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# Numerical Simulation of Supersonic Free-Flow Stationary Disturbances Caused by Two-Dimensional Roughness in a Turbulent Boundary Layer

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Stationary disturbances in a free supersonic flow caused by two-dimensional roughness in a turbulent boundary layer on a wall were investigated using numerical simulation in the FlowVision software package. Calculations were performed for cases where the roughness heights were significantly smaller than the thickness of the boundary layer. In order to reduce the numerical oscillations, the computational grid has been adapted to the perturbation fronts by means. It was found that a disturbance in the form of a small amplitude N-wave is formed in the flow above the boundary layer. The effect of roughness height on disturbances formed in a free flow was studied. It was found that as the roughness height increases, there is an observed increase in the amplitude and spatial scale of the disturbance. It was also found that the gradient of the flow parameters between the disturbance fronts remains practically unchanged for all roughness heights considered. The numerical results were verified with experimental data. A strong agreement was achieved between the simulation and experimental result.

*Keywords: supersonic flow, turbulent boundary layer, two-dimension roughness, N-wave.*

## Introduction

The study focuses on investigating the impact of two-dimensional roughness on a wall in a turbulent boundary layer on stationary disturbances in a free supersonic flow above it. The case of a small roughness height compared to the thickness of the turbulent boundary layer is being considered. The relevance of this problem stems from the fact that roughness on the test section wall generates disturbances in the free flow during wind tunnel experiments [11]. These disturbances take the form of an N-wave, with weak shock waves forming at the fronts. When this disturbance impacts the leading edge of the model, significant distortions occur in both the mean flow and pulsation field within the laminar boundary layer on the model. Subsequently, it was experimentally shown that, in this case, the laminar-turbulent transition in the boundary layer can shift significantly upstream compared to the undisturbed case [9]. It has also been shown that the sensitivity of the boundary layer to such freestream disturbances depends on the bluntness of the leading edge [7], as well as its sweep angle [6].

In addition to experimental studies, the influence of free-stream disturbances from two-dimensional roughness on the wall of the test section on the flow in the boundary layer on the model is carried out using numerical simulation [2, 4, 5]. These works are focused on the influence of N-waves in the free stream on the boundary layer transition. The free-stream disturbance (N-wave) is specified using boundary conditions on the side boundary of the computational domain. This approach is described in detail, for example, in [3].

The influence of surface roughness on turbulent flow at supersonic speeds is studied in detail, for example, in [1, 8, 10]. However, they are primarily focused on studying the influence on the flow within the boundary layer, and the issues regarding the formation of disturbances in a free flow have not been sufficiently researched.

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The amplitude and spatial characteristics of free-stream disturbances can significantly impact the transition from laminar to turbulent flow in boundary layers. Therefore, it is necessary to develop a technique for predicting the amplitude and spatial characteristics of free flow disturbances based on the parameters of two-dimensional roughness located within the turbulent boundary layer on the wall of the wind tunnel's test section.

This paper presents the results of a numerical simulation that investigates the formation of stationary free flow disturbances caused by small two-dimensional roughness in a turbulent boundary layer on a wall. The simulation was conducted using the FlowVision software package. The influence of roughness height on the generation of stationary disturbances in a free flow at Mach number $M = 2$ is studied. Additionally, the results of the numerical simulation are validated using experimental data. The article is organized as follows. Section 1 is devoted to a description of the problem statement and the approaches used in this work. Section 2 presents the results of numerical studies. A comparison with experiments is also presented. Conclusion summarizes the study.

## 1. Simulation Set-Up

Figure 1 schematically shows the calculations set-up. In a turbulent boundary layer, a two-dimensional roughness of height $h$ is established that is significantly less than the thickness of the boundary layer $\delta$. A stationary disturbance is formed in a supersonic flow above the boundary layer.

