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NUMERICAL INVESTIGATION OF THE EFFECT OF A RECESS ON THE CHARACTERISTICS OF A PULSATING GAS FLOW

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A supersonic flow past a recess with pressure fluctuations in the separation zone is simulated numerically. The effect of the gasdynamic and geometric parameters determining the flow in the recess on the character of the pressure fuctuations is studied. Different shapes of the recess are considered. To simulate flow in the recess kinetically consistent difference schemes that have proved themselves good in describing complex flows are used. Obtained results of numerical calculations are compared with experimental data.

Introduction. A rather large number of papers have been devoted to the study of unsteady flows in recesses. In [1, 2] an unsteady flow structure was revealed by shadowgraphs. Empirical methods allowing one to calculate frequencies of pressure fluctuations are suggested in [1-5]. However, the empirical methods mentioned do not make it possible to obtain the values of the fluctuation amplitudes or to determine characteristics of an unsteady flow field at every instant of interest. A complete flow pattern can be obtained only by numerical simulation of this problem. In [6-9] complete nonstationary Navier–Stokes equations closed by different models of eddy viscosity, namely, Cebeci–Smith [7], Baldwin–Lomax [8, 10], $k-\varepsilon$ model [9], are solved. In [10] Navier–Stokes equations are solved in a thin-layer approximation. Works [8, 9] are carried out for the same flow parameters but using different models of eddy viscosity in two-dimensional [9] and three-dimensional [8] formulations. Comparison of the obtained computational values in [8] and [9] showed that the pulsating flow is basically two-dimensional. Calculations of [7-9] give rather accurate values of fluctuation frequencies, mean static pressure, and total level of acoustic pressure. However, overestimation of the amplitudes of the pressure fluctuations compared to experiment is noted in all the papers. In the aforementioned computational works the authors succeeded in reproducing the unsteady flow pattern for turbulence. It was emphasized in [7] and [8] that when the turbulence model is not employed, i.e., a laminar flow is modeled by the same difference algorithms, fluctuations do not arise in the calculations. This means that only the mechanism of onset of pressure fluctuations that is associated with small-scale turbulence of the incident flow is considered in these works. The authors did not succeed in obtaining pressure fluctuations in a laminar flow in this case.

Moreover, it should be noted that the aforementioned numerical investigations were conducted for supersonic flows that are realized near rectangular recesses. The effect of the recess shape on the characteristics of the pressure fluctuations was not analyzed.

This work is a continuation of numerical investigations of unsteady supersonic flows [11, 12] and is concerned with the study of a laminar supersonic viscous gas flow past recesses of different shapes in the presence of strong resonance pressure fluctuations. The mechanism of formation and the main sources of the pressure fluctuations are considered numerically. Much attention is paid to analysis of the effect of geometric and gasdynamic parameters on the character and quantitative characteristics of the flow.

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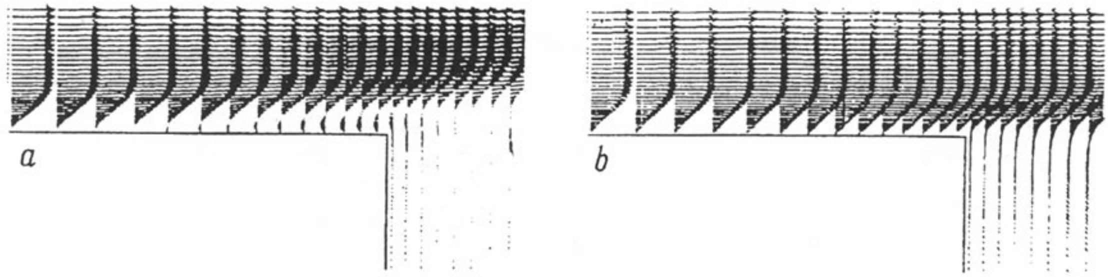


Fig. 1. Process of separation-zone formation on the leading edge of the recess.

For the calculations we used kinetically consistent difference schemes (KCDS) obtained in [13] and successfully employed to numerically simulate unsteady viscous compressible gas flows. These schemes can be treated as ones for Navier–Stokes equations for a specially constructed artificial viscosity.

