Identification of UAV Engine Parameters

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Abstract: - The design of low-cost and efficient configurations of UAV (Unmanned Aerial Vehicle) becomes increasingly more important for improving the performances, flight characteristics, and increase of a payload. Ability of vertical take-off and landing is a challenging but important task for the UAV to achieve a high level of autonomy. The fundamental requirement for vertical take-off or landing is the ability to precisely direct and control the air thrust against ground, which plays a vital role in stability of the airplane. When dealing with low-cost components (ducted fan motors and its controller), parameters of mechanical and electrical systems of vital importance are unknown or partially known, and thus some kind of identification process has to be done. This paper focuses on identification of thruster motor parameters and aspects related to electric and electronic devices. Motor and motor controller is modelled as MISO system (Multiple Input Single Output) whose parameters are identified. Identification is performed in a laboratory, by feeding the motor controller with series of an input signals and measuring motor thrust in dynamic conditions by the force transducer.

Key-Words: - UAV, VTOL, ducted fun motor, motor parameters identification, motor thrust, systems theory.

1 Introduction

Since the beginning of mankind, flying creatures has aroused the curiosity of the human mind. During only a few centuries, humanity succeeded in overcoming the power of gravity, and to successfully conquer air and space. When analyzing the history of aviation, it is seen that air vehicles have varied greatly, from hot air balloon to space crafts, jumbo jets, and military fighters [1]

The governments that recognized the importance of the air power has considerably invested in this field. Thanks to these investments over last few decades, many features of the vehicle such as technical parameters, control algorithms, and maneuverability have significantly increased [2,3,4]. Recent advances allowed engineers to produce Unmanned Air Vehicle (UAV) that can perform tasks with only a fraction of production and maintenance costs of manned counterparts [2]. The UAVs are used for both military and civilian purposes, including surveillance, remote measuring and search & rescue operations [2,3,4,5]. UAVs range from small tactical bird- sized machines with only minimal sensors, to fully armed aircraft capable of operating from remote locations. At the moment UAVs seem to be the most attractive military and law-enforcement flying machines due to lower maintenance costs, lower operational costs, and most importantly smaller risk to human personnel. The current state of UAVs throughout the world used for remote sensing and photogrammetry is presented in [6].

The design of low-cost and efficient configurations of UAV becomes increasingly more important for improving the performances, flight characteristics, and increase of payload. Recently growing demand for this type of the aircraft encouraged developments of numerous types of unmanned helicopters [7,8,9,10]. They offer many advantages, most important is the ability to fly within a narrow space and the unique hovering and Vertical Take-Off and Landing (VTOL) flying characteristics. Configuration of this type of aircrafts does not allow significant autonomy, in terms of flight endurance. On the other side, fixed-wing aircraft allow better autonomy, but fail in VTOL abilities.

Autonomous vertical flight is a challenging but important task for UAV to achieve high level of autonomy [11]. Features such as Vertical Take Off and Landing (VTOL) capability has further enhanced the use of MAVs (Manned Air Vehicle), mostly helicopters, in congested environments where the vehicle has little space for take-off and landing [12]. The fundamental requirement for vertical take-off or landing is the ability to direct and control the air thrust against ground. In these situations, even a small error in produced air trust or inability to control airplane during air turbulences would result in airplane instability and possible destruction of the whole vehicle [13].

Many types of small jet engines are currently being manufactured and sold throughout the world. However, these engines have very low efficiencies and high specific fuel consumptions. [14,15]. Permanent Magnet Brushless DC motors (PMBLDC) are commonly considered the best possible choice for the propulsion of an Aerial Vehicle [14]. PMBLDC motors have many advantages over other motors due to their high efficiency, low weight, silent operation, compact size, high reliability and low maintenance requirements [16,17]. There are few examples of PMBLDC motors successfully use in solar powered UAVs, which is another proof of their energy efficiency [18]. When enclosed in housing, together with adequate propeller, they create small and capable drive, known as ducted fan. This type of airplane drive provides safe operation in cluttered environments where the objects in the proximity of the vehicle are protected from the propeller and vice versa [19,20,21].

