Determining the flow separation near a small UAV by unsteady pressure sensors

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Abstract. Experimental studies of pressure pulsations on the surface of a small unmanned aerial vehicle (SUAV) are carried out in a wind tunnel. The onset of the separation flow is determined on the basis of PIV and loads measurements. It is found that an increase of pressure pulsations does not always correspond to flow separation. The paper proposes to use correlation analysis to determine the flow separation by finding large-scale coherent structures generated by the separation.

1. Introduction

The flight of small unmanned aerial vehicles (SUAV) mainly occurs at altitudes less than 5 km in the atmospheric boundary layer [1]. For this flight area there is a high probability of atmospheric turbulence, which can have a significant effect on the flight of a SUAV. For example, at a flight speed of 20 m/s a vertical wind gust of 2 m/s will change the angle of attack by approximately 5 degrees. This can lead to the SUAV exceeding the critical angle of attack and accordingly the emergence of a stall for the aircraft. Therefore, in order to ensure a safe flight, it is necessary to develop a method for determining the separation flow near the aircraft.

The flight of the SUAV occurs at Reynolds numbers Re ≈10⁴-10⁵, characteristic for the laminar flow on a significant part of the wing [2, 3], which is sensitive to disturbances. For example, heating or contamination of the wing surface can change the state of the boundary layer from laminar to turbulent, which will change the critical angle of attack [4]. Therefore, the determination of the flow separation by the value of the angle of attack may lead to inaccuracies in the detection of the flow regime of SUAV.

Separated flows on airfoils have been well studied [5, 6]. It is known that flow separation is accompanied by an increase in pressure pulsations on the wing surface [7, 8]. Assumingly, the information received by unsteady pressure sensors may be used to detect the separation flow at the wing of SUAV. Experimental studies of this issue are carried out in this paper.

2. Experimental setup

The small unmanned aerial vehicle ZOHD Nano Talon Evo has been selected for experimental research. The aircraft has a V-shaped tail, the aspect ratio of the wing of the aircraft is approximately 5, the span of the model is L = 860 mm, the chord of the wing near the fuselage is b = 170 mm, and the
The aircraft is equipped with a pusher propeller. The wing profile of the aircraft is close to that of NACA 3513.

The experiments are carried out in the wind tunnel T-503 NSTU (Novosibirsk State Technical University) at flow velocities $V = 5-20$ m/s and ambient temperature $T = 20-23$ C. The T-503 NSTU is a closed-type wind tunnel with an open test section of a circular cross-section with a diameter of 1.2 m and a length of 2.0 m. The experimental model is attached to three-axis load cells, installed on the alpha mechanism of the aerodynamic wind tunnel. To obtain the quantitative data on the characteristics of the flow near the wing the PIV method is used (figure 1). To carry out these experiments the flow is seeded by particles with an average diameter of about 1-2 μm. The main measurements are carried out in the section $Z/L = 0.13$. The calculation of statistical characteristics is carried out on the basis of 1400 instantaneous velocity fields.

The UAV was equipped with 4 unsteady pressure sensors and three miniature electret microphones. Differential pressure sensors 1 INCH D1-P4V-MINI with a response time no less than 0.1 ms and a measurement range of $\approx 250$ Pa were used in the experiments. The VS4011S36 with a frequency range of 50-10000 Hz and a diameter of 4 mm were used as microphones.

**Figure 1.** Photo of an experimental model in a T-503 wind tunnel.

### 3. Experimental results

The lift force versus angle of attack (AOA) is shown in figure 2. It is clearly seen that an increase in the incident flow velocity (Reynolds number) leads to a slight increase in the critical angle of attack, which is approximately 15 degrees. The deviation from the linear increase in lift with increasing angle begins from approximately 12-14 degrees. The drop of lift after the critical angle of attack occurs smoothly.

Figure 3 shows an example of the results measured by PIV by the measurement method in the section $Z/L = 0.13$ for an angle of attack of 16 degrees and a speed of 10 m/s. The figure clearly shows the presence of a fully separated flow at the leeward side of the airfoil. On the distribution of the root mean square (RMS) velocity pulsations, the main peak of the RMS is found near the leading edge. The reason for this is the turbulization of the flow in the laminar separation bubble, which arise near the leading edge of the airfoil. Analysis of the velocity fields measured at other angles of attack in the leeward side of the airfoil allows establishing (for case of 10 m/s) that: if the angle of attack is less than 4 degrees, the flow is mainly laminar; at an angle of attack $> 4$ degrees a laminar separation bubble arises near the leading edge, in which the flow is turbulized; the main separation point moves smoothly from the trailing edge to the beginning of the leading edge at 14 degrees.
Figure 2. Lift coefficient vs angle of attack.

