Hypersonic boundary layer stabilization by using a wavy surface

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Abstract. Numerical simulation of hypersonic ($M_{\infty}=6$) flow and evolution of disturbances on a smooth plate and a shallow grooved plate was performed by solving two-dimensional Navier–Stokes equations. Computational software verification was conducted by comparison with existing data of pressure pulsations on plates surface. It was showed that wavy surface significantly decrease pressure pulsations on plate surface and does not increase the value of mean heat fluxes. Data about effect of wavy surfaces with different form on the disturbances intensity in hypersonic boundary layer was obtained.

1. Introduction

Laminar-turbulent transition in the compressible boundary layers was the subject of research for many years [1]. It is known that the laminar–turbulent transition in hypersonic flows depends on the parameters of the mean flow and may be initiated by two instability modes. The first mode is associated with Tolmin–Schlichting waves, which are vortex perturbations, and the second one is associated with inviscid instability and it is acoustic in nature. The second or Mack [2] mode dominates when the Mach number is fairly high. In this case, acoustic perturbations are trapped by a boundary layer, grow in amplitude and eventually may cause nonlinear processes [3–5] and turbulization of the flow (laminar–turbulent transition).

In the past decade gas permeable porous materials has been actively used for suppression of acoustic disturbance in order to prolong laminar flow regime [6–9]. These phenomena are based on dissipation of the energy of acoustic disturbances, which are a dominating mode of instability of a hypersonic boundary layer, owing to friction in pores of the coating.

On the other hand, the second-mode instability can also be affected by local shaping of the body surface. It is well known that increasing Mach number produces a stabilization effect on the flow in free shear layers and wakes (e.g., [10, 11]). It is natural to assume that a relatively long free shear layer formed near a streamlined surface may decrease the growth rates and damp the second-mode disturbances with a short wave length (of the order of the layer thickness). This could be achieved with the help of a shallow, grooved, wavy surface, which produces a relatively stable free shear layer bridging neighboring cavities. This wavy-wall stabilization (WWS) concept was confirmed by experiment and 2-D DNS [12].

This method is new and the integral effect of wavy surface is not been sufficiently investigated. The main objective of this work is to examine the stabilization of boundary layer by wavy surfaces of different type. These studies are useful for prediction of laminar-turbulent transition on wavy walls which are arising naturally in the swelling of heat-shielding panels of aircraft.
2. Numerical simulation of supersonic flow over smooth plate and plate with wavy surface

Numerical simulation of supersonic flow was carried out by solving unsteady 2D Navier–Stokes equations using the ANSYS Fluent program package. Computations were performed using parameters according to free stream conditions in experiments performed in the wind tunnel Transit-M ITAM SB RAS[12]: Mach number $M_\infty=6.0$, free stream velocity $U_\infty=790.38$ m/s, unit Reynolds number $Re_1=10.5 \times 10^6$ m$^{-1}$, total pressure $P_0=7 \times 10^5$ Pa, free stream static pressure $P_\infty=445$ Pa, free stream static temperature $T_\infty=43.08$ K, total temperature $T_0=354.06$K, wall temperature $T_w=293$ K.

Air was considered as ideal gas with heat capacity ratio $\gamma=1.4$ and Prandtl number $Pr=0.72$, molecular viscosity $\mu$ were set by Sutherland’s law. The left (input) boundary is located at 10 computational cells upstream from the leading edge of plate, the right (output) boundary was shifted to 40 computational cells from the trailing edge of the plate so that the flow in the exit section was completely supersonic. The computational domain height was chosen under the condition that the bow shock wave did not interact with the upper boundary of the computational domain (36mm). Plate length was taken equal to 176mm which is smaller than experimental model (350mm) in aim to create more precise mesh in wavy surface region.

