EXPERIMENTAL STUDY OF UNSTEADY EFFECTS IN SHOCK WAVE / TURBULENT BOUNDARY LAYER INTERACTION

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Supersonic flow around aircraft elements contains shock waves and expansion waves interacting with boundary layer developing on the surface of the aircraft. If the interaction is strong enough it results in arising of extensive separation zones considerably changing flow pattern, dynamic and thermal loadings. Many experimental and computational studies are devoted to understanding of features of turbulent separation in supersonic flow (see, for example, reviews [1], [2], [3]). Significant progress was made in simulation of such flows by now but the unsteady effects arising at shock wave boundary layer interaction are still an unexplored area. It is well known, that such separation flow is unstable. The reflected shock wave (caused by separation flow) oscillates with significant amplitude, and this movement is three-dimensional and low-frequency in comparison with all characteristic frequencies of stream.

To study of unsteady effects in flow separation the series of wind tunnel experiments have been performed in T-325 for Mach number \( M_\infty = 2 \), total pressure \( 0.79\cdot10^5 \) Pa ±3 %, total temperature 286 K and freestream unit Reynolds number \( \text{Re}=10.5\cdot10^6 \) m\(^{-1}\). Test section of the wind tunnel is of size 200×200 mm.

The experimental model was a flat plate with sharp leading edge. This flat plate 390×200 mm is attached to side walls of test section. A turbulator made from copper wire of diameter 0.1 mm was placed at position 10 mm from the leading edge. The shock wave was generated by a wedge with flow turn angle of 8 degrees. The shock wave generator (or wedge) is hinged to sidewalls to set desirable shock wave angle. CAD drawings of installation are shown in Fig. 1. Test section is equipped with two optical windows of diameter 120 mm to provide optical access to region of interaction. The flat plate has the changeable circular insert to place surface probes (such as steady and unsteady pressure sensors).

Hot-wire anemometry, Schlieren photography by high-speed camera, measurements of pressure on model surfaces, and oil-flow visualization were used to study of the flow. The pressure on the wall was measured in 23 points on the model axis (\( z=0 \)). Traversing gear is able to hold hot-wire probe and leaned on the model surface to minimise vibrations. Accuracy of probe positioning is 0.01 mm in vertical direction and 0.1 mm in streamwise and spanwise directions.

Fig. 1 General view of the model and shock generator

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Mean value and fluctuations of mass flux were measured by means of constant temperature hot-wire anemometer. Probes were made of a tungsten wire of 10 µm diameter. The aspect ratio of wires was larger than 150, and the overheat ratio was about 0.8 so the probe is mainly sensitive to the momentum fluctuation \((\rho u)'\). The resulting bandwidth is about 100 kHz in the external flow.

The output of the anemometer was amplified and analog signals were finally digitalized with sampling frequency of 750 kHz by CAMAC A/D converter. The subsequent data processing was performed by PC. Two series of 65536 samples were recorded in every point.

The processing of \((\rho u)'\) fluctuations were performed by fast Fourier analysis. Statistical properties (RMS, spectral distributions) were calculated using 65536*2 points. Spectra were obtained by ensemble averaging of 60 blocks of 4096 samples each, that yields a frequency resolution of \(\Delta f = 183.105\) Hz.

Calibration of the wire was carried out in a free stream by variation of total pressure. The recovery factor was assumed to be constant (0.96) across a boundary layer. Such calibration and data processing does not allow to measure transonic profiles correctly \((M < 1.1)\). Therefore points measured below \(M = 1.1\) should not be trusted.

Profiles and spectra of inflow turbulent boundary layer (160 mm from the leading edge) are presented in Fig. 2 \((P_0 = 0.8\) bar, \(T_0 = 286\) K, \(M = 2)\). The transformed mean velocity and spectra in a logarithmic region plotted in Kolmogorov scales. Presence of logarithmic area in distribution of mean velocity is obvious from Fig. 2 (a). In Fig. 2 (b) the inclination of spectra curve in logarithmic area is close to -5/3 (Kolmogorov inclination). These data demonstrates equilibrium turbulent boundary layer.

The transformed velocity was calculated from natural velocity by following formulas:

\[
U^* = \frac{u_c}{b} \sin^{-1} \left[ \frac{2b^2 \left( u_c / u_e - a \right)}{\sqrt{(a^2 + 4b^2)}} \right], \quad a = \left(1 + \frac{\gamma - 1}{2} M_e^2 \right) T_e \frac{T_e}{T_w} - 1, \quad b^2 = \frac{\gamma - 1}{2} M_e^2 \frac{T_e}{T_w}.
\]

Formulas for calculation of Kolmogorov’s scales have been taken from Ref. [4].

