

# A Wide-range Velocity Measurement Method for Motion Control

Toshiaki Tsuji, *Member, IEEE*, Takuya Hashimoto, *Student Member, IEEE*, Hiroshi Kobayashi, *Member, IEEE*, Mariko Mizuuchi, and Kouhei Ohnishi, *Fellow, IEEE*

**Abstract**—This paper discusses velocity measurement for motor drives with optical encoders. Although many methods on velocity measurement have been proposed, accurate measurement was not achieved in a high-speed range. This paper therefore proposes “synchronous-measurement method (S method)” that measures the velocity synchronized with alteration of pulse numbers in each sampling period. Accurate velocity measurement is achieved in all speed ranges with this method. Furthermore, other velocity prediction methods are applicable in addition to the method. Simulation and experimental results verify the validity of the proposed method.

**Index Terms**—motion control, mechatronics, velocity measurement, optical encoder, acceleration control, tachometers

## I. INTRODUCTION

Motion control is a fundamental subject for robots, vehicles and so on. Accurate and rapid velocity measurement is vital for high-performance motion control. In order to acquire velocity information rapidly, the authors have proposed a multi-rate sampling method with a shorter output sampling period[1]. In a control system with a short output sampling period, measurement noise on the velocity response limits the ability of the system. There are many studies on velocity measurement or prediction applying an optical encoder since many control systems derive the velocity from the position obtained by an optical encoder[2]-[15]. Among them, there are two commonly used methods: M method and T method. Accuracy deteriorates in a low-speed range with M method, while T method achieves high accuracy. However, T method is applicable only to the low-speed range. Ohmae, Matsuda, Kamiyama and Tachikawa [2] proposed M/T method, which works in all speed ranges and has a 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) [3]. It is more easily incorporated into a controller operating with a constant sample time.

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T. Tsuji is with the Dept. of Electrical and Electronic Systems, Saitama University, 255 Shimo-ohkubo, Sakura-ku, Saitama, Japan. (E-mail:tsuji@ees.saitama-u.ac.jp)

T. Hashimoto and H. Kobayashi are with the Dept. of Mechanical Engineering, Tokyo University of Science, 1-4-6 Kudan-kita, Chiyoda-ku, Tokyo, Japan. (E-mail:tak@kobalab.com, hiroshi@kobalab.com)

M. Mizuuchi and K. Ohnishi are with the Dept. of System Design Engineering, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama, Japan. (E-mail:mariko@sum.sd.keio.ac.jp, ohnishi@sd.keio.ac.jp)

Velocity prediction methods with Kalman filter improve the velocity standard deviations [4], [5]. Instantaneous speed observer [6], [7], a discrete-time observer to grasp the velocity between the encoder pulses, is an effective tool for accurate velocity prediction. However, these methods require plant models. The FIR filter is also an effective solution while it requires large computing time[8].

The velocity measurement method in this study should satisfy the following terms: 1) high accuracy, 2) wide speed range, 3) rapid response, and 4) measurement without any models. Although M/T method almost satisfies the terms, it only has high accuracy in a low speed range. It was believed for a long time that no one measurement algorithm is best for a system with a large dynamic range of speeds, large transients, and an imperfect encoder[9]. However, this paper proposes a velocity measurement method with high accuracy in all speed ranges. The method is implemented to an acceleration control system with disturbance observer(DOB)[16]. Since disturbance observer strongly requires accurate velocity measurement, the control performance is enhanced with the method. Although the design of LPFs and knowledge of motor parameters are also important issues for acceleration control, previous studies have discussed them in detail[17], [18]. Hence this study concentrates on a velocity measurement method.

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 requires accurate velocity measurement. Section IV shows conventional methods of velocity measurement. Their resolution and measurement time are also introduced. The proposed method is described in Section V. The validity of the proposed method is verified by simulation and experiment in Section VI and Section VII, respectively. Finally, this paper is concluded in Section VIII.

## II. EXPERIMENTAL SETUP

Fig. 1 shows an overview of the experimental system in this study. The mechanical part of the system is a 1 DOF flywheel driven by a DC motor. An optical encoder generates pulses in proportion to arm displacement. A counter board counts pulses from the optical encoder and a PC reads a pulse number from the board. The pulse number denotes the number of pulses on every sampling period  $T_s$ . In this study, the pulse number is treated as a negative value when the shaft rotates in the negative direction although the real pulse number is an absolute value.  $T_s$  is controlled to be constant with the real-time architecture of RT-Linux.

The parameters on the setup are shown in Table I.

