Evolution of a localized wave packet in the boundary layer of the swept wing at \( M = 2 \)

A A Yatskikh\(^1,2\), Y G Ermolaev\(^1\), B V Smorodsky\(^1\), A V Panina\(^1\), N V Semionov\(^1\) and A D Kosinov\(^1,2\)

\(^1\)Khristianovich Institute of Theoretical and Applied Mechanics SB RAS, 630090 Novosibirsk, Russia
\(^2\)Novosibirsk State University, 630090 Novosibirsk, Russia

E-mail: 73.yatskikh@gmail.com

Abstract. The evolution of an artificial localized wave packet in a supersonic boundary layer of a swept wing is experimentally investigated at Mach number \( M = 2 \). The wave characteristics of the development of disturbances at various frequencies are determined. The growth increments of the most increasing modes of the wave packet are estimated. Comparison with the results of calculations based on the linear theory of stability is carried out.

1. Introduction

The study of the development of artificial localized disturbances (wave packets) in the boundary layers is an effective approach for the study of laminar-turbulent transition. The evolution of localized disturbances models the scenario of a natural laminar-turbulent transition, when disturbances with different frequencies grow in the boundary layer. Experimental studies with using controlled localized perturbations have led to significant progress in understanding the late stages of the laminar-turbulent transition in boundary layers at subsonic flow speed [1-5].

A method of exciting localized wave packets in a supersonic boundary layer using a surface pulsed glow discharge was proposed and tested in [6, 7]. Single wave packets in the flat-plate boundary layer were generated using a pulsed glow discharge. Studies of the evolution of wave packets in a two-dimensional supersonic boundary layer have shown that for different modes of the wave packet, strongly inclined waves are the most increasing downstream.

Investigations of excitation of localized wave packets in three-dimensional boundary layers with the Mach number of the stream \( M = 2 \) were carried out in [8]. In the experiments, a model of swept wing with a lenticular profile with a thickness of 7.7\% was used, which was set at a zero angle of attack. The sweep angle of the leading edge of the model was 40\(^\circ\). A significant difference in the structure of the wave packet in the three-dimensional boundary layer from the two-dimensional case was found. In the boundary layer of the swept wing, the wave packet is asymmetric.

In this work, the wave characteristics of downstream evolution of wave packets in a supersonic boundary layer of a swept wing are determined from experimental data [8]. The most unstable modes of the wave packet are determined. Estimation of growth increments is carried out. Inclination angles of the most unstable waves are determined too.
2. Experimental setup and data process
The experiments were performed in a low-noise supersonic wind tunnel T-325 ITAM SB RAS at Mach number \( M = 2 \) and unit Reynolds number \( Re_1 = 6 \times 10^6 \text{ m}^{-1} \). A swept-wing model with a lenticular profile with a thickness of 7.7% was used, which was set at a zero angle of attack. The sweep angle of the leading edge of the model was 40°.

The experimental scheme with the coordinates used in the work is presented in figure 1. Controlled localized wave packets were generated using a pulsed glow discharge on the surface of an experimental model. The source of disturbances was at a distance of \( x \approx 29 \text{ mm} \). The mass flow pulsations of the boundary layer were measured using a constant-temperature hot-wire anemometer. The recording of the signal of the hot-wire anemometer was synchronized with excitation of the controlled wave packets. Using the synchronous averaging of 320 signal realizations, artificial perturbations were distinguished from the background of the natural pulsations of the boundary layer.

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

Three sections parallel to the leading edge at \( x = 49, 59 \) and 69 mm were measured. The hot-wire probe was installed in the supersonic part of the boundary layer in the region with the maximum level of pulsations. In figure 1, the wave vector of perturbations is conventionally designated as vector \( \mathbf{k} \). Its slope relative to the direction of the incident flow is denoted as \( \chi \).

For individual frequencies, wave disturbance spectra are considered. Amplitude and phase distributions over the transverse wavenumbers \( \beta' \) for various frequencies are constructed. For this, a discrete Fourier transform was performed in time and space.

Calculations on the linear stability theory were performed on the basis of the Liza-Lin equations using the orthogonalization method. The flow parameters and model used in the calculations are close to the experimental ones.

