A Novel Fast-Filtering Method for Rotational Speed of the BLDC Motor Drive Applied to Valve Actuator

Marko Nerat and Damir Vrančić

***Abstract*—A novel fast-filtering method for rotational speed measurements, applied to the brushless direct current motor drives, is proposed and tested in the paper. The spatial misalignment of the sensor for rotor position (Hall sensor), as well as its inhomogeneous magnetization, causes the measured rotational speed to jitter around its average value even when the rotor rotates at constant speed. The proposed fast-filtering algorithm is based on the assumption that the speed jitter is periodic, since the measured speed pattern is repeated after each one revolution of the rotor. The algorithm is tested on a valve actuator. The experimental results show that the speed jitter is substantially reduced, whereas fast reaction of the speed control loop is preserved in contrast with the classical filtering methods.**

***Index Terms*—Brushless direct current (BLDC) drives, fast-filtering method, rotational speed measurement, rotational speed jitter cancellation, valve actuator.**

I. Introduction

NOWADAYS, the devices that are commonly used in households (e.g., vacuum cleaners, washing machines) or in industry (e.g., conveyor tapes and drilling machines at production lines) are driven by different types of electromotors. These electromotors are electromechanical devices that convert electrical energy to rotational motion of the rotor. The asynchronous electrical motors are often the most appropriate choice due to their robust construction, high output power, and relatively simple control [1]. However, the rotor must be supplied with current through sliding brushes and contact pads that are prone to sparkling and wear. In the last decade, brushless direct current (BLDC) motors have replaced AC and DC motors with brushes in great extent, especially where low power is needed for driving the appliances [2]–[6]. The BLDC motors have high torque to weight ratio [7], high efficiency [8], and precise detection of rotational angle with sensors for rotor position (Hall sensors) [9]. The BLDC motors are thus especially suited to be used in micromanipulators due to precise rotational control, electric bikes due to high efficiency and torque, or electromotor driven actuators due to precise rotational control, high efficiency, and torque [7]–[9].

The positioning speed of these actuators needs to be precisely controlled and as stable as possible to prevent microvibrations in the mechanical system. The vibrations are undesirable since they increase mechanical wear of the actuator's transmission system and the BLDC motor itself, which is critical problem during the long-term operation.

When the BLDC motor rotates at some (constant) speed, the measured speed is noisy due to inhomogeneous magnetization and misalignment of the Hall sensors, which are used to detect the rotor's position. These inherent inaccuracies cause erroneous detection of the rotor's position and transitions between electric phases [10]. Single-chip design can minimize the misalignment of Hall sensors due to more accurate placement [11], but it is commonly applicable to miniaturized brushless motors only. However, the mentioned solution cannot avoid the problems due to inhomogeneous magnetization of the permanent magnets that are placed around the rotor's circumference. The difference between the spatial distributions of magnetic fields induced by two adjacent permanent magnets causes error in detection of the current rotor's position with Hall sensors.

Since the rotational speed is calculated as the difference of rotor's position over a period of time, the measured speed jitters around its average value even when the actual speed is constant. This speed jitter undesirably excites the (PID) control loop that controls the rotational speed of the BLDC motor. The control loop tries to maintain the reference speed, but due to the erroneous speed measurement, it cannot completely remove the actual speed jitter, which can be generated, measured, and analyzed in different ways [12]–[14]. Moreover, the jitter is present in the control signal and, therefore, in the actual torque of the motor. This causes additional mechanical vibrations.

The jitter of the measured rotational speed is obviously governed by inaccurate placement of Hall sensors or/and inhomogeneous magnetization of permanent magnets within the BLDC motor, so the jitter is not random, but rather periodic. The period of jitter is equal to one revolution of the BLDC rotor (angle of 360°) since the sensors' misalignment pattern (or/and the spatial distribution of the permanent magnets with inhomogeneous magnetization) repeats afterwards, as can be seen in Fig. 1.

The relative jitter (d_i) at rotational position i is the ratio between the measured ($v(i)$) and the actual rotational speed v_a:

$$d_i = \frac{v(i)}{v_a}. \tag{1}$$

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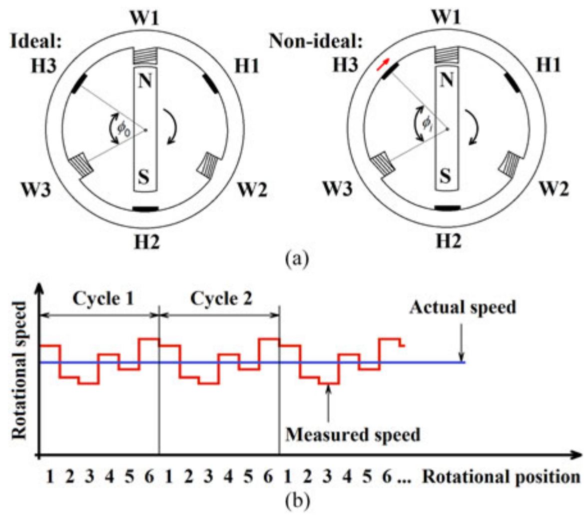

Fig. 1. (a) Schematic of the BLDC motor: stator windings are denoted by W1, W2, and W3, rotor is N-S, Hall sensors H1, H2, and H3 are positioned ideally and nonideally, respectively. (b) Actual rotational speed (ideal) and measured rotational speed (nonideal).

