《高阶会员专属视频》-第21期

IEEE期刊导读：如何发展算法自动找出运动控制系统的共振频率点并消除机械共振？

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The Detection of Resonance Frequency in Motion Control Systems

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***Abstract*—Because of the flexibility of mechanical linkages and high control gains, mechanical resonance may occur, causing torsional vibrations between the motor and load in servo control systems. These vibrations generate velocity and positioning errors for the control system and may damage the system components. This study presents a resonance frequency tracking scheme for servo control systems. The scheme uses velocity error and bandpass filters to track resonance frequencies. After detection, a notch filter in series to the current command is enabled to suppress the vibration. This scheme can be employed during the initial setup and for online resonance frequency tracking. In addition, the proposed scheme can be used to identify all vibrational frequencies in systems with multiple resonant frequencies.**

***Index Terms*—Frequency tracking, motion control, resonance.**

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Many techniques for overcoming mechanical resonance have been proposed. Torsional vibrations can be reduced using measurements of load velocity and acceleration feedback [1], [2]. Certain schemes use fast Fourier transform [3]–[6], shifted discrete Fourier translations [7], or discrete wavelet transforms [8] to calculate the resonance frequency before tuning filters to suppress resonance vibrations. The implementation of these schemes generally necessitates complex theories, calculations, and powerful memory. Alternative strategies for estimating resonance frequency are presented in [9], whereby frequency weighting functions are used to scan the system. However, the

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algorithm is complex and difficult to implement for industrial servo drives. Disturbance observers are also employed to feedback torsion torque and vibration suppressions [10]–[15]. These techniques also require prior knowledge of drive parameters such as torque constant for implementation.

In this paper, a novel resonance frequency detection scheme for servo control systems is presented. The scheme uses velocity errors and bandpass filters to track resonance frequencies. After detection, a notch filter in series to the current command is enabled to suppress the vibrations.

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II. System Model and Signal Preprocessor

Fig. 1 shows a block diagram of a servo control system with the proposed resonance frequency tracking and suppression system. The motor controller has a cascaded position and velocity control loop. Motor position and velocity errors are regulated separately in these loops. When the motor with resonant load is operated, vibrations occur in controller errors and the drive current command (i^*). The proposed scheme uses velocity errors as a source for detecting vibration frequency, although position errors and the drive current can also be employed. In addition, the scheme can be applied to other types of position- and velocity-controlled systems. As shown in Fig. 1, the calculated vibration frequency is loaded into a notch

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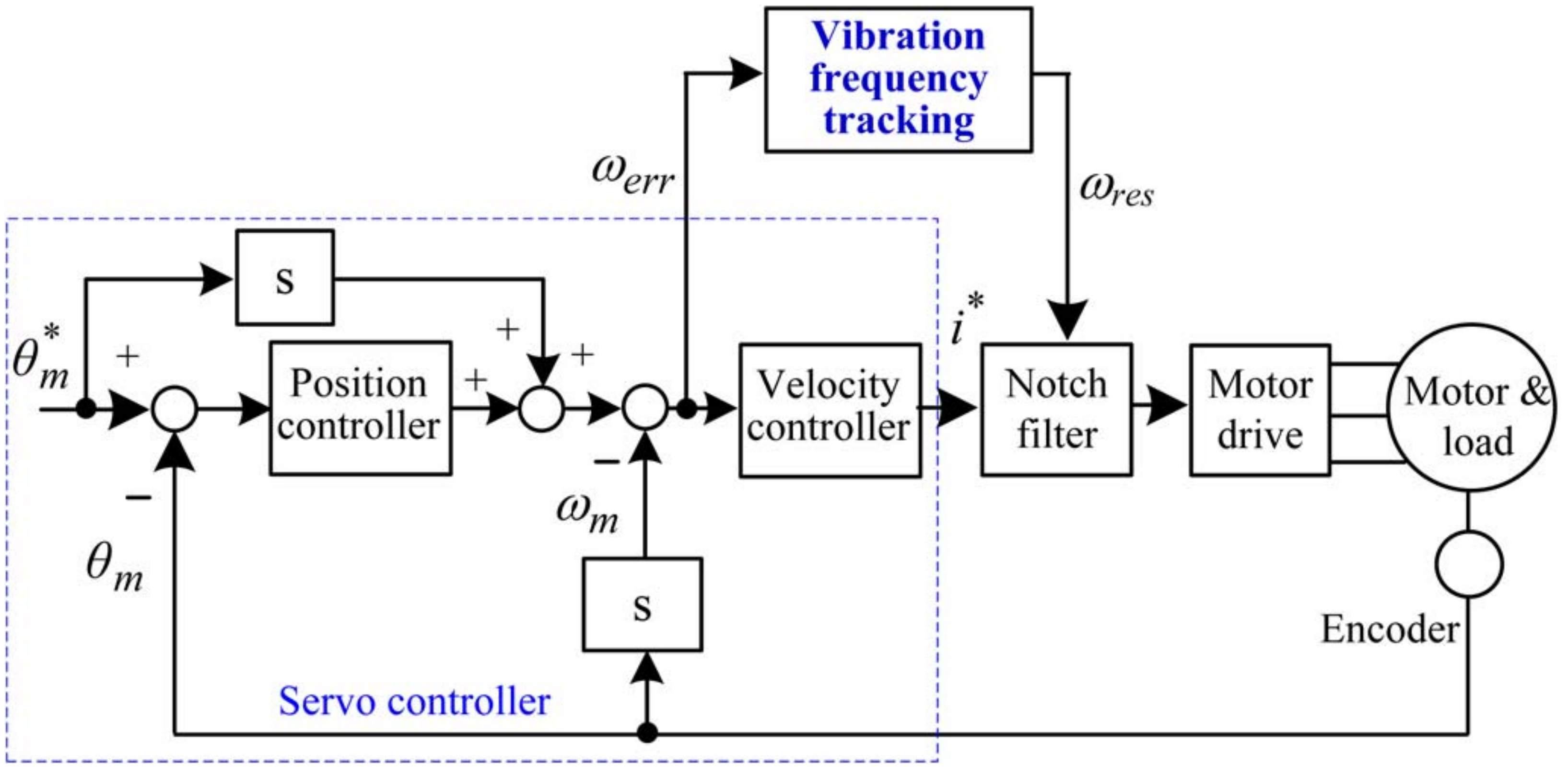