The independent vectoring of fans would allow the yaw motion and forward flight with minimal or no pitch movement of the aircraft [19]. Multiple rotor platforms, on the other hand yet need to undergo roll and pitch movements for forward and sideways flight [7,8]. System with multiple ducted fans would provide even greater maneuverability than is possible with quad-rotor systems or co-axial helicopters [22,23]. Unlike single ducted fan systems, this design provides space for carrying a sizable payload in its bays [11,12,22]

This paper focuses on the aspects related to electric and electronic devices and actual properties and capabilities of ducted fan drive, which parameters are unknown. Research performed in this paper is part of development of a low-cost fixed-wing UAV with VTAL capabilities, whose propulsion is based on ducted fan motors.

The paper is organized as follows: Section 2 outlines the formulation of the motor model; Section 3 describes the identification procedures and laboratory measurements. The results of ongoing work are presented in Section 4, and Section 5 concludes the paper.

2 Motor Model

It is absolutely necessary to precisely know the electrical, magnetic and mechanical parameters in order to ensure an optimal tuning of the regulators that control the motor. Usually, the manufacturer does not mention all the parameters in the data sheets. That means that a designer of an electrical drive control system has to approximately determine the unknown parameters or to execute identification experiments [24,25]. Precise identification is even more demanding when system is used in unstable conditions (like VTOL and hovering), where small error could cause loss of a whole aircraft.

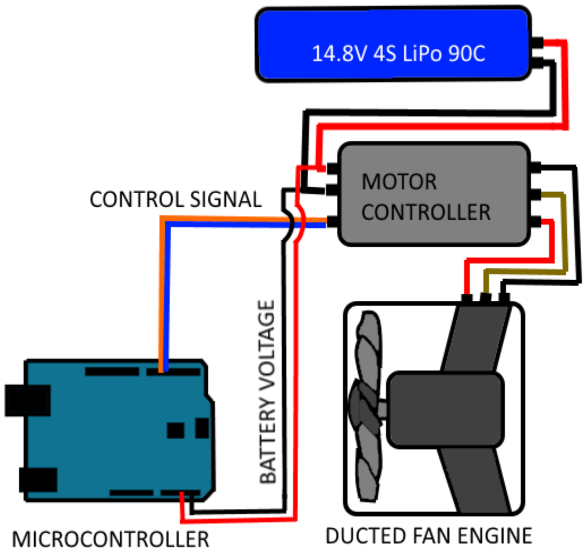

Fig.1. Components of UAV motor drive

This paper focuses only on power system, which components are depicted in Fig. 1. The power system includes the brushless DC motor with the ducted propeller, the electronic regulator, the batteries and main microcontroller. The high-speed spinning propeller provides the power for the small ducted fan. The thrust of the ducted fan aerial vehicle generated by the propeller is considered only in direction of motor axis, where thrust in other directions is negligible and not analyzed. The thrust output force of the dynamic system caused by the propeller rotation are measured and analyzed in laboratory conditions. Microcontroller's objective is to receive command, calculate required motor thrust force, measure battery voltage, and then generate control signals to motor controller, which would result in desired air thrust.

Identification could be done according to the continuous or discrete model [24,25,26]. The identification methods based on continuous models offer few advantages: an easier use of the model obtained by the supervision level in adaptive systems, the change of the sample rate of control system (which is usually different from the sampling rate used for identification) and an easy physical interpretation and evaluation of process parameters (time constants, damping coefficients, etc) [26]. A mathematical model for a complex system such as an Unmanned Aerial Vehicle (UAV) requires estimation of aerodynamic, inertial and structural properties of many elements of the platform, together with estimation of drive capabilities [27]. This physical modeling approach is labor intensive and requires approximations to be made in calculations.

2.1 Mathematical model

The thrust forces generated by the ducted fans are the forces that enable the VTAV to take off and fly. The relationship between the generated thrust T and the angular velocity of the motor can be approximated by (1)

$$T = C_t \varpi_f^2 \tag{1}$$

Where C_t is a constant that depends on the propeller diameter, thrust coefficient of the propeller and the air density and ϖ_f is the angular velocity of the propeller [19]. Unfortunately, measurement of propellers angular velocity would require additional sensors. It is also required to precisely determine relationship between propeller's angular velocity and microcontroller's output PWM (Pulse Width Modulation) signal to motor controller, and impact of battery voltage to mentioned parameters.

2.2 Model Reformulation

Alternative approach is to consider whole drive system (battery, motor controller and ducted motor) as a single MISO (Multiple Input Singe Output) system [24], as is depicted in Fig 2.

