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Tactical UAV Flight Performance Estimation and Validation

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ABSTRACT

The information presented in this paper describes the procedure for flight performance estimation of a single pusher-propelled Tactical unmanned aerial vehicle and the flight test verification of its results. The aerodynamic data has been obtained from several sources and integrated into the flight mechanics equations of motion for a typical unmanned aerial vehicle configuration to provide a sufficient basis for estimating flight performance. Subsequently, the development of the UAV's flight performance equation is described. The implemented numerical method is a proven standard in the aircraft industry and should produce reliable results with deviations up to 10 %. Finally, flight tests have been conducted to validate the performance estimation results.

Keywords: UAV; Flight testing; Aerodynamics; Flight performance

NOMENCLATURE

UAV	: Unmanned Aerial Vehicles
HALE	: High Altitude and Long Endurance
VTI	: Military Technical Institute, Belgrade
CFD	: Computational fluid dynamics
RPM	: Revolutions per minute
J	: Advance ratio
V	: Airspeed
N	: Propeller rotational speed
D	: Propeller diameter
t	: Time
c_t	: Thrust specific fuel consumption
T	: Thrust
W	: UAV's weight
C_L	: Lift force coefficient
C_D	: Drag force coefficient
m	: UAV mass
g	: Acceleration due to gravity
ρ	: Air density
S	: Wing surface area
P_R	: Required power
P_A	: Available power
P_{engine}	: Engine power
η_{engine}	: Engine efficiency
η	: Propeller efficiency
γ	: Flight path angel
T_R	: Necessarily thrust
D	: Drag force
R_{cScA}	: Range at constant airspeed/constant attitude cruise
R_{cAcA}	: Range at constant altitude/constant attitude cruise
BHP_{ALT}	: Engine break horsepower at some altitude
BHP_{SL}	: Engine break horsepower at sea level altitude
σ	: Ratio of density at sea level/density at some altitude
V_{TAS}	: True airspeed
V_i	: Indicated airspeed
V_{min}	: Minimum airspeed
$V_{\max}$	: Maximum airspeed
V_W	: Airspeed for best rate of climb
$_{SL}$	: Sea level
$_{ALT}$	: Some altitude
cScA	: Constant airspeed/constant attitude
cAcA	: Constant altitude/constant attitude
w	: Climb speed

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1. INTRODUCTION

The history of Unmanned Aerial Vehicles (UAV) has undergone a significant change in the past few decades. In the twenty-first century, there has been a constant increase in interest in the design and application of UAVs. The most fascinating concepts include MALE (Medium Altitude and Long Endurance) UAVs such as Tactical UAV presented in this paper, and UAVs with VTOL (Vertical Take-off and Landing) capabilities. The dramatic improvement in aeronautical and aerospace technology promises to deliver solutions to many problems present in the civil and especially military sectors.

Fixed-wing UAVs have become popular due to their relatively simple and well-known design, as well as their potential for excellent aerodynamic characteristics. They typically exhibit excellent endurance and range, with adequate stability and control characteristics. Since one of the first successful remotely piloted UAV solutions[1], many UAVs have been constructed, built, and evaluated through flight tests, achieving varying levels of success. All of them aim to capitalize on improved performance characteristics. The presented design incorporates the effect of twin fins on an isolated horizontal tail[2]. This design is widely used as it exhibits good stability and control characteristics, and a rearward position of the centre of gravity compared to the conventional tail configuration[3-4]. These UAV solutions are popular in military applications and can be used for rescue operations, public safety assessments, data acquisition, mapping buildings in hard-to-reach areas, surveillance, and more. Every day, new users employ UAVs in different applications. The flight performance estimation and validation of these UAVs have been well documented in the recent works[5-7].

Aerodynamic, geometric, and inertial data for Tactical UAVs analysed in this paper have been provided from research programs at the Military Technical Institute (VTI Belgrade). These data have been integrated with propeller efficiency and engine data sheets into the flight mechanics equations of motion for a typical unmanned aerial vehicle configuration to provide a sufficient basis for estimating flight performance. The Tactical UAV has been analysed[8-9] aerodynamic optimisation were formed. Researchers from VTI have generated a large number of relevant reports[10]. The research program was carried out by the Military Technical Institute in partnership with China[11], achieving the first international project of UAV design in the Republic of Serbia. The UAV is controlled by a military-grade flight control system with an advanced fibreoptic gyro-based inertial navigation system that provides adequate levels of stability and control characteristics, as well as reliable attitude and position measurement.