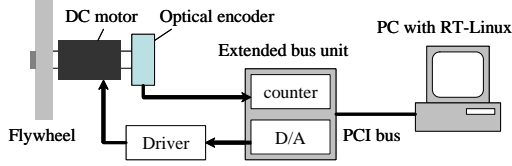


Fig. 1. Overview of experimental setup

TABLE I  
EXPERIMENTAL PARAMETERS

Sampling period	[ms]	1.0
Flywheel MOI	[Kgm <sup>2</sup> ]	0.003
Type of motor		Maxon RE40
Stall torque	[mNm]	2500
Torque constant	[mNm/A]	60.3
Type of optical encoder		Maxon HEDS 5540
Resolution	[PPR]	500
Type of motor driver		Servotechno PMA4
Switching frequency	[kHz]	40
Time constant	[ms]	0.1

### III. ACCELERATION CONTROL

#### A. Acceleration control with disturbance observer

This subsection describes a mechanism of acceleration control. This study applies disturbance observer as basic technique for acceleration control. Fig. 2(a) is the block diagram of disturbance observer. Here,  $\tau_l$  is a mechanical load,  $\hat{\tau}_{dis}$  is estimated disturbance torque,  $G_{dis}$  and  $G_v$  are cut-off frequencies of disturbance observer and the low-pass filter (LPF) for velocity measurement, respectively.  $I_a$  is input current,  $K_t$  is a torque constant,  $\theta$ ,  $\omega$  and  $J$  are the position response, the velocity response and the inertia of the controlled object, respectively.  $s$  denotes a Laplace operator, a bar over a variable denotes a calculated value, a subscript  $n$  denotes a nominal value, superscripts  $ref$  and  $cmp$  denote a reference value and a compensation value, respectively.

In order to reduce noise amplified by the calculation, disturbance torque is estimated through the LPF as shown in (1).

$$\hat{\tau}_{dis} = \frac{G_{dis}}{s + G_{dis}} \left( K_{tn} I_a^{ref} - \frac{G_v}{s + G_v} J_n \omega s \right) \quad (1)$$

Disturbance observer estimates disturbance on the control system and compensates it. This disturbance estimation is based on the acceleration  $\omega s$  derived from the output of the optical encoder. In other words, the control system has acceleration feedback in essence.

#### 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. 2(b) shows the equivalent transformation form of disturbance observer. Equation (2) shows  $\hat{\tau}_{dis}$  estimated in practice.

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

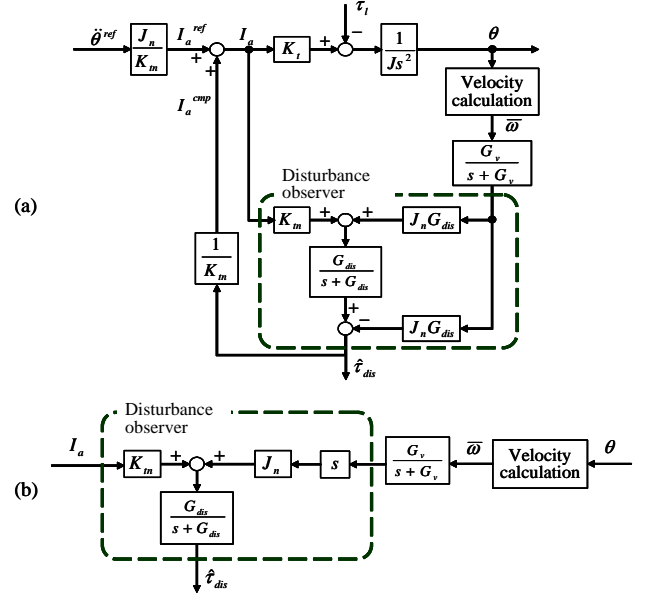


Fig. 2. Disturbance observer

$\bar{\omega}$  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 is the simplest method while it amplifies the noise. LPFs are effective for reducing the noise while they cause a delay on disturbance estimation. The cutoff frequencies of the LPFs should be high since this delay may deteriorate the performance of the control system. Hence accurate velocity measurement is indispensable to heighten the cutoff frequency.

### IV. RELATED RESEARCH

This section reviews velocity measurement methods in previous studies and compares their performance.

#### A. M method

M method is the most widely used method to measure the velocity from encoder pulses. The principle is shown in Fig. 3(a).  $m_e$  is the number of pulses in a fixed sampling period  $T_s$ .  $m_e$  is utilized for velocity calculation by finite-difference derivative.

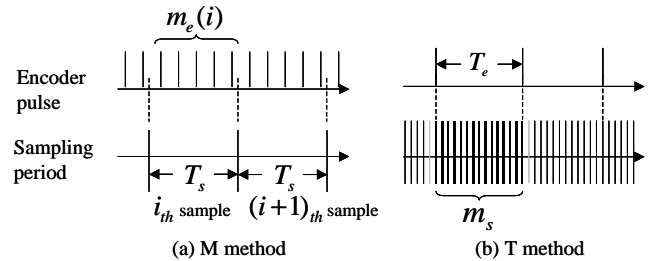


Fig. 3. Principle of M method and T method

The measured velocity  $\bar{\omega}$  is figured out by (3). Following equations show velocity resolution and measurement time.

$$\bar{\omega} = \frac{2\pi m_e}{PT_s} \quad (3)$$

$$Q_V = \frac{2\pi}{PT_s} \quad (4)$$

$$T_m = T_s \quad (5)$$

where  $P$  denotes the encoder pulse number per rotation.  $Q_V$  stands for the absolute velocity resolution.  $V$  denotes the actual angular velocity. Measurement time  $T_m$  is equal to the sampling period  $T_s$ . Here, a sampling period stands for interval time to count a pulse number periodically. On the other hand, measurement time stands for interval time to calculate the velocity based on the pulse number counted in single or multiple sampling periods.