1. Physics of the Onset of Pressure Fluctuations in Open Cavities. For certain gasdynamic and geometric parameters a flow past a recess is an example of unsteady separating flow. The interaction between the mixing layer and the outer flow creates a periodic supply of mass to the recess and removal of mass from it near its rear wall. At the moment when the point of attachment of the mixing layer shifts below the rear edge, mass is supplied to the recess and a pressure wave originates that propagates upstream. Precisely the interaction between the shear layer and the outer flow causes the onset of flow pulsations.

It should be noted that experimental data indicate different characters of the mechanism of the onset of pressure fluctuations.

When the flow past the recess is turbulent, the mechanism of the onset of discrete components in the range of pressure fluctuations is caused by the development of large-scale coherent structures in the turbulent mixing layer and the presence of feedback between the source of the oscillations and the site of formation of large-scale vortices [4]. As is shown by experiment [1, 5], maximum pressure fluctuations originate in the vicinity of the points of separation and attachment of the boundary layer. In the first case pressure fluctuations are excited by the near-wall turbulent boundary layer, in the second case they are caused by the turbulent mixing layer interacting with the surface.

In a laminar flow the onset of resonance pressure fluctuations caused by the interaction between the shear layer and the outer flow is also observed, but the mechanism of the onset of fluctuations in this case is different because a laminar boundary layer, in contrast to a turbulent one, does not generate vortical structures. In a laminar flow the critical pressure drop that may cause boundary-layer separation in the vicinity of the front corner of the cavity is rather small. Therefore, when a compression wave approaches the leading edge of the recess a pressure drop exceeding the critical one is created and microseparation of the boundary layer occurs in front of the recess.

The flow in this separation zone is determined by a pressure wave (generated during interaction between the mixing layer and the rear edge of the recess), and it first reaches maximum and then decreases. In accordance with this the zone of the separating flow first increases and then contracts and disappears. A shock wave that moves simultaneously with the increase and decrease of the separation zone is formed in front of it. When this zone disappears in front of the recess, the shock wave is stalled by the flow [1].

The numerical technique used in this work made it possible to reproduce the described mechanism of onset of pressure fluctuations in a laminar flow past a recess. The computational algorithm and results of numerical simulation of the flow are given in [11] for a two-dimensional recess and in [12] for a three-dimensional geometry.

The process of separation-zone formation in front of the leading edge of a recess is given in Fig. 1, where two typical instants of time are presented (one in the instance of a maximum separation zone (Fig. 1a), the other in the instance of its complete degeneration (Fig. 1b)).

2. Results of Numerical Experiments. We used experimental data given in [1]. The experiments were conducted in wind tunnels and anaeroballistic duct. In the latter, shadow pictures of the flow field around the model were taken at nine points of the trajectory with an exposure of 10^{-7} sec, and in the wind tunnels shadow pictures with a magnification of about 6 were taken with an exposure of $\sim 10^{6}$ sec. In the tunnels pressure fluctuations were

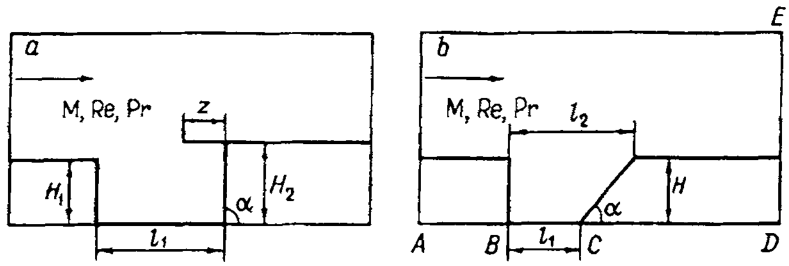


Fig. 2. Schematic diagram of the computational region: a) two-dimensional recess with a lid; b) the same with an inclined wall.

measured by miniature microphones, and high-speed shooting (250–500 thousand frames per second) was performed that allowed determination of the velocity of perturbation propagation with an error of about 15%; the error of measurement of pressure fluctuation levels was 2–3 dB.

