A New Velocity Estimator for Motion Control Systems

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Abstract: -In motion control systems, differentiated position signal is commonly used to estimate velocity, and used for speed feedback control. Position quantization error can result in the amount of noise jamming, which affects system control precision and stability. In this paper, a reliable velocity estimator is proposed to estimate velocity from the measured position. This estimator consists of two parts: a traditional moving-average filter for data smoothing process, and a closed-loop PID controller to compensate the phase lag caused by smoothing process. Simulation and experimental results demonstrate that the quantization error in the velocity feedback signal can be reduced dramatically when the proposed estimator is used for velocity estimation, the estimated signal has fewer phase lag than the traditional velocity estimation method, and the current noise of motor is reduced as well.

Key-words: -Velocity Estimator, Motion Control, PID

1 Introduction

Precise motion control is necessary in robotics and CNC machines. The main objective is to guarantee accurate tracking of position and velocity profiles with large disturbance. Therefore, the general motion control is divided into 3 control loops: velocity loop, position loop and current loop. The current loop is used for controlling the output torque, the position loop and the velocity loop are used to control a mechanical actuator's position and velocity. In order to make a motor control system with a large bandwidth, it must have sufficient accuracy and large bandwidth of the transducer to get the information of position, velocity and acceleration [1]. Incremental encoders are the most commonly used positioning transducers in industry today. Using separate transducers for position and velocity measurement would be both mechanically difficult and costly. Therefore, to employ a position transducer and estimate velocity from the measured position with backward difference is commonly used in industry practice. However the position obtained by an optical encoder is a discrete-time, quantized signal; hence a quantization noise is superimposed on the real value. This is a broadband noise whose amplitude is proportional to the encoder resolution and sampling time [2]. The noise may lead to mechanical vibration or the reduction of the motor's electrical energy utilization efficiency.

In order to attenuate the noise of the velocity signal, different solutions have been proposed. The approaches can be divided into two kinds: predictive post filtering techniques and linear state observers. Predictive post filtering techniques perform a filtering on differentiated position signals, a differentiator based on the Newton predictor has been proposed which assuming that the position can be approximated with a low-degree polynomial [5]. Differentiators based on FIR or IIR filters have been used for velocity estimation [6]. Both methods lead to the phase lag which makes the motion system unstable. A different approach for the velocity estimation relies on state observers' theory which estimates the velocity through position signal directly. Estimators based on Kalman filter, Luenberger observers and nonlinear observers [7, 8, 9] require accurate system models to be available. Data based observers using neural networks [10] or fuzzy logic [11] estimate the velocity using only the position information. These techniques are attractive since only software modification is required to upgrade from a differentiator-based estimator, but need to obtain the accurate parameters of the system model which can't always be met, and most of the algorithms are too complicated to apply in real-time control.

In this paper, a reliable velocity estimator is proposed. This estimator consists of a traditional moving-average filter for data smoothing process, and a closed-loop PID controller to compensate the phase lag caused by smoothing process. The estimator bandwidth is high enough to track the changes of velocity with low noise.

2 Velocity Estimator

The equation for a differentiator-based velocity estimator can be written as,

$$\omega_{dif}(k) = \frac{\theta(kT) - \theta[(k-1)T]}{T} \qquad (1)$$

Where,

T , the sampling period,

θ, the position,

ω_{dif} , the differentiated velocity,

kT , the present sampling instant,

$(k-1)T$,the previous sampling instant.

This method is simple , its usefulness is limited by the accuracy and quantization noise. In a servo motor drive, the velocity loop is the innermost state loop and its performance is generally required to be better than the outer loops, therefore its gains are higher than the gains of the outer loops. However, the higher gain requirement for the velocity loop causes quantization noise to appear directly in the motor current command, limiting the achievable bandwidth of the feedback controller and increasing power dissipation of the motor drive. Therefore, FIR or IIR type filters are used to attenuate the noise of the estimated velocity by backward difference. These methods results in big phase lag, and make the velocity loop controller unstable. So a velocity estimation method which based on traditional moving-average filter and PID controller is proposed.

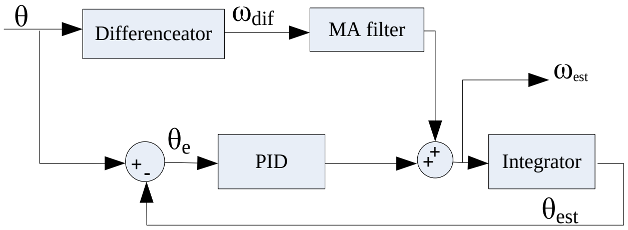


Fig.1 Velocity estimator

The scheme of the proposed estimator is reported in Fig.1. The estimated velocity ω_{dif} is the differential result of position signal which contains a lot of noise. A moving-average filter cascaded after the differentiator which gives a smooth velocity. The smooth velocity signal used to estimate position through an integrator. The position estimation error is used to compensate the phase lag through a PID controller.