As shown in (4), velocity resolution becomes larger as the sampling period becomes shorter. The easiest way to improve accuracy is averaging. The average of  $n$  sampling periods is acquired by (6). The absolute resolution and measurement time are shown in (7) and (8). These equations show that averaging improves the accuracy to the  $n$ th part of the resolution while measurement time becomes  $n$  times longer.

$$\bar{\omega}(i) = \frac{2\pi \sum_{j=0}^{n-1} m_e(i-j)}{nPT_s} \quad (6)$$

$$Q_V = \frac{2\pi}{nPT_s} \quad (7)$$

$$T_m = nT_s \quad (8)$$

### B. T method

T method measures the velocity by dividing the interpulse angle by the pulse interval time as shown in Fig. 3(b). In the figure, encoder pulses come successively with  $T_e$  intervals. Assuming that interpulse angle of the optical encoder is completely accurate, accuracy of this method only depends on the measurement of interval time  $T_e$ .  $T_e$  is substituted by  $T_m = m_s T_s$ . Here,  $m_s$  is the number of sampling periods during pulse interval.  $T_m$ , an approximate value of  $T_e$ , contains an error less than  $T_s$  since  $m_s$  is an integer.

The velocity is calculated by (9). Equations (10) and (11) show the performance.

$$\bar{\omega} = \frac{2\pi}{m_s PT_s} \quad (9)$$

$$Q_V = \frac{2\pi}{m_s(m_s-1)PT_s} \quad (10)$$

$$T_m = m_s T_s \quad (11)$$

$$m_s = \frac{2\pi}{P\omega T_s} \quad (12)$$

It is shown from the equations that T method reduces the maximum error inversely proportional to  $m_s(m_s-1)$  while measurement time becomes  $m_s$  times longer. It is obvious that accuracy improves much more than averaging. However, there are several problems on this method. Firstly, the pulse interval is not measurable if it is shorter than the sampling period  $T_s$ . In other words, this method is only applicable to a low-speed range. Secondly, the measurement time  $T_m$  is fluctuant and

it depends on the velocity. Therefore the measurement delay may become large.  $m_s$  is an integer in practice while (12) generally derives a fractional value.  $m_s$  is either an integer with fractions omitted or an integer with fractions counted.  $m_s$  alters between the two integers stochastically.

### C. M/T method

M/T method is an effective measurement method that combines M method and T method. It improves the measurement accuracy in a low-speed range and furthermore, it works in all speed ranges. Its performance is in proportion to T method in the low-speed range and M method with averaging in the high-speed range. Performance of the method is shown as follows:

$$\bar{\omega}(i) = \frac{2\pi \sum_{j=0}^{m_s-1} m_e(i-j)}{m_s PT_s} \quad (13)$$

$$Q_V = \min\left(\frac{2\pi |\sum_{j=0}^{m_s-1} m_e(i-j)|}{m_s(m_s-1)PT_s}, \frac{2\pi}{m_c PT_s}\right) \quad (14)$$

$$T_m = m_s T_s \quad (15)$$

$$m_s = \frac{2\pi}{P\omega T_c} \left( \left\lceil \frac{P\omega T_c}{2\pi} \right\rceil + 1 \right), T_c = m_c T_s \quad (16)$$

where  $T_c$  is a prescribed minimum measurement time,  $|\cdot|$  represents the absolute value of the argument, and  $\lceil \cdot \rceil$  represents the largest integer number that is less than, or equal to, the argument.

## V. PROPOSED METHOD

### A. Principle of proposed method

The object of this study is to acquire high accuracy in all speed ranges. Firstly, this subsection discusses why T method achieves high accuracy. Secondly, a novel measurement method is proposed. It achieves the accuracy of T method in all speed ranges.

T method has high accuracy since velocity calculation is synchronized with the timing of encoder pulses. Fig. 4(a) shows an example when averaging calculation is not synchronized. The 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 the timing of the pulses. The 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 the calculated velocity. However, T method is 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 the unit velocity  $\omega_u = \frac{2\pi}{PT_s}$ . Here, the unit velocity is 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.