The experimental investigations of [1] showed that a change in the recess shape exerts a strong effect on the basic spectral characteristics of the pulsating flow. Thus, the value of the pressure fluctuations is maximum for $\alpha = 90^{\circ}$ (Fig. 2a) and decreases as α deviates from 90° (Fig. 2b). This can be explained by the fact that as α decreases, the intensity of the shock wave in the vicinity of the rear wall falls. Moreover, the mixing layer that passed through the shock wave interacts with the rear wall at an angle $\alpha < 90^{\circ}$. These effects lead to a reduction in the pressure fluctuation level.

Recess with a shield. The effect of a shield of different lengths (Z), placed on the rear wall of the cavity, and the height of this wall H_2 on the characteristics of the pulsating flow in the recess was studied (Fig. 2a).

The gasdynamic parameters are the Mach number in the outer flow $M_\infty = 1.35$, 2.1, 2.9, the Reynolds number calculated from the incident-flow parameters and the recess depth $Re_{H_1} = 3.3 \cdot 10^4$, and the relative boundary-layer thickness in front of the recess $\delta/H_1 = 0.041$. The geometric characteristics of the recess are $l/H_1 = 2{:}1$ and the shield length Z/H_1 varying from 0.25 to 0.5.

A change in the recess shape can cause a decrease or increase in the reduced spectral level of the pressure fluctuations L at different points on the cavity surface; this level characterizes the fluctuations in decibels (db) and is calculated by the formula

$$L = 20 \log_{10} \left(\frac{\sigma_{1\text{Hz}}}{\sigma_0} \frac{p_{\text{st}}}{p_\infty} \right), \tag{1}$$

where $\sigma_0 = 2 \cdot 10^{-5}$ Pa is the audibility threshold; $p_{\text{st}} = 101.325$ kPa.

We consider the region in the vicinity of the upper corner of the recess rear wall. In interacting with the rear wall the mixing layer causes intense acoustic perturbations. In the vicinity of the corner the strongest interaction occurs and maximum level of fluctuations is attained.

Figure 3 presents graphs of spectra of frequencies of pressure fluctuations at the point on the corner of the rear wall in a flow past a simple rectangular recess and a recess with a shield of length $Z/H_1 = 1/4$ on the upper right-angle corner. The amplitudes of the harmonics calculated by Eq. (1) are laid on the ordinate. It is seen from the graphs that for the recess with the shield the pattern of fluctuations is more complex and additional harmonics appear. We note that for the simple recess the amplitudes of the discrete components of the fluctuation spectrum are much greater and the noise level along the entire spectrum of fluctuations is also higher. The presence of new harmonics is caused by acoustic perturbations that are generated in interaction between the mixing layer and the shield. We also note that installation of the shield exerts a weak effect on the frequencies of the fundamental harmonics. When the height of the recess rear wall is increased by 10% (in the previous calculations $H_2 = H_1 = 1$), the intensity of the fluctuations also grows and their character becomes more complicated.

The distribution of the reduced total level of acoustic pressure L_Σ over the recess bottom for the simple cavity and the cavity with the shield is given in Fig. 4. L_Σ is calculated by the formula

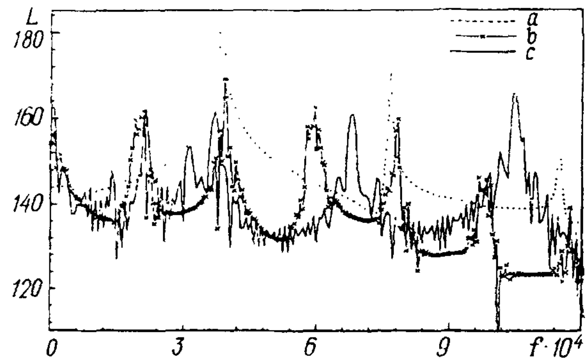


Fig. 3. Comparison of frequency spectra for recesses of different shapes (M_∞ = 1.35, l = 2.1): a, b) for recesses without and with a shield with Z/H_1 = 1/4; c) for a recess with walls of different heights H_2/H_1 = 1.1. L, dB; f, Hz.