Since the jitter is caused by sensors misalignments, the relative jitter d_i is also proportional to the ratio between the ideal (ϕ_0) and the actual angle (ϕ_i) between two rotational positions, as can be seen in Fig. 1(a):

$$d_i = \frac{\phi_0}{\phi_i}. \tag{2}$$

In practice, a low-pass or moving average digital filter is usually used to filter out measured speed before it is applied to the control loop. The speed is either filtered or averaged so that the jitter is reduced to a level still acceptable for a specific application.

However, these filters have detrimental effect on the control loop since they add time delay into the system. The delay depends on the filter time constant or the number of speed samples used for averaging within one revolution (cycle) of the BLDC rotor. Due to the delay, the rotational speed control loop becomes slower and inefficient, and sometimes even unstable. Fig. 2 shows an example where the low-pass and moving average filters are used.

Another approach for improving filtering performance is to use Kalman filter. The filtered rotational speed can be calculated from the measured rotational speed and the signal applied to the BLDC motor [15]. However, such methods would require precise mechanical and electrical models of the system and precise measurements of voltages, currents, and load (torque) on the shaft, which would be too costly for practical implementation. Some authors also proposed filtering methods that are based on neural networks [16]. Recently, some advanced methods for measuring the rotational speed have been presented, e.g., instantaneous angular speed [17], [18], moving synchronous average [19], and angular sampling [20] for determining cyclic rotational speed. These methods apply filtering to improve accuracy of the position measurement unit, and thus, their applications

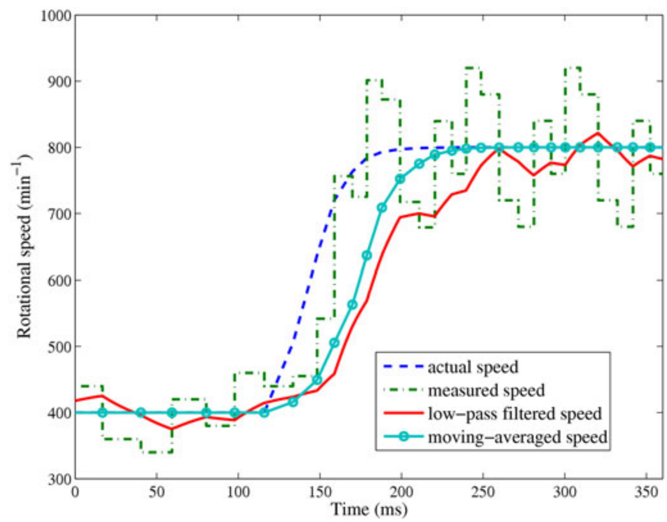

Fig. 2. Actual, measured, low-pass filtered, and moving-averaged speed in revolutions per minute (min^{-1}).

are not intended to fully cancel out oscillations of rotational speed around its average value.

Our goal was to develop an algorithm, which cancels out jitter in rotational speed measurements instantly and solves the before-mentioned problems implicitly. The algorithm should reduce mechanical stress (vibrations) and energy consumption. The proposed algorithm is applied to hydraulic valve actuator and is more suitable compared to other more complex and sophisticated algorithms when a simple implementation with low computational power is required.

This paper is organized as follows. In Section II, the fast-filtering method is elaborated. The concept of adaptive fast-filtering algorithm with its limitations is described. Furthermore, its implementation in terms of software code, which is appropriate for running on low-cost microcontrollers, is proposed. In Section III, the experimental results from testing on valve actuator are presented and discussed. In Section IV, a short conclusion with possible improvements of the presented algorithm is given.

II. Adaptive Fast-Filtering Method

The speed measurement introduces undesired jitter into the speed control loop, which can be reduced by filtering the speed signal. The classical filtering methods, as mentioned in Section I, add some delay into the speed control loop. This delay makes it slower and inefficient or even unstable.

Therefore, the major challenge was to develop an appropriate filtering method, which has to be able to detect changes in measured speed (even step-like change) and correct the calculated speed accordingly. On the other side, the algorithm should be as simple as possible to be suitable for running in real time on low-cost microcontrollers.