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**Fig. 2** a - Log-linear plot of velocity profile for compressible turbulent boundary layer, b - Spectra in the boundary layer, plotted using Kolmogorov scales. All data are taken from the logarithmic region of profile \((u_e = 25.7\) m/s, \(Re_1 = 10.5 \times 10^6\) m⁻¹, \(x = 160\) mm).
The basic parameters of inflow turbulent boundary layer are presented in table.

<table>
<thead>
<tr>
<th>d₀, mm</th>
<th>d*, mm</th>
<th>Q, mm</th>
<th>Re₀ = ( \frac{\theta \cdot U_0 \cdot \rho_0}{\mu_0} )</th>
<th>( u_\tau, \text{ m/s} )</th>
<th>( \tau_\omega, \text{ Pa} )</th>
<th>( C_f = \frac{2 \cdot \tau_\omega}{\rho_0 \cdot U_0^2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>0.757</td>
<td>0.228</td>
<td>2.7 \cdot 10^3</td>
<td>25.7</td>
<td>85.86</td>
<td>5.06 \cdot 10^{-3}</td>
</tr>
</tbody>
</table>

At Fig. 3 shows schlieren photo of shock wave / boundary layer interaction. Horizontal and vertical lines are position of profiles of mass flow and mass flow pulsations measured by hot-wire anemometer. The origin of the longitudinal coordinate x is set to the mean position of the reflected shock X₀ (X₀ = 175.5 mm) and x is normalized by the length of the interaction zone L which corresponds roughly to the distance between the foot of the RS and the reattachment point (L=28 mm). The dimensionless longitudinal coordinate is \( X^* = (X_0 - X)/L \). The interaction extends downstream up to \( X^* = 1 \), which corresponds approximately to the end of the separated bubble. The dimensionless normal coordinate defined as \( y^* = y/d_0 \).

In the Fig. 4 the longitudinal wall pressure distribution along the plane of symmetry are plotted. This pressure distribution is typical for this kind of interaction. In the pressure distribution a typical plateau may be found at the zone of separation \( X^* = 0 \div 1 \).
Section II

In Fig. 5 and Fig. 6 the vertical profiles of the mass flow and root-mean-square (RMS) values of pulsations of the mass flow normalized by local value of the mass flow are plotted. In vertical profiles at \( X^*=0.339, 0.589 \) (inside of separation zone) and at \( X^*=1.411 \) (wake) it is possible to find two maxima of RMS value of pulsations. The first maximum (neighbouring to the wall) is a part of the boundary layer. Second maximum of RMS is located at \( y^*=0.677, 1.387, 1.677 \) for \( X^*=0.339, 0.589, 1.411 \) correspondingly. The third maximum in profile at \( X^*=0.339 \) is supposed to be in a zone of the reflected shock wave. Analyzing of the distribution of the mass flow in a zone of these second maxima it is easy to see that inflection points present here.

It is possible to see from distributions of power spectra (Fig. 7) that in these regions the spectrum falls more quickly, than in a boundary layer and low frequencies (200-2000 Hz) predominate (the shock wave moves with frequency of about 600 Hz).
Fig. 6 Vertical profiles of mass flow pulsations (RMS values)

Fig. 7 Power spectra $E(f)$ of mass flow pulsations normalized by rms value of mass flow for profiles at $a - X^* = 0.339$ and $b - X^* = 0.589$

Fig. 8 Normalized power spectra
In Fig. 8 the comparison of normalized power spectra in the zone of a shock wave, in the region of mixing, and in the zone of turbulent boundary layer for three vertical profiles $X^*=0.339, 0.589, 1.411$ are shown. Each spectrum is normalized by its maximum value. The spectra obtained in the region of reflected shock wave are similar to ones, measured in mixing layer for various $X^*$. But it is possible to see that with the increasing of $X^*$ high-frequency pulsations in the mixing layer are growing due of the recovery of equilibrium turbulent boundary layer. It can be concluded that low-frequency pulsations in the zone of mixing layer interrelated with low-frequency pulsations of reflected shock wave. The question about primary source of these frequencies (the shock wave of mixing layer itself) can not be answered basing on the data available.

