An Experimental Study of Receptivity of Supersonic Boundary Layer on a Blunted Plate

Nickolay V. Semionov, Alexander D. Kosinov

Abstract— The leading edge receptivity of a supersonic boundary layer on a flat plate with blunted leading edge to the controlled disturbances is experimentally studied. Experimental study of the controlled disturbance field, introduced into free stream with the help of the local source of disturbances, was carried out. The controlled disturbances were excited using the local disturbances generator designed on the discharge in chamber in the plate. Quantitative comparison of levels of controlled acoustic disturbances and eigen oscillations of a supersonic boundary layer excited by them are carried out and transformation coefficients are obtained. It is found, that the excitation of disturbances in the boundary layer by external controlled disturbances at the blunted leading edge is higher then at the sharp leading edge. The transformation coefficients for the oblique waves in the boundary layer are above the level of the plane wave at $\beta\approx 0$.

Keywords— receptivity, supersonic boundary layer, blunted leading edge, stability, transformation coefficient.

I. Introduction

PREDICTION of laminar-turbulent transition of supersonic boundary layer remains an unsolved problem despite a significant amount of research carried out during the past few decades. Is now standard, that the laminar-turbulent transition in boundary layer is connected with instability (the character of the development of disturbances causing the transition) and receptivity (how, by means of what mechanisms different environmental disturbances enter the boundary layer and generate unstable waves causing the transition) [1].

The majority of theoretical and experimental researches on receptivity are carried out for subsonic flows. The task is more complicated at supersonic speeds and it was not still studied in detail. At the present time, the receptivity mechanisms are poorly understood, especially at high Mach numbers. Exhaustive reviews of theoretical study of supersonic boundary layer receptivity can be found in [2]–[5]. Obtained, that the receptivity process generally comes about through non-parallel mean flow effects, which may arise either in the leading-edge region, or in a localized region farther downstream in the boundary layer. Receptivity of supersonic boundary layer to longitudinal structures generated by external vortical and thermal waves was studied in [6]. It was established that longitudinal velocity and mass flow disturbances inside the boundary layer can exceed the amplitude of external vortical wave in several times. Influence of thermal external waves on the flow structure in the boundary layer is much weaker.

Very few experimental investigations of supersonic receptivity phenomena were fulfillment up to date. Note Kendall's experiments [7], where the development of natural disturbances in the boundary layer was studied, and the correlation factor between the free-stream and boundary layer oscillations was measured at Mach number M=1.6–8.5. A high intensity of disturbances was found in the boundary layer close to the leading edge. It was induced by an external acoustic field. Creation of a source of controlled disturbances at supersonic speeds [8] has allowed also carrying out experimental study the receptivity problem [2], [9]–[13], [15]. In [9] was established, that the most intensive generation of eigen oscillations of the supersonic boundary layer by the sound waves take place in areas: the leading edge, lower branch of a neutral stability curve and "sound" branch. A wave structure of disturbances in the boundary layer, induced by the sound waves falling on the flat plate leading edge from above, was investigated in [10].

The leading edge receptivity was recently investigated experimentally in [2], [11]–[12] In this case acoustic waves were felling from below and the excitation of unstable wave take place only in the leading edge region. This method allowed to obtain transformation coefficients K (the ratio of generated disturbances in the boundary layer to the amplitude of the acoustic waves falling on the leading edge) for the first time. It was found, that receptivity coefficients depend on the longitudinal phase velocity C and inclination angle of external acoustic waves χ. Experimental investigations of hypersonic leading edge receptivity were beginning with the help of our method [13]. It was found that acoustic waves impinging on the leading edge generate Tollmien-Schlichting waves in the boundary layer. The receptivity coefficients were obtained for several radiation conditions and intensities. It was shown that there is a dependence of receptivity coefficients on the wave

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inclination angles.

The majority of theoretical and our experimental researches [2], [9]-[13], [15] of receptivity problem of supersonic boundary layer were carried when the models were flat plates with sharp leading edge. Study of blunted edge receptivity is only beginning [3], [5], [14]. Obtained, that bluntness tends to stabilize the boundary layer. In [5] for Mach number M=4.5 the effect of acoustic wave incidence angle is also studied and it is found that the receptivity of the boundary layer on the 'windward' side (with respect to the acoustic forcing) decreases by more than a factor of four when the incidence angle is increased from 0° to 45°, and the receptivity coefficient for the 'leeward' side is found to vary relatively weakly.