A. Adaptive Fast-Filtering

The proposed adaptive filtering algorithm is based on assumption that the rotational speed jitter pattern is periodic. Aperiodic

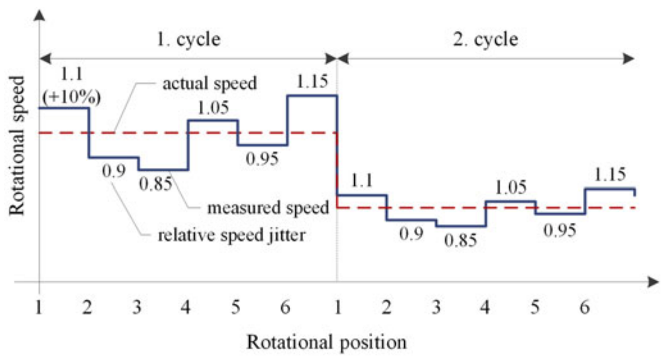

Fig. 3. Actual and the measured speed with relative speed jitter at different rotational positions.

jitter in BLDC motors can appear due to measurement uncertainty when detecting transitions of Hall sensors output levels and the resolution of microcontroller's counter. It could also appear due to variation of currents in stator coils inside the BLDC motor, but due to the construction of BLDC motors and strong permanent magnets, such variations are usually negligible.

The relative jitter remains the same for different rotational speeds, e.g., if the actual speed is two times lower, the speed jitter decreases by factor 2 as well, as shown in Fig. 3.

Therefore, the relative rotational speed jitter does not depend on the actual rotational speed, but only on rotational position. If the relative rotational speed jitter is known for each rotational position, it can be used for calculating the actual rotational speed from the measured one, as can be derived from expression (1):

$$v_a = \frac{v(i)}{d_i}. \tag{3}$$

For example, if the speed jitter at the current rotational position is 1.1 (the measured speed is 10% higher than the actual speed) and the measured rotational speed is 660 min^{-1}, the actual speed is 600 min^{-1}.

The proposed calculation of the actual speed is relatively simple, but the question that remains is how to obtain the relative speed jitter at each rotational position automatically during normal operation.

Namely, the jitter should be measured only when the actual rotational speed is constant. If the actual speed is constant, then the measured speeds at all rotational positions are almost the same as the speeds measured one revolution before, as can be seen in Fig. 1(b). The differences between measured speeds are mainly governed by the measurement uncertainty at detecting transitions of Hall sensor's output levels and the resolution of microcontroller's free running counter for measuring the period between two consecutive transitions. By considering that these differences are negligible, the jitter at each rotational position (i) can be calculated as

$$d_i = \frac{v(i)}{v_{\text{avg}}} \tag{4}$$

where v_{avg} is the average measured speed within one revolution (rotation cycle). Note that if the direction of rotation changes (e.g., forward to backward), the rotational speed jitters might slightly change as well. Therefore, the jitters should be measured independently for both directions.

The proposed approach of measuring the rotational speed has an important advantage over the classical low-pass or moving-average filtering, since it instantly calculates the actual rotational speed and removes measuring jitter even when the speed changes rapidly.

Remark 1: The proposed approach is based on assumption that the rotational speed should remain almost constant for at least two revolutions to calculate relative speed jitters. In other words, each absolute difference between the measured speed samples at the same spatial position, obtained after the former and the latter revolution of the BLDC rotor, should be smaller than e. The difference e should be as small as possible value that still enables reliable detection of constant rotational speed. As already mentioned, the differences between the measured speeds in two consecutive revolutions, during constant rotational speed, are mainly governed by the measurement uncertainty and microcontroller time resolution.

Remark 2: The constant speed detection should not be performed when the motor does not rotate or rotates slowly. In practice, the minimum speed for detection should be chosen appropriately (e.g., 25% of the nominal speed), since the calculation of jitters (4) can become less accurate because of rounding errors (for integer speed variables).

Remark 3: The relative jitter vector d_i and the average speed v_{avg} are not updated if any speed sample in current revolution changes more than e when compared to the previous rotation cycle. This implies that abrupt variation of speed does not cause calculation error of the actual (fast-filtered) speed, since the previous d_i elements are used in (3).

Remark 4: The rotational speed is usually controlled by the control system (e.g., PI or PID controller). This means that some jitter signal (due to jittered rotational speed) can appear at the controller output. Therefore, some actual rotational speed jitter can appear even when the reference rotational speed is constant. However, in most cases, the proposed algorithm should substantially decrease the mentioned jitters due to negative control feedback.

B. Jitter Cancellation Algorithm

The proposed algorithm is based on the adaptive fast-filtering principle. In general, it is divided into four parts as can be seen in Fig. 4. The first part is initialization part, the second is speed measurement part, the third is calculation of the actual (fast-filtered) speed, and the fourth is detection of constant rotational speed.