The transfer function of the diagram can be expressed as,

$$H(z) = \frac{G_1(z) + G_3(z)}{1 + G_2(z)G_3(z)} \qquad (2)$$

where $G_1(z)$ is the differentiator with a moving-average filter, and $G_2(z)$ is the integrator, $G_3(z)$ is the PID regulator. The transfer functions are as follow:

$$G_1(z) = (1 - z^{-1})(\frac{1}{N}\sum_{i=0}^{N-1} z^{-i}) \qquad (3)$$

where, N is the length of the moving-average filter.

$$G_2(z) = \frac{zT}{z-1} \qquad (4)$$

$$G_3(z) = k_p + k_i\frac{zT}{z-1} + k_d\frac{z-1}{zT} \qquad (5)$$

where k_p is the coefficient of proportion, and k_i is the coefficient of integrator, k_d is the coefficient of derivative.

Substituted $G_1(z)$, $G_2(z)$ and $G_3(z)$ into Eq. (2), we can get the transfer function as Eq. (6).

$$H(z) = \frac{k_iT(1-z^{-1}) + k_p(1-z^{-1})^2 + (\frac{k_d}{T} + \frac{1}{N}\sum_{i=0}^{N-1} z^{-i})(1-z^{-1})^3}{(k_iT^2 + k_pT + k_d + 1) - (k_pT + 2 + 2k_d)z^{-1} - (1+k_d)z^{-2}} \qquad (6)$$

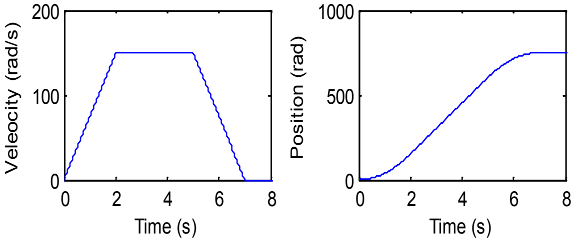
From the Eq. (6) we can find that the coefficient k_d and k_p have more influence, and k_i has little effect on the output. So the system response can be adjusted by setting $k_i = 0$, only need to modify k_d and k_p.

3 Simulation Results

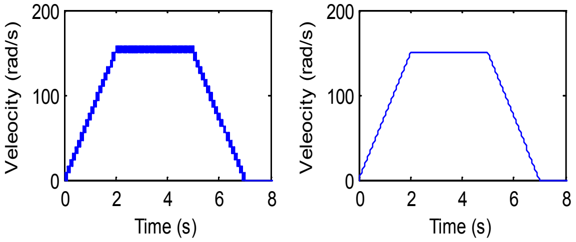
Simulink is used to establish the simulation model of motor drive control and velocity estimator to verify the performance of the algorithm. In Fig.2 (a) & (b), the position and velocity profiles used in the simulations are shown. The adopted profile is similar to the ones normally used in motion control applications, a velocity transient from 0 rad/s to 150 rad/s and then decrease to 0 rad/s. In the simulation tests, the encoder output is obtained by means of the quantization of the position profile shown in Fig.3, the encoder's resolution is 8000 inc/rev and the sample period of velocity loop is 100 μs. Using a pure backward differentiation to estimate velocity, the quantization noise amplitude would be respectively,

$$\Delta\omega = \frac{2\pi}{T \times 8000} = 7.854 rad/s \qquad (7)$$

In the simulation test, the gain of control loop is kept constant. In Fig.2 (c) & (d) the velocity profiles estimated by backward differentiation and the proposed method are shown. The quantization noise amplitude is large in Fig.2 (c) but small in Fig.2 (d) which has little difference compared with original profile.



(a) Velocity reference. (b) Position reference.



(c) Velocity estimated by backward difference. (d) Velocity estimated by proposed method.

Fig.2. Position, velocity profiles and estimated results by different methods.

In order to contrast with the proposed method, velocity is estimated by the backward differentiator, FIR filter, and first-order IIR filter, and the results are shown in Fig. 3, and4.

