PROGRESS OF AERODYNAMIC RESEARCH AT THE INSTITUTE OF THEORETICAL AND APPLIED MECHANICS, SIBERIAN BRANCH, ACADEMY OF SCIENCES OF THE USSR

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From the very beginning of the foundation of the Institute of Theoretical and Applied Mechanics (ITAM), its founder, the eminent scientist in mechanics Academician S. A. Khristianovich, promoted the solution of practical aerodynamics problems as one of the major scientific directions. Theoretical investigations were initiated in the areas of transsonics, supersonics, and hypersonics (theory of short waves, wing theory, jet flow, and so on). The foundation was laid for the development of experimental aerodynamics which became the center of organizational and technical objectives when the Institute came under the direction of Acad. V. V. Struminskii. During the short period (1966-1969) the wind-tunnel T-313 was considerably modernized, the low turbulence tunnels T-324 and T-325 were built and became operational, and hypersonic facilities IT-301, T-326, T-327, etc., were developed. During the same period fundamental and applied research were initiated in hydrodynamic stability, turbulence, and rarefied gas dynamics. In the following years under the guidance of Acad. N. N. Yanenko, further progress was made in these directions mainly on account of the widespread use of modern computational techniques. A computer base has been set up, including the computers BÉSM-6, Elbruce-1 K-2, and also a series of minicomputers with all the major wind-tunnel facilities. The presence of a well developed computer base made it possible to analyze and create specialized complexes and groups of applied programs based on modern numerical modeling methods.

Thus, during the preceding decade, a balanced experimental and computational base had been created at the Institute which made it possible to organically synthesize experimental and numerical methods in the solution of fundamental and applied aerodynamic problems. This is especially important since the adequate modeling of complex three-dimensional flows which is necessary for flight and other technologies cannot yet be achieved either in wind tunnels which have design and economic limitations or in numerical experiments where the limitations are associated with the lack of sufficient understanding of the physics of turbulent flows. Hence, it is possible to conclude that significant progress in aerodynamics takes place through a symbiosis of computational and physical experiments which complement each other. Considering the continuous progress made in computational aerodynamics and the growing application of computers in aerodynamic experiments, it is possible to forecast an increased effectiveness in the solution of promising aerodynamic problems with more accurate modeling of physical phenomena.

A description of the automated aerodynamic complex at ITPM and a summary of some of the most significant scientific achievements are described in this paper.

1. At present the wind-tunnel complex of the Institute [1] covers the Mach number range 0.01 to 25 and Reynolds number from 10^4 to $50 \cdot 10^6$, which make it possible to model flow conditions at altitudes from 15 to 90 km (Fig. 1), conduct basic research on the fine structure and characteristics of complex laminar and turbulent flows from low subsonic to hypersonic speeds, including the transition region between continuous media and rarefied gas.

One of the critical similarity parameters in aerodynamics along with the fundamental (M and Re) is the turbulence level in the flow. The solution of the basic problems in viscous fluid dynamics requires the design of wind tunnels with low freestream turbulence. Such objectives were met in the wind tunnel T-324 (Fig. 2, 1×1 m^2 test section, speed range 5 to 100 m/s) in which special techniques were used to achieve 0.02% turbulence level in the test section. This wind tunnel was used to obtain fundamental results in the origin of turbulence

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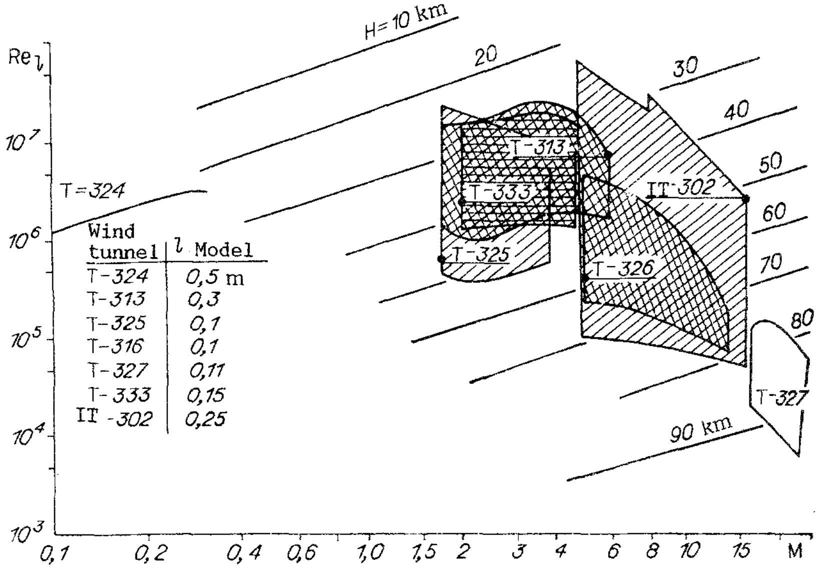

Fig. 1

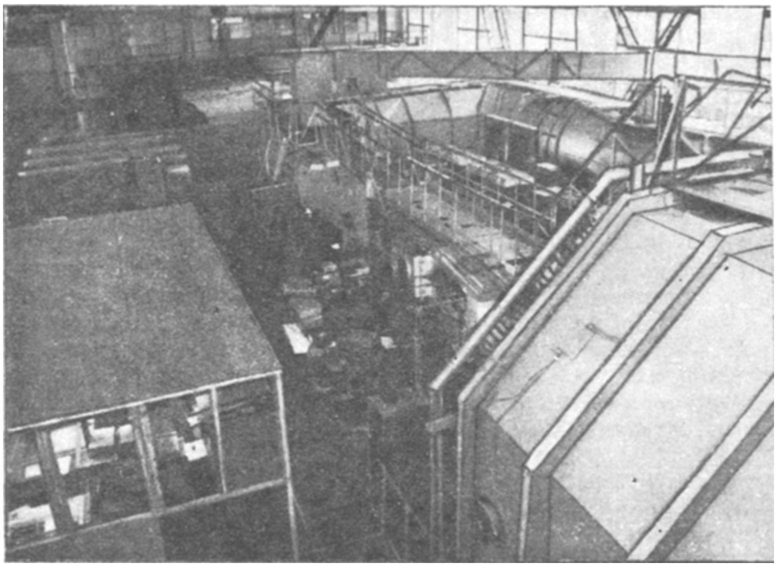

Fig. 2

[2], nonstationary processes in separated flows [3], structure of three-dimensional turbulent boundary layers [4], interaction of external disturbances with coherent structures in turbulent flows [5], and shear flow control [6].

The supersonic wind tunnel T-313 (0.6 × 0.6 m^2 test section, M = 2-6) has a high quality flow and an extremely well developed instrumentation-computer complex. Significant modernization of its basic components, carried out from 1967 to 1985, made it possible to extend the Mach number range to M = 6, reduce pressure fluctuations in the settling chamber by an order of magnitude (up to 0.1%) and further develop measurement automation and control systems. The unsteadiness in test section velocity field was maintained at a level not exceeding 0.5%. Repeated measurements of accuracy and agreement in the aerodynamic characteristics of standard models with similar data obtained in aerodynamic research centers in USA, France, and FRG (Fig. 3) speak well of the high flow quality and accuracy of the state of the art measurement complex of the wind tunnel T-313 which make it one of the best wind tunnels of such a class. A wide spectrum of basic and applied problems in aerodynamics was solved in this tunnel (two- and three-dimensional separated flows [1], complex three-dimensional corner flows [4], aerodynamic interference of different flight vehicle components [8]. boundary-layer transition on different models [9], aerodynamics of nonplanar wings [10], etc.).

