Modified acceleration feedback for practical disturbance rejection in motor drives

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Abstract: Acceleration feedback techniques have been used in control systems for a long time in order to improve the stiffness. Basically, the acceleration of the motor is calculated using speed or position measurements and the current command is adjusted using the acceleration data for avoiding deviations from the commanded speed. This method has to deal with two challenges. The first challenge is calculating the acceleration correctly. If it is calculated by double differentiation of position feedback of a servo motor, it may lead to a high amount of noise. On the other hand, if observer techniques are used, the error and variation in system parameters and quantization noise in the measured current may lead to incorrect calculation of the motor acceleration. The second challenge is avoiding performance degradation in the transient response of the system and preventing oscillations. Since acceleration feedback will try to avoid any acceleration in the system, it may severely affect the transient-state performance. This paper presents a disturbance rejection method that does not depend on system parameters and that does not affect the transient-state response of the system. The method provides very significant improvement in disturbance rejection over a wide frequency range. The magnitude of disturbance response was –29.6 dB in the original scheme at its peak frequency of 5.17 Hz; using the proposed method, it improved to –44.7 dB at the same frequency.

Key words: Disturbance rejection, acceleration feedback, motor control, servo systems, motor drives

1. Introduction

Acceleration feedback techniques slow down or speed up the motor according to the acceleration data [1]. The ideal form of this method is illustrated in Figure 1 [2]. In this figure, $G_{PC}(s)$ denotes the current loop dynamics. K_T is the current to torque transfer coefficient and J_T is total inertia. $1/s$ is the acceleration to velocity integrator. K_{AFB} stands for acceleration feedback coefficient and is used to adjust the strength of the acceleration feedback signal before tailoring the current command.

Assuming the current loop has ideal dynamics, i.e. $G_{PC}(s) = 1$, and applying the $G/(1 + GH)$ rule for calculating closed-loop transfer functions, the arrangement in Figure 1 yields Eq. (1). Here $\omega_M(s)$ is the velocity of the motor and $I_C(s)$ denotes the current command.

$$\frac{\omega_M(s)}{I_C(s)} = \frac{K_T/J_T}{1 + (K_T/J_T) \times (J_T/K_T)K_{AFB}} \times \frac{1}{s} \tag{1}$$

After reduction, Eq. (2) is obtained.

$$\frac{\omega_M(s)}{I_C(s)} = \frac{K_T/J_T}{1 + K_{AFB}} \times \frac{1}{s} \tag{2}$$

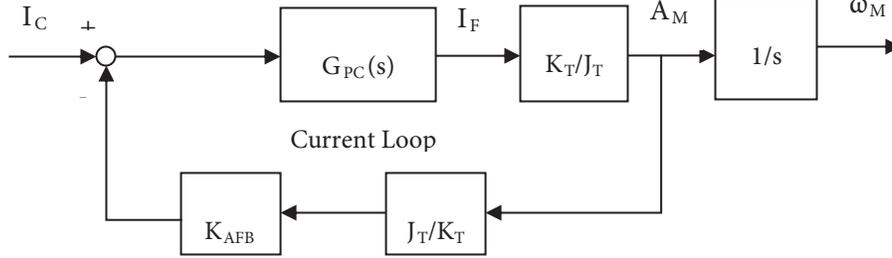[*]Correspondence: ahmet.gurhanli@bou.edu.tr

Figure 1. Ideal acceleration feedback: K_T is current to torque transfer parameter. J_T is total inertia of the system. Measured acceleration is transferred into current signal by scaling with J_T/K_T. This signal is adjusted by the K_{AFB} parameter and subtracted from the current command signal to slow down undesired deviations from the commanded speed.

Eq. (2) clearly shows that the inertia of the system (J_T) is increased by a factor of $(1 + K_{AFB})$. This makes the system more resistant to disturbances. K_{AFB} in this equation is called electronic inertia.

The scheme in Figure 1 improves the disturbance response, but it may severely degrade the command response. In order to keep the command response unaffected, current command is scaled by $1 + K_{AFB}$ as shown in Figure 2. In this figure, $G_C(s)$ is the current loop control law and usually a PI controller is employed here. The second 1/s denotes the integrator that transfers velocity to position.
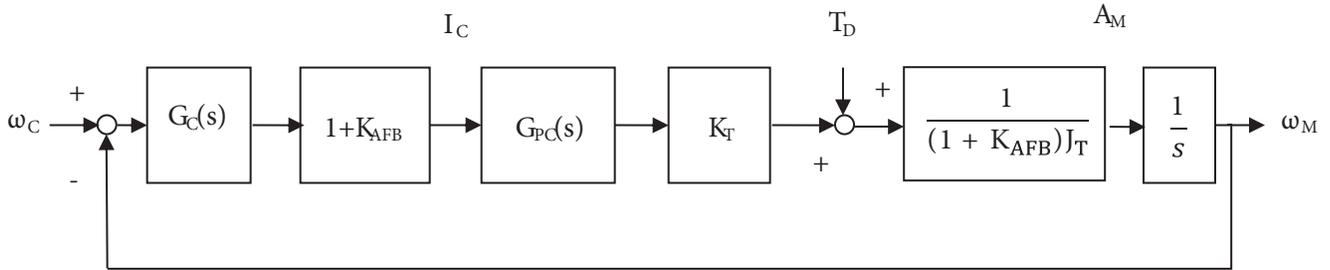

Figure 2. Speed loop based on ideal acceleration feedback: system inertia is increased by a factor of $(1 + K_{AFB})$. For keeping overall system gain unaffected open speed loop gain is multiplied by $(1 + K_{AFB})$.

