SONIC BOOM AND MINIMIZATION OF ITS IMPACT

S.L. Chernyshev, L.G. Ivanteeva, V.V. Kovalenko, L.L. Teperin

Central Aerohydrodynamic Institute named after prof. N.E. Zhukovsky (TsAGI), Zhukovsky, Russia

Growing interest to the development of supersonic transport (SST) requires additional efforts in studying and eventually solving the sonic boom problem. Without essential progress and acceptable solution of this problem it seems impossible to further proceed with a new generation SST. The tools available today for sonic boom research allow to determine various characteristics of this phenomenon with rather good accuracy. They can be used also for optimizing aircraft configuration to minimize shock wave impact.

Presented paper provides brief overview of some research efforts carried out at TsAGI in the area of sonic boom prediction method, calculation and optimization.

Particularly, quite efficient algorithms and computer codes of sonic boom calculation have been developed at TsAGI. They are based on the Euler equations integration for the near field and asymptotic quasi-linear acoustical solution for the far field [1].

The new method of designing a mean camber of SST wing surface has been recently developed. The design principle is in the construction of a mean camber line of the wing profiles, providing minimum pressure drag induced by the lift and, simultaneously, in the fulfillment of sonic boom level restrictions. The method is applyed at the cruise regime of flight, which is determined by Mach number and flight altitude. The wing plan form, thickness distribution and weight of an airplane are considered to be given. The classical theory is applied to the problem of sonic boom minimization; the use of this makes it possible to determine the optimum form of a sonic boom signature for given values of airplane's length, weight and Mach number. The type of optimum signature (flat-top, ramp or hybrid type) is a parameter of the task. For the given profile of the sonic boom signature, it is possible to determine the cross section area distribution of equivalent body of revolution that gives the same as airplane the shape and intensity of shock wave on the ground. The area distribution derivative of equivalent body of revolution is an input data for the optimization task.

To connect a perturbed field near an airplane (near field) with the form of an equivalent body of revolution, the theorem of Professor Yu.L.Zhilin [2] is applied. This theorem connects the given derivative of area distribution with an integral of perturbed velocity components. The signature of sonic boom wave uniquely determines the form of an equivalent body of revolution, but the transition from a body of revolution to an airplane can be accomplished in uncountable number of ways. In the given work, the aircraft configuration sought for is limited to a type "Flying Wing". Since the plan form and thickness distribution of a wing is set, as well, the task of design of the optimum shape of mean camber surface for the wing may be considered to be closed.

The panel method of the linear theory is used in the given work to solve the problem of supersonic flow and determine the near field parameters and aerodynamic characteristics. The wing is replaced in this method by a great number of trapezoidal panels with hydrodynamic singularities (sources and vortexes) with distributed on these. A piecewise linear distribution of sources simulates the thickness of a considered wing, and a piecewise linear distribution of vortexes simulates lifting properties of the wing. Distribution of wing thickness is set, hence, according to the linear theory; intensities of sources are completely determined (by the first derivative of profile half-thickness line in a chordwise direction). The only unknown parameter (or the function sought for) is a distribution of the intensity of vortexes. There is a linear dependence between the angle of panel inclination (or the derivative of a mean camber line of a wing profiles) and strength of vortexes. The matrix of aerodynamic influence characterizes the mentioned dependence. Functional to be minimized is a function dependent on the distribution of intensity of vortexes. This function is determined by the pressure drag of a thin lifting surface and by restrictions (relied with lift coefficient, coefficient of longitudinal moment and values of the area derivative of cross sections of an equivalent body of revolution in some points along the axis of aircraft) multiplied by Lagrange multipliers.

The condition of extremality leads to the system of linear algebraic equations (with reference to unknown vortex strengths and Lagrange multipliers). Aerodynamic coefficients and inclinations of the mean camber surface are determined by predicted vortexes intensities. Thereafter, the sonic boom signature at the ground may be calculated using the program "BOOM" of Kovalenko V.V.

In case of “Flying wing”, the signature of minimum sonic boom and corresponding distribution of derivative of cross section area of equivalent body of revolution (fig.1) were set for the following cruise flight regime parameters:

Weight 188 t.