Estimating the UAV flight performance requires a representative mathematical model of the object of interest. In the first steps the aerodynamic data of the Tactical UAV has been estimated in commercial ANSYS Fluent software by the finite volume methods. Next, the performance has been estimated by standard flight mechanics equations. After successfully meeting all the initial requirements, the UAV configuration is frozen, and prototype fabrication is taken up for flight testing. Initial flight tests were carried out to demonstrate take-off and landing performance[12] which was then followed by subsequent flight tests to validate the aircraft performance. The results of the above flight tests and their comparison with the theoretical predictions will be presented in this paper.

2. FLIGHT PERFORMANCE

Any flight can be divided into several segments, each clearly distinguished by its nature[13]. These segments include take-off, cruise, descent, landing, and climb. This paper will evaluate the cruise speed, maximum speed, maximum climb speed, and endurance of the Tactical UAV (Fig. 1) in an unarmed configuration.

It is well known that UAVs can be sold based on their performance, additional value to the customer, and payload. The method for estimating aircraft performance presented[13], is a proven standard in the aircraft industry. However, the

Figure 1. Tactical UAV.

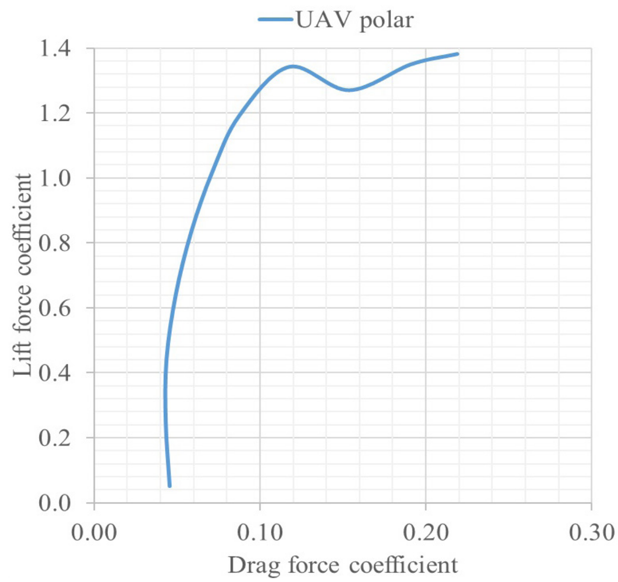

Figure 2. Tactical UAV polar.

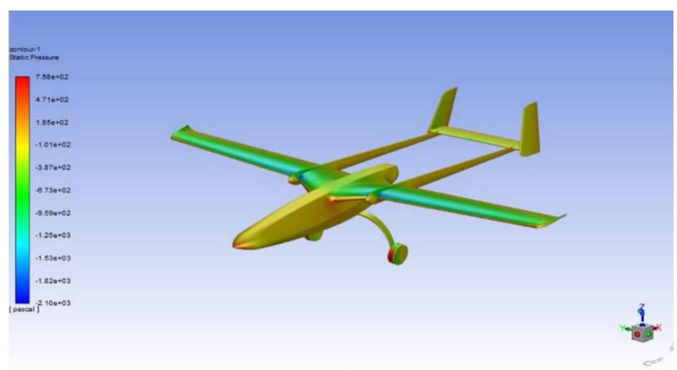

Figure 3. Contours of static pressure around Tactical UAV.

accuracy of calculations depends heavily on the quality of the aerodynamic and inertial properties data used. The lift and drag force coefficients were provided in the Military Technical Institute[14] and are given in Fig. 2. This report included Computational Fluid Dynamics (CFD) analysis of the Tactical UAV model. As a part of the analysis[14], Fig. 3 shows the contours of static pressure around the UAV.

CFD analysis is a useful tool for predicting aerodynamic characteristics[15] at low Reynolds numbers, which is especially important for nonconventional shapes such as electro-optic payloads. Wind tunnel tests can be prohibitively expensive for this type of UAV, so commercially available software like ANSYS Fluent has been used. The Reynolds average Navier Stokes system of equations was solved for compressible flow using a pressure-based solver. Different turbulent models and mesh sizes have been used for different UAV configurations. As one example, for the UAV in clean configuration with the payload in the fuselage, a half model has been used in order to speed up the calculation process. The mesh used for this case has 4.7 million cells. K-ω SST turbulent model has been chosen. The working fluid has been defined as an ideal gas (air). Velocity inlet boundary conditions have been used for defining the velocity and direction of the free stream. Computations have been done until the convergence criteria has been achieved.