In Fig. 4, parameter N stands for the number of rotational positions within one entire rotation, d is the relative speed jitter vector, i stands for the current rotational position, v is the current measured speed, v_a represents the actual (fast-filtered) speed, v_m is a vector of the previous measured velocities (within one entire rotation), v_{avg} represents the average speed in one entire rotation, e is defined largest difference between two consecutive measured speeds at the same rotational position, and $v_{\min}$ is

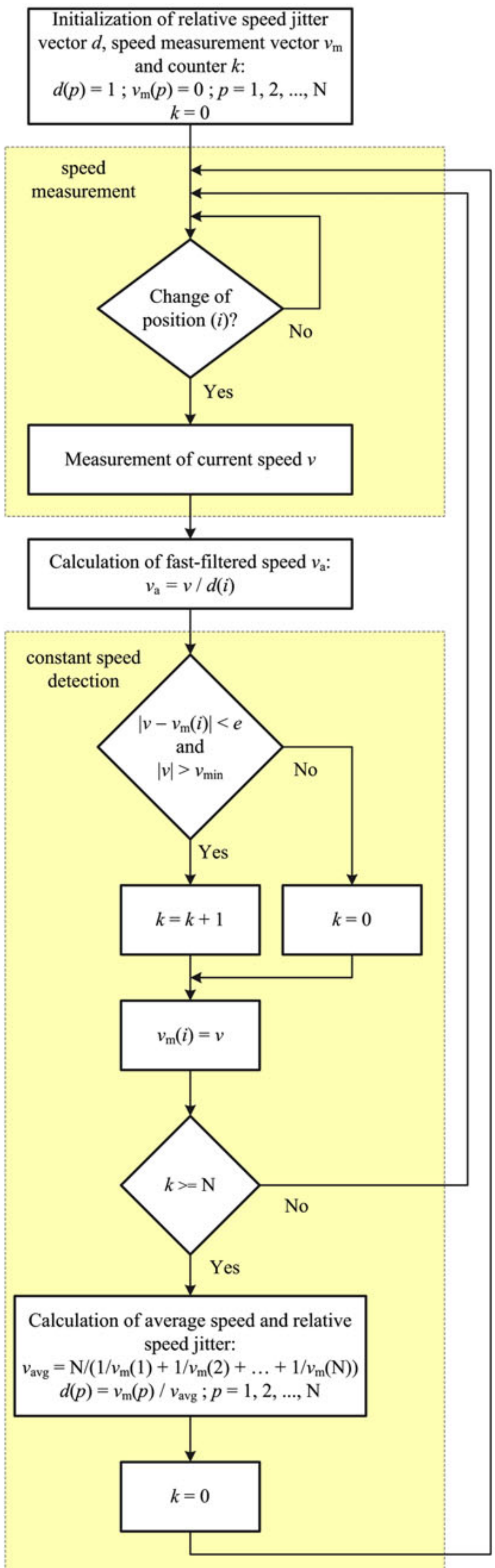

Fig. 4. Schematic diagram of the proposed fast-filtering algorithm.

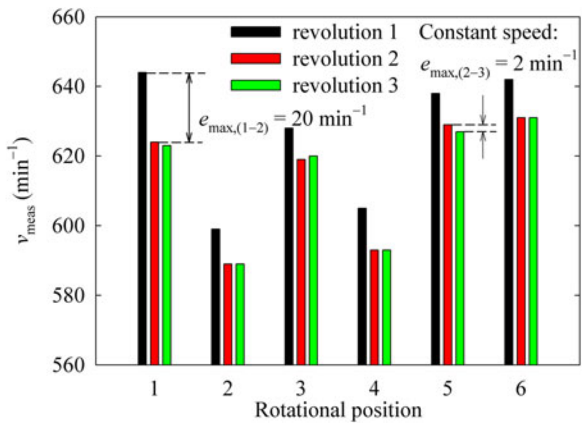

Fig. 5. Example of constant speed detection measurement.

defined minimum speed required for constant speed detection. The algorithm runs as follows:

1) In the first part (labeled with number 1 in Fig. 4), it initializes relative speed jitter vector *d* to value 1 (it is supposed that there is no speed jitter) and counter *k* to zero. The counter holds the number of consecutive speed measurements, which are similar to those from the previous rotation cycle at the same rotational position.
2) In the second part, the algorithm measures the current speed (v) when rotational position changes. In practice, the speed is calculated by measuring the time difference between two changes of rotational position.
3) In the third part, the algorithm calculates the actual (fast-filtered) speed v_a from the current speed and the jitter vector *d*. Note that the actual speed remains the same as the current one before the constant speed v is detected for the first time.
4) The fourth part is dedicated to constant-speed detection. Constant speed is detected when the measured velocities at one full rotation are equal or very similar to the velocities measured one revolution before, as illustrated with an example in Fig. 5. The algorithm first checks if the current measured speed is large enough (for example, $|v| > 150$ min^{-1}) and similar (for example, $|v - v_m(i)| < 5\,\text{min}^{-1}$) to the last measured one at the same rotational position (one revolution before). If this is true, the counter *k* increases; otherwise, it resets to zero. If *k* becomes equal to or larger than *N* (number of rotational positions in one revolution), it means that the speed is (almost) constant. In this case, the algorithm calculates the average speed v_{avg} and the elements of speed jitter vector *d*. When the next current speed is measured, it will be automatically corrected in the third part of the algorithm. Detailed implementation of the proposed algorithm, in the form of MATLAB code, can be found in [21].