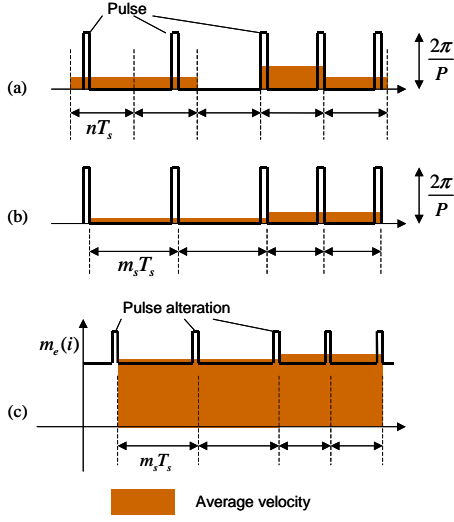


Fig. 4. Pulse pattern in low and high-speed range

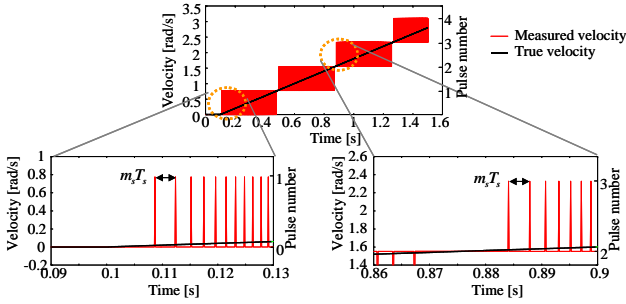


Fig. 5. Pulse pattern in simulation

However, the patterns of the velocity response 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. 4(c), should be detected so as to synchronize the velocity calculation with it. The alteration is called “pulse alteration”.

The procedures of velocity measurement are shown 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 number alters (i.e. if pulse alteration occurs).

The velocity value is derived from (17).

$$\bar{\omega}(i) = \frac{2\pi \sum_{j=0}^{m_s-1} m_e(i-j)}{m_s P T_s} \quad (17)$$

The equation is quite similar to M method with averaging and the same to M/T method. The difference is that averaging calculation of the proposed method is synchronized with pulse alteration. Equations (18) and (19) show that the performance is equivalent to T method. Furthermore, this method works in

all speed ranges.

$$Q_V = \frac{2\pi}{m_s(m_s-1)PT_s} \quad (18)$$

$$T_m = m_s T_s \quad (19)$$

$$m_s = \frac{2\pi}{P|\omega - \omega_u[\frac{\omega}{\omega_u} + \frac{1}{2}]|T_s} \quad (20)$$

The proposed 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.

### B. Performance of velocity measurement methods

Fig. 6 compares the measurement time on each method. M method acquires the velocity information in every sampling period. Averaging makes the measurement time longer while it improves the accuracy. The measurement time depends on pulse interval in M/T method. The measurement time is long in the low-speed range while it is almost constant in the high-speed range. Measurement time is fluctuant in S method. It becomes long when the velocity is around multiples of the unit velocity since pulse alteration does not often occur. This deteriorates the control performance when adverse effect of delay is larger than that of the quantization error. Combination with velocity prediction methods like Kalman filter or instantaneous speed observer is one of the solutions while the adverse effect still remains due to the accumulation of error. Therefore a method to modify the measurement time[19] is applied. In this method, the velocity is calculated compulsory if measurement time exceeds a threshold. Maximum measurement time is 10 ms in this study. Other methods in this paper also have the same maximum measurement time.

Fig. 7 compares the measurement resolution on each method. M/T method is more accurate than T method in a velocity range from 3.2 rad/s to 12.5 rad/s since its measurement time is modified to be longer than  $T_c = 0.004$  while the measurement time of T method is shorter in the range. Meanwhile, M/T method has large  $Q_v$ , the absolute velocity resolution, in a high-speed range. A comparison between (14) and (18) infers that resolution of M/T method and S method with the same measurement time are equal when  $|\sum_{j=0}^{m_s-1} m_e(i-j)| = 1$ . Otherwise, the resolution of M/T method degrades since  $|\sum_{j=0}^{m_s-1} m_e(i-j)| > 1$ . Hence, S

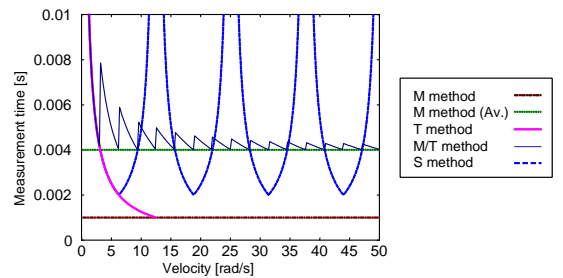


Fig. 6. Measurement time on each method

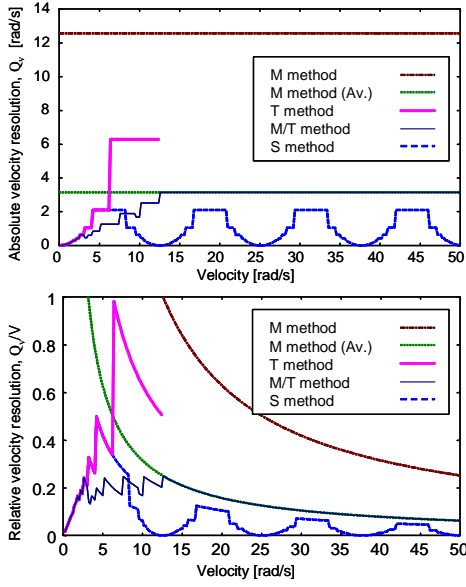


Fig. 7. Measurement resolution on each method

method has an advantage over M/T method when  $|\omega| > \frac{2\pi}{PT_c}$ , the velocity  $|\sum_{j=0}^{m_s-1} m_e(i-j)| > 1$  is true.