Command response of the loop in Figure 2 is given in Eq. (3) and it is not affected by the acceleration feedback. In this equation, $\omega_M(s)$ stands for measured velocity and $\omega_C(s)$ is used for commanded velocity. Other abbreviations have the same meaning as above.

$$\frac{\omega_M(s)}{\omega_C(s)} = \frac{G_C(s)\, x\, G_{PC}(s) \times K_T/J_T}{s + G_C(s)\, x\, G_{PC}(s) \times K_T/J_T} \tag{3}$$

On the other hand, the disturbance response of the system is improved by a factor of $1 + K_{AFB}$. This might be seen by applying the G/(1 + GH) rule to the system in Figure 2. In this case, G is the forward path from disturbance input to the output, and H is the feedback path from output to the disturbance input. The transfer function in Eq. (4) is obtained, in which the disturbance response is reduced by a factor of $1 + K_{AFB}$. In this equation, $T_D(s)$ stands for disturbance torque, and the abbreviations have the same meanings as above.

$$\frac{\omega_M(s)}{T_D(s)} = \frac{1/[(1+K_{AFB})J_T]}{s + G_C(s) \times G_{PC}(s) \times K_T/J_T} \tag{4}$$

A naïve approach may suggest calculating the acceleration by differentiating the position feedback two times. This will yield a very noisy signal, as shown in Figure 3. In this figure, the upper signal is calculated by double differentiation and clearly it cannot be used for tailoring the current command. Calculating the acceleration by means of an observer is much more easily applicable.
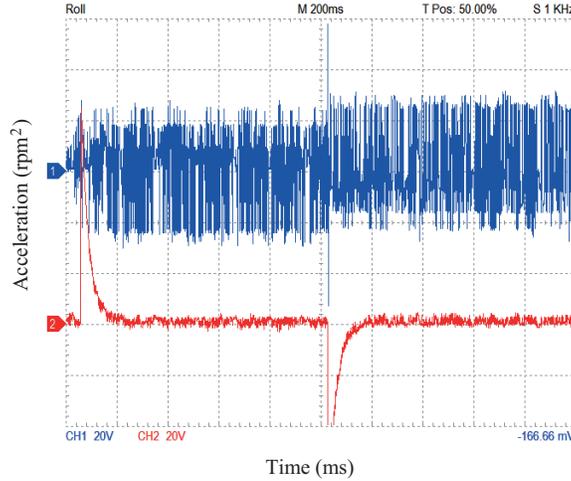

Figure 3. Acceleration signals calculated by double differentiation (upper signal) and observer method (lower signal).

An acceleration observer based on position tracking and current to acceleration conversion was proposed by Ellis [1]. This technique is depicted in Figure 4. First, acceleration is predicted using current feedback by the formula below.

$$\dot{\omega} = (K_{Test}/J_{Test}) \cdot i_f \tag{5}$$

Here $\dot{\omega}$ denotes motor acceleration, K_{Test} is estimated torque constant, J_{Test} stands for estimated inertia, and i_f represents measured feedback current. Knowing that calculating the true acceleration value using this formula is not so easy, a feedback system is established for tracking the motor acceleration. The command input of the feedback observer is the output of the position sensor. The error between sensed position and observed position is passed through a control law and added to the acceleration value calculated from the feedback current. This value is supposed to be the acceleration of the motor, and it is integrated two times for producing the observed position signal. This observed position tracks the sensed position.

The calculated acceleration is transferred to current by scaling with J_{Test}/K_{Test}, and finally the strength of the signal is adjusted by a parameter called K_{AFB} and this signal is subtracted from the current command. Before this subtraction, current command is multiplied by $1 + K_{AFB}$ in order to keep the speed loop gain unaffected.

This method performs pretty well in computer simulations. The technique gives the plots in Figure 5a and 5b when simulated using MATLAB/Simulink. Figure 5a is the simulation result of the original system. A much lower deviation from the commanded speed can be seen in Figure 5b when the same amount of disturbance torque hits at t = 0.25 s. Besides, the command response is not affected by acceleration feedback negatively; on the contrary, after acceleration feedback a faster response is observed.

