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Determination of the efficiency of the BLDC motor based on the analysis of the measured vibrations

KEYWORDS
vibrations, motor efficency, BLDC motor, Discrete Fourier Transform

ABSTRACT
The results of efficiency tests for the brushless BLDC motor are presented. The efficiency of the motor was tested by measuring vibrations in the motor and propeller system. Measurements were taken across the entire range of motor speeds, with each subsequent measurement increasing the engine speed. An accelerometer was used as the vibration registering system, while communication was done through the I2C bus and UART bus. The measured vibrations underwent signal processing and analysis. Signal processing and analysis involved the use of a Discrete Fourier Transform (DFT), followed by plotting the amplitude-time and amplitude-phase characteristics. As a result, the obtained test results clearly illustrate the output characteristics of the brushless BLDC motor. The entire system, functioning as a mobile vibration measurement system, can be utilized as a safety component in drones.

1. Introduction

BLDC motors find applications in various industries. As referenced in [1, 2], a BLDC motor is a pulse-powered brushless DC motor with electronic commutation. They are widely used in unmanned aerial vehicles, commonly known as drones, for propulsion. Drones incorporate safety features that enable swift response upon detecting a low battery level. During startup, the on-board computer can verify the operational status of all systems, the power supply voltage of the motors, and their proper connection, often indicated by audible signals. Enhancing security can be achieved through various means, one of which involves improving the characteristics of the BLDC motor, as mentioned in [3]. It is possible to measure the motor's current draw while simultaneously gathering information about vibrations, which can provide insights into potential short circuits [4]. Photo-optical sensors, as described in [5], can also be employed. Another approach is to compare the measured characteristics against the specifications provided by the motor manufacturer. Vibrations are typically measured in the time domain, resulting in varying amplitudes. Amidst the vast amount of data that can be challenging to interpret, the Discrete Fourier Transform (DFT) proves to be beneficial, as mentioned in [6, 7, 8]. The Fourier transform allows us to convert the collected data from the time domain to the frequency domain, yielding an amplitude-phase characteristic that is easier to interpret. This test aims to determine the motor's efficiency and compare the obtained results with the theoretical rotational speeds stated by the manufacturer. One notable aspect of this solution is the ability to wirelessly gather data on the technical condition of the motors by measuring vibrations. This feature provides an extra level of security for drone operators.

2. Experimental Procedures

The measurement system comprised of an engine with an attached propeller. The motor under test was a Rocket X2212 with a 950kV rating, indicating 950 revolutions per volt of the supply voltage. Measurements were conducted for constant rotational speeds, ranging from 5% PWM (Pulse Width Modulation) to 100% PWM. Each subsequent measurement increased the power transmitted to the motor by 5% PWM. Vibrations were captured using the LSM303d digital accelerometer, which was connected to the STM32 microcontroller. The microcontroller acted as a data receiver from the sensor and simultaneously converted the received data into the frequency domain. Communication was established via the I2C bus. The transformed data was then transmitted from the STM32 microcontroller to the connected desktop computer using the UART bus. The data files were processed in CSV format, and amplitude-time and amplitude-phase characteristics were plotted in Excel. Finally, the comparison runs were plotted to assess the measured rotational speeds against those specified in the technical documentation of the motor. The second run depicted the recorded deviation level between the measured rotational speeds and the specified values in the documentation.

3. Results and Discussion

Results can vary due to several factors that influence the actual engine speed. The primary factor is the supply voltage and how the BLDC motor is controlled by the electronic speed controller (ESC). The LSM303d accelerometer is a system that allows for vibration measurements in three perpendicular axes. In the accelerometer-engine reference system on the drone's arm, the X and Z axes correspond to vibrations recorded in the horizontal plane, while the Y-axis captures vibrations parallel to the force of gravity. Figure 1 displays the recorded vibrations in the Y-axis as an amplitude-time characteristic for 10% PWM.

