The controlled periodic impact on the longitudinal vortex in the boundary layer at Mach 2

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Abstract. Experimental data on the development of controlled disturbances in the boundary layer with a longitudinal vortex are analysed. It is found experimentally that the mean flow nonuniformity can vary from 0.7 to 0.9 V in terms of the CTA mean voltage or 30–40% in \(\rho U\). Such flow nonuniformity complicates the estimation of the wave spectra, where normalization on the mean voltage of the anemometer is required. The applicability of the standard processing procedure is investigated. Comparative analysis of the data shows that both normalization types considered in the work can be applicable. However, in the case of flow nonuniformity in the transverse direction, it is preferable to use the normalization on the median value over the mean voltage spanwise distribution.

1. Introduction

The laminar-turbulent transition phenomenon is of great importance in aerohydrodynamics. Its study is necessary for the modern aviation technology development. At supersonic flow velocities, perturbations in the form of Mach waves can be emitted from the surfaces of aircrafts. This process affects downstream wings, leading edges, and other parts of the aircrafts. Experimental studies of such an effect are described in \([1-5]\). As a result it was found that a two-dimensional roughness on the wall of the test section generates a disturbance in the form of N-wave in space. When it interacts with the flow near the model, the mass flow pulsations level increases significantly. Also a mean flow distortion is observed and what is more, the stationary longitudinal vortices are generated in the boundary layer. In \([6, 7]\) the N-wave influence on the perturbations development in the boundary layer was studied. It is shown that stationary longitudinal vortices do not affect the beginning of the laminar-turbulent transition, however, at the same time, its end is shifted downstream.

The experimental data techniques processing used previously \([8, 9]\), was developed for the boundary layer homogeneous in the transverse direction. Since the measurements are performed at \(y = \text{const}\), the mean flow inhomogeneity in the transverse direction is fixed in the form of \(E(z)\) dependence. However, for the Fourier processing, the scaled (dimensionless) output signal of the hot-wire anemometer is used, and the modulated nature of \(E(z)\) dependence, in accordance with the Fourier transform properties, will affect the wave spectra estimation results by \(\beta\).

The aim of this work is the study of experimental data techniques processing applicability for the case of an inhomogeneous flow in the boundary layer.
2. Experimental set up and data processing

The experiments are carried out in a T-325 ITAM SB RAS supersonic wind tunnel at Mach number $M = 2$. The detailed description of the used equipment and experiment set up is given in [6, 10, 11]. In this study, the model of a flat plate with a sharp leading edge was installed in the wind tunnel test section at the zero attack angle. Figure 1 shows the experiment scheme.

![Image](image-url)

**Figure 1.** Experiment with 2D-irregularity on the test section wall, the discharge is on

The processing of the experimental data involves the collection of the frequency-wave spectra of the controlled disturbances [12]. The frequency-wave spectra of the controlled (periodic) disturbances were determined by the discrete Fourier transform (DFT) in the following form:

$$
\tilde{A}(x_k, \beta, f_i) = \frac{\sqrt{2}}{\delta \cdot T \cdot Q} \sum_{n=1}^{N} \sum_{j=1}^{M} A(x_k, z_j, t_n) \cdot e^{-i(\beta z_j - \alpha z_j)} \Delta z_j \Delta t ,
$$

(1)

where $\delta = 1\ \text{mm}$ is the boundary layer thickness scale; $T$ is the implementation length over time; $Q$ is the sensitivity coefficient to mass flow pulsations; $A(x_k, z_j, t_n)$ is the instantaneous value of dimensionless pulsations of the hot-wire anemometer output signal; $\Delta z_j$ is the analog-to-digital converter time sampling step.

