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A novel feedforward control technique for a flexible dual manipulator

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ABSTRACT

This paper proposes a feedforward control technique for two flexible links attached to one motor to suppress residual vibrations in a point-to-point motion. In the proposed method, we attempt to express the trajectory of the joint angle using a combination of cycloidal and polynomial functions, which enables the easy generation of a smooth motion. The generated trajectory depends on the coefficients of the polynomial function. To minimize the residual vibrations of the two flexible links, the coefficients are tuned using a particle swarm optimization algorithm, which is a type of a metaheuristic algorithm. The optimal trajectory obtained by this approach can suppress residual vibrations; i.e., multimode vibration control can be realized. Simulations and experiments are performed to evaluate the applicability and effectiveness of the proposed method.

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1. Introduction

To enable industrial robots to perform energy-conserving and high-speed operations, reducing the weight of robotic manipulators is desired. However, vibrations in such modified robotic manipulators occur easily because of their decreased rigidity. Thus, fundamental studies of vibration control in flexible manipulators have been widely undertaken by many researchers [1–3]. Feedforward and feedback schemes are two typical vibration control techniques. Feedforward schemes enable the suppression of unwanted vibrations without using sensors to measure the vibration. Therefore, when considering the construction and maintenance costs of controllers, feedforward schemes are said to be superior to feedback schemes, which require sensors.

Regarding recent studies on the feedforward control of flexible manipulators, Feliu et al. [4] investigated a method that combines feedforward control with an optimal mechanical design to cancel vibrations in a multimode single-link flexible manipulator. They employed the so-called dynamic model inversion technique derived from the discretization of the system dynamic model as the feedforward controller design. Kojima and Hiruma [5] used a genetic algorithm to present an evolutionary learning acquisition method of the optimal joint angle trajectories of a flexible robot arm for residual vibration reduction. Alam and Tokhi [6] applied a multiobjective genetic algorithm to design command-shaping techniques for the vibration control of a single-link flexible manipulator. Mimmi et al. [7] investigated the effectiveness of input preshaping techniques for flexible manipulators; in their investigation, they compared the results of traditional input shaping [8] with those of extra-insensitive input shaping [9]. Cole and Wongratanaphisan [10] presented a general approach to input shaping with finite impulse response (FIR) filters, the performance of which was evaluated experimentally with a laboratory-scale two-link manipulator having rigid and flexible links. They also presented an adaptive control method based on the FIR input-shaping methodology for achieving zero residual vibration in the rest-to-rest motion of flexible structures [11]. An approach based on the Gauss pseudospectral and direct shooting methods to optimize the joint trajectory of free-floating manipulators to reduce the vibrations of flexible links was proposed by Yihuan et al. [12]. Pereira et al. [13] addressed the vibration control problem for single-link flexible manipulators under large changes in the payload mass and proposed an adaptive input shaper composed of a robust input shaper and an algebraic identification of the natural frequency. Boscariol and Gasparetto [14] addressed the problem of the planning of a jerk-constrained trajectory for flexible-link mechanisms, in which a nonlinear FEM dynamic modeling was used for maximum accuracy. However, in the reports described above, constructing controllers was apparently difficult for engineers because of the complex methodologies.

Under these considerations, the authors of the present study [15,16] developed a trajectory planning method based on a particle

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swarm optimization (PSO) algorithm [17] for suppressing the residual vibration of a flexible manipulator system with a point-to-point (PTP) motion. In this method, the joint angle trajectory was expressed using a cubic spline function, and the interpolation points were regarded as optimized. Then, the optimized parameters were tuned by PSO so as to cancel the residual vibration. An advantage of this method is that the feedforward control scheme can be easily constructed using PSO. In addition, the present authors [18] demonstrated an energy-conserving feedforward control technique for suppressing the residual vibration of a flexible manipulator, in which an artificial neural network (ANN) used to generate the desired joint angle [19] was learned by a multiobjective optimization technique. By this technique, they confirmed that under the residual vibration suppression, additional energy conservation was achievable relative to the previous method in which a cubic spline was used. Because an ANN can generate a smooth trajectory [19], this technique can be used to suppress the residual vibration in flexible structures [20,21]. However, the computational cost is increased in the ANN because many optimized parameters are required for optimal trajectory generation.

In this paper, we propose a simple feedforward control scheme for suppressing the residual vibration of a flexible manipulator system with a PTP motion, which consists of two flexible links attached to one motor hub. Note that the natural frequencies differ in the two flexible links. In previous studies [18–21], the trajectory of the manipulator was generated by giving the output of the ANN as the input of a cycloidal function. Herein, we attempt to employ a polynomial function introduced by Narita [22] for vibration analyses of anisotropic rectangular plates. Contrary to that in the ANN, the trajectory depends on the coefficients of the polynomial function. To cancel the residual vibrations of the two flexible links, the coefficients are tuned by PSO. By driving the joint angle of the manipulator along the optimal trajectory, the residual vibrations can be suppressed; i.e., feedforward vibration control can be achieved. We performed experiments based on offline simulation to verify the validity of the vibration control method. Results obtained from the simulations and experiments demonstrate that the present method suppresses the residual vibrations of the two flexible links.