The main reason why the CFD result has been used during detailed UAV design is that it has good agreement with the result from the wind tunnel test for the full-scale UAVs in previous project[16]. In this test, the lift and drag force have been investigated in detail, and excellent agreement between the CFD and wind tunnel test result has been reached for the UAV Sparrow (up to 10 % for angle of attack up to 12 degrees). Additional benefit from CFD was the possibility to test UAV at a high angle of attack that was impossible in a wind tunnel (usually 20-25 degrees). The obtained CFD data are also useful for estimating the UAV loading and stability characteristics, but they will not be discussed in this paper.

The report[14] contains CFD analysis results for the Tactical UAV model in various configurations, ranges of sideslip and angle of attack, and control surface deflections. These results are especially useful in predicting stall and separation characteristics as they are presented in Fig. 4.

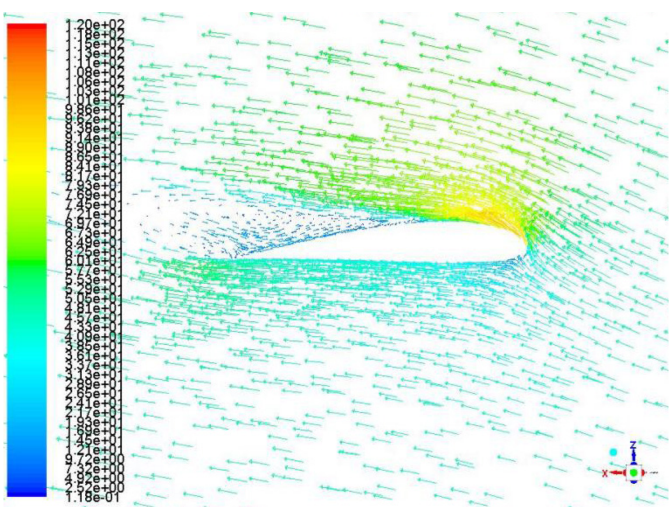

Figure 4. Prediction of local airflow separation on the wing.

However, it is important to note that the CFD results are best used in the final stages of the design and construction phases, while standard aerodynamic equations[17-18], should be used for conceptual design. The main challenge with using standard aerodynamic equations[17-18] is that the semiempirical constants are typically confirmed for higher Reynolds numbers.

As it can be seen from initial UAV[10], and data presented in Table 1, the maximum UAV mass increased as a consequence

Table 1. The UAV geometry

Wing span (with winglet)	7.025 m
Wing aspect ratio	9.08
Length	5.556 m
Mean aerodynamic chord	0,736 m
Wing area	4.33 m^2
Engine power	38.8 KW
Propeller diameter	0.86 m
Maximal mass of UAV	265 kg
Maximal mass of usable fuel	70 kg

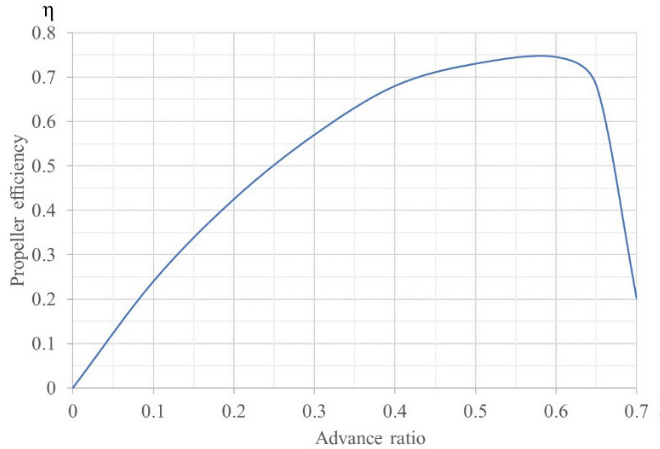

Figure 5. Propeller efficiency.

of arming the UAV, which led to a change in wing geometry and installed engine power. In the presented case, we have a pusher propeller engine. Figure 5 presents the propeller efficiency.

The propeller efficiency depends on the propeller RPM, true airspeed, and propeller diameter. All of these parameters can be represented by a single non-dimensional parameter called the advance ratio, which is given by Eqn. (1):

$$J = \frac{V}{ND}. \tag{1}$$

In Eqn. (1), N represents the propeller rotational speed, D is the propeller diameter, and V is the true airspeed. As shown in the diagram (Fig. 5), increasing the UAV airspeed improves the propeller performance until the maximum designed speed is reached. Given a known true airspeed, chosen propeller size, and propeller rotational speed, the advance ratio and propeller efficiency can be completely defined. To estimate the UAV's performance, an engine data sheet was obtained[19]. By analysing the nature of the forces that act on UAVs in steady-state conditions of level flight, climb, or turn, the performance characteristics of any UAV in various attitudes of flight can be easily determined[20].

