“N-wave” propagation in supersonic flow at flow past the flat plate with sharp edge

Yu G Yermolaev\textsuperscript{1,2}, Yu I Chudinova\textsuperscript{1,3}, A D Kosinov\textsuperscript{1,2}, N V Semionov\textsuperscript{1}

\textsuperscript{1}Khristianovich Institute of Theoretical and Applied Mechanics SB RAS, 4/1, Institutskaya str., Novosibirsk, 630090, Russia
\textsuperscript{2}Novosibirsk State University, 1, Pirogova str., Novosibirsk, 630090, Russia
\textsuperscript{3}Novosibirsk State Technical University, 20, Prospekt K. Marksa, Novosibirsk, 630073, Russia

yermol@itam.nsc.ru

Abstract. The paper discusses the results of an experimental study of the propagation of the “N-wave” in a supersonic flow and its interaction with the bow shock wave, which is formed at flowing around a flat plate with a sharp leading edge. It was found that the “N-wave” does not change its direction when interacting with the bow shock. However, this interaction leads to a reduction of the “N-wave”. Estimates of the propagation angles of the “N-wave” in a supersonic flow are also obtained.

1. Introduction
The problem of passing weak pressure shock through the bow shock wave during the flow around aerodynamic bodies and their impact on the boundary layer is still relevant. So, a small disturbance of the oncoming flow can cause high-intensity low-frequency oscillations in the shear layer \cite{1, 2}, which usually leads to a local increase in heat fluxes. The models of a delta wing and a flat plate with blunt leading edges were used in previous experiments, but the case of a sharp leading edge, where an attached bow shock is realized, remains open. This work is devoted to the study of the development and interaction of the “N-wave” with the bow shock when flowing around the flat plate with a sharp leading edge.

2. Experimental setup
The experiments were carried out at the Joint Access Center “Mechanics” ITAM SB RAS in a low-noise supersonic wind tunnel T-325 at Mach number of 2.5. The experimental setup is described in detail in \cite{3}. The flat plate with a sharp leading edge located at a zero angle of attack was used in experiments. The thickness of the leading edge did not exceed 0.1 mm. The “N-wave” was generated by a sticker mounted on the side wall of the wind tunnel test section. The sticker was a scotch tape 14 mm wide and 130-135 \textmu m thick. The experimental scheme is shown in figure 1. The constant temperature hot-wire anemometer was used to measure the mean and fluctuation characteristics of a supersonic flow. The analog pulsed signal of the hot-wire was digitized by a 12-bit analog-to-digital converter with a sampling time $\tau = 1.33$ \textmu s. The waveforms had length of 65536 ADC samples and four measurements were performed at each point in space.
3. Results
First, we consider the results of measurements in the oncoming flow. The measurements were carried out in the transverse direction $z$ at a distance of 10 mm in front of the plate at a unit Reynolds number $Re_1=8\times10^6$ 1/m. In these experiments, the sticker was located at the distance of $L=225.5$ mm in front of the plate. The experimental data of the mean flow and integral pulsations are shown in figure 2. From the distribution $\rho U(z)$ it can be seen that the radiation from the scotch tape is reminiscent of the well-known “N-wave”. It consists of two weak shock waves, which, apparently, arise in the vicinity of front lug and trailing scarp of the sticker. Weak shock waves locally distort the mean flow by 3-4% and increase the level of pulsations several times relative to the undisturbed flow. We note that the highest level of rms pulsations is observed in the regions of the maximum gradient of the mean flow. The maximum in the integral distributions of pulsations at $z=9.6$ mm corresponds to a weak shock wave from the front lug of the sticker (shock wave 1), and the maximum at $z=-7.4$ mm corresponds to a weak shock wave from the trailing scarp (shock wave 2). The stream region at $z>10$ mm is undisturbed and corresponds to the oncoming flow.

Analysis of the amplitude-frequency spectra provides more complete information. The frequency spectra of pulsations in the propagation region of weak shock waves are shown in figure 3: graphs (a) and (b) correspond to the leading and trailing edges of the “N-wave”. Each graph shows amplitude spectra in the region of the passage of a weak shock wave, where the rms pulsations are maximal. Also, the amplitude spectrum in the region of the undisturbed oncoming flow ($z$=13.3 mm) is shown for comparison. Spectral analysis data show that a weak shock wave causes a growth of fluctuations in a wide frequency range. Disturbances are amplified with frequencies up to 20-30 kHz. However, the largest increase of disturbances in the oncoming flow occurs for low-frequency oscillations with a frequency of less than 1 kHz, which is consistent with [3].

