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# On Driving Signal of Electronic Speed Controller for Small Multi-Rotor Helicopter

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***Abstract*— In this paper we experimentally investigate on relations between dynamic characteristics of thrust subsystem of small drones and driving signal of ESC (Electronic Speed Controller). As a case study, it is shown that with a fixed ESC firmware both driving mode and PWM (Pulse Width Modulation) frequency do not change the transfer function between ESC command and thrust force. In contrast, we also found that a different ESC firmware could significantly change the thrust dynamics.**

***Keywords*— *Electronic Speed Controller, Thrust Dynamics, Multi-rotor Helicopter***

## I. INTRODUCTION

Motivated by various applications such as search and rescue operation, mapping, aerial photograph, surveillance and so on, multi-rotor helicopters or *drones*, attracted much attention from both general public and academic community. In particular, small-size battery-operated drones are widely sold for toys and industrial applications in market and at the same time those drones are also employed for academic research [1,2,3,4].

This might be partially because mechanical components, actuators and electronic parts used for commercial small drones are diverse, relatively cheap and easy to obtain. In many cases however technical information on those components are not available for end-users. From this deficiency it is often difficult to make use of those components for series academic research.

A battery-powered drone is composed of mechanical frames, BLDC motors, propellers, batteries and electrical boards for stabilization, guidance and sensing capability. Most drones have simple mechanical structures (body) and thus the dynamic motion of drone body can be precisely modeled with ease. However it is harder to properly model the dynamics of BLDC motor, ESC and aerodynamic forces and torques generated by propellers. In order to circumvent this difficulty, the author of [5] have proposed an experimental procedure for identifying the transfer function between the PWM commands for ESC unit and the thrust force generated by a propeller. It is however not considered in [5] that the transfer function might depend on user-programmable parameters of ESC. In this paper as a case study we will investigate on how user-programmable settings of an ESC can effect on the thrust dynamics.

Most commercial ESCs follow a special protocol for its PWM (Pulse Width Modulation) input command. For a long time such protocol has been a standard and widely used for RC (remote controlled) cars and helicopters. The PWM frequency of the standard ESC command is fixed to be 50 Hz and the duty ratio ranges between 5% and 10%.

However many drone designers have reported that the fixed PWM frequency of 50 Hz is very restrictive in the sense that the dynamics of drones requires swifter actions compared to RC cars and helicopters in general. This situation motivated many users in RC community to replace a factory firmware in a commercial ESC with a custom one. This allowed them to select a much higher PWM frequency along with many other parameters seeking for faster motions of drones. For an example, the authors of [4] addressed that they also made used a custom ESC firmware but details are not explained.

In this paper we present experimental results on ESC driving signals of ESC employing a custom firmware, and discuss how those signals are related to the thrust dynamics of drones.

## II. BACKGROUNDS

### *A. Two Interpretations of PWM Signal*

Most commercial ESCs use a PWM driving signal of a fixed 50 Hz frequency. In addition, the PWM duty ratio, the proportion of high-level duration compared to the full period of 20 milliseconds, is about 5-10 %. Hence a typical PWM command consists of on (high) signal for 1-2 milliseconds and following 18-19 milliseconds of off (low) signal. The on-signal of 1 millisecond corresponds to the slowest motor speed and two milliseconds to the fastest speed.

A PWM signal can be interpreted by an ESC from two different viewpoints. An ESC can focus on either the absolute duration of on-time or the relative proportion of on-time, i.e., the duty ratio. The first interpretation of a PWM signal is a basis of the so-called PPM (Pulse Position Modulation) signal which is widely used in RC community. A PPM signal is composed of a series of on-off signals whose total length is 20 milliseconds. The duration of the first on-time determines the speed of the first motor and the second one for the second motor and so on. In other words, in this interpretation of a PWM signal, an ESC does not care about the PWM frequency and focuses only on the duration of on-time. As a result, in theory, the 5% duty ratio with 50 Hz PWM is exactly the same as the 10% duty ratio with 100 Hz signal as both have the same 1 millisecond on-time.

