Stabilization of a Hypersonic Boundary Layer Using a Wavy Surface

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Stability of a supersonic near-wall flow over a shallow grooved plate in the freestream of Mach 6 is investigated by means of numerical simulations and wind-tunnel experiments. Numerical solutions of two-dimensional Navier–Stokes equations are used to model propagation of artificial disturbances of several fixed frequencies generated by an actuator placed on the wall. It is shown that the high-frequency forcing excites unstable waves in the flat-plate boundary layer. These waves are relevant to the second-mode instability. The wavy wall damps the disturbances in a high-frequency band while it enhances them at lower frequencies. Stability experiments are conducted in the Institute of Theoretical and Applied Mechanics Transiti-M shock tunnel under natural freestream conditions. The measured disturbance spectra are similar to those predicted numerically. They contain a peak associated with the second-mode instability. This peak is damped by the wavy wall, while a marginal increase of the disturbance amplitude is observed at lower frequencies. Although the experiments qualitatively confirm the wavy-wall stabilization concept, further stability and transition measurements are needed to clarify its robustness.

Nomenclature

\[ A = \text{spectral density for disturbance} \]

\[ c_p = \text{pressure coefficient} \]

\[ f = \text{frequency} \]

\[ M = \text{Mach number} \]

\[ p = \text{pressure} \]

\[ T = \text{temperature} \]

\[ t = \text{time} \]

\[ Re_1 = \text{unit Reynolds number} \]

\[ U = \text{streamwise velocity} \]

\[ (u, v) = \text{flow velocity component} \]

\[ x = \text{streamwise coordinate measured from the plate leading edge} \]

\[ y = \text{vertical coordinate measured from the flat-plate surface} \]

\[ \gamma = \text{specific heat ratio} \]

\[ \Delta = \text{difference between values from disturbed and steady fields} \]

\[ \delta = \text{boundary-layer thickness} \]

\[ \mu = \text{dynamic viscosity} \]

\[ \rho = \text{density} \]

Subscripts

\[ 0 = \text{total} \]

\[ w = \text{on the wall} \]

\[ \infty = \text{freestream} \]

I. Introduction

LAMINAR–TURBULENT transition leads to substantial increase of the aerodynamic drag and surface heating, and it reduces the efficiency of propulsion systems of hypersonic vehicles [1,2]. Smoothing and shaping of the vehicle surface helps to avoid early transition due to roughness, leading-edge contamination, and cross-flow and Görtler instabilities. However, with these measures, the laminar run may still be short because of the amplification of unstable disturbances of the first and/or second mode during the linear phase of the transition process. The wall cooling, which naturally occurs on hypersonic-vehicle surfaces, strongly stabilizes the first mode, while it destabilizes the second mode. In this case, transition can be second-mode-dominated, and laminar flow-control (LFC) concepts should address the second-mode instability.

The following are the categories of LFC techniques [3]: 1) passive techniques such as shaping and passive coatings; 2) active techniques such as suction, local cooling, or heating; and 3) reactive techniques such as actuators and microelectromechanical systems. Because of severe environmental conditions of a hypersonic flight associated with large heat fluxes and high temperatures of the boundary-layer flow, it is difficult to use the active and reactive techniques. The
passive techniques are of primary interest for hypersonic LFC studies.

In connection with this, Fedorov et al. [4] showed that a porous coating providing absorption of disturbance energy can massively suppress the second-mode instability. These theoretical results were confirmed by the experiments of Rasheed et al. [5], conducted on a sharp cone in the Graduate Aerospace Laboratories of the California Institute of Technology T5 high-enthalpy shock tunnel as well as by direct numerical simulations (DNS) [6]. A review of studies related to this LFC concept is given in [7].

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., [8,9]). 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 wavelength (of the order of the layer thickness). This hypothesis was motivated by the numerical studies [10,11] addressing stability of the supersonic (freestream Mach number 5.373) flow over a 5.5 deg compression corner. It was found that the second mode grows exponentially in the regions lying upstream and downstream from the separation bubble, while it remains neutral across the separated region. Similar, although less pronounced, stabilization effect is present in the numerical simulations [12] of two-dimensional (2-D) disturbances in a Mach 4.8 flow over a 6 deg compression corner.

