

Technical Issues on Velocity Measurement for Motion Control

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Abstract—Robust motion control requires accurate velocity information. The authors have proposed “synchronous-measurement method (S method)” that measures the velocity synchronous with alteration of pulse numbers. Accurate velocity measurement is achieved in all speed ranges with this method. The method, however, has several technical issues for application in practice: accuracy often deteriorates with nonideality of interpulse angles in optical encoders; and disturbance observer needs modification to deal with nonregular velocity measurement. This paper proposes some solutions for the issues in S method. Experimental results verify the validity of the solutions.

I. INTRODUCTION

Motion control is a fundamental subject for robots, vehicles and so on. There are a lot of strong demands for a control system with rapid response and high robustness. Acceleration control is indispensable for constructing this kind of system. Hence, many studies on motion control have focused on acceleration control. Disturbance observer[1] is well known as a useful tool to develop an acceleration control system with simple parameter modification.

An accurate and rapid velocity measurement is vital for high-performance acceleration control. The authors have proposed a multi-rate sampling method with a shorter output sampling period to acquire velocity information rapidly[2]. In the study, a quantization error in an optical encoder limited accuracy of velocity measurement. There are many other studies on velocity measurement or estimation by an optical encoder since motion control systems often use optical encoders. Among them, there are two commonly used methods: M method and T method. M method, also called fixed-time method, counts the number of pulses from an optical encoder during a fixed interval of time and calculate velocity by finite-difference derivative. On the other hand, T method, or fixed-position method, calculates velocity as an interpulse angle divided by time between sequential pulses. Relative velocity resolution deteriorates in a low-speed range with M method, while T method achieves high resolution in the range. T method, however, is applicable only to the low-speed range. Ohmae, Matsuda, Kamiyama, and Tachikawa [3] proposed M/T method that works in all speed ranges and has high accuracy in the low-speed range. The method has been applied in many studies since it is effective for practical use. This method is extended to a system termed constant sample-time digital tachometer (CSDT) [4]. It is more easily incorporated into a controller operating with a constant sample time. The authors have proposed

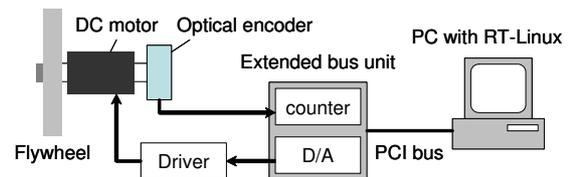


Fig. 1. Overview of experimental setup

S method, a method that measures velocity synchronous with alteration of pulse numbers[5]. Comparing to M/T method, S method has an advantage of acquiring high accuracy in all speed ranges.

Velocity estimation method with Kalman filter improves the velocity standard deviations [6]. Instantaneous speed observer, a discrete-time observer to grasp the velocity between the encoder pulses [7], is also an effective tool for accurate velocity estimation. These methods, however, require plant models.

This study focuses attention on velocity measurement without any plant models. In particular, it deals with technical issues on S method. The authors have proposed a method in T method to modify measurement time based on the relationship between measurement delay and accuracy[8]. The method is also applicable to S method. S method still has an issue that its accuracy often deteriorates with nonideality of the interpulse angle in optical encoders. Another issue for S method is how to modify disturbance observer to deal with nonregular velocity measurement. The modification provides further improvement on performance of acceleration control. This paper shows the technical issues and proposes solutions for them. Experimental results show the validity of the solutions.

Section II is a description of the experimental setup in this study. In Section III, the mechanism of acceleration control is described to show why acceleration control badly requires accurate velocity measurement. Section IV is a review of S method. Some technical solutions for S method are proposed in Section V to solve the problem in the method. The validity of the S method is verified from experimental results in Section VI. Finally, this paper is concluded in Section VII.

