Supersonic airplane engine jet influence on the intensity of tail shock wave of sonic boom waveform

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Abstract. The paper presents the computational experiment results aimed at studying the influence of the aircraft propulsion system on the sonic boom parameters. As a result, at large distances from the disturbances source at jet temperature of 2400° K and velocity of 1700 m/s at the nozzle exit, the trailing shock wave intensity in the sonic boom profile was significantly reduced by 50% compared to the profile generated by the aircraft without considering the jet influence.

1. Introduction
Strict environmental requirements are imposed on supersonic passenger aircrafts to limit the sonic boom level. A preliminary analysis conducted at TsAGI [1] showed that the supersonic passenger aircraft cannot provide acceptable levels of sonic boom $\Delta P_{sb} < 5 \text{ kg m}^{-2} (\Delta P_{sb} < 50 \text{ Pa})$ without a noticeable deterioration in economic performance. In this regard, the implementation of supersonic flights on routes passing over the water surface or over uninhabited land is envisaged.

The solution to the question of whether flights of supersonic aircraft over populated territories will be possible depends on the sonic boom made by these aircrafts.

According to the systematic calculations of the sonic boom intensity [2-5] for various parameter values, methods of the sonic boom intensity reduction were established by changing the aircraft layout. These methods include: shifting the wing back relative to the fuselage, increasing the wing root chord, reducing the relative profile thickness, increasing the relative midship of the fuselage, etc.

The influence of the layout elements of the supersonic passenger aircraft model on the sonic boom parameters was investigated in [5]. In this paper the optimal layout is selected from the analysis of the parametric calculations results. Selected layout provides a significant reduction in the sonic boom level at large distances from the source of disturbances and without reducing aerodynamic quality. In the early works [2-5], the methods of sonic boom reduction were applicable only to aircraft airframes without taking into account the propulsion system influence. This setting does not reflect the real physical phenomenon, the influence of the propulsion system jets on the disturbed flow generated by the aircraft at large distances from the source.

2. Jet propulsion modeling
To solve this problem, the theoretical foundations of Laval nozzle calculations were used [6, 7].
- Gas constant of air $R = 287 \text{ J kg}^{-1} \text{ K}^{-1}$, adiabatic index $k = 1.4$.
- Pressure and temperature of air at the nozzle inlet $P_0^*, T_0^*$.
- Air pressure at the nozzle exit $P_e$.

The flow regime is determined by the comparison of the pressure ratio $\beta_i = \frac{P_i}{P_0^*}$ with the critical ratio

$$\beta_c = \frac{P_e}{P_0^*} = \left[ \frac{2}{k+1} \right]^\frac{k}{k-1}$$

where $P_i$, $P_e$ – static pressure in $i$-section and in critical section, $P_0^*$ – total pressure at the nozzle inlet, $k$ – adiabatic index. In this study, the working fluid is air, for which $k = 1.4$ and therefore $\beta_c = 0.528$.

Calculation Procedure: find the nozzle pressure ratio if: when $\beta_e < \beta_c$ the flow regime is supersonic.

To determine the speed of the jet at the nozzle exit, the pressure ratio was taken equal to $\beta_e = \frac{P_e}{P_0^*} = 0.05$, which provides supersonic flow regime.

$$w_e = \sqrt{\frac{2 \cdot k}{k-1} \cdot R \cdot T_0^* (1 - \beta^\frac{k}{k-1})}.$$

### 3. Calculation methods and conditions

To quantify the sonic boom impact on terrestrial objects, it is necessary to have a method of the shock wave intensity calculation at large distances from an aircraft.

The calculation method based on linear theory leads to the need to determine the shape factor of the aircraft, which makes the task difficult to solve for a real configuration because of the analytical description impossibility of the body geometry. On the other hand, the presence of engine nacelles in the aircraft design limits the applicability of linear theory. In this regard, it seems appropriate to use the flow parameters in the near zone of the model, which can be obtained experimentally or numerically, for their subsequent conversion to the far zone.

The use of numerical methods for solving the supersonic flow problems around the aircraft to determine its aerodynamic characteristics and the parameters of the sonic boom created by it at large distances is associated with some limitations.

In particular, the width of the perturbed region is much smaller than the characteristic radius of front curvature and the characteristic distance at which the parameters of the perturbed environment change significantly. Under this condition, it is advisable to calculate the propagation of small perturbations using the linear theory provisions described in [8,9]. In the calculations of perturbations at large distances from the source, the perturbed flow parameters in the near zone, determined by the numerical solution results of the flow around the model, were used as initial data.

The problem of disturbances propagation over long distances and the formation of the sonic boom wave generated by the aircraft layout was solved in two stages.

At the first stage, the problem of supersonic flow around the layout with the free-stream Mach number $M_\infty = 2.03$ was solved. Based on the results of this problem numerical solution, the aerodynamic characteristics and parameters of the perturbed flow generated by the layout in the near zone were determined on the control surface at a given distance from the body axis.

The control surface (figure 1) in the perturbed region is a cylinder with a radius $R = R/L_f = 1.33$ whose axis coincides with the layout axis. The perturbed pressure parameters on the control surface are used as initial data to the problem solution.