Altitude 16500 m.

Mach number 2.

Airplane length 54 m.

Optimum distribution of derivative of cross section area of equivalent body of revolution (fig.1) was introduced into the task of designing the mean camber surface of flying wing, as a restriction. Distribution of derivative of cross section area of equivalent body of revolution obtained from optimum problem solution is shown in fig.1 by markers.

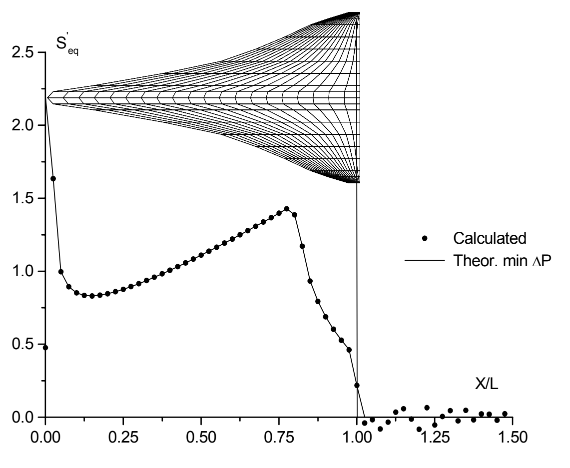

Fig. 1. Distribution of theoretical and predicted optimum derivatives f cross-section area of equivalent body of revolution.

It is seen that the given distribution S'_{eq} is exactly equal to predicted one in separate points (for X/L<1).

By that, the number of point is a parameter of task and may be increased up to several hundreds.

The comparison of two configurations, traditional one (like the Tu-144 aircraft) and “Flying wing”, is shown in fig.2. Both aircraft have equal weight and are considered to be in flight at equal altitude and equal Mach number. The head shock intensity of sonic boom wave for the “Flying wing” is seen to be reducible up to the level being in 2.5 times lower, than for traditional configuration at the same lift-to-drag ratio. It is possible to achieve this due to a greater lift-to-drag ratio possessed by configuration “Flying wing” in case of discarded restrictions on the form of the equivalent body of revolution. Restrictions on the sonic boom level inevitably lead to an inferior lift-to-drag ratio coming to the level of the traditional configuration.

Test calculations demonstrated a readiness of developed method for the designing of surface of the supersonic passenger aircraft within the scope of linear theory. In the further researches, it is supposed to expand capabilities of the method with the purpose of including the geometrical data determining a wing plan form into a class of unknown parameters.

Some peculiarities of secondary sonic boom (SSB) propagation have been investigated. Method to calculate sonic boom intensity in the vicinity of turnaround point in windy stratified atmosphere has been conducted. Consideration of elementary ray tube area has allowed us to reduce the problem analytically to the evaluation of $0 \cdot \infty$ type of mathematical uncertainty that always stays finite. The way to extend the solution continuously into secondary zones of influence has been found. SSB intensities in turnaround points have been analyzed for different airplane flight regimes. Conditions for focussing occurrence in turnaround point have been considered. Locus to fall SSB of maximal intensities has been defined.

Criterion to occur secondary sonic boom propagation has been written.

First computational results have revealed some features of SSB propagation. The effects of atmospheric and issuing parameters on every propagation of SSB disturbance towards the ground are individual. Every disturbance turns around at its specific altitude and fan of disturbances propagates in secondary zone of influence in the way that radically differs from cylindrical flow.