In [11], it is also shown that the second-mode amplitudes decrease in a separated mixing layer. This is consistent with the numerical investigation [13] of the disturbance evolution in a Mach 4.8 flat-plate boundary layer with a localized 2-D roughness element. It was found that the disturbance was strongly damped behind the roughness element, where the separation flow mimics the flow structure over the compression corner considered in [11].

It should be noted that acoustic disturbances are effectively excited in a relatively long separation bubble [11]. They, in turn, generate the second-mode waves, which grow rapidly downstream from the reattachment point. It is assumed that, if a long separation bubble is replaced by a sequence of small ones, it is feasible to exploit the aforementioned stabilization effect of the free shear layer and, at the same time, avoid detrimental acoustic resonances within the bubbles. 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 our 2-D DNS [14]. It was shown that the second-mode waves of high frequency are stabilized by the concave wavy wall comprising several shallow cavities of a half-sinus shape. As expected, the stabilization effect is not observed for low-frequency disturbances with the length scale of the order the waviness period. It was also found that the wavy surface weakly affects the acoustic component of disturbances in the boundary layer (i.e., the waviness does not produce detrimental effects associated with secondary reflections of acoustic waves in the separation regions). It was pointed out that naturally occurring wavy surfaces (such as bored panels of thermal protection system [15]) do not necessarily lead to more unstable flow and premature transition. These configurations need special treatments of the interaction between instability and mean-flow irregularities.

Note that the aforementioned 2-D numerical simulations do not capture Görtler vortices and other three-dimensional (3-D) disturbances that could grow on concave surfaces and lead to premature transition. The main objective of this paper is to validate the WWS concept by experiments. Experimental and 2-D DNS results are presented for unsteady hypersonic flow over a wavy plate at the freestream Mach number 6. The study addresses the second-mode instability of the near-wall flow comprising a set of local separation bubbles. In accord with our previous DNS results [14] as well as additional parametric computations, a wavy-plate model was designed and manufactured. The model was tested in the Mach 6 shock tunnel with measurements of the natural disturbance spectra. For the freestream parameters related to these experiments, the DNS was conducted for 2-D disturbances generated by a local forcing (periodic suction–blowing). The DNS results are compared with the experimental data.

II. Problem Formulation

A. Experimental Setup

The experiments are carried out in a Ludwieg-type short-duration wind tunnel, the Tranzit-M of the Institute of Theoretical and Applied Mechanics, Siberian Branch of the Russian Academy of Sciences, at the freestream Mach number $M_{\infty} = 6$. The wind-tunnel layout is shown in Fig. 1. Air is heated up by ohmic heaters and is gathered in the plenum chamber under pressure up to 200 bar. After opening the fast-acting valve, air flows to the settling chamber and to the test section through the contoured nozzle of 300 mm exit diameter. Then, gas is compressed by a diffuser and flows to the vacuum tank. The run time is about 300–350 ms, depending on the initial pressure. During the run, the total pressure $p_0$ and the stagnation temperature $T_0$ are measured in the plenum chamber with the relative error of 1.5% for $p_0$ and 0.9% for $T_0$.

Unfortunately, there are no data on the freestream noise in this tunnel at $M_{\infty} = 6$. Measurements of the $p'_0$ pressure pulsations (behind a normal shock) have been conducted at $M_{\infty} = 4$ in the frequency band from 1 to 200 kHz. The rms value of these pulsations is $4.0 \pm 0.2\%$ at the stagnation pressures 4 and 8 bar and stagnation temperatures 290 and 450 K. Although the Tranzit-M wind tunnel is a conventional noisy facility, the freestream noise is relatively small in the high-frequency band related to the second-mode instability and its higher harmonics.