Fig. 1. Block diagram of the servo control and the vibration frequency tracking system.

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At the beginning of the resonance frequency tracking process, a segment of velocity errors are sampled and stored, and data are denoted as $\omega_{err}(t)$. The sampling process is established to facilitate the acquisition of at least one error vibration cycle. Preprocessing is then performed with these data. Fig. 2 is a flowchart of the preprocessing procedure. First, a high-pass filter is used to remove the low frequency and dc components in velocity errors. A bandpass filter is then applied to discriminate

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the frequency content of the errors. The transfer function of the bandpass filter can be expressed as

$$\frac{\omega_{errf}}{\omega_{err}} = \frac{2\zeta\omega_b s}{s^2 + 2\zeta\omega_b s + \omega_b^2} \tag{1}$$

where ζ is a constant, ω_b represents the frequency of the bandpass filter, and ω_{errf} represents the filtered output. Finally, the average absolute value of the filtered outputs is calculated. The preprocessor can be expressed as follows:

$$E(\omega_b) = \frac{1}{T}\int_0^T \left| BPF\left[HPF\left(\omega_{err}(t)\right)\right]\right| dt \tag{2}$$

where $E(\omega_b)$ represents the preprocessor output and BPF and HPF represent the bandpass and high-pass filtering, respectively. Fig. 3 shows a typical preprocessor frequency response when the velocity error contains only one vibrational frequency component. According to the figure, the maximum $E(\omega_b)$ occurs at $\omega = \omega_b$. This property is used to track resonance frequency.

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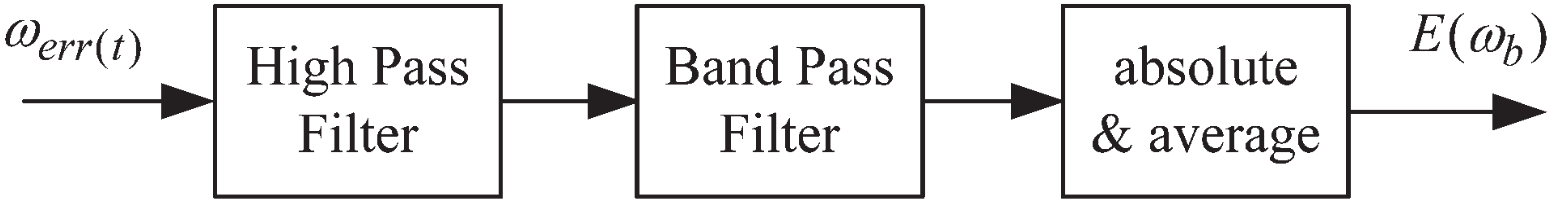

Fig. 2. Flowchart for the preprocessor.

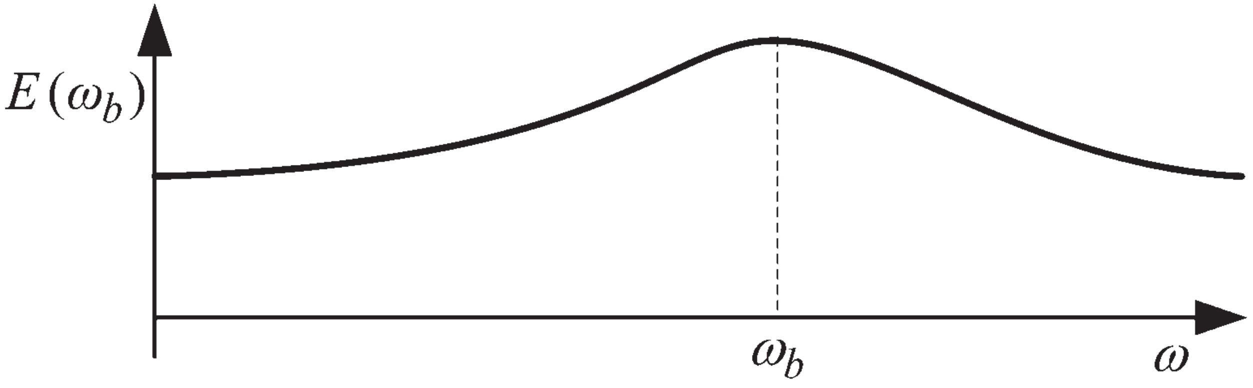

Fig. 3. Typical frequency response of the preprocessor output.

