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DEVELOPMENT OF PHYSICAL METHODS OF THE SUPERSONIC AIRPLANE NEAR-FIELD INVESTIGATION AIMED AT THE SONIC BOOM MINIMIZATION

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Abstract. *New facility for experimental and computational studies of sonic boom from aircraft is designed and manufactured in TsAGI. The equipment was mounted in supersonic wind tunnel with 0.6×0.6 m^2 cross section. Tests were performed at Mach numbers 1.75, 2.0 and 2.25 with the use of two different models, the first being the cone-cylinder body and the second is the simplified supersonic airplane configuration with the triangle wing. The method implies the application of fluorescent pressure-sensitive paints for measurements of pressure distribution in the near field of the model. The experimental facility was designed using modern CFD approaches. Pressure distributions obtained in the near field of the model using the experimental method are compared with numerical simulations based on the software package ANSYS CFX. This comparison enables to estimate the possibilities of both the experiment and numerical simulation in prediction of the shock waves formation in the near-field of the disturbed flow.*

1 INTRODUCTION

The problem of the sonic boom influence on people and the environment became acute at the beginning of the 70th of the last century when the Soviet Tu-144 and the British-French “Concord” supersonic jets appeared in the sky. Flights of the civil passenger aircrafts with their regularity and proximity to big cities leads the sonic boom problem into the focus of interest. The opinion of its low importance and far-fetched nature was quickly replaced by anxiety and introduction of restrictive measures [1].

In the USA, the Federal Aviation Agency (FAA) prohibited flights of aircrafts at the supersonic speeds over the populated areas. The flights of aircrafts which can generate the sonic boom approaching the USA territory were also forbidden. In France and the UK such restrictions were not introduced at the state level, but the airlines did not allow flights with the sonic boom creation over the densely populated regions of these countries.

In the Soviet Union after the beginning of Tu-144 aircraft exploitation the state standard (GOST 23552-79) was introduced which allowed the flights of the supersonic commercial aircrafts over the populated regions. The sonic boom level of 90 Pa ±20 Pa in the real atmosphere conditions was pointed out as acceptable one.

After certain weakening of interest to the supersonic transport in the 80th due to its economical inefficiency, at the beginning of the 90th leading aviation countries and companies developed the investigations of possibility and expediency of creation of the second generation supersonic transport (SST-2). The topicality of this task is not decreasing nowadays. Special interest is shown in the small-size supersonic business jets (SSBJ) with the mass of 40 to 60 tons.

The aviation community closely approached to practical realization of the idea to create a new type of the airplane. Researches in this direction are made by “Lockheed-Martin” and “Gulfstream” companies in the USA, and by “Dassault Aviation” in the EU. In Russia such projects are supported by Sukhoi and Tupolev leading aviation design bureaus in cooperation with Central Aerohydrodynamic Institute (TsAGI) and Central Institute of Aviation Motors (CIAM).

Toughening of ecological demands to future generation of the aviation transport implies first of all the solution of the sonic boom problem for supersonic civil aviation. The International Civil Aviation Organization (ICAO) ordered airlines to avoid unacceptable situations for people with the sonic boom (ICAO resolution A33-7, 1998) and requested the ICAO Council to take action to achieve an international agreement about measuring the sonic boom, quantitative and qualitative definition of the expression "unacceptable situation for the population" and establish appropriate limits (ICAO resolution A38-18, 2013).

Since the requirements to aircraft configurations for reducing sonic boom and for increasing the aerodynamic quality are in contradiction, so for configurations with reduced level of sonic boom the problems occur to ensure acceptable aerodynamic characteristics and, consequently, economic efficiency of the aircraft.

Theoretical analysis of the phenomenon of sonic boom has now reached a sufficiently high level. In particular, in TsAGI algorithms and computer programs are developed on the basis of which formulated recommendations for the formation of the SST configurations of different classes with a reduced level of sonic boom. The redistribution of the fuselage thickness, the deformation of its axis and different V-shape of the wing root and tip parts are used [2].

2 METHODS OF EXPERIMENTAL STUDIES OF THE SONIC BOOM

At present, in view of the difficulties in direct numerical simulation of the sonic boom phenomena, the calculation is based on an integrated approach. This approach consists in defining the parameters of disturbed flow in near field region using numerical methods based on integrating Euler equations or Reynolds-averaged Navier-Stokes (RANS) equations, and then calculating the parameters of the sonic boom at greater distances from the aircraft using the quasilinear theory [3]. When performing such calculations, a number of problems appear associated with both the description of the complex geometry of the aircraft and long computational domain (hundreds of plane lengths), where levels of disturbed pressure vary by several orders of magnitude. In this regard, the selection of complex configuration that provides low level of sonic boom and acceptable aerodynamic efficiency should go hand in hand with experimental research aimed at obtaining more reliable information.

