Wind resistance of Unmanned Aerial Vehicles (UAVs) investigated in large-scale wind tunnels at the Wind Engineering Laboratory of the Cracow University of Technology

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SUMMARY
Wind remained one of the main factors limiting the safe and stable operation of Unmanned Aerial Vehicles. This issue became especially important when UAVs were expected to operate in variable atmospheric conditions and in environments where disturbed airflow could affect stability and control. The study investigated the wind resistance of a conventional UAV in the large-scale wind tunnels of the Wind Engineering Laboratory of the Cracow University of Technology. The work focused on the development of a repeatable testing methodology for assessing UAV behaviour under controlled flow conditions. Particular attention was given to wind velocity, turbulence intensity, wind angle, tunnel effects, mounting interference, and uncertainty of the adopted procedure. The outcome was a methodological framework for future wind tunnel investigations and a set of practical recommendations for evaluating UAV stability and operational limitations in disturbed airflow.
Keywords: UAV aerodynamics, wind tunnel testing, wind resistance

1. INTRODUCTION

Wind strongly affects UAV operation and can determine whether a platform performs its mission safely and effectively (Flaga, 2008; Krzysiak, 2017). For this reason wind resistance assessment is an important stage in UAV design and evaluation). This study examined a conventional UAV as a representative object for future wind tunnel tests in the Wind Engineering Laboratory of the Cracow University of Technology. The aim was to assess UAV behaviour under controlled airflow conditions and to develop a reliable and repeatable testing methodology. The study also focused on the representativeness and uncertainty of the results. This required consideration of similarity criteria, tunnel effects, mounting interference, sensor selection, calibration and repeatability (Barlow et al., 1999; Pankhurst and Holder, 1965).

2. METHODS

The study was carried out in the large-scale wind tunnels of the Wind Engineering Laboratory at Cracow University of Technology. This environment allowed controlled and repeatable changes in wind velocity, turbulence intensity and wind angle (Barlow et al., 1999; Pankhurst and Holder, 1965). It provided a reliable basis for assessing UAV behaviour under disturbed flow conditions. The test environment is shown in Fig. 1.

Figure 1. Infrastructure of the Wind Engineering Laboratory (LIW) and the Environmental Aerodynamics Laboratory (LAŚ) at the Cracow University of Technology planned for use in tests of the proposed aero-robotic inspection and repair system: **A** – the large-scale wind tunnel for snow engineering at LAŚ PK; **B** – the large-scale wind tunnel for building aerodynamics at LAŚ PK; **C** – the large-scale climatic wind tunnel at LAŚ PK.

The investigation concerned a conventional UAV prepared as a representative research model. The work included UAV configuration, development of a dedicated test stand and definition of the main test procedure. Particular attention was given to repeatable model positioning, reduced mounting interference and tunnel effects that could affect result interpretation. The research focused on the influence of selected flow parameters on UAV stability and operational limits. The methodology included repeatability checks, calibration, flow quality measurement and basic uncertainty assessment to ensure reliable and comparable results (JCGM 100:2008). Qualitative flow visualization was also considered as support for later interpretation. An example of the test arrangement is shown in Fig. 2 (Pilch et al., 2020).

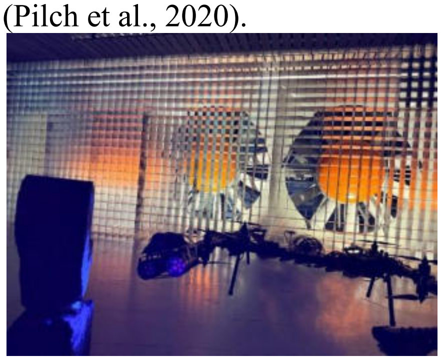

Figure 2. Example of the planned UAV test arrangement in the wind tunnel test section.

The drone tested in the preliminary study was a heavy-lift quadcopter with a payload capacity of 15 kg. It was equipped with two green laser indicators with dedicated mounting attachments. Indicator 1 showed the drone position in the horizontal XY plane by projecting a green point onto the test section floor. Indicator 2 showed the drone position along the vertical Z axis by projecting a green point onto the side wall of the wind tunnel. The preliminary tests measured changes in the drone position indicated by Indicators 1 and 2 under airflow at different wind speeds and angles of attack. The tests were carried out in terrain category I with no turbulence-generating elements. Angles of attack ranged from 0° to 180° in 30° increments and wind speeds ranged from 1 to 15 m/s. The drone position marked by the indicators was recorded using a standard CCD camera Manta Allied Vision Mg235B PoE 14-bit monochrome CCD camera.

3. RESULTS & DISCUSSION

The recorded UAV displacements showed a strong non-linear dependence on wind velocity and angle of attack. The results indicate that the aerodynamic response of the platform depends on the combined effect of flow direction and dynamic pressure. At the lowest wind velocity of 1 m/s the observed displacements were relatively small. Horizontal XY deviations ranged from about 4 to 10 mm and vertical Z displacements ranged from 0 to 4 mm (Fig. 3). The maximum displacement occurred at 90° when the projected frontal area of the UAV relative to the incoming flow was the largest. This agrees with the expected increase in aerodynamic drag and destabilizing forces under perpendicular flow conditions. The response was not fully symmetric in the 0°–180° range which may indicate structural asymmetry, rotor wake interactions or minor flow non-uniformities in the measurement section.