The available power from the engine at the same speed determines climb or level flight characteristics. Available and required power determine maximum and minimum speed if minimum speed is not determined by the maximum lift force coefficient.

The best rate of climb can easily be determined numerically by finding the speed at which the difference between the available and required power is greatest. Range and endurance, or the time that a UAV can spend in the air while consuming available fuel[13], is one of the most important UAV characteristics. From Eqn.:

$$dt = \frac{-1}{c_t T} dW \quad (2)$$

The endurance estimation can be solved through numerical integration. In the previous equation, the limits represent the final and initial weight during the analysed segment. This is commonly known as the "Breguet" endurance Eqn. In Eqn. (2), t represents time, c_t represents thrust-specific fuel consumption (in 1/sec), T represents thrust (in N), and W represents the UAV's weight (in N). It is important to mention that when using the International System of Units (SI), some constants given in[13], must be converted into an SI system. The estimation of flight performance can be summarized in a few steps: For the chosen flight speed V and altitude, the lift force coefficient is calculated using the equation:

$$C_L = \frac{2mg}{\rho V^2 S}. \quad (3)$$

From known aircraft polar drag force coefficient can be determined:

$$C_D = f(C_L). \quad (4)$$

Required power is estimated by the equation:

$$P_R = mg \frac{C_L}{C_D} V. \quad (5)$$

Available power is determined by the Eqn.:

$$P_A = P_{engine} \eta_{engine} \eta. \quad (6)$$

As it can be seen from Fig. 6 the maximum UAV speed at a standard atmosphere altitude of 0 m is defined by P_A=P_R and the minimum speed is defined by lift capabilities. It is important to mention that propeller efficiency is a function of the advance ratio and that the calculated performance has been done with the goal to have propeller efficiency as close to the maximum value (0.73). Engine RPM has been optimized at different airspeeds in order to have maximum propeller efficiency. This is the reason for the available power curve changing its slope in Fig. 6.

In order to estimate the climb performance, the lift force coefficient is defined by the Eqn.:

$$C_L = \frac{2mg \cos\gamma}{\rho V^2 S}. \quad (7)$$

where, γ represents flight path angle. In this case the required thrust force is increased by the gravity component:

$$T_R = \mathrm{D} + \mathrm{mg}\sin\gamma. \quad (8)$$

Required power is estimated by Eqn.:

$$P_R = T_R V. \quad (9)$$

The climb speed is estimate by Eqn.:

$$w = V \sin\gamma. \quad (10)$$

This system of Eqn. with the defined limits has been solved numerically for selected altitudes, airspeed range (90-160 km/h) and flight path angle range (0°-20°). It was assumed that thrust line inclination to UAV X axis is equal zero. It is usually a small angle, and its contribution can be neglected for standard UAV configuration and aircraft or UAV without thrust vectoring. In order to get representative results, taking in mind that maximum power or thrust cannot be used continuously for a long time and that aircraft or UAVs cannot stay on the corner of the flight envelope for a long time, the numerical results

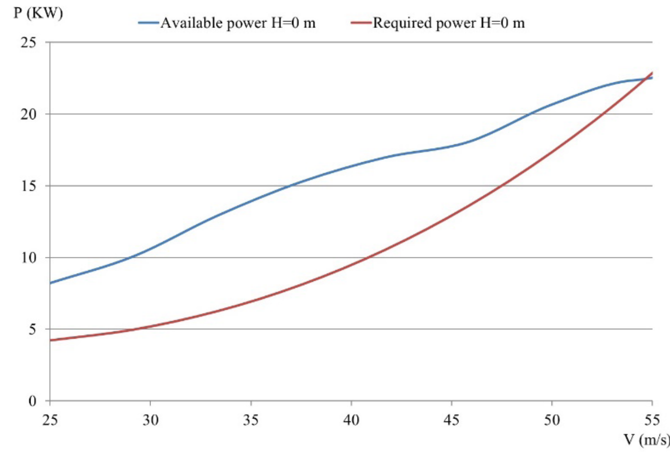

Figure 6. Maximum UAV speed from calculated data.

