Gas-dynamic factors controlling the level of the sonic boom generated by two bodies in a supersonic flow

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Abstract. The results of calculation of the sonic boom generated in a supersonic air flow by two bodies (disk and slender body of revolution) are presented. The bodies are arranged one behind the other. The slender body is aerodynamically shaded by the disk. The free-stream Mach number is 2. The calculations are performed by a combined “phantom bodies” method. The sonic boom level can be reduced by more than 12% via the disk position and size changing, as compared to the sonic boom generated by the slender body. The gas-dynamic factors affecting the sonic boom level are described on the base of the calculation results.

1. Introduction

The sonic boom problem comprises a study of the dynamics of weak shock waves at large distances from the flight trajectory and ways to reduce the sonic boom level on the ground surface. The studies of the sonic boom problem have already been reviewed in [1, 2].

Currently, researchers develop different methods to reduce the sonic boom level from a supersonic airplane, which requires the knowledge of gas-dynamic factors reducing the sonic boom level from a body in a supersonic flow. One of the active methods to affect the sonic boom is to change the oncoming flow parameters using aerodynamic surfaces in front of the body [3, 4].

This paper describes the gas-dynamic factors changing the sonic boom level from a slender body of revolution located in an aerodynamic shadow of another body. The aerodynamic shadow is formed by a disk located in front of the slender body perpendicular to the oncoming supersonic flow.

2. Calculation method

The slender body with the disk located perpendicularly to the oncoming air flow is illustrated in figure 1. The Mach number of the oncoming flow is \(M_0 = 2\). The surface of the slender body of revolution in dimensional values is specified by the equation \(r = 0.2(x - x^2/L), 0 \leq x \leq L\), where \(L\) is the body length, \(x\) is the longitudinal coordinate counted from the tip of the body downstream, and \(r\) is the radial coordinate. The distance from the disk to the tip of the body is \(x_d/L = 0.025\). The disk thickness is \(h_x/L = 0.000125\).

The calculation of the near field of the flow is carried out using an ANSYS Fluent software package with the help of a viscous heat-conducting gas model. Computational parameters: \(M_0 = 2\), \(L = 40\) m, \(p_0 = 5474.87\) Pa, and \(T_0 = 216.65\) K. Here, \(p_0\) is the static pressure in the oncoming flow, and \(T_0\) is the static temperature in the oncoming flow. The calculations are carried out in the Cartesian and cylindrical coordinate systems. The three-dimensional flow of the near field is calculated using the Cartesian coordinate system \(\{x, y, z\}\): \(x\) is the longitudinal coordinate counted from the tip of the body downstream,
y is the vertical coordinate, \{xy\} is the symmetry plane, and z is the lateral distance from the symmetry plane. The near field of the flow having axial symmetry is determined using the cylindrical coordinate system \{r,x\}: r is the radial coordinate, and x is the longitudinal coordinate counted from the tip of the body downstream.

![Figure 1](image1)

**Figure 1.** Body with the disk: 1 – slender body of revolution; 2 – disk.

The near-field parameters are used as the initial data for calculating the far field, which is carried out via the “phantom bodies” method [5]. The overall schematic of the method is shown in figure 2.

![Figure 2](image2)

**Figure 2.** Overall schematic of the “phantom bodies” method: 1 – shock wave sources; 2 – excess pressure profile in the near field; 3 – phantom body; 4 – excess pressure profile in the far field.

The near-field parameters (pressure profile 2) are used to construct the “phantom body”. The phantom body is given by a discrete sequence of points 3 on a flight trajectory in which the values of the Whitham function and the longitudinal coordinates of the points are calculated. The excess pressure profile in the far field 4 is constructed using the analytical solutions of Landau [6], Whitham [7], and Rao [8] in the coordinate system with the axial symmetry. The initial data in the 3D flow calculations are chosen on the azimuthal plane \{\phi = \text{const}\} in the cylindrical coordinate system \{r,\phi,x\}, as shown in figure 3.

![Figure 3](image3)

**Figure 3.** Initial data choice: 1 – slender body; 2 – shock waves; 3 – pressure profile in the near field.

In this case, the corresponding phantom body is constructed in each plane \{\phi = \text{const}\}, and the far field is calculated independently in each azimuthal plane in the cylindrical coordinate system \{r,x\} with
the axial symmetry. The axis of symmetry is the x axis. The spatial pattern of the flow is obtained by calculations in several azimuthal planes. The potential of this method is indicated in [9] and validated in [5] in solving spatial problems.

The “phantom bodies” method was tested in [4, 5]. The test calculations of the dynamics of shock waves from the slender body of revolution (the Mach number of the oncoming flow was \( M_0 = 2.4 \)) and blunt bodies (\( M_0 = 1.8 \)) were performed. For the slender pointed body, the calculation results were compared with analytical solutions and the results of calculations carried out using other methods. The possibility of calculating the sonic boom from blunt bodies with a departing shock wave was studied using the example of the sphere problem in a supersonic gas flow. The test material was the results of experimental studies of sonic booms with spheres of different diameters in ballistic ranges and wind tunnels [10]. The test calculations showed that the “phantom bodies” method could be applied to calculate the shock wave parameters in the far field.

3. Results and discussion

Figure 4 presents the diagram of the flow near the body with the disk and the results of calculating the far field parameters. The denotations are as follows: \( \Delta p \) is the excess pressure and \( d \) is the disk diameter.