Full information about the parameters of the sonic boom wave generated in the real atmosphere, may be provided by the flight experiment. However, at the stage of research on the formation of the aircraft configuration, flight tests are extremely expensive, and their results are heavily dependent on atmospheric conditions, precision of the flight regimes simulation and other factors, and the information obtained is limited to existing types of aircrafts.

Wind tunnels (WT) allow simulate with good accuracy the appearance of waves of sonic boom that provides the opportunity to explore:

− the influence of the body shape and flow regime;
− the influence of the lift force;
− the influence of spatial effects;
− the influence of flow non-uniformity;
− the interaction of shock waves;
− minimization of the sonic boom.

3 SONIC BOOM SIMULATION IN THE WIND TUNNELS

The possibility of modeling in WT the area of disturbed flow generated by a model of the aircraft, are determined by the transverse dimensions of the test section and the characteristic dimensions of the model. The size of this area (height) is determined by the similarity parameter, equal to the ratio of the realized model distance from the measuring base *(H)* to the length (or diameter) of model - $K = H/L$. The size of the near field is about the length of the aircraft *($K \sim L$)*. The far zone, where the profile shape of the perturbed pressure acoustic shock wave is transformed into *N*-shaped wave, and the parameters are changed virtually asymptotic is implemented at distances corresponding to hundreds lengths of the aircraft. The middle zone, being intermediate between the near and far zones, is characterized by the presence of the intermediate shock waves generated by the aircraft layout basic elements, such as wing consoles and nacelles. When the model length $L = 0.1$ m, even for implementing the removal coefficient $K = 100$ the transverse dimension of the supersonic flow should be 10 m, which indicates a limited ability of the sonic boom modeling in existing WT.

3.1 Experimental and computational method of the sonic boom modeling

The combined experimental and computational method allowing to determine full disturbed flow field generated by the supersonic airplane was developed in ITAM SB RAS [4, 5].

The method is based on measurement of the flow characteristics in the near field of the model mounted in the wind tunnel test section, and then calculating the evolution of the measured pressure profiles at the long distances considering 2D or 3D character of flow [6].

Experimental part is based on modeling of the sonic boom near zone in the WT of small dimensions T-313 (0.6 × 0.6 m) and T-325 (0.2 × 0.2 m) with relatively large models. In this case, the disturbed pressure measurements near model are performed either with a special plate with array of pressure taps, or using the measuring probe in a dynamic mode (i.e. during continuous movement of the model relative to the probe).

3.2 Implementation and development of experimental and computational method of the sonic boom modeling in TsAGI wind tunnels

TsAGI assumes the introduction and development of the experimental-computational method of the sonic boom modeling in large industrial wind tunnels. At the first phase, this method is expected to be introduced into T-113 WT (similar to ITAM T-313).

For this purpose, the bench for implementation of the experimental and computational method of the sonic boom studying was designed and mounted in T-113 wind tunnel. As stated above, for the static pressure field measuring in similar situation ITAM specialists used the coordinate mechanism with a probe or a special plate with pressure taps rows. In TsAGI the static pressure fields on the measuring plate surface were measured using the fluorescent pressure transducers (pressure-sensitive paints, PSP). Application of the PSP method should in principle ensure the acquisition of continuous pressure distribution on the control surface in the near-field of the model, calculation of Zhilin's integral [7] on its basis and definition of the sonic boom wave profile at large distances using the quasi-linear theory. Yu. L. Zhilin showed that the desired asymptotically-remote solution at the certain assumptions may be associated with the near-field integral over a surface S_2, placed at a relatively small distance from the airplane (about 0.1-0.5 of its length, Figure 1).

The surface enveloping the control volume (Figure 1) is as follows. The surface S_1 is a boundary between the disturbed and undisturbed flow (Mach cone), S_2 plane is parallel to the x axis is located under the tested body without touching it. On this plane the isolated segment AB is outlined with points A and B lying on the intersection of plane S_2 and surface S_1. Planes S_3 and S_4 are the envelopes of the inverse Mach cones emanating from the segment AB.