II. EXPERIMENTAL SETUP

Fig. 1 shows an overview of the experimental system in this study. It is a 1 DOF flywheel driven by a DC motor. An optical encoder generates pulses in proportion

TABLE I
EXPERIMENTAL PARAMETERS

Sampling period [ms]	1.0
Flywheel MOI [Kg m^2]	0.003
Type of motor	Maxon RE40
Stall torque [mNm]	2500
Torque constant [mNm/A]	60.3
Type of optical encoder	Maxon HEDS 5540
Pulse per revolution [pulse]	500

to rotation of the flywheel. A counter board counts pulses from the optical encoder and a PC reads a pulse number from the board. Here, pulse number denotes the number of pulse signals in every sampling period T_s . T_s is controlled to be constant with the real-time architecture of RT-Linux. The authors examined performance of the proposed method by this system. The parameters in the experimental setup are shown in Table I.

III. ACCELERATION CONTROL

A. Acceleration Control System with Disturbance Observer

This subsection shows a mechanism of acceleration control. This study applies disturbance observer as a basic technique for acceleration control. Fig. 2 is a block diagram of disturbance observer. Here, τ_l is a mechanical load, $\hat{\tau}_{dis}$ is estimated disturbance torque, G_{dis} is a cutoff frequency of disturbance observer, G_v is a cutoff frequency of the low-pass filter (LPF) for measured velocity, I_a is an input current, K_t is a torque constant, θ is a position response of the controlled object, ω is a velocity response, J is inertia, s is a Laplace operator, a bar over a variable denotes a calculated value, a subscript n denotes a nominal value, a superscript ref denotes a reference value, and a superscript cmp denotes a compensation value.

Disturbance torque τ_{dis} is figured out from input and output values as shown in (1).

$$\tau_{dis} = K_{tn}I_a^{ref} - J_n\omega s. \quad (1)$$

Here, the Laplace operator s denotes a derivative calculation. The first term $K_{tn}I_a^{ref}$ in (1) is based on an input current, and the second term $J_n\omega s$ is based on an output response. Disturbance torque is estimated through an LPF to reduce noise.

$$\hat{\tau}_{dis} = \frac{G_{dis}}{s + G_{dis}} \left(K_{tn}I_a^{ref} - \frac{G_v}{s + G_v} J_n\omega s \right) \quad (2)$$

Disturbance observer estimates disturbance on the control system as shown in (2) and compensates it. This disturbance estimation is based on the acceleration ωs derived from the output of the optical encoder. In other words, the control system has acceleration feedback in essence. Consequently the control system with disturbance observer is an acceleration control system.

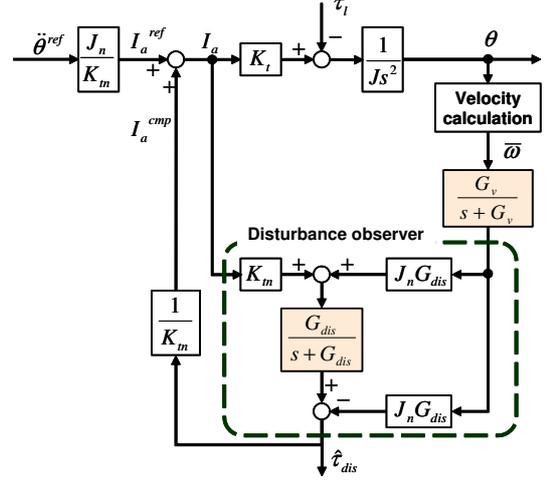


Fig. 2. Disturbance Observer

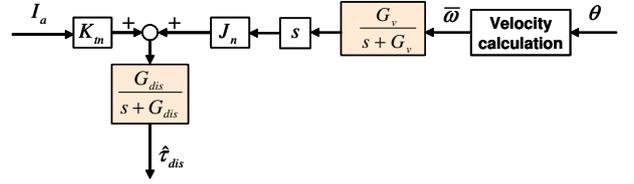


Fig. 3. Equivalent transformation form of disturbance observer

B. Quantization error in acceleration control

This subsection describes the influence of a quantization error on optical encoders to show the importance of velocity measurement accuracy in acceleration control. Fig. 3 shows the equivalent transformation form of disturbance observer. Equation (3) shows $\hat{\tau}_{dis}$ estimated in practice.