Accuracy of velocity measurement is often compared by  $Q_v/V$ , the relative velocity resolution. Although M/T method has large  $Q_v$  in a high-speed range,  $Q_v/V$  is kept small in all speed ranges. In this point of view, M/T method is effective for many motion control systems. However, acceleration control regularly requires accuracy in all speed ranges. The accuracy in the acceleration dimension is in proportion to  $Q_v$ , the absolute velocity resolution. Hence small  $Q_v$  is indispensable for acceleration control. The result shows that S method achieves small  $Q_v$  in all speed ranges.

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 range. Furthermore, this method is also applicable to a system with a high-end processor or an auxiliary processor to acquire a shorter sampling period. In this case, accuracy of the velocity measurement improves with the shorter sampling period. However, it should be noted that S method needs additional processing: detection of pulse alteration and modification of measurement time. It infers that S method has a limit for shortening the sampling period.

### C. Comparison to M/T method with additional timer unit

The previous subsection compared M/T method and S method with the same sampling time. However, in contrast to S method, M/T method may have much higher time measurement resolution when the processor has an additional timer unit. In fact, many DSPs have a timer unit. Fig. 8 compares the ideal measurement performance in such a case.  $Q_v T_m$ , the velocity resolution times measurement time, is compared as a parameter to show the control performance since both  $Q_v$  and  $T_m$  fluctuate depending on the velocity. Note that

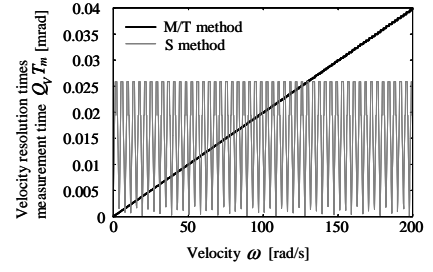


Fig. 8. Performance comparison of M/T method and S method

the velocity resolution and measurement time are in trade-off relationship and the product of them is one of the indices to show the measurement performance. A measurement system with an 81000 PPR optical encoder is assumed. Sampling time  $T_s$  of M/T method is 200 ns and minimum measurement time  $T_c$  is 20  $\mu$ s. Sampling time  $T_s$  of S method is 20  $\mu$ s, the same to  $T_c$  in M/T method. The result shows that M/T method has an advantage in the low-speed range while S method has an advantage in the speed range larger than approximately 130 rad/s. In the middle-speed range, superiority of M/T method and S method alternates. The result shows that S method only has advantage in the high-speed range of a high resolution encoder in case of a processor with an additional timer unit.

### D. Solution for disordered pulse alteration

Fig. 9(a) shows an experimental result of velocity values measured without an LPF. The flywheel was rotating around the unit velocity. Constant torque input without any feedback was given so as to eliminate errors due to the control feedback.

Disordered pulse alterations around the unit velocity were confirmed from the result of M method. The pulse number around the unit velocity irregularly altered from 0 to 2 in the experiment. The disordered pulse alterations also occur at other multiples of the unit velocity. The measurement time of S method utterly varies with them.

Aspects of the disordered pulse alteration were inquired to search the solution. After reviewing the data in Fig. 9(a), the following aspects were discovered:

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

This 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; and small oscillation of a shaft. The small oscillation of the shaft, mainly due to the noise in motor input current, is real while nonuniformity of the scale brings irreal error. These two terms are indistinctive and small. Although they are small, they appear as disordered pulse alteration and cause seriously 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. 10 shows how the small oscillation raises alternate pulses when the velocity is about zero. If the shaft oscillates

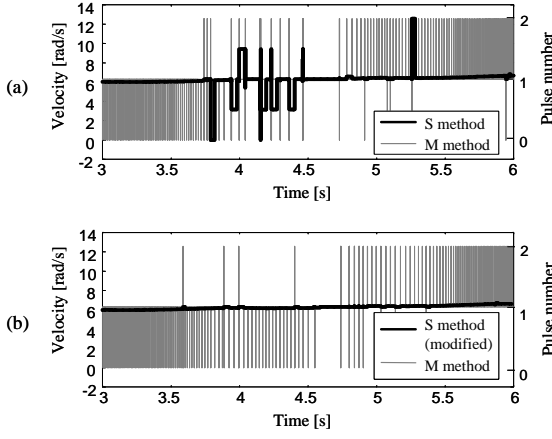


Fig. 9. Velocity measurement with alternate pulse alteration

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 small oscillation. It should be noted that the average velocity between alternate pulses is 0 because the detected positions of alternate pulses are physically identical[20]. 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 the zero velocity but also around multiple of the unit velocity. The mechanism of alternate pulse alteration is similar to the mechanism around the zero velocity. Hence, alternate pulse alteration should be canceled out in the same fashion.