It is well known that skewness distribution in turbulent boundary layer has a negative value near inviscid fluid and positive near the wall. In logarithmic region the pulsation distribution conform the normal law ($g_1=0$ (skewness), $g_2=3$ (kurtosis)). But inside of separation zone and the wake turbulent boundary layer is non-equilibrium and this distribution is broken. In the experiments negative value of skewness was obtained between the first and second maximum of $<\rho u>$ (values of skewness and kurtosis in the peaks of $<\rho u>$ approximately correspond to normal distribution ones).

Let's consider the skewness and kurtosis at different frequency bandwidth (Fig. 9) in the wake ($X^*=1.411$). We can see that deviation skewness from zero may be found mainly at low frequencies up to 10 kHz, and there is a little influence in the frequency range of $10 \div 20$ kHz. Kurtosis does not change a lot with increasing of frequency. The deviation is more distinct for frequencies up to 10 kHz for $y^*=0 \div 1.5$.

Such a change in the distribution of skewness can be explained by the availability of large-scale vortex structures generating negative pulsations of the flow speed near the edge of the boundary layer ($y^*=2.2$ for $X^*=1.411$) and positive pulsation at the wall, which is typical for equilibrium turbulent boundary layer. And there are additional large-scale vortex structures that cause deviation of skewness in zone $y^*=0.5 \div 1.5$ for $X^*=1.411$. Kurtosis mainly depends not on the scale of structure but on the nature of the flow, therefore the distributions vary a little with change of frequency band. Variations of kurtosis in the zone $y^*=0.5 \div 1.5$ for the frequency range up to 10 kHz confirms the availability in this region of new large-scale vortex structures.

![Fig. 9 Vertical profiles for different frequencies range at $X^*=1.411$](image)
To determine the point of onset of new large-scale structures let's consider the distribution of skewness along $X^*$ at $y^*=0.323$ (Fig. 10) and normalized spectra $fE(f)$ for typical points (Fig. 11). From Fig. 10 it is possible to see that the zone of migration of reflected shock wave is $X^*=0.05 \div 0.21$ (in this location shock wave has not yet formed). Further, with increasing $X^*$ the skewness become negative and reaches a minimum at point $X^*=0.33$. Because we are far from the inviscid flow, the origin of negative value of skewness is connected to presence of large-scale structures as noted above. Then at $X^*=0.33$ skewness begins to grow, due to the rapid growth of the boundary layer.

The power spectra $fE(f)$ in characteristic stations are presented in the same figure. Station #1 is located in the inviscid flow at the position of reflected shock wave oscillation. In the spectrum, we can see a maximum (600 Hz) related with low-frequency movements of the shock wave. Station #4 corresponds to the center of oscillations of reflected compression waves and its spectrum also has a maximum at frequency of 600 Hz and well coincides with the spectrum obtained at station #1 up to 2 kHz. The station #4 is located inside the boundary layer that explains the increase of level of pulsation for $f>2$ kHz.

Spectra obtained at stations #3 and #6 show correspond to the turbulent boundary layer inside separation zone. Spectra in these points have characteristic frequency 3-4 kHz. Stations #2, #7, #8 correspond to the second maximum of $<\rho_u>$. Spectrum at station #2 coincides with the spectra obtained at stations #1 and #4 in the region of shock wave oscillations for $f<2$ kHz (this is also indicated earlier).

The station #5 located at $X^*=0.211$, $y^*=0.323$. Analyzing the distribution of skewness along $y^*=0.323$ the assumption was made that point #5 corresponds to location of arising of new large-scale structures. Power spectrum at point #5 confirms this assumption due to availability of maximum at the frequency of the shock wave oscillations (600 Hz). As a result, we can say that these structures originate near the wall close to a base of the reflected shock wave and propagating downstream along the "mixing layer". The shedding frequency of these structures corresponds to the frequency of the shock wave oscillations.

From spectrum at station #5 it is clear, that besides the first low-frequency peak there are also high-frequency pulsations (7 kHz), corresponding to self-frequency of pulsations of the separation
bubble. It was obtained in the experiment that these fluctuations penetrates upstream through subsonic area of the boundary layer and may be found upstream of the front of the reflected shock wave. Nevertheless the reflected shock wave is not oscillating at that frequency (7 kHz).

From the data obtained it follows, that low-frequency large-scale structures are connected with low-frequency movement of shock wave. Moreover, fluctuations of shock wave are not influenced by high-frequency self-resonant fluctuations of separation bubble.

REFERENCES