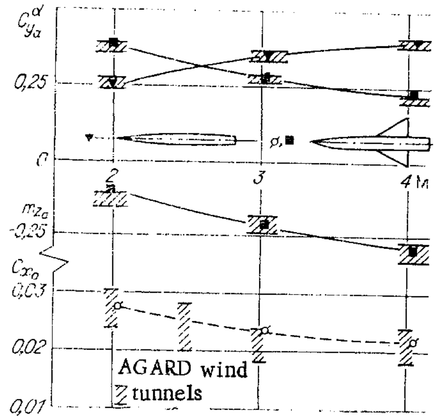

Fig. 3

The wind tunnel T-325 (0.2 × 0.2 m^2 test section, M = 2-4) is intended for flow physics research. Detailed information on fluctuating flow characteristics in the test section and disturbance sources made it possible to study the nature of their development in supersonic boundary layers of models depending on the level and spectral content of freestream disturbances. The instrumentation complex for the wind tunnel includes in-house developed constant current hot-wire anemometer [11] with a frequency band up to 200 kHz, which ensures correct measurement of turbulent characteristics at supersonic speeds. Important results have been obtained on the stability of laminar boundary layers [12], the structure of separated flows, shock-boundary layer interactions [13] and others.

The wind tunnel T-326 with Eiffel chamber (nozzle diameter 0.2 m) [14] produces a range of hypersonic speeds. For M = 6-8 a resistance heater is used to heat the air and for M = 10-14 a plasma (heater) is used. The single-pass wind tunnel contour, the set up for quick model installation in the flow, and the special optical mirror system make it possible to conduct research on aerodynamic heating and aerothermodynamic dissociation.

The hypersonic tunnel T-327 (nozzle section diameter 0.22 m, M = 16-25) uses nitrogen of high purity as the working fluid which is heated in a unique graphite heater up to 2500 K. Flow condition with stationary values of all parameters (M_0, p_0, T_0) were realized with explosive start-up. The instrumentation for this tunnel includes unique strain gauge balances, electron-beam diagnostics (flow visualization, velocity measurement using phosphorescence of nitrogen, density and temperature fluctuations in the flow), and also thermal visualization and heat flux fields, developed at ITPM [15]. Such a tunnel is unique in the USSR. Basic and applied experimental research are conducted in this tunnel. In particular, the heat transfer at M = 20 [16] and homogeneous condensation [17] have been investigated. Theoretical studies on the structure of hypersonic flow at the molecular level formed the basis for the application of electron-beam diagnostics [18].

The hypersonic shock tube IT-302 (nozzle section diameter 0.3 m, M = 5-12) unlike other known similar facilities, has constant stagnation parameters p_0 and T_0 at test conditions (50-100 msec). This is achieved by forced displacement of working fluid using pressure multiplier [19]. The creation of such a tunnel at the Institute significantly extended the scope of solving problems on aerodynamic heating, supersonic combustion, external and internal gas dynamics.

The tunnel T-333 is meant for modeling flight stagnation temperature at supersonic speeds (test section diameter 0.3 m) [20]. It is equipped with resistance heater of air with 8000 kW power which allows flight stagnation parameters for M = 2; 2.5; and 3 and parameters close to the flight for M = 4 and 5, at wide range of flight altitudes. It is used to study supersonic combustion, heat and mass transfer, jet interaction with extenal flow and stress.

The large complex of methodical experiments in the entire range of parameters indicates good flow quality in the test sections of all facilities.

The standard as well as new measurement techniques have been widely used in experiments: excitation of disturbances in boundary layers of models using vibrating ribbon (T-324) and electric arc discharge (T-325); visualization of three-dimensional flows using smoke-wire

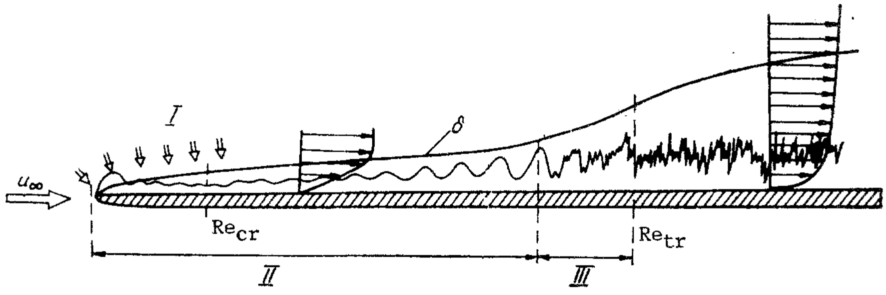

Fig. 4

technique (T-324), "laser knife" (T-313); measurement of temperature heat flux fields using liquid crystal techniques (T-326), thermal visors (T-327); measurement of static pressure field on the basis of multichannel pressure transducer MID-100 using suspended orifice tube applied to thin wings with subsonic leading edge (T-313); simultaneous measurements of individual interference components of aerodynamic characteristic (T-313); measurement of velocity and density in hypersonic flows using electron-beam diagnostics (T-327); measurements of turbulence characteristics in supersonic flows using hot-wire anemometer developed at the Institute, TPT, and others.

Practically all types of experiments are automated. In accordance with the concept of the automation of scientific studies conducted at the Institute, a trilevel system has been developed using the computers "Électronik-60", SM-3, SM-4, and BÉSM-6, which sequentially collect information and carry out the first and second analysis of measured data [21]. Each experimental facility is equipped with data-logging and processing system including analog and pneumatic commutators, analog—digital converters, the apparatus KAMAK, external printer and graphic plotters and others. The initially processed information enters BÉSM-6 where the data base is concentrated in order to collect, analyze, and secondary analysis of the results of series of experiments. The system thus developed significantly enhanced the effectiveness of conducting a number of experiments. Here it became possible, in interactive mode, to compare experimental data with computed results, obtain the necessary empirical data to improve the computational model and so on. Thus, such an automated system demonstrates the possible path to overcome the shortcomings of modeling in wind tunnels as well as the limitations of computational methods. According to the conclusions of the interdepartmental reception committee it "ensures the conduction of fundamentally new types of aerophysical research, enhances the quality and reduces the time required to conduct conventional aerodynamic investigations."

The wide experience gained at TsAGI (Central Aero-Hydrodynamic Institute named after Zhukovskii) was used in the design of a number of wind tunnels. For the development and the creation of automated aerodynamic complexes the group of scientists from ITPM, TsAGI, and the Scientific Research Institute (NII) of Mechanics of MGU (Moscow State University named after Lomonosov) received award from the Council of Ministers of USSR in 1985.

