–6.1	12.8–7.6
59	428–390	397–430	5.1–4.2	6.3–5.2
60	548–492	436–466	5.7–4.6	7.1–7.8
61	687–624	445–476	6.9–5.7	8.6–7.1
62	373–334	427–463	4–3.2	5–4
63	246–223	405–440	2.8–2.3	3.47–2.9

Results

The flow conditions are given in Table 1. Because the temperature inside the settling chamber is not controlled, the total temperature is spread in the range $392\ \mathrm{K} \leq T_0 \leq 485\ \mathrm{K}$. For the model temperature being $T_w = 289$–292 K, the wall temperature ratio lies in the range of $T_w/T_0 = 0.60$–0.74. Although uncertainty in T_w/T_0 leads to an appreciable scatter of experimental data, it does not affect the basic trends discussed herein. Total temperature and total pressure are measured with an accuracy of 0.2 and 0.5%, correspondingly. Heat flux is measured with an accuracy of 10%.

Because the flow conditions altered during the run, the unit Reynolds number Re_1 decreases by approximately 20% during the measurement period of 200 ms. To account for this altering, the measurement period was subdivided into five equal intervals. Within each interval variations of Re_1 do not succeed $\pm 2\%$ and the flow is treated as steady.

Figure 1 show the RMS values $\langle q \rangle$ of heat-flux fluctuations in the band of 1–600 kHz as functions of the local Reynolds number Re_{Xe}. Here, symbols represent experimental data, and lines show their polynomial fit.

In the solid wall case, $\langle q \rangle$ grows fast (squares in Fig. 1) and reaches its maximum at $Re_{X\mathrm{tr}} = 3.25 \times 10^6$ corresponding to the transition end. The disturbance growth on the porous surface occurs later and the transition end Reynolds number is $Re_{X\mathrm{tr}} = 3.9 \times 10^6$ (triangles in Fig. 1); that is, the UAC causes about 20% increase of $Re_{X\mathrm{tr}}$. For $Re_{Xe} > 5 \times 10^6$, the transition process is completed and the boundary layer can be treated as turbulent.

Figure 2 shows the disturbance spectra on the solid and porous surfaces at different Re_{Xe}. On the solid surface, there is a high peak in the frequency band 150–200 kHz. This peak is observed in the laminar and transitional boundary layers and corresponds to the second-mode instability. Its amplitude grows with Re_{Xe}, and its frequency increases from 115 to 180 kHz due to decreasing of the boundary-layer thickness. The first harmonic of the second mode is also clearly seen. For $Re_{Xe} > 3 \times 10^6$, the second-mode amplitude saturates and eventually decreases. This process is accompanied by a simultaneous growth of disturbances in a wide-frequency band that indicates nonlinear breakdown to turbulence. On the porous wall, the second-mode peak is totally suppressed.

The disturbance Fourier amplitude $A_f(f)$ for transitional ($Re_{Xe} = 2.59 \times 10^6$) and turbulent ($Re_{Xe} = 5.36 \times 10^6$) flows on the solid and porous surfaces are shown in Fig. 3. In the transitional boundary layer (solid lines), the coating weakly affects the low-frequency (less than 100 kHz) disturbances whereas it massively suppresses the high-frequency (greater than 100 kHz) disturbances. In the turbulent boundary layer (dashed lines), the coating causes