$$\hat{\tau}_{dis} = \frac{G_{dis}}{s + G_{dis}} \left(K_{tn}I_a^{ref} - \frac{G_v}{s + G_v} J_n\bar{\omega} s \right) \quad (3)$$

$\bar{\omega}$ includes a certain amount of noise due to the quantization error on the optical encoder. Its accuracy and delay depend on the calculation method. Finite-difference derivative amplifies the noise. Velocity values are derived by finite-difference derivative of position values. At the same time, acceleration values are derived by finite-difference derivative of the velocity values. The noise on the acceleration value becomes extremely large due to twice of finite-difference derivative. Two LPFs are introduced to reduce this noise while they cause a delay on disturbance estimation. The cutoff frequency of the LPFs should be high since this delay may deteriorate the performance of the control system. Accurate velocity measurement is indispensable to heighten the cutoff frequency.

IV. REVIEW OF S METHOD

Principle and procedure of S method are shown in this subsection. This subsection firstly discusses why T method achieves high accuracy. Secondly, S method is introduced.

T method calculates velocity by dividing interpulse angle $\frac{2\pi}{P}$ by interval time T_e . Here, P denotes the pulse number per revolution. Interval time T_e is substituted by multiple of sampling period $m_s T_s$ where m_s denotes the number of sampling periods during the pulse interval. In other point of view, T method averages the velocity synchronous with pulses.

Velocity measurement is more accurate in T method since velocity calculation is synchronous with the timing of encoder pulses. Fig. 4(a) shows an example when averaging calculation is not synchronous. Average velocity is irregular since sum of pulse numbers in n samples fluctuates depending on the calculation timing. Fig. 4(b) shows the other example when averaging calculation is synchronized with pulses. Average velocity is smooth in this case since sum of pulse numbers does not fluctuate. Consequently, the synchronization in T method reduces the noise in calculated velocity. T method is, however, limited in a low-speed range because it is impossible to measure the interval time if pulses occur in every sampling period.

Fig. 5 shows a simulation result of velocity values measured by M method without an LPF. Since M method calculates a velocity value immediately after the pulse number is counted, the velocity value on M method also represents a pulse number in each sampling period. The pulse number is derived by dividing the velocity on M method by unit velocity. Here, unit velocity means the velocity on which exactly one pulse occurs during one sampling period. Interval time between sequential pulses is not measurable in a high speed range since pulses occur in every sampling period. However, the patterns of the waveform in a high-speed range are quite similar to that in a low-speed range. We can presume the patterns in a high speed range as occasional pulses with a certain amount of offset. Hence alteration of pulse numbers, as shown in Fig. 6, should be detected so as to synchronize the velocity calculation with it. We call the alteration ‘‘pulse alteration’’.

The procedures of velocity measurement are shown as follows:

- 1) count the pulse number $m_e(i)$ in each sampling period

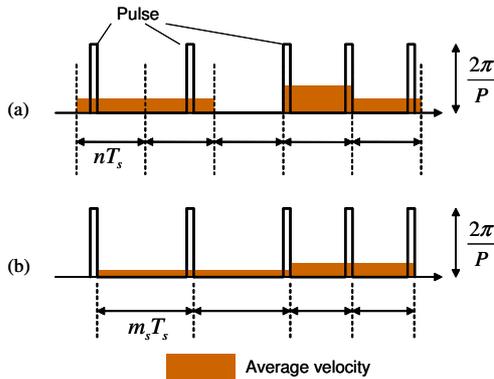


Fig. 4. Pulse pattern in low-speed range

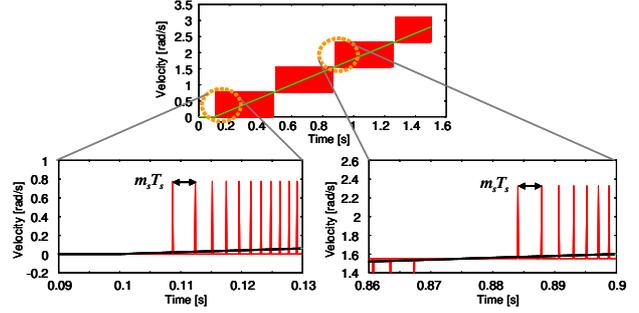


Fig. 5. Velocity measured by M method

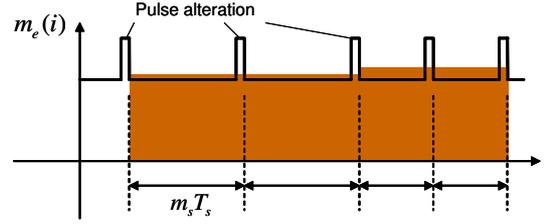


Fig. 6. Pulse pattern in high-speed range

- 2) do not update the velocity value while the pulse numbers are constant
- 3) calculate and update the velocity value if the pulse numbers alter (i.e. if pulse alteration occurs).

The velocity value is derived from (4).

$$\bar{\omega}(i) = \frac{2\pi \sum_{j=0}^{m_s} m_e(i-j)}{m_s P T_s} \quad (4)$$

Here, m_s is the sample number during interval of pulse alteration. The equation is quite similar to M method with averaging. The difference is that averaging calculation of the method is synchronous with pulse alteration. Equations (5), (6) and (7) show that the performance is equivalent to T method. Furthermore, this method works in all speed ranges.

$$Q_V = \frac{2\pi}{m_s(m_s-1)P T_s} \quad (5)$$

$$\frac{Q_V}{V} = \frac{2\pi}{m_s(m_s-1)P T_s V} \quad (6)$$

$$T_m = m_s T_s \quad (7)$$

Here, Q_V stands for absolute velocity resolution and $\frac{Q_V}{V}$ stands for relative velocity resolution. V denotes actual angular velocity. Measurement time T_m is defined as an interval time for updating velocity values.

The method is named ‘‘synchronous-measurement method (S method)’’ since its calculation is synchronous with pulse alteration. High accuracy of T method, which is synchronous with pulses but not with pulse alteration, is expanded to a high-speed range with this method.

The procedures of S method are carried out on a PC with RT-Linux in this study. One of advantages of this method is that it is applicable to a system with a relatively long sampling period since it works in all speed ranges. Note that T method often requires a short sampling period for extension of its measurable speed

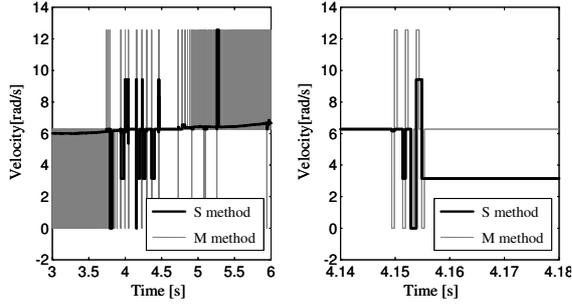


Fig. 7. Error due to disordered pulse alteration

range. Furthermore, this method is also applicable to a system with an auxiliary processor to acquire a shorter sampling period. In this case, accuracy of the velocity measurement improves with the shorter sampling period.

V. TECHNICAL ISSUES

As shown in the previous section, S method achieves high accuracy in all speed ranges. Although it is very effective in theory, there are some considerable problems in practice. This section describes some technical issues for S method.

A. Solution for disordered pulse alteration

Fig. 7 shows an experimental result of velocity values measured without an LPF. The flywheel was rotating around unit velocity then. Constant torque input without any feedback was given so as to eliminate errors due to the control feedback.

Disordered pulse alterations around unit velocity were confirmed from the result of M method. Pulse number around unit velocity irregularly altered from 0 to 2 in the experiment. The disordered pulse alterations also occur at other multiples of unit velocity. The measurement time of S method utterly varies with them. They enlarge the measurement error since accuracy of S method strongly depends on the accuracy of time measurement between two pulse alterations.