III. Experimental Results and Discussion

The proposed algorithm was implemented on a motor-driven valve actuator prototype HD22 by producer Danfoss

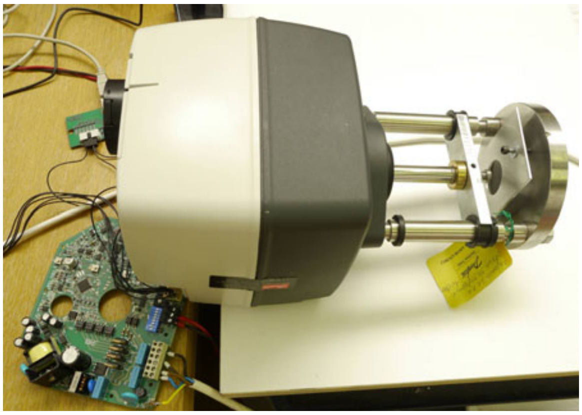

Fig. 6. Valve actuator with prototype electronics.

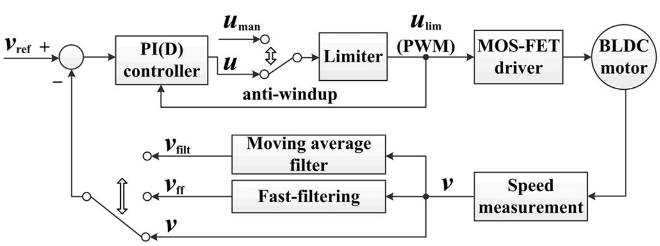

Fig. 7. Schematic of the rotational speed control loop.

Trata, d.o.o. The actuator consists of housing, BLDC motor DR-38312-020 from manufacturer Shinano Kenshi, gearbox, spindle, movable shaft, and two rails for fixing the actuator to the valve, as can be seen in Fig. 6.

The microcontroller is the core of electronics. It is used to acquire, filter, and process input signals and to generate output control signals for the BLDC driver.

The common PI-controller algorithm (with proportional gain $K_p = 1.5$ and integration time $T_i = 1$ s) is implemented in the microcontroller's firmware that generates a digital signal u, which is converted to pulse width modulation (PWM) output signal. The PWM signal is used to control rotational speed of the BLDC motor by adjusting the mean voltage on the stator coils. The schematic of the rotational speed control loop is shown in Fig. 7.

Digital communication with a personal computer (PC) can be carried out by the RS232, RS422, or RS485 serial protocol. The first was used for acquiring the reference speed, the measured speed, the filtered speed, and the PWM signal with sampling time of 1 ms by HyperTerminal application installed on the PC.

In all the experiments, parameter $v_{\min} = 150$ min^{-1}, $e = 5$ min^{-1}, and the number of rotational positions $N = 36$ (one BLDC revolution) have been used in fast-filtering algorithm (see Fig. 4). Similarly, in all the experiments, the moving average filter size was 36 samples. Fig. 8 shows the acquired measurements after the microcontroller's reset.

The experiment was set as follows. The reference speed was changing between ±625 min^{-1} (forward and backward direction), while the controller reference speed ($v_{\rm ref}$), the measured speed ($v_{\rm meas}$), and the proposed fast-filtered ($v_{\rm ff}$) rotational

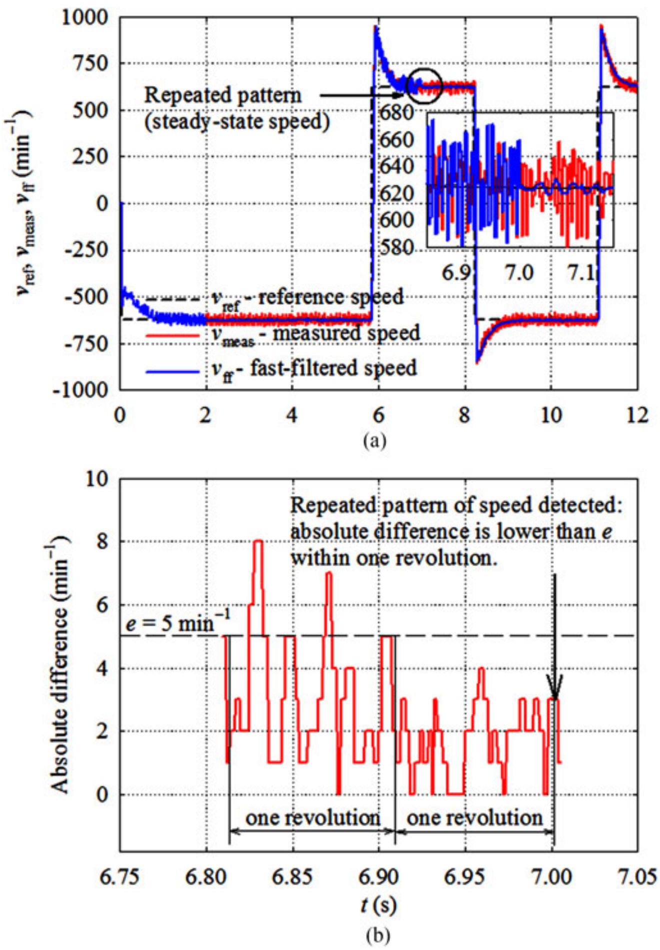

Fig. 8. (a) Reference ($v_{\rm ref}$), measured ($v_{\rm meas}$), and fast-filtered ($v_{\rm ff}$) rotational speed of the BLDC motor after the microcontroller's reset. (b) Absolute difference of measured speed samples between two consecutive full revolutions of BLDC rotor, as a function of time t.