![Figure 4](image_url)

**Figure 4.** Body with the disk in the flow and the relative shock wave intensity: 1 – slender body of revolution; 2 – disk; 3 – sonic line; 4 – shock wave from the disk; 5 – shock wave from the body (barrel shock); 4+5 – shock wave formed after the shock waves from both the disk and the body become combined; 6 – tail shock wave; 7 – relative excess pressure profile; 8 – relative intensity of the bow shock wave from the slender body with no disk.

The calculation results related to the relative intensity of shock waves for the body with disks of different diameter and the corresponding relative excess pressure profiles behind the shock waves are shown for the distance \( r/L \sim 520 \). For comparison, the figure illustrates the relative intensity of the bow shock wave from the slender body without disk. The “+” sign denotes the shock wave formed after the shock waves are combined. Clearly, the disk size and the size of the aerodynamic shadow affect the
sonic boom level in the far field. For the disk with a diameter $d = 0.03L$, the shock wave from the body catches up with the shock wave from the disk, combines with it, and the sonic boom in the far field becomes stronger than that from the original slender body. In the near field, the intensities of the shock waves from the disk and the body are smaller than those from the bow shock wave from the slender body with no disk, which allows one to preliminarily predict a decrease in the sonic boom level in the far field. Using the near-field data to predict the sonic boom level in the far field without precise calculations is often unreasonable and yields erroneous results. The disk with the diameter $d = 0.04L$ is in such a position relative to the body and creates such an aerodynamic shadow that the shock waves from the disk and the body do not combine within the distance of $r/L \sim 520$, thereby reducing the sonic boom. As the disk diameter increases up to $d = 0.05L$, the aerodynamic shadow becomes larger, but the intensity of the shock wave from the disk increases, too. The intensity of the shock wave from the body decreases, but the sonic boom level is determined by the shock wave from the disk and exceeds the sonic boom level from the original body.

Figure 5 shows the calculation results for the body with the disk $d = 0.04L$.

**Figure 5.** Body with the disk $d/L = 0.04$ (axial symmetry). Relative intensity of shock waves (a) and the flow velocity vector field (b): 1 – slender body of revolution; 2 – disk; 4 – relative intensity of the shock wave from the disk; 5 – relative intensity of the barrel shock; 4’ – relative intensity of the shock wave from the disk with no body; 8 – relative intensity of the bow shock wave from the slender body with no disk.

Figure 5(a) illustrates the frontal image of the body with the disk and the calculations of the relative intensity of shock waves at different distances $r/L$ from the axis of symmetry $x$. The flow velocity vector field is shown in the plane $\{rx\}$ in figure 5(b). An aerodynamic shadow with a subsonic reverse flow is formed behind the disk. A barrel shock is formed in the outer flow above the region of the aerodynamic shadow (see figure 4). The barrel shock propagates through the gas which parameters are given by a rarefaction wave following the shock wave from the disk. The barrel shock relative intensity at all distances $r/L$ is smaller than the bow shock wave relative intensity from the body with no disk. The relative intensity of the shock wave from the disk coincides with that of the shock wave from the disk with no body. As is shown by the calculations, a decrease in the sonic boom level in the far field can reach a value of 12 percent and larger. At the distances $r/L > 520$, the barrel shock catches up with the shock wave from the disk, and they combine.

Figure 6 shows the calculation results for the body with the disk $d = 0.04L$, that is displaced in a negative direction along the y axis at a distance of $0.005L$. Figure 6(a) shows the frontal image of the
body with the displaced disk and the calculations of the relative shock wave intensity at different distances \( r/L \) from the \( x \) axis in azimuthal planes \( \{\phi = 0^\circ\} \) and \( \{\phi = 180^\circ\} \). Figure 6(b) shows the flow velocity vector field in the plane \( \{xy\} \).

**Figure 6.** Body with the disk \( d/L = 0.04 \) (flow with no axial symmetry). The relative shock wave intensity (a) and the flow velocity vector field (b): 1 – slender body of revolution; 2 – disk; 4 – relative intensity of the shock wave from the disk for different azimuthal planes; 5 – relative intensity of the barrel shock for different azimuthal planes; 4’ – relative intensity of the shock wave from the disk with no body; 8 – relative intensity of the bow shock wave from the slender body with no disk.

Thus, the disk displacement reduces the aerodynamic shadow size in the top section of the space on the body surface. In the bottom section of the space, the size becomes larger as compared with the axisymmetric case. One could expect that the sonic boom level varies in accordance with the changes in the aerodynamic shadow size, i.e., expect the sonic boom level decrease in the bottom section of the space and an increase in the sonic boom level in the top section of the space. However, the calculations of the flow field near the body show that there are azimuthal flows, and as a result the pressure on the top and bottom surfaces of the body becomes higher than the pressure obtained for the axisymmetric case. The changes in the layout increase the sonic boom level because the intensity of the barrel shock that follows the shock wave from the disk becomes larger than that in the axisymmetric case.

4. Conclusion

Thus, it can be concluded on the basis of the calculations that there are dimensions and positions of barriers in front of the body that reduce the sonic boom at large distances from the body by forming an aerodynamic shadow.

The results show that the displacement of blunt-nosed bodies in the layout does not ensure the sonic boom level reduction in the chosen azimuthal plane. The sonic boom can be amplified due to the development of azimuthal flows.

There are two gas-dynamic factors determining the sonic boom level from two bodies in a supersonic flow. The first one is the aerodynamic shadow behind the first body with the second body placed within it. The second factor is the azimuthal flows forming near the body surface in the case of an asymmetric flow.
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