However, this method is not so easy to implement in real life. Section 3 presents the practical limitations of acceleration feedback techniques and proposes a scheme that will address those challenges. Before that, let us take a wider look at related work in order to see various applications of acceleration feedback.
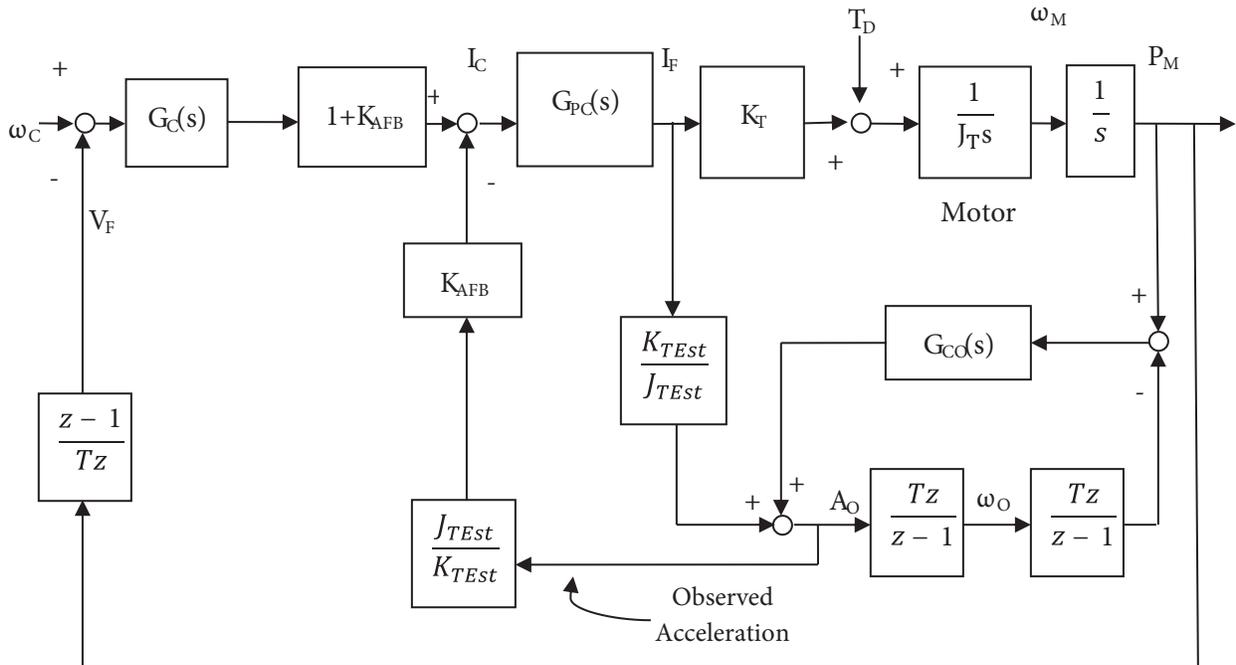
Figure 4. Observer-based acceleration feedback proposed by Ellis [1]: acceleration is predicted using feedback current calculated by Eq. (5). The command input of the feedback observer is the output of the position sensor. Error between sensed position and observed position is passed through a control law and added to the acceleration value calculated from the feedback current.
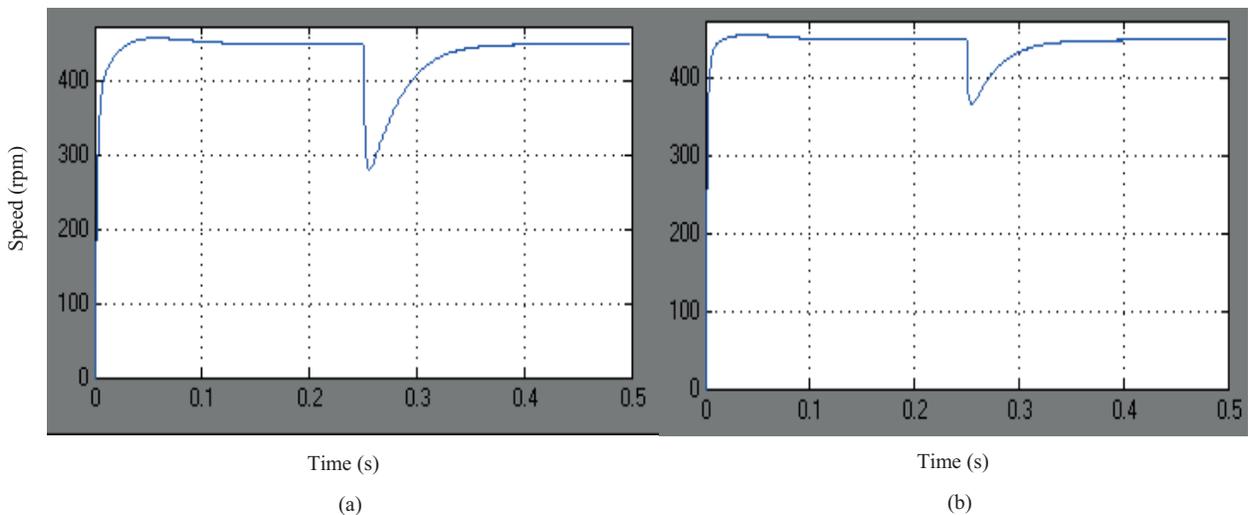

Figure 5. Simulation results showing calculated motor speed due to classical speed control and Ellis's acceleration feedback method. Figure 4a belongs to the classical control loop. Figure 4b is obtained by applying the acceleration feedback scheme proposed by Ellis.