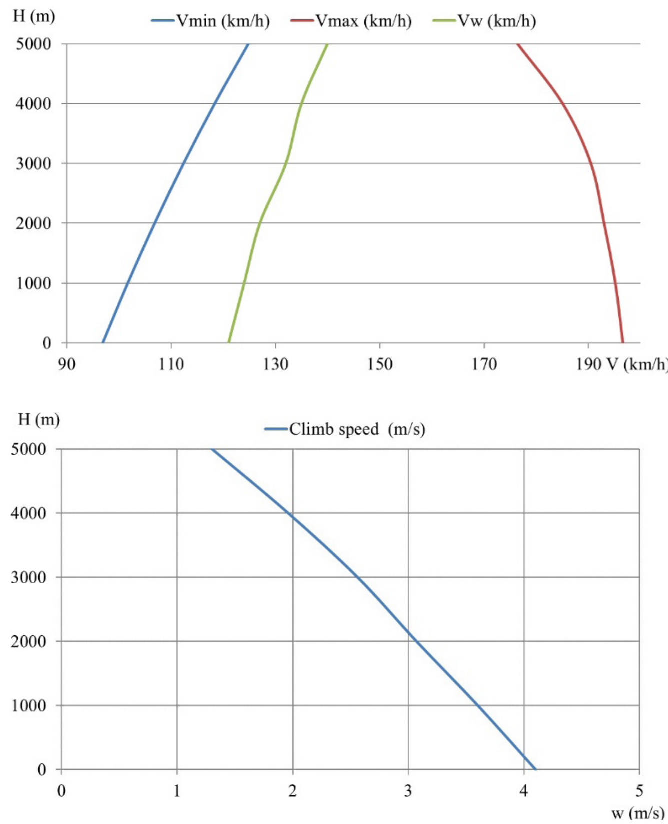

Figure 7. Estimated Tactical UAVs performance chart.

must be reduced. Usually the maximum continuous power is 80 % of the maximum power for piston engines so a reduction of 15 % - 20 % should give representative results. Figure 7 provides an estimate of the tactical UAV's performance. In Fig. 7, the minimum speed has been defined by the maximum lift force coefficient, the maximum speed has been defined by PA=PR, and the climb speed and UAV speed for the best rate of climb have been determined by numerical methods in the defined airspeed range (90-160 km/h).

In order to estimate range/endurance it is necessary to find the specific fuel consumption[19].:

- Constant airspeed/constant attitude cruise (cScA),
- Constant altitude/constant attitude cruise (cAcA),
- Constant airspeed/constant altitude cruise.

In this paper, we have applied the first two methods to the Eqn.:

$$R_{cScA} = \frac{V}{c_t}\frac{C_L}{C_D}\ln\left(\frac{W_{initial}}{W_{final}}\right),$$

$$R_{cAcA} = \frac{1}{c_t C_D}\sqrt{\frac{8C_L}{\rho S}}\left(\sqrt{W_{initial}} - \sqrt{W_{final}}\right). \tag{11}$$

The changes in engine power with altitude are estimated using the Eqn.12[21]:

$$BHP_{ALT} = BHP_{SL}\left(\sigma \cdot \frac{1-\sigma}{7.55}\right) \text{ where } \sigma = \frac{\rho_{ALT}}{\rho_{SL}}, \tag{12}$$

The results of the just mentioned analysis are given in the Table 2, and the results of the analytically calculated UAV capabilities are given in the standard performance diagram[22] (Fig. 7).

Table 2. Estimated tactical UAVs endurance

V (km/h)	T_{cScA} (h)	t_{cAcA} (h)
120	12.67	12
135	11.28	10.45
150	10.5	9.73

3. FLIGHT TESTING

The well-known procedure for testing aircraft or UAVs has a similar description in all regulations[23-24]. The primary objective of the mentioned test is to verify the tactical and technical requirements, which are partially presented in this paper as UAVs performance. Initial requirements are a maximum speed of not less than 180 km/h, a service ceiling of not less than 5000 m, and an endurance of not less than 10 hours. When testing the maximum speed, the UAVs are in the initial flight-testing conditions that are defined by altitude >2000 m and true airspeed >180 km/h, where true airspeed is defined by the equation:

$$V_{TAS} = V_i\sqrt{\frac{\rho_{SL}}{\rho_{ALT}}}. \tag{13}$$

The procedure is done in two directions to eliminate the wind effect. The same applies to the cruise speed, which has varying speed limits between 130 km/h and 150 km/h. On the other hand, when testing for service ceiling, it is just necessary that UAVs reach an altitude that is greater than 5000 m. During this test, it is possible to evaluate the rate of climb. Finally, to evaluate endurance, the UAV climbs to the cruise altitude, adjusts the engine throttle to an appropriate level, and then the UAV will fly at the cruise speed at a defined altitude >2000 m. UAV must spend more than 10 hours in the air and the remaining fuel amount in UAV after landing must be greater than some safe reserve.

