Torque Control in a Two-Mass Resonant System: Simulation and Dynamic Analysis

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***Abstract*— A multi-mass system is a mechanical system that consists of several masses such as a motor, load, and gear that are connected by a flexible shaft. The mechanical fluctuations in drives with flexible coupling between the motor and the driven device can no longer be ignored, as they could in the past when requirements for speed control dynamics were low. These prerequisites pertain to the regulation of the rotational speed and position of the servo drive and are quantified by the magnitude of speed step response time and speed fault elimination time caused by the step change of load torque, which, in modern drives, can be measured. In this study, the dynamical behavior of a two-mass resonant system with a three-term controller for control of torque and speed is investigated using eigenvalues analysis. The proposed control strategy aims to eliminate the rotational fluctuations of the motor shaft, dampen the load torque disturbance impact, provide a quick response to changes in the base speed while avoiding increases in the load speed, and be resilient to instability. Finally, numerical outcomes demonstrate the effect of the presented controller application on improving the dynamic demeanor of the two-mass test system. Based on the outcomes, the effectiveness of the proposed control scheme is highly dependent on system parameters. Due to the inherent parameter uncertainty in the multi-mass system, the use of parameter estimators based on artificial neural networks (ANNs) is suggested for future work.**

Keywords—Multi-mass electromechanical system; Eignevalues; Artificial neural networks (ANNs); Torque contro; Control system.

I. Introduction

A multi-mass system can be employed to model the mechanical system in motor-driven industrial equipment [1,2].

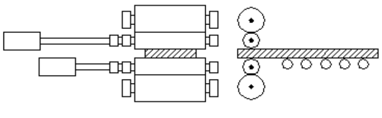

Fig. 1. Steel roller machine system

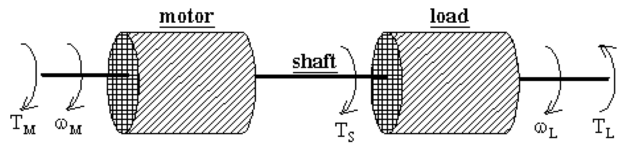

Fig. 2. Two-mass resonant system

In many cases, the model is considered by the two-mass system for the first mode of exacerbation [3,4]. If the shaft connecting the motor and load remains stationary, the animatronic motor system reaches a state of mechanical oscillation known as a two-mass resonant system [5]. The objective of control in a multi-mass reson-an-t system is to suppress shaft rotational changes, the return of the torque load disturbance, and the rapid response to the change in base speed without increasing the load speed and stability [6]. Fig. 1 shows a roller machine system that can be structured as a two-mass system. A simple structure of the motor drive system with a running load is shown in Fig. 2 [7]. The component parts of the system include a drive motor and a single load that is shaft-coupled to the drive motor. The mechanical oscillation system will be found if the shaft has a low level of stiffness.

So far, various studies have been carried out on the application of the multi-mass system model and its control [8]. In [9], the implementation of a sliding mode control theory and a conventional PID controller throughout a dynamic multi-mass electro-mechanical system to control the system's shaft speed is demonstrated. A robust control strategy with an adaptive sliding neuro-fuzzy speed regulator based on the feedback from the motor speed with the flexible joint is suggested in [10], This controller is designed based on a structural two-mass system that has unknown values for its parameters. The implementation of pseudorandom binary signals for the characterization of electrical drives is illustrated in [11]. In this study, the frequency response measurement is included as part of a parameter identification strategy that is conducted during the automatic establishment of the drive. [12] presents a model predictive controller regulator that can be used for controlling the location of an electrical drive that has an elastic correlation. In [13], the authors design three distinct controllers according to an integral–proportional–derivative controller to regulate the speed of a two-mass system by employing a normalized approach and a polynomial procedure. This research is carried out to ensure that it is possible to have adequate damping in the multi-mass system.

A fuzzy Luen-Berger observer for a motor drive system with an adaptable joint is addressed in [14]. The fuzzy approach determines the location of the observer poles based on fault signals between the plant's desired output and the predicted outputs. In addition, [15] proposes a nonlinear, quasi-time-optimal, state-feedback control scheme for the torsional torque of a two-mass system. The control algorithm is based on the outcomes of the common outline of optimal control and leverages the presumption of a bang-bang configuration for the actuation.