$$L_\Sigma = 20 \log_{10} \left(\frac{\sigma_\Sigma}{\sigma_0} \frac{p_{st}}{p_\infty} \right); \quad \sigma_\Sigma^2 = \overline{p'^2} = \left(\frac{1}{t_f - t_i} \right) \int_{t_i}^{t_f} (p - \bar{p})^2 \, dt, \quad \bar{p} = \left(\frac{1}{t_f - t_i} \right) \int_{t_i}^{t_f} p dt. \tag{2}$$

We note that in Eq. (2), in contrast to Eq. (1), $\sigma_{1\mathrm{Hz}}$ is replaced by the root-mean-square value of the amplitudes of the pressure fluctuations σ_Σ, which characterizes the energy of the oscillatory process as a whole ($\bar{p}$ is the mean pressure). As the shield length increases, the energy of the pressure fluctuations decreases.

Physically the process of pressure-fluctuation excitation in the presence of the shield consists in the following. The flow pulsations depend on the acoustic perturbations that arise in the interaction between the mixing layer and the recess rear wall [4]. The intensity of the shock wave near the rear wall in the case of the recess with the shield is smaller than for the simple rectangular recess. Moreover, due to the presence of the shield the mixing layer is divided to two parts, with the lower one moving under the lid and interacting with the recess rear wall. An increase in the shield length leads to attenuation of the interaction between the mixing layer and the cavity rear wall, a reduction in the velocity and, as a result, a drop in the velocity head $q = \rho u^2$ in the flow under the shield. Since $\sigma_\Sigma \sim q$, the pressure fluctuations become weaker. An increase in the shield length will result in a reduction in the interaction between the mixing layer and the rear wall, and the intensity of the perturbations arising here becomes insufficient to generate flow pulsations.

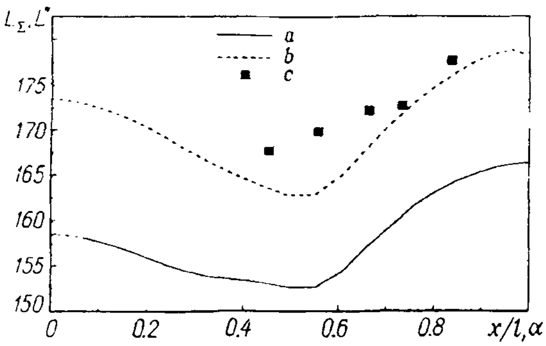
An increase in M_∞ from 2.1 to 2.9 leads to the following results. A steady flow is realized for the recess with the mounted shield, and for the simple recess at M_∞ = 2.1 the flow remains periodic, but the amplitude of the oscillations decreases. At M_∞ = 2.9 the flow is steady for both cases. These results of the numerical experiment agree with empirical techniques [4, 5], from which it follows that the maximum intensity of acoustic fluctuations is observed for $M_\infty \approx 1.0$, and when $M_\infty > 2.5$ fluctuations are not excited.

It was found in the calculations that for a longer shield Z/H_1 = 1/2 the fluctuations attenuate and the flow past the cavity becomes steady.

Thus, mounting of a shield on the cavity corner and a change in the height of the recess rear wall lead to a considerable decrease in the amplitudes and the total level of the acoustic pressure, thus making the overall pattern of the pulsating flow more complicated.

The results obtained agree with an experimental study of the flow past recesses of the same geometry [1].

Recess with an inclined wall. Experiments show that the conditions in the zone of mixing-layer attachment on the recess rear wall substantially affect the formation of a pulsating flow in the cavity. The angle of inclination of the recess rear wall α is one of the most important parameters determining the process of interaction between large-scale vortices and the wall. The intensity of the acoustic waves formed in the vicinity of the attachment point becomes weaker with decrease in α. If $\alpha < \alpha_{cr}$, the acoustic waves propagating inside the recess cease to generate large-scale vortical structures on the front wall of the cavity, and the flow becomes steady. According to experimental data [3], in the case of a turbulent flow at M_∞ = 2.1 and l_2/H = 2.1 (see Fig. 1b) $\alpha_{cr} = 45^\circ$. In the