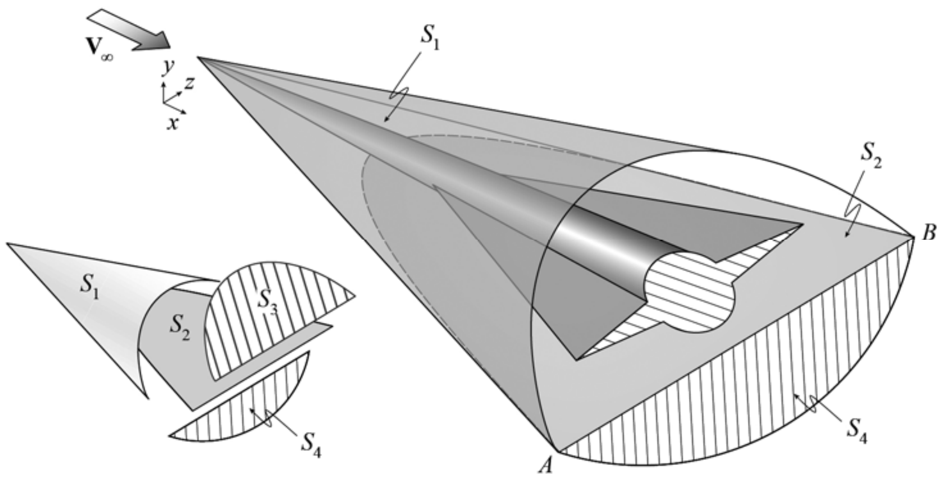

Figure 1: Control volume of the supersonic flow over the airccraft configuration.

In the case when the plane S_2 and the segment AB are perpendicular to the axis of y, for the direction "straight down", Zhilin's integral gives the following expression for calculation of derivative of the cross sectional area of the equivalent body of rotation S_{eq} :

$$\frac{dS_{\mathrm{eq}}(x_0)}{dx_0} = -\frac{1}{V_\infty}\int_{z(A)}^{z(B)}(\beta u + v)dz = -\frac{2\beta}{V_\infty}\int_{z(A)}^{z(B)} u dz = -\frac{2}{V_\infty}\int_{z(A)}^{z(B)} v dz. \quad (1)$$

Here x_0 — coordinate of the point of intersection of the S_3 with the axis x; u and v are components of the vector of the perturbed velocity along the axes x and y, $\beta = \sqrt{M_\infty^2 - 1}$. For an arbitrary direction the coordinate system (x, y, z) may be selected so that the plane S_2 and the segment AB are perpendicular to the axis y.

An important feature of the formula (1) is that at the fixed position of the plane S_3 it is possible to change the distance of the plane S_2 from the x-axis. For example, we can place this plane at a sufficient distance from the body so that the provisions of the linear theory would be valid (R ~ 0.3...0.5 L), but at the same time a lot closer than it is required to establish the asymptotic behavior of the solution (R ~ 3...5 L).

PSP-method is based on the phenomenon of quenching of the organic luminophors luminescence by air oxygen. For implementing the method, the studied surface is covered with special paint which is a thin layer of polymer permeable to oxygen and containing molecules of the luminophor. The luminophor is excited by light of appropriate wavelength and then the luminescence intensity or the life time of excited molecules is measured. The luminescence intensity and lifetime is inversely proportional to the pressure. To control the accuracy of the PSP-method the measuring plate has a row of pressure taps in the central section.

The designing of the test bench in T-113 wind tunnel was carried out with the assistance of modern software tools of computational fluid dynamics. The main goal of mathematical modeling was to predict the flow structure in the near field of the model and calculate the distributions of the overpressure generated on the measuring plate. The simulation was carried out using the software ANSYS CFX [8] (TSAGI license No. 501024), based on solving the Reynolds-averaged Navier-Stokes equations.

The shock waves propagating from the model fall on the plate interact with the boundary layer and generate reflected shock waves. There is a complex three-dimensional flow pattern and interaction of shock waves with the boundary layer on the measuring plate and with each other. In order to adequately resolve the most important (from the physical point of view) phenomena, in the regions of interaction between shock waves and boundary layer on the plate surface the construction of appropriate mesh is required. An example of such a computational mesh is shown in Figure 2, [9].