speed of the BLDC motor have been measured. It can be seen in Fig. 8(a) that the fast-filtered speed is equal to the measured speed when the BLDC motor was initially started into forward or backward direction. After a short period of time, the repeated pattern of measured speed was detected, since the absolute measured speed ($v_{\rm meas}$) was higher than $v_{\min} = 150$ min^{-1} and the absolute difference was smaller than $e = 5$ min^{-1} for all measured speed samples within the last revolution compared to those samples obtained one revolution before, as shown in Fig. 8(b).

Therefore, the steady-state speed pattern was detected and the jitter vector was calculated. The measured speed was fast-filtered from this moment on.

Another experiment has been performed, where the measured and the fast-filtered signals have been obtained at different BLDC rotational speeds, as shown in Fig. 9.

As expected, it can be seen that the standard deviation of the measured speed at high rotational speed 1000 min^{-1} ($\sigma = 39.4$ min^{-1}) is approximately two times larger than the measured speed deviation at lower speed 500 min^{-1} ($\sigma = 18.6$ min^{-1}), all according to Fig. 3. On the other hand, standard deviation of the fast-filtered speed is significantly reduced at all three speeds ($\sigma_{\rm ff}$ is between 4.4 min^{-1} and 4.8 min^{-1}). The resulting

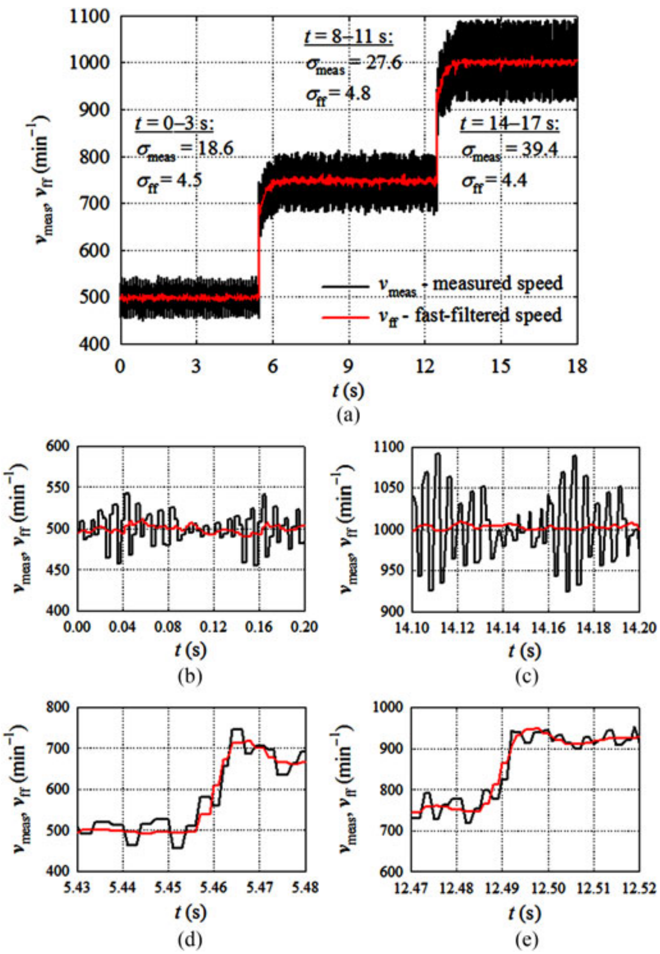

Fig. 9. (a) Measured (v_{meas}) and fast-filtered (v_{ff}) speed as a function of time (t) when the v_{ref} is abruptly increased by increments of 250 min^{-1} from 500 min^{-1} to 1000 min^{-1} with corresponding standard deviations (σ_{meas} and σ_{ff}, respectively) in the steady-state conditions. (b) and (c) Detailed view of v_{meas} and v_{ff} under steady-state operation and (d), (e) during transients.

deviations are mainly governed by the measurement uncertainties and microcontroller resolution, as already mentioned in Section II.

Fig. 9(d) and (e) also shows that v_{ff}, during transients, immediately follows the measured speed v_{meas} without any delay, even though the speed changes are made within 10% of one rotation cycle.

Fig. 10 shows the measured and the fast-filtered speed and their mutual differences (v_{diff}), whereas Table I shows statistics of the measured and fast-filtered speed samples within two revolutions before (cycle 1 and 2) and one revolution after (cycle 3) detecting repeated speed pattern.

The jitter amplitude of fast-filtered speed is approximately seven times lower than the jitter of measured speed if the differences between maximum (max) and minimum (min) values of v_{meas} and v_{ff} are compared.