Fig. 3 shows the estimated result of velocity instruction; the instruction varies from uniformly accelerated to constant. In the acceleration section, use of the proposed estimator is basically to eliminate the effect of noise and minimize the phase lag. FIR filtering has higher phase lag, but the smoothing effect is poor. First-order IIR filter has very big phase lag, and is easy to make the system unstable. Fig.4 shows the velocity estimation error of all of methods. The proposed estimator has minimum error of estimation, which is lower than 0.3 rad/s.

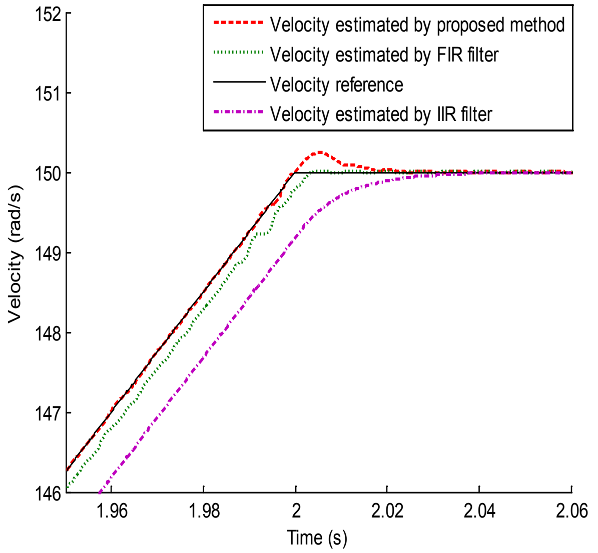
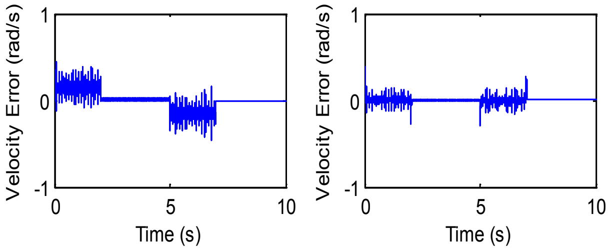
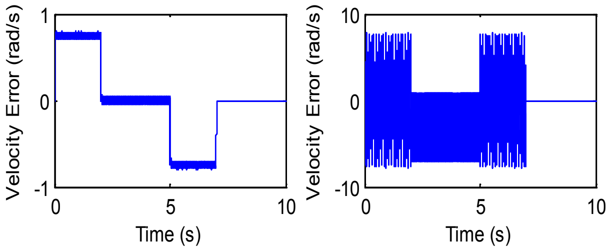


Fig.3. Velocity estimation results by different methods.

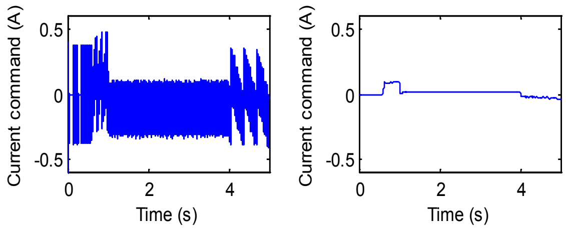


(a) Using the FIR filter. (b) Using the proposed method.

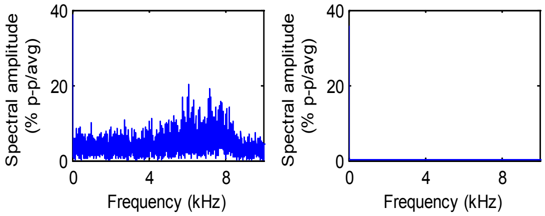


(c) Using the IIR filter. (d) Using the backward difference.

Fig.4. Velocity estimation error by different methods.



(a) Using backward difference. (b) Using proposed method.



(c) Frequency spectra when using backward difference. (d) Frequency spectra when using proposed method.

Fig.5. Torque (current) command profile and frequency spectra when using estimated velocity for feedback control.

Fig.5 compares the torque command's profile and its frequency spectra when the backward difference and proposed estimator were respectively used for velocity feedback for the servo controller. The noise of the control using the proposed estimator was significantly less than that found in the control where the backward difference was used. Since the control cycle of the current loop is 50μs, the noise distributed from 0 Hz to 10 kHz will be reflected in the final torque output from the motor, resulting in torque ripple.

4 Experimental Results

Experiments were performed to evaluate the performance of the proposed method described in the previous sections. The motor controller was implemented with a TMS320F2812 DSP controller. A 400 W PMSM motor was used in the experimental setup, with a 2500 lines/rev shaft encoder mounted on the motor for position measurement. A feedback controller which uses standard vector control strategy was used to control the motor; with a velocity loop's sampling frequency at 10000 Hz. The experimental setup is shown in Fig.7. And the control diagram of the experimental system is shown in Fig. 7.