We will call this interpretation of PWM signal as *on-duration mode* or *PPM mode*

In PPM mode, there is a limit on available PWM frequency as most commercial ESCs have their own ranges of acceptable on-time length. For an example, if an ESC can accept only 1-2 milliseconds, then it is not possible to use a PWM frequency greater than 1 kHz because even 100% duty ratio PWM gives only one millisecond, the smallest on-time length.

In addition to the *on-duration* interpretation of a PWM signal, an ESC can also employ the standard *duty-ratio* interpretation of a PWM signal. In this case an ESC cares about not the absolute duration of on-time but the duty-ratio. In this case therefore one can freely choose a much higher PWM frequency in principle even though in practice a typical ESC can accept a set of PWM frequencies. Let us call this standard interpretation of PWM signal as *duty-ratio mode*.

Most commercial ESCs with default (factory) firmwares can accept the PPM mode only. In contrast, ESC with many custom firmwares support both the on-duration (PPM) mode and duty-ratio mode and they automatically choose one of the two modes by monitoring an input signal at power-on stage.

Presumably the dynamic behaviour of thrust subsystem may depend on the above modes and PWM frequency. This point however seems to be yet considered in literature within the author's knowledge. As a key contribution of this paper, we present an experimental result on this point.

### B. *ESC Custom Firmware*

Among various methods for replacing a factory firmware in an ESC with a custom one, we chose the tools provided by a software entitled *BLheliSuite 14.2.0.1* [5]. The screenshot in Fig. 1 shows ESC parameters available with BLheliSuite.

Among many ESC parameters in Fig.1, we have changed the parameter "*Enable PWM Input"* emphasized with a red box in Fig. 1 which allows ESC to understand the PWM mode.

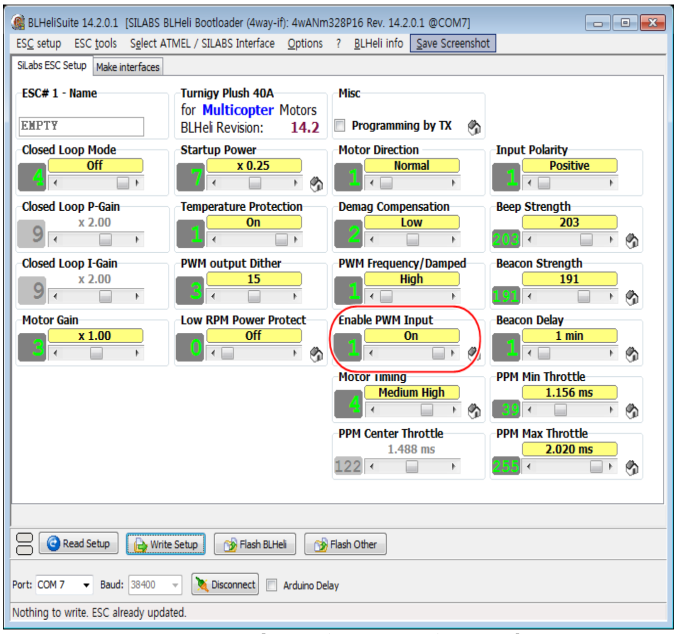


Figure 1. BLHeliSuite (ver. 14.2.0.1) Screenshot

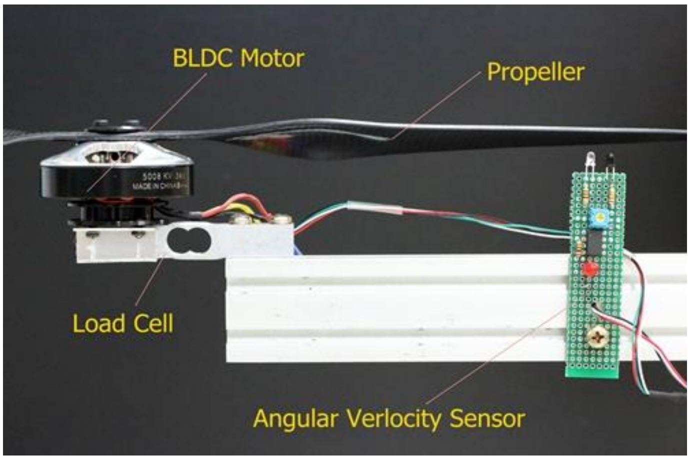


Figure 2 Experiment Setup

### C. *Measurement System*

In order to measure the dynamic thrust force of a propeller actuated by a BLDC motor and an ESC with a custom firmware, we have implemented two sensors.