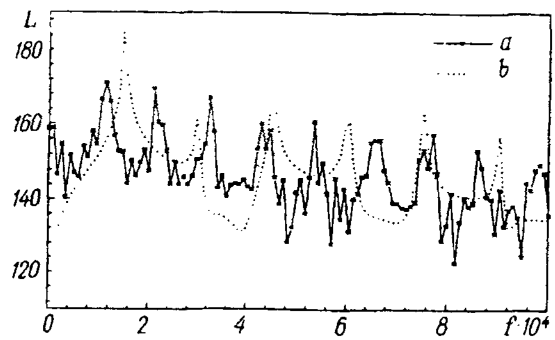


Fig. 4. Distribution of the reduced total level of the acoustic pressure L_Σ over the recess bottom [a) with a shield, b) rectangular] and dependence of the maximum level of fluctuations of the discrete fundamental harmonic L^* on the angle of inclination α of the recess rear wall (c), $l = 2.1$. α, rad.

Fig. 5. Comparison of frequency spectra for different angles of inclination of the recess rear wall: a) $\alpha = 32^\circ$; b) 48°. L, dB; f, Hz.

case of a flow past a recess of the same size at $M_\infty = 1.35$ the intensity of the pressure fluctuations is higher than in the case of $M_\infty = 2.1$, and α_{cr} can be expected to be smaller.

To study this phenomenon we simulated numerically an unsteady flow past a recess with an inclined wall for the following gasdynamic and geometric parameters: $M_\infty = 1.35$, $Re_{H_1} = 3.3 \cdot 10^4$, $\delta/H_1 = 0.041$, $l_2/H = 2.1$, $\alpha = 32-90^\circ$. We note that in this case l_2/H = const and the length of the cavity bottom $l_1/H \neq$ const (see Fig. 1b) for different angles of inclination α of the recess rear wall.

Figure 4 presents the dependence of the maximum level of the discrete fundamental harmonic L^* on the angle of inclination α of the rear wall (for recesses with a constant length l_2). A decrease in the angle of inclination of the rear wall results in a reduction in the maximum level of the discrete harmonic. It should be noted that the frequencies of the discrete harmonics virtually coincide for different angles of inclination, i.e., do not depend on α.

We now consider the case where the length of the recess bottom l_1 = const and the length of the recess itself l_2 changes with α. A change in the angle of inclination α of the rear wall changes the position of the additional imaginary sources of acoustic waves because in this case the recess length l_2 (for a constant bottom length) either increases or decreases. For certain positions these additional sources of oscillations can either enhance or weaken the resonance pressure fluctuations excited in the vicinity of the leading edge of the recess and, as a result, the intensity of large-scale vortices separating from the leading edge. Thus, the effect of the acoustic waves on the character of the pressure fluctuations is governed by the angle of inclination of the recess rear wall and can lead to the appearance of additional frequencies in the spectrum of pressure fluctuations. These additional frequencies characterize a different scale of vortices separating from the leading edge of the recess. To observe this effect in the numerical experiment the recess length l_2 was varied from 2.1 to 5.8 at a constant bottom length l_1 and an angle $\alpha = 15-90^\circ$.

When $\alpha = 32^\circ$ and $l_2 = 3.7$ (see Fig. 5), the spectrum becomes "wide-band," and additional frequencies appear in it. This frequency spectrum does not possess specific discrete components but has some features of the "white noise" spectrum. Such a frequency spectrum arises when vortex structures of different scales are present in the mixing layer. The formation of vortex structures of different scales occurs due to the fact that pressure fluctuations excited by different sources (real and imaginary) will interact with the recess rear wall in different phases. This phenomenon disappears at $\alpha = 48^\circ$ (Fig. 5). Obviously, in this case pressure fluctuations going from different sources to the recess corner occur coherently and generate vortex structures of a certain frequency. When $\alpha < \alpha_{cr}$ (in our case, when $\alpha < 15^\circ$), feedback between the recess leading edge and rear wall is interrupted due to very weak acoustic perturbations in the vicinity of the attachment point. This results in attenuation of the pressure fluctuations.

