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An effective trajectory planning method for simultaneously suppressing residual vibration and energy consumption of flexible structures

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ABSTRACT

This paper presents a proposal for a minimum energy feedforward control technique for flexible structures to suppress residual vibrations in point-to-point (PTP) motion. In the proposed method, the trajectory profile of the PTP motion is generated through a cycloidal function whose input is the output of a polynomial function. The obtained trajectory is dependent upon the coefficients of the polynomial function. To achieve the suppression of the residual vibration as well as the operating energy of this PTP motion, the coefficients are tuned by metaheuristic algorithms. In the numerical simulations, we investigated the PTP motions of a single-link flexible manipulator and a robotic arm attached to a flexible link. The simulation results were compared with those of previous studies, revealing the effectiveness of the proposed method.

1. Introduction

Flexible manipulators, which comprise thin slender arms, can enable higher-speed operation and lower energy consumption because their weight is typically lower than that of a rigid manipulator. Moreover, light-weight manipulators are beneficial for cutting down transport costs of industrial or space robots. Therefore, flexible manipulators are superior to rigid manipulators in the above respects. However, it is well known that flexible manipulators are easily deformed due to their low flexibility; therefore, unwanted vibrations, which have a harmful effect on working effectiveness, occur easily. Thus, to avoid the unwanted vibrations of flexible manipulators, many researchers have attacked the vibration problem and have presented various control schemes [1–3]. In particular, trajectory planning methods are one of the best ways to control the vibrations for point-to-point (PTP) motion tasks of flexible manipulators [4–19]. However, to the best of the author's knowledge, studies on reducing the operation energy required to run manipulators have been limited to rigid manipulators (e.g., [20–22]). A trajectory planning method that simultaneously suppresses the residual vibration and driving energy of a flexible manipulator has not been presented. Energy savings for flexible manipulators are very important for space robots because there is a limited amount of energy available for tasks.

With this background in mind, a trajectory planning method was developed; it enables to simultaneously minimize residual vibrations and the driving energy for a single-link flexible manipulator [23] and a robotic arm mounted on a flexible link [24]. For this trajectory planning method, an artificial neural network (ANN) was employed to generate the joint angles

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of both manipulator [23] and robotic arm [24]. Because the generated joint angle trajectory depends on the parameters of the ANN, we tuned the parameters to simultaneously minimize the residual vibration and driving energy. Therefore, for this minimization, metaheuristic algorithms were utilized. One notable feature of the trajectory planning method is that one can easily construct an energy-conserving open-loop controller because the methodology is based on metaheuristic algorithms. However, although the ANN can generate a smooth trajectory, many parameters are required; thus, the computational cost to do so is relatively high. Conversely, the author in reference [25] also dealt with PTP motion of two flexible links attached to one motor hub and proposed trajectory planning methodology to cancel the residual vibrations; for this, a combination of cycloidal and polynomial functions was utilized to generate the trajectory. It was demonstrated that by tuning only four parameters multimode vibration control could be achieved. Because this trajectory planning method enables the easy generation of a smooth motion, there is a strong likelihood that further energy saving of flexible structures will be achieved by using it.

In this study, we investigate the possibility of further reducing the driving energy for PTP motion of flexible structures; to achieve this, we employ a combination of cycloidal and polynomial functions to generate the trajectory [25]. The trajectory profile developed here is dependent upon the coefficients of the polynomial function. To accomplish the minimization of not only the driving energy but also the residual vibration of the PTP motion, the coefficients were tuned by metaheuristic algorithms; thus, the optimal trajectory can be obtained. We performed the numerical simulations for a single-link flexible manipulator and a robotic arm attached to a flexible link. Then, we compared the results with those of previous studies [23,24]. This comparison demonstrates that the proposed method is superior at increasing energy savings. The main contribution of this paper is to show that the trajectory planning method developed here for a PTP motion of a flexible manipulator system can achieve further energy saving with zero residual vibrations.

2. Optimal trajectory profile

In the present study, we studied a PTP motion task of a flexible manipulator system that has one revolution joint; we try to generate an optimal trajectory enabling the suppression of residual vibration under minimum energy conditions. The optimal trajectory profile of the joint angle is given as follows using a cycloidal function:

$$\theta_{opt}(t) = (\theta_E - \theta_S)\left\{U(t) - \frac{1}{2\pi}\sin[2\pi U(t)]\right\} + \theta_S, \tag{1}$$

where θ_S, θ_E, and T_E are the initial angle, target angle, and travelling time for the PTP motion, respectively. The input function of time t is denoted by $U(t)$. The differentiation of Eq. (1) yields the profiles of the angular velocity and acceleration:

$$\dot{\theta}_{opt}(t) = 2(\theta_E - \theta_S)\sin^2[\pi U(t)]\,\dot{U}(t), \tag{2}$$

$$\theta_{opt}(t) = (\theta_E - \theta_S)\sin[\pi U(t)]\,\{2\pi\cos[\pi U(t)]\,\dot{U}^2(t) + \sin[\pi U(t)]\,U(t)\}. \tag{3}$$

For the cycloidal motion, the input function is defined as

$$U(t) = \frac{t}{T_E}. \tag{4}$$

We can confirm from Eqs. (1)–(4) that the cycloidal motion naturally satisfies the boundary conditions as

$$\left.\begin{array}{l} \theta_{opt} = \theta_S, \dot{\theta}_{opt} = \theta_{opt} = 0, \text{for} U = 0 (t = 0) \\ \theta_{opt} = \theta_E, \dot{\theta}_{opt} = \theta_{opt} = 0, \text{for} U = 1 (t = T_E) \end{array}\right\}; \tag{5}$$

that is, smooth motion is generated, in which the velocity and acceleration are equal to zero at the start and end points of the PTP motion. However, the cycloidal motion induces large residual vibrations in the PTP motion [13,16,23–25].

Thus, in the present study, we attempt to express the input function as

$$U(t) = \frac{t}{T_E} + (1 - T^2)\sum_{n=1}^{N} a_n T^{n-1}, \tag{6}$$

where

$$T = -1 + \frac{2t}{T_E}. \tag{7}$$

The input function in Eq. (6) meets the conditions $U = 0$ for $t = 0$ and $U = 1$ for $t = T_E$; that is to say, smooth motion satisfying the boundary conditions in Eq. (5) can be generated. The polynomial function in Eq. (6) shapes the input of the cycloidal function and then an arbitrary trajectory profile can be obtained from Eq. (1) [25]. In this case, the trajectory profile is dependent upon the coefficients a_n in the polynomial function. Hence, it is necessary to tune the coefficients so as to simultaneously minimize the residual vibration and operating energy of a flexible manipulator system. In the present study, we employ a