The purpose of this research is to develop a torque controller for application in a two-mass resonance system and then analyze the effect that this controller has on the dynamic behavior of the system. In the beginning, the equations of the two-mass resonance system are represented in open loop mode (which means there is no controller) and the transfer functions that correlate to state variables are discovered. After that, the closed-loop system that includes the controller is put into action so that the efficiency of the suggested controller is evaluated. This control strategy aims to eliminate the shaft's rotational changes and suppress the load torque disturbance effects by providing a fast response to the change in base speed without increasing the load speed or resistance stability. This paper is structured as follows: Section II presents the fundamental system equations of a multi-mass resonant system. In this part, the open-loop and close-loop system equations (with or without a controller) are described. In Section III, the numerical results based on the two-mass electromechanical test system are carried out to demonstrate the efficiency of the proposed control scheme. Eventually, this paper is concluded in Section V.

II. System Equations

A. Open Loop System

Block diagrams describe the relationship between system equations and are used in the examination and configuration of control procedures [16].

The transformation function model only provides a description of the input-output behavior of the system, and therefore it is called an external description [17,18]. The state variables describe the system's internal dynamics, and the state space mod-eling is called the internal description of the system [19,20]. By choosing two input variables load disturbance torque (T_S) and motor torques (T_M), and three state variables shaft torsional torque (T_S), load speed (ω_L) and motor shaft speed (ω_M), two-mass system state equations are [21]:

$$\frac{d}{dt}\omega_M = -\frac{B_M}{J_M}\omega_M - \frac{1}{J_M}T_S + \frac{1}{J_M}T_M \tag{1}$$

$$\frac{d}{dt}T_S = (K_S - \frac{B_M B_S}{J_M})\omega_M - (K_S - \frac{B_L B_S}{J_L})\omega_L - B_S(\frac{1}{J_M}+\frac{1}{J_L})T_S + \frac{B_S}{J_M}T_M + \frac{B_S}{J_L}T_L \tag{2}$$

$$\frac{d}{dt}\omega_L = -\frac{B_L}{J_L}\omega_L + \frac{1}{J_L}T_S - \frac{1}{J_L}T_L \tag{3}$$

where K_S is shaft stiffness coefficient, B_S is shaft damping coefficient, J_L is load inertia, J_M is the inertia, B_L is load damping coefficient and B_M is damping constant. Based on the above equations, the configuration of the two-mass system is illustrated in Fig. 3.

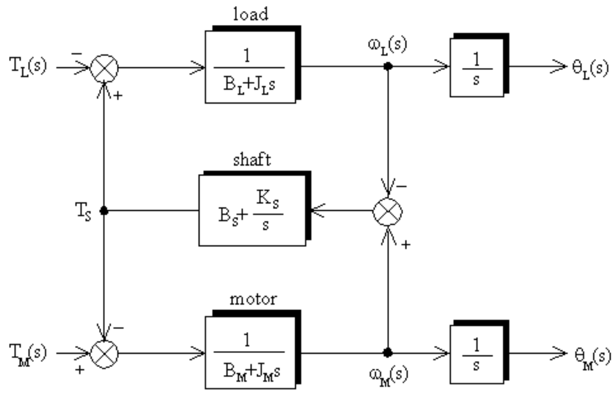

Fig. 3. The configuration of two-mass resonant system

The detailed equation of the open-loop two-mass electro-mechanical system is given by:

$$\Delta(s) = s^3 + \frac{J_L(B_M+B_S)+J_M(B_L+B_S)}{J_M J_L}s^2 + \frac{B_M B_L + B_S(B_M+B_L)+K_S(J_L+J_M)}{J_M J_L}s + \frac{K_S(B_L+B_M)}{J_M J_L} \tag{4}$$