The experimental model is shown in Fig. 2. It is a stainless steel plate with a nominally sharp leading edge. The plate has a length of 350 mm, width of 200 mm, and thickness of 15 mm. The side and leading edges are beveled from below with the angle of 30 deg for the side edges and 20 deg for the leading edge. The plate is polished to the nominal surface finish 0.8 micron. The region of grooved wavy surface comprises nine round arc cavities. Deviations of the actual arc
μ is calculated using Sutherland
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dimensionless conservative form of these equations written in
(stagnation temperature
and grooved regions of the model are performed simultaneously.
relative error of 10%. During each run, the measurements on the flat
the surface shape. Downstream from the wavy region, the fluctuations
These sensors have a diameter of 3 mm and a frequency band from
11 kHz to 1 MHz. They are small in size, and they weakly influence
(high-frequency integrated circuit-piezoelectric (ICP) pressure sensors
model has several technological holes for the sensors: 12 holes of
52 mm, and 2 holes of 3.2 mm diameter for the pressure sensors (Fig. 2).
Disturbances in the wavy surface region are measured by the
Disturbances are measured by the fast-response heat-flux ALTP sensors with
relative error of 10%. During each run, the measurements on the flat
and grooved regions of the model are performed simultaneously.
B. Numerical Problem

The computations are carried out at the freestream conditions
(corresponding to the shock tunnel run 579, which represents the
WWS effect in a full manner. These conditions are: Mach number
M∞ = 6.0, unit Reynolds number Re∞ = 10.5 × 106 m−1 (stagnation pressure p0 = 7.0 × 105 Pa), and temperature T∞ = 43.18 K
(stagnation temperature T0 = 354.06 K). The wall is isothermal with
temperature T∞ = 293 K.

The Navier–Stokes partial-differential equations for 2-D viscous
compressible unsteady flows are solved numerically. We use the
dimensionless conservative form of these equations written in
curvilinear coordinates. Curvilinear coordinate system acts as
computational space, where a grid is formed uniformly in all directions.

The fluid is assumed to be a perfect gas with specific heat ratio
γ = 1.4 and Prandtl number Pr = 0.72 (air). The dynamic viscosity
μ is calculated using Sutherland’s formula \( \mu = \mu_\infty T^{3/2}(S + 1)/ (\delta + T) \), where \( T/T_\infty \) is the dimensionless temperature, and
S = 110 [K]/T_\infty. The second viscosity is assumed to be zero.

The Navier–Stokes equations are integrated using the in-house
solver HSFlow, which implements an implicit finite-volume shock-
capturing method with the second-order approximation in space and
time. A Godunov-type scheme [17] with a Roe approximate Riemann
solver is used. Reconstruction of dependent variables at the grid cell
boundaries is performed using the weighted essentially non-
oscillatory (WENO) approach. The system of nonlinear algebraic
equations (which approximate partial differential equations) is solved using
the Newton iteration method. At every iteration step, the corresponding linear algebraic system is solved using the generalized
minimal residual (GMRes) method.

This approach is most efficient if the computational domain
contains shock waves and other strong spatial inhomogeneities of the
flow such as boundary-layer separations. Using the HSFlow solver, it
was feasible to perform numerical simulations of boundary-layer
receptivity [18] and stability [17], including configurations with
separation bubbles [11], as well as the laminar flow control using
porous coatings [19]. Note that these simulations were carried out
with the help of the total variation diminishing scheme, which is
rather dissipative. To reduce the dissipative effects and improve
accuracy, the WENO scheme is used herein.

The computations are carried out for the flow over a grooved wavy
plate with nine cavities. The surface shape corresponds to the model
and is shown in Fig. 3. Namely, each cavity has a form of round arc
given by the following formula:

\[
y(x) = \sqrt{R^2 - (x - x_0 - l/2)^2} - R
\]

\[
R = \frac{h}{2} + \frac{l^2}{8h}, \quad x_e < x < x_c
\]

where \( l = 12 \) mm, and \( h = 1.8 \) mm. Dimensions for the first cavity
are \( x_0 = 46 \) mm, \( x_e = 52 \) mm, and \( x_c = 58 \) mm; for the second
one, \( x_0 = x_e = 58 \) mm, \( x_c = 70 \) mm, and so on. The depth \( h = 1.8 \) mm is approximately equal to the boundary-layer thickness
\( \delta \) (for the flat-plate case \( \delta \approx 2.1 \) mm at \( x = 100 \) mm). Preliminary
parametric studies showed that the cavities of these sizes provide
gentle reattachment and separation of the shear layer on the top of
each bump.