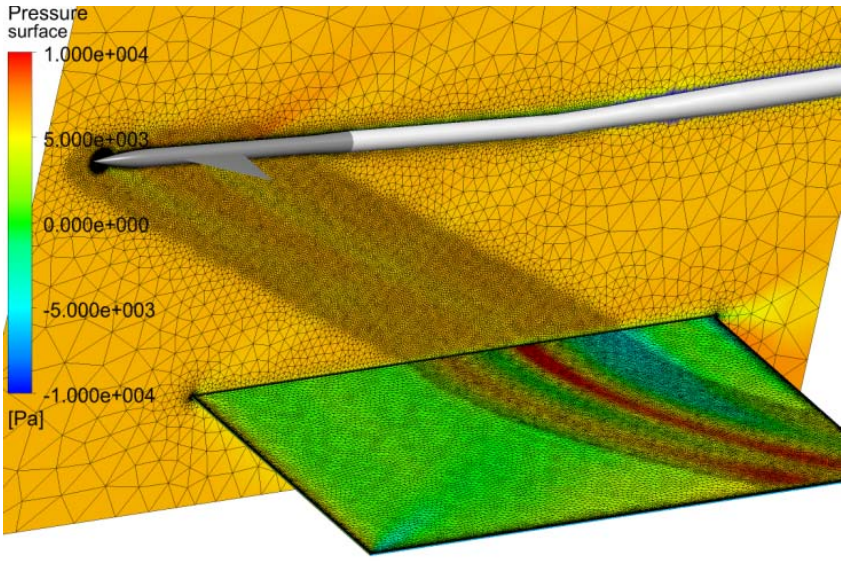

Figure 2: View of the spatial structure of the computational mesh in the symmetry plane and on plate surface for modeling the propagation of shock waves on the plate

The results of mathematical modeling were also used for comparison with the experimental data. Comparison with the experimental pressure distribution on the measuring plate mounted at a certain distance from the model in the WT test section, allows for evaluating the possibility of experiment and numerical simulation in predicting the formation of shock waves in the near zone of disturbed flow.

In the supersonic T-113 wind tunnel selected for testing a new technique there is no optical windows on the top and bottom walls of the test section and the PSP method has never been used here. Existing side-wall widows designed for Toepler device, do not pass ultraviolet radiation required for the excitation of the PSP. It was decided to use PSP, which is excited by soft ultraviolet radiation passing through the side windows of the WT. This sensor was invented and widely used in the USA [10] (in Russia is not patented).

For fluorescence excitation the LED illuminator was used, and the luminescence was registered by two CCD cameras "VIDEOSCAN-V2-285/P1-33" with multiple exposure mode. Two cameras are needed to measure the lifetime of the luminescence. At the time of measurement LED illuminator flashed for 100 μs with a period of 220 μs (4.54 kHz), while one camera has been accumulating the light intensity of the coating during the flash (first 50 μs), and the second after the flash for 110 μs.

The experimental studies were carried out both without models in the test section of WT and with two generating near-field models representing a schematized supersonic delta-wing plane and the axisymmetric cone-cylinder configuration. The tests were conducted at three Mach numbers: M = 2.0, 2.25 and 1.75. The scheme of the model and the measuring plate arrangement in the WT test section is shown in Figure 3.

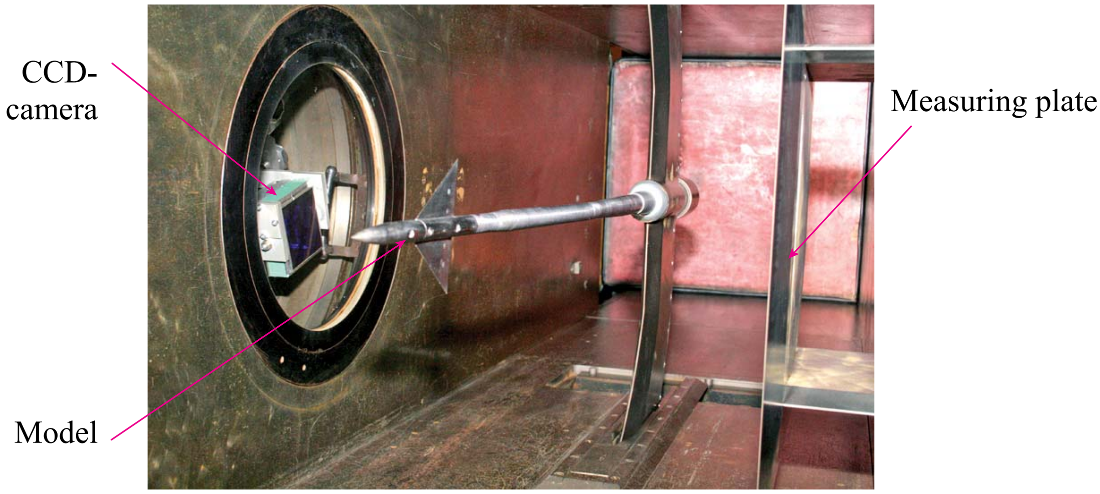

Figure 3: Experimental equipment in TsAGI T-113 WT.