According to the configuration of the system, the load and motor speeds in the two-mass system are given by:

$$\omega_L(s) = \underbrace{\frac{G_L(s)G_M(s)G_S(s)}{1+G_M(s)G_S(s)+G_L(s)G_S(s)}}_{H_{LM}(s)}T_M(s) - \underbrace{\frac{G_L(s)T_L(s)[1+G_S(s)G_M(s)]}{1+G_S(s)G_L(s)+G_S(s)G_M(s)}}_{H_{LL}(s)} \tag{5}$$

$$\omega_M(s) = \underbrace{\frac{G_M(s)[1+G_S(s)G_L(s)]}{1+G_M(s)G_S(s)+G_L(s)G_S(s)}}_{H_{MM}(s)}T_M(s)$$

$$-\frac{G_S(s)G_M(s)G_L(s)}{\underbrace{1+G_S(s)G_L(s)+G_S(s)G_M(s)}_{H_{ML}(s)}}T_L(s) \tag{6}$$

where $G_S(s)$, $G_M(s)$ and $G_L(s)$ are transfer functions of the shaft, motor, and load, respectively. The pole and zero representation of the transfer function corresponding to the motor speed, regardless of the system attenuation is shown in Fig. 4. The inertia ratio (K_J), resonant frequency (ω_R), anti-resonant (ω_A) and resonance ratio are given by [22]:

$$K_J = \frac{J_L}{J_M} \tag{7}$$

$$\omega_R = \sqrt{K_S \frac{J_M + J_L}{J_M J_L}} \tag{8}$$

$$\omega_A = \sqrt{\frac{K_S}{J_L}} \tag{9}$$

$$K_R = \frac{\omega_R}{\omega_A} = \sqrt{1+K_J} \tag{10}$$

B. Close Loop System

In the drive system of motors, if the load and the motor are connected by a fixed shaft, the movement of the motor system finds an electromechanical oscillation, which is called a two-mass oscillating system. The control objective in the two-mass oscillating system is to eliminate the rotational changes of the shaft, return the load torque disturbance effect, quick response to the base speed change without increasing the load speed and resistant stability.

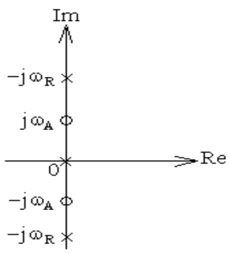

Fig. 4. Pole and zero of $H_{MM}(s)$

The PID controller is frequently used as a straightforward control approach for regulating the torque of the two-mass system to prevent electro-mechanical fluctuations [23-27]. Fig. 5 is a schematic representation that demonstrates the torque control for a two-mass resonant system that employs a PID controller. The controller's transfer function, which is denoted as $G_T(s)$, is different from the torque command, which is written as T_C.

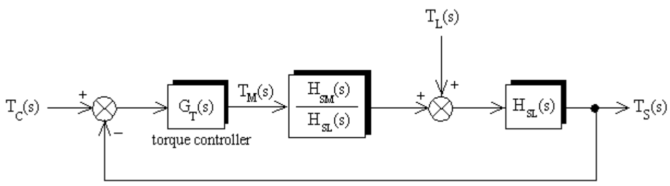

Fig. 5. Two-mass system with torque control

III. Simulation Results

The two-mass resonance system is stable in the uncontrolled state due to the presence of poles with a negative real value, but because of the proximity of the poles to the imaginary axis, the shaft torque will fluctuate. The parameters utilized in the case study are shown in Table I.

TABLE I. TWO-MASS SYSTEM PARAMETERS

Symbol	**Value**	**Unit**
B_L	0.0688	Nm.s/rad
K_J	0.1789	-
J_L	0.0086	Kg.m^2
ω_L	53.5	rad/s
B_S	0.101	Nm.s/rad
K_S	137.6	Nm/rad
ω_R	138	rad/s
J_M	0.0479	Kg.m^2
ω_A	127.1	rad/s
B_M	0.00131	Nm/rad

In without controller mode, the characteristic equation has a negative real pole and two conjugate poles, that its imaginary part is almost equal to the system's resonant frequency. The eigenvalues of the system are -1.2426 and -10.26-j137.14.