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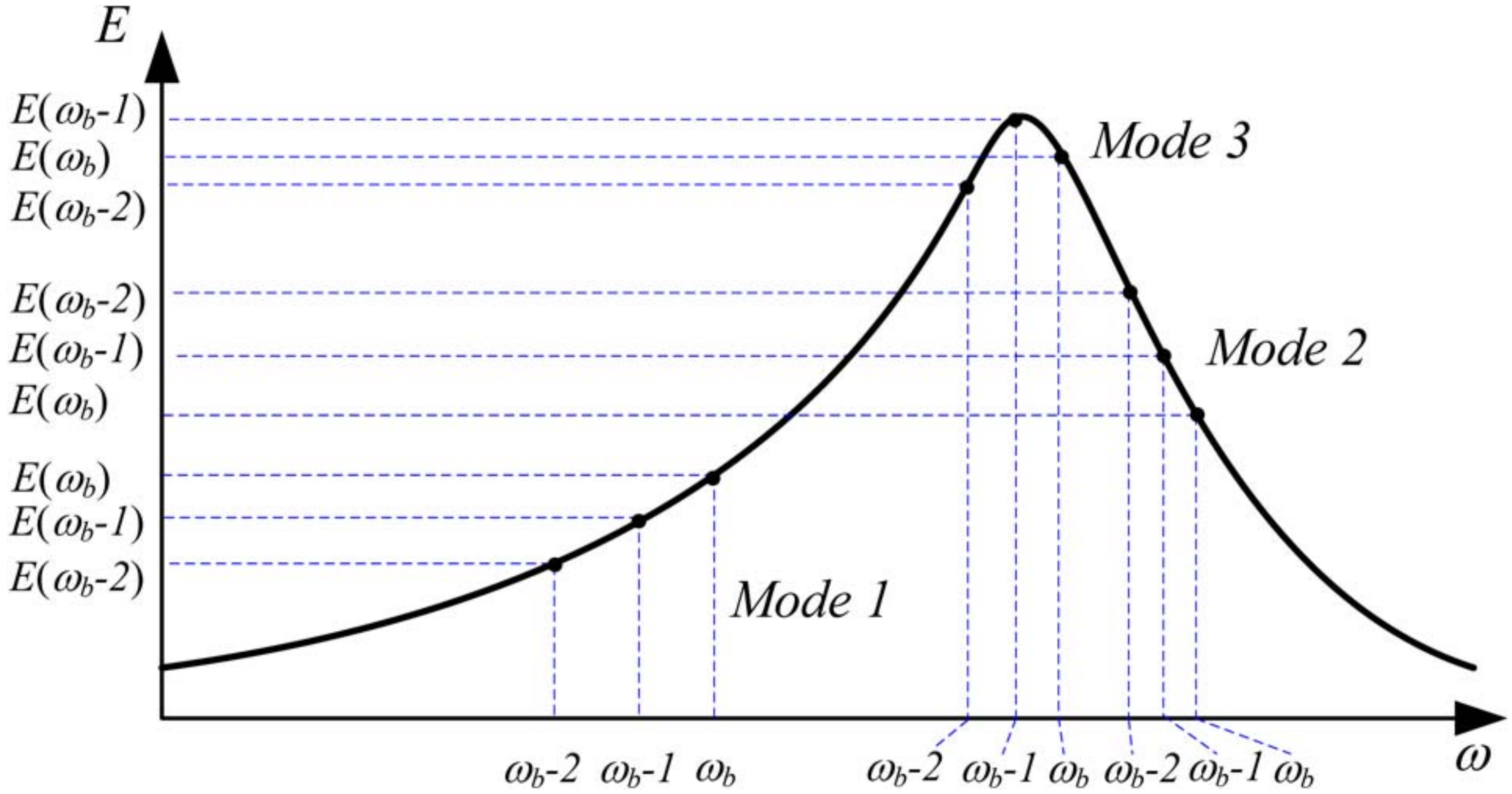

Fig. 5. Modes of the preprocessor outputs.