2. The problem of the origin of turbulence with more than a hundred-year history of investigations still remains one of the central unsolved fundamental problems of mechanics. Significant progress in the understanding of processes leading to the appearance of turbulence has been made during the last 10-15 years. Two special symposia of the International Union of Theoretical and Applied Mechanics (IUTAM) were devoted to the discussion of results. An independent reflection on the recognition of achievements of ITPM in this area was the holding of the latest of these symposia at Novosibirsk (1984). The formulation of the problem of the origin of turbulence at ITPM dates back to the end of 1960s and the beginning of 1970s. As a result of aerodynamic direction of the Institute the attention was focussed mainly on processes taking place in boundary layers. Results of studies are reflected in [2, 6, 22-26] and also in many publications of scientific periodicals.

The process of the origin to turbulence in boundary layers can be schematically expressed in terms of three stages (Fig. 4), where I is the transformation of external disturbances (freestream turbulence, acoustic excitation and vibrations) into characteristic waves of the boundary layer; II is the linear development of characteristic waves (the so-called Tollmien-Schlichting (TS) waves); III are the nonlinear processes of the growth and interaction of characteristic waves leading to the destruction of laminar flow and the appearance of turbulent conditions.

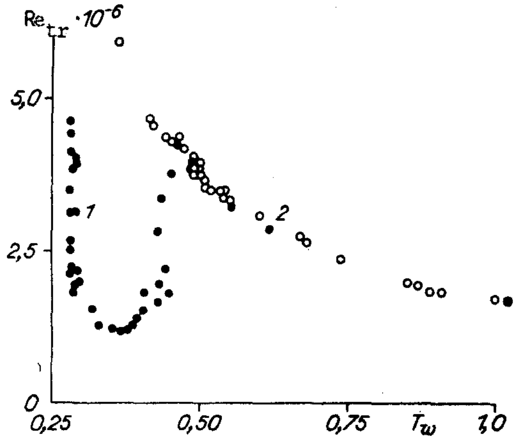

Fig. 5

The linear stability theory to describe the growth of disturbances in stage II was well developed at ITPM by this time. However, the results of classical "nonparallel" theory were only in qualitative agreement with experiment. Detailed experimental study of the flow structure in the linear disturbance growth region showed significant influence of weak nonparallelness of boundary layer flow [2]. Experimental results established reliable basis for the correction linear theory (Saric and Nayfeh (USA), V. N. Zhigulev et al. (USSR)). Nonlocal stability theory has been developed for periodic flows as in the case of flow past wavy surfaces and with the superposition of acoustic field [2, 27], and also for flow past porous surface [23]. Experiments have supported the nonlocal theory [2]. As a result of these and other theoretical and experimental studies [28] it is possible to confidently state that the linear segment of the disturbance growth is adequately described by hydrodynamic stability theory for subsonic flows.

It is somewhat more complex for supersonic and especially for hypersonic boundary layers. If the most amplified waves in the linear region of subsonic flows are plane waves, at supersonic speeds the most amplified disturbances travel at some angle to the mean flow direction. This situation makes it difficult to conduct sufficiently accurate experiments. In spite of the many efforts (Laufer, Vrebalovich, Kendall, Dimetriades (USA)), reliable experimental data on the growth of disturbances in supersonic boundary layers did not exist. Only during the most recent times it was possible to obtain them through the introduction of wave packets in boundary layer with subsequent computational analysis of measured data using spatial Fourier transforms [29]. On the other hand, computations of stability characteristics of supersonic flows do not pose major difficulties at present. Such computations aimed at estimating the influence of various factors (heat transfer, pressure gradient, chemical reaction, etc.) on the stability of supersonic boundary layers were carried out over a wide range of parameters [23, 30]. However, the question of total adequacy of theoretical models used in computations to actual process is still open. In this connection it is interesting to refer to the history of the search for an explanation for reverse transition. Even in the 60s, experiments here as well as abroad showed that in supersonic boundary layer, surface cooling results initially in stabilization (an increase in transition Reynolds number) corresponding to the linear stability theory but subsequent more intense cooling leads to a strong destabilization followed by a similar sharp stabilization (Fig. 5). Reshotko (USA), apparently, found an explanation for this phenomenon on the basis of the asymptotes of the stability equation suggested by him. However, numerical integration of more complete equations [23] contradicted the conclusions of the asymptotic theory and the problem remained open many years until it was experimentally shown that the double transition reversal is the result of the test conditions (conditions for the formation condensate at the model surface) [31]. This is demonstrated in Fig. 5 where the dependence of transition Reynolds number Re_{tr} on surface temperature is shown in the presence of condensation at the surface (point 1) and in its absence (point 2).

The foundation for theoretical models of nonlinear processes (zone III, Fig. 4) for a long time was based on the experimental results of the National Bureau of Standards (NBS, USA) published during the 50s and 60s and a number of others, practically repeating them. These experiments gave detailed information on the growth of disturbances at the transition to

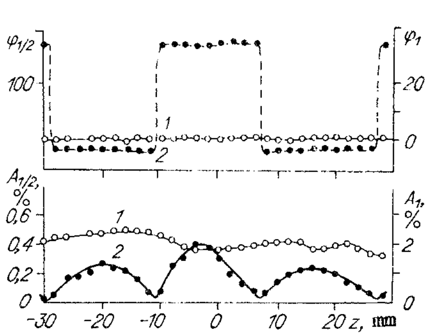

Fig. 6

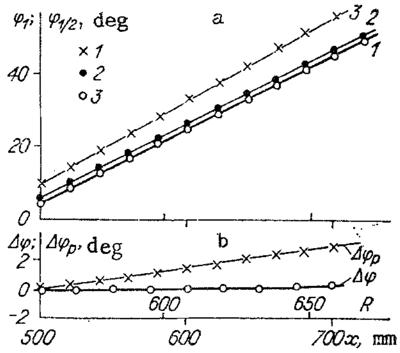

Fig. 7

turbulence during the stages of development of three-dimensionality of the disturbance field with relatively large initial amplitudes of waves excited in the boundary layer. For the transition process with nonlinearity introduced at the very initial stages there is a characteristic sharp amplification of disturbances at each period of the fundamental TS wave. Such a phenomenon was associated with secondary (high frequency) instability. The cause of transition for the two-dimensional picture of disturbance growth in the linear region to significant three dimensionality is not explained.

In the experiments of ITPM devoted to nonlinear processes, the disturbance growth was followed, starting from the linear stage when small amplitude disturbances are excited in the boundary layer. It was found that the transition process developed not exactly as in the experiments of NBS (called the K-type transition, named after Klebanoff, one of the authors). Instead of the high-frequency instability, the generation of a packet of low frequency fluctuations was recorded, and, what is especially important, subharmonic disturbance was discovered for the first time, i.e., wave with frequency equal to half the fundamental TS frequency. The important role of higher harmonics interacting with low frequency fluctuations was observed. In fact a new type of transition to turbulence in boundary layer was discovered [2]. It is extremely important that it is realized with small initial amplitude of disturbances and, probably, occurs under natural flight condition in the atmosphere which is known to have very low level of such turbulence scales.