Many forms of acceleration feedback have been developed for several purposes. Hori realized disturbance suppression and impedance control based on acceleration control techniques [3,4]. However the disturbance suppression was practiced on DC motors only, while most widely used motors in the industry are of AC type. Ohishi et al. announced a DSP-based DC servo acceleration control technique without a speed sensor [5]. Here

the focus was on developing an acceleration controlled servo system rather than disturbance rejection. Schmidt and Lorenz employed acceleration feedback to improve the performance of DC drives [6]. This work focused on improving stiffness; however, this technique was only applied on DC drives, as well. Moatemri et al. designed a DSP-based acceleration feedback robot controller [7]. They favored hardware acceleration observers, saying that software observers produced noisy signals. Nevertheless, in microcontroller-based systems, mostly software observers are employed. Dumetz et al. applied an acceleration feedback controller to a flexible robot for which the position and velocity of the load were not measured [8]. The research showed that acceleration feedback can lead to exact tracking of motor position even under nonlinear flexibilities and measurement disturbances. Li et al. proposed a procedure for acceleration feedback control of a delayed nonlinear teleoperation system [9]. In this work, acceleration information of the slave was used to improve the tracking performance and to avoid the contact instability. Kotnik et al. employed acceleration feedback for control of a flexible manipulator arm [10]. In the experiments, endpoint acceleration was used as the noncollocated feedback signal. Stehman and Nakata used acceleration feedback for control of force tables with force stabilization in the earthquake engineering field. [11]. Direct acceleration feedback produced more accurate tracking than conventional displacement-controlled methods.

The aim of this research is developing a practical and easy-to-apply technique for achieving disturbance rejection, especially in AC motor drives. In this paper, the practical barriers of applying acceleration feedback in commercial AC servo drives have been investigated and solution suggestions are offered.

2. Modified acceleration feedback for practical disturbance rejection

A practical control system should be less parameter-dependent, immune to calculation errors, and easily tunable by end-users. Keeping this in mind, several modifications in both acceleration calculation and current command tailoring are needed.

The developed technique for disturbance rejection using acceleration feedback is illustrated in Figure 6. This method has differences both in terms of acceleration calculation and current command adjustment.

2.1. Calculating the acceleration

The observer loop in the proposed scheme tracks the speed feedback in state of the sensed position. The obvious advantage of this scheme is that the observer plant function includes only one integrator. Plants having two integrators need much more control effort and PI controllers are not sufficient for such plants, so differential action is needed. High control parameters and differential action leads to a noisy acceleration signal. On the other hand, building the observer as a velocity tracker has a drawback in AC servo drives: the velocity signal is obtained by differentiating the position feedback and therefore it includes some noise. However, this noise is filtered out by two mechanisms: the low-pass filter located at the entrance of the observer loop, and the observer loop itself, which has a limited bandwidth. Thus, this arrangement produces a less noisy acceleration signal.

Eq. (5) was employed by Ellis to calculate acceleration using current feedback, but it is a simplified formula. Yang and Deng used a more realistic version for their observer-based inertia identifier [12]:

$$J\frac{d\omega_r}{dt} + b \cdot \omega_r = k_t \cdot i - T_L \tag{6}$$

In Eq. (6), J is the equivalent motor and load inertia, ω_r is the speed, b is the viscous damping coefficient, k_t is the motor torque constant, i is the motor current, and T_L is the external disturbance torque. Calculating
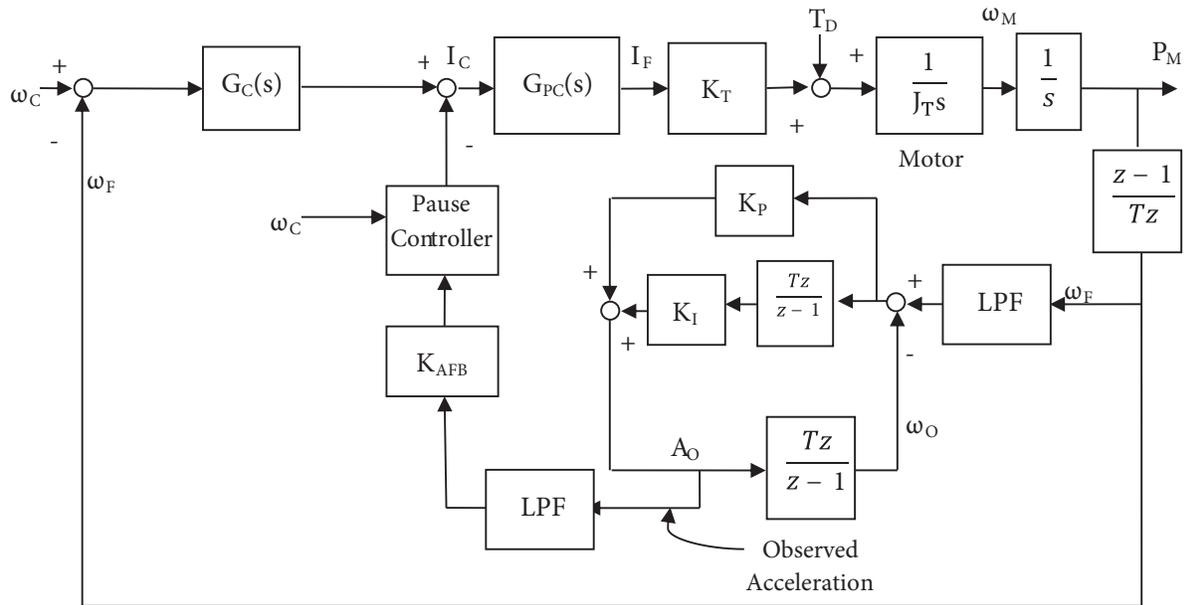
Figure 6. Proposed technique for steady-state disturbance rejection using acceleration feedback: acceleration feedback is paused to keep transient response fast and robust. Feedforward path is removed since it caused undesired oscillations and classic observer loop proved to be fast enough. Low-pass filters are added to increase signal quality.