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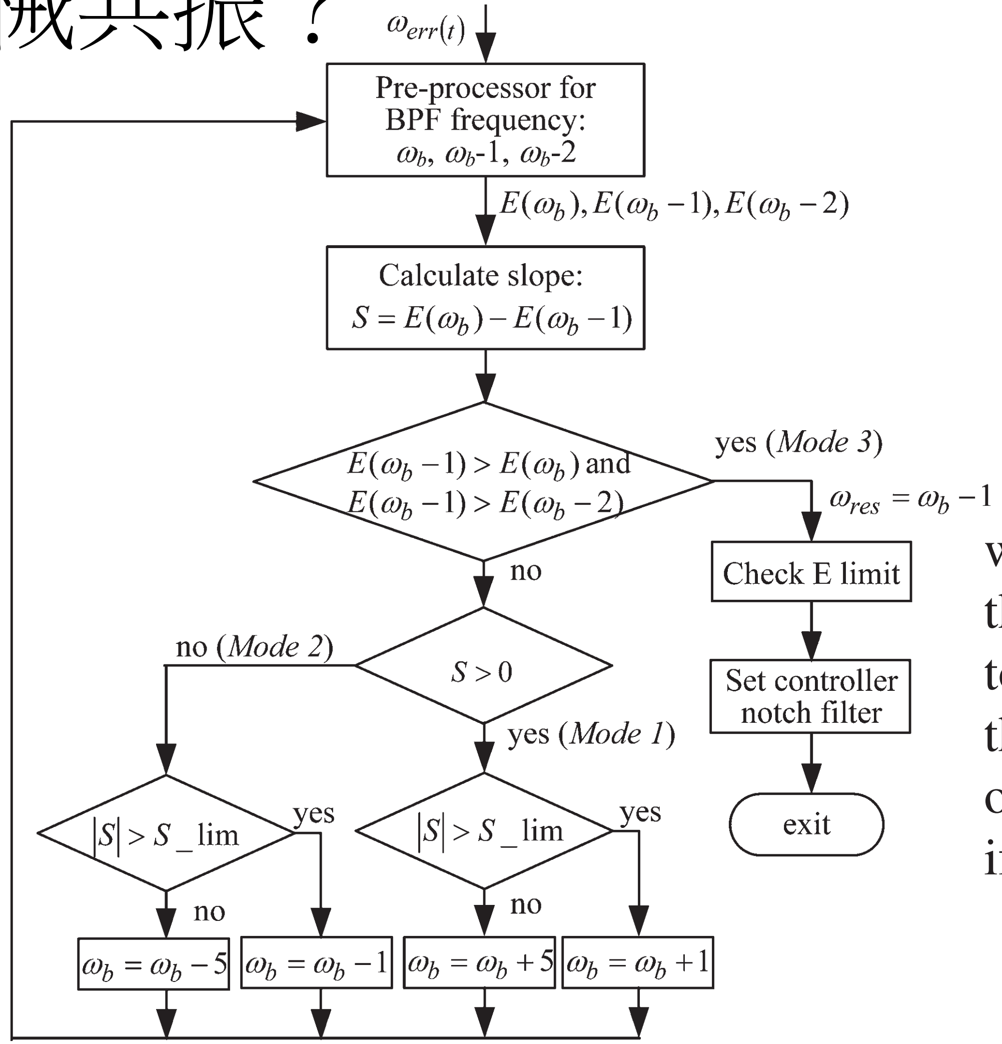

Fig. 4. Flowchart of the frequency tracking process.

value for simplicity. However, to reduce the tracking time, incremental frequency is set to a low value (e.g., 1 Hz) if the slope is higher than a preset limit (S_lim); otherwise, it is set to a higher value (e.g., 5 Hz). After the new ω_b is determined, the prestored data are reprocessed.

After tracking is completed, $E(\omega_{res})$ is checked to determine whether the amplitude of the oscillation is sufficient to initiate the controller notch filter. The E limit can be adjusted according to the allowable maximum velocity ripple of the motor drive; in this study, it was set to approximately $+-10$ r/min oscillations of the velocity error. The controller notch filter was set to ω_{res} if $E(\omega_{res})$ exceeded this value; otherwise, it was disabled.

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IV. Experiment Results

A 400-W 1200-r/min permanent-magnet synchronous servo motor drive was used for experimental verification. Two mechanical loads were established for the motor drive, as shown in Figs. 6 and 7. Both systems contained pulleys, belts, linkages, and an inertia disk. Because the stiffness of the belts used in these systems differed, the resonance frequencies of Systems A and B were approximately 380 and 30 Hz, respectively. In both systems, an encoder was attached to the rotary shaft with a load disk for performance evaluations. A digital signal processor was used to control the motor and detect and track the resonance frequency. The controller was executed at 5 kHz. The controller gains were tuned to ensure controller stability when the belts and load disk were disconnected. Velocity errors of approximately 0.1 s in length were sampled for the preprocessor.

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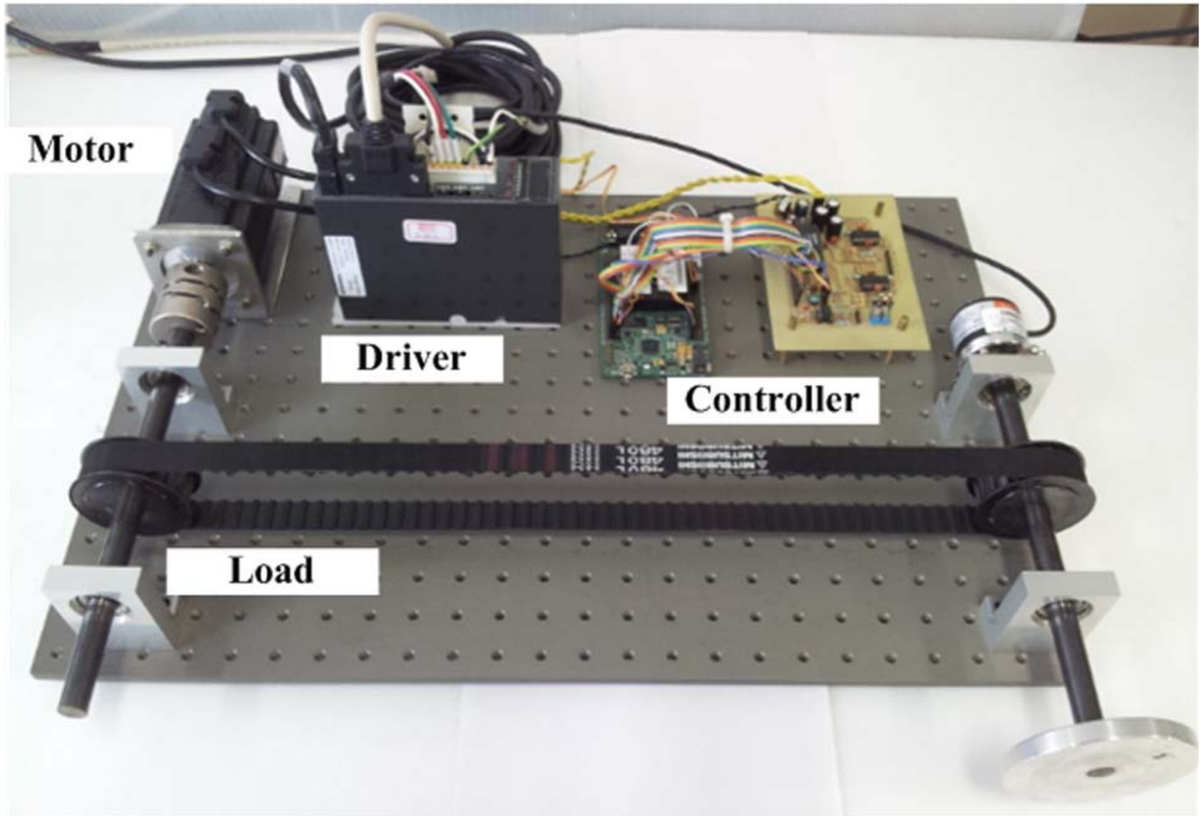