Theory suggested a possible mechanism for the generation of subharmonics. Computations carried out in [32] showed rapid growth of disturbances with subharmonic frequency due to nonlinear resonant interaction of plane TS wave with a pair of three-dimensional subharmonic waves. Further development of resonant interaction theory [33] gave results which qualitatively as well as quantitatively agreed with experimental data. Detailed experimental study of such a transition process was conducted in [34] and continued in [35]. The results conclusively show that the growth of subharmonics and the entire packet of low frequency disturbances is due to resonant interaction of plane and three-dimensional waves. This is also the cause of the development of three dimensionality of the disturbance field in the nonlinear region. Figure 6 [34] shows the distributions of amplitude A and phase φ of the fundamental wave (point 1, index 1) and subharmonic (point 2, index 1/2) disturbance in the transverse direction relative to the mean flow direction. It indicates that in boundary layer, the development of the fundamental plane wave is accompanied by the development of a pair of waves propagating at equal but opposite angles relative to the direction of the mean flow.

Figure 7 demonstrates the phase synchronism of the fundamental and subharmonic waves (Figs. 1 and 2). Points 3 were obtained for plane wave with subharmonic frequency. Figure 7b shows the difference in phases between the fundamental wave and the spatial $\Delta\varphi$ and plane $\Delta\varphi_p$ subharmonics. A three dimensional distortion of the plane TS-waves takes place in the nonlinear region and a system of Λ-type vortices is formed. Figure 8 [35] is a flow visualization picture using smoke-wire technique and demonstrates the difference between the K- and subharmonic conditions of transition. In the K-type condition, vortices are formed at each period of the fundamental wave and travel strictly one behind the other. In the subharmonic case vortices are distributed in the order of a chess board, and they follow each other with twice the fundamental period. Even the forms of the vortices are different.

Experimental results for the K-type transition in boundary layer [36] indicate the need to reconsider the basic assumptions on this condition. In particular, high frequency

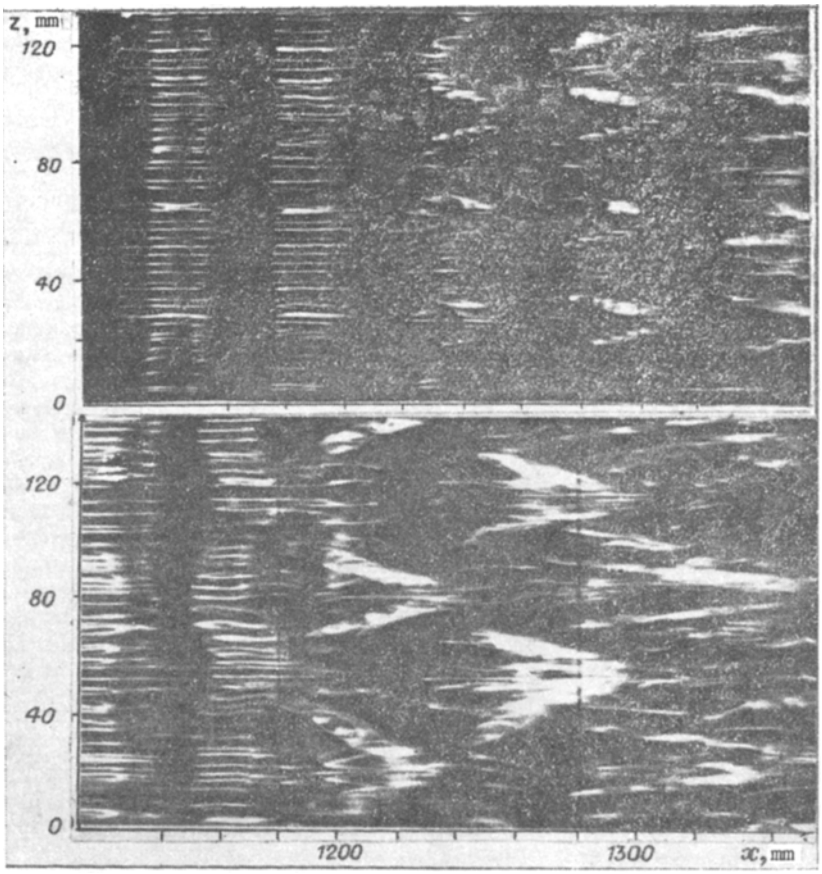

Fig. 8

secondary instability has not been observed and it has been explained that the wave interaction plays the crucial role even in this type of transition process.

In a series of experiments in the plane Poiseuille flow between two parallel flat plates it was found that the transition to turbulence takes place similar to the transition in a boundary layer (contradicting previous theoretical concepts). K-type and subharmonic transition processes have been identified [6, 37]. The experimental results have established the basis for the reconsideration of theory and corresponding computations have been carried out by Gol'dshtik and Shtern (ITF SO AN SSSR*). The interaction of large scale vortex structures with the mean flow during transition to turbulence was theoretically studied [38]. Further development was made with the nonlinear theory of hydrodynamic stability [49], first suggested by Acad. Struminskii in 1960s.

In ITPM, systematic investigations were first carried out for the initial stages of the origin of turbulence, viz., the transformation of external disturbances into characteristic (eigen) fluctuations in the boundary layer. This problem is not trivial since the wavelength and the propagation velocity of external disturbances and TS-waves are inherently different. It has been established, on the basis of a series of experiments, that at subsonic speeds the most intense process of the transformation of external disturbances into characteristic waves takes place in the neighborhood of the concentrated effect on the flow (sharp leading edge, individual roughness elements on the surface and so on), where strong local gradients in the flow direction are present. During these experiments and also in studies on "natural" transition [40], the critical role of the very small surface vibration was observed. Experimental data on the transformation of weak acoustic and vortex disturbances into characteristic waves of the boundary layer was obtained in [41]. In some particular cases it was possible to compute the process of generation of characteristic waves [42, 43]. At supersonic speeds it has been theoretically shown [44] and experimentally confirmed [45] that it is possible to effectively convert external acoustic field into characteristic waves of the boundary layer in the boundary layer itself.

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*ITF SO AN SSSR: Institute of Theoretical Physics, Siberian Branch, Academy of Sciences of the USSR — Publisher.

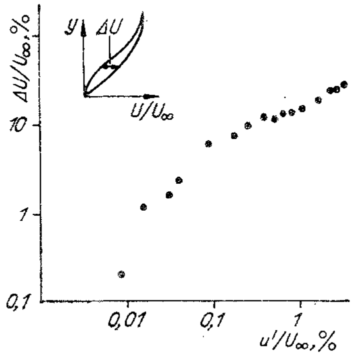

Fig. 9

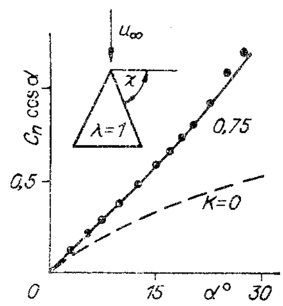

Fig. 10

The solution to the problem of the production of characteristic waves is a necessary step for the development of the complete transition theory since it will ensure the initial conditions for the computation of the linear region and the following nonlinear processes. On the other hand, the study of wave generation processes in the boundary layer and explanation of the role of the concentrated effects were necessary for the development of concepts like the so-called "active" control of transition. Unlike the traditional methods to delay transition (laminarization) by modifying the mean flow in order to increase its stability to small disturbances, "active" control attempts to influence the characteristic wave developing in the boundary layer by another, artificially generated wave of the same type. Obviously, it is necessary to seek effective and, at the same time, practical methods for exciting waves. Such techniques include, e.g., localized surface vibrations, periodic localized boundary layer suction—blowing, etc. Using these techniques, it was possible to significantly delay transition to turbulence in experimental simulation [6]. An understanding of the fundamental processes taking place in subharmonic transition made it possible to develop theory for active control [46].