The comparison of calculated and measured (using the PSP-method) pressure coefficient distributions on the measuring plate when the shock waves are generated by the delta-wing plane model at M = 2 are shown in Figure 4.

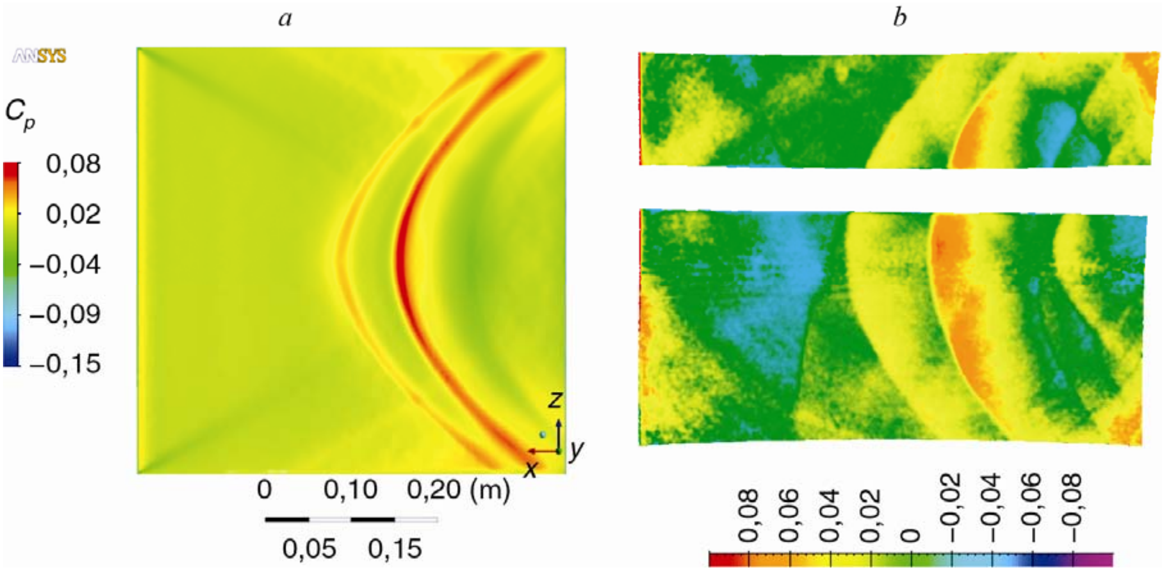

Figure 4: Pressure coefficient distributions over the measuring plate generated by the delta-wing plane model at M = 2: CFD prediction (*a*), PSP-measurements (*b*).

As can be seen from the above data, the position of the shock waves arriving at the measuring plate from the model agrees well with the CFD results.

Pressure perturbations registered by the control plate when testing models contain disturbances of an empty WT. To improve the results of pressure distribution measurements on the control plate, the background distributions obtained in empty WT are subtracted from the initial data. Then, on the basis of the Zhilin's integral [7], the derivative of the cross section area of equivalent body of revolution and pressure coefficient at the middle cross section of the measuring plate is calculated. The procedure of subtraction of "background" values of the pressure coefficient distribution registered by the measuring plate in empty WT, can significantly improve the final pressure distribution and the derivative of the cross section area of equivalent body of revolution. These results are used further to determine the intensity of the sonic boom wave on the ground.

Sonic boom can be calculated using as the derivative of the cross-section area of the equivalent body of revolution *dS/dx* and the pressure distribution in the initial sound wave, however, the calculation with the use of *dS/dx* should give a more accurate result. Red color in Figure 5 shows the distribution obtained from the numerical solution of the Euler equations.

Comparison of the results obtained by numerical methods with the experimental data of the first tests allows us to make conclusions about the prospects of the PSP-method in the studies of the near-field of aircraft models in the supersonic wind tunnel. At the same time, the analysis of the experimental results and their processing to obtain the source data in the form of derivative of area of the equivalent body of revolution showed the following:

1) In the WT tests without models, high level of the background disturbances is detected. Sometimes these disturbances are of the same order of magnitude as the values, induced by the shock generators (configurations "wing-body" and "cone-cylinder").