The boundary layer receptivity process due to the interaction of three-dimensional slow (with phase velocities $C = 1 - 1/M$) and fast acoustic disturbances (with $C = 1 + 1/M$) with a blunted flat plate is numerically investigated at Mach number M=3.5 in [14]. It was obtained, that the initial amplitudes of the instability waves near the neutral points, the receptivity coefficients, are about 1.20 and 0.07 times the amplitude of the free-stream disturbances for the slow and the fast waves respectively. This implies that the slow waves are more efficient, about 17 times, in generating instability waves inside the boundary layer than the fast waves, and the slow acoustic waves are the main catalyst in causing the transition. It was also revealed that small isolated roughness element does not enhance the receptivity process for the given nose bluntness.

In this paper some results of experimental study of receptivity of supersonic boundary layer on blunted plate are presented.

II. Experimental Set-up

The experiments were performed in the supersonic wind tunnel T-325 of the Institute of Theoretical and Applied Mechanics of the Russian Academy of Sciences with the test section dimensions 600×200×200 mm at Mach number M=2. In receptivity experiments a model consists of two flat plates. A generator of periodic disturbances, based on electrical discharge, was mounted on the plate *1* [2], [11], [12], [15]. Controlled disturbances were generated by using discharge with frequency f=20 kHz. The artificial disturbances penetrate through the aperture of the plate into the boundary layer and develop. This process was accompanied by the sound radiation into the free stream. More precisely this radiation was used as external controlled disturbances.

Scheme of receptivity experiment is presented on fig.1. The plate *1* with generator of periodic disturbances was mounted on traversing equipment bar and could be moved during experiment on various distances from a wall of a test section of a wind tunnel. The sizes of a plate *1* are 80 mm length, 80 mm width at a top and 60 mm at a basis, 5 mm thickness. Slope angles of leading edge and lateral sides are 14°30′. The design of the generator periodic disturbances is based on electric discharge in chamber. The artificial disturbances were entered into supersonic flow through an aperture with diameter of 0.5 mm in the working surface of the flat plate. Coordinates of the source are: x=18±0.25 mm, z=0, where x is streamwise coordinate from the leading edge of plate *1*, z is transversal coordinate from a symmetry plane of the plate *1*.

The plate *2* was fastened to pylon. Plate *1* was placed below the plate *2*. The distance between plates in normal direction is 40 mm. The sizes of plate *2* are 280 mm length, 160 mm width at top and 80 mm at basis, 7 mm thickness. The radius of the leading edge bluntness was equal r=2.5 mm. These experiments have been conducted at the case when radius of blunted leading edge sufficiently big in contrast with the boundary layer thickness. An opportunity for remounting of plate *2* in streamwise direction on various distances (see Fig. 1) between leading edges of plates was provided.

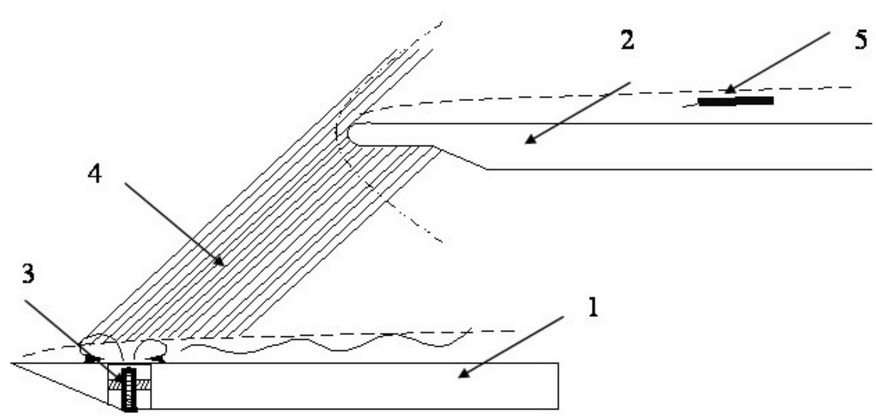

Fig.1. Scheme of experiment: 1 – plate with the discharge in chamber, 2 – plate with blunted leading edge, 3 – source of controlled disturbances, 4 – radiation of artificially excited boundary layer, 5 - hot-wire probe.

The controllable disturbances fell on the leading edge of the plate **2** from below. In this case generation of disturbances in the boundary layer by the external controlled acoustic field takes place only near the leading edge of the plate *2*. [12].

Stability experiments were performed on this plate and another plate with the length 440 mm, width 200 mm, and thickness 10 mm. Both plates had a leading edge with the radius 2.5 mm. Evolution of "natural" and controlled disturbances were studied. The source of controlled disturbances, based on discharge in chamber, was similar to the ones in [16].