Fig. 6. Experimental System A.

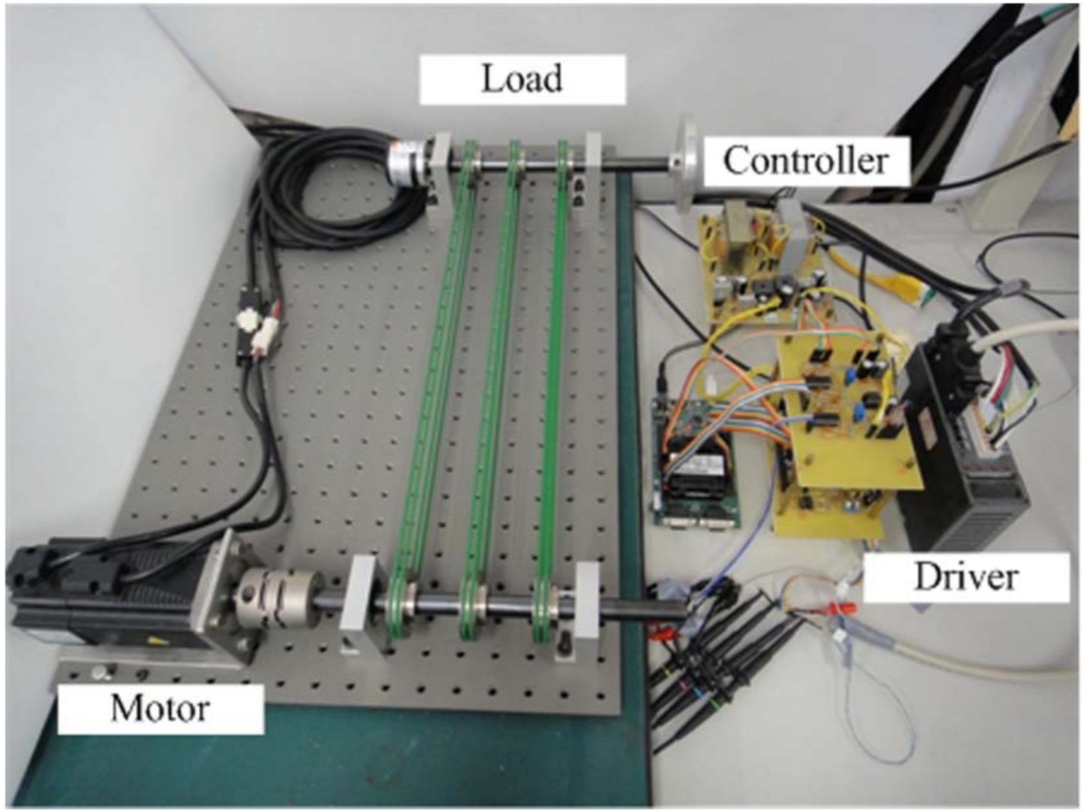

Fig. 7. Experimental System B.

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A. Experimental Results for System A

Fig. 8 shows the results of resonance frequency scanning when the motor was operated at 1200 r/min. In this experiment, the preprocessing technique shown in Fig. 4 was performed with ω_b varying from 10 to 600 Hz. The frequency of maximum E was calculated during the scanning process. The controller notch filter was set to this frequency immediately after the scan was complete. The results in Fig. 8 show that the maximum E occurs at approximately 380 Hz, which is the system resonance frequency. Regarding motor speed, considerable oscillations were observed during scanning; however, these oscillations ceased after the controller notch filter was set.

