Application of the time-frequency technique for analysis of velocity fluctuations in the wake of a teardrop profile in the presence of a localized flow inhomogeneity

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Abstract. Experimental simulation of the inhomogeneity of the incident flow localized in time and space on a bluff tear-drop airfoil is carried out. It is shown that in the region outside the aerodynamic wake of the tear-drop airfoil, the presence of inhomogeneity leads to an increase in the amplitudes of velocity fluctuations in a wide frequency range. In the region inside the wake, the presence of inhomogeneity leads to the suppression of velocity fluctuations at the frequency of vortex shedding by a factor of 2–3 in amplitude. The intensification of fluctuations at frequencies above the main one was also noted, and there was no effect on fluctuations at lower frequencies.

1. Scheme of experiments

Experiments to simulate a sudden change in the conditions of flow around a tear-drop airfoil were carried out in T-325M wind tunnel of the ITAM SB RAS with a test section of 40×40 mm². According to the coordinates of the profile used in [1], a two-dimensional model of a tear-drop airfoil with a thickening of 40% was made for the entire width of the test section, with a chord length of 10 mm. The model was installed on the side wall of the test section on a swivel mechanism based on a stepper motor, which allows changing the angle of attack with an accuracy of 0.1°.

To simulate a rapid change in the flow conditions, a local inhomogeneity generator was manufactured. It was installed 30 mm upstream of the tear-drop airfoil. The generator is actually a cylinder 6 mm in diameter located in the plane of symmetry of the test section of wind tunnel in its upper wall perpendicular to the streamlined body model. To generate a local inhomogeneity, the generator was moved into the flow core using an electromagnetic drive for a given time. Full extension is about 23 mm. Velocity measurements were carried out with a constant temperature hot-wire anemometer CTA-5 developed and manufactured at ITAM SB RAS. The probe was installed at a distance $x = 32$ mm from the tear-drop airfoil on a coordinate device providing transverse movement. So the profiles of the mean and fluctuations components of the longitudinal velocity were obtained.
2. Data analyzing technique

The hot-wire anemometer signal was digitized using an L-Card E20-10 ADC with a sampling rate of 1 MHz. As a time-frequency method of data analyzing, the Hilbert–Huang transform [2] was used, which consists of the empirical mode decomposition which presents the signal in terms of intrinsic mode functions (IMF) with the subsequent application of the Hilbert transform to these modes.

Empirical mode decomposition is based on a sifting process, when intrinsic mode functions are gradually subtracted from the signal, plotted as the average of the envelopes of local minima and maxima, with interpolation using a cubic spline. As a result of decomposition, the original signal, in this case the dependence of the flow velocity on time, is represented as a sum

\[ V(t) = \sum_{i=1}^{n} c_i + r_n \]  

where \( c_i \) – intrinsic mode functions, corresponding to some fluctuation processes in the flow in a narrow frequency band, \( r_n \) – trend or constant value of a signal. It follows from the decomposition algorithm that the characteristic frequency of individual IMFs decreases with increasing number. A distinctive feature of the result of such decomposition is that it does not have a predetermined basis, unlike, for example, the Wavelet transform. With the correct decomposition, each of the IMF has one value of the instantaneous frequency at each moment of time, and as a result of applying the Hilbert transform for each IMF, it is possible to plot the frequency and amplitude distributions of the signal over time.

3. Experimental results

Experiments on the study of flow around a tear-drop airfoil were carried out at the freestream Mach number \( M = 0.13 \). The angles of attack was varied from \(-20^\circ\) to \(+20^\circ\). The control signal to move the generator of the localized inhomogeneity into the flow was supplied 100 ms after the start of recording the implementation. After another 100 ms, a return signal was given. The transition time of the generator from one position to another, without taking into account the delay time before the generator starts moving, was about 30 ms.

According to the results of the spectral analysis of velocity fluctuations in the wake behind the tear-drop airfoil in the absence of an inhomogeneity generator, at the used flow velocity, it was found that a vortex shedding behind the airfoil has a characteristic frequency of about 2.5 kHz at zero angle of attack. At angles of attack of \( \pm 20^\circ \), the frequency is decreased to 1.7 kHz due to an increase in the effective transverse dimension of the streamlined airfoil.

In Figure 2 examples of typical profiles of velocity fluctuations in the wake behind a tear-drop airfoil are presented at angle of attack of \( +5^\circ \). The profile \( \langle u \rangle \) was obtained in the experiment when the localized inhomogeneity generator was not entered into the test section of the wind tunnel. Profile
<u_in> was obtained in the case when the generator of the localized inhomogeneity is in the flow, and <u_out> - the generator is entered into the working section, but it is in the retracted state. By the coincidence of the profiles of the velocity fluctuations <u> and <u_out>, we can conclude that the installation of the generator does not affect the flow pattern when it is retracted.

![Figure 2. Velocity fluctuations profiles in a wake behind tear-drop airfoil at α = +5°.](image)

An increase in the level of velocity fluctuations in the region outside the wake behind the tear-drop airfoil (region \( y > 11 \) mm) in the presence of a generator inside the test section is due to the fact that a wake is formed behind it and it itself is also a source of a vortex shedding. In this case, the maximum level of velocity fluctuations is about 12\% and is close to the maximum level generated in this section by the tear-drop airfoil itself. However, in the area of the wake of the tear-drop airfoil, the presence of a generator leads to a twofold decrease in the maximum level of fluctuations. In the region \( y < -2 \) mm, the presence of an inhomogeneity generator does not affect the velocity fluctuations profile, which corresponds to the length of the cylinder - generator.