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,
 
$$\bar{\omega}(i) = \frac{2\pi \sum_{j=0}^{m_s-1} m_e(i-j)}{m_s P T_s}$$
  - if sign of the alteration is different to the last one,
 
$$\bar{\omega}(i) = \frac{2\pi m_e(i-1)}{P T_s} \text{ (multiple of the unit velocity).}$$

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

The procedure has conditional branching while (21) derives the same velocity value without any conditional branching.

$$\bar{\omega}(i) = \frac{2\pi(\frac{1}{2}m_e(i-m_s) + \sum_{j=1}^{m_s-1} m_e(i-j) + \frac{1}{2}m_e(i))}{P m_s T_s} \quad (21)$$

Fig. 9(b) shows the measurement result with the proposed modification. It is confirmed that oscillation due to the alternate pulse alteration practically disappeared.

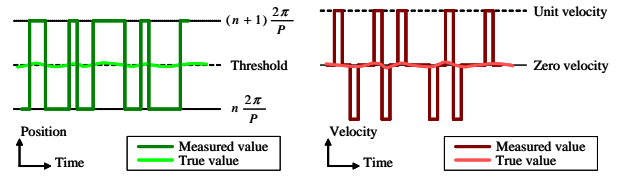


Fig. 10. Mechanism of alternate pulse alteration

### E. Modification in disturbance observer

Conventional disturbance observer with a constant sampling period  $T_s$  provides sufficient control performance by applying S method. Moreover, the performance of acceleration control is further improved with modification in disturbance observer. The modification is to synchronize calculation of 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. The modified filtering calculation is based on an analytical solution of an LPF. The calculation is given by (22).

$$y = (1 - \exp^{-G m_s T_s})(u - y_0) + y_0. \quad (22)$$

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[21]. Equation (22) is substituted to the conventional LPF for velocity measurement and that for disturbance observer.

Although it is also available to execute the filtering process by repetitive calculation of digitized LPF, it may require much calculation amount when  $m_s$  is large. Furthermore, the analytical solution provides much accurate filtering since the digitized LPF is approximation of an analogue LPF. Although the dynamic properties of the velocity signal may vary with S method, the LPF for fluctuant time has an effect to reduce the modulation as long as measurement time is shorter than time constant of the LPF.

Secondly, the form of disturbance observer should also be modified due to the fluctuant measurement time. Fig. 2(b) is for a constant measurement time. The authors applied and modified the form as shown in Fig. 11. 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. SIMULATION RESULT

Simulations were executed to compare the accuracy of velocity measurement methods in the completely same conditions.



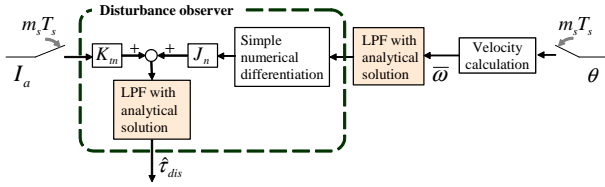


Fig. 11. Disturbance observer modified for fluctuant measurement time

Parameters were equal to those of the experiment. In each simulation, no control input was given while the same sequence of external force input was applied. The reason to give no control input is to compare only accuracy of measurement.

Fig. 12 shows the velocity measurement results of M method, M/T method and S method, respectively. M method was averaged and the sample number for averaging was 4. The velocity resolution is constant and large in M method. On the other hand, M/T method achieves high resolution in the low-speed range while the resolution is still low in the high-speed range. The result shows that high resolution in all speed ranges was achieved by S method. As described in Section V-B, maximum deviation of the velocity response depends on the velocity. The amount of the deviation corresponds to the theoretical result in Fig. 7.

## VII. EXPERIMENT

### A. High-gain feedback control with S method

The authors applied PD control with disturbance observer to the experimental system. The command velocity was kept constant after it was raised from 0 rad/s to 40 rad/s in 5 seconds. Virtual disturbance of 0.2 Nm was given for 0.5 second when 7 seconds passed from the beginning of the

