Numerical simulation of sonic boom near-field flow over 69-degree delta wing body

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Abstract. Fast and accurate prediction of sonic boom intensity is important in performing design and optimization studies of a supersonic aircraft. The paper presents the computational mesh generation technique for sonic boom prediction in the near field of complex geometry body. Studies are done on a 69-degree delta wing body model used for testing various prediction techniques in the framework of the AIAA Sonic Boom Prediction Workshops.

1. Introduction
Many researches are developing technologies to enable future supersonic civilian aircraft to fly efficiently with reduced sonic boom (SB). The main problem of SB modelling is the large extent of the area under investigation, where the perturbed pressure levels vary by several orders of magnitude. Usually the sonic boom is studied in the near and far fields. The near field of the SB adjoins the aircraft and has a complicated flow structure with shock waves, rarefaction and compression waves; its length is about the aircraft length ($K = H/L \sim L$, where $H$ is the height distance from the aircraft, $L$ is its characteristic size). The length of the far field where the sonic boom parameters vary feasibly in accordance with the asymptotic law, realizes within the distances of $K \sim L^2$. Numerical simulation is the main research method, but it requires huge computational resources, the construction of complex grids to describe aircraft configurations, and, in addition, contains some assumptions. In the case of a large model with complex geometry, the time spent on meshing is significant. A reasonable alternative for this kind of simulations is a quick automatic mesh generation. At the same time you need to create more uniform meshes for improved convergence and accuracy. The challenge here is to provide a quick automatic mesh with good accuracy.

2. Numerical simulation

2.1. Numerical simulation conditions
The flow around a body is solved in a three-dimensional mode. SOLIDWORKS Flow Simulation solver is utilized for the solution process. Flow Simulation is a full Navier-Stokes solver for structured grids, however, in this study the code is run in laminar mode without taking into account friction on the model surface since viscous effects are negligible for sonic boom prediction. The calculation was carried out for a stationary flow of an ideal gas with the specific heats ratio $\gamma = 1.4$. The surfaces of the model were impenetrable, without roughness, without thermal conductivity. This does not allow
simulating the boundary layer, but made it possible to correctly simulate the propagation of shock waves, compression and rarefaction waves in the near field. Initial conditions were normal corresponding to the altitude of 15000 m.

2.2. Cartesian mesh generation

The 69-degree delta wing body geometry taken from [4] is shown in figure 1. This model is used for testing various prediction techniques in the framework of the AIAA Sonic Boom Prediction Workshops.

![Figure 1. 69-degree delta wing body geometry.](image)

The rectangular computational domain is shown in figure 2. The dashed line in figure 2 shows a symmetrically reflected region. One of the faces passes through the model symmetry axis. The inflow and outflow boundaries are set at Mach angles for M = 1.6. So the faces were tilted at the angle of weak shock waves [5]. The boundaries of the computational domain were located at a sufficient distance to exclude some artifacts are reflected back. Such a boundary condition is supposed to allow the disturbances to pass through the boundary. Each face of the computational domain was divided into three subregions: near the model, far from the model, and the transition between them. A Cartesian grid was used. Near the model the cell size was 0.005×0.0026×0.004 m, in the distance - 0.022×0.01×0.012 m. The grid covering up to $H/L = 4$. Here $H$ is the distance from the model in the vertical direction, $L$ is the length of the model.

The mesh in the symmetry plane of the model is shown in figure 2. Inside the computational domain, a flow feature-based subdomain was used, in which the cell size was refined by 4 times. The geometry of the subdomain is shown in figure 3. An additional 4-fold grid refinement was used near the surface of the model.

![Figure 2. The computational grid in the symmetry plane of the model.](image)  

![Figure 3. A subregion for grid refinement.](image)
3. Numerical results

Figure 4 shows the distribution of excess static pressure along the control line at a distance of $K = H/L = 3.6$. The $x$-axis, passing through the model axis, is plotted along the horizontal direction. The origin is chosen arbitrarily. On the ordinate axis is the excess (relative to the incident flow pressure $P_{\text{inf}}$) static pressure. The result is shown for the base grid.

![Figure 4. Distribution of excess static pressure along the control line in the near field of the model.](image)

As can be seen, the head SW has the intensity of approximately 0.01, formed as a result of the flow around the nose of the model, followed by the rarefaction wave, which leads to a decrease in pressure to a value lower than in free stream. Next, at the point $x \approx 0.95$ the SW formed by the wing is observed. The tail shock wave ($x \approx 1.05$) closes the profile.

To reduce the computation and retain the results the cell sizes in the region remote from the model (see figure 5, region III) were changed. As shown in [5], it is acceptable to use “elongated” cells when shock-grid alignment is present. The cells with the aspect ratio of 4.4:1 were selected as base cells. Then cells length in region III was varied along the $x$ direction. The test computations were performed for cells two times longer and two times shorter than the base cells. So, in these cases the intensity and position of the shock wave from the nose of the model did not change. Figure 6 shows the intensities of the wing SW for different refinement factors in the region III. The lines denoted as “0.5”, “1” and “2” correspond to the cell sizes $0.088 \times 0.01 \times 0.012$ m, $0.022 \times 0.01 \times 0.012$ m and $0.011 \times 0.01 \times 0.012$ m, respectively. It can be seen that a decrease in the cell size leads to a decrease in the intensity of the shock wave. The difference between the cases “0.5” and “2” is about 1%.

![Figure 5. Grid adaptation regions.](image)

![Figure 6. Shock wave from the wing.](image)
Next, we studied the effect of the subdomain transverse size on the intensity of the shock wave on the symmetry plane. For this, the size of the region of cell refinement was varied, which was specified by the angle $\alpha$ (see figure 7). The figure 8 shows the results of numerical modeling for the convergence angle of refinement subdomain: 10, 20, and 30 degrees. It can be seen that the results coincide for subdomains with $\alpha = 20, 30$ degrees. For $\alpha = 10$ degrees, the SW intensity is less, due to the influence of the SW dissipating on a coarse grid in the transverse direction.

Figure 7. Grid adaptation subdomain.

Figure 8. Shock wave from the wing.

Figure 9 shows a comparison with the results of numerical simulations obtained by researchers from Boeing, Dassault Aviation, JAXA, NASA, and ONERA [4]. The shock waves intensity in the present computation is higher than the average value, however, it is at the level of the values obtained in Boeing, Dassault Aviation and JAXA. It should also be noted that the pressure gradient on the shock waves is maximum in the calculation results of Boeing and ITAM SB RAS.

Figure 9. Comparison of the results of numerical modeling obtained by different researchers.
4. Conclusions
The computational mesh generation technique for sonic boom near field prediction of complex geometry body is presented. The rectangular computational domain consists of elongated cells and contains subdomain for a flow feature-based grid refinement. It is shown, that a decrease in the cell size of base domain leads to a decrease in the intensity of the shock wave. The difference between the results obtained with the 4 fold refinement is about 1%. Subdomain transverse size affect the shock intensity on the symmetry plane, when this size is less than $Z/L = 3$.

Studies are done on a 69-degree delta wing body model used for testing various prediction techniques in the framework of the AIAA Sonic Boom Prediction Workshops. Numerical simulation of the near-field flow of the 69-degree delta wing body model was conducted. The results have a good agreement with the results obtained by different researchers.

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