As a result of using the empirical mode decomposition to the signal measured at the probe position \( y = 15 \) mm, the original signal was decomposed into 18 intrinsic mode functions (IMF). Figure 3 shows, for example, the dependence on time of the amplitude of IMF #6. This intrinsic mode function has a center frequency of 3.6 kHz.

![Figure 3. Time depended amplitude of velocity fluctuations of IMF #6.](image)

Since the hot-wire probe is located in the free flow region (at \( y = 15 \) mm), the amplitude of velocity fluctuations at the initial moment of time is practically zero. As the generator extends, the amplitude
gradually increases to a value of 2–5 m/s (the longest in time). Similar amplitude behavior is observed for all other IMFs, whose center frequencies decrease with increasing of IMFs number. Thus, the interaction of the wake of a localized inhomogeneity generator, for which the characteristic frequency of vortex generation is about 1.6 kHz, with a tear-drop airfoil leads to the generation of velocity fluctuations in a wide frequency range, both higher and lower the main one. On the opposite side of the wake behind the tear-drop airfoil, the generation of fluctuations during the extension of the generator of localized inhomogeneity is not observed.

Let us consider the effect of the generator of localized inhomogeneity on the velocity fluctuations at the probe position $y = 7$ mm, where the total level of fluctuations does not change with its extension (see Figure 2). The amplitude of high-frequency fluctuations (see Figure 4 a), which correspond to IMF #4 and #5 with central frequencies of the order of 6 and 5 kHz correspondingly, increases insignificantly in the time interval from 0.13 to 0.23 s. In this case, it can be noted that high-amplitude velocity fluctuations are observed noticeably more often, compared with time intervals when there is no inhomogeneity generator in the flow. For IMF #7 with a central frequency of 2.5 kHz, corresponding to the process of vortex shedding behind the tear-drop airfoil, the opposite effect is observed - the amplitude of the velocity fluctuations decreases by 2 times while the inhomogeneity generator is in the extended position. Thus, the presence of a localized inhomogeneity in front of the streamlined airfoil leads to the destruction of the vortex shedding in the wake behind this airfoil and the intensification of fluctuations at higher frequencies, despite the deficit in the velocity of the flow created by the inhomogeneity generator oncoming the airfoil.

For probe positions $-2 < y < 7$, where a decrease in the total level of fluctuations is observed (see Figure 2), the presence of a localized inhomogeneity leads to a decrease in the amplitude of the velocity fluctuations at the fundamental frequency (corresponds to IMF #7, Fig. 5 b), and at higher (corresponds to IMF #4, 5, Figure 5 a). It should be noted that the presence of a localized inhomogeneity does not affect the fluctuations, the frequencies of which are lower than the
fundamental frequency of vortex shedding process. This can be seen on the example of the time
dependence of the amplitude of IMF #8 in Figure 6, the center frequency of which is 1.2 kHz.

![Image of time depended amplitudes of velocity fluctuations of IMF #4,5 and IMF #6 at y = 5 mm.](image1)

**Figure 5.** Time depended amplitudes of velocity fluctuations of IMF #4,5 a) and IMF #6 b) at y = 5 mm.

![Image of time depended amplitude of velocity fluctuations of IMF #8 at y = −2 mm.](image2)

**Figure 6.** Time depended amplitude of velocity fluctuations of IMF #8 (1,2 kHz).

At the lowest point of equal levels of total fluctuations at the probe position y = −2 mm (see
Figure 2), the effect of inhomogeneity is similar to that at y = 7 mm, i.e. there is a decrease in the
amplitude of fluctuations by two times at the main frequency of vortex shedding process, and a slight
increase at higher ones. Due to the fact that the inhomogeneity generator is located opposite the point
y = −2 mm for a shorter time interval, the time of changing of the amplitudes is also shorter.

At other investigated angles of attack of the tear-drop airfoil, similar effects are observed for the
extension of the inhomogeneity generator on the structure of fluctuations in the wake. In this case, the
position of the maximum of velocity fluctuations in the absence of the inhomogeneity generator is
shifted relative to the position y = 0 in the corresponding direction, depending on the sign of the angle
of attack. In the position of the maximum level of velocity fluctuations, the maximum effect of decreasing the amplitude of the velocity fluctuations at main frequency of vortex shedding process is observed when a local inhomogeneity is introduced into the flow by using a generator.

Conclusions
A generator was developed and manufactured for introducing a localized inhomogeneity into flows with a response time of the order of 30 ms. The influence of the created inhomogeneity on the characteristics of the flow in the wake behind the tear-drop airfoil in the range of angles of attack from −20 to +20 was investigated. It is shown that in the region outside the tear-drop airfoil wake the presence of an inhomogeneity generator leads to a significant increase in velocity fluctuations in a wide frequency range. In the area inside the wake, the presence of inhomogeneity leads to a 2-fold decrease in the total level of pulsations in comparison with the maximum value in the center of the wake due to a decrease in the amplitude of velocity fluctuations by a factor of 2–3 at the fundamental frequency of the vortex shedding process. In this case, there is a slight increase in the amplitudes of the velocity fluctuations at frequencies above the main one; for lower frequencies, no change in the amplitudes is observed. Despite the fact that, according to the results of additional measurements, the generated inhomogeneity covers the entire tear-drop airfoil, it does not affect the lower outer boundary of the wake.

Acknowledgments
The work was carried out within the framework of a grant from the Russian Science Foundation # 20-49-08006.

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