A solution for this issue is indispensable for high performance control. Aspects of the disordered pulse alteration were inquired to search the solution. The right side of Fig. 7, a close-up of the left side, implies the aspects as follows:

- positive and negative pulse alteration occurs alternately;
- size of disordered pulse alteration is always 1.

These kind of disordered pulse alteration is not expected from the ideal model of the optical encoder. The alteration could be due to following terms:

- nonuniformity of a scale;
- minute oscillation of a shaft.

The minute oscillation of the shaft, mainly due to the noise in motor input current, is real while nonuniformity of the scale brings unreal error. These two terms are indistinctive and small. Although they are small, they appear as disordered pulse alteration and cause seriously

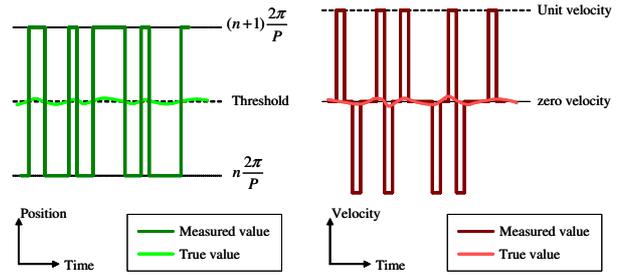


Fig. 8. Mechanism of alternate pulse alteration

large errors. Hence the solution is to somehow ignore these terms without distinguishing them. The following discussion assumes that the disordered pulse alteration occurs because of shaft oscillation. However, the solution also works when nonuniformity of the scale exists.

Fig. 8 shows how the minute oscillation raises alternate pulses when velocity is about zero. If the shaft oscillates around a threshold of position determination, measured position shifts even if the oscillation is small as shown in the left figure. Positive and negative pulse alteration occurs alternately each time the shaft overstrides the threshold as shown in the right figure. In this way, disordered pulse alteration occurs with minute oscillation. Lee and Song[9] have already remarked that an error on velocity measurement occurs when the sign of the velocity flips.

The alternate pulses are often due to quite small oscillation while they appear as extremely large oscillation in measured values. Indeed, average velocity between alternate pulses is 0 because the detected positions of alternate pulses are physically identical as shown in [9]. The solution to solve this issue is to cancel out the pulses when positive and negative pulses occur alternately.

This method is applicable not only around zero velocity but also around multiple of unit velocity. The mechanism of alternate pulse alteration is similar to the mechanism around zero velocity. Alternate pulse alteration should be canceled out in same fashion around multiple of unit velocity.

The procedures of velocity measurement are revised as follows:

- 1) count the pulse number $m_e(i)$ in each sampling period;
- 2) do not update the velocity value while the pulse numbers are constant; and
- 3) calculate and update the velocity value if the pulse alteration occurs
 - if sign of the alteration is the same to the last one,
$$\bar{\omega}(i) = \frac{2\pi \sum_{j=0}^{m_s} m_e(i-j)}{m_s P T_s}$$
 - if sign of the alteration is different to the last one,
$$\bar{\omega}(i) = \frac{2\pi m_e(i-1)}{P T_s} \text{ (multiple of unit velocity).}$$

Note that regular pulse alteration has the same sign except the moment the velocity overstrides the multiple of unit velocity.

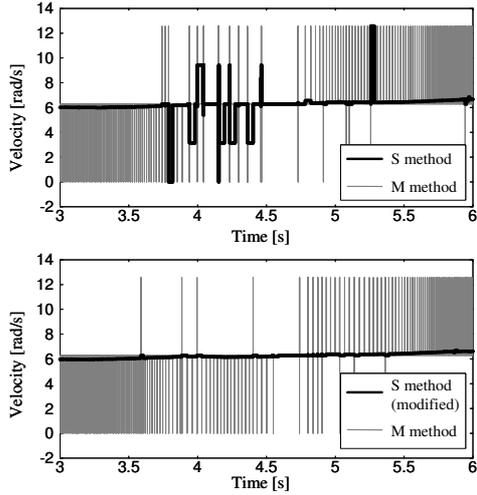


Fig. 9. Velocity measurement with alternate pulse alteration

Fig. 9 compares the measurement results with and without the proposed modification. No LPFs were applied here. It is confirmed that oscillation due to the alternate pulse alteration practically disappeared with the modification.

