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Detection and reduction of middle frequency resonance for an industrial servo

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ABSTRACT

This work proposes a novel strategy for middle frequency resonance detection and reduction for the speed control of industrial servo systems. The report includes an analysis of the drawbacks of the traditional resonance reduction method based on an adaptive notch filter in the middle frequency range, and the main drawback is summarized as the difference between the resonance frequency and the oscillation frequency. In the proposed method, a self-tuning low-pass filter with a corner frequency determined using FFT results and several self-tuning rules is introduced in the speed feedback path. Consequently, the effective range of the adaptive filter is extended across the middle frequency range. The simulation and experimental results show that the frequency detection is accurate, and the resonances are successfully reduced during steady-state and dynamic speeds.

1. Introduction

Servo drives are used in a wide range of industrial applications, including metal cutting, packaging, textiles, web handling, automated assembly and printing. Closed-loop speed controllers with proportional-integral control laws are universally adopted in servo drives, and such controllers must be configured with high gains to achieve high performance. However, the high-gain configuration of the speed controller often causes mechanical resonances within the torsional spring connection between the motor and the load (Zhang & Furusho, 2000).

Several techniques have been investigated and developed to reduce these mechanical resonances. The simplest approach is to decrease the gain of the servo driver speed loop, which usually limits the bandwidth of the speed loop to 1/3 of the resonance frequency or less, resulting in notably poor speed control performance. An alternative approach is to increase the stiffness of the mechanical coupling such that the resonance frequency becomes too high to excite continuous oscillation. However, the re-design or installation of new mechanical components is difficult and costly. A third approach to reducing the resonance involves the introduction of an additional feedback loop via measurement of the load velocity signal (Vukosavic & Stojic, 1998) or shaft torque (Sugiura & Hori, 1996; Szabat & Orlowska-Kowalska, 2004). This loop actively dampens the resonant frequencies experienced by the load. The measured signal is transferred through an additional filter and fed directly to the current command to produce a motor torque that cancels the oscillations. However, measurement of the load velocity or torque output is not available in certain applications, and the additional sensors required for the load are also costly. The methods described above are either unsatisfactory in performance or infeasible for hardware configuration, and thus the following methods have become more popular in recent years.

The most frequently reported methods are based on state variable feedback in which unmeasured variables are obtained via observers, and the controller is designed using pole assignment (Hori, Sawada, & Chun, 1999; Ohmae, Mastuda, Kanno, & Saito, 1987; Hori, Iseki, & Sugiura, 1994). However, practical problems such as online tuning of the observer gains and limitations in the bandwidth of the filters still exist. Because of these drawbacks, these methods are seldom adopted in applications with oscillation frequencies greater than 200 Hz (Orlowska-Kowalska & Szabat, 2004; O'Sullivan, Bingham, & Schofield, 2006; Ellis & Lorenz, 2000). Another well-studied remedy for mechanical resonances is the use of an adaptive notch filter based on oscillation frequency detection (Schmidt & Rehm, 1999). The required structure and design are less complex than that of the state variables feedback method, leading to high performance in many applications with high oscillation frequencies. However, the effectiveness of the notch filters relies on the accuracy of the frequency detection (Kang & Kim, 2005; Wang, Lee, & Lee, 2006). In certain situations, the results may be insufficiently accurate when the resonance frequency is approximately equal to the crossover frequency of the speed loop, which falls in the middle frequency range of 200–500 Hz for industrial servos. Consequently, this frequency range becomes a "blank area" in which both methods encounter difficulties.

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In this paper, the drawbacks of the traditional adaptive notch filters in the middle frequency range are analyzed, and an improved resonance frequency detection and reduction method based on a self-tuning low-pass filter is proposed. In contrast to the traditional methods that use an adaptive notch filter, an additional self-tuning low-pass filter is introduced in the speed feedback path. The parameters of the low-pass filter are updated by FFT results and several self-tuning rules. The system diagram of the proposed strategy is shown in Fig. 1. With this method, the effective range of the traditional adaptive method is extended across the middle frequency range. The blank area between the state variable feedback methods and the traditional adaptive notch filter methods is thus eliminated.

2. Problem description and existing solution

2.1. Modeling of the compliantly coupled two-mass system

A torsional spring connection consists of such components as shaft joints, gearboxes, lead screws, and belt pulley sets, and the mechanical stiffness of these components is limited. If the inertia of the transmission components is small compared to that of the motor and the load, the stiffness of the components can be treated as a single, composite, equivalent spring constant that interconnects with the motor and the load. The mechanical drive train can thus be modeled as a compliantly coupled two-mass system, as shown in Fig. 2, where T_M is the motor torque output, J_M and J_L are the moments of inertia of the motor and the load, respectively, and K_S is the equivalent spring constant.

A detailed block diagram of the torsional-spring-connected mechanism is shown in Fig. 3. The equivalent spring constant K_S provides torque to the load in proportion to the difference between the motor and load positions. To represent the loss-producing properties, a mechanical damping term is applied to produce torque in proportion to the velocity differences via the cross-coupled viscous damping coefficient b_S.

