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WIND TUNNEL AERODYNAMIC INVESTIGATION OF QUADPLANE IN TRANSIENT STATE

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ABSTRACT:

This article presents wind tunnel investigation of aerodynamic properties of lightweight UAV in QuadPlane configuration. Such design combines Vertical Take-Off and Landing (VTOL) characteristics of multicopter with high speed, long range and endurance capability of Fixed Wing (FW) aircraft. QuadPlane is based on the coaxial quadcopter configuration crossed with conventional twin-boom airplane in pusher engine configuration. Both underlying configurations i.e. quadcopter and conventional airplane have been already well tested and documented [7,2,3], contrary to their combination, especially in the transient state, between fixed-wing and quadcopter flight modes.

The extensive wind tunnel test program has been devised to examine aerodynamic characteristics of working FW-VTOL propulsion system in different flow and thrust conditions [4] and to check selected configuration of contra-rotating propeller sets [5,6]. The program has been divided into two separated phases, first: investigation of the single tail-boom mock-up with fully functioning VTOL propulsion, and second: tests of the semi span, 1:1 scale, fully functioning QuadPlane model. Both testbeds have been connected to aerodynamic 6-elements balance on turntable in the wind tunnel. This paper describes test results together with methodology and technology employed in Phase I of QuadPlane investigation [7].

1. INTRODUCTION

Currently the market of small UAVs (up to 25 kg) is more and more dominated by multicopters [8]. This is due to their ability of vertical take-off and landing which addresses lack of landing space. However, the main limitation of multicopters is their range due to the fact that all necessary lift force is created only by rotors, even during steady and level flight, and is not energy efficient. A much more effective method of horizontal flight is used by conventional aircraft, where the lift force is generated by the wing. On the other hand, the disadvantage of the conventional aircraft for typical UAV purposes is the need for the runway. There are many ideas on how to combine VTOL and fixed wing capabilities in one vehicle, which is called FW-VTOL. The main types of such vehicles available in literature and on the market belong to following groups:

- Tilt Rotor, Tilt Prop, Tilt Duct,
- Tilt Wing,
- Tail Sitter,
- QuadPlane.

The selection process has been conducted to find optimal configuration for wide class of mission profiles. The wining configuration belongs to the Lift+Cruise class [9], where two separate propulsion systems are used for hover (Lift) and fixed wing forward flight (Cruise). This configuration is called QuadPlane (Fig. 1) and it allows to separately optimize efficiency of both propulsion systems working in very different aerodynamic conditions.

The selection of the QuadPlane configuration was based on its advantages and characteristics summarized below:

- Conventional layout design – very well tested
- No moving parts – lower failure risk
- Redundant VTOL propulsion (coaxial)
- Robust flight dynamics
- Relatively simple VTOL and transition phase

The selected configuration of aircraft geometry and fixed wing VTOL is composed of two separated propulsion systems, one for forward flight and second for VTOL maneuvers. Forward flight thrust is provided by the pusher engine, while VTOL propulsion system consist of four pairs of coaxial contra-rotating rotors mounted on two tail-booms.

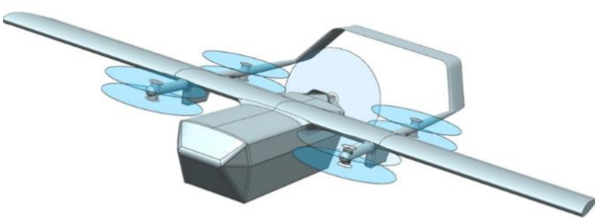

Figure 1 QuadPlane layout

The major aerodynamic challenge of QuadPlane encompasses interference of the wing and tail surfaces with VTOL propulsion operation during transient flight condition. Especially, the problem of optimal acceleration and deceleration profiles of quadcopter with substantial wing surfaces is neither well investigated nor documented.

To address this challenge two-phase wind tunnel experiment has been designed. First phase is concentrated on testing aerodynamic properties of VTOL propulsion system in coaxial quadplane configuration without wing. Its aim is to investigate coaxial rotors configuration mounted on tail-boom structure without aerodynamic interferences of aircraft's main wing. Second phase is based on semi span, fully functioning QuadPlane model, specifically designed to investigate optimal acceleration and deceleration profiles, which can help reduce total mass of VTOL batteries necessary to complete flight mission.
Experiment division into phases helps for better understanding of coaxial quad rotor sizing and then its complex interaction with wing disturbed flow in transient phase. Additionally, experience gained in the first phase helps in better preparation and more robust design of the second phase.