The amplitude and phase of the disturbances were calculated after the DFT using the formulas:

$$
A(x_k, \beta, f_i) = \text{mod} \left[ \tilde{A}(x_k, \beta, f_i) \right],
$$

$$
\Phi(x_k, \beta, f_i) = \text{arctg} \left\{ \frac{\text{Im} \left[ \tilde{A}(x_k, \beta, f_i) \right]}{\text{Re} \left[ \tilde{A}(x_k, \beta, f_i) \right]} \right\} .
$$

(2)

3. Results

For this problem statement, the experimental data processing procedure allows for three different normalizations for the instantaneous value of the pulsation signal of the hot-wire anemometer $A(x_k, z_j, t_n) = e'(x_k, z_j, t_n)/E_m(x_k)$:

- to local measured voltage value $E_i = E(x_k, z_j)$,
- $E_2$ mean voltage (mean(E)) [13],
- $E_3$ median voltage value (median(E)) [13].

Table 1 shows the average and median voltage values for the cross sections $x = 60 - 100\ \text{mm}$ and the difference between these values $\Delta$ in percent. Evident that these values are different for each $x$. Although the difference is small, nevertheless, it is necessary to study the applicability of normalization to mean(E) and median(E).
Table 1. Evolution of the mean, median voltage value and their difference downstream.

| x, mm | mean(E), V | median(E), V | Δ, % |
|-------|------------|--------------|------|
| 60    | 8.51       | 8.52         | 0.1  |
| 70    | 8.47       | 8.49         | 0.2  |
| 80    | 8.51       | 8.47         | 0.5  |
| 90    | 8.71       | 8.67         | 0.5  |
| 100   | 8.64       | 8.61         | 0.3  |

Figure 2. Mean mass flow defect downstream evolution (longitudinal vortex): a) x = 60 mm; b) x = 70 mm; c) x = 80 mm; d) x = 90 mm; e) x = 100 mm
Figure 3. Amplitude $\beta$-spectra for the cross section $x = 60$ mm:

a) $f = 10$ kHz; b) $f = 20$ kHz; c) $f = 30$ kHz; d) $f = 40$ kHz.
In figure 2, the curve \( E(z) \) displays the voltage values measured by the hot-wire anemometer sensor. The area \( z > 0 \) corresponds to the undisturbed flow. In the interval from \( z = -4 \text{ mm} \) to \( z = 0 \), the stationary longitudinal vortex generated by a weak shock wave from 2D - irregularity can be identified.

From the voltage distributions a) - e) shown in figure 2 one can see that in this case it is preferable to use the normalization on the median voltage value (mean(\( E) \)), because it lies closer to the values of \( E(z) \) in the unperturbed flow region than the average voltage (mean(\( E) \)).

Further, in the work, the instantaneous value of the pulsation hot-wire anemometer signal was dimensionless by the median voltage value. Figures 3 and 4 show the amplitude and phase \( \beta \)-spectra, received via various normalizations. The data for the case of normalization on the values of \( E(z) \) were taken from [14].

Comparison of these results shows that the difference between the spectra is insignificant, and both types of normalization are applicable.

![Figure 4. Phase \( \beta \)-spectra for the cross section \( x = 60 \text{ mm} \): a) \( f = 10 \text{ kHz} \); b) \( f = 20 \text{ kHz} \); c) \( f = 30 \text{ kHz} \); d) \( f = 40 \text{ kHz} \)](image)

### 4. Conclusion

Analysis of experimental data [14] on the development of controlled disturbances in the boundary layer with a longitudinal vortex is performed. The measurements in [14] are conducted at a fixed height of the hot-wire above the model surface. The choice of this height is based on the maximum location of the disturbance profile in the boundary layer for each value of the \( x \) coordinate varying from 60 to 100 mm at the same value of the \( z \) coordinate approximately equal to -16 mm. It is found under the experimental conditions that the nonuniformity of the mean flow can vary from 0.7 to 0.9 V in terms of
the CTA mean voltage or 30–40% in terms of the mean mass flow $\rho U$. Such flow nonuniformity complicates the estimation of the wave spectra, where normalization on the mean voltage of the anemometer is required. The purpose of this work was to obtain the amplitude and phase $\beta$-spectra using various normalizations.

The applicability of the standard processing procedure is investigated. Comparative analysis of the data shows that both normalization types considered in the work can be applicable. However, in the case of flow nonuniformity in the transverse direction, it is preferable to use the normalization on the median value over the mean voltage spanwise distribution.

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