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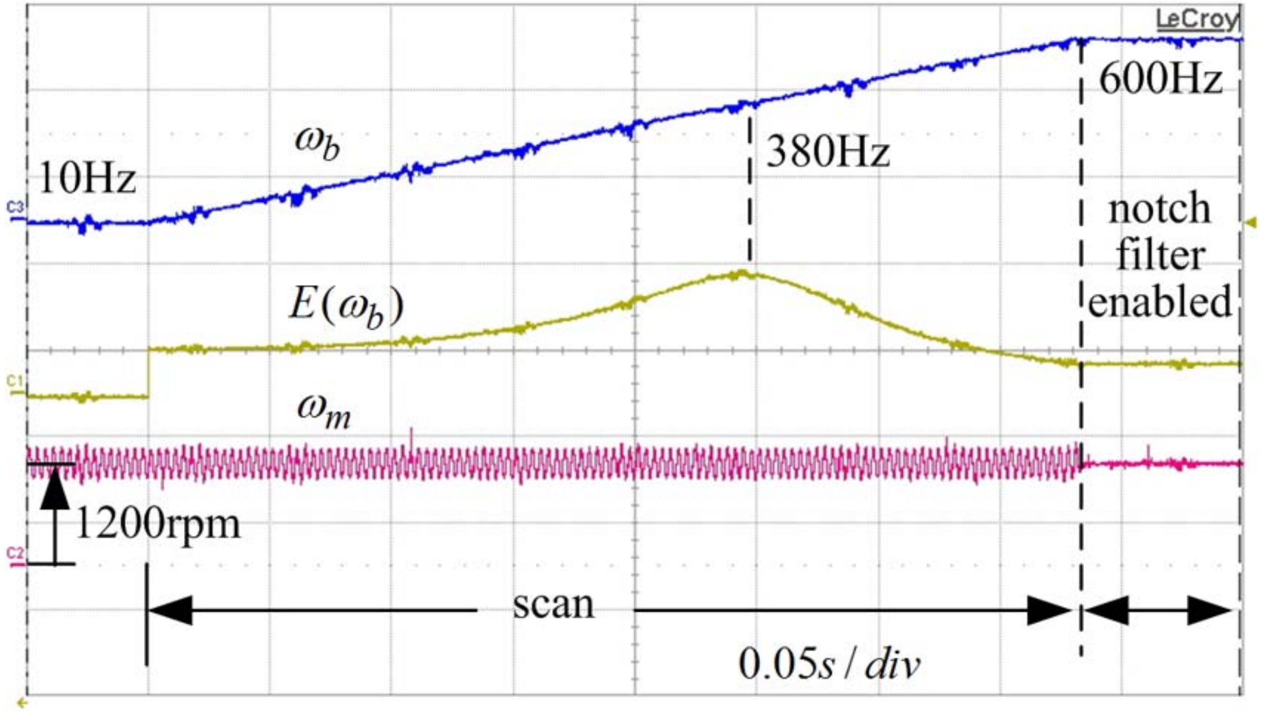

Fig. 8. Experimental System A was scanned from 10 to 600 Hz, controller notch filter was set to 380 Hz after the scan completed, and motor was operated at 1200 r/min.

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Figs. 9 and 10 show the resonance frequency tracking response when the motor was operated at 1200 r/min; the initial frequency was set to 100 and 600 Hz, respectively. Fig. 11 shows an amplified view of the region where the tracking was performed in Fig. 9. The results show that, for both cases, tracking was completed in less than 0.3 s. In this experiment, the frequency of the controller notch filter was set to ω_b after each iteration to examine the effectiveness of the tracking algorithm. Consequently, the velocity oscillations declined gradually as ω_b approached the resonance frequency.

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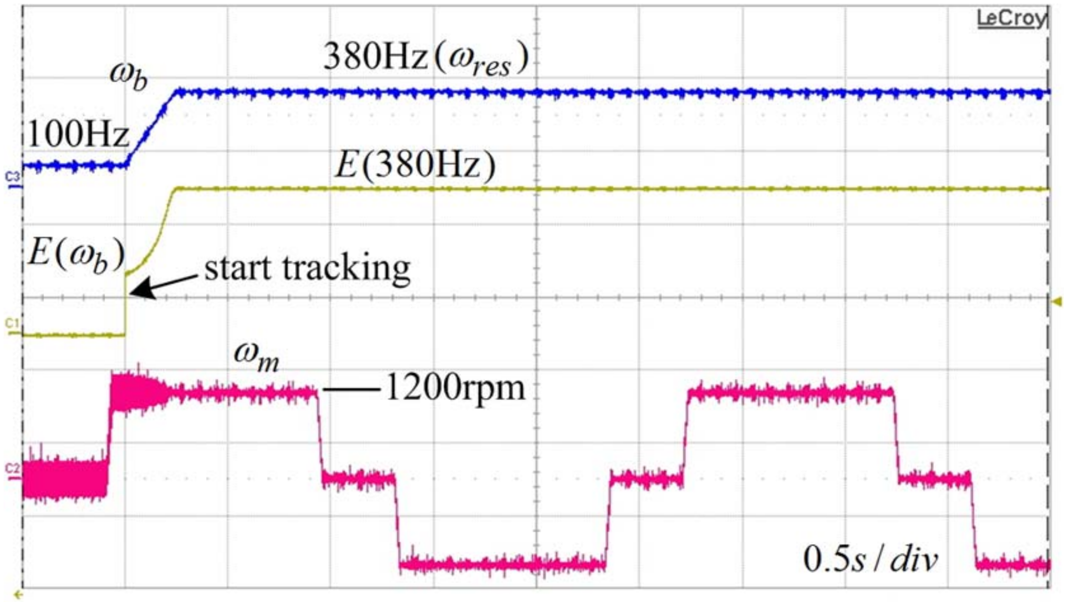

Fig. 9. Resonance frequency tracking response for System A when $\omega_m = 1200$ r/min and initial frequency was set to $\omega_b = 100$ Hz.