acceleration using this formula is quite challenging, because the total inertia will vary during motor operation and external disturbance torque is hard to predict. Incorrect calculation will worsen the system's performance, and such a system would be very hard to calibrate by the end users. The acceleration observer presented here is merely constructed on the basis of a feedback loop and a feedforward signal is not used. This is because the observer loop's bandwidth has proven to be quite enough for tracking the speed signal of an AC servo motor. It is not needed to deal with correct parameter estimations, inertia, and disturbance torque calculations.

2.2. Modifying the current command

The scheme in Figure 2 assumes a perfect acceleration calculation. Ellis [1] constructed his technique based on that assumption, and in his algorithm current command is multiplied by $1 + K_{AFB}$, then scaled acceleration feedback is subtracted from that signal. This operation does not affect the transient state if a correct acceleration value can be obtained, but what may occur if the acceleration value slightly mismatches the real one? Figure 7a shows the command response of the original algorithm and Figure 7b is obtained using a system employing an overly slow acceleration observer. The settling time in Figure 7b has been severely worsened. Therefore, the multiply and subtract technique is not so dependable for industrial applications.

This would be a safer strategy: "At the times when you do not want something to affect your system, just disable it." Thus, a pause controller for mixing the acceleration feedback signal with the current command is employed in this technique. When there is a commanded acceleration, this controller disables the acceleration feedback signal, and the disabling duration is equal to the system's settling time. After the system reaches the commanded speed, acceleration feedback is enabled again. In the algorithm, calculated acceleration is passed through a low-pass filter for noise reduction, and finally the magnitude of the acceleration feedback signal is controlled by parameter K_{AFB}. Figure 8a is the plot obtained from the original system, and Figure 8b shows that, after using the pause controller, performance degradation in command response has been eliminated.
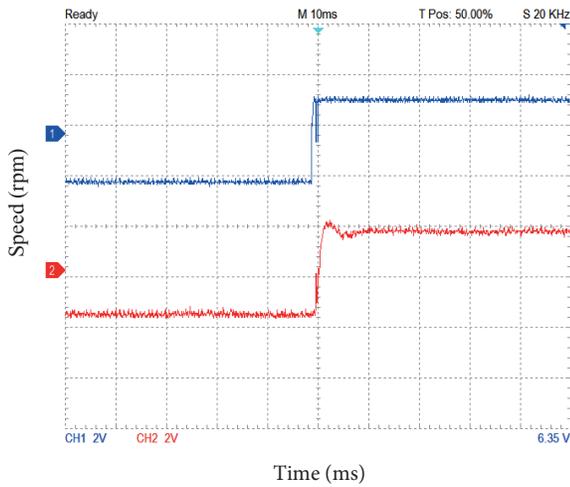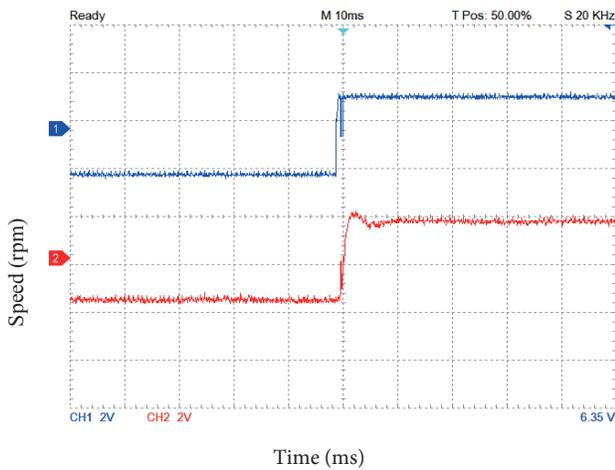
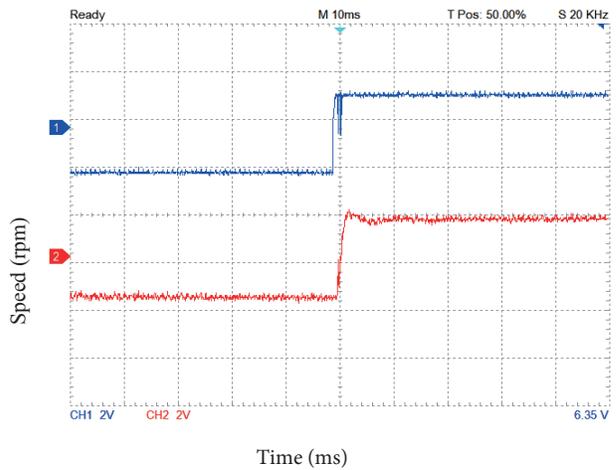(a) Original Algorithm Upper signal: Speed Command Lower Signal: Speed Feedback
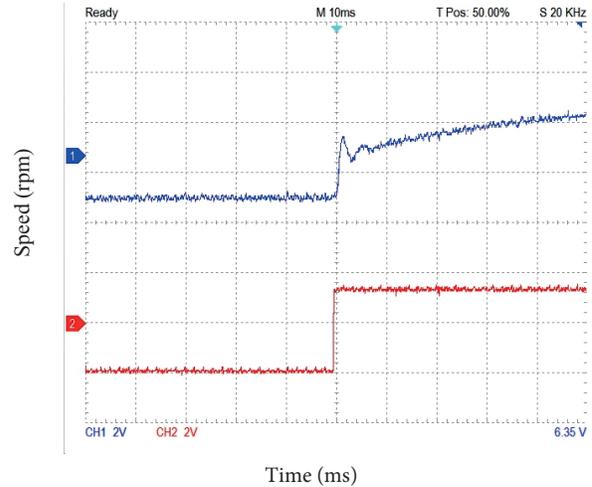
(b) Algorithm with slow acceleration observer Upper signal: Speed Feedback Lower Signal: Speed Command