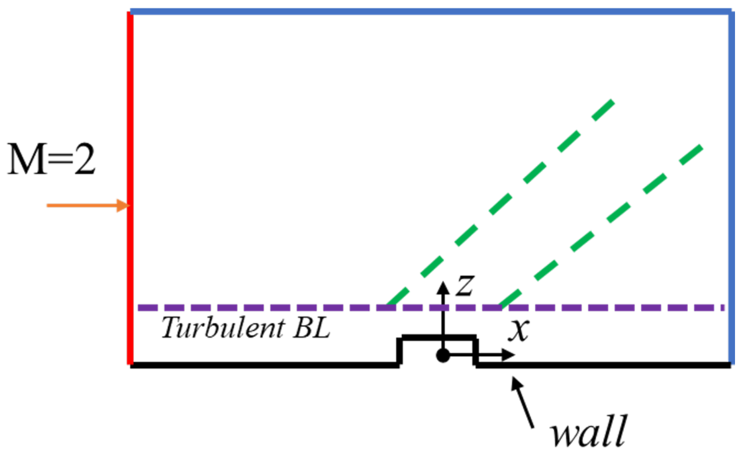



**Figure 1.** Computational domain

Numerical simulation was conducted using the FlowVision software package to study the formation of free flow disturbances caused by two-dimensional roughness on the wall. The flow is described within the framework of a continuum model for a compressible, viscous, and heat-conducting gas (air). Calculations were carried out in a two-dimensional formulation.

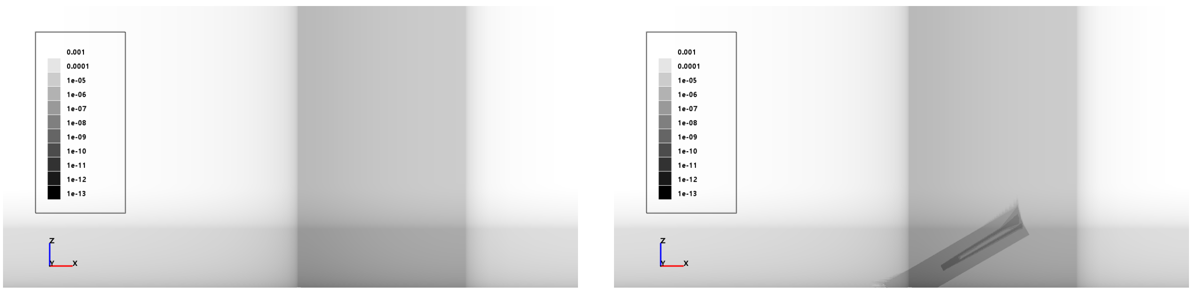
The entry condition was set at the left boundary of the computational domain. The flow parameters closely resemble those of the experiments conducted in the T-325 wind tunnel of the ITAM SB RAS at a Mach number of $M = 2$. The outlet condition was set at the upper and right boundaries. A zero temperature gradient was applied, and for velocities and pressure at the boundary, values equal to the value in the center of the boundary cell were set. This boundary condition is known as the supersonic outlet and is built into FlowVision. The wall and two-dimensional roughness were modeled using the no-slip boundary condition, as well as the zero heat flux condition.

To simulate the turbulent boundary layer on the wall, the SpalartAllmaras turbulence model was used. To achieve a developed boundary layer in the roughness region, the computational domain was extended longitudinally upstream. In the roughness region, the Reynolds number, calculated from the longitudinal coordinate, was $Re_x = 4 \cdot 10^6$, and the thickness of the boundary layer significantly exceeded the height of the studied roughness.

As it is known from experiments, in such a setting, a disturbance in the form of an N-wave of small amplitude is formed in the flow above the boundary layer. At the N-wave fronts, the flow parameters change abruptly. If the computational grid resolution is insufficient, significant numerical oscillations can form at the fronts, which can make it difficult to determine the position of the fronts and the amplitude of the disturbances.

To minimize the influence of numerical oscillations, the FlowVision tool is used in this work to adapt the computational grid. In the calculation process, the computational cells were divided to account for the propagation of disturbances in the free flow and two-dimensional roughness regions. The calculation scenario was as follows. At the start, uniform initial parameters were set in the computational domain. The initial mesh was condensed in the area of the wall and roughness. After the solution reached a constant value, the first adaptation was applied: according to the condition of the density gradient, the mesh was refined in the area of roughness and disturbance in the free flow. After stabilization of the solution, another adaptation was carried out. A total of four adaptations of the computational grid were carried out.