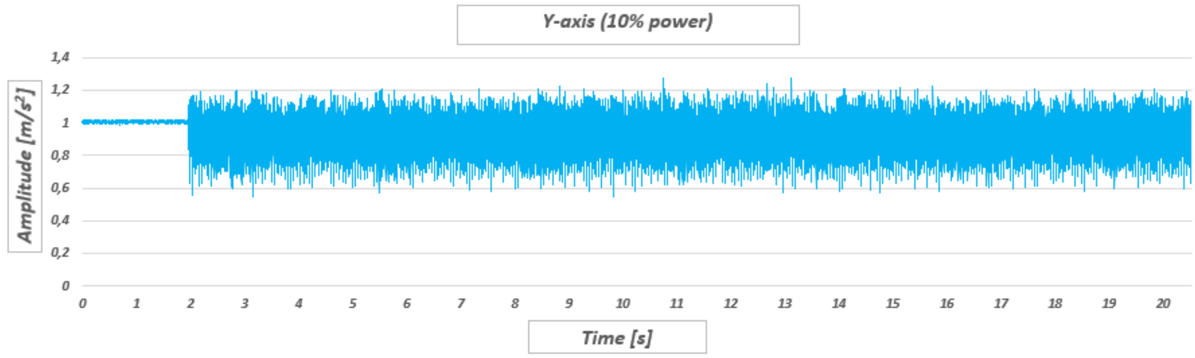

Figure 1. Amplitude-time characteristics for 10% PWM for a BLDC motor

As depicted in Figure 1, the recorded vibrations appear illegible when attempting to determine the motor speed and efficiency. However, the subsequent step involved utilizing the Discrete Fourier Transform (DFT) to obtain data that enables the plotting of the amplitude-phase characteristic. On the plotted characteristic, distinct peaks known as harmonics of the system become evident. Figure 2 illustrates the amplitude-phase characteristics with identified harmonics corresponding to the engine rotational speed and twice the rotational speed. In the tested engine and propeller system, vibrations are generated with such intensity that, as observed in Figure 2, the desired harmonics can be identified. If the measured vibrations were of lower magnitude, signal filtering techniques such as those described in [9] could be employed. According to [10], the application of Kalman filtering to the Fourier transform is a viable approach. Implementing such enhancements in signal processing would improve the quality of the obtained results.