The length of the computational domain is 200 mm, which is less
than the experimental model length (350 mm) to save grid nodes. The
computations are performed on a structured curved orthogonal grid
with 3001 × 401 nodes in a single block. The mesh is generated using
Numerical conformal mapping of a rectangle onto the computational domain. The mapping method is described in [20] and is implemented in the third-party open-source tool. It generates a grid that fits well to the surface shape and has low cell skewness (Fig. 4). The grid is clustered near the surface so that approximately 200 grid lines are within the boundary layer or in the separation region with the mixing layer.

Several computations were also performed on 6001 × 401 and 3001 × 801 grids to verify convergence. The discrepancy in disturbance amplitudes was less than 0.97%.

The numerical problem is solved in two steps. First, a steady laminar flowfield is computed using a time-dependent method. Then, unsteady disturbances are introduced by a local periodic suction–blowing on the plate surface. This is made via the boundary condition for the mass-flow perturbation:

\[
\tilde{q}_w(x, t) = \varepsilon \sin\left(2\pi \frac{x - x_1}{x_2 - x_1}\right) \sin(2\pi f t), \quad x_1 \leq x \leq x_2
\]

where \(\tilde{q}_w = \rho_w v_w / (\rho_{\infty} U_{\infty})\) is dimensionless mass-flow in the normal wall direction (\(\rho\) is density, \(v\) is vertical velocity component), and \(x_1 = 10\) mm and \(x_2 = 15\) mm are boundaries of the suction–blowing region.

The calculations are conducted at 17 forcing frequencies from \(f = 88.28\) kHz to \(f = 176.58\) kHz that correspond to the frequency parameters \(F = 2\pi f / \text{Re}_{\lambda w}\) from \(0.6667 \times 10^{-4}\) to \(1.333 \times 10^{-4}\), where \(f = \lambda / U_{\infty}\) is dimensionless frequency. This range was identified using the experimental spectra. To ensure the linear evolution of excited disturbances in front of the wavy region, we chose a small forcing amplitude \(\varepsilon = 10^{-3}\).

### III. Results

#### A. Experimental Results

Figure 5 shows the pulsation spectra measured by the ICP sensors on the wavy and flat surfaces. On the flat surface (black lines), a peak with central frequency \(f \approx 170\) kHz is related to the second-mode instability. On the wavy surface (gray lines), this peak is shifted to the lower central frequency \(f \approx 135\) kHz and has essentially a smaller level, indicating that the wavy wall stabilizes the second-mode waves. Figures 6 and 7 show the spectra of wall heat-flux fluctuations, which were measured using the ALTP sensors located downstream from the wavy region (see Fig. 2). These spectra also clearly show damping of the second-mode waves.

The ICP spectrum (Fig. 5) has a new peak around the frequency \(f \approx 75\) kHz. With available experimental data, we can only speculate on the physical nature of this peak. The wavy surface induces a steady perturbation, which leads to modulation of the flow disturbances propagating in the near-wall region. With the assumption that the disturbance speed is close to the speed \(U_{\lambda}\) of the outer mean flow, this modulation should give a spectral peak at the frequency \(f \approx U_{\lambda}/\lambda \approx 78\) kHz, where \(\lambda\) is the wavelength of the wavy surface. This estimate correlates well with the experimental data. Such a modulation should vanish downstream from the wavy region. Indeed, Fig. 7 shows that the ALTP 1 spectrum just behind the wavy surface (solid blue line) has a low-frequency peak of much smaller amplitude. Further downstream (see the ALTP 2 spectrum shown by the dashed blue line), the peak is not observed. This allows us to assume that the

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**Fig. 4** Fragment of the computational grid; the bold black curve is the model shape.