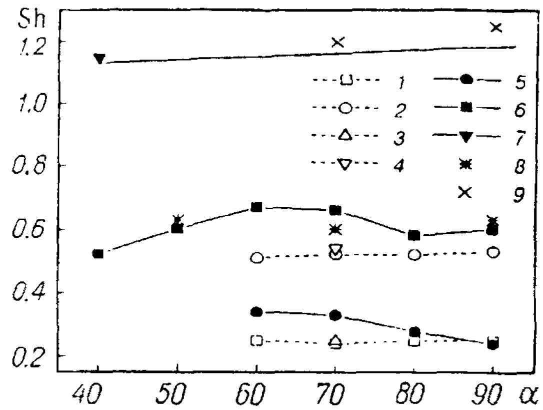


Fig. 6. Comparison of numerical and experimental results: 1, 2) experiment [3] (M = 2); 3, 4) calculation (M = 2); 5-7) experiment [3] (M = 1.5); 8, 9) calculation (M = 1.5).

It should be noted that the Strouhal numbers $Sh = fl_2/u_\infty$ for recesses of different lengths l_2 and $\alpha > 32^0$ have close values (for the discrete fundamental harmonic Sh = 0.63–0.707). This fact was also observed in experimental studies.

The real recesses whose experimental study is given in [1] are axisymmetric. A detailed comparison with experimental data (with respect to the frequencies of the fundamental harmonics) was conducted for a mathematical model that is more adequate for real applications. A supersonic laminar flow past axisymmetric free cavities with an inclined wall was considered in the $r-z$ geometry for the following gasdynamic and geometric parameters: $M_\infty = 1.5, 2.0, 2.5$; $Re_{H_1} = 2\cdot 10^4$; $\delta/H_1 = 0.053$; $L_2/H_1 = 2$; $\alpha = 40-90^0$. Correspondingly, the difference schemes (KCDS) used for the numerical calculations were written for the case of the $r-z$ geometry.

Figure 6 presents dependences of the Strouhal number (for the first and second oscillation modes; the data of the experiment 5-7 are for three oscillation modes) on the angle of inclination α obtained from experiment [3] (for similar parameters) and in the present work. As a whole, good agreement is observed between experimental and calculated data. It was noted above that Strouhal numbers for different angles of inclination of the recess rear wall have close values, which is seen in the graphs presented. We also note good agreement between frequencies obtained numerically and ones calculated by empirical techniques in [3].

Conclusion. This paper present results of numerical calculations of pulsating flows in the vicinity of recesses of different shapes. A detailed comparison is made between calculated Strouhal numbers and amplitudes of pressure fluctuations in the recess and experimental data. The effect of the angle of inclination of the recess rear wall on the character of the flow is studied. It is found that the oscillations decay with reduction of the angle of inclination of the rear wall to some critical value α_{cr}. The effect of shield erection on the recess rear wall on the development of the oscillation regime is studied. With the shield length exceeds half the cavity length, oscillations are not excited. The studied changes in the recess shape for which the level of the oscillations in the cavity decreases substantially can be regarded as a means for preventing unnecessary flow pulsations.

NOTATION

M_∞, Mach number of the incident flow; Re_{H_1}, Reynolds number calculated from the depth of the recess front wall and the incident-flow parameters; Pr, Prandtl number; Sh, Strouhal number; L, spectral level of the pressure fluctuations; σ_0, reference acoustic pressure; $\sigma_{1\,Hz}$, root-mean-square value of the amplitudes of the pressure fluctuations in a frequency band of 1 Hz; L_Σ, total level of the acoustic pressure; L^*, maximum level of the discrete components; p_∞, static pressure in the environment; p_{st}, standard atmospheric pressure; q, velocity head; l_1, recess bottom length; l_2, length of the line connecting the leading and rear edges of the recess; Z, shield length; H_1, H_2, height of the front and rear steps of the recess, respectively; α, angle of inclination of the recess rear wall; t, time. Subscripts: f, final value; i, initial value.

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