![Figure 1. Scheme of the experiment.](image)

![Figure 2. Distributions of the mean mass flow rate and rms pulsations in the transverse direction of z at x=-10 mm](image)
Next, consider the result of the passage “N-wave” through the bow shock wave originating from the leading edge of the plate. “N-wave” partially dissipates at interaction with the bow shock. This is seen in figure 4 (a), where the data on the mean flow and rms pulsations in the free flow above the plate at $x = 60$ mm are represented. Above the plate, the “N-wave” locally distorts the mean flow by 2% relative to the oncoming flow. This is 1.5-2 times less than before the bow shock wave.

Also, the attenuation of the “N-wave” can be seen by the dependence of the integral pulsations in the transverse direction. This is especially markedly for a weak shock wave, which makes up the leading edge of the “N-wave”. So, the level of integral pulsations in the vicinity of shock wave 1 in front of the plate is 1%, and above the plate, about 0.3%. For shock wave 2, which originates from the rear edge of the sticker, the situation is less critical, but there is still a decrease in integral pulsations. Note that the level of rms pulsations in the undisturbed flow in front of the plate and above it is the same. The results of measurements inside the supersonic boundary layer at $x = 60$ mm are shown in figure 4(b).

The amplitude-frequency spectra of disturbances in the area of passage of weak shock waves, measured in a free supersonic flow above a plate at $x = 60$ mm, are shown in figure 5. Shock wave 1 in the free flow above the plate causes a growth in fluctuations in the frequency range up to 7 kHz, which is much smaller than in the case in front of the plate. If it compare the frequency spectra measured at $x = -10$ and 60 mm, it can come to the conclusion about the attenuation of the intensity of the “N-wave” when it passes through the bow shock from the plate.
Figure 5. The amplitude-frequency spectra of disturbances in the vicinity of the fronts of “N-wave” above the plate at $x=60$ mm and $y=5$ mm

In paper [4] studied the propagation of the “N-wave” and its interaction with the bow shock which is formed at flowing around a plate. The flat plate in these experiments had a large blunting radius of the leading edge. Estimates of the propagation angle of the leading edge of the “N-wave” in oncoming flow and its change during the passage of the bow shock were made in [4] by using optical visualization of the flow. The results of these estimates show that the “N-wave” deviates by about 1.5 degrees when interacting with the detached bow shock wave. Therefore, in our case, at the passage of the attached bow shock which is formed at flowing around a sharp flat plate, the “N-wave” practically does not change its direction. Also, in consideration of the fact that, disturbances from the fronts of “N-wave” propagate parallel to the oncoming flow in the boundary layer from the leading edge of the model [5], it can be estimate the propagation angles of the “N-wave” in the oncoming flow with a Mach number of 2.5.

Figure 6. The propagation angles estimation of the fronts of the “N-wave” in a supersonic flow at $M = 2.5$

The results of estimates of the propagation angles of weak shock waves formed during the flow around the front and rear edges of the sticker are shown in figure 6. The basic error in determining the angles is associated with the initial position of the hot-wire sensor. Estimates show that the trailing edge of the “N-wave” propagates in a supersonic flow at a Mach angle equal 23.6 degrees at $M = 2.5$. The propagation angle of the leading edge of the “N-wave” in oncoming flow is 24.8 degrees, which coincides with the results of [4]. Approximation of the data on the side wall of the wind tunnel test
section shows that the weak shock waves that make up the “N-wave” originate in the vicinity of front lug and trailing scarp of the sticker.

4. Conclusion
Experimental studies of the propagation of the “N-wave” in a supersonic flow and its interaction with the bow shock formed during the flow around a flat plate with a sharp leading edge have been performed. The measurements in an oncoming flow, free stream above the plate, and in the boundary layer were carried out. Inside the boundary layer, disturbances caused by the “N-wave” propagated parallel to the oncoming flow. Above the plate in free flow the “N-wave” does not change its direction after passing through the bow shock. Estimates show that the pressure wave generated by the trailing scarp of the sticker propagates at the Mach angle. The propagation angle of the wave generated by the front lug of the sticker is larger than the Mach angle and coincides with the results of the optical experiment [4]. The interaction of the “N-wave” with the bow shock leads to its attenuation.

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