Quad-copter UAV BLDC Motor Control: Linear v/s non-linear control maps

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Deep Parikh, J B Patel and J. J. Barve

Abstract—**This paper presents some investigations and comparison of linear versus non-linear static motor-control maps for the speed control of a BLDC (Brush Less Direct Current) motors used in quad-copter UAV (Unmanned Aerial Vehicles). The motor-control map considered here is the inverse of the static map relating motor-speed output to motor-voltage input for a typical out-runner type Brushless DC Motors (BLDCM). Traditionally, quad-copter BLDC motor speed control uses simple linear motor-control map defined by the motor-constant specification. However, practical BLDC motors show non-linear characteristic, particularly when operated across wide operating speed-range as is commonly required in quad-copter UAV flight operations. In this paper, our investigations to compare performance of linear versus non-linear motor-control maps are presented. The investigations cover simulation-based and experimental study of BLDC motor speed control systems for quad-copter vehicle available. First the non-linear map relating rotor RPM to motor voltage for quad-copter BLDC motor is obtained experimentally using an optical speed encoder. The performance of the linear versus non-linear motor-control-maps for the speed control is studied. The investigations also cover study of time-responses for various standard test input-signals e.g. step, ramp and pulse inputs, applied as the reference speed-commands. Also, simple 2-degree of freedom test-bed is developed in our laboratory to help test the open-loop and closed-loop experimental investigations. The non-linear motor-control map is found to perform better in BLDC motor speed tracking control performance and thereby helping achieve better quad-copter roll-angle attitude control.**

Index Terms—**Quadcopter, BLDC Motor, Linear**

I. Introduction

During the past decade, BLDCM has been becoming increasingly popular as a viable actuator choice for various motion control applications including industrial, aerial and surgical robotics; aerospace; automatic machine tools; electric propulsion applications etc. [1],[2]. BLDCMs have several advantages over conventional brush-type DC motors motivating many researchers and designers to come-up with newer schemes involving application of BLDCM as actuators for more efficient and reliable motion-control operations [3]. The key advantages are: reduced friction-loss allowing higher motor-efficiency, relatively smaller motor-size, reduced maintenance requirements, susceptibility

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Fig. 1: Trunigy multi-star 2213 935-kv, out runner BLDC motor

to harsh environments, increased torque/force generation ability, higher operating speeds, and better heat-dissipation characteristics [4],[5],[6]. These advantages are manifested by the elimination of direct physical contact between stator and rotor due to avoidance of brushes [5].

Based on physical configuration and construction, BLDCM are classified in two broad categories namely in-runner and out-runner type motors. The in-runner type BLDC motors are generally more efficient and useful for high-torque applications, but their increased gearbox and mechanical complexity makes them more expensive. In contrast, the out-runner type BLDC motors have low torque, but mechanical simplicity making them cheaper and less expensive to use and maintain them [7]. The reduced complexity of their gearbox also reduces the overall weight of the aircraft, an important design trade-off for many applications [4]. Thus, the out-runner is a viable low-cost alternative for many motion control applications to drive electric aircraft propellers e.g. quad-copter UAV propellers.

In practice, the modelling, simulation, analysis and control design of BLDCM, is usually carried out based on various assumptions to simplify functional complexities involved in the actual BLDCM, such as, assumption of uniform air-gap and/or non-saturating linear properties of the magnetic materials during the whole operating range. However, such linearization assumptions are few and may hold good for some specific operating scenario, but are not realistic and practical in several other operating scenario [7],[8],[9],[10],[11],[12][13], and [14]. One such popularly used simplification is assumption of linear relationship between BLDCM voltage (input variable) versus motor or rotor RPM (output variable) – called as a linear motor control-map in our work. Although, this assumption of linear motor-control map holds good if BLDC motor operates within a small speed-range around any fixed operating speed. But, if the BLDC motor operates across wide speed-range (as is commonly required in case of quad-copter

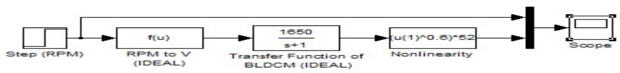

Fig. 2: General block diagram of BLDCM speed control system

UAV), the presence of variable reluctance and magnetic saturation makes this motor voltage-versus-speed relationship as non-linear [2]. In [12], Person and Buric constructed a model based on assumption of uniform air gap and linear magnetic material. Jahns [9] and Krause et. al. [10] have constructed mathematical models, which includes various effects of variable reluctance but assumed absence of magnetic saturation. Finally, Neyram and Ming [3] constructed a model considering effects of magnetic saturation and variation in reluctance.