The methodology for the study of the origin of turbulence in a boundary layer has been extended in recent years to other types of fluid flows. On studying separated flows, it has been established that there is a close relationship between flow separation and instability [3, 6, 47]. In particular, the presence of small linear disturbances U'/U_∞ leads to significant changes in the mean velocity ΔU (Fig. 9). Analogous to the process of generating TS-waves there is a generation of coherent structures in turbulent flows due to external disturbances [5]. It has been discovered that under certain conditions coherent structures can be developed without interacting with each other which suggests that it may be possible to use linear theory to describe them [6].

Thus, as a result of theoretical and experimental studies at the Institute a big step ahead has been taken into the study of fundamental processes responsible for the transition of laminar flows to turbulent condition.

3. Various types of separated flows are some of the most complex and simultaneously the most important problems for further development of aviation, energetics, and shipbuilding. Well-known monographs of Chen (1972), Belotsevkovskii, Nisht (1978), Gogisah, Stepanov (1979) and Borovyi (1983) are devoted to separated flows and give a survey of experimental data, principal directions and computational techniques within the framework of nonviscous and viscous fluid flows. However, the extremely large variety of practical applications and the exceptional complexity of external and internal turbulent flows dictate the necessity and the urgency of further development of computational techniques as well as experimental investigation of three-dimensional separated flows.

At large Reynolds numbers ($Re \to \infty$) the inertial forces acting on streamlined bodies, like flight vehicles, appreciably exceed viscous forces. Hence the lifting characteristics of such bodies could be described by nonviscous flow model. The natural requirements on flight vehicles, as also on low drag bodies, justify the study of the flow past bodies causing small flow disturbances within the framework of potential flow theory when the vorticity regions are represented as free vortex surfaces, and the propagation of disturbance waves in supersonic flow follows laws of acoustics. Such an approach makes it possible to explain the structure of disturbed regions due to flow past complex three-dimensional configurations and in the final analysis determines the aerodynamic characteristics of the flight vehicle and its components.

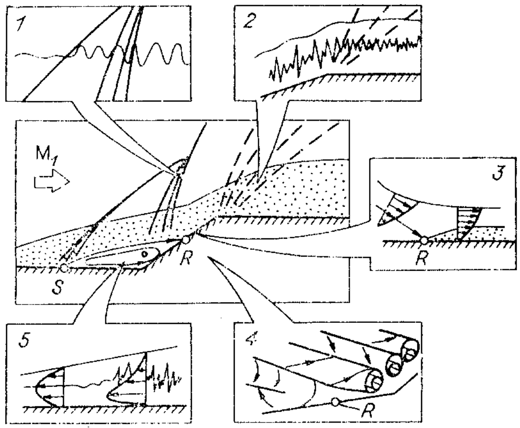

Fig. 11

In the vortex theory of finite-span wings in potential flow, it is usually postulated that there is an attached or separated flow with an assumed continuous transition of the bound vortex into free vortex sheet. However, the strength of vortex sheet rolling up from the leading (lateral) edges depends on the wing geometry and especially on the configuration of edges. The vortex model of the finite-span wing in subsonic flow in which this relation is taken into a consideration in [48]. Starting from the hypothesis on the nature of branching of vortex lines in potential flow past leading (lateral) edge and conservation of vortex lines in potential flow for thin wings an explicit relation has been found between the strength of rolled vortex sheet and the angle of attack of leading edge sweep, $K = 1 - \cos \chi$. A change in the strength of the rolled up vortex sheet (by deforming the edges) has an exceptionally strong influence on the flow past the entire ring and its aerodynamic characteristics of low aspect ratio wings. Figure 10 shows the computed relation between lift coefficient and angle of attack for a delta wing with aspect ratio $\lambda = 1$ ($\chi = 75°$). The inclusion of the parameter $K = K(\chi)$ ensures satisfactory agreement with experimental data. Thus, unique physically justified condition has been established for the convergence of vortex sheet which uniquely determines the problem and thereby makes it possible to develop a better algorithm for the design of finite aspect ratio wings of arbitrary platform for sufficiently wide range of angles of attack.

For attached supersonic flow past bodies the propagation of disturbances has a wave nature in which reflections and diffractions of disturbances at obstacles significantly affect the flow characteristics. In linear theory for the isolated finite aspect ratio wing when boundary conditions reduce to one base plane the problem of the end effects is practically the problem of diffraction at the edge of the plate. Modern supersonic flight vehicle is a combination of wing with superstructures (fuselage, nacelles) that introduce additional disturbances in the flow on which transformation of disturbances takes place. It was suggested [48] to move the boundary conditions from the surface of the light vehicle to a prismatic base configuration with a similar design so that the principal laws of reflection and diffraction of disturbances on superstructures are conserved. Within the framework of linear theory [48, 49] solutions have been found in quadratures for the supersonic flow past surfaces differing little from prismatic configurations: flow past parallel wings with arbitrary dihedral angles; flow inside prism with dihedral angles $\gamma = \pi/n$. In this case the region of disturbed flow is divided into simple prismatic configurations in each of which the solution to the problem is known. The solutions are matched at the boundaries of simple regions not belonging to the body surface. The problem is reduced to a system of integral equations of the Volterra type.

It is necessary to take into account real fluid properties to develop adequate models for separated flows. For turbulent flow this could be achieved only on the basis of complete experimental data on the mean and fluctuating flow characteristics. Investigations conducted at ITPM on different classes of supersonic separated flows are based on the use of the most modern experimental techniques: optical (qualitative and quantitative); pneumometric, hot-wire anemometry, calorimetric, and others. Thus, in the case of flow past ramps (Fig. 11) with a wide range of flow inclinations ($\beta = 8$-$90°$) at $M = 2$-4 and $Re = (25$-$60)\cdot 10^6$/meter, different stages of turbulent flow separation near shocks and expansion waves were studied and