**Fig. 5** Spectra of pressure pulsations on the model wall; disturbances are measured using an ICP sensor in the wavy region: \(\text{Re}_{\lambda w} = 15.41 \times 10^6 \text{ m}^{-1}\) (run 583: \(\rho_0 = 10.188 \times 10^3\) Pa, \(T_0 = 352.35\) K) and \(\text{Re}_{\lambda w} = 12.67 \times 10^6 \text{ m}^{-1}\) (run 584: \(\rho_0 = 8.3902 \times 10^3\) Pa, \(T_0 = 352.70\) K).

**Fig. 6** Spectra of heat-flux fluctuations on the wall measured by ALTP sensors: high freestream Reynolds numbers \(\text{Re}_{\lambda w} = 12.25 \times 10^6 \text{ m}^{-1}\) (run 581: \(\rho_0 = 8.3547 \times 10^3\) Pa, \(T_0 = 358.73\) K) and \(\text{Re}_{\lambda w} = 12.16 \times 10^6 \text{ m}^{-1}\) (run 505: \(\rho_0 = 8.5124 \times 10^3\) Pa, \(T_0 = 364.19\) K).

**Fig. 7** Spectra of heat-flux fluctuations on the wall measured by ALTP sensors: low freestream Reynolds numbers \(\text{Re}_{\lambda w} = 10.50 \times 10^6 \text{ m}^{-1}\) (run 579: \(\rho_0 = 7.0 \times 10^3\) Pa, \(T_0 = 354.06\) K) and \(\text{Re}_{\lambda w} = 10.14 \times 10^6 \text{ m}^{-1}\) (run 507: \(\rho_0 = 7.0338 \times 10^3\) Pa, \(T_0 = 362.27\) K).
low-frequency peak is associated with the modulation of disturbance field, and it does not represent a new instability.

In the location ALTP 5 (far downstream from the wavy region), the spectra on both halves of the model resemble turbulent spectra. Unfortunately, these data do not provide information of the transition location. Additional experiments are needed to clarify the wavy-wall effect on the transition locations.

B. Numerical Results

The computed steady-flow Mach-number field over a grooved plate is shown in Fig. 8. The viscous-inviscid interaction leads to formation of a weak shock wave in the leading-edge vicinity. Further downstream, the cavities induce oblique shocklets emanating from the reattachment regions on the bump tops. Figure 9 shows flow recirculation inside the cavities (dark regions) as well as a weakly perturbed shear layer (light gray strip), which smoothly bridges the neighboring cavities.

The upper boundary of each separation region 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 flat-plate case.

The wave (pressure) drag coefficient on the wavy wall is
\[
\frac{c_{D_P}}{\rho U_\infty^2} = 4.04 \times 10^{-4},
\]
which is greater than zero for the flat wall. However, the wavy wall leads to the reduction of friction drag from
\[
\frac{c_{D_f}}{\rho U_\infty^2} = 9.53 \times 10^{-4},
\]
and the total drag is relatively small (\(c_{D_T} = 1.97 \times 10^{-4}\)). The heat flux to the grooved wavy surface is close to that in the flat-plate case. As shown in Fig. 10, the cavities cause relatively small periodic heat-flux perturbations without average overheating.

Thus, the wavy surface weakly affects the global flowfield over the boundary layer. At the same time, this surface produces a mixing layer that bridges the cavities and resembles a free shear layer with almost parallel edges.

Analysis of the numerical unsteady solution is done using the instantaneous disturbance fields. They are obtained as the difference between a disturbed flowfield at some instant and a steady-state field (the initial field before introduced forcing), i.e., the disturbance of a certain value \(\phi(x, y)\) is calculated as
\[
\Delta \phi(x, y) = \phi(x, y) - \phi_{0}(x, y).
\]