2. THEORETICAL CONSIDERATIONS

Two coordinate systems (Fig. 2) have been defined to allow the analysis and presentation of the results.

First coordinate system named "tail-boom" coordinate system: X_b pointing to the front of the beam, Z_b in the negative direction of the propellers' thrust forces and Y_b according to the right-hand rule.

Second coordinate system named "aerodynamic" coordinate system: "tail-boom" coordinate system rotated by the angle of attack about Y axis.

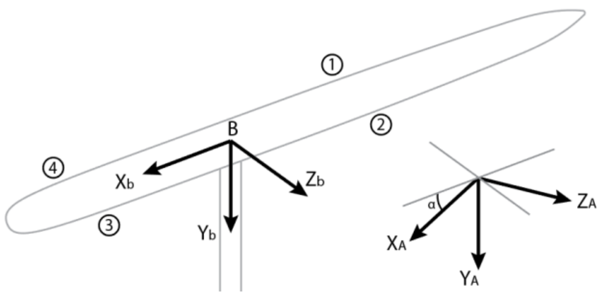

Figure 2. Tail-boom and aerodynamic coordinate system (compare with Fig. 4)

Primary source of the *Fbz* force is the thrust of the engines. The *Fbx* force is the "drag" of the tail-boom and propellers. Another important effect is the pitching moment with respect to the Y_b-axis. Its source is the thrust value difference between front and rear propellers (numbers 1,2 and 3,4).

Following the transition model presented in **INTRODUCTION**, it had to be examined if the eight hovering propellers could provide the necessary thrust. For this purpose, examine Fig. 3. It shows one of two tail-booms at an angle to the flow (for simplification, the angle of attack is the same as the pitch angle). The *Fbx* and *Fbz* forces are the resultant propulsion and thrust forces of four propellers.

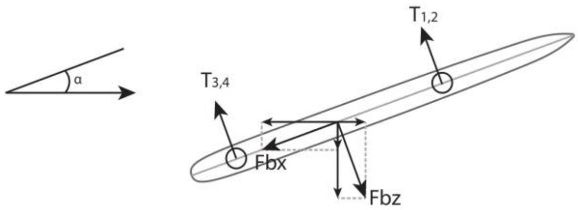

Figure 3. Propulsion forces

Transition to the aerodynamic coordinate system is according to Eq. 1.

$$\begin{aligned} Fax &= Fbx\cos(\alpha) + Fbz\sin(\alpha) \\ Faz &= Fbz\cos(\alpha) - Fbx\sin(\alpha) \end{aligned} \tag{1}$$

These considerations are valid only for one tail-boom. For the full aircraft model, they must be expanded by adding forces of the second tail-boom and remaining aircraft components (e.g. lifting surfaces, fuselage).

3. WIND TUNNEL INVESTIGATION

Phase I of wind tunnel tests are concentrated on verification of simplified analytical solution [10,11], and enhancing quantitative and qualitative data necessary for the QuadPlane project design. Existing literature describing properties of conventional aircraft and multi-rotors does not take into account high geometric asymmetry of coaxial rotors environment or horizontal flight aerodynamics in copter mode when forward thrust is provided by separate forward flight propulsion system.

The following types of asymmetry and their impact on the coaxial rotors aerodynamic characteristics were investigated:

- asymmetry within single coaxial pair (mounted on top and below the tail-boom structure): mutual rotor interference with additional blockage effect of tail-boom structure in function of rotors' disks distance and flow parameters.
- asymmetry between front and back pairs: different blockage effect due to various extent of tail-boom structure obstructing front and back rotors' flow.

- asymmetry in one motor failure scenario: because of aforementioned asymmetries results in differential thrust condition of VTOL system affecting possibility of flight continuation.

Based on the wind tunnel measurements, the differential control of coaxial rotors necessary to balance the resulting pitching moment was calculated and then verified in the wind tunnel for various angles of attack, flow velocities and four possible scenarios of one engine failure.

The wind tunnel used in the tests was the Variable Turbulence Wind Tunnel of Warsaw University of Technology. Flow velocity range was 5-25 m/s. Measurements were collected with 6-elements tensometric balance.

The tests were conducted for a fixed pitch propeller (19''x5.7''), for two wind velocities (10 and 20 m/s). The primary goal of the tests was to investigate the effect of wind velocity and angle of attack on the forces generated by and on the propellers. The following parameters were investigated: static thrust, dynamic thrust for two wind velocities (4 engines running) and dynamic thrust for two wind velocities (3 of 4 engines running – simulated failure of each of the engines).