Three type of wavy surface were considered (Figure 1). In all cases the beginning of wave surface region $x_b=52$mm, the end of wave surface region $x_e=160$mm. Wavy surface 1 has 9 grooves in arc form and were defined by the equation $y=h(\cos(\pi(x-x_b)/l)-1)$, where $h=1.8$mm – height of wavy element, $l=12$мм – length of wavy element. This shape of wavy surface corresponds to the experimental model [12] and is shown in Figure 1a. Wavy surface 2 has 9 grooves in sawtooth form with height and length as in wavy surface 1 (Figure 1b). Wavy surface 3 was a sequence of 6 triangular cavities, the same as on the wave surface 2.

![Figure 1. Plate with wavy surface of different shapes.](image)

The drawing of model geometry and computational domain and creating of a regular computational grid were performed using ANSYS ICEM. The allocation of subdomain with a height of 0.003m was made near the surface of the plate, which corresponded to the thickness of the boundary layer (according to preliminary calculations) for detailed resolution of the boundary layer. Computational domain was divided into two subdomains: a subdomain with a height of 0.003 m, including boundary layer, with uniform grid and a subdomain outside this zone with a grid refinement toward the plate surface. The total number of meshes was 568000.

The computations were performed using the density-solver with explicit/implicit scheme of the second-order accuracy in space and the Roe-FDS method of convective flux splitting and explicit Runge–Kutta method. The problem of numerical simulation of a supersonic flow of air was solved in two stages. First, numerical simulation of steady flow was performed using implicit scheme in space. After that, unsteady disturbances of the periodic suction-blowing type are introduced locally (on the surface area from $x_1=0.01$m to $x_2=0.015$m). These disturbances were introduced by the periodic boundary condition on the transverse velocity component: $u_w(x,t)=A\sin\left(2\pi \frac{x-x_1}{x_2-x_1}\right)\sin(2\pi f t)$, where $f$ – frequency, $A=\varepsilon \rho_u U_\infty / \rho_w$ – amplitude of introduced disturbance. To ensure the linear evolution of introduced disturbances in front of the wavy region a small amplitude was chosen $\varepsilon=2 \times 10^{-3}$. Boundary condition of the transverse velocity component was set at the region $x_1x_2$ on the wall surface by using UDF (User Defined Function). Up to ten processors of the Information-
Computational Center of the Novosibirsk State University and the Siberian Supercomputer Center were used in the computations.

3. Results
Primarily in test reason of computational method numerical simulation of flow over wavy plate 1 was performed to make comparison with computational data from [12]. The computed steady-flow Mach-number field over smooth plate and plate with wavy surface 1 are shown on figure 2a,b. In both cases viscous- inviscid interaction leads to formation of a weak shock wave near the leading edge region the slopes of which are the same. The cavities of the wavy surface induce oblique shocklets emanating from the reattachment regions on the tops of wavy surface the interaction of which with the flow in the boundary layer causes recirculation inside the cavities (with a negative horizontal velocity, as shown on Figure 2c). Near the separation and attachment points, a compression wave is clearly observed. The upper boundary of each separation zone and the entire layer above the wavy surface is almost a straight line, which is typical for supersonic flows. As a result, the upper boundary of the whole mixing layer over the wavy plate remains almost unchanged compared to the smooth plate case. The wavy surface has little effect on the global flow field over the boundary layer. At the same time, this surface generates a mixing layer that connects the cavities and resembles a free shear layer with almost parallel edges.

Figure 2. Mach-number field of steady flow (a,b) and velocity counters near the region of wavy surface with velocity isolines (c): (a) smooth plate, (b,c) plate with wavy surface 1.
Figure 3. Instantaneous pressure pulsation field due to suction-blowing disturbances with amplitude $A=8.76$ and frequency $f=138.74$ kHz: a – smooth plate; b – plate with wavy surface 1.

Figure 3 shows the appearance of cellular structures in the flow, divided into two fronts, behind a source of blowing-suction disturbances for a smooth plate and a plate with wavy surface 1. In the case of a wavy plate, the disturbances in the shock layer (above the mixing layer and behind the bow shock) have similar behavior to the case of a smooth plate, because the upper boundary of the mixing layer is weakly affected by the separation bubbles within the cavities. The evolution of disturbances on the wavy plate in the near-wall region is completely other: disturbances interact with shocklets induced by tops of wavy surface and with the cavity flows. While the structure of the disturbances field is rather complicated, there is no evidence of local amplification of the disturbance amplitude, which could be caused by these interactions.