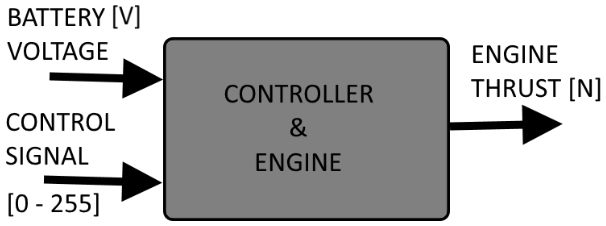

Fig.2. Motor modelled as MISO system

This model could be described using state space equations (2)

$$T = [A] \cdot \begin{bmatrix} u_{PWM} \\ e_{BATTERY} \end{bmatrix} \tag{2}$$

Where A is system matrix, T is obtained air trust force, u_{PWM} is PWM control signal which controls motors angular velocity, and $e_{BATTERY}$is battery voltage level. This state space model is valid inside limited u_{PWM} range (minimal u_{PWM} required to start the engine, and maximal $u_{PWM}$where additional air thrust is not gained with u_{PWM} increase.

3 Identification process

Identification procedure is planned as a two part procedure, which is in details described in the following section.

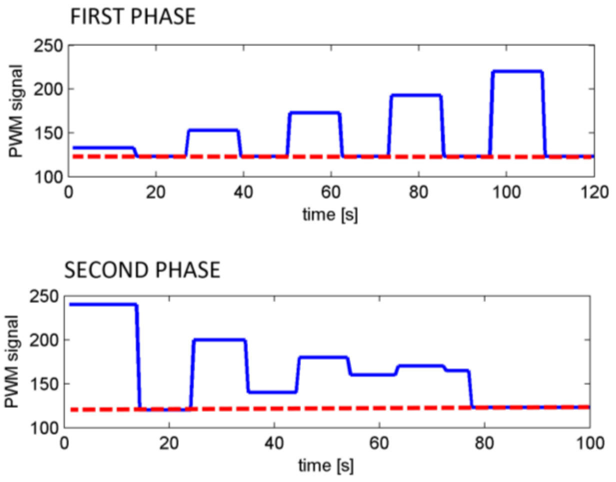

Fig.3. Microcontroller's PWM signals used for identification and validation of obtained model

Phase I: First phase is devised to identify system parameters. Motor controller is feed with series of limited input step signals, where their values change in constant increments, until they reach maximal useful u_{PWM}, Generated signals used for first phase of identification are depicted in top pane of Fig. 3. Red dashed lines on Fig.3. represent minimal PWM signal required to start the motor.

Phase II: Second phase is devised as a validation of previously obtained motor parameters. Motor controller is feed with series of alternating step-like signals, where values between two succeeding u_{PWM}constantly decrease, until u_{PWM} reach middle of its working range. Generated signals used for validation purposes are depicted in bottom pane of Fig. 3.

3.1 Measurement procedure

For the purpose of this paper, identification procedure was executed on two 10 cm ducted fan motors with completely unknown parameters (documentation was sparse and inadequate). Both motors were controlled by Mystery Pentium 100A motor controller. Power source for both motors was Tunergy 4S LiPo 14.8V 3 Ah battery pack (max 90C in burst mode). Motor controllers were feed with PWM signals by Arduino MEGA microcontroller attached to computer workstation for monitoring and diagnostic purposes.

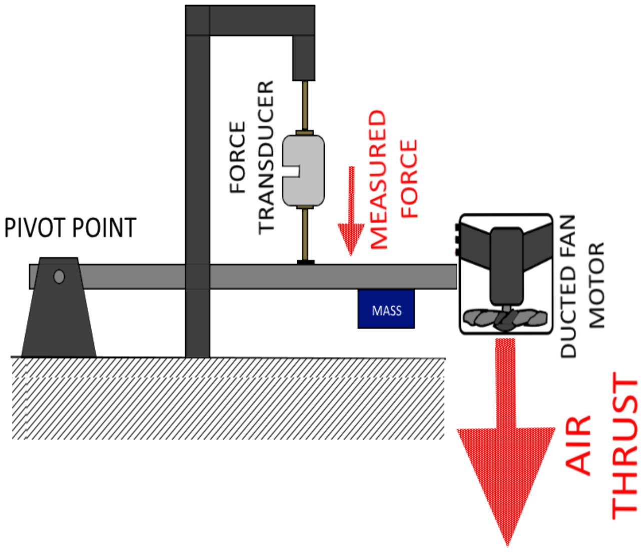

Fig.4. Laboratory setup

Special metal construction was devised, in order to achieve reliable measurement of motor thrust in vertical direction. Schematics of the whole construction are depicted in Fig. 4. Motor is placed on far end of hard metal shaft.