2. Experimental setup and mathematical model

Fig. 1 shows a photograph of the flexible dual-manipulator system used as the experimental setup in this study, which has two flexible links attached to one motor hub. Brass beams of 550 mm in length, 50 mm in width, and 0.8 mm in thickness were used as the flexible links. The size of the two flexible links was the same, whereas a weight with a mass $m=36$ g was attached to the endpoint of the flexible link 1. The displacement of the flexible links was measured using a strain gauge attached at a distance of 30 mm from the clamped end. The joint angle (i.e., the rotation angle of the hub) was actuated by an AC servomotor (SGMMJ; Yaskawa Electric Corp.). The servomotor was operated in the speed control mode using a servo drive unit (DGDV; Yaskawa Electric Corp.). The measurement and control of the experimental setup were implemented on a digital signal processing board (DS1104; dSPACE GmbH) with a sampling time of 2 ms.

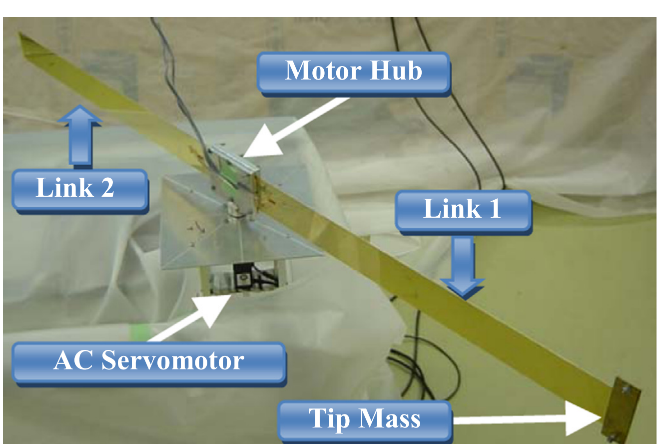

Fig. 1. Photograph of the experimental setup.

The performance of feedforward controllers is well known to depend on the accuracy of the mathematical models of controlled objects. Therefore, precision mathematical models must be used. To obtain an accurate mathematical model of the manipulator system, we performed an identification experiment and theoretical analysis. The equation of motion for the flexible links i ($i=1$, 2) was then obtained as follows [16]:

$$\ddot{W}_i + 2\varsigma_i\omega_i\dot{W}_i + \omega_i^2 W_i + \alpha_i\ddot{\theta} + \beta_{1i}W_i\dot{\theta}^2 = 0, \ (i = 1, 2), \tag{1}$$

where W_i signifies the displacement of the first vibration mode of the flexible link i, and θ is the joint angle. The values of the coefficients ω_i, ζ_i, α_i, and β_{1i} are as follows:

$$\left.\begin{array}{l} \omega_1 = 7.961 \ \text{rad/s}, \ \ \varsigma_1 = 9.636\times10^{-3}, \ \ \alpha_1 = 3.899\times10^{-1}\ \text{kg m}^2, \ \ \beta_{11} = 3.583\times10^{-3} \\ \omega_2 = 10.37 \ \text{rad/s}, \ \ \varsigma_2 = 1.967\times10^{-2}, \ \ \alpha_2 = 2.389\times10^{-1}\ \text{kg m}^2, \ \ \beta_{12} = 3.020\times10^{-3} \end{array}\right\}. \tag{2}$$

Note that ω_i denotes the natural frequency of the flexible link i. The derivation of the equations of motion is detailed in Appendix A.

3. Optimal trajectory generation method

As described in this paper, we considered a PTP control problem of the flexible dual manipulator system for a fixed target angle θ_E and traveling time T_E. We then attempted to generate the optimal trajectory of the joint angle $\theta_{opt}(t)$ by suppressing the residual vibrations of the two links simultaneously. The concept of the proposed method can be illustrated using the scheme presented in Fig. 2. As shown in the figure, we used a polynomial function, for which the input was given by time t until the traveling time T_E. The polynomial function is defined as follows:

$$u(t) = \frac{t}{T_E} + (1 - T^2)^2 \sum_{n=1}^{N} a_n T^{n-1}, \tag{3}$$

where

$$T = -1 + \frac{2t}{T_E}. \tag{4}$$

The second term of the right-hand side of Eq. (3) denotes a displacement function introduced by Narita [22] for vibration analyses of composite laminated rectangular plates. Using this displacement function, the complex vibration modes of composite laminated plates and shells have been investigated (e.g., [23,24]). Thus, we employed the polynomial function in the trajectory planning method. For the PTP motion of the manipulator, the angular velocity and acceleration are desired to be equal to zero at the start and end points. Therefore, we imposed the boundary

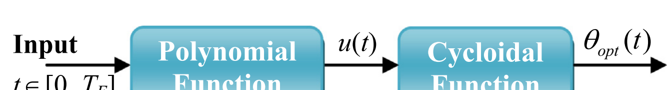

Fig. 2. Schematic of the trajectory generation.

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