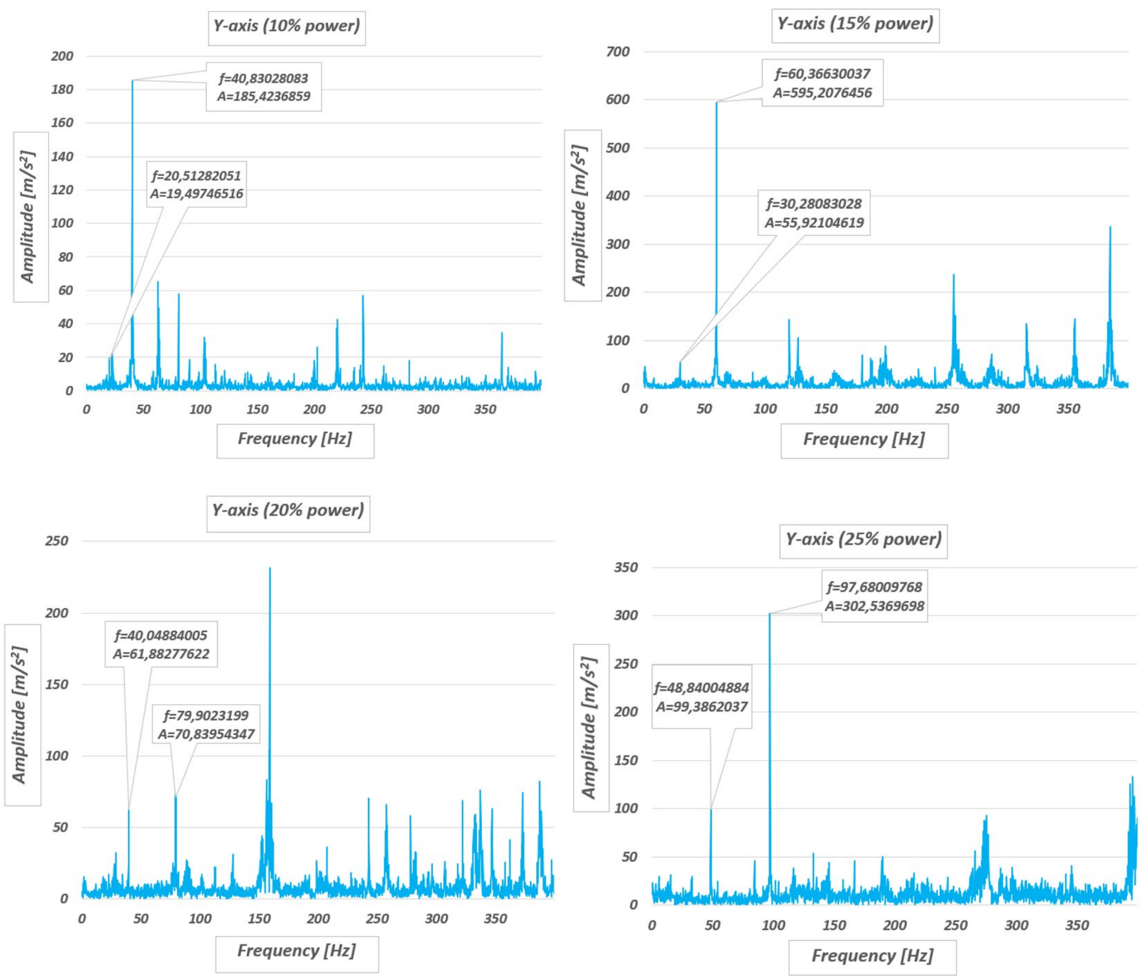

Figure 2. Amplitude-phase characteristics for different engine speeds

Table 1 presents the results of all measurements carried out. The table consists of columns corresponding to: signal fill (PWM), harmonic frequency related to rotational speed, Calculated engine rotational speed, rotational speed from the technical documentation, speed deviation.

Table 1. Harmonic frequency, revolution per minute from calculation, revolution per minute from documentation and difference between both revolution values

PWM [%]	Frequency (Hz)	Revolutions (rpm)	Revolutions in documentation [rpm]	Engine speed difference [rpm]
5	8,59	515	599	-84
10	20,51	1231	1197	34
15	30,28	1817	1796	21
20	40,04	2402	2394	8
25	48,84	2930	2993	-63
30	56,45	3387	3591	-204
35	64,08	3845	4190	-345
40	73,78	4427	4788	-361
45	82,91	4975	5387	-412
50	92,01	5521	5985	-464
55	99,08	5945	6584	-639
60	107,25	6435	7182	-747
65	114,91	6895	7781	-886
70	123,73	7424	8379	-955
75	139,88	8393	8978	-585
80	151,59	9095	9576	-481
85	167,51	10051	10175	-124
90	177,28	10637	10773	-136
95	182,01	10921	11372	-451
100	185,39	11123	11970	-847

Using the data contained in Table 1, it is possible to determine the characteristics of the rotational speed depending on the PWM signal as Fig. 3. It is possible also plot the ideal characteristic using data from the technical documentation of the BLDC motor as Fig. 4. Based on the data on the difference in rotational speeds from the measurements and the documentation, the characteristics of the difference in rotations were plotted in Fig. 5.