Other end of shaft is attached to the stable grounded base, where shaft rotation is allowed only over pivot point. Force transducer is attached between central parts of movable shaft and fixed outer construction.

The motor is controlled by series of PWM signal from microcontroller. During the testing experiment, motor can make the propeller spin, and apply the pulling force that is capable of lifting the whole movable part of construction. Instead of lifting the movable part of a construction, air thrust force is pressing force transducer which is preventing its motion. The force transducer sensor measures dynamic change in force between shaft and outer construction. Additional 1 kg weight was added to motor shaft in order to achieve that motor thrust would not reverse transducers measured force direction (would not lift shaft), that may cause further complication in correct results interpretation. Prior to the measurement, force transducer was calibrated with etalon weights (1 kg) placed in center of motor shaft.

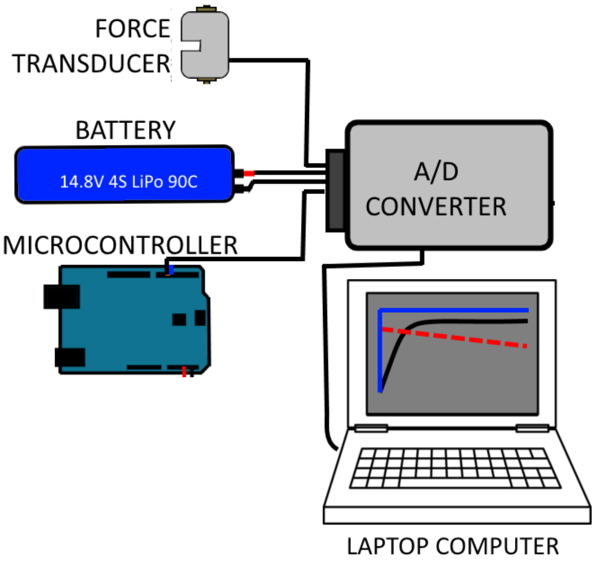

Fig.5. Components involved in data collection

Pushing force was measured using Lorenz Messtechnik K-25 sensor, connected to NI 16-bit A/D card. Together with force data, referent sync signals from microcontroller (transmitted after each change in PWM input signal) and battery voltage state were also measured. Measurement was supported by NI Labview software. Data was sampled with 128 samples per second. Components involved in data collection were depicted in Fig. 5. Resulting data matrix obtained by LabView was exported to Matlab 2010b to further analyzed.

4 Results interpretation

Simplified motor system is devised as a first order system, which could be described using first order transfer function with the following equation (3)

$$W_{motor} = \frac{K}{TS+1} \tag{3}$$

Where T is time constant, and K is gain coefficient. Preliminarily analysis of obtained results showed that system cannot be described as a simple first order system without modifications, as coefficient K and T both depend with change in value of PWM input signal and battery voltage. Additional analysis showed that variations of time constant with change of PWM signal and battery voltage values are minimal. Despite of evident non-linear dependency, parameter T is linearized and calculated against central value of input PWM signal. As opposed to time constant, dependency of coefficient K with PWM input signal and battery state significantly varies, obtaining reliable relation between values is mandatory. For this purpose, motors response to each step signal is analyzed and divided in three phases, as depicted in Fig 6.