All measurements were carried out using constant temperature hot-wire anemometer. We used probe with tungsten wire of length l=0.76 mm and the diameter 5 microns. Measurement of controlled disturbances field from source was carried out at frequency 20 kHz. For these measurements the selective amplifier with bandwidth of 1% was used, output of which was connected with ADC. Application of the selective amplifier has allowed reducing number of summations over realizations up to 200 (with the purpose to determine of controlled signal), that has sped up measurements. Complete length of each realization was 4096 points, but to average the first 200 points only were used (that corresponds to four periods at frequency 20 kHz). During experiment was supervised each, from averaged 200 times, oscillograms, and then it was recorded in file of data. The source generated disturbances with divisible frequencies by 10 kHz, however disturbances with frequency 20 kHz were more other on amplitude. On the other hand as controlled disturbances are rather small in free stream therefore it is necessary many more summations to detect them from complete signal. We were limited by measurement disturbances of one frequency with gain in accuracy and in speed of measurements. As the purpose of this work was to determine the level of controlled disturbances field, for processing of oscillograms the Fourier-transformation was used only in time in kind of a Fourier series:

$$\boldsymbol{e}_f(x,y,z) = e_f(x,y,z)e^{i\Phi(x,y,z)} =$$

$$\frac{2}{T}\int_0^T e(x,y,z,t)e^{-i\omega t}dt = \frac{2}{N}\sum_{j=1}^{N} e(x,y,z,t_j)e^{-i\omega t_j}$$

where T is length of realization in time, N is number of points in realization, e_f is amplitude of Fourier components, and Φ is its phase. Discrete Fourier transform was used to define amplitude $e_f(\beta)$ and phase $\Phi(\beta)$ wave spectra of pulsations over β:

$$e_f(x,\beta)\exp(i\Phi(x,\beta)) = \sum e_f(x,z_j)\times\exp(-i\beta z_j)$$

It is well known method, proposed by Kovasznay [17], that are applied to the interpretation of the hot-wire measurements in the supersonic flows [17]–[19]. The technique of experiment and procedure of data processing was described in [19] in detail.

III. Results

A. Initial data

Detailed information about the receptivity process can be obtained only by carrying out experiments in controlled conditions using artificial disturbances. A method using controlled disturbances has been developed at ITAM SB RAS to study the wave processes in supersonic flows [8]. The modified method of generation of controlled disturbances [15] was used in these experiments. Disturbances were generated by the source designed in discharge in chamber.

B. Pulsation diagrams

Hot-wire measurements were performed with regard for determination of mode structure disturbances on method, proposed by Kovasznay [17]. The fluctuations mode diagrams of controlled disturbances in free stream at M=2 are presented in fig.2. The calibrating measurements were made for different meaning of longitudinal coordinate x (different zone of radiation). As the fluctuations mode diagrams had for all measurements a linear kind [17]-[19], the equation describing them may be written by:

$$\Theta = r\langle m'\rangle + \langle T_0'\rangle$$

where r is the relative sensitivity, $<m>$ - dimensionless mass flow fluctuations, $<T'_o>$ - dimensionless stagnation temperature fluctuations. The fluctuations diagrams, shown in fig. 2, have a linear kind and $<T'_0>$ is small, that indicates on acoustic nature of radiated waves [17]-[19]. Values of the mass flow and stagnation temperature pulsations are given on plots.

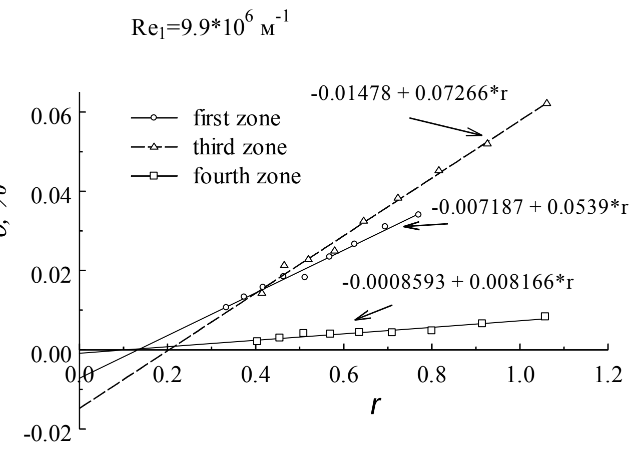

Fig.2. Fluctuation diagrams.

C. Controlled disturbances in free stream

First of all consider the streamwise distributions of the amplitude and phase of controlled pulsations in the free stream. The initial field of controlled fluctuation in free stream was measured in a plane of the plate *2* (plate *2* was established downstream and was used as a support for the traversing gear). The initial amplitude of controlled disturbances from the local source was fixed during all measurements.