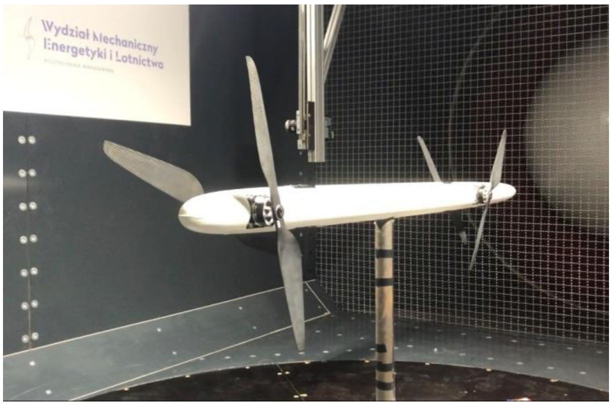

Figure 4. Tail-boom in the Wind Tunnel

The dynamic thrust tests were performed in the equilibrium state i.e. for the angle of attack 0, the *Fbz* force equal to the weight of the aircraft (the cases of 25%, 50%, 75% and 100% of the weight – 12.5kg) and the *Mby* moment equal to 0.

4. RESULTS

From the wind tunnel tests following can be determined:

1. The *Fbx* force is constant versus angle of attack. The value increases as the wind velocity increases. It can be estimated as shown in Eq. 2. This represents the equivalent drag for a sphere shape with a drag coefficient equal to 0.5, ρ = 1.225 kg/m^3. Data from the wind tunnel showed that diameter of this body (d) was equal to 0.5m.

$$Fbx = -\frac{1}{2}\rho V^2 S C_D = -\frac{1}{2}\rho V^2 \pi \frac{d^2}{4} C_D = 0.24\, V^2 d^2 \quad (2)$$

2. The *Fbz* force increases with increasing angle of attack. The slope of the function is higher, the higher the wind velocity. In other words, it can be expressed as in Eq. 3. Data collected from the tests shows that ζ is a function of only wind velocity. This function can be estimated based on data from Table 1. Note the negative sign, which is due to the chosen coordinate system Z-axis direction.

$$Fbz = Q + \zeta(V) \cdot \alpha \quad (3)$$

Table 1. ζ(V) function.

V [m/s]	0	10	20
ζ(V) [N/deg]	0.00	-0.26	-1.91

Variable ***Q*** in the equation stands for the force equilibrium values (weight percentage as stated in **WIND TUNNEL INVESTIGATION**).

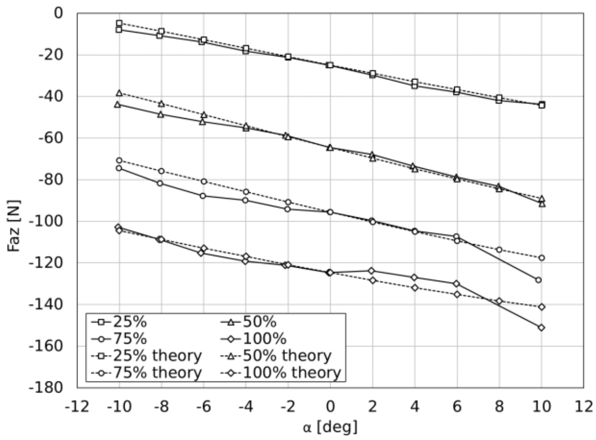

Figure 5. Comparison of experimental and theoretical data – Fax force.

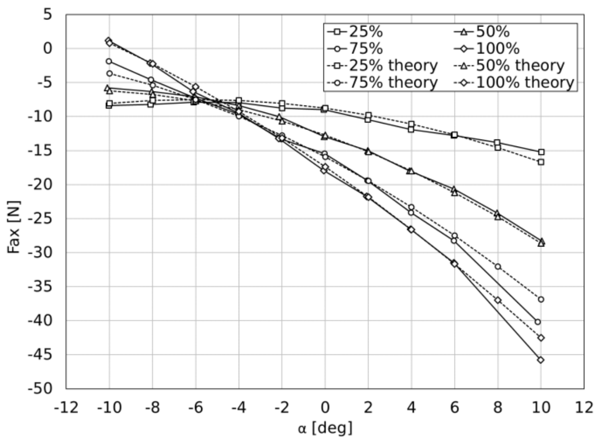

Figure 6. Comparison of experimental and theoretical data – Fax force.

3. The *Mby* moment increases with increasing angle of attack. This is an adverse effect that will cause the aircraft's static instability and must be corrected by the autopilot. The specific experimental values were not investigated.