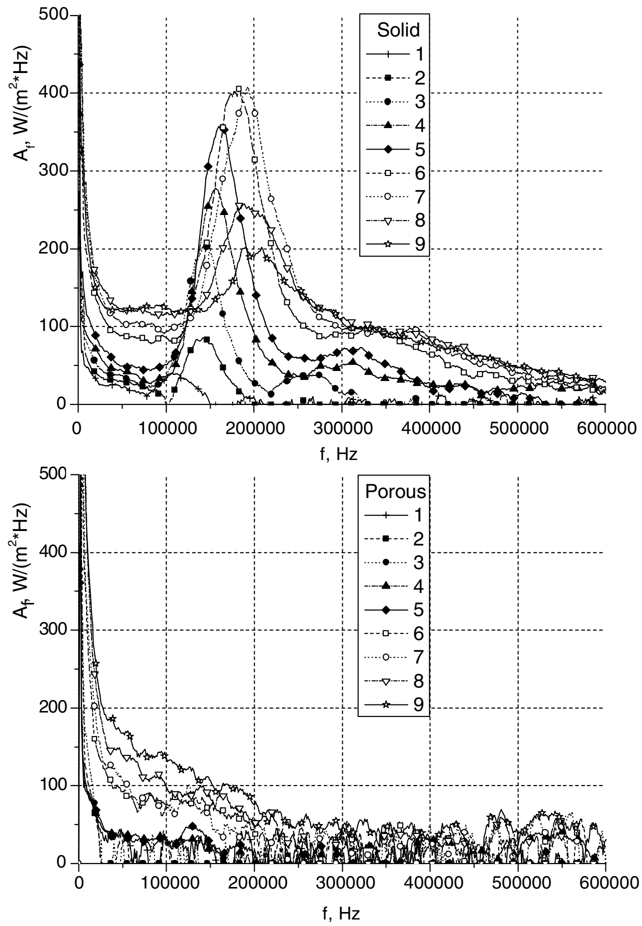

Fig. 2 Disturbance spectra at $Re_X \times 10^{-6}$: 1 is –1.3, 2 is –1.88, 3 is –2.14; 4 is –2.37; 5 is –2.74; 6 is –3.08; 7 is –3.23; 8 is –3.61; and 9 is –3.74.

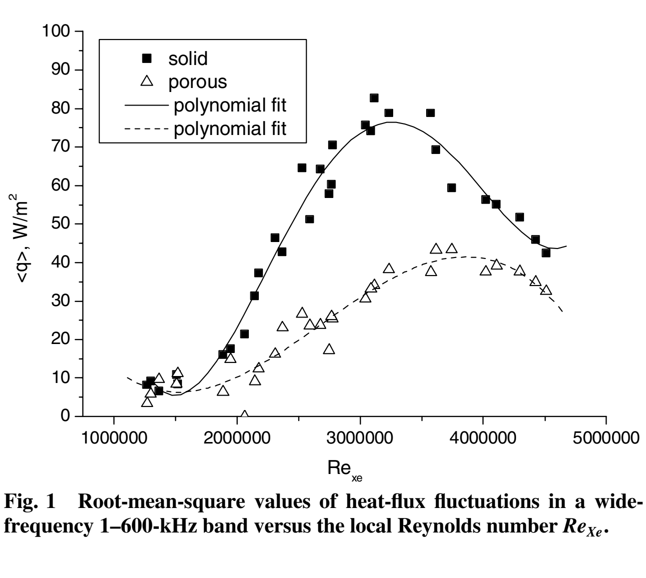

Fig. 1 Root-mean-square values of heat-flux fluctuations in a wide-frequency 1–600-kHz band versus the local Reynolds number Re_{Xe}.

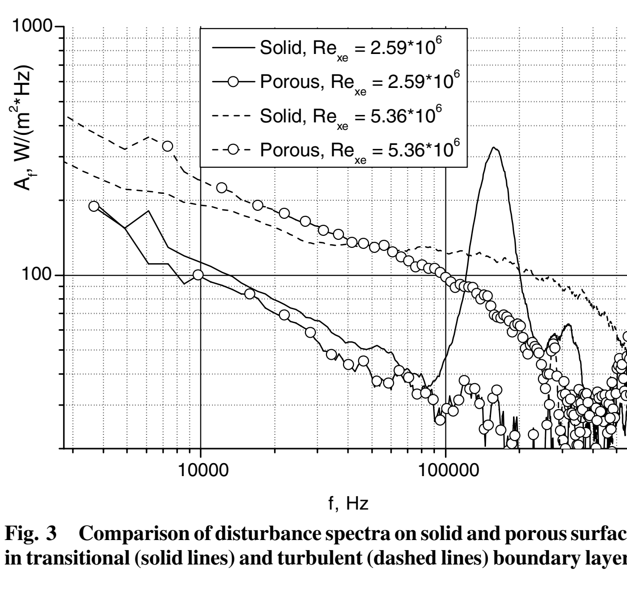

Fig. 3 Comparison of disturbance spectra on solid and porous surfaces in transitional (solid lines) and turbulent (dashed lines) boundary layers.

approximately 30% increase of the low-frequency (less than 60 kHz) disturbances and dramatic reduction of the high-frequency (greater than 60 kHz) disturbances.