It can be noticed that standard deviation σ_{ff} is also approximately seven times lower than standard deviation σ_{meas}. These observations indicate that fast-filtered speed is significantly smoother than measured as the jitter is considerably reduced.

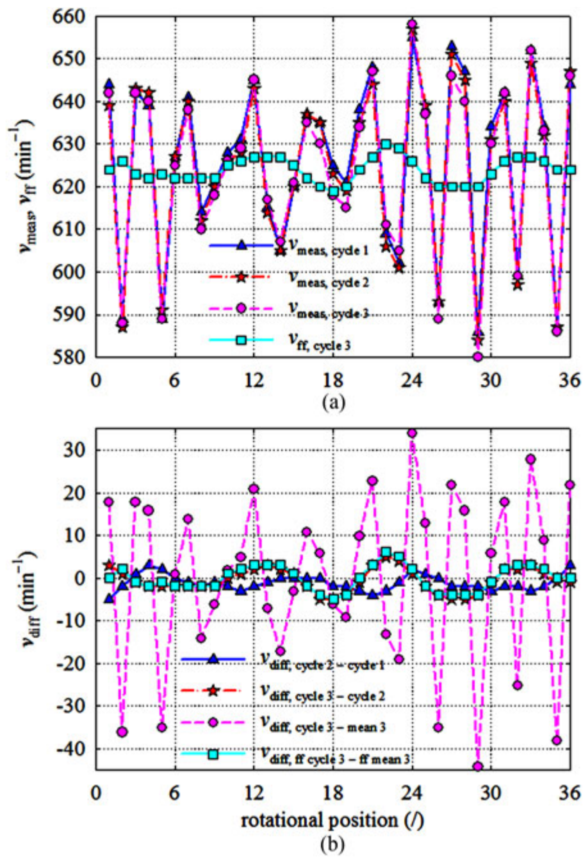

Fig. 10. (a) Measured (v_{meas}) and fast-filtered (v_{ff}) speed. (b) Their mutual differences (v_{diff}) as a function of rotational position within three consecutive rotational cycles.

TABLE I

STATISTICS OF MEASURED AND FAST-FILTERED SPEED SAMPLES (IN REVOLUTIONS PER MINUTE, min^{-1}) WITHIN THREE FULL REVOLUTIONS (CYCLES 1, 2, AND 3) OF THE BLDC MOTOR, INCLUDING THEIR MINIMUM (min) AND MAXIMUM (max) VALUES, DIFFERENCES (diff), MEAN VALUES (mean), AND STANDARD DEVIATIONS (σ)

Cycle/Value	min	max	diff	mean	σ
v_1 cycle 1	586	655	69	625.8	20.7
v_2 cycle 2	584	657	73	624.7	20.7
v_3 cycle 3	580	658	78	624.2	20.8
v_{ff} cycle 3	619	630	11	623.9	2.9
v_{diff} $v_2 - v_1$	−5	3	8	−1.1	1.9
v_{diff} $v_3 - v_2$	−5	5	10	−0.5	2.8
v_{diff} $v_3 - v_{3,\mathrm{mean}}$	−44	34	78	0	20.8
v_{diff} $v_{\mathrm{ff}} - v_{\mathrm{ff,mean}}$	−5	6	11	0	2.9

The next experiment was done when the actuator was started running in backward direction at nominal rotational speed ($v_{\mathrm{ref}} = -625\ \mathrm{min}^{-1}$). As can be seen in Fig. 11, the fast-filtered speed (v_{ff}) instantly follows the measured speed, whereas the filtered speed (v_{filt}) from the moving average filter needs about 70 ms to reach the nominal speed.

The difference between fast-filtered and measured speed $(\varepsilon_{\mathrm{ff}})$ is very small during speed transient, whereas the difference between filtered and measured speed $(\varepsilon_{\mathrm{filt}})$ is relatively large. The latter might have serious impact on stability and response time of the speed control loop if the v_{filt} is used as controller's input instead of the v_{meas}.

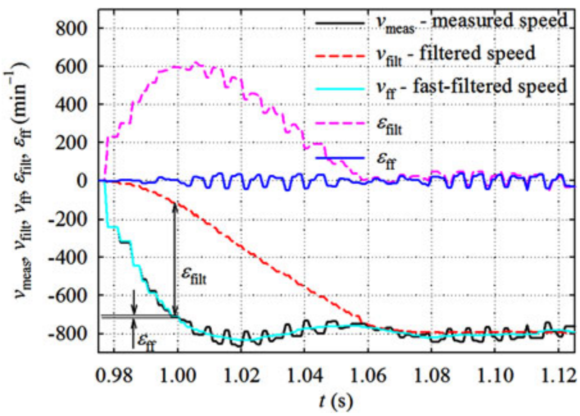

Fig. 11. Measured (v_{meas}), filtered (v_{filt}), and fast-filtered (v_{ff}) rotational speed of the BLDC motor, after running to backward rotational direction, as a function of time *t*. The difference between v_{filt} and v_{meas} and the difference between v_{ff} and v_{meas} is denoted with $\varepsilon_{\mathrm{filt}}$ and $\varepsilon_{\mathrm{ff}}$, respectively.