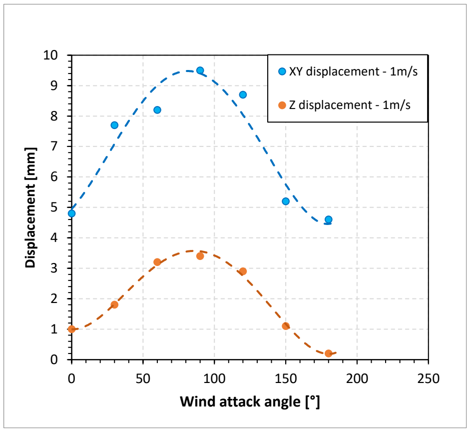

Fig.3. Dependence of UAV displacement on the wind attack angle at a wind velocity of 1 m/s.

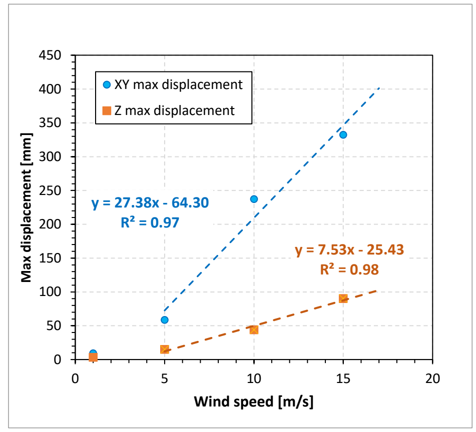

Fig.4. Dependence of the maximum UAV displacement on wind velocity in the wind tunnel within the range of 4 m/s to 15 m/s.

As wind velocity increased to 5 m/s the displacements increased significantly. XY values were about five times higher than at 1 m/s and reached about 60 mm at 90°. Z displacements increased to about 15 mm. This increase is consistent with the quadratic dependence of aerodynamic forces on flow velocity (Barlow et al., 1999; Flaga, 2008). The scaling was not fully proportional which may indicate flow separation, rotor–wake coupling or compensation by the UAV control system (Krzysiak, 2017). At a wind velocity of 10 m/s the UAV showed much larger deviations. Maximum XY displacements exceeded 200 mm and Z displacements approached 50 mm. The dependence on angle remained similar with the most critical case at 90°. A clearer asymmetry between 60° and 120° was also observed. This may result from the directional sensitivity of the UAV geometry and anisotropic aerodynamic properties including the orientation of the arms relative to the flow direction.

For the highest analysed wind velocity of 15 m/s the displacements reached their maximum values. XY deviations were up to about 330 mm and Z displacements were about 90 mm. In this range the UAV response was clearly non-linear and the increase in displacement was disproportionate compared to lower velocities. This suggests that the system approached or exceeded the limits of stable operation. The decrease in displacements above 90° in the range of 120°–180° may indicate partial aerodynamic shielding or flow reattachment effects depending on UAV orientation. The relationship between maximum UAV displacement and wind velocity in both XY and Z directions was approximately linear from 4 to 15 m/s. However this fit was based on only three measurement points and is valid only within this limited range. Over the full velocity range the relationship was non-linear.

For all velocities the displacement profiles as a function of angle of attack formed an asymmetric curve with a maximum near 90° (Fig. 4). This asymmetry suggests that rotor-induced flow, mounting effects and minor geometric imperfections influenced the results even under controlled wind tunnel conditions. Vertical Z displacements followed similar trends to horizontal XY displacements but had lower amplitudes. This indicates the dominance of lateral forces.

However the increase in Z displacement at higher velocities shows the growing influence of lift fluctuations and vertical flow components (Fig. 4).

4. CONCLUSIONS

The obtained results show that wind velocity and wind direction have a critical influence on UAV positional stability. The observed non-linear changes and asymmetry confirm that simplified aerodynamic models are not sufficient to describe UAV behaviour under disturbed flow conditions. Additionally it was shown that:

- UAV displacements rise nonlinearly with wind velocity consistent with quadratic aerodynamic force scaling.
- Maximum positional deviations occur near a 90° angle of attack where aerodynamic loading is highest.
-The displacement characteristics are asymmetric with respect to the flow direction (0°–180°) indicating sensitivity to UAV geometry rotor configuration, and flow-structure interactions.
-Horizontal displacements (XY) dominate over vertical ones (Z) although the contribution of vertical displacements increases with wind velocity.
-At wind velocities of 10–15 m/s the UAV approaches the limits of operational stability as evidenced by large deviations and increasing non-linearity of the response.
-The results indicate that a reliable assessment of UAV behavior under wind conditions requires consideration of both flow velocity and direction as well as real effects such as rotor-flow interaction and structural asymmetry.
- The optical tracking method using laser markers and CCD imaging effectively analyzed UAV displacements in wind tunnel conditions.
- The results provide a solid basis for further research on control system optimization aerodynamic stabilization and validation of numerical UAV models in disturbed flow (Pilch et al. 2020).

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