In this paper, we present our investigations covering the comparison of BLDCM response considering its motor voltage-to-speed characteristics as a linear versus non-linear map; and the improvements in BLDCM speed control in a quad-copter UAV system by using the non-linear control map, instead of linear-control map. The transfer function model of BLDCM is taken based on previous research work and the simulation study is carried out in matlab-simulink platform. The non-linear map is experimentally derived for the BLDCM available in our quad-rotor UAV system using an optical speed encoder to measure its speed. The non-linear map is approximated using a second order polynomial fit.
newline

As most robotic systems using BLDCM usually do not consider nonlinearity present in the system for simplicity and hence works based on the linear control laws such as PID controls. But, it is very important to determine boundary conditions under which this assumption of linearity provides satisfactory output. In this paper, we will present some theoretical and empirical results, which helps to improve controller design for such system using BLDCM as actuators. It also helps in developing a more realistic over all model of a quad-rotor vehicle system. Finally, the effect of linearization is also observed on the attitude control of quad-rotor UAV through various flight data plots through simulation and experimental test-bed results. Also, a simple two degree-of-freedom test-bed is developed to enable roll and pitch attitude control study.

II. SIMULATION STUDY: LINEAR VERSUS NONLINEAR CONTROL MAPS

Figure 2 shows general block diagram of system consisting of BLDCM and its speed controller. The desired RPM request is converted into the voltage request by the speed controller. The function f(u) represents this nonlinear relationship. This conversion generally assumes linear relationship between applied motor-voltage and the motor speed (RPM) for across its speed operating range. The behaviour of an ideal BLDCM system is simulated as the first-order system with its gain as kv of the motor [2]. But because of nonlinearity present in the system, a step-change in motor-voltage at the speed-controller output, if computed based on such linear motor-control map, actually results into the motor-speed that is different (greater) than the desired speed command.

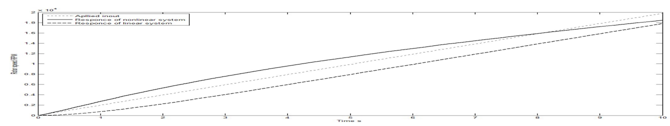

Fig. 3: Open loop speed control response to ramp-input in speed-command for linear and non-linear BLDCM systems

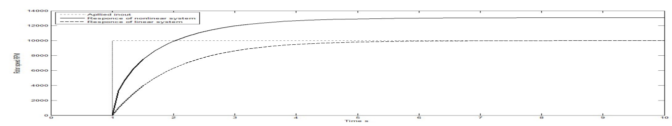

Fig. 4: Open loop speed control response to step-input in speed-command for linear and non-linear BLDCM systems

A. Open-loop speed control response for linear and non-linear BLDCM

Figure 3 shows comparison of open-loop speed response to ramp-input in speed-command for linear versus non-linear BLDCM. It is observed that the error due to nonlinearity is significant during motor speed from 4,000 RPM to 16,000 RPM. Similarly, figure 4 shows comparison of open-loop speed response to a step-change in speed-command for linear versus non-linear BLDCM. A step-change of amplitude 10,000 RPM is applied at 1-sec. The rotor reaches to constant speed after some settling time based on the transient response characteristics of the motor. It is observed that the rotor speed reaches to desired RPM in case BLDCM is linear as represented by the motor control-map used in the motor model. But, in practical case of actual BLDCM having non-linear motor-control map, the steady-state rotor speed reaches a different RPM than the set-point speed target (in open loop due to absence of closed loop speed control of BLDCM). The error in motor speed actually depends upon the amount of nonlinearity present in the system which changes with operating point.