B. Modification on disturbance observer

Conventional disturbance observer with a constant sampling period T_s provides sufficient control performance by applying S method. Moreover, performance of acceleration control is further improved with modification on disturbance observer. The modification is to synchronize disturbance observer with pulse alteration. Its scheme is described in this subsection.

Firstly, the digitized LPF for velocity measurement should be modified for fluctuant measurement time due to S method. S method calculates velocity at the moment pulse alteration occurs. The calculated velocity stands for an average velocity of m_s samples. Therefore the digitized LPF should be applied for m_s times. For this filtering process, the author calculated an equivalent value from the solution of an analysis of the LPF. Although it is also available to execute the filtering process by repetitive calculation of digitized LPF, it may require much calculated amount when m_s is large. Furthermore, the analytical solution provides much accurate filtering since the digitized LPF is approximation of an analogue LPF.

The analytical solution of normal LPF is given as follows:

$$y = (1 - \exp^{-GT_s})(u - y_0) + y_0. \quad (8)$$

Here, u stands for an input to the LPF and y stands for an output. G is a cutoff frequency of the LPF. y_0 is the initial value on each sampling period. It is assumed that a constant input u is given during the sampling period T_s .

Its response is equal to an LPF in discrete time realized by using invariant impulse response Z-transform[10]. Equation (8) is expanded to (9), an equation of an LPF

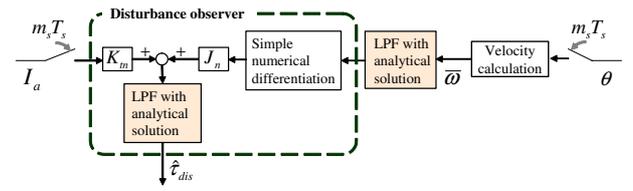


Fig. 10. Disturbance observer modified for fluctuant measurement time

for a fluctuant measurement time.

$$y = (1 - \exp^{-Gm_s T_s})(u - y_0) + y_0. \quad (9)$$

Equation (9) is substituted to the conventional LPF for velocity measurement and that for disturbance observer.

Secondly, the form of disturbance observer should also be modified due to the fluctuant measurement time. Fig. 3, an equivalent transformation form on disturbance observer, is for a constant measurement time. The authors applied and modified the form as shown in Fig. 10. Velocity information $\bar{\omega}$ and input current I_a are given to the disturbance observer synchronous with the pulse alteration. The LPF in disturbance observer is also synchronized with the pulse alteration. In this way the disturbance torque is calculated synchronous with the pulse alteration.

VI. EXPERIMENT

The following results were demonstrated to verify contribution of the technical solutions to control performance. PD control with disturbance observer was applied in the experiment. Control parameters are shown in Table II. Command velocity was shifted from 0 rad/s to 39 rad/s which is quite near a multiple of unit velocity. Command position was derived by integrating command velocity values. Three cases for S method were compared: (a) without any technical solutions, (b) canceling out alternate pulse alteration, (c) canceling out alternate pulse alteration and synchronizing disturbance observer with velocity measurement.

Fig. 11 compares the results in each case. In the figure, multiples of unit velocity are represented by dot lines. Quite large sound noise was generated and velocity deviated from the command value when no technical solutions were applied. The deviation became larger when velocity of the flywheel was around a multiple of unit velocity. After applying the method of canceling out alternate pulse alteration, the velocity deviation became smaller. It is inferred from these two results that disordered pulse alteration caused the large deviation. The velocity deviation further reduced by synchronizing disturbance observer with velocity measurement.