Figure 7. Effect of multiply and subtract algorithm on command response: if the system cannot be well tuned by the user, speed tracking can be severely worsened.

(a) Original Algorithm Upper signal: Speed Command Lower Signal: Speed Feedback

(b) Acceleration Feedback Alg orithm with Pause Controller Upper signal: Speed Command Lower Signal: Speed Feedback

Figure 8. Pause controller eliminates the performance degradation in command response.

3. Experimental results

The proposed technique has been implemented in a TECO JSDAP-15 AC servo drive. This servo drive includes a RENESAS SH7243 processor for realizing the control algorithms. The sampling period is 100 μs. The employed servomotor is TECO JSMA-PSC04AB, which has an encoder of 2500 pulses/s, and whose rated power is 400 W. The experimental setup is given Figure 9. Disturbance torque is applied to this motor using another servomotor. The response for step disturbances and sinusoidal disturbances has been measured. Finally, the Bode plot of the disturbance response has been constructed by means of a dynamic signal analyzer.
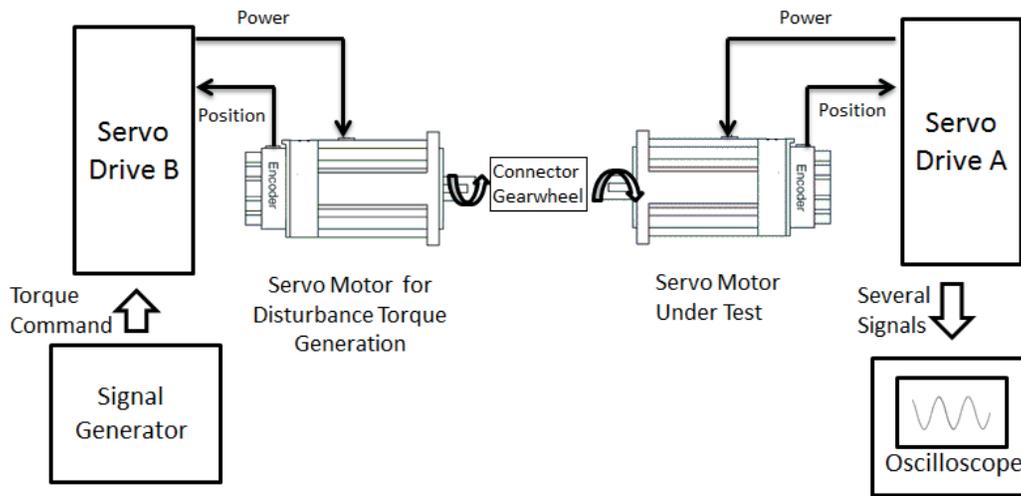
Figure 9. Basic diagram of the experimental setup: disturbance torque is applied to the servo motor under test using another servo motor. Sinusoidal and step disturbances are obtained by means of a signal generator. Several signals in the drive controlling the servo motor under test are observed by means of an oscillator.

3.1. Response to step disturbances

Step response offers a good performance evaluation because a step includes a wide range of frequencies and calibrating a system according to step response is usually a good strategy. Figure 10 shows the response of the servo system to step disturbances as K_{AFB} varies. Figure 10a belongs to the original algorithm. A severe deviation from the commanded value can be seen and the speed of the motor approaches 0 rpm, and while returning to the commanded value it overshoots. Besides, there is significant overshoot in the current command. Figure 10b shows much better disturbance response when K_{AFB} is set as 96/128 (K_{AFB} is divided by 128 using shift operations constantly to avoid decimal arithmetic and time-consuming division operations). The speed deviates much less than before and it does not overshoot when reverting back. The overshoot in the current command has been eliminated, as well. When K_{AFB} is increased to 128/128 a similar speed feedback in Figure 10c can be observed, but oscillations begin in the current command especially when the disturbance torque is removed suddenly. Current command becomes noisier when K_{AFB} is increased to 256/128, as illustrated in Figure 10d, and even fewer deviations occur from the commanded speed. For this servomotor K_{AFB} should not be increased more than 256/128; otherwise, it may lead to instability in the current loop. $K_{AFB} = 96/128$ might be an optimal setting for this servomotor.