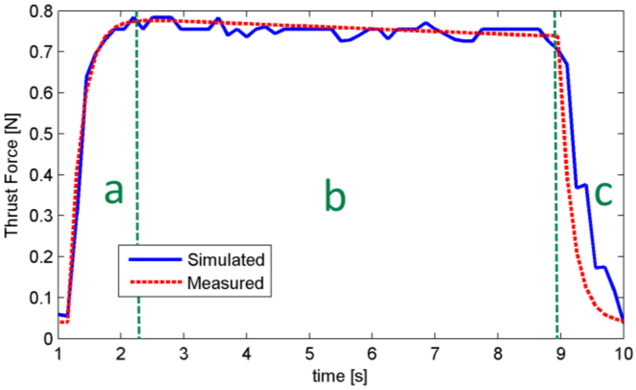

Fig.6. Motor response to step signal, note drop in motor Thrust in middle part of response

Motors thrust responds to limited step PWM signal (10 s in time) is divided in tree regions, (a), (b) and (c) respectively. Regions (a) and (c) are systems response to changing input signal (rising and dropping edge). Using a linear regression, dependencies of coefficient K could be calculated in respect to value of PWM input signal, as effect of battery voltage drop in small time frame is negligible. Time constant is also calculated by analyzing system behavior in regions (a) and (c). Middle region (b) is used to calculate coefficient K correlation with battery voltage, where drop of motor thrust is observable due to change in battery voltage levels (PWM input signal is constant). With all obtained parameter, complete Simulink model of system is built and presented in Fig. 7. Few non-linear components were added to model, as motor controller responds only on limited rage of input PWM signals.

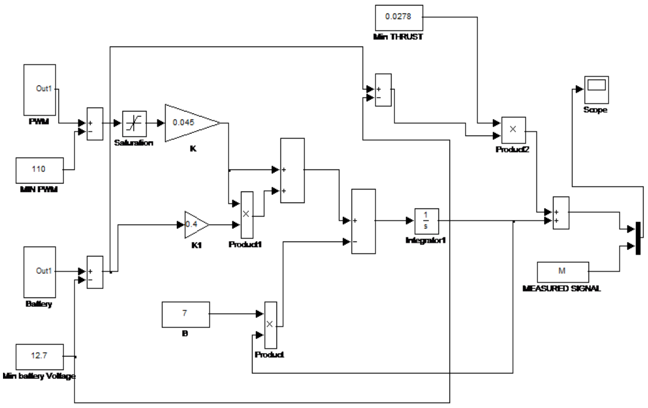

Fig.7. Simulink model of motor and motor controller

After all relevant system parameter were obtained, model performance was tested with measured signal used for model validation (second phase of measurement). Results both for model response and measurement are presented in Fig 8, where proposed model showed good correspondence with data measured data.

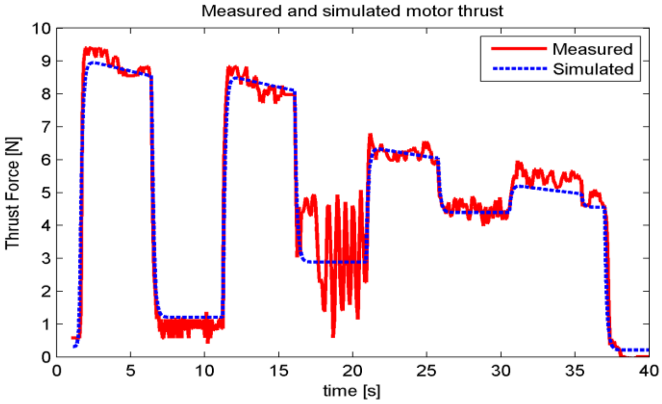

Fig.8. Performance of model tested with validation measurement

When comparing measured and simulated data, for the case example presented in this work, mean error for validation signal was 0.0099 N with standard deviation of 0.0599 N. Example that is presented in this study was selected intentionally, to demonstrate some of motor drive imperfection, as large vibrations (noise) are present during low duct motor RPM between 15 and 20 s.

5 Conclusion

The need for highly reliable and stable hovering for VTOL class of UAV has increased. It is mandatory to perfectly master UAV's motors and to precisely deliver vectored air thrust against ground, in order to achieve stable vertical takeoff, landing or even hovering. As motor system is complex, and consist of battery pack, microcontroller, motor controller and ducted fan engines, where technical data is usually sparse, identification of system parameters has to be done. System is considered as a MISO, which is in basic first order system with varying parameters. Measurement was done in laboratory conditions, where thrusters' response to series of step signals was analyzed. Simulink model was made, and its performance was tested against another series of varying input signals. Model showed good performance with mean error of less than 0.01N and 0.06N of STD. In conclusion, work done in this paper is a good basis for developing a fixed wing UAV with VTOL abilities and great maneuverability.

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