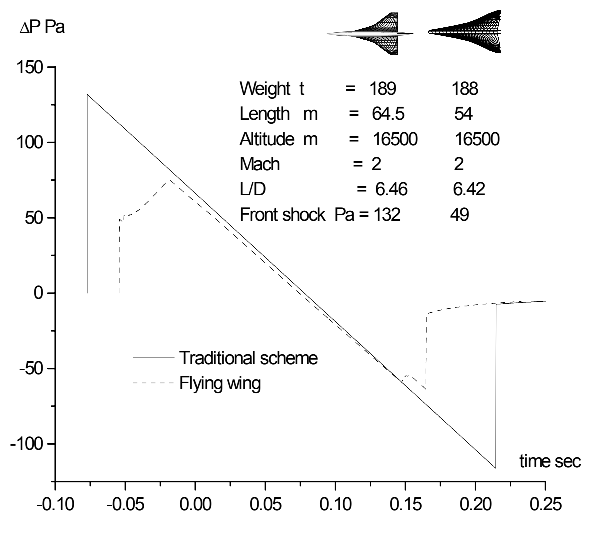

Fig. 2 Comparison of sonic boom signature for aircraft of traditional type and for “Flying wing” configuration

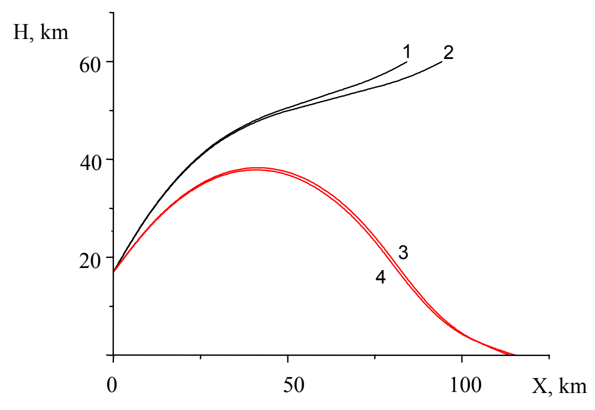

Fig. 3. Distinction between cylindrical flow (rays 1-2) and propagation of SSB waves (rays 3-4).

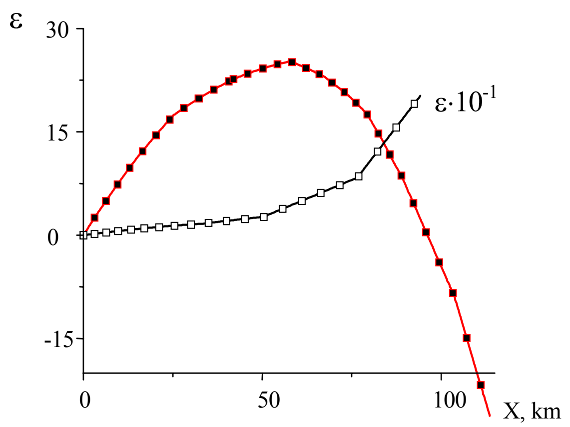

Fig. 4. Elementary ray tube area ε characterizes focusing and defocusing tendencies (red color – propagation of the SSB wave, black color – cylindrical flow).

Generally, an intensity of a disturbance becomes stronger on its way back to the ground and, most likely, crosses a caustic (as shown on fig. 3); the sonic boom intensity on the ground in that case depends on focusing height. Analysis of the situation has been carried out by taking into consideration only the value of elementary ray tube area that highlights focusing and defocusing tendencies in wave propagation (fig. 4) and represents key parameter in estimation of sonic boom intensity.

The essential effect of acceleration (flight velocity M = 2,0) on elementary ray tube area is demonstrated. Analogous dependencies for primary sonic boom one can hardly distinguish from each other.

In reality we used to deal with decelerated landing regime and then well-known ZEPHYRUS code [3] is not quite correct, because it works only for steady level flight regime. Discrepancy between SSB intensities for steady and decelerated flight regime behaves in non-predictable way, the less the value of elementary ray tube area, the more pronounced is the effect of acceleration and even type of waves may be changed. Fig. 5 illustrates the effect of deceleration (-1/3 m/c^2) on intensities of N-wave type disturbances. All signatures are referred to the maximal value of primary sonic boom intensity.

To make the analysis of SSB propagation complete, it is necessary to investigate passage of disturbances through caustic and afterwards - phenomena of energy dissipation in sonic boom wave.

At present, along with the scientific and technical development, the task of sonic boom exposure limit determination takes the critical importance. This problem should be solved on the basis of collected field experience of supersonic airliners cruise path over land and sea and numerous results of flight tests.