3.2. Response to sinusoidal disturbances

The significance of the acceleration feedback disturbance rejection might be clearer if the improvement in response to a steady sinusoidal disturbance is investigated. Such disturbances or noise might occur in industrial systems very often and affect the smooth rotation of motors. The resonance frequency of a system may cause such steady vibrations very often. Sinusoidal disturbance torques have been applied at several frequencies, and in all cases significant improvement in the performance has been observed. Figure 11 is obtained by applying a 300 Hz sinusoidal disturbance torque. As shown in Figure 11a, the servomotor running with the original control algorithm rotates in a shaky and wavy manner. Figure 11b has been obtained after applying acceleration feedback disturbance rejection, and a very smooth rotation has been observed.
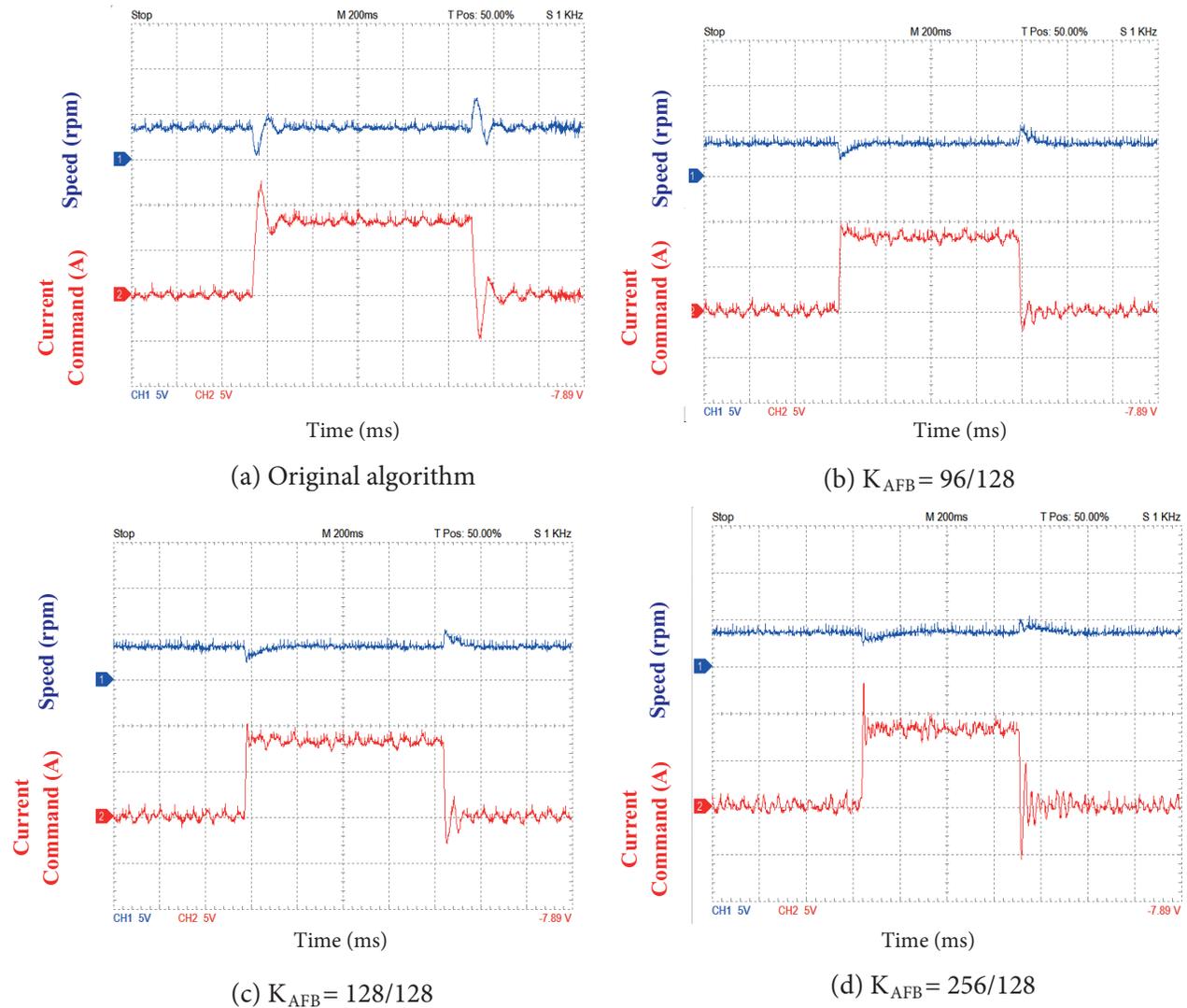
(a) Original algorithm

(b) $K_{AFB} = 96/128$

(c) $K_{AFB} = 128/128$

(d) $K_{AFB} = 256/128$

Figure 10. Response to step disturbances as K_{AFB} varies. Upper signal is the speed feedback, and lower signal is the current command. As K_{AFB} increases deviations from commanded speed decreases, but current command becomes less stable.