Figure 2a shows distribution of the cell volume of initial mesh, normalized to the volume of the computational domain. Figure 2b shows distribution for the final computational grid. It can be seen that in the region of propagation of the disturbance from roughness the best mesh resolution is observed. The final computational grid had approximately 11 million cells. In the roughness region, wall distance of the boundary cells $y^+ < 0.2$.



(a) Initial grid (b) Final grid

**Figure 2.** Distribution of cell volumes for the initial and final computational grids

Figure 3 shows distribution of pressure disturbances in the control section at various levels of adaptation of the computational grid. With the initial grid, the N-wave fronts are blurred. As the size of the cell decreases, the disturbance fronts become sharper, but numerical oscillations appear. With a further reduction in the size of calculation cells, the numerical oscillations decrease. In the final configuration, their amplitude is significantly smaller compared to the amplitude of the disturbance caused by roughness.

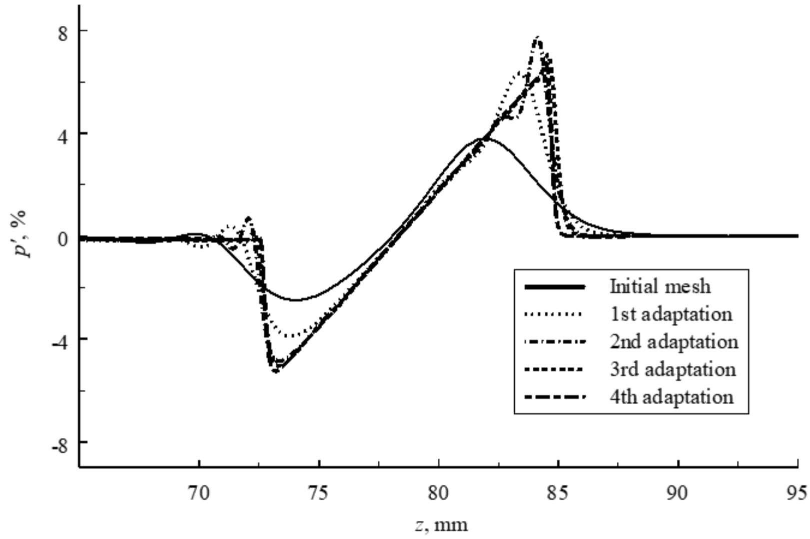



**Figure 3.** Pressure disturbance at different levels of computational grid adaptation

Calculations were performed using the FlowVision software package version 3.13.02 on a computing node equipped with two 64-core AMD EPYC 7763 processors and 512 GB of RAM. The calculation for each case took approximately 30 hours.

To analyze the results in this study, we examine the distributions of pressure disturbances in the flow along the normal to the wall coordinate $z$. These distributions were determined as follows:

$$P' = \frac{P - P_\infty}{P_\infty} \cdot 100\%, \qquad (1)$$

where $P_\infty$ is pressure in the undisturbed flow above the boundary layer. Mass flow disturbances $m'$ are determined similarly. The main analysis is carried out in a control section at a distance of 128 mm from the roughness.