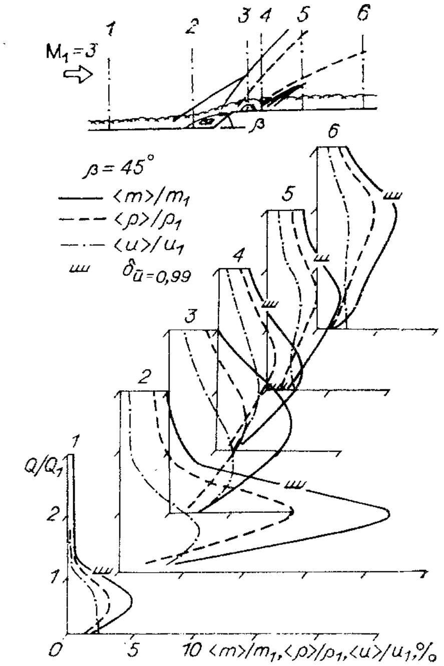

Fig. 12

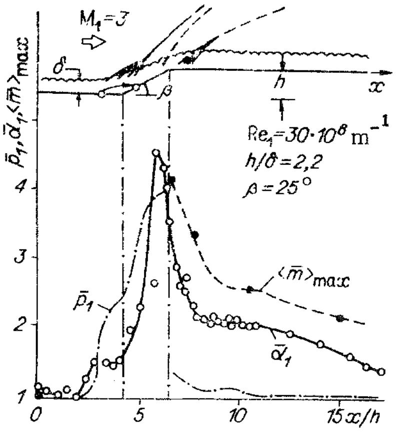

Fig. 13

the critical physical processes have been identified [50, 51]. It is shown that such flows are characterized by a strengthening of turbulence near the shocks in the outer flow as well as in the boundary layer 1, weakening of fluctuations in expansion waves 2, formation of a new boundary layer in the wall region of the reattaching mixing layer 3, formation of Gortler vortices at reattachment regions 4, and relaminarization of the reverse flow in the separated region 5. The development of such flows with increasing β is accompanied by a sequential appearance of the separated region initially at the compression corner and the presence of local separation behind the peak of the expansion corner. Profiles of fluctuations in mass flux, density, and velocity normalized with respect to the corresponding mean values m_1, ρ_1, u_1 in the basic flow (Fig. 12) indicate the significant influence of disturbances and separation on turbulence characteristics. The vertical coordinate is the cumulative flux Q normalized with respect to the total flux Q_1 across the undisturbed boundary layer. The variation of relative fluctuation level of mass flux $\langle \underline{m} \rangle_{max}$ along lines of maximum values in the boundary layer (Fig. 13) finds a weaker stabilizing action of expansion waves compared to the turbulence intensifying influence of shocks of same strength. This in particular explains the anomalous growth of the relative heat transfer coefficient $\bar{\alpha}_1$ after flow reattachment [52]. The characteristic surface pressure distribution is shown by dashed-dotted lines.

An even more complicated topology of separated flows is observed in flow past three-dimensional configurations. The phenomenon of the formation of supersonic zones, zones of maximum pressures and heat flows, discovered by Avduevskii, Zubkov, Medvedev, Panov, and Chernyi is extremely important for the understanding of three-dimensional separated flows. Furthermore, many applications as well as the development of computational techniques necessitate further investigation of structural schemes and laws of separated flow. In order to achieve this objective systematic experimental studies were conducted at ITPM on the turbulent boundary layer—shock interaction near vertical and half cones (Fig. 14a) where the flow is accompanied by the appearance of secondary separation boundary by lines of inflow C_2 and outflow P_2 in the primary separated region. Experiments conducted over a wide range of leading edge sweep angles of keels (χ = 0-60°), shock strength ($0 < \xi < 6.5$) at M = 2-4 and Re = (15-60) × 10/ meter [53-55] made it possible to determine boundaries of the existence of six characteristic interaction conditions (Fig. 14b, c). Along with the previously known stages of the development of such flows (I-interaction without separation, II-appearance of the primary separation C_1 and reattachment P_1 lines, III-development of secondary separation C_2 and reattachment P_2 lines). The phenomenon of reversal of secondary separation comprising of a weakening IV, practically complete disappearance V, and repeated appearance VI of secondary lines of separation and reattachment was found in the presence of sufficiently strong shock. The repeated appearance of second separation

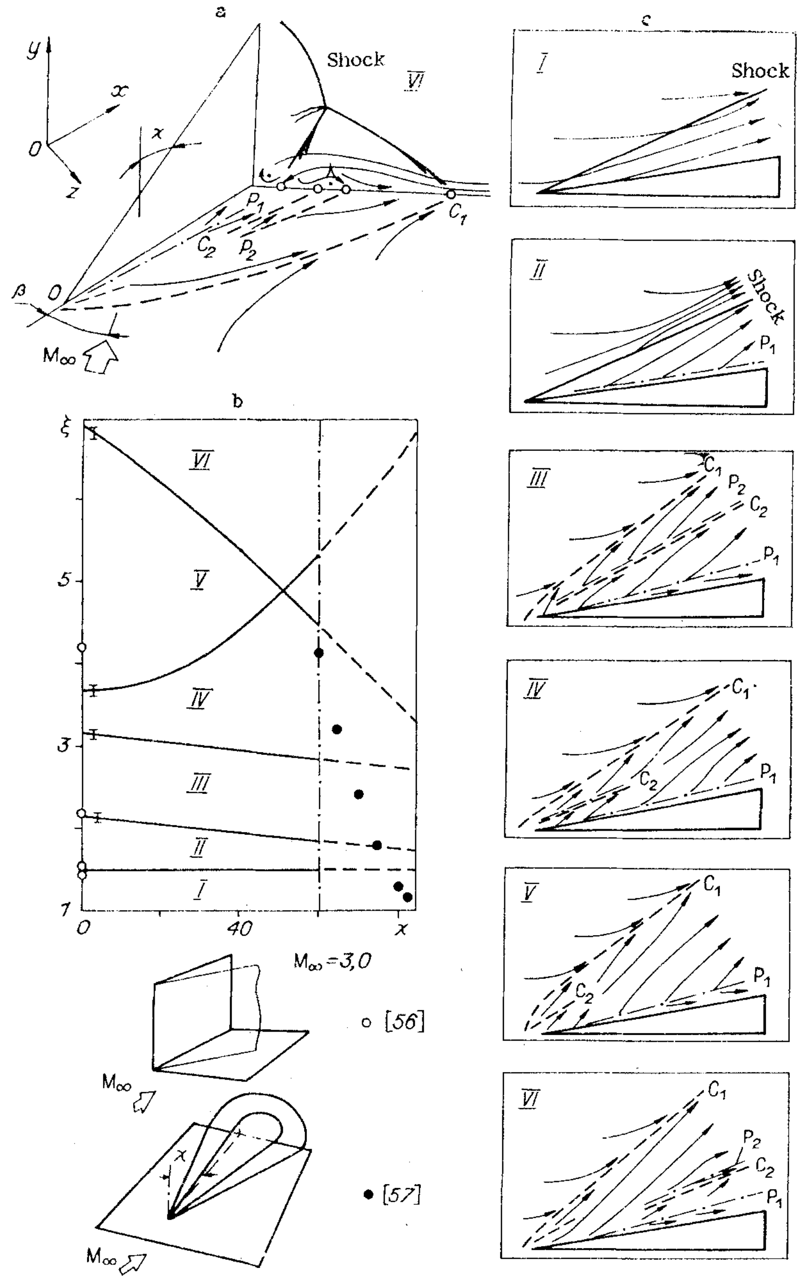

Fig. 14

corresponds to the critical strength of local oblique shock in the recirculating flow, equal to 1.5. This made it possible to suggest that this discovered "reversal" of secondary separation is caused by the transition of the recirculating boundary layer to turbulence.