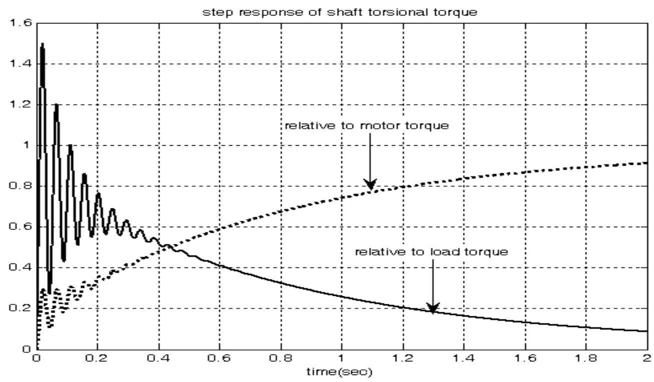

Fig. 6. Step response of the torsional torque

The response of the shaft torsional torque in the system without a control system is depicted in Fig. 6. This result is represented in response to step inputs of both the motor torque and the load torque. As can be seen, the oscillations in the shaft torque disappear after approximately 0.2 seconds, and the torque reaches its final value after roughly 2 seconds.

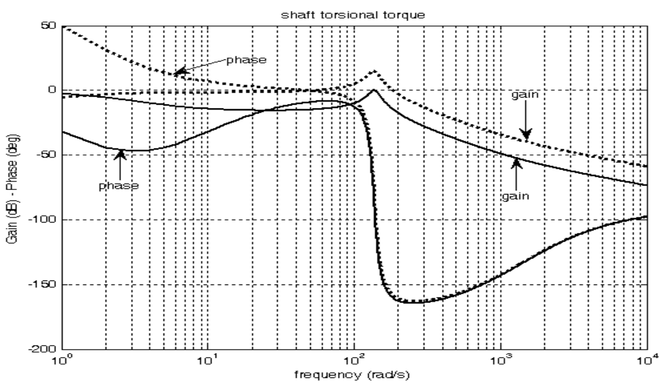

Fig. 7. Frequency response of shaft coupling transfer function

The frequency results of shaft coupling transfer function to motor shaft and load disturbance coupling is show in Fig. 4. The geometric location of the roots of the characteristic equation based on shaft hardness variation with torque control is show in Fig. 5. The geometric location of the roots of the characteristic equation based on changes in the integral coefficient of the controller with torque control is show in Fig. 6.

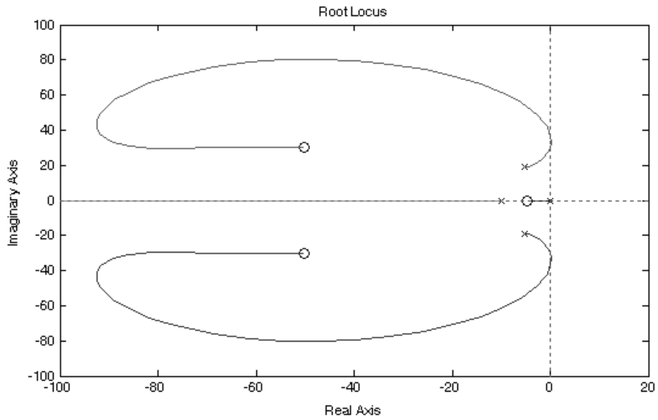

Fig. 8. Ggeometric location based on shaft hardness variation with torque control

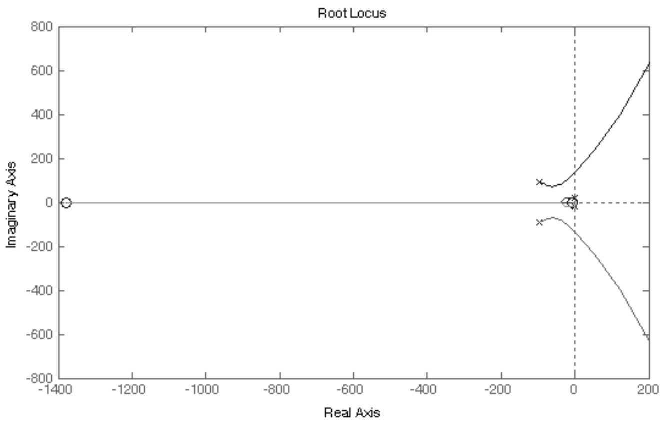

Fig. 9. Geometric location based on changes in the integral coefficient of the controller

As seen from the geometric location of the roots, the system is stable for all proportional gain values. But the integral and derivative interest stability criterion is:

$$K_D > \frac{J_M K_I}{K_P K_S + J_M \omega_R^2} \tag{11}$$

$$K_I < K_D(\omega_R^2 + \frac{K_P K_S}{J_M}) \tag{12}$$

Figs. 7 and 8 are demonstrated the outcomes of motor torque and shaft torque for three controllers PID, PID-P and I-PD, respectively. As it is seen, in PID controller, the overshoot value of the response is highest and in the I-PD mode there is no overshoot in the response. The getting instantaneous of the step response in the three controllers is the same, but the rise time in the I-PD controller has the lowest value. According to the numerical results presented in this paper, the effectiveness of the proposed control scheme is highly dependent on system parameters.