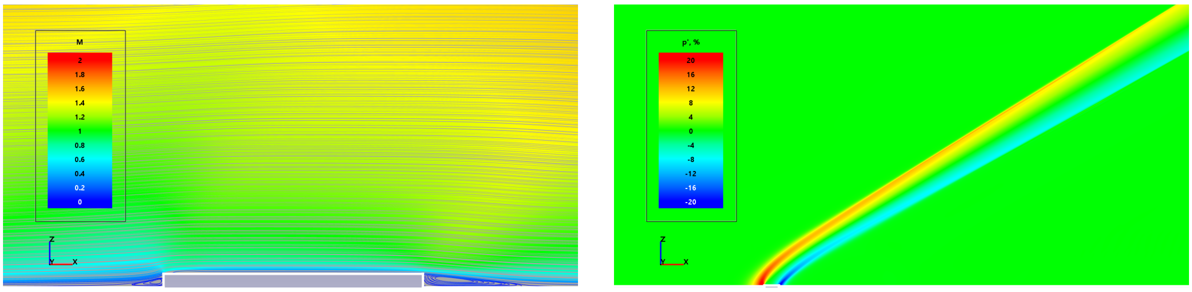
In this work, cases with different roughness sizes are considered: the length in the longitudinal direction of the roughness is constant in all cases and is equal to $0.23 \cdot \delta$, the height of the roughness is $h/\delta = 0.005$ (wall distance calculated for smooth surface $h^+ \approx 4$), 0.012 ($h^+ \approx 8$), 0.020 ($h^+ \approx 14$) and 0.034 ($h^+ \approx 24$). All calculations were carried out at the flow Mach number $M = 2$.

## 2. Results

In the described research setting, it is possible to consider the propagation of disturbances caused by roughness in a turbulent boundary layer, both in the free flow and within the boundary layer. Figure 4a shows the streamlines in the region of roughness. The color of the lines represents the Mach number. Figure 4b shows the distribution of pressure disturbances.

Calculations show that flow separation zones are formed in front of and behind the roughness. The pressure fields clearly show that the disturbance fronts bend inside the boundary layer. This must be taken into account when setting up experimental studies.

It is also clearly seen from the pressure disturbance fields that the amplitude of the disturbance generated by the roughness decays downstream. This is consistent with the results of [3],



(a) Streamlines in the roughness region (b) Distribution of pressure disturbances

**Figure 4.** Streamlines in the roughness region and the field of pressure disturbances.

in which the disturbance is specified by using boundary conditions. Moreover, our calculations show that the maximum pressure disturbance is observed within the boundary layer.

Calculation results for cases with varying roughness heights are presented in Fig. 5. The pressure disturbances of the free flow in the control section, located 128 mm downstream from the roughness, are shown.

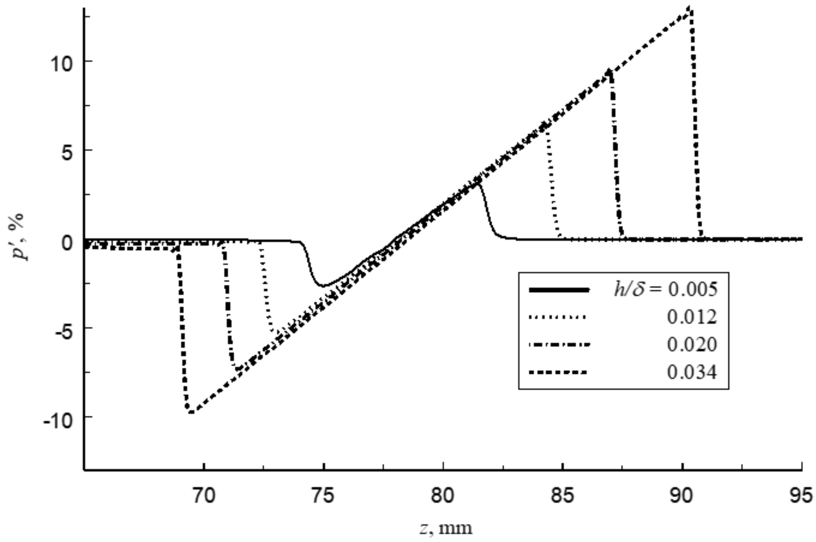



**Figure 5.** Free-flow pressure disturbances at various roughness heights

As the height of the roughness increases, there is an observed increase in the amplitude of the disturbance. At the same time, the spatial scale of the disturbed zone also increases, indicating a change in the angles of propagation of the disturbance fronts. The pressure gradient between the disturbance fronts remains practically unchanged in all cases.