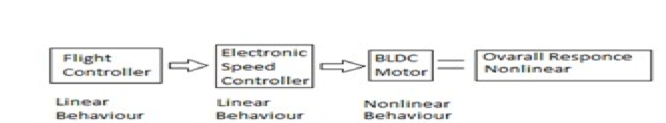

Fig. 5: Speed control of BLDCM in quad-copter system based on traditional approach of using linear motor-control map

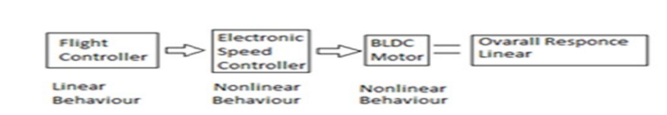

Fig. 6: Speed control of BLDCM in quad-copter system based on proposed approach of using nonlinear motor-control map

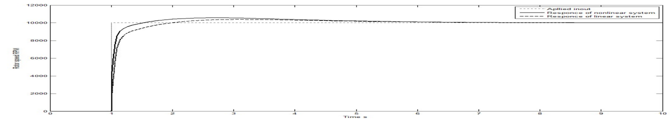

Fig. 7: Closed loop speed control response to step-input in speed-command for linear and non-linear BLDCM systems

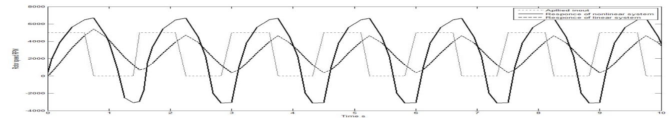

Fig. 8: Closed loop speed control response to pulse-input in speed-command for linear and non-linear BLDCM systems (Uses same PID controller gains – tuned for linear BLDC motor system – for both cases)

B. Closed-loop speed control for linear and non-linear BLDCM

Furthermore, to analyse closed-loop speed-control behaviour (with PID controller) of nonlinear BLDCM for various standard input signals. Simulink model shown in figure 12a is developed. In this model error between actual rotor speed and desired speed is given to a standard PID controller, whose task is to achieve and maintain the desired speed. Here, speed response for linear and nonlinear BLDCM is simulated and compared. The block-diagram schematic of two approaches i.e. traditional linear motor-control map based and the proposed non-linear motor-control map based speed-controller are shown in figure 5 and figure 6.

Figure 7 shows the closed loop speed-control response to step input in speed-command for both cases i.e. linear and non-linear BLDCM systems. Here, the PID controller parameters (or gains) for both the cases are tuned using automatic PID tuning tool of MATLAB for a linear BLDCM system model. A higher peak-overshoot is observed in case of a non-linear BLDCM system as compared to linear BLDCM system. Whereas, figure 8 shows the closed-loop speed-control response when a pulse-train input command signal is applied to linear and nonlinear BLDCM systems. Again, it is observed that the controller tuned reasonably well for linear BLDCM system does not perform well for nonlinear BLDCM system.

The closed loop response can be improved by better tuning of the controller for each case. There exist many automatic PID controller tuning algorithms and their applications. This is demonstrated in figure 9 through closed loop simulation study for a pulse-input, where the PID auto-tuning is used to find PID controller parameters at some suitable operating point. When the simulated system is considered as linear, the gains set by auto-tune feature gives satisfactory results with output satisfactorily following a given pulse input. Whereas, if the simulated system is considered as non-linear, the same PID controller parameters perform somewhat poorly while tracking the reference input across wide range of operational speed of quad-copter BLDC motor. Thus, even the customized tuning for non-linear system case, if done based on single operating point based controller tuning, is also found less effective when operated across the wide operating speed-range. One approach to handle such non-linearity issues is the advancement in manufacturing techniques and good quality magnetic materials which can help reduce such non-linearity effects significantly than was observed before.

Still, the presence of any such reasonable non-linear behaviour poses a control engineering challenge (and opportunity) to enhance performance via non-linear control design and implementation. One such popular non-linear control design approach is to improve the closed loop control performance for such wide-range operation for the nonlinear system case namely adaptive control. Where, the controller parameters are changed continuously or intermittently, as the system traverses through multiple zones across the operating regime. However, design and testing of such adaptive control scheme is out of scope in our present work.

Besides the graphical representation of the input-output characteristics of the key sub-blocks for linear and non-linear motor-control-map cases are shown at the end of this paper - see in figure-12 and 13. Figure 12a and Fig. 13a show the (same) non-linear maps of the BLDC motor representing the characteristics between motor-voltage (as motor-input) and motor-speed or RPM (as motor-output). Figure 12b shows the linear map used by the motor-speed controller block relating the desired motor-speed command (as an input to speed-controller) and respective value of the desired motor-input voltage (as an output from the speed controller) in the overall quad-copter BLDCM speed-control system. Whereas, Figure 12c shows the combined characteristics of the above two blocks (i.e. motor speed-controller block and motor block) together relating the motor-speed or RPM command signal (as input to speed-controller) to actual motor speed or RPM as the motor-output. This overall characteristic is non-linear when a linear motor-control map is used by the BLDC motor controller block.