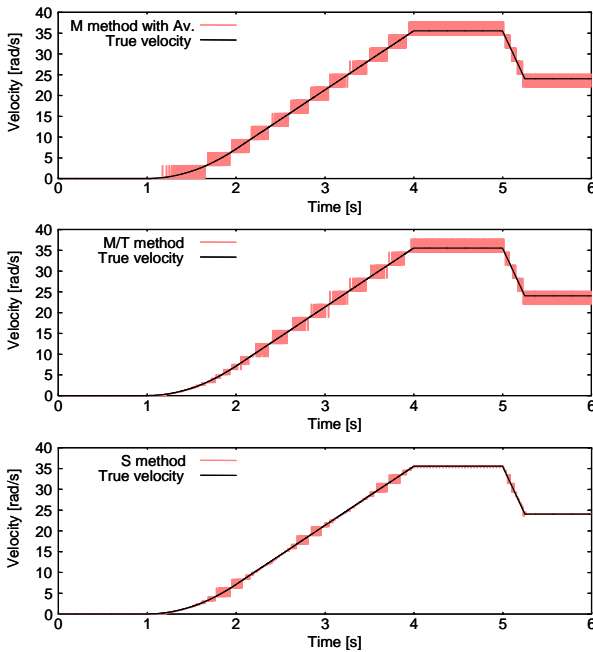


Fig. 12. Velocity measurement on each method

experiment. The disturbance was given by adding a current input to the control system. Fig. 13 shows the results. Here,  $k_v$  denotes a derivative gain of the PD controller. In order to show a fair comparison, all of the response values in the figure are derived by M method with an LPF. In other words, the values in the figure are just to show and they are different from the velocity values for control feedback.  $G_v$ ,  $G_{dis}$  and  $k_v$  were changed in each experiment while  $k_p$ , a proportional gain, was 20.0 in all cases. The experimental results compare the best performance of each method while only  $k_p$  is intentionally set low so that the proportional feedback does not affect the velocity tracking performance.

The motor made a sound noise when  $G_v$  and  $G_{dis}$  were larger than 20.0 rad/s in M method. A large oscillation is confirmed when  $G_v = G_{dis} = 50.0$  [rad/s] in M method. On the other hand, acceleration control with  $G_v = G_{dis} = 50.0$  [rad/s] was achieved without a sound noise in S method. The result shows that the performance of acceleration control improved with S method. Furthermore,  $k_v$  could be heightened more without any destabilization due to the high resolution of the measured velocity. It is confirmed from the result that an error on velocity control reduced with higher  $k_v$ .

### B. Verification of technical solutions

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

Fig. 14 compares the results in each case. In the figure, dot lines represent multiples of the unit velocity. A large sound noise was generated and the velocity deviated from the command value when no technical solution was applied.

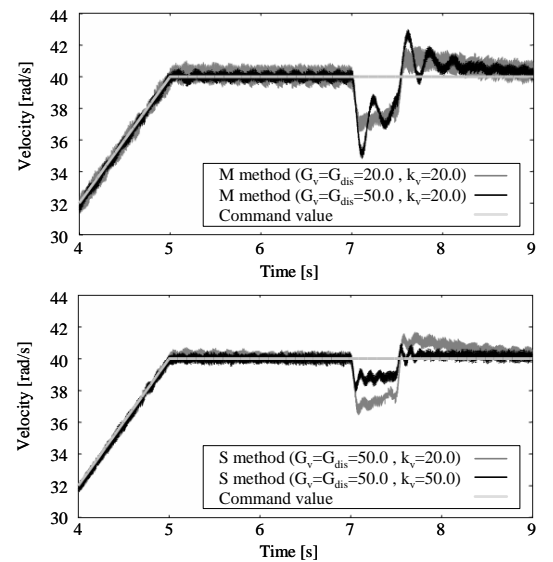


Fig. 13. Experimental result of PD control with disturbance observer

TABLE II  
CONTROL PARAMETERS IN EXPERIMENT

$k_p$	Proportional gain	100.0
$k_v$	Derivative gain	30.0
$G_{dis}$	Cutoff Freq. of DOB	40.0
$G_v$	Cutoff Freq. of LPF for velocity	40.0

The deviation became larger when the velocity of the flywheel was around a multiple of the 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 decreased by synchronizing disturbance observer with velocity measurement.

The velocity values in the figure are all derived by M method with LPF of a 30.0 rad/s cutoff frequency. Maximum deviation in static state were 4.82, 2.36, and 0.52 rad/s in case (a), (b) and (c), respectively. Fig. 14(d) shows velocity response without the LPF in case (c). It shows that the velocity value measured by S method had smaller errors although disordered pulse alteration occurred around multiples of the unit velocity.

### C. Quantitative assessment of control performance

This subsection describes a quantitative assessment of the proposed method. The experimental setup was the same while the sampling time was shortened to 20  $\mu$ s, and the pulse signal was multiplied by four. The command velocity was given by a sine curve  $\omega_{cmd} = \frac{200}{\pi}(1 - \cos(\frac{\pi}{10}t))$  so that the velocity command includes both zero speed and high speed. At the same time, the integration value of the command velocity was given as the command position. Some cases with different velocity feedback gains  $k_v$  are compared by root mean square(RMS) of the velocity tracking error. Other control parameters were modified along with  $k_v$ :  $k_p = (\frac{1}{2}k_v)^2$  and  $G_{dis} = G_v = 2k_v$ . Fig. 15 compares the results. Each plot shows the RMS value of the experiment for 10 seconds.