4. FLIGHT TEST RESULTS

All flight tests were conducted in an environment where the air temperature at the ground ranged from 17° to 35° Celsius and the wind speed was up to 3 m/s. RTK (Real-time kinematics) GNSS (Global Navigation Satellite System) was used with no less than nine satellites for precise measurement of UAV position, attitude, and speed. The Fiber-optic gyroscope, RTK GNSS, and MEMS (microelectromechanical systems) integrated into the UAV allowed the accurate measurement. Airspeed and barometric altitude were measured using the Air Data Unit, which contains a high-accuracy, temperature-calibrated pitot sensor, and static air data sensor. The unit is connected to an Inertial Navigation System (INS) to provide navigation accuracy when GNSS is not available. The flight test data presented in Fig. 8 - Fig. 11[25], is used to verify the performance of the Tactical UAV.

During all the analysed flight segments presented in this paper, the UAV was in autonomous flight mode. Taking in mind that the UAV has been driven by a fixed-pitch propeller, the engine throttle settings and RPM have been controlled by the flight control computer in order to satisfy the predefined limits.

5. ANALYSES OF THE RESULTS

Key parameter indices of all UAVs are minimum power consumption[13], maximum possible angle of attack, platform geometry, optimal throttle settings, and minimum time to reach targets. Therefore, a well-optimised conceptual design and estimated flying qualities of UAVs[26], are essential for their optimisation.

Flight test data given in Fig. 8 - Fig. 11 provides data for the verification of the tactical and technical requirements of Tactical UAV. The presented flight test data given in Fig. 8

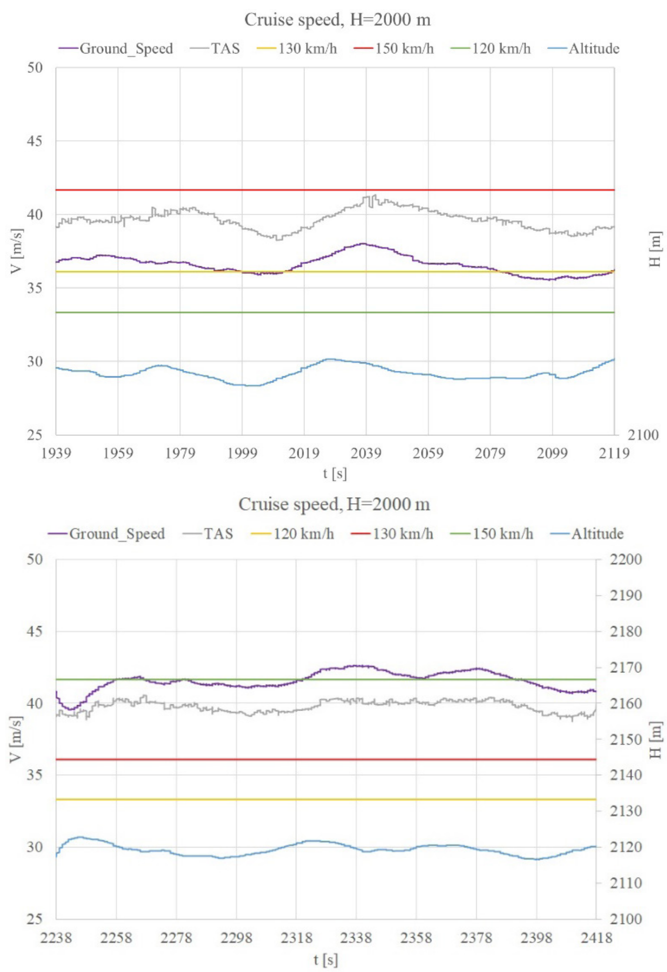

Figure 8. Altitude and velocity holding during flight test at cruise speed.

and Fig. 9 show that a Tactical UAV can easily control flight speed and altitude within pre-defined limits. Data given in Fig. 7 suggested that the theoretical service ceiling is somewhere between 5500 m and 6000 m. Since the calculated rate of climb at an altitude of 5000 m is 1.3 m/s (Fig. 7), and the rate of climb decreases by 0.6 (m/s)/km higher altitudes than 5000 m are possible according to the calculated results. As the service ceiling of not less than 5000 m has been an initial goal and there was limited time for all flight testing the maximum UAV climb altitude has not been determined.