Relations of amplitude and phase of controlled disturbances $A_0(x)$ and $\Phi_0(x)$ over the longitudinal coordinate in section z=0 are shown in fig.3. On an initial part of distribution $A_0(x)$ the disturbances amplitude is close to zero, it mean that the hot-wire probe was displaced in nonperturbed region. The undisturbed region was observed for $x \leq 24$ mm.

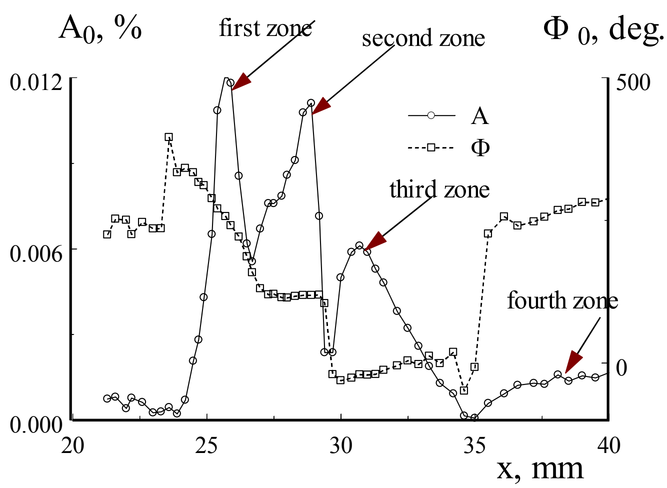

Fig.3. Dependence $A_0(x)$, $\Phi_0(x)$ of controlled initial disturbances at the position of plate *2* (plate *2* removed).

At the analysis of the experimental data in [2, 12, 15] simplified physical model of disturbances generation near to the source was used. The artificial disturbances penetrate through the aperture of the plate *1* into the boundary layer. Thus in result of braking of a flow in the near field of upstream and downstream of the discharge, possibly the vortices was formatted with different directions of rotation in the plane *yx*. Further downstream, the generated disturbances induce to origin of Tollmien-Schlichting (TS) waves in the boundary layer of plate *1*. All this process was accompanied by radiation of various types of controlled disturbances into the free stream. The radiation propagates inside the Mach cone from the discharge, and the radiation is propagated along lines of Mach from a boundary layer. The acoustic nature of the radiation was obtained in [19, 20].

Such physical model was based on distributions, similar adduced on fig.3. where relations of amplitude and phase of controlled disturbances $A_0(x)$ and $\Phi_0(x)$ over the longitudinal coordinate in section z=0 are shown. On the basis of this model, typical regions corresponding to various types of controlled disturbances were identified from the functions $A_0(x)$ and $\Phi_0(x)$.The first zone corresponds to acoustic waves, radiated by disturbances from the source, propagated upstream in the boundary layer of the plate *1* (in fig.2 this zone about corresponds to area of the first maximum at 24 mm < x < 27 mm, where phase reduction with increasing of the coordinate x was observed). The upstream propagation of disturbances in a supersonic or hypersonic boundary layer was revealed in [21], [22]. Let's mark, that the expansion of this area (2-3 mms) same, as was obtained in [21] at boundary-layer measurement at M=2 near to the controlled disturbances source. The second zone (disturbances radiation directly from the aperture of the source) corresponds to the area of the second maximum in fig.1. The third zone corresponds to radiation from the vortex behind of the aperture (on fig.1 this zone about corresponds to area of the third maximum at x from 30 mm up to 35 mm). The fourth zone is observed for x>35 mm as radiation from TS waves.

At a following stage of measurements more in-depth research of the controlled disturbances field in the free stream was carried out. Measurements of $A_0(x)$ and $\Phi_0(x)$ in free stream had allowed to define border on the coordinate x of area of excited disturbances and to began more in-depth researches of initial disturbances. For this purpose measurements of transversal distributions of amplitude and phase $A_0(z)$, $\Phi_0(z)$ of controlled disturbances in the plane of the plate *2* were made for values of the longitudinal coordinate from x=24 mm (the border of excited disturbances) up to x=40 mm with a step 1 mm. Lines of equal amplitude of artificial disturbances, obtained after the processing of the distributions $A_0(z)$, $\Phi_0(z)$ with the help of spline, are shown in fig.4. The border of perturbed area for the radiation is good observed in the plot. Before, (value of coordinate x from 28 up to 30 mm) and behind aperture of the discharge the vortical structures are generated. The boundaries of disturbances from vortexes before and behind the source combine all together at x=36 mm. The radiation is spread inside a Mach cone from the source. It is necessary to mark, that the behavior of a phase of controlled disturbances $\Phi(z)$ for different zones of radiation also differs from each other. The structure of radiation from the artificially excited supersonic boundary layer was described in detail in [20].