3.3. Bode plot

The disturbance response between 1 and 100 Hz has been measured using a dynamic signal analyzer. The result is given in Figure 12. A significant improvement in a wide range of frequencies can be seen easily on the plot. The original algorithm makes peak at 5.17 Hz with –29.6 dB. When K_{AFB} is set to 1.56, at the same frequency, disturbance response decreases to –44.7 dB, improving the performance significantly. Vibrations were observed on the servomotor working with the original algorithm, and those vibrations were eliminated after using acceleration feedback. The peak of the plot shifted to the 10–20 Hz range after application of acceleration feedback, and the response is higher than that with the original algorithm in this region. However, it is already below the observable magnitude. If it is needed to improve the rejection further, the pass-band of the low-pass filters might be widened or the gains of the observer's PI controller can be increased, but both operations may inject noise into the current command.
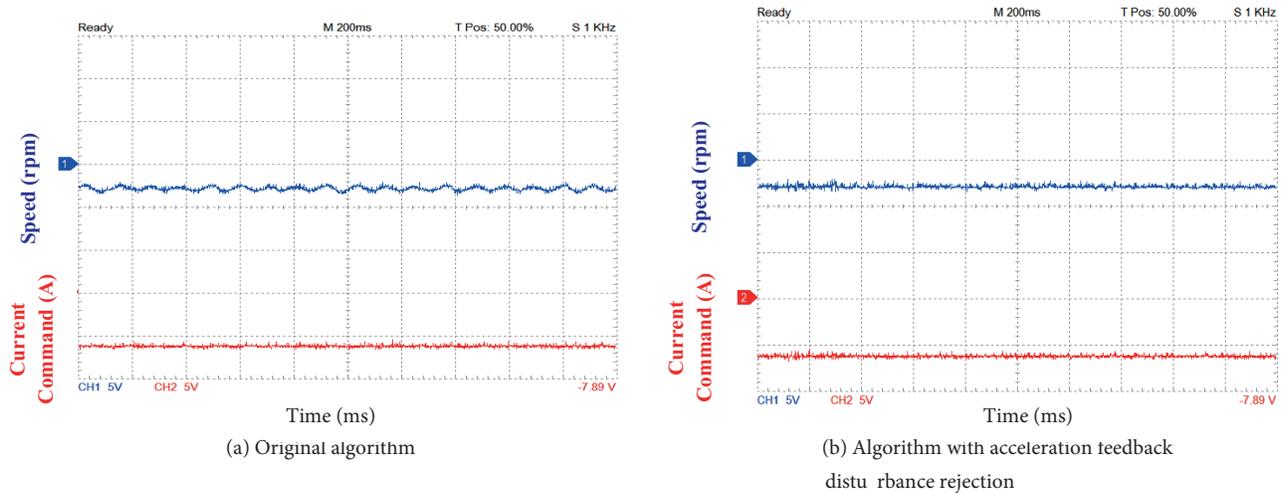
(a) Original algorithm

(b) Algorithm with acceleration feedback

distu rbance rejection

Figure 11. Response to a 300 Hz sinusoidal disturbance. Upper signal is the speed feedback, and lower signal is the current command. Shaky rotation is totally eliminated.
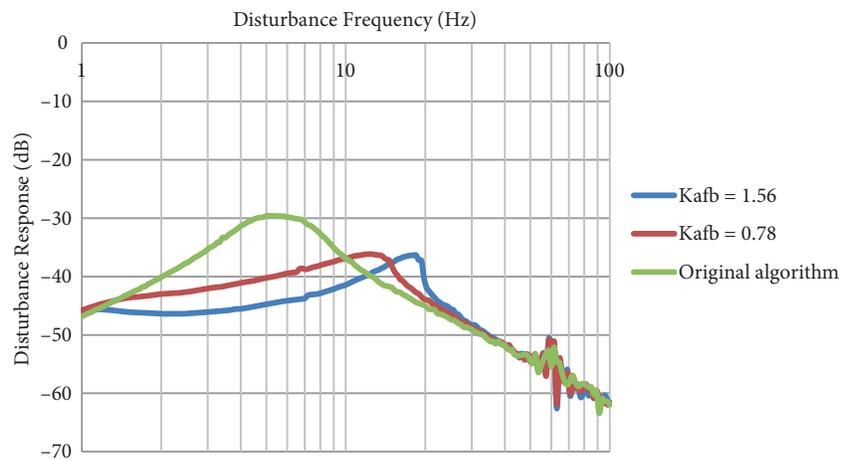

Figure 12. Bode plot that shows response to disturbance torques with frequencies between 1 and 100 Hz. The magnitude of disturbance response was –29.6 dB in the original scheme at its peak frequency of 5.17 Hz; using the proposed method, it was improved to 44.7 dB at the same frequency.

4. Conclusion

A practical technique for improving the disturbance rejection of AC servo drives using acceleration feedback has been introduced. The same method might easily be implemented in AC motor drives. Practical acceleration calculation and current command modification methods are given. Impacts on transient-state response have been avoided by disabling the acceleration feedback signal using a pause controller, and significant improvements in steady-state response have been observed. Deviations from the commanded speed decreased significantly in response to step disturbances. Shaky rotations under the impact of sinusoidal disturbances have been eliminated and smooth operation has been observed for all frequencies applied. The Bode plot of the disturbance torque response has verified the effectiveness of the proposed algorithm. The original algorithm made a peak at 5.17 Hz with –29.6 dB. When K_{AFB} was set to 1.56, at the same frequency, disturbance response decreased to –44.7 dB, improving the performance significantly.

Acknowledgment

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