2) Flow disturbances, generated by tested configurations ("wing-body" and "cone-cylinder") may be effectively refined by means of subtraction of the corresponding background pressure coefficient field.

3) In further research on determination of initial data for solution of the sonic boom problem it is necessary to improve the accuracy of the pressure coefficient measurements.

4) For further studies some geometrical parameters should be changed, for example, it is necessary to place the measuring plate closer to the model. This should lead to higher levels of induced perturbations, reduce the impact of side effects on the edges of the plate and to ensure more uniform flow on it.

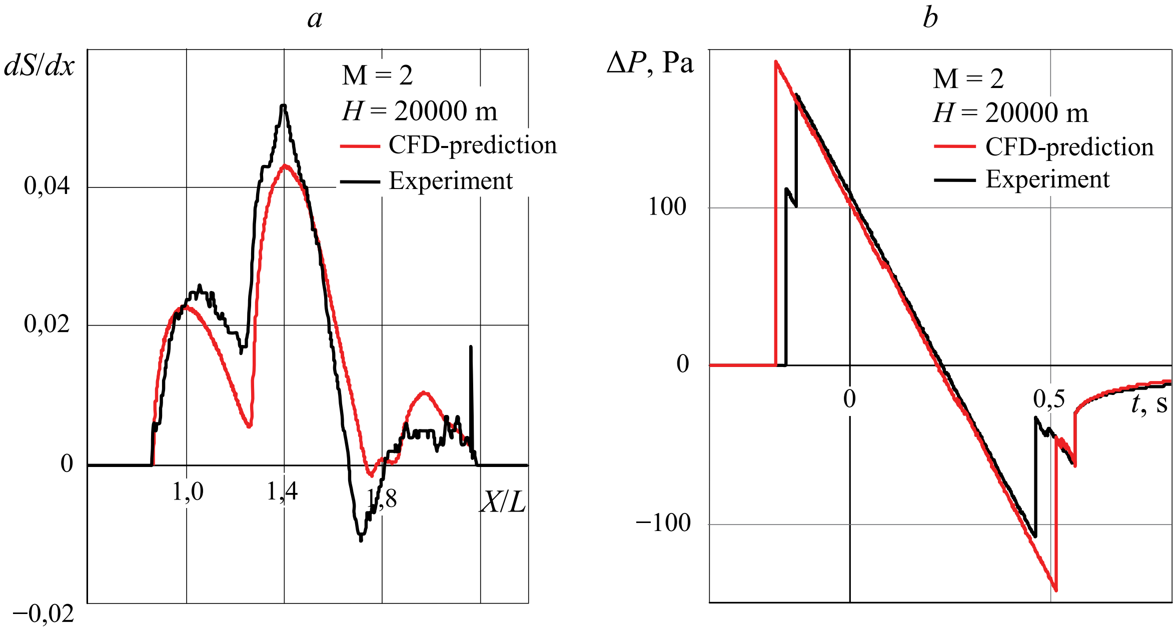

Figure 5: Distribution of the derivative of the cross-section area of equivalent body of revolution used for the sonic boom prediction (*a*), and the shock wave signature (*b*).

4 CONCLUSIONS

- On the basis of numerical simulation results, the test bench for sonic boom studies is designed and assembled in TsAGI T-113 WT. New test bench should allow for realization of experimental and computational method of the sonic boom prediction.
- For measurements of the static pressure distributions in the model near-field (on the measuring plate surface) the pressure-sensitive paints (PSP) method is used. Application of the PSP method should in principle ensure the acquisition of continuous pressure distribution on the control surface in the near-field of the model, calculation of Zhilin's integral on its basis and definition of the sonic boom wave profile at large distances using the quasi-linear theory.
- In the WT tests without models, high level of the background disturbances is detected on the measuring plate surface. Sometimes these disturbances are of the same order of magnitude as the values, induced by the shock generators (configurations "wing-body" and "cone-cylinder").
- Flow disturbances, generated by tested configurations ("wing-body" and "cone-cylinder") may be effectively refined by means of subtraction of the corresponding background pressure coefficient field.
- In further research on determination of initial data for solution of the sonic boom problem it is necessary to improve the accuracy of the pressure coefficient measurements. Recommendations are drawn for changes in some geometric parameters of the test bench.

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