For a measurement of a thrust force, we used a low cost load-cell which is composed of a strain gauge and an IC amplifier HX711 from AVIA Semiconductor ©. The digital signal from HX711 is converted to an analog signal for an easy monitoring with an oscilloscope.

A simple optical sensor module is designed and installed to measure the rotational velocity of a propeller. The load cell and optical sensors are installed as shown in Fig. 2.

### D. *Components Technical Specification*

Several technical specifications of components which were used in our experiment are given in Table 1.

## III. MAIN RESULTS

### A. *Satic Thrust*

We have tested two PWM frequencies 50 Hz and 100 Hz for our ESC. It was experimentally confirmed that in both cases the ESC could complete a successful arming process with duty ratios 5% (50Hz) and 10% (100Hz). It was also found that ESC can drive our BLDC motor over the range of duty ratio around 6-10% for 50 Hz and 12-20% for 100Hz PWM signal, which implies that our ESC has on-duration around 1.2 -2.0 milliseconds.

TABLE I. COMPONENTS SPECIFICATION

| | | |
|---|---|---|
| BLDC Motor | Model Name | Tarot 5008 |
| | Speed per Volt | 340 RPM /V |
| Propeller | Length | 18 Inches |
| | Pitch | 5.5 Inches |
| Load Cell | Capacity | 5 kg |
| | Nonlinearity | 0.05 % |
| ESC | Model Name | FLYFUN 40A |
| | Refresh Rate | 50 Hz – 432 Hz |
| Battery | Type | LiPo - 6 Cells |
| | Capacity | 10000 mAh |

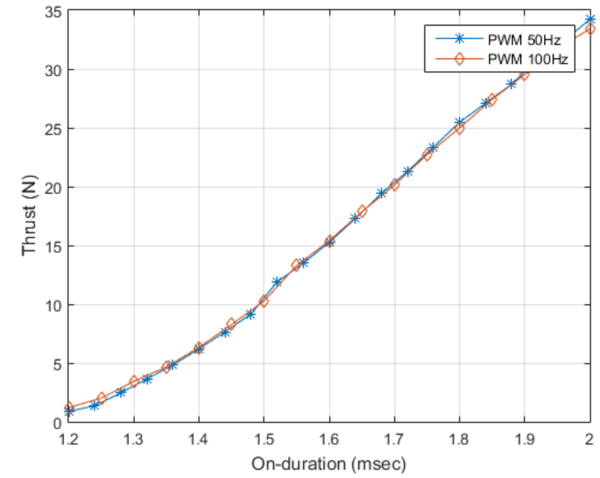

Figure 3 Static Thrust (PPM mode)

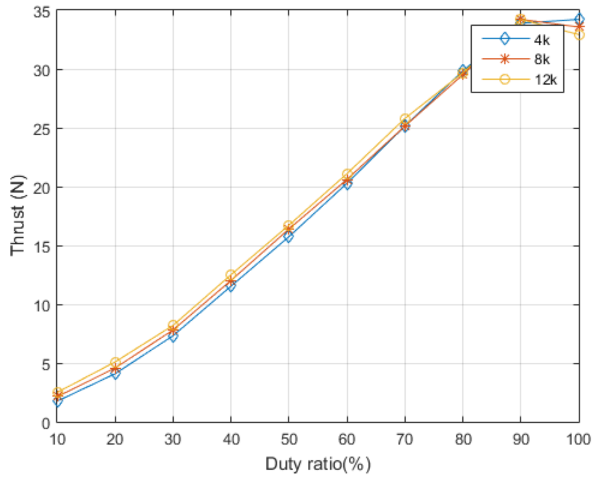

Figure 5 Static Thrust (duty-ratio mode)

