Studying the unsteady characteristics of a laminar transonic buffet depending on the angle of attack

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Abstract. Laminar transonic buffet on the airfoil for low Reynolds numbers of 0.5-0.7×10^6 was experimentally studied. Basic experiments were performed using high-speed schlieren imaging. The unsteady flow structure was investigated using various methods. It was found that shock wave oscillations can be significantly different from the turbulent case. The frequency and amplitude characteristics of oscillations from the angle of attack were found.

1. Introduction
The flow separation on the airfoil is mainly characterized by significant nonstationarity [1]. For transonic velocities the flow separation may result in a transonic buffet which is periodic oscillations of the zone of separation and the shock wave [2, 3]. This case leads to significant periodic loads, which can structurally damage the airplane. To avoid this regime, there is a need to predict its appearance [4] and to develop methods of flow control that will suppress it [5, 6].

Since the main state of the boundary layer for modern airliners is the turbulent regime, most of the studies investigated transonic buffet at the turbulent state of the inflow boundary layer. However, modern technical solutions allow gradually implementing the laminar flow on some elements of airliners [7]. This leads to the need to investigate transonic buffet for the laminar state of the inflow boundary layer. There are several papers devoted to laminar transonic buffet, for example [8, 9]. In some articles, no significant differences in the oscillation frequency of laminar and turbulent transonic buffet were found [8]. In others, significant differences were revealed [9]. The analysis of the studies shows that the data are provided only for several angles of attack, which complicates understanding of the development of unsteady processes for laminar transonic buffet. Therefore it was decided to perform experiments in a wide range of angles of attack for a laminar transonic airfoil.

2. Experimental setup
The experiment was carried out in a T-325 wind tunnel of the ITAM SB RAS. A transonic test section allowing to vary the Mach number in the range of M = 0.5–0.8 was used. Based on preliminary experiments the following flow parameters were selected: the freestream Mach number M = 0.7, the flow stagnation temperature T0 = 293 K, and the stagnation pressure P0 = 50–75 kPa. The width and height of the wind tunnel test section were 200 mm and 208 mm.

The experiments were carried out on a laminar airfoil with a chord b = 70 mm (figure 1). Relative profile thickness c/b = 14.3% (c - maximum model thickness, b - chord). The model was mounted on a holder, which allowed changing the angle of attack during the experiment. In the study, the angle of attack was changed in the range of 3-8 ° with a step of 0.5 degrees.
In the experiments the Reynolds number calculated from the wing chord length was about $Re = 4.5 \times 10^5$. For these Reynolds numbers for most subsonic airfoils a turbulent flow is found [10]. But with an increase in the Mach number the transition Reynolds number can increase significantly [11]. For transonic speeds airfoils with Natural Laminar Flow make it possible to achieve the laminar case up to Reynolds numbers $10-35 \times 10^6$ [12]. Thus the experiments were carried out at Reynolds numbers at which laminar flow is possible. Schlieren photo confirmed that the thickness of the boundary layer and the configuration of zone of shock wave boundary layer interaction corresponded to the laminar case. The installation of the turbulator on the leading edge led to the suppression of the laminar bubble and the appearance of a lambda structure in the zone of shock wave boundary layer interaction, which is characteristic for the turbulent flow. This confirms that the experiments were carried out for the laminar case.

Schlieren visualization using a high-speed camera (FASTCAM NOVA S9) was used as the main measurement technique. The camera frequency was 20-40 kHz, and the exposure was 1.4 μs. The knife was installed vertically.

On the figures the nose of the airfoil was taken as the zero longitudinal coordinate and the trailing edge was taken as the zero normal coordinate.

![Figure 1. Photo of an experimental model in a wind tunnel T-325.](image1.png)

![Figure 2. Example of Schlieren photo.](image2.png)

An example of the image is shown in figure 2. The presence of two main shock waves is clearly seen. The first "separation shock wave" is closer to the leading edge and arises due to the displacement of the shear layer by a laminar separation bubble. The "final shock wave" is closer to the trailing edge. Boundary layer turbulization was found near the final shock wave. Figure 2 shows the coordinate system. The zero of the longitudinal coordinate is the leading edge of the airfoil. The zero of the normal coordinate is the trailing edge of the airfoil.
3. Experimental results

Figure 3 demonstrates the example of changes in intensity of the Schlieren image along the red line (figure 2) versus time for the total pressure of 50 kPa. The red line in Fig. 2 is drawn parallel to the profile and offset from the airfoil by a few pixels up. In fig. 3a three periodic oscillatory phenomena with a frequency of about 250 Hz can be seen. In the range \( X = 40-60 \) mm a blue line is seen associated with the oscillation of the final shock wave. The bright yellow line (\( X = 25-40 \) mm) corresponds to the oscillation of the shear layer in the zone of the laminar separation bubble. Oscillations of the separation shock wave are observed in the range of \( X = 10-25 \) mm. An increase in the angle of attack by two degrees (figure 3b) leads to a significant increase in the oscillation frequency to about 1500 Hz.