At first, the disturbance fields were computed for the flat plate at different forcing frequencies from \(f = 88.3\) to 176.6 kHz. It was found that the suction–blowing actuator predominantly excites acoustic waves in the shock-layer region and the second-mode waves in the boundary layer, e.g., Fig. 11 shows the instantaneous disturbance field of the pressure coefficient
\[
\frac{c_p}{\rho U_\infty^2} = \frac{p-p_{\infty}}{\rho U_\infty^2}
\]
at the forcing frequency 138.74 kHz. The cell-type structures in the outer flow behind the actuator correspond to the interference between the rear and fore fronts of acoustic waves. The rear fronts are related to the slow acoustic waves and the fore fronts to the fast acoustic waves. For \(x > 80\) mm, the disturbance in the boundary layer corresponds to the second-mode wave. This wave propagates downstream with the phase speed, which is slightly smaller than the mean-flow velocity at the upper boundary-layer edge; its amplitude grows downstream, its wavelength is \(\approx 2\delta\), and it induces two-cell structures of the pressure-disturbance field.
locations of ICP, ALTP 1, and ALTP 2 sensors (Fig. 2).

The region of its instability agrees with that predicted by the linear stability theory for the second mode [21].

In the case of the wavy plate (Fig. 12), the acoustic disturbances in the shock layer (above the mixing layer and behind the bow shock) behave similar to the flat-plate case, because the upper boundary of the mixing layer is weakly affected by the separation bubbles within the cavities. In the near-wall region, evolution of disturbances is completely different. The disturbances interact with the shocklets induced by the surface bumps and with the cavity flows. Although the fine structure of the disturbance field is rather complicated, there is no evidence of local amplification of the disturbance amplitude, which could be caused by these interactions.

Figure 13 shows the streamwise distributions of the pressure coefficient disturbance on the wall. In the flat-plate case (black line), the second mode amplitudes starting from $x \approx 80$ mm and reaches its maximum amplitude at $x \approx 150$ mm. In the wavy-plate case (gray line), the disturbance growth is reduced. The wall-pressure amplitude is modulated versus $x$ with the period of wall wavinss. As shown in Fig. 14, this damping is not instantaneous but persists with time.

By processing the time dependencies of the wall-pressure disturbances (such as those shown in Fig. 14) for every forcing frequency, we obtained asymptotic values for the disturbance amplitudes in the $x$ station related to the ALTP 1 coordinate. These amplitudes form the spectra $\Delta p_{\text{w}} = f n(f)$ shown in the upper panel of Fig. 15. For comparison, the lower panel shows the spectra that were measured using the ALTP 1 sensor located just downstream from the wavy region.

Both DNS and the experiment show reduction of the maximal amplitude that qualitatively confirms the WWS concept. Nevertheless, there are essential differences. In the experiment, the wavy wall shifts the second-mode peak to lower frequencies and causes a massive reduction of high-frequency disturbances. In the DNS, the peak is not shifted, and high-frequency disturbances are weakly affected. The relative reduction of the peak maximum is about 50% in the experiment, whereas it is about 35% in DNS. Furthermore, the peak central frequency predicted by DNS ($f \approx 129$ kHz for a flat plate) is lower than in the experiment ($f \approx 143$ kHz). Presumably, these discrepancies are due to the differences in the external forcing and receptivity mechanisms. In the DNS, the disturbances of all frequencies are excited by the 2-D suction–blowing actuator, which is located at a fixed $x$ station and has the same shape and amplitude. In the experiment, the second-mode waves are predominantly excited by 3-D acoustic disturbances, which have nonuniform distributions of their amplitude versus frequency and wave-front angles. Furthermore, receptivity to acoustic disturbances may be nonuniform versus $x$, which also affects the shape and locus of the second-mode peak observed in the final $x$-station.

It should be noted that the damping effect was not observed in the case of the rounded compression corner [11], where the separation bubble was much longer. This can be explained by comparisons of the pressure disturbance fields inside the separation bubble. In the compression corner, a waveguide is formed within a long separation zone, and acoustic waves of appreciable amplitudes are excited via the resonance mechanism. These acoustic waves effectively generate the boundary-layer disturbances growing downstream from the reattachment point. For the configuration considered herein, the separation bubbles are relatively short, which prevents the resonant excitation of acoustic disturbances within cavities. Furthermore, the boundary-layer reattachments on the groove tops are gentle and relatively short, which also prevents the intensive second-mode growth in these regions.