The transfer function from the torque output of the motor T_M to the motor velocity V_M can be written as:

$$\frac{V_M}{T_M} = \frac{1}{J_M+J_L}\frac{1}{s}\frac{J_L s^2+b_s s+K_S}{(J_L J_M/J_L+J_M)+b_s s+K_S} \tag{1}$$

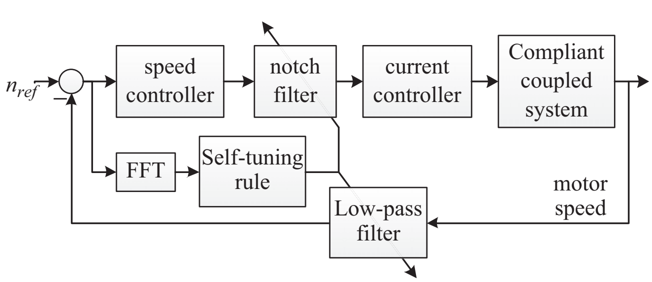

Fig. 1. System block diagram of the speed control loop in the proposed method.

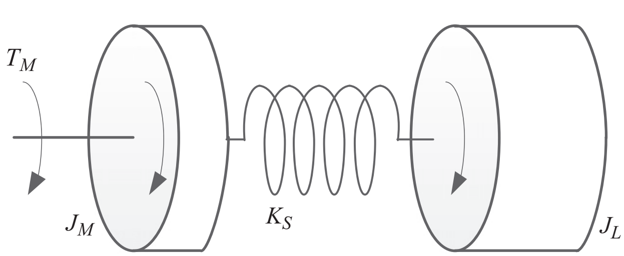

Fig. 2. Two-mass system with a torsional spring connection.

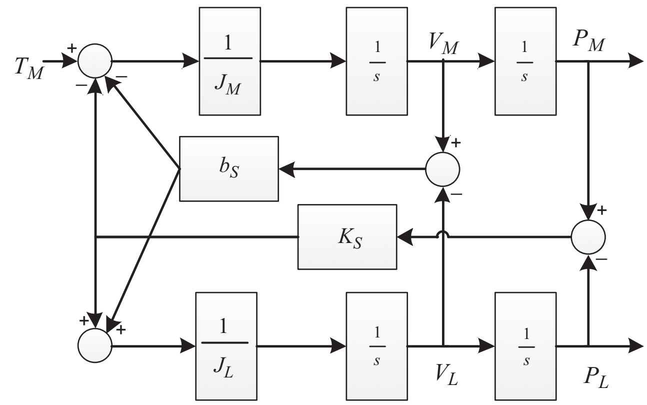

Fig. 3. Block diagram of the torsional spring connected mechanism.

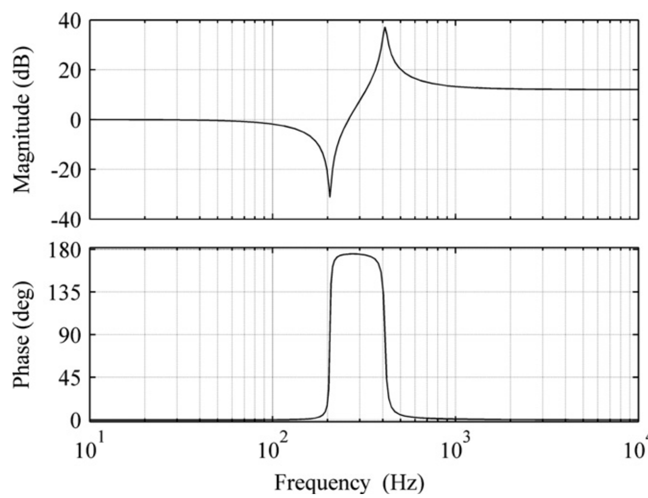

Fig. 4. Bode diagram of the quadratic function.

The transfer function shown above can be viewed as a pure inertia term (the left part) and a dual quadratic function (the right part) caused by the torsional spring connection.

If the viscous damping coefficient b_S is relatively low, then both the numerator and denominator of the dual quadratic function are lightly damped, producing a low gain at the anti-resonant frequency f_{ares} at which the numerator is minimized and a high gain at the resonance frequency f_{res} at which the denominator is minimized. The values of these frequencies can be calculated as shown below:

$$f_{ares} = \frac{1}{2\pi}\sqrt{\frac{K_S}{J_L}}, \quad f_{res} = \frac{1}{2\pi}\sqrt{\frac{K_S(J_L+J_M)}{J_L J_M}}, \tag{2}$$

The dual quadratic function produces severe changes in both the amplitude and the phase of the baseline speed control system (speed control system with a rigid connected load). Specifically, in the range close to the resonant frequency, the peak of the amplitude reduces the gain margin and can easily cause instability, as shown in Fig. 4. Methods for resonance reduction rely on modifying the effects of the dual quadratic term.

2.2. Drawbacks of the traditional adaptive notch filter

An infinite impulse response notch filter is widely used because of its large amplitude reduction and small phase lag at