The numerical solution of the flow around the layout determining the flow parameters in the perturbed region was carried out in the framework of the Navier-Stokes equations.
Figure 1. Control surface in the vicinity of the investigated layout.

The geometric models formation of monoplane and tandem layouts was carried out by combinations of its constituent elements joints. The necessary elements for creating layouts are the following:

- **Fus1** - axisymmetric body with ogival head part with elongation $\lambda = 4.5$ and total elongation $\lambda = 15$;
- **Win1** - trapezoidal wing with sweep along the leading edge $\chi = 56^\circ$ with a flat median surface with a 3% rhomboid profile;
- **Win2** - trapezoidal wing with a basal influx with sweep along the leading edge $\chi_1 = 76^\circ$ and $\chi_2 = 56^\circ$, with a flat median surface with a 3% rhomboid profile;
- engine nacellas.

The model geometric layout is shown in figure 2, (a). The mathematical model of supersonic flow around a tandem layout with running engines is shown in figure 2, (b).

Figure 2. Jet modelling: (a) - optimum tandem layout with nacelles; (b) - tandem layout with a propulsion system.

For visualization of jets and features of the parameters distribution in the disturbed region the temperature fields are presented in the calculation region.

4. Computational experiment results

To conduct the computational experiment to determine the sonic boom wave intensity in the cruise flight mode at a distance from the source of disturbances and without loss of aerodynamic quality [6], the optimal tandem configuration layout of the aircraft was used (figure 2, (a)).
At a large distance from the source, the sonic boom wave profile induced by the tandem arrangement with predetermined front wing positions contains shock waves spaced along the longitudinal coordinate – the train of shock waves (figure 2, label 1). These include the leading shock wave generated by the bow of the hull with the front wing, the shock wave from the rear wing and the trailing (tail) shock wave. It should be noted that an effective reduction in the sonic boom level is achieved when the effect of the leading and following shock waves was perceived by the observer as separate pops. This condition, the so-called solvability condition of shock waves, is determined by the flight time of the distance between the leading and following shock waves, which should be $\Delta t_0 \geq 40$ ms, which corresponds to the frequency of their impact on the observer $f_0 = 25$ Hz. Otherwise, at a frequency $f > f_0$ these pops are perceived by the observer as continuous noise, which pressure level corresponds to the total overpressure of the leading and following shock waves.

A comparison of the obtained results is shown in figure 3, where the markers indicate: 1 – the sonic boom wave profile generated by the optimal tandem layout with engine nacelles [6] without taking into account the influence of the propulsion system jets; 2 - the generated sonic boom wave profile in the disturbed region with the jets of the propulsion system with a temperature at the nozzle exit $T = 1200$ K; 3 – sonic boom wave profile in the disturbed region with the jets of the propulsion system with a temperature at the nozzle exit $T = 2400$ K.

![Figure 3](image)

**Figure 3.** Sonic boom wave profiles at a distance $K = r/L_f = 450$ from the disturbances source.

It can be noted in this figure that the influence of the propulsion system jets is accompanied by significant changes in the parameters of the sonic boom wave profile (figure 3, marks 3-4). This can be attributed to: the distance between the leading and following shocks on profiles 3, 4 is significantly reduced in comparison with profile 1. This distance is much less than the distance satisfying the condition for solvability of shocks in the sonic boom wave profile, which the observer perceives as a leading pop in the N-profile of perturbed pressure waves.

The level of tail shock wave intensity of the sonic boom is reduced by more than 50%. A decrease in the intensity level of the tail shock is accompanied by a decrease in the wavelength of the sonic boom.

It should be noted that the perturbed flow parameters behind the closing shock asymptotically approach the unperturbed flow parameters.

The dimensional values of the excess pressures in the table 1 are applicable to the estimation of the sonic boom parameters created by the tandem layout with length $L_f = 40$ m, mass $G = 40$ ton in the cruise flight mode at a speed corresponding to the Mach number $M_\infty = 2.03$ at altitude $H = 18$ km.
Table 1. Shock intensities in the profile of the sonic boom wave.

| No | \( \Delta P_s \) | \( \Delta P_t \) | \( \Delta P_{ts} \) | dB   |
|----|-----------------|-----------------|-----------------|------|
| 1  | 0.001075        | 29.7            | 0.000696        | 117.0|
| 3  | 0.001191        | 33.0            | 0.000325        | 115.0|
| 4  | 0.001191        | 33.0            | 0.000431        | 116.0|

\( p_h \) – atmospheric pressure at flight altitude,
\( p_g \) – atmospheric pressure at earth surface,
\( \Delta P_t \) – tail shock intensity of sonic boom.

5. Conclusion

The results of a computational experiment aimed at studying the influence of propulsion system jets on the formation of the sonic boom wave profile generated by the supersonic passenger plane at large distances from the disturbances source (about \( K = 450 \)) are presented. The data obtained are compared with the corresponding data received for the airframe with optimal tandem layout. It is shown that the jet outflow is accompanied by a significant decrease in the intensity of the closing shock in the profile of the sonic boom wave (about 50%).

References

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