Figure 3. Fields of the a) mean longitudinal velocity component and b) RMS of the longitudinal velocity component for an angle of attack of 16 degrees Styles bar. 16 AOA.

An example of the RMS pulsation obtained on two unsteady sensors is shown in figure 4 ($X/b = 0.57$). For the sensor located on the wing, the main growth of disturbances is found at approaching the critical angle of attack (figure 4a). The dimensionless level of pulsations in the separation region is approximately constant. For angles of attack in the case of unseparated flow, a small level of pulsations is usually found. The exception is the narrow peak (second peak), which is in the range of 2-10 degrees of AOA, depending on the flow velocity. An increase in the flow velocity leads to a decrease in the dimensionless amplitude of the second peak of pulsations. For a flow velocity of 10 m/s this peak is found for an AOA of 4-6 degrees, which corresponds to the onset of the laminar separation bubble (according to PIV data). It may be assumed that the second peak is caused
by powerful turbulent structures that generated in the zone of the laminar separation bubble and move downstream. These flow structures lead to an increase in pressure fluctuations on the wing surface. An increase in the velocity leads to earlier turbulization of the shear layer in the laminar separation bubble, which shifts the pulsation peak to the region of small angles of attack.

![Figure 4](image1.png)  
*Figure 4. Pressure pulsations depending on the angle of attack (a – Z/b = 0.27, b – Z/b = 0.03).*

![Figure 5](image2.png)  
*Figure 5. Spectra of pressure pulsations depending on the angle of attack at Z/b = 0.27 (a – V = 5 m/s, b – V = 10 m/s).*

Figure 5 shows the pulsation spectra obtained for the sensor located on the wing for two flow velocities. An increase in pressure pulsations in the separation region occurs for frequencies less than 200-300 Hz. The second peak of pulsations arising from turbulent structures generated in the region of the laminar separation bubble for a velocity of 10 m/s is found for frequencies of about 500-700 Hz. Therefore, for this velocity the flow separation can be detected by the growth of pulsations in the frequency range of 0-300 Hz. However, a decrease in the inflow velocity to 5 m/s (this speed is typical for landing regimes) leads to the coincidence of the frequency ranges of both pulsation peaks, which does not allow detecting the separation by an increase in the RMS pulsations for low flight speeds.
Figure 6. Coherence spectrum between the sensors located at \( Z/b = 0.13 \) and \( Z/b = 0.27 \) depending on the angle of attack (a – \( V = 5 \) m/s, b – \( V = 10 \) m/s).

Figure 7. Phase lag between the sensors located at \( Z/b = 0.13 \) and \( Z/b = 0.27 \) depending on the angle of attack (a – \( V = 5 \) m/s, b – \( V = 10 \) m/s).

The coherence spectra obtained between two sensors located on the wing at a span distance of about 120 mm are shown in figure 6. A high level of coherence is observed for areas with a low level of pulsations (figure 5). This is most likely due to matched circuit noise. This hypothesis is confirmed by the near-zero phase shift for these regions (figure 7). In the frequency range less than 1 kHz a low level of signal coherence is observed in areas with a high level of pulsations. Probably the distance between the sensors is greater than the characteristic scale of main disturbances. Nevertheless, the phase lag (figure 7) clearly shows the appearance of a well observed deviation from zero at the separation flow (the angle of attack is more than 15 degrees). For the second peak of the pulsations, there is no significant deviation of the phase lag relative to zero. Most likely the scale of separation structures is more significant compared to turbulent structures generated by laminar separation bubble. The results of this paper suggest a method based on the detection of a separation flow by correlation measurements. This method will be based on the detection of the appearance of large coherent structures in separation flows. This will be more reliable in comparison with the method based on the measurement of the RMS pulsation.

Conclusions
Experimental studies of the flight characteristics of the small unmanned aerial vehicle ZOHD Nano Talon Evo have been carried out. On the basis of the PIV data the separated flow on the wing of the
aircraft has been studied. A significant increase of the pulsations measured by unsteady pressure sensors is found not only in the separation region. This complicates the use of the data based on the RMS pressure pulsations for detecting the separated flow.

It is shown that for an unambiguous determination of the separated flow, the criterion of the occurrence of a significant phase shift between two sensors should be used. This measurement method is based on the emergence of large coherent structures for a full flow separation on an aircraft wing.

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