The sonic boom exposure limit determination requires more thorough knowledge of the mechanism of this phenomenon as well as particular qualities of shock waves propagation and its esthesia depending on various flight regimes, weather conditions, surface geometry, etc.

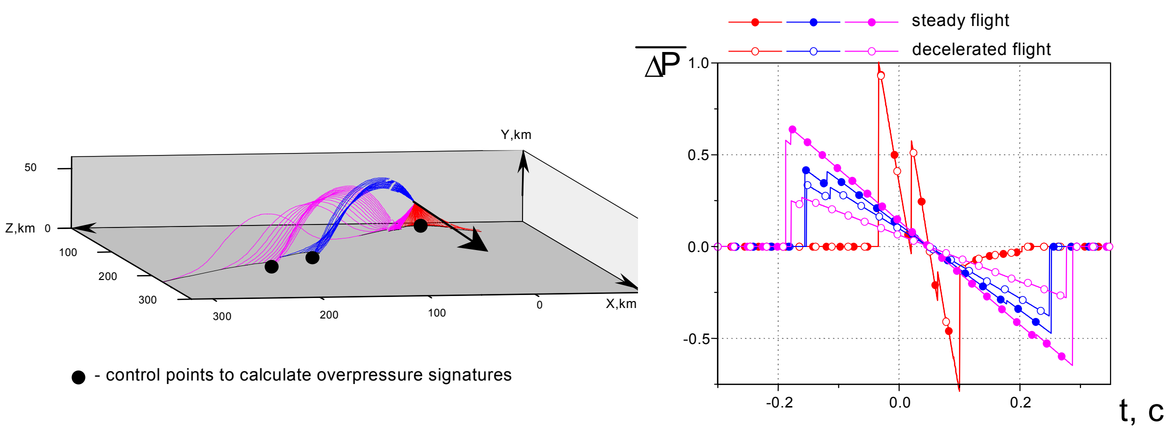

Fig.5. Relationship between sonic boom overpressure and aircraft flight acceleration. Red color represents primary sonic boom, blue and purple colors represent secondary ones or the shock waves traveling at the beginning in upper and lower semi sphere respectively.