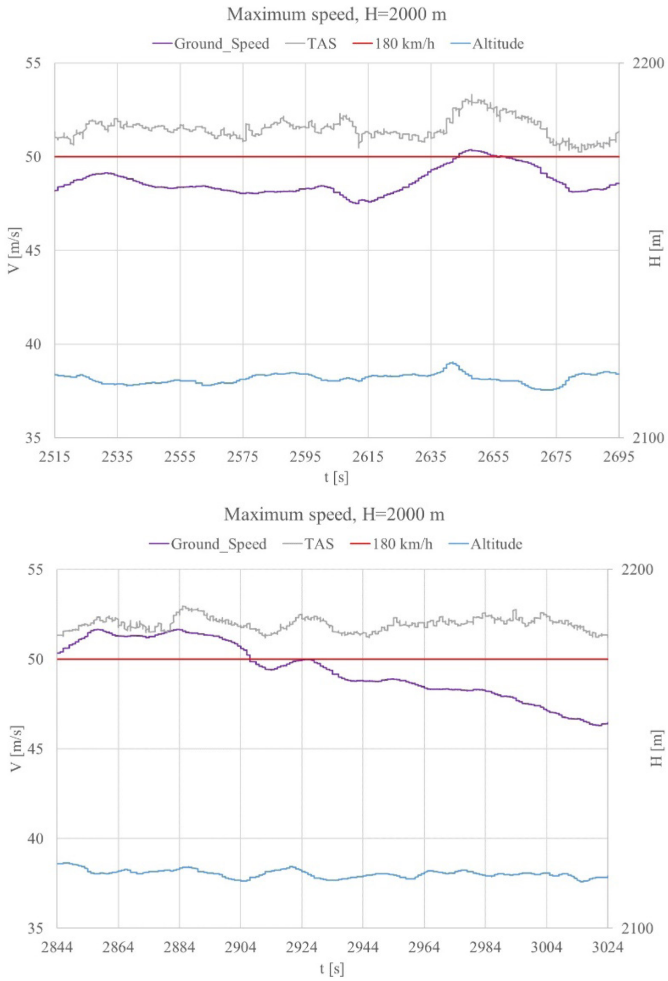

Figure 9. Altitude and velocity holding during flight test at maximum speed.

Calculated data suggested an even higher service ceiling, but it must be the consequence of using the Eqn. 12 for estimated engine power with the altitude. Eqn. 12 should give accurate results for reciprocating engines[21], but caution is necessary if extrapolating engine power with altitude for more than 3000 m.

Data given in Fig. 10 shows that in flight, the rate of climb became less than 1 m/s at an altitude of 5000 m. It will close to 0.5 m/s (service ceiling) at altitudes between 5300 m and 5600 m. The highest reached altitude was 5188 m, according to the measured flight test data.

When analysing the data given in Fig. 11, it is important to mention that the maximum endurance must be evaluated with precise measurement of the remaining fuel after the landing.

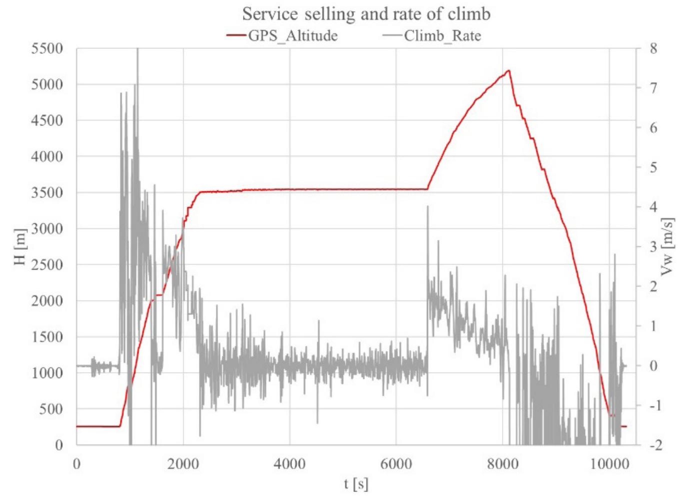

Figure 10. Service ceiling and rate of climb from flight tests.