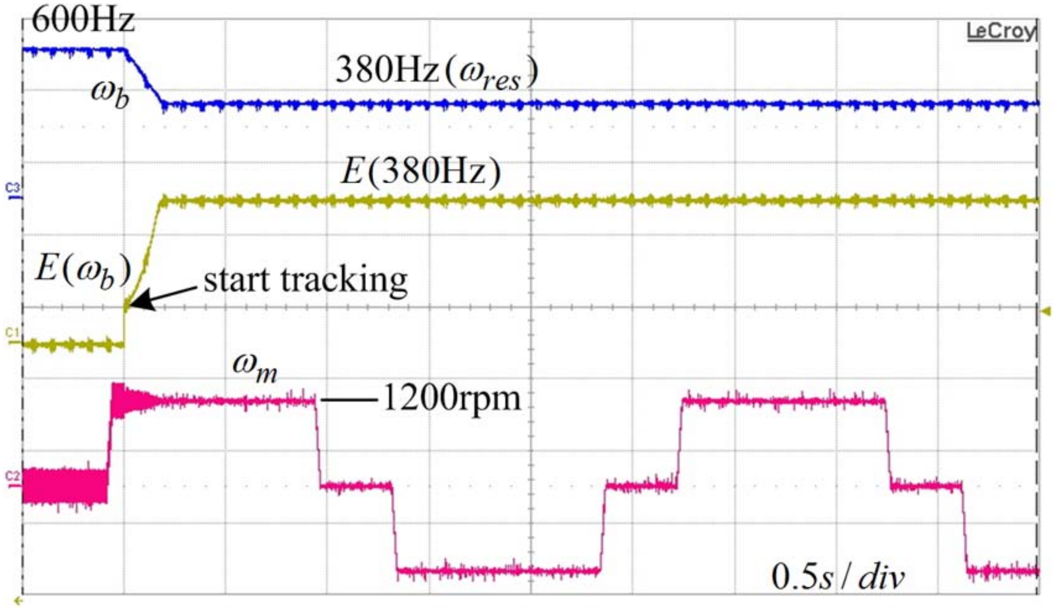

Fig. 10. Resonance frequency tracking response for System A when $\omega_m = 1200$ r/min and initial frequency was set to $\omega_b = 600$ Hz.

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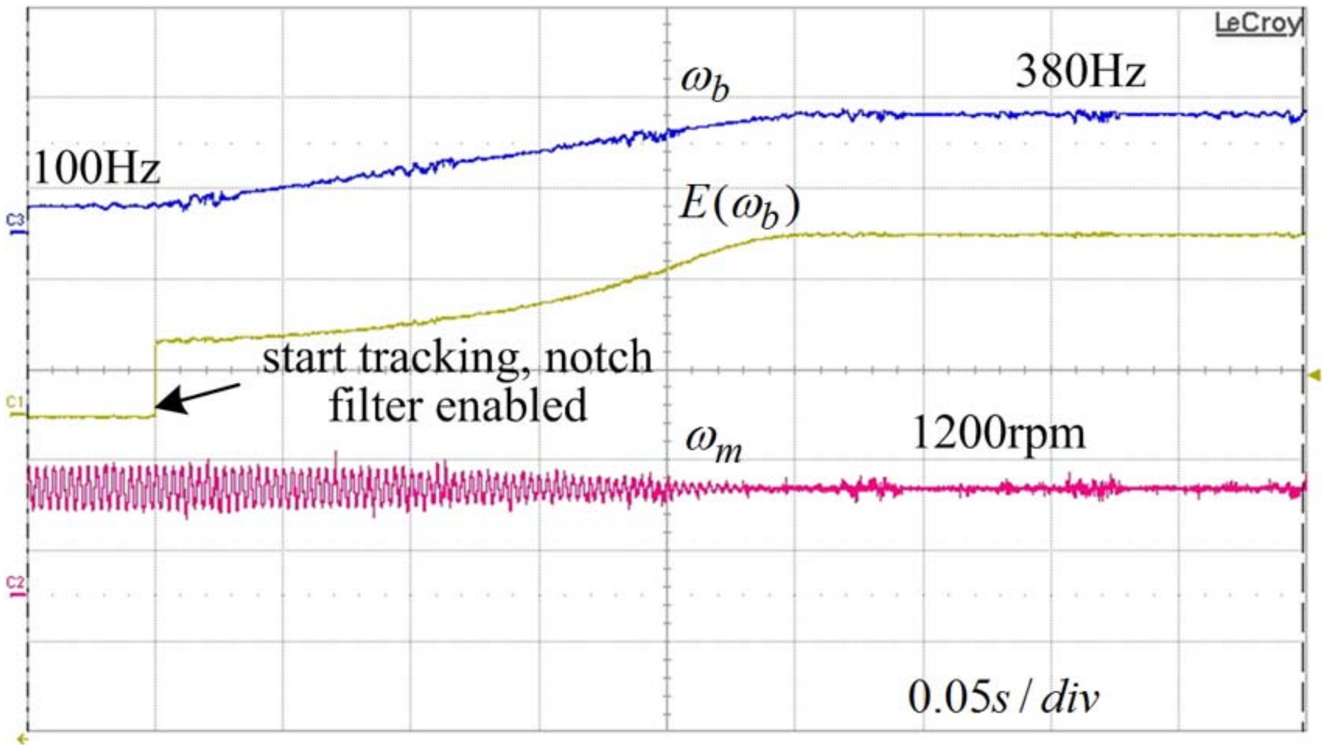

Fig. 11. Amplified view of the region just after the tracking started in Fig. 9.

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Figs. 12 and 13 show the resonance frequency tracking response when the motor was at standstill; the initial frequency was set to 100 and 600 Hz, respectively. The results are similar to those shown in Figs. 9 and 10. The tracking process converged to the correct resonance frequency within 0.3 s. In addition, based on experimental results not presented in this paper, the tracking process can be executed at any speeds within the range of the motor drive, and the time required for convergence is generally less than 0.3 s. Furthermore, the execution time can be reduced by reducing the length of the data processed.