Figure 4 shows an example of the distribution of the root mean square (RMS) of the insensitivity of schlieren image. Three main zones can be found in the figures. The first narrow inclined region is located near the leading edge and corresponds to the oscillations of the separation shock wave. The bright region near the model corresponds to the oscillations of the shear layer of the laminar separation bubble. The widest region is located in the zone of oscillation of the final shock wave. An increase in the angle of attack from 4.5 to 6.5 degrees is accompanied by an increase in the laminar separation zone, which displaces the separation shock wave upstream. The final shock wave changes its position only slightly. Note that the distributions of the RMS pulsations do not show significant changes in the characteristics of oscillatory phenomena.

![Figure 3. Image intensity vs time (a – \( \alpha = 4.5^\circ \), b – \( \alpha = 6.5^\circ \)).](image1)

![Figure 4. RMS pulsation of a schlieren image (a – \( \alpha = 4.5^\circ \), b – \( \alpha = 6.5^\circ \)).](image2)
Frequency characteristics were found by fast Fourier transform for each point of the image. To study the structure of unsteady flow it was decided to use POD (Proper orthogonal decomposition) \cite{13} and DMD (Dynamic mode decomposition) \cite{14} data processing methods. Figure 5 shows the power spectral density (PSD) of image pulsations obtained by integrating the PSD at all points of the processed image (red dashed line). Additionally the amplitude of the modes found on the basis of DMD analysis is plotted on the graph (solid blue curve). In Figure 5 the amplitudes of the DMD modes ($\phi$) and value of PSD are shown in arbitrary units. One can see a good agreement of data match for two data processing methods.

Beginning from an angle of attack of 4 degrees the weak low-frequency oscillations of the shock wave appear ($f \approx 270$ Hz, $St = f b / U \approx 0.08$). The oscillation process is similar to transonic buffet for the turbulent case. An increase in the angle of attack to 4.5 degrees leads to an increase in the amplitude of low-frequency oscillations (figure 5a). From an angle of 5.5 degrees the low-frequency oscillations begin to differ from sinusoidal ones, which is detected in the spectra as the appearance of a harmonic with a frequency of about 550 Hz. In addition, the high-frequency oscillations appear ($f \approx 1600$ Hz, $St \approx 0.5$). Most likely the high-frequency oscillations are caused by the oscillations of the laminar separation bubble and the separation shock wave. This flow pattern is maintained up to an angle of attack of 6.5 degrees. After exceeding this angle of attack the high-frequency oscillations disappear. But the low-frequency oscillations of the final shock wave significantly increase and make up more than half of the wing chord. Since the velocity of the final shock wave upstream is significantly different, in addition to the main frequency, numerous harmonics appear in the spectrum. Thus it can be seen that the frequency characteristic oscillations significantly change with the angle of attack.

Figure 5. Spectra pulsation of a schlieren image
(a – $\alpha = 4.5^\circ$, b – $\alpha = 5.5^\circ$, c – $\alpha = 6.5^\circ$, d – $\alpha = 7.5^\circ$).
An example of the second POD mode and the history of this mode in time for several angles of attack are shown in figure 6. Figure 6 shows the amplitude \( A \) in arbitrary units. The oscillation frequency with the maximum amplitude is indicated in the figure. For the angle of attack of 4.5 degrees POD mode corresponds mainly to low-frequency oscillations of the final shock wave. The oscillation process of this mode is close to sinusoidal. An increase in the angle of attack to 5.5 degrees leads to a violation of the sinusoidal oscillations of the second POD mode, which complicates accurate estimate of the frequency. However, the oscillation pattern is similar to the angle of attack of 4.5 degrees. For an angle of attack of 6.5 degrees the correlation between oscillations of the separation and final shock waves are clearly visible. The frequency of time fluctuations of this mode increases. For an angle of attack of 7.5 degrees the low frequency pulsations are returned. Meanwhile, the structure of a POD mode is significantly different from a small angle of attack. The reason for this is a significant increase in the length of the shock wave travel along the profile and the appearance of powerful vortex-like structures in the wake behind the shock wave. Based on the analysis of the POD modes it can be concluded that the low-frequency oscillations of the final shock wave and the oscillations of the separation shock wave are coherent. High-frequency pulsations are mainly concentrated in the region of the separation shock wave and poorly match oscillations of the final shock wave.

![Figure 6](image)

**Figure 6.** The second POD mode and the evolution of this mode in time
(a – \( \alpha = 4.5^\circ \), b – \( \alpha = 5.5^\circ \), c – \( \alpha = 6.5^\circ \), d – \( \alpha = 7.5^\circ \)).
Conclusion
Experimental studies of unsteady effects for laminar airfoil at transonic velocity have been carried out for various angles of attack. It has been found that laminar transonic buffet is characterized by oscillations at two frequencies. Low-frequency oscillations (St≈0.08) are similar to the oscillations of the turbulent transonic buffet. High-frequency oscillations (St≈0.5) are associated with a laminar separation bubble. With a change in the angle of attack the frequency and amplitude of the oscillations change significantly.

Acknowledgments
The research was carried out within the framework of the Program of Fundamental Scientific Research of the state academies of sciences in 2021-2023 (project No. 121030500162-7). The study was conducted at the Joint Access Center “Mechanics” of ITAM SB RAS.

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