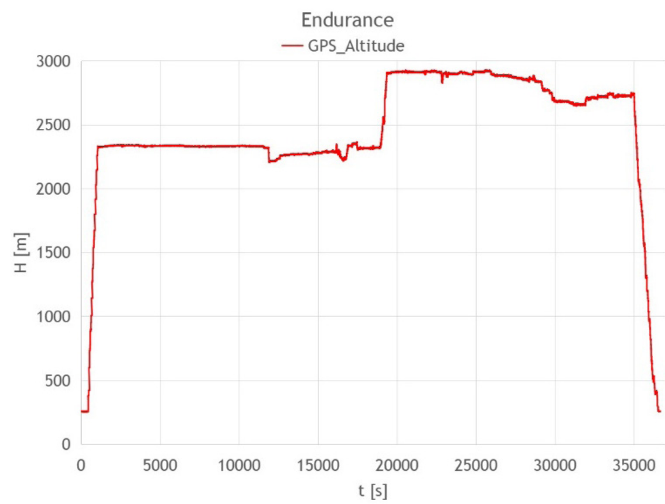

Figure 11. Endurance from flight tests.

The flight was performed with maximum UAV mass and full fuel capacity at take-off.

By taking this information into account, the actual flight endurance can be greater than 12 hrs. The maximum required UAV speed of not less than 180 km/h has been confirmed by the data given in Fig. 9. By comparing the results of flight tests and numerical simulations (Table 3), it is evident that Tactical UAV exceeds the initial tactical and technical requirements and should be evaluated in the next testing phase.

Table 3. Required, estimated, and flight test data

	V_{max} [km/h]	H_{max} [m]	t [h]	w_{max} [m/s]
Required value	180	5000	10	-
Estimated value	196	6000	11.3	4.1
Flight test data	191	5188	12	5.3

The maximum flight speed and endurance have excellent agreement (less than 6 % deviations). The service ceiling error is 15.7 % but it will be less than 10 % if the UAV has reached the practical service ceiling. The rate of climb estimation has the highest error of 22.6 %. The reason for this big deviation is the conservative approach when calculating climb speed by numerical method and sensitivity of measure result to the weather condition.

The objective of this paper was to do a comparison of flight performance from theoretical methods with the flight testing results. It was possible to predict stall and separation characteristics of the UAV and estimate lift and drag force accurately in order to estimate flight performance. Additionally, it was possible to estimate UAV lift and drag force coefficients at high angles of attack. The implemented design method has provided adequate results that completely eliminated the need for wind tunnel testing.

6. CONCLUSION

The mathematical models used for performance evaluation of the twin-boom horizontal tail UAV configuration appear to be satisfactory for low-speed flight dynamics.

To predict the UAV performance, the propeller efficiency and engine data must be provided from other sources. A sufficiently precise CFD UAV model should be created, an adequate turbulent model must be selected, defined calculated domain and boundary conditions, and this process requires a significant amount of time.

Based on the flight test data, it can be concluded that the Tactical UAV meets the initially defined requirements in its unarmed configuration and validates the performance estimation results. Compared to the state-of-the-art result in CFD analysis[15,27], the implemented CFD approach (by using the commercial software ANSYS Fluent) has been able to discover complex aerodynamic phenomena such as local airflow separation on the wing and UAV stall characteristics. The dynamic flight manoeuvres had not been analysed but it would certainly require a dynamic mesh technique and additional time to obtain accurate results. The flight test results also indicate that the UAV has capabilities beyond the initial requirements and may need further testing and evaluation in the future. The importance of good aerodynamic design and optimization for UAVs is highlighted by the success of Tactical UAV in meeting its performance goals.

Flight testing indicates that the lowest UAV airspeed is defined by maximum lift capabilities. The combination of flight testing and computational fluid dynamics has proven to be a reliable approach for evaluating UAV performance and improving their design. This approach allows for a more comprehensive evaluation of the UAV's aerodynamic characteristics and flight performance, including its stability and controllability. This is especially important when there is a need to predict aerodynamic characteristics at low Reynolds numbers, and when the experimental results for the nonconventional shape of electro-optics payload solutions for providing optimal observation, surveillance, tracking, and targeting capabilities are not known. As such, it is likely that this approach will be used more in future UAV development to ensure that new designs meet the required tactical and technical requirements and possess desirable flight characteristics.

The presented work with the cooperator[11], indicates that future development of UAVs can be successfully carried out in collaboration with international partners[28-29], to gain benefits that domestic industries may not possess. In the next phase of development, it will be necessary to define the ultimate UAV performance at the edge of the flight envelope.

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