However, in our work, the use of a non-linear motor-control map is proposed for the BLDC motor speed-controller block (See Figure 13b). This non-linear relationship is chosen to be an inverse (i.e. reverse-map) of the actual non-linear characteristics i.e. non-linear map of a BLDC motor. Thereby, the combined relationship between motor-speed command-input to motor speed-controller and the actual motor-speed as an output from the BLDCM becomes linear due to

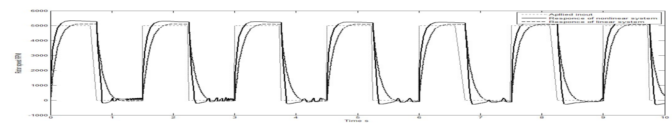

Fig. 9: Closed loop speed control response to pulse-input in speed-command for linear and non-linear BLDCM systems (PID gains are auto tuned for both systems separately)

nonlinearity cancellation or compensation by two reverse nonlinear static-maps appearing back-to-back. If these two non-linear relationships are in exact cancellation, then the overall characteristics relating motor-speed-command to actual-motor speed can become the perfect linear relationship (See Fig. 13c). At the end, also the snap-shot of the matlab-simulink based simulator developed and used in this work is shown at the end of this paper, see figures 14.

III. PRACTICAL IMPLEMENTATION AND TEST RESULTS

To improve performance of the speed-control of quad-copter BLDC motor, actual nonlinear behaviour is accounted for by using an inverse of the nonlinear motor-map as the motor-control map. The motor-map relates BLDC motor speed as a function of the motor-control voltage. This map is non-linear, particularly in our applications i.e. quad-copter UAV due to operation across wide speed range. Figure 13a shows typical characteristics of BLDCM in the form of relation between the motor input voltage (i.e. controller output voltage) and the motor speed or rotor RPM. The inverse of this motor-map can be configured or programmed as motor-control-map in the reprogrammable ESCs. Such programmable ESC are commercially available and is used in our work to compensate for the motor nonlinearity effects without adding any extra computational burden on the main flight controller.

A. Polynomial approximation and implementation of non-linear motor-control-map in ESC

In our work, to decide the amount of nonlinearity, to be considered while programming as a motor-control-map in the programmable ESC, first a test is carried out on our BLDCM by plotting a graph of BLDCM rotor speed (RPM) versus applied motor-voltage Vs. After that this motor voltage-speed map is approximated by fitting a suitable polynomial equation to generate a reverse-map relating the (target) input motor-voltage Vs as the dependent (i.e. output) variable and the (target) motor-speed, i.e. rotor RPM, as the independent (i.e. input) variable. However, a selection of the appropriate polynomial degree requires a trade-off between accuracy and computational complexity. Because very low polynomial-degree cannot represent the exact dynamics of the system, whereas very high polynomial degree requires high computational power while implementing such non-linearity map in programmable ESC controller. So, generally 3 degree of polynomial is optimum choice for most of the out-runner BLDCMs available.

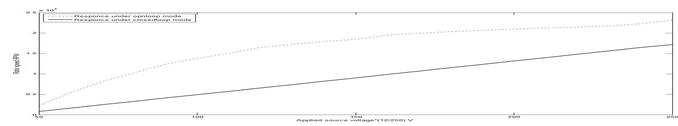

Fig. 10: Response of our Nex-Robotics make BLDCM before and after compensation.