The hypothesis [7] is confirmed by the recent experiments [54] using artificial turbulization of the boundary layer in the recirculation region near the reattachment point P_1. It is significant that experimental data [56] obtained for corner flows and also [54] for the cases of flow past half-cones (Fig. 14b) prove the generality of flow conditions for different configurations. The conclusion established in [7, 57] on the correctness of the theory of free interaction for the above-considered class of three-dimensional separated flows with cylindrical and conical symmetry served as the basis for the development of semiempirical computational models.

Complex turbulent flows are also realized at the junctures of aerodynamic surfaces of different flight vehicle components: wing-fuselage, wing-prismatic nacelles, flow through turbomachinery blades, and flows in channels of noncircular cross sections. Computation of such three-dimensional flows is made difficult by the presence of transverse gradients in Reynolds stresses that cause complex vortex flows along corner lines.

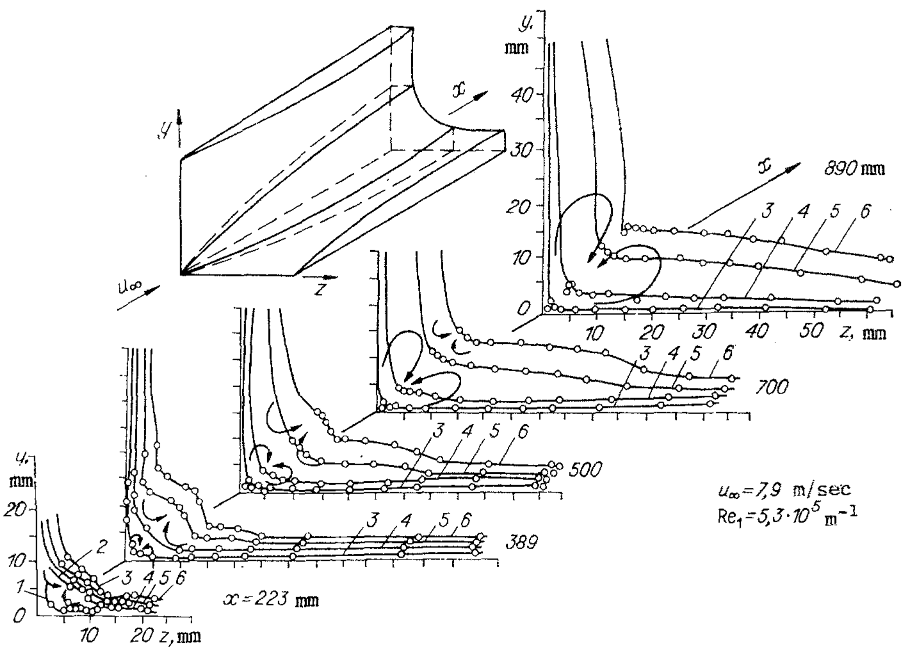

Fig. 15

In such cases, in order to clarify the structural details and laws, experiments should give complete information containing results of measurements of the streamwise and transverse mean velocity profiles, pressure distribution, variation of skin friction, and tensor components of Reynolds stresses. Results of complex experiments conducted at ITPM [4, 58, 59] for symmetric and asymmetric corner configurations made it possible to discover and explain a number of effects and features of flow past corners. The representation of isoclines at sections along the corner angles (Fig. 15) indicated the transformation of secondary flow with the transition of the laminar boundary layer to turbulence. The comprehensively studied structure of transverse flows (transverse velocity profiles) made it possible to explain the mechanism of the transformation of the rotation of symmetric vortex formations and, as a result, the deformation of isotachs (transformation of convex isotachs to concave). It is shown that the convex nature of isotachs is due to the local pressure gradient near the leading edges of the corner. As one moves away from the corner in the clockwise direction, the vortices produced by them are gradually displaced by newly generated counterrotating vortices. These, in accordance with Prandtl's hypothesis, are caused by the transverse gradient of Reynolds stresses as a function of the boundary layer transition to turbulent flow.

In special experiments the convexity of isotachs disappeared when the local pressure gradient was practically absent. In this case there is a satisfactory agreement between experiment and computational results based on full Navier-Stokes equations (Ghia, U.S.A., 1974) in which pressure gradient was not taken into consideration. Consequently, more adequate models to compute laminar flows in real corner configurations should consider pressure gradients introduced by the edges. At supersonic speeds there is practically no laminar region in the bisector plane and its neighborhood and hence the isotachs in the transverse sections have only concave nature. Extensive information has been obtained on the integral characteristics of boundary layer, extent of three-dimensional region of flow over a wide range of Mach numbers, Reynolds numbers, pressure gradients, and radius of the juncture. It was possible to use that to recommend a number of empirical relations to estimate boundary-layer thickness in the bisector plane, extent of three-dimensional region along the span at subsonic and supersonic speeds. The introduction of the juncture radius leads to a smooth degeneration of longitudinal vortex formations and the flow asymptotically becomes two-dimensional. This is indicated by variations in critical Reynolds numbers at supersonic speeds, distribution of relative skin friction coefficients in transverse sections at low speeds, and also lines of equal fluctuations of longitudinal velocity component for different radii. It means that when a certain corner radius is achieved, vortex resistance is completely eliminated, skin friction is somewhat increased, and the flow becomes two-dimensional and irrotational.