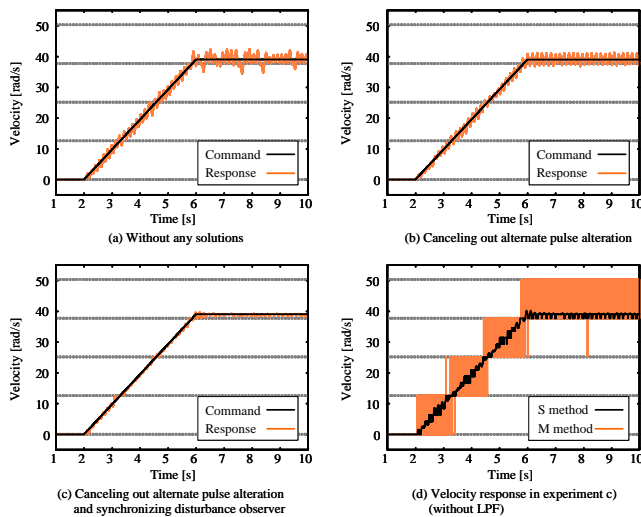


Fig. 14. Experimental results comparing validity of technical solutions

The cross marks show the results of the velocity and the disturbance feedback measured by M/T method. On the other hand, the square marks show the results by S method. The figure shows that the two methods have almost the same control performance with a low feedback gain while the performance of M/T method degrades with a higher feedback gain. The minimum RMS value of S method is smaller since S method did not generate oscillation with a higher feedback gain. In all cases, RMS values were derived based on the velocity response measured by S method with a 200 rad/s LPF. The same velocity measurement was used for error assessment since noise produced by different measurement may affect the assessment.

## VIII. CONCLUSION

This paper proposed S method, a novel method of velocity measurement for motor drives with optical encoders. In S method, the velocity measurement is synchronized with alteration of pulse numbers. High accuracy of T method is acquired in all speed ranges due to this synchronization. Furthermore, other estimation methods are applicable in addition to S method since it does not require any model of a control object. Simulation and experimental results verified the validity of the method. Although the method is a fundamental technique for all motion control systems with optical encoders, it is particularly effective for acceleration control systems. Our future work is to implement the algorithm to a control system with FPGA and verify the control performance under an extremely-short sampling period.

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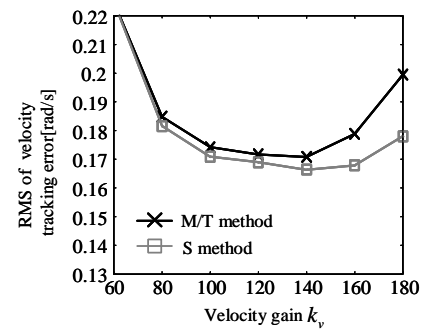


Fig. 15. Comparison of RMS of velocity tracking error



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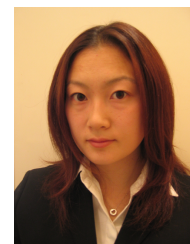
**Toshiaki Tsuji** (S'05, M'06) received a B.E.(2001), M.E. (2003), and Ph. D (2006) degrees from Keio university. He was a research associate in Department of Mechanical Engineering, Tokyo University of Science from 2006 to 2007. He is currently with Department of Electrical and Electronic Systems, Saitama University. His research interests include motion control, decentralized control and control of biped robots. He received the FANUC FA and Robot Foundation Original Paper Award in 2007 and 2008.



**Takuya Hashimoto** (S'06) received B.E. and M.E. degrees from Tokyo University of Science in 2004 and 2006, respectively. He is currently a Ph.D. student in Dept. of Mechanical Engineering, Graduate School of Engineering, Tokyo University of Science. He is interested in human-robot interaction, robotic system and welfare engineering.



**Hiroshi Kobayashi** (S'92, M'95) received B.S., M.S. and Ph.D degrees in mechanical engineering at Science University of Tokyo, Japan. He was a Post-doctoral Researcher at AI Lab., University of Zurich, Switzerland from 1996. He is at Science University of Tokyo since 1998, and has been a Professor since 2008. His research interests include human-robot communication and to develop a human support apparatus, especially no-nonsense practical system. He is a member of IEEE, JSME, RSJ and HIS.



**Mariko Mizouchi** received her B.E. and M.E. degrees from Keio University in 2004 and 2006, respectively. Her research interests include motion control, multirate control and bilateral control. She received the FANUC FA and Robot Foundation Original Paper Award in 2008



**Kouhei Ohnishi** (S'78, M'80, SM'00, F'01) received B.E. (1975), M.E. (1977), and Ph.D (1980) degrees, all in electrical engineering from University of Tokyo. Since 1980, he has been with Keio University. His research interests include robotics, motion control and haptics. He received the EPE-PEMC Council Award and the Dr.-Ing Eugene Mittelmann Achievement Award in 2004.