The proposed controller can be used in engineering systems because of its attributes of a straightforward structure, practical parameter, and simple application. However, when designing controllers, it is assumed that the system models are known and that the system's flexible Shaf stiffness and resonant frequency are explicitly specified as design parameters. In real-world engineering applications like rolling machines, machine tools, and other mechanical systems with a flexible connection, measuring the system's parameter is challenging because of the unknown coefficient of the flexible Shaf. Artificial neural networks (ANNs) have become increasingly popular in recent years for use in the business world [28]. They've been used in a variety of manufacturing processes. Therefore, to address the issue of parameter uncertainty in two-mass resonant systems, the authors aim to evaluate the efficacy of applying artificial neural network-based estimators to the control architecture of the multi-mass electromechanical system in future work [29].

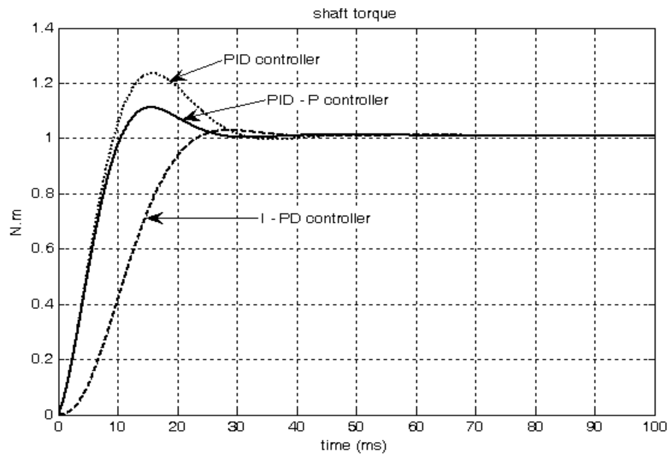

Fig. 10. Step response of shaft torque for three controllers

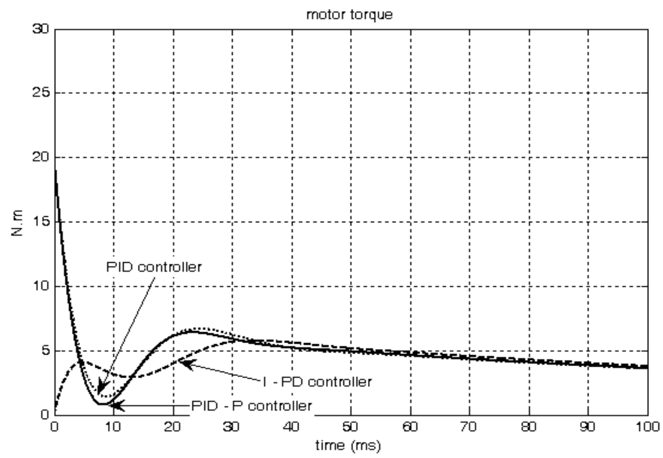

Fig. 11. Step response of motor torque for three controllers

IV. CONCLUSION

The aim of the torque regulation approach in the two-mass resonance system is to remove shaft coupling oscillations. The proposed control approach aims to minimize motor shaft rotational oscillations, mitigate the effect of load torque disturbances, develop a fast response to variations in the base speed without causing the load speed to expand, and be stable under a variety of conditions. This paper also presents a state-space description of the two-mass resonance system, and the block diagram was represented as a multi-input multi-output system. The simulation results in the time domain and frequency domain represent the controller's consequence on the dynamic reaction of the system. The effectiveness of the proposed control scheme is strongly reliant on system parameters, according to the results. Considering the inherent parameter uncertainty in the multi-mass system, future work could also consider using parameter estimators based on artificial neural networks (ANNs).

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