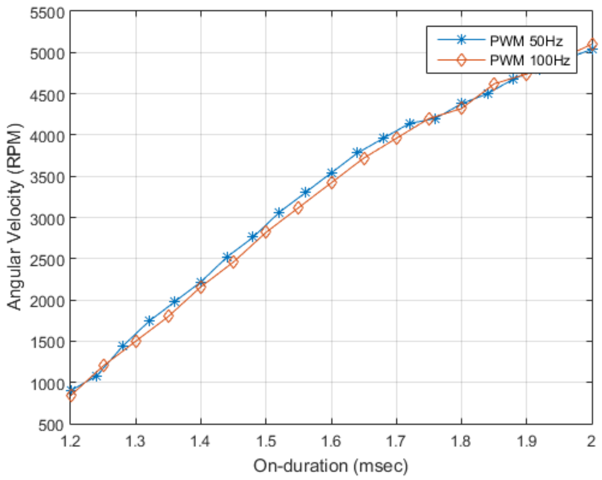

Figure 4 Propeller Speed (PPM mode)

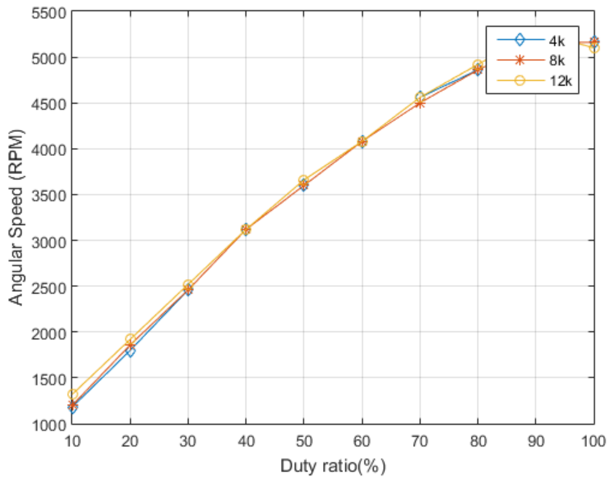

Figure 6 Propeller Speed (Duty-ratio-mode)

Our first aim was to check whether or not the same on-duration from two different PWM frequencies would result in the same static thrust force. Our experiments gave the results shown in Fig. 3 and Fig. 4. The experimental results strongly suggest that, except some experimental errors, both the propeller angular velocity and thrust force are determined by the on-duration, irrespective of PWM frequency, when ESC is in the PPM (on-duration) mode.

Our second aim was to experimentally measure the thrust force when an ESC is running in the duty-ratio mode, and to check whether or not the same duty-ratio with different PWM frequencies gives the same thrust force.

For this experiment, we have used PWM signals of three frequencies (4 kHz, 8 kHz, and 12 kHz). Firstly we have checked that with those PWM frequencies, our ESC could be armed with duty ratio 0.4 % (4 kHz), 0.7% (8 kHz) and 1.03% (12 kHz). By changing the duty-ratio of three PWM signals, we have measured static thrust and propeller angular velocity as shown in Fig. 5 and Fig. 6. As was the cases of the PPM mode, we have found that the thrust and angular velocity are almost independent of the frequency of PWM signal.

Furthermore, from a comparison of Fig. 3-6, it is clear that static thrust and angular velocity does not depend on the driving modes (PPM or duty-ratio) of ESC.

### B. *Dynamic Thrust*

In this paper, we regarded the actuator subsystem of a drone which is composed of an ESC, BLDC motor and a propeller as an unknown black-box whose dynamical properties should be identified. It was found in [1] with the same actuator subsystem used in this paper that the black-box dynamics can be properly modeled as a first-order transfer function near an operating point defined by a nominal angular velocity and an on-duration length. That identification result was obtained from a step-response of the thrust force with respect to a step change of the on-duration length.

The same step-response approach as in [1] was repeated but this time we used two different driving modes of an ESC with PWM frequencies. Furthermore, in this paper, we focused on not a dynamic modeling of thrust dynamics but possible differences in dynamic characteristics of actuator-subsystem, if any, caused by different driving modes and parameters.

For a proper normalization, a step input to ESC was defined as a variation from 20% to 80 % of the full range of on-duration in PPM mode. For instance, in the case of 50 Hz PPM mode, the on-duration was found to be in the range [1.2,2.0] milliseconds and thus step input of this case is defined as an abrupt increase of the on-duration from 1.36 (=1.2+0.8*0.2) to 1.84 (=1.2+0.8*0.8) milliseconds. In the cases of PWM mode, step input is defined as a switching from 20% to 80% as usual.