The positions of the disturbance fronts in the flow differ significantly from the estimates made for Mach waves. Thus, if we consider the roughness edges as the source of Mach waves, their position in the control section should be at $z = 75.3$ and 73.9 mm. This differs significantly from the results of provided calculations that take into account the turbulent boundary layer.

It should also be noted that at the first front of the disturbance (which is fixed at large values of the $z$ coordinate), in all cases under consideration, the amplitude of changes in the flow parameters is approximately 1.3 times greater than at the trailing front of the disturbance.

Figure 6 shows a comparison between these calculations and the experimental results. The experiments were conducted in the T-325 wind tunnel at the ITAM SB RAS. A two-dimensional roughness was applied to the wall of the test section, and measurements were carried out using a constant temperature hot-wire anemometer. From the experimental data, the mass flow disturbance was determined. The mass flow rate was also determined using the numerical data for direct comparison. Figure 6 shows the perturbations of the mass flow $m'$ for two different heights of two-dimensional roughness.

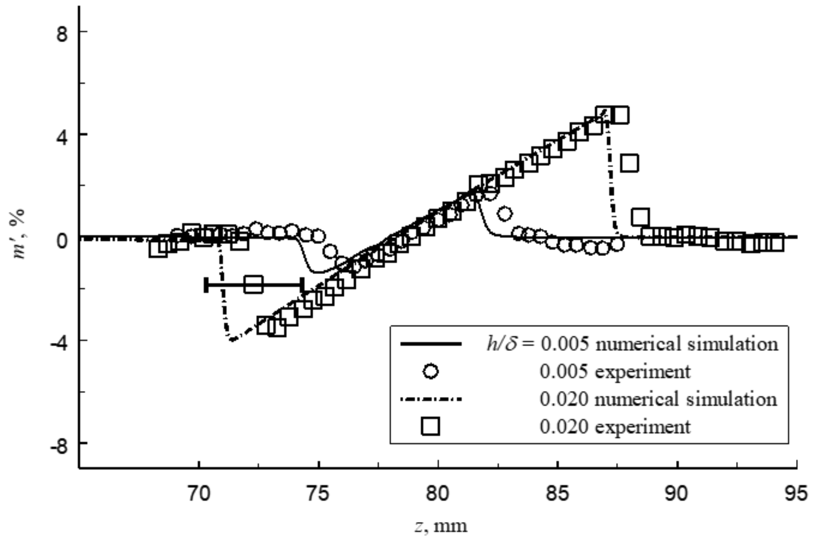



**Figure 6.** Comparison of numerical results and experimental data

The calculated data is in good agreement with the experimental results. The amplitude of disturbances, the gradient of mass flow between the disturbance fronts, and the spatial scales in calculations and experiments are similar. The differences in the spatial position of the disturbances are less than the error in determining their position in the experiment, which is attributed to the accuracy of the setting. In the experiment, the disturbance fronts are smoothed due to the physical dimensions of the sensitive element of the hot-wire probe.

## Conclusion

An efficient calculation set-up has been developed in the FlowVision software package to numerically simulate the formation of stationary free flow disturbances caused by two-dimensional roughness in a turbulent boundary layer on a wall. The case of small height roughness compared to the thickness of the boundary layer has been considered. To mitigate numerical oscillations, the FlowVision tool has been used to adapt the computational grid to disturbance fronts.

Numerical simulations have shown that flow separation zones are formed in front of and behind the two-dimensional roughness. The highest amplitude of disturbances is observed within the turbulent boundary layer. In a free flow, an observed disturbance in the form of an N-wave decays downstream.

The results of numerical modeling were verified using experimental data. A strong agreement was achieved between the simulation and experimental results, both in terms of the amplitude and spatial position of the disturbances. It has been shown that it is possible to predict the amplitude, spatial scale, and location of a disturbance in a supersonic flow.

The influence of roughness height on the generation of stationary free flow disturbances has been studied. It was found that as the height of the roughness increases, there is an observed increase in the amplitude and spatial scale of the disturbance. In this case, the gradient of flow parameters between the disturbance fronts remains practically unchanged for all roughness height considered.

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