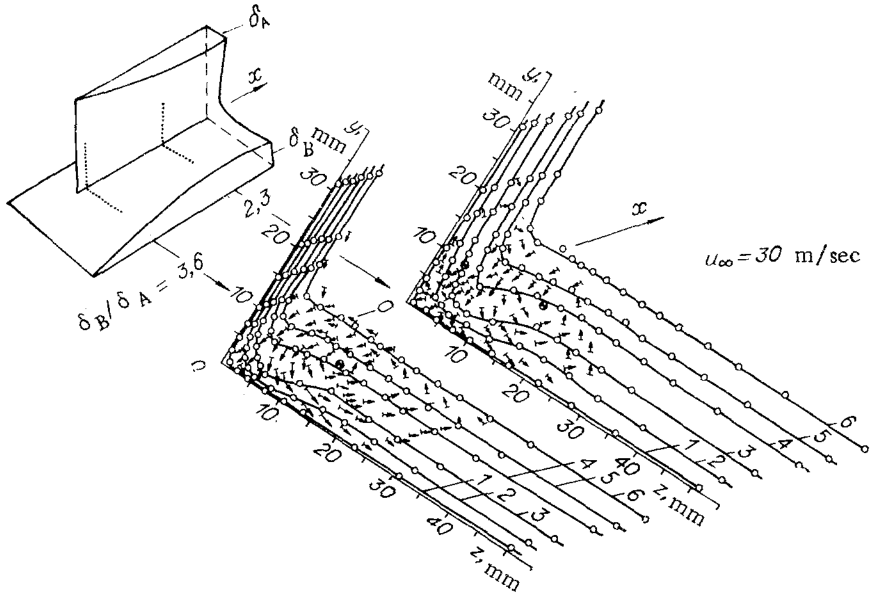

Fig. 16

More complex flows appear during the interaction of asymmetrically developing boundary layers, e.g., at wing-fuselage junctures. The degree of asymmetry is characterized by the ratio of boundary-layer thicknesses δ_B/δ_A which was changed from 1 to 3.6. In this case longitudinal vortex formations differ by their strength and the greater their asymmetric location relative to the bisector plane, greater the degree of asymmetry. This is clearly illustrated by the distribution of isotachs and lines of equal fluctuations as a function of the degree of asymmetry. The nature of the distribution of lines of equal vorticity computed from results of the measurement of the vector field of transverse flow, leaves no doubt that in symmetric and asymmetric case of interactions of boundary layers away from the leading edges, a pair of counterrotating vortices are formed, i.e., there exist secondary flows of Prandtl's second type. Such a statement remains in force even for different geometry of the corner leading edges. Their variation from values of the ratio of radii of semiellipse 1:12 to 1:1 indicate that everywhere the isotach distributions on the background of vector fields of secondary flow ilustrate flow of the second type, i.e., two-vortex flow structure is clearly seen though there is a significant increase in the distortion of contours and vortex scale of the longer edge. At the same time, results of analogous measurements at the section close to the leading edge of the shorter side ($\delta_B/\delta_A = 3.6$) provide basis to conclude that a single vortex structure is observed in its neighborhood (Fig. 16). The reason for the appearance of secondary flows of this type is flow separation realized in the flow past curvilinear surface of the leading edge region A. Such flows, according to Prandtl's classification, are called secondary flows of the first type.

Thus, it has been established that secondary flows of the first type appear in the neighborhood of leading edges of the asymmetric corner configurations, and with the development of turbulent boundary layer the gradient of Reynolds stresses in the transverse direction induce secondary flows of the second type characterized by asymmetric pair of vortices. The extremely important role of the geometry of leading edges in the formation of flow structure along the corner has been conclusively shown in the above cases. For symmetric interaction of boundary layers a transformation of vortex formations is observed, in the asymmetric case the flow of the first type (single vortex structure) is gradually replaced by the flow of the second type (two-vortex structure). These results indicate that only complex experiments will make it possible to obtain complete information on the structure and properties of such complex flows which is necessary for the development of models and computational algorithms related to modern requirements.

4. Research in hypersonics was frequently mentioned above but only in connection with general hydrodynamic problems. However, from the very beginning hypersonic phenomena in aerodynamics were objectively and methodically investigated at the institute.

The search for optimal configurations and parameters of flight vehicles (FV) to ensure maximum flight effectiveness is a difficult problem. The difficulty sharply increases with increasing flight speeds. The lifting body-powerplant integration for potential hypersonic flight vehicles, especially with airbreathing jet engines, determines the significantly three-dimensional nature of the disturbed flow. Mathematically, hypersonic flow models remain significantly nonlinear. A large number of new effects of hydrodynamic and physico-chemical nature occur. They justify the devotion of an independent area of goal-oriented investigations of almost exclusively fundamental nature to hypersonics.

V. G. Dulov [60] gave unique mathematical basis for approximate methods in hypersonic aerodynamics. This result has been generalized for the case of three-dimensional flows using the suggested general algorithm for the development of approximate computational techniques with specified accuracy.

In studies conducted by a number of authors the gas-dynamic design method was further developed for the single-point design of configurations of conceptual hypersonic flight vehicles (HFV) by matching flow regions of smaller scale. New types of HFV configurations were designed in [61] and their aerodynamic characteristics were investigated at the principal flow conditions. New configurations of theoretically more advanced (convergent) air intakes were designed [62, 63] using gas-dynamic design method. Experimental results on convergent air intakes confirmed their good effectiveness even at off-design conditions. A detailed review of studies on the design of convergent air intakes is given in [62].

Extensive computational and experimental material on aerodynamic characteristics of simplified HFV configurations over a wide range of Mach numbers is given in [64-67]. These results make it possible to evaluate aerodynamic characteristics of practical configurations based on their principal integral geometric parameters.

A new class of three-dimensional configurations with stepped longitudinal and transverse contours, including in particular, body of revolution, multiple-cantilevered wing, and half-wedge body have been discussed in [68] within the framework of Newtonian approach with correction for skin friction. As a result of optimization of shapes based on minimum total drag it has been established that for aspect ratios less than four, star-shaped midsections are optimal three-dimensional configurations.

Theoretical studies on the design and optimization of supersonic and hypersonic plane unsymmetric nozzles with interacting contours with different gas-dynamic and geometric constraints are discussed in [69-75]. In particular, the variational problem has been solved for the design of nozzle for specified lift and length of the lower contour. A strong relationship has been established between nozzle configuration and the specified value of lifting force. Also solved is the problem on the nozzle design having maximum moment with limitations on geometric and force characteristics. It has been established that a small reduction in powerplant thrust can be used to vary the nozzle moment and lift over a wide range.

Numerical analyses of supersonic plane unsymmetric nozzles have been carried out in [76-78] for off-design conditions including overexpanded conditions in the presence of external, in particular, hypersonic flow; computations have been carried out for the determination of the effectiveness of different laws to regulate nozzles.

Principles have been formulated for the development of functional mathematical models of flight vehicles [79]. Functional mathematical model for the power plant of HFV [80] has been established. The powerplant thrust-economy characteristics have been investigated for different conditions. Mathematically modeled object simulating HFV has been developed in [81, 82] and it is used to study the characteristics of hypersonic flight control.

Promising flight vehicles and astronautical systems determine the most realistic directions for the progress of aerodynamic investigations.

1. The development of scientific principles for the control of aerodynamic processes and characteristics of supersonic and hypersonic flows past bodies includes the problem of drag reduction, control of aerodynamic efficiency and vortex formations, boundary-layer control using external disturbances, application of external heating, blowing of single and two-phase jets for the control of wave structures and others. With this objective further development is recommended for fundamental studies of the detailed structures of different aeromechanical phenomena with close combination of numerical and physical experiments.

2. In-depth development of techniques and means for the study of transsonic flows presumes the development of new methods for mathematical and experimental modeling, and also

the construction of a new generation of transsonic wind tunnels operating under cryogenic temperatures in order to more adequately simulate Reynolds numbers. The near-sonic speed range still remains relatively less investigated theoretically as well as experimentally, though it is critical not only for flight vehicles with transsonic cruise speeds but also for supersonic and hypersonic flight vehicles.

3. Computational modeling of problems in continuum mechanics includes improvement and creation of new physical and mathematical models of various processes based on numerical and analytical methods, algorithms, and applications oriented program packages to solve aero-gas-dynamic problems.

There is sound basis today to state that significant progress in aerodynamics, could be expected along the path of symbiosis of numerical and physical experiments. Hence special attention should be paid to the development of computational aerodynamics as well as intense computerization of aerophysical experiments. Successful development in this direction makes it possible to predict significant reduction in time for aerodynamic design with more complete modeling of phenomena under laboratory conditions.

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