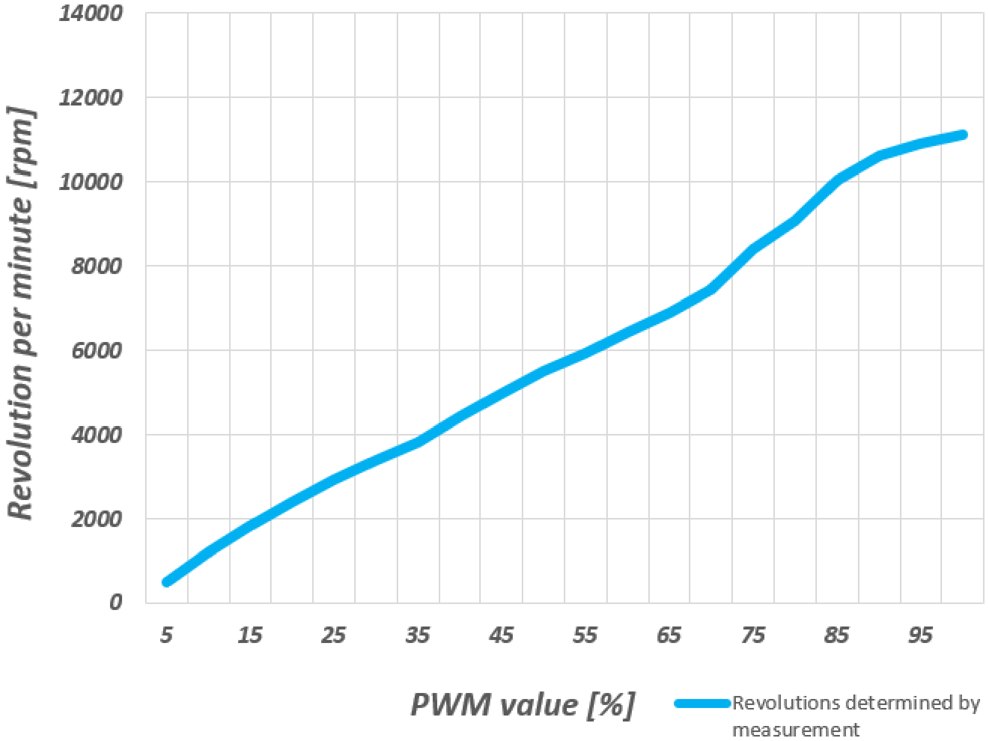

Figure 3. Presentation of the characteristics of determined speed on the PWM value, measurements carried out for the voltage of 12.60 V

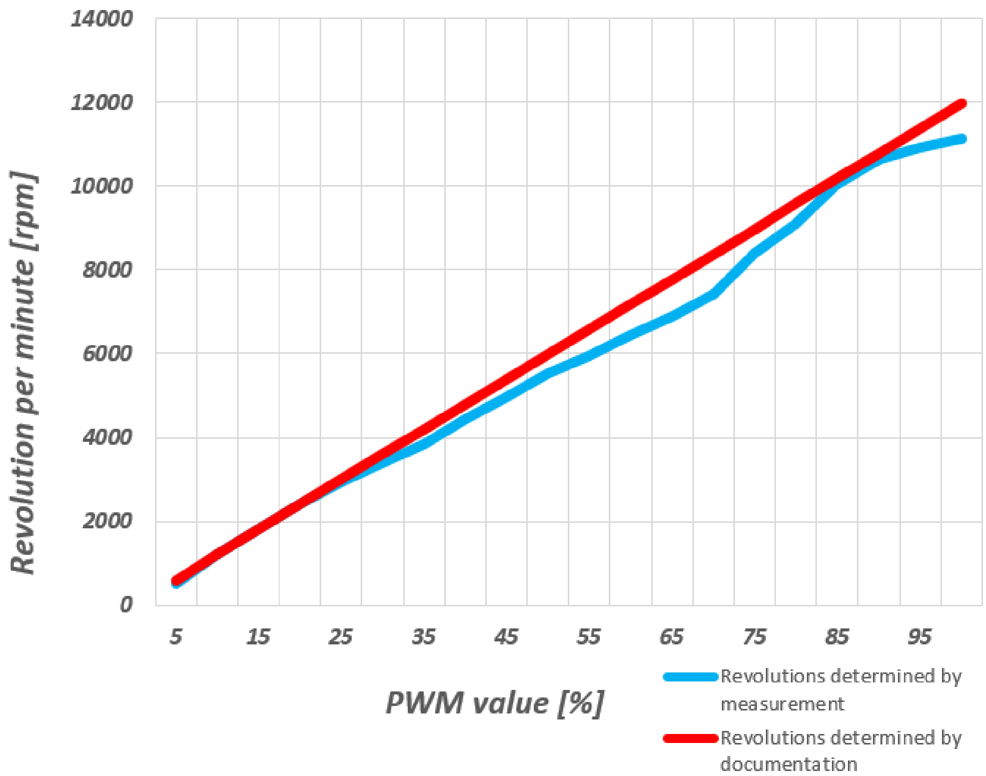

Figure 4. Ideal and calculated motor speed characteristics for PWM values, measurements carried out at 12.60V