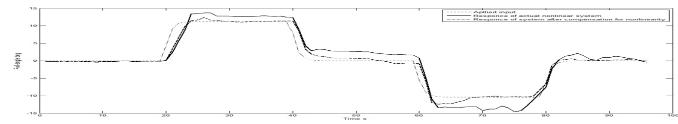

Fig. 11: The closed loop control test-data of our quadcopter attitude control implementation.

$$\begin{aligned} TargetSpeed &= (MaximumSpeed)\cdot \\ &(MaximumInput - MinimumInput) \end{aligned} \tag{1}$$

As shown in equation (1), Target-speed is computed according to the input given by the controller. This target speed is further fed to the controller, which computes as its output the voltage that should be given to BLDCM to make the overall response liner. This controller uses the polynomial coefficients derived in earlier stage. To determine such coefficients, various curve fitting algorithms can be used. In our work, a linear regression with the gradient decent algorithm is used.

$$\begin{aligned} OutputVoltage = p_0 + p_1\cdot(TargetSpeed) + p_2\cdot(TargetSpeed)^2 + \\ p_3\cdot(TargetSpeed)^3 + ... + p_n\cdot(TargetSpeed)^n \end{aligned} \tag{2}$$

where, p0, p1, ..., pn are coefficients of the polynomial used to approximate the non-linear map relating the motor voltage to motor-speed obtained by the test-experiment to characterize our BLDCM.

B. Open-loop study: controller-ESC-motor system

First, the behaviour of speed-control section, i.e. controller-ESC-motor section, is tested based on the implementation of a traditional linear motor-control map in ESC. This results in the non-linear behaviour of the overall (controller-ESC-motor) system due to absence of non-linearity compensation despite the presence of nonlinearity in the actual BLDCM. Next, the use of our proposed non-linear motor-control map in the motor speed control section allows one to make the overall (controller-ESC-motor) system behaviour as linear. Figure 10 shows comparison of both these approaches for the BLDCM available in our laboratory

(Nex-robotics make BLDCM with kv = 1650). As seen in figure 10, the amount of nonlinearity present in this BLDC motor is significant. Hence, 2nd degree polynomial approximation as per equation (2) is used to implement the proposed non-linear motor-control map in the programmable ESC during this open-loop system behaviour study. This helps to compensate for motor non-linearity and approximately linearizes the overall (controller-ESC-motor) system. Behaviour of BLDCM with compensation is fairly linear. There exists some bias (or zero-shift) error, which can be due to some approximation error during the curve fitting and due to elimination of constant-term while computing the controller output signal during test-case implantation. This error can be easily overcome by bias-correction in future.

C. Closed-loop Roll attitude control study: controller-ESC-motor plus quad-copter system

To validate theoretical results, the proposed non-linear motor-control map is implemented on our quad-copter vehicle having BLDCM as a propulsion system. The testing is done mounting the vehicle on the test-bench specially developed by us for this purpose. The test-bench allows us to test the vehicle operating it with a single degree of freedom i.e. rotation around roll or pitch axis. In our experiment, a quad-copter UAV is given a command-input to adjust its roll-angle to a desired value given as a reference command input. The test is performed for 2 cases: case-i) using a linear motor-control-map and case-ii) using a non-linear motor-control map. For exact comparison of time-responses, it is necessary to ensure that the same command input is applied during both these test-cases. For this, an autonomous command-script is developed in the quad-copter control-board that applies the same command input to the quad-copter UAV for both test-cases. In our test, a reference command to UAV system is to stabilize its roll angle alternately at +11.24 and -11.24 degree at different point of time. Results of these experiments are compared and shown in the Fig. 11. The results show significant amount of overshoot, steady-state error and larger settling-time in case of linear motor-control-map. Whereas, in case of nonlinear motor-control-map case a considerable improvement in the closed-loop time-response is observed showing relatively lower overshoot, faster settling-time and smaller steady-state roll-error.

IV. CONCLUSION

Results, achieved using theoretical synthesis and practical test-observations, show that there is a sufficient improvement in the response of the quad-copter UAV propulsion system (i.e. BLDCM control) after applying non-linearity compensation through use of non-linear motor-control map in the BLDCM speed controller block. Compensated system has less overshoots, considerably less settling time and lower steady-state tracking error. These improvements may not seem to have feasible impact during free-lance outdoor flights of quad-copter UAV. However, in many quad-copter UAV applications, such as trajectory following, ball catching, obstacle avoidance etc., improved BLDCM speed-control response can prove valuable due to help in accomplishing better flight-path tracking accuracy, precision and stability. In many cases, state-of-art control algorithms fail to perform desired tasks just because of neglecting compensation of such non-linear actuator or propulsion e.g. nonlinearity of BLDCM. In this paper, it is clearly demonstrated that these type of compensation techniques, when applied for better actuator-control, actually helps the overall performance by the main flight-control algorithms without increasing its computational burden.

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