Figure 4. Longitudinal distributions of normalized pressure pulsations at the plate surface $\Delta c_p = (p - p_\infty)/\left(\rho_\infty U_\infty^2/2\right)$. In the case of a smooth plate, the pulsations increase at $x > 80$ mm and reach maximum amplitude at $x \approx 155$ mm. On the wavy surface the pressure pulsations decrease in amplitude in comparison with a smooth plate, and it is seen their variations along $x$ which depend on the period of wall waviness. The wavy surface decrease the growth of disturbances because the free shear layer formed on the wavy surface is more stable than the boundary layer. The reduction of pulsations on a wavy surface confirms the concept of stabilization of a hypersonic boundary layer by a wavy wall.
Figure 5a shows that the decrease of pulsation amplitude on a wavy surface is not instantaneous, since it persists with time. The values of the heat flux on the wavy surface are close to the values of the heat flux on the smooth plate. As shown in Figure 5b, the cavities cause relatively small periodic perturbations of the heat flux without an average overheating.

![Graph showing pressure coefficient and heat flux distribution](image)

**Figure 5.** Time dependency of the calculated disturbance amplitudes of pressure coefficient on the wall at \( x = 165 \) mm (a) and heat flux distribution (b). \( A = 8.76, f = 138.74 \) kHz: 1 – smooth plate; 2 – plate with wavy surface 1.

Figure 6 shows the Mach-number field of steady flow (a) and the velocity field at the wavy surface region with velocity isolines (b) in the flow over the plate with wave surface 2. One can see that in the case of wavy surface 2 (a sawtooth surface), the size of vortices appear in the region of cavities is somewhat larger than in case 1 (Figure 2c) because of the larger cavity size. It is also seen that the boundary of the mixing layer becomes more curved in the region of the waviness peaks. Despite some differences in the flow in the region of a wavy surface, the general behavior of the flow is analogous to case 1, i.e. the formation of a mixing layer which is more stable than the boundary layer.

![Mach-number field and velocity field](image)

**Figure 6.** Mach-number field of steady flow (a) and the velocity field at the wavy surface region with velocity isolines (b) in the flow over the flat plate with wave surface 2.

Figure 7 shows the normalized pressure pulsations on the plates with different wavy surface (a,c) and the distribution of heat fluxes (b,d). Comparison of these data for three different types of wavy surface shows their similarity. Some differences in the distribution of heat flux are seen at the tops of wavy surface. It is seen that in comparison with the wavy surface 1 (Figure 5b), sawtooths surfaces 2 and 3 with sharp tops give peaks on the distributions of heat fluxes (Figure 7b,d).
Figure 7. Normalized pressure pulsations on the plates with different wavy surface (a,c) and the distribution of heat fluxes (b,d): $A=8.76$, $f=138.74$kHz: 1 – smooth plate; 2 – wavy plate with wavy surface, (a,b) – waviness 2, (c,d) – waviness 3, blue vertical lines indicate the waviness position.

4. Conclusions

Numerical simulation of supersonic ($M_\infty = 6$) flow over the smooth plate and the plate with a wavy surface of different types was performed by solving the two-dimensional Navier–Stokes equations with using the ANSYS Fluent package. The program modules for introduction of disturbances of blowing-suction type into the boundary layer were created. The verification of the computational program was performed by comparison with the data available in the literature.

Numerical studies have shown that wavy surfaces form an almost parallel layer of mixing, connecting adjacent cavities with soft separations and reattachments. Such waviness slightly perturbs the external flow, and at the same time, weakens the growth of perturbations in the boundary layer and does not increase the values of the average heat fluxes.

It is shown that the flow behavior does not change for different types of wavy surface: a mixing layer is formed, which effectively prevents the growth of perturbations in the boundary layer.

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