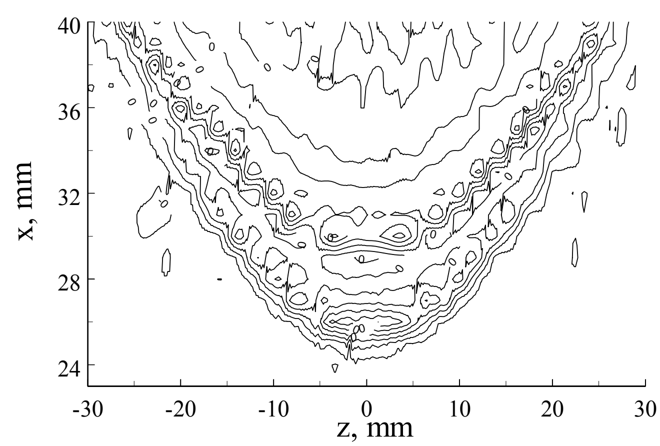

Fig.4. Lines of equal amplitude of initial artificial disturbances at the position of plate *2*.

D.Boundary layer response

The distributions $A_0(z)$ and $\Phi_0(z)$ of initial controlled disturbances were measured for cross-sections x=const in four different regions of radiation (x=26, 29, 31 and 38 mm) in free stream. These values of the coordinate x were chosen from distributions $A(x)$ and $\Phi(x)$ presented in fig.3. At study of a field of boundary layer disturbances induced by the external controlled waves, the plate *2* was established so that its leading edge consistently placed precisely in those sections, where external disturbances, belonging to various areas of radiation, were investigated (i.e. coordinate of the leading edge was x=26, 29, 31 and 38 mm). The distributions $A(z)$, $\Phi(z)$ of disturbances were measured in the boundary layer of the plate *2* at x^* equal to 40 and 50 mm (here x^* is the distance from the leading edge). The measurements were carried out in an unstable region of disturbances development in the supersonic boundary layer. In this way the structure of external disturbances and the waves generated by them in the boundary layer were defined.

E. Spanwise distributions of controlled disturbances in boundary layer

Only the data correspond to the leading edge coordinate x=31 mm are presented in the paper. The amplitude and phase spectra of external acoustic disturbances and eigen oscillations generated by them are compared in fig.5 as functions of transversal coordinate. Here distributions at x^*=0 correspond to the initial controlled disturbances in free stream at x=31 mm.

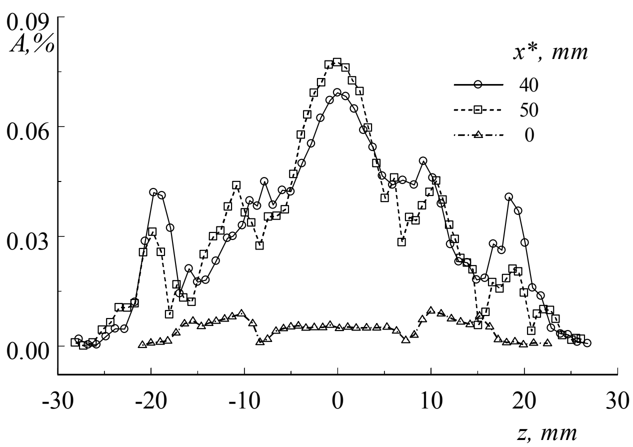

Fig.5a. Distribution of $A(z)$ over transversal coordinate for leading edge coordinate x=31 mm.

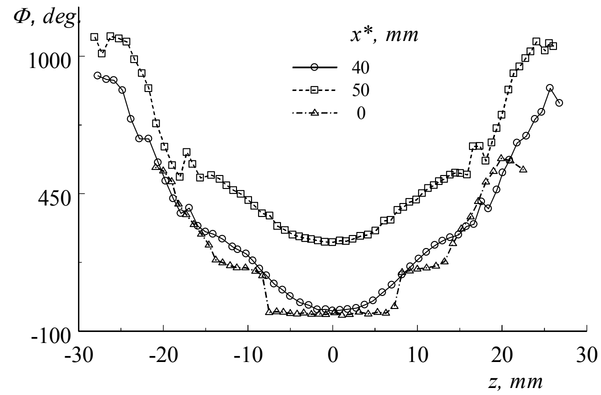

Fig.5b. Distribution of $\Phi(z)$ over transversal coordinate for leading edge coordinate x=31 mm.

Though distributions $A(z)$, $\Phi(z)$ for oscillations in the boundary layer shows, that the generation of eigen oscillations by the external controlled disturbances takes place. The amplitude of excited disturbances in the boundary layer exceeds amplitude of initial controlled disturbances in several times.