The UAC differs from the solid wall by the two major characteristics: distributed roughness and porosity. Hereafter we examine their influence on the turbulent boundary layer. Distributed roughness can significantly disturb the viscous sublayer, which plays important role in turbulent near-wall flows [15,16]. Surface roughness falls into three categories depending on its height k^+ expressed in the nondimensional log-law coordinates as

$$k^+ = \frac{k u_\tau}{\nu_w}, \qquad u_\tau \sqrt{\frac{\tau_w}{\rho_w}}, \qquad \tau_w = c_f \frac{\rho_e u_e^2}{2} \tag{1}$$

On a hydraulically smooth surface ($k^+ < 4$), roughness elements are buried within the viscous sublayer and do not affect the flow. Large roughness elements ($k^+ > 60$) eliminate the entire viscous sublayer, they fall within the fully rough flow region that does not depend on viscosity. Between these two extremes ($4 < k^+ < 60$), there is a transitional regime in which roughness affects the flow by reducing the sublayer thickness [17]; namely, it causes the velocity defect in the near-wall region, whereas the outer region remains undisturbed.

Assuming that this treatment is relevant to the case considered herein, we can estimate the UAC roughness effect as follows. The local skin-friction coefficient is evaluated using the extended Frankl–Voishel relation for a flat plate and taking into account that in a cone case c_f is 10–15% higher [16]. Assuming that the roughness height equals to the fiber diameter, $k \approx 30$ μm, we obtain $k^+ \approx 4.5$ for the experimental conditions considered herein. This indicates that distributed roughness is small and it should not affect the turbulent boundary layer.

The porosity effect on turbulent flows has been investigated for subsonic speeds in connection with the skin-friction control [18,19]. Jimenez et al. [18] carried out direct numerical simulation of this effect on the fully turbulent subsonic flow in a channel. It was found that a passive porous wall leads to the skin-friction increase by substantial amounts, which are limited to about 40% by occurrence of local flow separations. It was shown that this effect is not related to roughness. About 10% of the total drag increase was due to the energy absorption by the porous layer. The rest was related to a large-scale reorganization of flow structures, which originates from instabilities resulting in coherent spanwise rolls. The rolls increase drag by creating large-scale sweeps, in which the velocity is directed to the wall, and ejections, in which the instability and intensity of the velocity streaks is enhanced. Although the paper [18] does not address porosity effects on high-frequency disturbances, it is reasonable to assume that the energy absorption increases with frequency and high-frequency turbulent fluctuations are effectively damped by the UAC. The behavior of disturbance spectra (dashed lines in Fig. 3) is consistent with the foregoing arguments. Namely, coherent structures incipient in the near-wall layer may enhance low-frequency disturbances (less than 60 kHz), whereas the energy absorption by the porous layer may strongly suppress high-frequency fluctuations.

Conclusions

Experimental studies of the porous (felt-metal) coating effect on transitional and turbulent boundary layers were performed on a sharp cone at zero angle of attack in the Mach-6 impulse wind tunnel. The atomic-layer thermopile gauges (ALTP) were used for measurements of heat-flux disturbances on the solid and porous surfaces in a wide-frequency band (up to 600 kHz). It was shown that transition is caused by the second mode. The porous coating effectively suppresses the second mode and higher-frequency disturbances (greater than 100 kHz), whereas it weakly affects the low-frequency disturbances associated with the first mode and freestream noise. In total, the felt-metal coating provides approximately 20% increase of the transition end Reynolds number. These results are consistent with previous measurements of disturbances in the transitional boundary layer on the felt-metal coating.

For the first time, it was shown that the porous coating significantly affects disturbance spectra in the turbulent boundary layer; namely, the low-frequency disturbances are enhanced by approximately 30%, whereas the high-frequency disturbances are massively suppressed, compared with the solid-surface case. The two major factors can cause these effects: distributed roughness and porosity. First-cut estimates showed that the coating surface was hydraulically smooth; that is, its roughness should not impact the turbulent boundary layer considered herein. Seemingly, porosity augments excitation of coherent structures in the near-wall layer that enhances disturbances of the low-frequency band (less than 60 kHz). On the other hand, fine pores effectively suppress high-frequency fluctuations. Further studies are needed to clarify details of this mechanism.

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