Substituting Eq. 2-3 into Eq. 1 and graphing them for wind velocity of 20 m/s and for various equilibrium state values ***Q***, Figs. 5-6 can be obtained. It shows a comparison between estimated *Fbz* and *Fbx* functions and experimental data. As can be seen, the curves for all ***Q*** values are consistent with experimental data. From that can be concluded, that the obtained model is valid and can be used further.

In Figs. 7-8 are shown *Fax* and *Faz* forces for equilibrium value of 122.5 N (100% aircraft half weight) for various wind velocities.

Variable ***Q*** in Eq. 3 can be considered as propellers' static thrust. Plotting similar graphs for other values of ***Q*** can be used to find a relation between pitch angle of the aircraft, loss of vertical force to sustain hover and the horizontal force gain to decrease transition time.

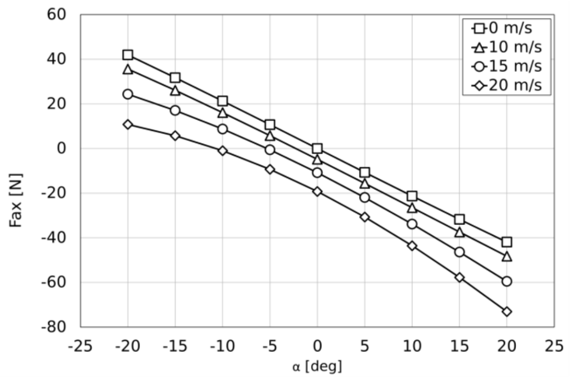

Figure 7. Theoretical model of Fax force for various wind velocities.

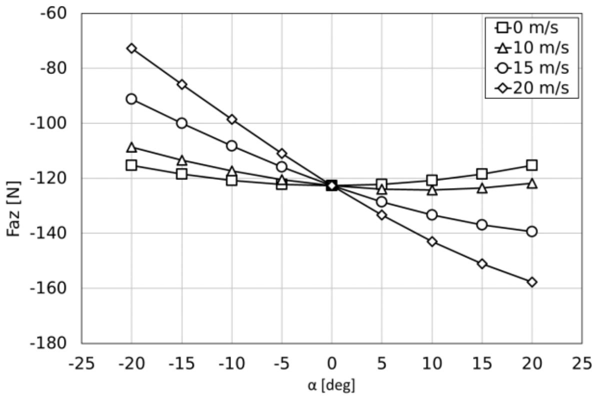

Figure 8. Theoretical model of Faz force for various wind velocities.

5. CONCLUSION

This paper presents wind tunnel investigation of coaxial contra-rotating rotor configuration used in VTOL propulsion system on the QuadPlane aircraft. Two sets of fully functioning coaxial rotors were mounted on tail-boom mock-up connected to aerodynamic 6-elements balance on turntable in the wind tunnel.

Due to high geometric asymmetries and strongly coupled aerodynamic condition and interferences of each rotor within one tail-boom, following properties has been observed and measured:

- Rotors mounted on top of booms are generating less trust (c.a. 10%) than bottom ones due to blockage effect. It is important information for the design of emergency control strategy when one of coaxial rotor fails.
- Coaxial rotors mounted before wing are producing more thrust due to smaller blockage effect caused by tail-boom interacting only with second half of the rotor area (tail-boom ends with front coaxial motors set). As a result, tail coaxial rotors have less thrust capacity, limiting aircraft' pitching moment recovery potential.
- Coaxial configuration proved full redundancy for any one of the front rotors failure, and limited redundancy (controlled crush landing) for tail rotors as a consequence of their smaller thrust.
- Drag force produced by working VTOL propulsion system is independent of the angle of attack and increases with the wind velocity. It can be approximated by equivalent sphere shape with 0.5m diameter. These results are still under investigation and are being planned for repetition in second phase.
- Due to relatively high Thrust to Weight ratio of VTOL propulsion system, excess power can be utilized for acceleration support of pusher engine in transient state. Wind tunnel measurements proves that VTOL system can be balanced in terms of vertical forces and moments up to minus 10 deg. angle of attack.

Conducted research has proven that simplified analytical methods need to be verified experimentally especially in such complex configuration. Presented observation demonstrates complicated aerodynamic characteristics of tail-boom mounted VTOL propulsion system, without influence of the wing during transient phase. Its complexity only shows the necessity of further investigation, which is planned in Phase II of wing tunnel tests.

6. ACKNOWLEDGEMENT

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