F. Spectra over wave numbers

The β-spectra were determined with the help of discrete Fourier - transformation under the data, presented in fig.6. The amplitude and phase spectra of external acoustic disturbances and eigen oscillations generated by them are compared in fig.6 as functions of the wave number β. Significant amplification of the external disturbances in the boundary layer is observed too.

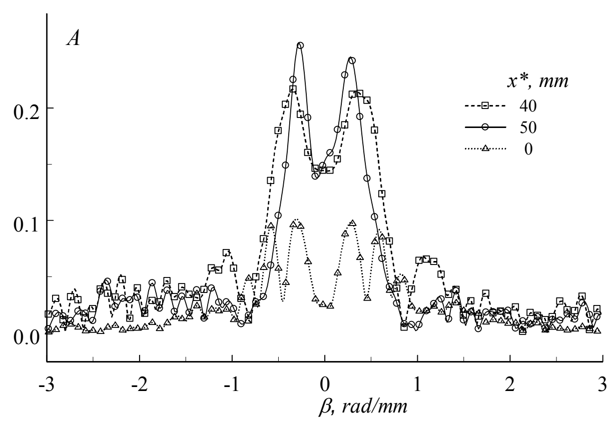

Fig.6a. Distribution of $A(\beta)$ over wave number β for leading edge coordinate x=31 mm.

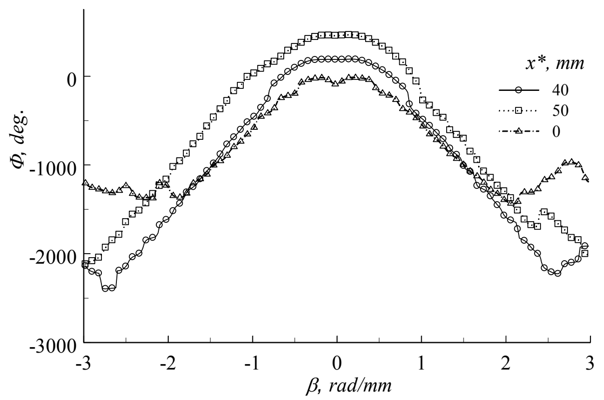

Fig.6b. Distribution of $\Phi(\beta)$ over wave number β for leading edge coordinate x=31 mm.

G.Transfer factors

Using obtained data the transformation coefficients of disturbances (coefficient of generation) can be found. In spite of excited disturbances were found anywhere, we shall estimate transfer factors for each of described above cases in boundary layer. It is necessary to do this for each x^*. The transfer coefficients were found from the relation

$$K(\beta) = \frac{m_f(\beta)\big|_{x=x_i}}{m_f(\beta)\big|_{x=x_0}}$$

i.e. relation of the excited disturbances amplitude in the boundary layer to the forced oscillations amplitude of the acoustic waves, falling on the leading edge.

Figure 7 shows the transfer functions of disturbances $K(\beta)$ obtained for the blunted leading edge. In the case of plate with the sharp leading edge the integrated transformation coefficient was close to the unit. Two typical regions of disturbances generation were found, namely, the region ±10° with the minimum transformation coefficients K (K<1) and the region ±(20°-40°) with the maximum coefficients (K>1) [11], [12]. It was obtained, that for the case of blunted leading edge the transformation coefficient greater the ones for the case of sharp leading edge. The maxima at β=±0.5 show that the inclined waves are excited in the boundary layer of the blunted plate. The existence of maximum in the distribution $K(\beta)$ in a vicinity of β=0 shows that acoustic are generated in the boundary layer too. Note that existence of sharp maxima in distribution of transformation coefficient is in a good agreement with theory [23].

Obtained experimental data have very complex structure. It is very hard to analyze this data. But on this experimental data it is possible also to define mean receptivity factors K. The total (integrated and dimensionless) controlled pulsation of mass flux was defined by:

$$m_{tot} = \int A(\beta)d\beta$$

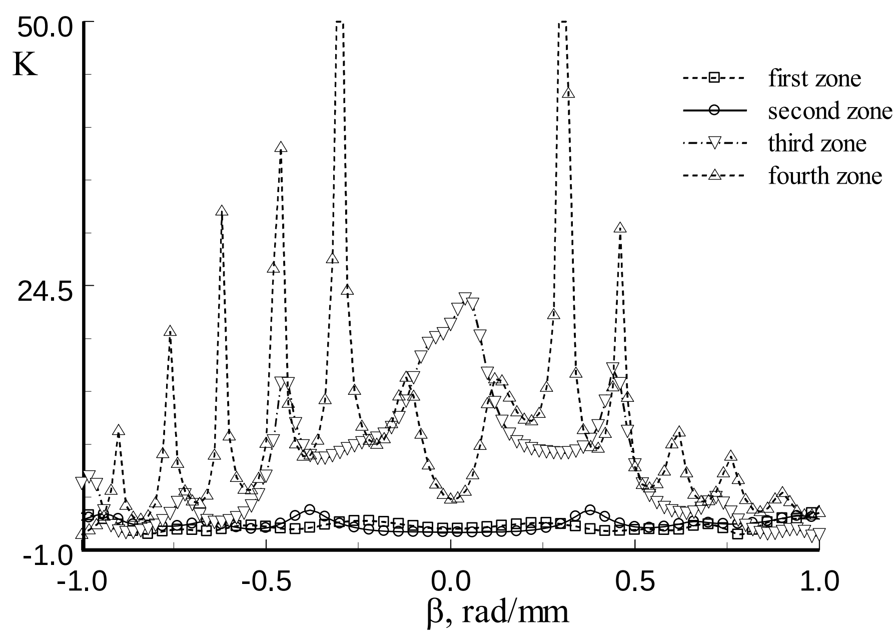

Fig.7. Transformation coefficients $K(\beta)$ over wave number β.

Mean transfer factors K were defined using values of m_{tot} by:

$$K = {m_{bl}}/{m_{fs}}$$

where m_{bl} and m_{fs} are mass flux pulsations in boundary layer and in free stream, respectively. Values of mean receptivity factors for the sharp leading edge are presented in table 1. Considering obtained transfer factors as mean values over β, we see that these factors increase from 2 (for the first zone) to about 6 (for the fourth zone) times. In another hand, using mean total values of mass flux fluctuations obtained in the free stream and in the boundary layer, we can determine mean transfer ratio for each case. Comparing these data with those obtained for sharp leading edge [2, 12], we conclude that mean transfer factors are 2-3 times more for boundary layer on blunted flat plate. As transfer factors decrease with increasing x^*, it means that the excited pulsations enter the stable zone of boundary layer on blunted flat plate.

Table 1.

	x=26 mm	x=29 mm	x=31 mm	x=38 mm
x^*=40 mm	K_1=2.36	K_2=1.48	K_3=2.51	K_4=5.5
x^*=50 mm	K_1=1.85	K_2=1.33	K_3=2.03	K_4=5.29

Known that the leading edge bluntness leads to formation of an entropy layer above the model and laminar-turbulent transition depends on values of the nose bluntness. We experimentally study stability of supersonic boundary layer on blunted plate [21], [24]. These experiments have been conducted at the case when radius of blunted leading edge sufficiently big in contrast with the boundary layer thickness. The investigations of mean flow and linear development of controlled disturbances in the boundary layer of the plate with the cylindrical leading edge with the radius 2.5 mm were presented in [21]. Pneumometric measurements of P_0' and P_{st} showed, that Mach number was equal M=2.0 before the shock wave and Mach number was equal M=1.93±0.2 in back of the shock wave in weakly gradient area. Measurements in transversal directions showed that flow is nongradient within the range of ±25 mm from a symmetry line of the model. It was obtained, that linear disturbances evolution in the boundary layer of blunted plate takes place like in the case of the plate with the sharp leading edge. But disturbances amplification in the boundary layer of blunted plate occurs more slowly. Some reduction of phase velocity for the case of the blunted plate was observed. Results of experimental study of the wave train nonlinear development in the boundary layer of the blunted plate were presented in [24]. It was obtained that the process of the subharmonic resonance takes place on the blunted plate. The triads were asymmetrical because of the fundamental wave was oblique. It was shown that the process is the same as for the plate with sharp leading edge, but several distinctions are observed.

To show which disturbances are generated by external controlled fluctuations in the boundary layer we consider phase velocity of waves. A data are shown in fig.8. Here the solid line which corresponds to critical phase velocity $C^*=1-1/(M^*\cos(\chi))$ distinguishes waves of discrete spectra. Some reduction of phase velocity for the excited disturbances is observed. The same result was obtained in [21], [24] too.

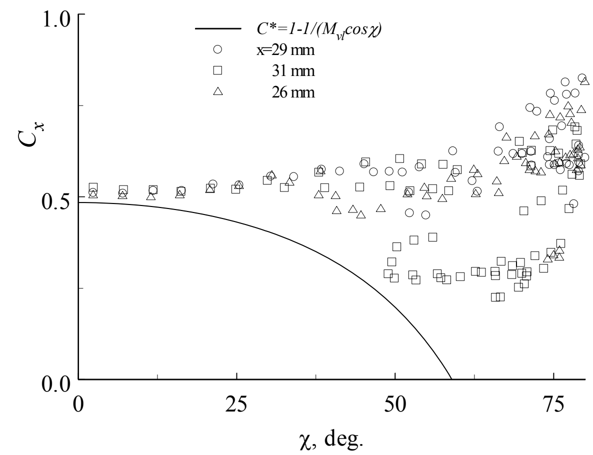

Fig.8. Phase velocities of excited disturbances in the boundary layer.