![Fig. 12](image1.png) Disturbance field of pressure coefficient at $t = 0.315$ ms for forcing of $f = 138.74$ kHz: $Re_{1\text{w}} = 10.50 \times 10^6$ m$^{-1}$, wavy surface. Triangles show locations of ICP, ALTP 1, and ALTP 2 sensors (Fig. 2).

![Fig. 13](image2.png) Disturbances of the calculated pressure coefficient along the wall at $t = 0.315$ ms for forcing of $f = 138.74$ kHz: $Re_{1\text{w}} = 10.50 \times 10^6$ m$^{-1}$; boundaries of the wavy region (1), and locations of the sensors ICP, ALTP 1, and ALTP 2 (2).

![Fig. 14](image3.png) Time dependency of the calculated disturbance amplitudes of pressure coefficient on the wall at $x = 165$ mm (ALTP 1 sensor location) for forcing of $f = 126.13$ kHz (left) and of $f = 151.35$ kHz (right): $Re_{1\text{w}} = 10.50 \times 10^6$ m$^{-1}$.
the help of integrated circuit-piezoelectric and atomic-layer thermopile sensors. The experimental results qualitatively agree with the direct-numerical-simulation predictions. Namely, it was found that the wavy wall leads to significant reduction of the spectral peak associated with the second-mode instability. However, a marginal increase of the disturbance amplitude is observed in the low-frequency band (80 < f < 100 kHz). Presumably this peak is associated with the modulation of the disturbance field produced by the wavy surface, and it does not represent a new instability. The nature of this peak as well as its relevance to transition should be clarified by further experimental studies. It is also important to test the wavy surface under quiet freestream conditions typical for actual flights.

These findings encourage us to continue the experimental and numerical studies of stability and transition on wavy surfaces. In particular, it is important to investigate the wavy-wall effect on the transition locus. Also, it is desirable to estimate the range of freestream parameters (Reynolds number and Mach number), where the wavy surface of fixed sizes affects the boundary layer instability. Besides the laminar flow-control issue, these studies could be useful for predictions of transition on naturally occurring wavy surfaces associated with bowed panels of thermal protection systems.

IV. Conclusions

The stability of a supersonic near-wall flow over a plate with a wavy surface has been investigated by means of numerical simulations and wind-tunnel experiments for the freestream Mach number 6.

Parametric numerical studies showed that it is feasible to design a wavy surface that maintains an almost parallel mixing layer, bridging the neighboring cavities with gentle separations and reattachments on the groove tops. Such a wavy surface slightly perturbs the outer flow while producing dramatic changes of the near-wall flow. Because the free shear layer is more stable than the boundary layer, the wavy wall may reduce the disturbance growth and, ultimately, increase the laminar run. This concept was partially confirmed by two-dimensional numerical simulations. It was shown that the second-mode instability is damped by the wavy surface in the frequency band from 110 to 150 kHz, while there is increase of the disturbance amplitude for frequencies less than 110 kHz.

The flat-plate model, with the grooved region comprising nine shallow cavities, has been designed and tested in the conventional shock tunnel Tranzit-M of the Institute of Theoretical and Applied Mechanics. Measurements of the wall-pressure and wall heat-flux fluctuation spectra were carried out on the flat and wavy surfaces with the help of integrated circuit-piezoelectric and atomic-layer thermopile sensors. The experimental results qualitatively agree with the direct-numerical-simulation predictions. Namely, it was found that the wavy wall leads to significant reduction of the spectral peak associated with the second-mode instability. However, a marginal increase of the disturbance amplitude is observed in the low-frequency band (80 < f < 100 kHz). Presumably this peak is associated with the modulation of the disturbance field produced by the wavy surface, and it does not represent a new instability. The nature of this peak as well as its relevance to transition should be clarified by further experimental studies. It is also important to test the wavy surface under quiet freestream conditions typical for actual flights.

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