This is investigated in detail in the last experiment to clearly show the advantages of using the proposed fast-filtering method when compared to moving average filter method. In this experiment, we have measured the forces on the actuator's shaft when hitting a rigid obstacle (e.g., closing the valve). The force on the shaft has been measured with TENSO T1/SK measurement equipment by using a 10-kN load cell. When hitting the obstacle, the force on the shaft increased from 2000 N (coincident with time $t = 9.3$ s in Fig. 12) to 5400 N (coincident with time $t = 9.5$ s in Fig. 12) in 0.2 s. The inner speed controller with dedicated algorithm, which reduces coil currents, should immediately start to reduce the current when detecting such an obstacle (change of PWM signal); otherwise, the obtained forces might damage the shaft or the valve. As can be seen in Fig. 12, the output signal from the PID controller, i.e., the rate of PWM ratio, reacted much faster when using the fast-filtered rotational speed signal than when using the speed signal filtered by the moving-average filter.

Therefore, using the fast-filtered signal resulted in much lower impact forces (more than 20%) and longer expected life span of the equipment.

The presented experimental results showed that the proposed fast-filtering algorithm has the following advantages.

1) The actual speed is calculated accurately without any delay for slow or fast changes of rotational speed (caused by change of stator current or variable load).
2) There is no additional delay in the rotational speed control loop, so the control loop can be more efficient.
3) The measurement jitter is significantly reduced in the steady state and during transitions, which can reduce vibrations and energy consumption in the system.
4) The method is simple for implementation even on low-cost microcontrollers.

IV. Conclusion

The fast-filtering method for rotational speed of the BLDC motor drive is presented in detail and tested on a valve actuator. The main advantage of the presented algorithm is simple implementation in software that can run sufficiently fast even on low-cost microcontrollers. The benefit of using fast-filtered speed is shown in the steady state and during the transients.

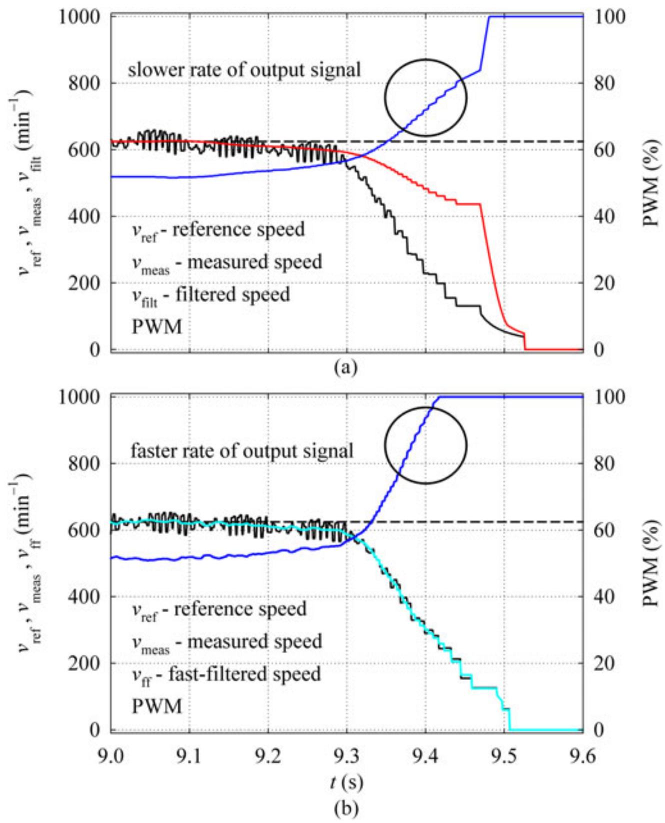

Fig. 12. Reference (v_{ref}), measured (v_{meas}), filtered (v_{filt}), and fast-filtered (v_{ff}) rotational speed of the BLDC motor as a function of time *t* when reaching the end position. (a) Filtered speed and (b) fast-filtered speed is used as PID controller's input. The output signal of PID controller is PWM ratio.

In the steady state, the fast-filtered speed jitter was significantly reduced (by factor 7), whereas the fast-filtered speed instantly follows the actual speed and corrects the speed measurements during the transients. The algorithm also preserves fast reaction time of the rotational speed control loop, which is crucial when the actuator stops instantly. This can happen due to the step change of speed reference or fast variation of load (when the actuator's shaft hits rigid obstacle). The benefit of using the proposed algorithm is expected to become evident after a long-term operation of valve actuator due to reduced stress on mechanical components, and, consequently, reduced wear. A lower consumption of electrical energy, a lower probability of failure during the operation, and longer life span of the device are expected.

However, some improvements of the proposed algorithm are still possible, e.g., detecting repeated jitter pattern at slow change of the actual speed (instead of at constant speed). The influence of the controller excitation on the jitter pattern will be considered as well. The results of these investigations are expected to be revealed in our future publications.

Acknowledgment

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