Obtained, that transformation coefficients for the case of blunted leading edge are higher than ones for the case of sharp leading edge. These data contradict theoretical results in [5]. Processes that take place near the blunted leading edge, in entropy layer and shock wave are the reason of such difference in our opinion. The excitation occurs in the small location at the leading edge, but this location is greater for the case of blunted leading edge. Furthermore a shock wave is formed near the leading edge. External controlled disturbances may interact with the shock wave. The shock wave become an additional source of disturbances by itself and excites oscillations in the boundary layer too.

Confirmation of this conclusion may be obtained from fig.9, where distributions of $A(x)$ and $\Phi(x)$ are presented in dependence of the longitudinal coordinate in free stream over the surface of the plate *2*. At the same measurement in the case of sharp leading edge the initial controlled disturbances were observed up to maximum, corresponded to the Mach line from the leading edge. The disturbances, correlated with the source, were close to zero in free stream after the Mach line [2], [12]. Another picture can be seen in fig.9, where disturbances in free stream over the surface of the plate *2* exceed initial controlled disturbances. Sharp peak in amplitude distribution (fig.9.a) corresponds to the shock wave. A significant growth of controlled disturbances is observed after shock wave. Also some modulation of amplitude is obtained. Existence of modulation may be explained by interaction external controlled disturbances with shock wave [25]. In [25] was demonstrated that external acoustic waves generate entropy-vortex fluctuations in the hypersonic shock layer.

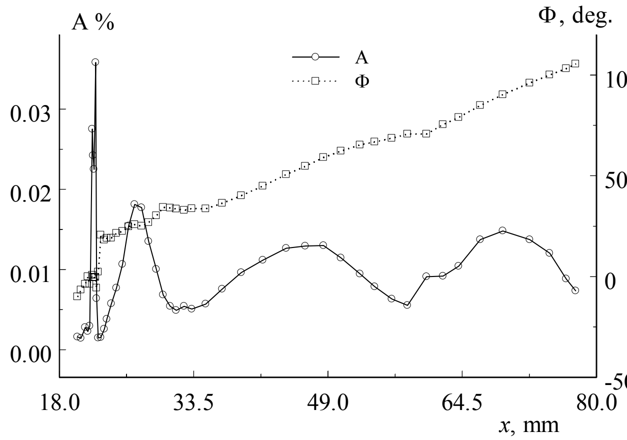

Fig.9a. Distributions of $A(x)$ and $\Phi(x)$ over longitudinal coordinate in free stream at the distance y=5.4 mm above the surface of the plate *2* at leading edge coordinate x=26 mm.

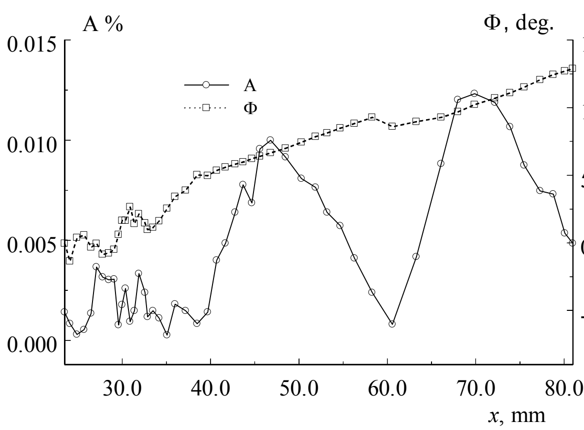

Fig.9b. Distributions of $A(x)$ and $\Phi(x)$ over longitudinal coordinate in free stream at the distance y=1.5 mm above the surface of the plate *2* at leading edge coordinate x=31mm.

IV. Conclusion

Experimental study of the controlled disturbances field, introduced into free stream with the help of the local source of disturbances, was carried out. Disturbances in the flat plate boundary layer, excited by the external controlled acoustic oscillations in the vicinity of the blunted leading edge, were measured.

Quantitative comparison of levels of initial acoustic disturbances in free stream and fluctuations of the supersonic boundary layer, caused by them, was made. The transformation coefficients of acoustic disturbances into oscillations of the supersonic boundary layer were obtained.

It was found, that the excitation of disturbances in the boundary layer by the external disturbances at the case of blunted leading edge occurs considerably more heavily than at the case of sharp leading edge.

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