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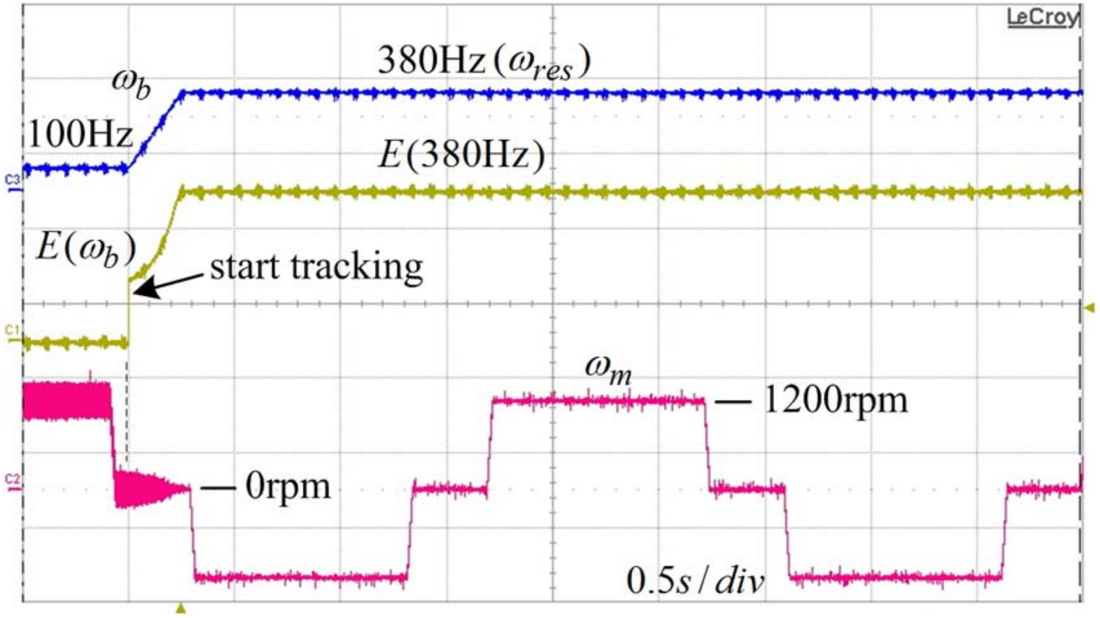

Fig. 12. Resonance frequency tracking response for System A when $\omega_m =$ 0 r/min and initial tracking frequency $\omega_b = 100$ Hz.

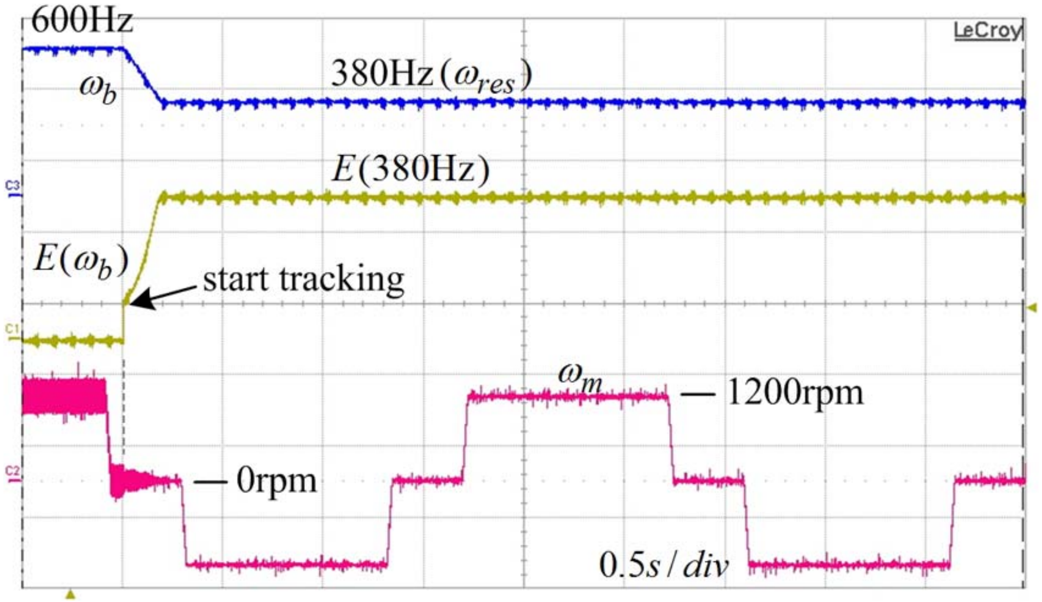

Fig. 13. Resonance frequency tracking response for System A when $\omega_m =$ 0 r/min and initial tracking frequency $\omega_b = 600$ Hz.

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V. Conclusion

This study presented a resonance frequency detection and suppression scheme for servo control systems. The proposed scheme uses velocity errors and bandpass filters to track vibration frequencies. After detection, a notch filter in series with the current command is set to suppress motor vibrations. The proposed scheme was verified experimentally. The results showed that the proposed scheme can effectively detect and suppress resonance vibrations ranging between 30 and 380 Hz. Furthermore, the operation of the scheme at any speeds within the speed range of the motor drive was stable. The time required for convergence was generally less than 0.3 s, declining further when the initial frequency is near the resonance frequency.