3. Results
The dependences of amplitudes and phases on the value of the transverse wave number at different values of the longitudinal coordinate \( x \) for the most growth of the wave are presented in figure 2. The wave spectrum of the wave packet in the boundary layer of the wing is asymmetric. For the frequency under consideration, the largest amplitudes are observed in the range of wave numbers \( \beta' = 1 \div 3 \text{ rad/mm} \) with maximum values at \( \beta' = 2 \text{ rad/mm} \). The phase distributions over the transverse wave numbers show that in the region of the maximum amplitude of controlled disturbances (in the range of transverse wave numbers \( \beta' = 1 \div 3 \text{ rad/mm} \)), the phase distribution decreases almost linearly with increasing \( \beta' \). Phase distributions do not have jumps characteristic of nonlinear interactions. In the specified range of wave numbers for the considered frequency, the phase distribution of the wave packet increases downstream monotonically.
With the evolution downstream, amplitudes of disturbances in the range of wave numbers $\beta' = 1\div3$ rad/mm grow downstream. Thus, the amplitude of pulsations at $x = 69$ mm is more than 4 times greater than the amplitude of disturbances in the initial section.

The amplitude and phase $\beta'$-spectra allow us to make estimates of the wave characteristics of the modes of the wave packet, in particular, the longitudinal wavenumber, the angles of inclination of the wave vectors, and the growth increments. From the data presented in figure 2, the values of the projected longitudinal wave vector on the axis perpendicular to the leading edge of the wing ($x'$ coordinate) are determined. The obtained dispersion dependence $\alpha_r'(\beta')$ is shown in figure 3.

The dependences $\alpha_r'(\beta')$ for the considered frequencies are linear. The angles of inclination of the curves for all considered frequencies are close. Based on the data presented, it is possible to estimate the angles of inclination of the disturbances. The values obtained are in the range $\chi = 65\div75^\circ$.

In addition, according to the data presented in figure 2, the growth increments of the wave mode of the wave packet can be estimated. The results of the estimation are shown in figure 4.
Figure 4. Increments of growth of disturbances for various frequencies.

Estimates show that disturbances with frequency $f = 24$ kHz and wave number $\beta' = 1.6$ rad/mm are the most unstable. The angle of the wave vector relative to the incident flow is approximately $\chi = 70\div 71^\circ$. Figure 5 presents the results of calculations on the linear stability theory. Theoretical calculations show that disturbances in the frequency range $f = 20\div 25$ kHz with wavenumbers $\beta' = 1.9$ rad/mm are the most unstable. For the most growing perturbations, the experimentally determined growth increments are numerically close to the calculation results.

Figure 5. Results of calculations by the linear stability theory.

Conclusion

The most increasing modes of the wave packet are experimentally determined. The estimates show that in the measured range the waves with frequency $f = 24$ kHz and transverse wave number $\beta' = 1.6$ rad/mm are the most growing downstream. The inclination angle of the wave vector relative to the incident flow is $\chi = 70\div 71^\circ$. Experimental results on the evolution of wave packets in a supersonic boundary layer of a swept-wing are compared with a linear stability theory.
Acknowledgments
This work was supported by the Grant of the President of the Russian Federation (MK-2491.2019.1). The study was conducted at the Joint Access Center “Mechanics” of ITAM SB RAS.

References
[1] Gorev V N and Katasonov M M 2004 Thermophysics and Aeromechanics 11 391
[2] Gorev V N, Katasonov M M and Kozlov V V 2007 Fluid Dynamics 42 732
[3] Gorev V N, Katasonov M M and Kozlov V V 2008 Thermophysics and Aeromechanics 15 415
[4] Katasonov M M, Pavlenko A M and Kozlov V V 2018 Thermophysics and Aeromechanics 25 801
[5] Dovgal A V, Katasonov M M, Kozlov V V and Pavlenko A M 2017 Fluid Dynamics 52 394
[6] Yatskikh A A, Ermolaev Y G, Kosinov A D and Semionov N V 2015 Thermophysics and Aeromechanics 22 17
[7] Yermolaev Y G, Yatskikh A A, Kosinov A D and Semionov N V 2016 AIP Conference Proceedings 1770 030037
[8] Yatskikh A A, Rumenskikh M S, Yermolaev Y G, Kosinov A D and Semionov N V 2017 MATEC Web of Conferences 115 02015