Since it is difficult to distinguish measurement error and deviation of true velocity, the velocity values in the figure are all derived by the same velocity measurement method: M method with LPF of 30.0 rad/s cutoff frequency. Note that the velocity value is only measured for comparison and it is different from the velocity value for control feedback measured by S method. Assuming if measurement error are the same in all cases, the difference of the

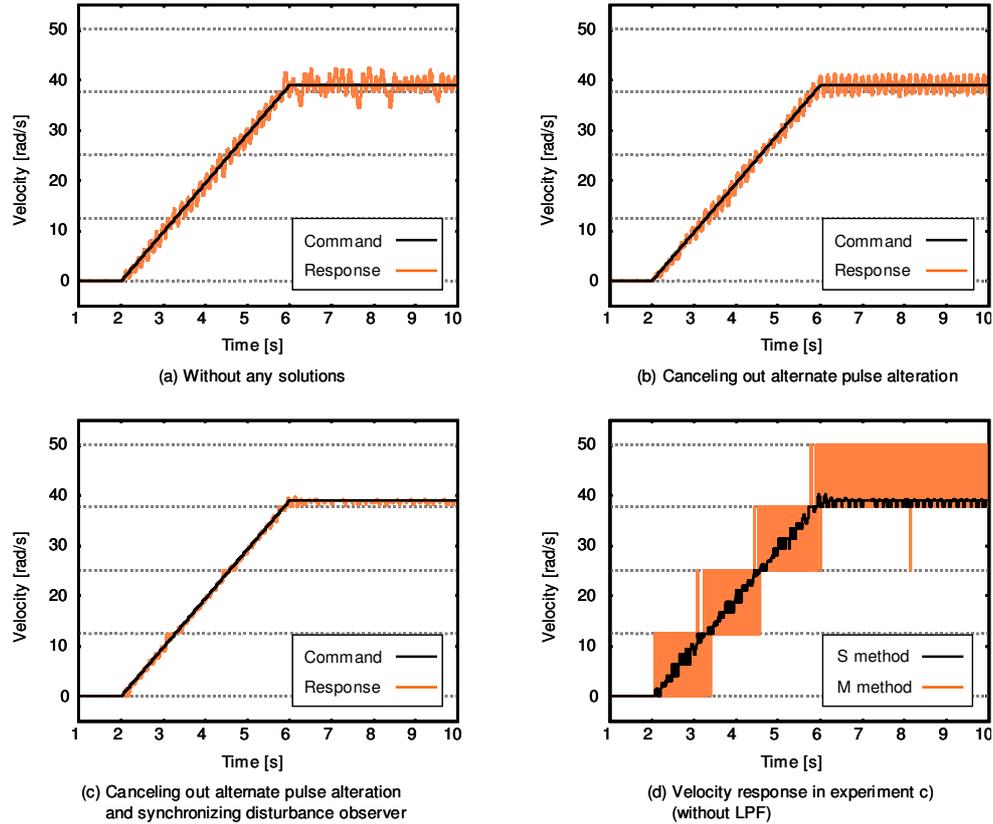


Fig. 11. Experimental results comparing validity of technical solutions

TABLE II
CONTROL PARAMETERS IN EXPERIMENT

K_p	Position gain on PD controller	100.0
K_v	Velocity gain on PD controller	30.0
G_{dis}	Cutoff frequency of DOB	40.0
G_v	Cutoff frequency of LPF on measured velocity	40.0

three cases shows the difference of the deviation from command value. In sum, Fig. 11 only compares control performance of the three cases. Maximum deviation in static state were 4.82, 2.36, 0.52 rad/s in case (a), (b) and (c), respectively. Fig. 11d) shows velocity response without the LPF in case (c). It shows that the velocity value measured by S method had small errors although disordered pulse alteration occurred around multiples of the unit velocity.

VII. CONCLUSION

This paper dealt with S method, a velocity measurement method for motor drives with optical encoders. Although S method acquires high accuracy in all speed ranges, its control performance is limited due to some technical issues. Hence two technical solutions were proposed for acquisition of a high performance motion control. Experimental results verified the validity of each method. Although the method is a fundamental technique for all motion control systems with optical encoders, it is particularly effective for acceleration control systems.

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