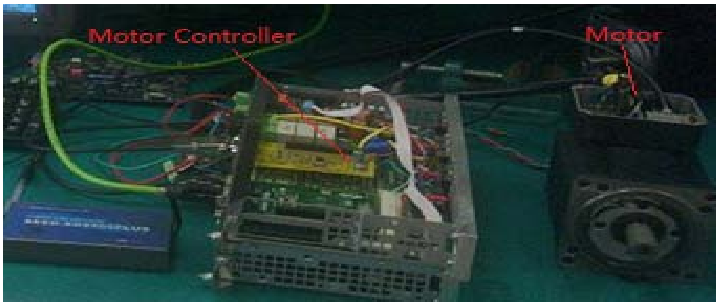


Fig.6. Experimental setup

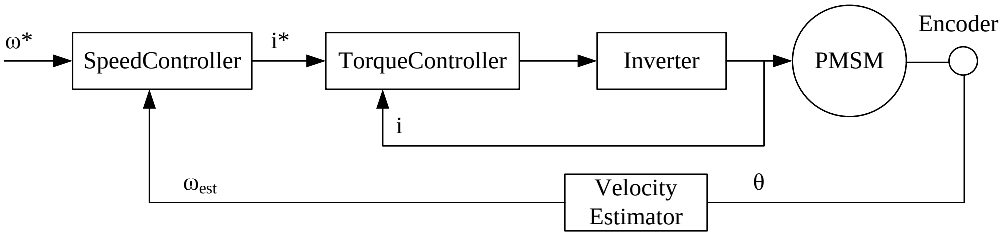
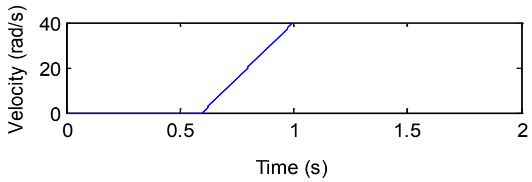
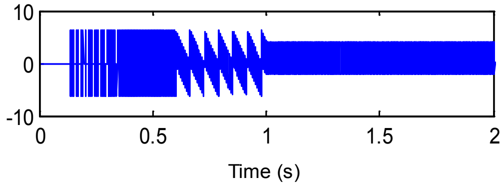


Fig.7. Control diagram of the experimental system

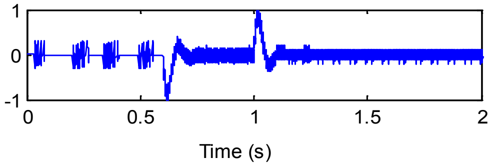
Fig. 8 shows the error between the velocity command and the estimated velocity when using backward difference, backward difference with IIR filter, backward difference with FIR filter and the proposed estimator, which use the estimated velocity as feedback for motor control. The experimental results show that the proposed velocity estimation method can reduce the velocity error dramatically. The velocity estimated by backward differentiator has the biggest noise, and the IIR filter or FIR filter can reduce the noise, but lead to phase lag resulting in overshoot when the velocity reference changes rapidly.



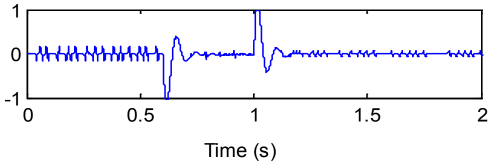
(a) Reference velocity.



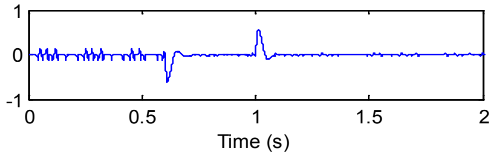
(b) Velocity error using backward difference.



(c) Velocity error using IIR filter.



(d) Velocity error using FIR filter.



(e) Velocity error using proposed method.

Fig.8. Experimental result of using different velocity estimation method.

5 Conclusions

This paper proposed a velocity estimator which combined traditional moving-average filter with a PID regulator. Simulation and experimental results indicate that the most noise in the estimated velocity caused by the quantization of measured position can be reduced with the proposed method, and the phase lag of the estimated velocity is smaller than the FIR filter and the IIR filter. The results also confirm that the proposed method can reduce the harmonic current of the motor which is good for the ripple reduction of the motor's torque.

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