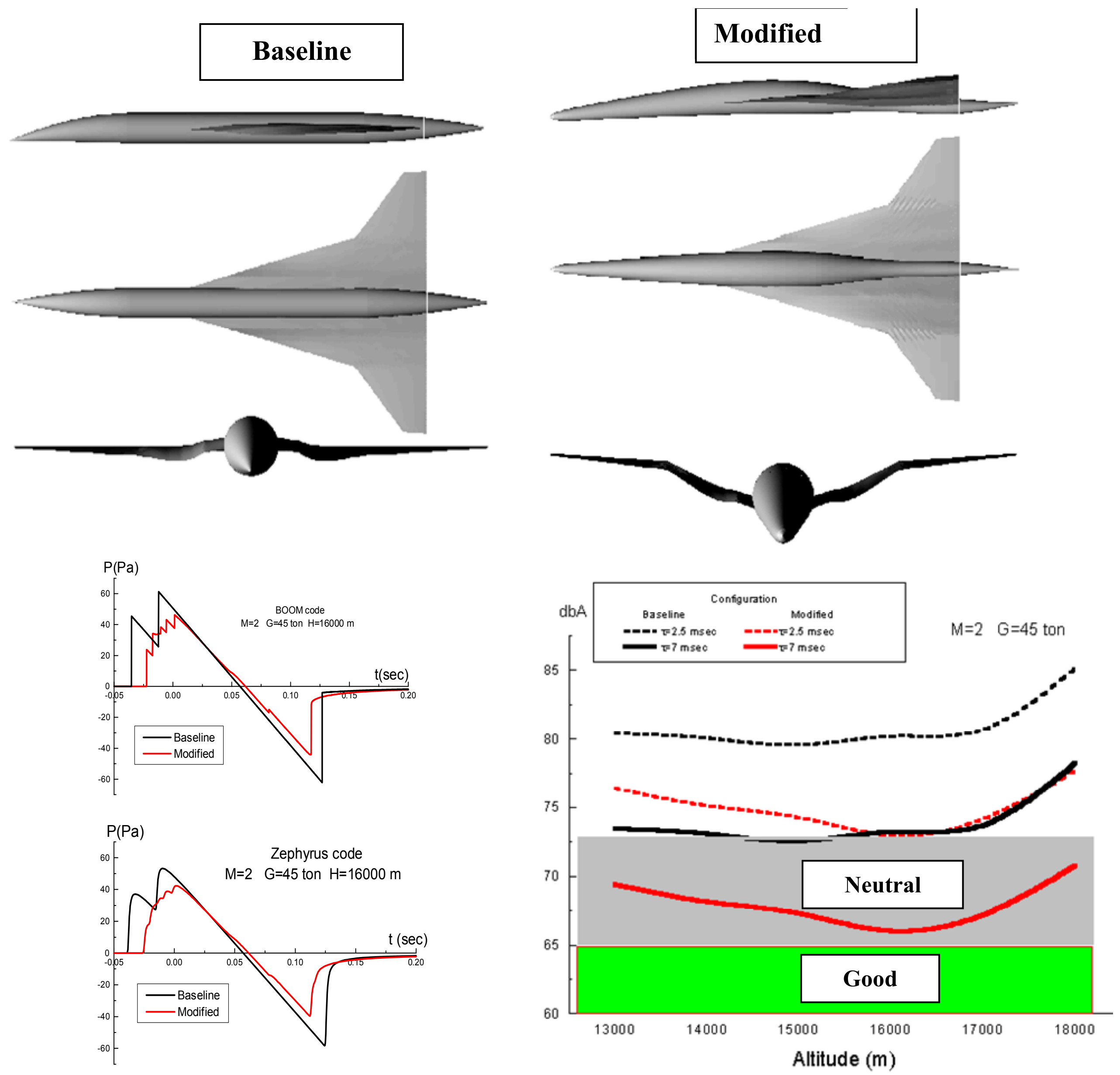

Fig.6. Influence of special configuration forming on sonic-boom signatures and loudness levels.

Based on recently performed numerous parametric calculations the area of «design-acceptable» variations of SST configuration has been defined.

Two programs were used to calculate a pressure profile in the wave of sonic boom:

- BOOM program that uses a classic theory;

- ZEPHYRUS program that accounts for adsorption and dispersion of frequency components of the package of disturbances.

Initial data for sonic boom task were formed using finite-difference calculation of the flow over bodies in the frame of the model that uses a complete system of Euler equations (XCODE program).

The choice of SST configuration is stipulated by their influence on the sonic boom signature. The results of numerical investigations of the influence of different elements (body, wing, horizontal tail and canard, engine nacelles) on signatures of disturbances near the body and in the sonic boom wave are summarized; influence of some parameters fixing the geometry (distribution of body thicknesses, angles of wing setting and coordinates of wing placing) was summarized as well (see, for example, Fig.6).

Low boom aircraft configuration means not only lower maximum overpressure in a shock wave but smoother pressure distribution *P=f(t)* with no intermediate jumps and, preferably, with prolonged time of shock pressure raise. Besides smoother pressure signature is quieter, having lower loudness.

Results of investigations show the opportunity of creation of SSBJ with mass G ~ 45 tons and general length about 40 meters with “admissible” sonic boom at cruise flight.

The International Science and Technology Center (ISTC) under Project No. 2249 supported some lines of these investigations.

References

[1] Ivanteeva L.G., Kovalenko V.V., Pavlyokov E.V., Teperin L.L., Racl R.G. Validation of sonic boom propagation codes using SR-71 flight test data. *J. Acoust. Soc. Am.*, 111, No. 1, Pt 2. 2002.

[2] Zhilin Yu.L., Kovalenko V.V. On relationship of near and far fields in the sonic boom task. Uchenye Zapiski TsAGI, Volume XXIX, № 3-4, 1998.

[3] Robinson L.D. 1991, Sonic boom propagation through an inhomogeneous, windy atmosphere. *Ph.D. dissertation, University of Texas.*