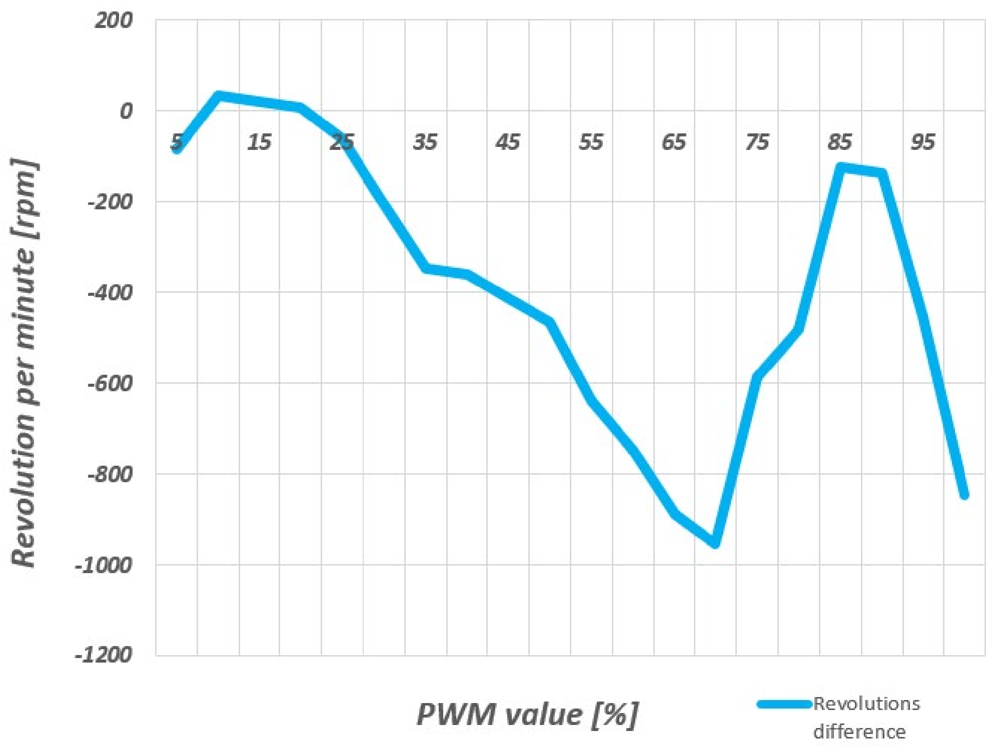

Figure 5. Presentation of difference values between revolutions determined by documentation and revolutions determined by measurements

4. Conclusions

Based on the conducted tests and subsequent analysis of the results, the following observations were made:

1. The rotational speed of the BLDC motor does not increase linearly with each PWM value. Instead, the speed increment occurs for each subsequent PWM value. At a constant voltage, the motor demonstrates an increase in speed as the PWM values increase.
2. The rotational speed error is not constant but varies within the PWM range of 20% to 100%. Notably, a decrease in the error is observed within the PWM range of 70% to 85%, suggesting that the motor exhibits higher efficiency in this range.
3. Vibration amplitude reaches its highest values at a PWM of 15%. Further research is required to determine whether this increase is due to system resonance, propeller design, or the material composition of the drone arm.
4. In terms of vibration measurements on the X and Z axes, the observed vibrations did not exhibit the same level of repeatability as the measurements on the Y axis. Consequently, it was not possible to identify the harmonic associated with the rotational speed for each PWM value in these axes.

These findings provide valuable insights but may require additional investigation and analysis for a comprehensive understanding of the system's behavior.

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