Experimental results are shown in Fig. 8 and Fig. 9. In each figure, both the actual output of thrust sensor (upper) and its normalized value (lower) are shown. From those results, one can make several interesting observations. Firstly, an unexpected result is that the dynamic behavior of thrust subsystem from ESC command input to thrust force output depends on neither the driving modes of ESC nor PWM frequency in overall, even though actual magnitudes of thrust do vary slightly.

This observation contradicts with a common belief, for examples in [2], that a higher PWM frequency can provide a swifter motion of a drone, at least with our particular actuator system. Presumable this is because mechanical inertias of moving parts in our case study is too big to follow the prompt changes of driving signal from ESC.

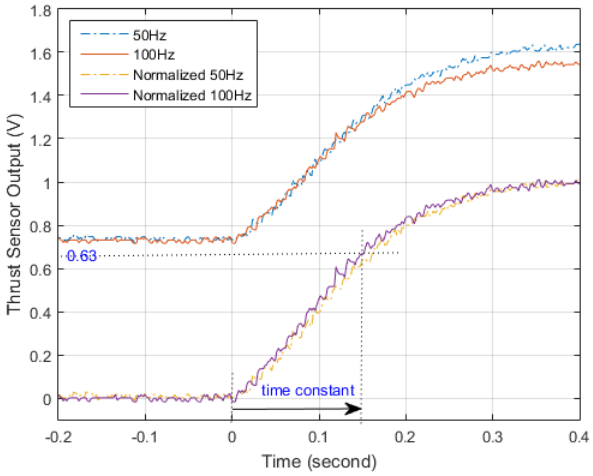


Fig. 8 Step Response (On-duration Mode)

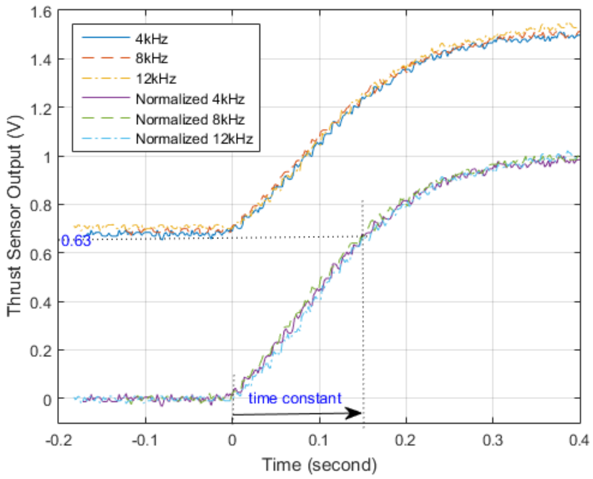


Fig. 9 Step Response (Duty-ratio Mode)

It follows from this observation that, irrespective of driving mode and frequency of ESC, our actuator subsystem from ESC input to thrust force can be described as a common first order transfer function, which can be found in [5].

A second observation is that, even with a standard PPM signal of 50 Hz, the thrust dynamical may heavily depend on a firmware of an ESC. It was shown in [5] (see Fig. 9) that with a factory firmware of the same ESC we have found that the time constant is almost 250 milliseconds. With a custom firmware provided by BLheliSuite and the same driving PPM signal of 50 Hz, Fig. 8 shows that the time constant is only 150 milliseconds. Probably this result can explain experiences of many RC hobbyist who reported that a custom ESC firmware could give better performances.

## IV. CONCLUSION

As a case study, we have experimentally investigated on possible relation between the dynamic characteristics of thrust subsystem of small drones and the ESC driving signal. Our ESC with a custom firmware could be driven in either the on-duration (PPM) mode with a low frequency (from 50 Hz up to several hundred's Hz in general) PWM signal or the duty-ratio mode with a relatively higher frequency (several kHz) PWM signal. It turned out that the thrust dynamics does not depend on the driving mode and frequency. It was also observed however that, even with the same driving signal, a custom ESC firmware can give smaller time constant, that is, a swifter motion of drones, compared to a factory firmware.

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