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Vibration suppression of rotating long flexible mechanical arms based on harmonic input signals

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ABSTRACT

The industrial long flexible arms usually have nonuniform cross sections and complex structures, leading to the difficulty of establishing accurate models. Moreover, the delay of dynamic response leads to the complexity of the state test and control. Correspondingly, the rotating residual vibration is difficult to control using existing feedback control methods. To this end, a feedforward strategy is presented in this paper to suppress the residual vibration of long flexible mechanical arms. Based on the Lagrange equation, an equivalent rotational flexible dynamic model is established. The model approximately describes the dynamic characteristics of long flexible arms, which exploits the existing mathematical foundation and extends it from the laboratory validation to the industrial application. It can be found that the starting and stopping signals are closely related with the residual vibration. According to harmonic response analysis, the input signals during the starting and stopping process are refined by using weighted Fourier series so as to suppress the residual vibration without considering input shaping filters. The performance is tested in the real industrial equipment that has long flexible arms, which validate the effectiveness of the proposed method.

1. Introduction

Flexible mechanical arms are widely used in the high-technique fields, including the aerospace, industrial robots, concrete pump trucks and overhead working cars [1–3]. Flexible arms have several attractive characteristics, such as the high ratio of load over self-weight, high efficiency, low energy consumption and flexibility. Recently, the flexible arms are becoming longer, and their motion characteristics have a great impact on (or even determine) the performance of the whole equipment. The rotation irregularity of long flexible arms will cause the residual vibration during motion, as well as the instability and fatigue failure, and seriously affect the fatigue life of the equipment [4–7]. Therefore, improving the rotation regularity and eliminating the vibration during the starting and stopping processes are key topics in both academic and industrial research.

Research on the flexible arms and their vibration control mainly focuses on the dynamics model, the numeric calculation, the laboratory validation, and the investigation of natural frequencies and modes of vibration characteristics [8–12]. In addition, many of existing studies on residual vibration control are at the stage of theoretical verification in a laboratory. Generally, there are two kinds of methods to suppress the residual vibration: the closed loop control and the open-loop control. Examples of the closed loop control methods include the sliding mode control [13,14], adaptive control [15], Modal control [16], high

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order harmonic control technology (HHC) [17], fuzzy control [18], intelligent PI control [19], PD control [20], and so on. Most of them require accurate models and the model based control for flexible arms is very difficult [21]. In addition, sensors are required to measure the vibration of the end points of the long flexible arms for all the closed-loop control methods, and the measurements are difficult to be implemented in industrial long flexible arms. The open-loop control methods do not have such high requirements on the model and do not need additional sensors. Among them, the input shaping is the most widely studied one ([22–25]). Although many variants exist for the input shaping method, the basic principle is consistent: the input shaping signal is the convolution of the initial input signal and a series of pulse signals. However, it needs to design input shaping filters under some constraints. The design parameters include the period, the pulse number, and the amplitude of the pulse signals.

The research object of this paper is the industrial long mechanical flexible arms. Due to its characteristics of non-uniform cross sections, complex structures and coupling of components [26], it is difficult to establish an accurate dynamic model. Meanwhile, the delay of dynamic response leads to the complexity of the state test and control, and thus, it is very difficult to use closed-loop control. Therefore, in this paper, a novel feedforward control approach is proposed with easier implementation in industrial long flexible arms. The main ideas are as follows:

(1) An equivalent rotation dynamics model for industrial long flexible arms is established from the view of energy based on the Lagrange equation, which exploits the existing mathematical foundation and extends it from the laboratory validation level to the industrial application level. Based on the model, the impact of the input excitation on the residual vibration is investigated.
(2) By exploiting the property that all bounded periodic functions can be expanded as Fourier series, a feedforward control strategy is proposed without considering input shaping filters. To be specific, for the object of zero residual vibration, the input signals during the starting and stopping processes are revised with weighted Fourier series.
(3) The performance is tested in the real industrial equipment that has long flexible arms instead of experiments in the lab.

The remainder of this paper is organized as follows. Section 2 briefly establishes the rotation dynamics model of long flexible arms. Section 3 conducts numerical calculation and experimental verification for the dynamics model, to show the rotation dynamic characteristics of long flexible arms. Section 4 proposes a novel feedforward vibration suppression strategy based on harmonic excitation. Section 5 conducts experimental verification. Section 6 describes the detailed adjustment of input excitation for multiple-link flexible arms. Finally, Section 7 concludes this paper and summarizes the achievements.

2. Rotation dynamics modeling of long flexible mechanical arms

Industrial long flexible mechanical arms usually have large inertia and large size. Besides the deformation of the rotation of the flexible arms, they also suffer from serious lags in the end point response. Generally, after starting the rotation, the end point is lagged behind with residual vibration, causing the phenomenon of the so-called “one fast, one slow.” After stopping, there exists damping vibration at the end point. Finally, the end point stops at the equilibrium position (i.e., the connecting line between the center of rotation and the end point in stable state). Therefore, the rotation dynamics and the vibration suppression of long flexible arms are typical structural dynamics problems: the input signal (e.g., the driving torque) acts directly on the flexible mechanical arm system and the output signal (e.g., the vibration, the rotation angle, the displacement, etc.) is the system response, which is shown in Fig. 1(a).

Because of the non-uniform cross sections and complex structures, it is very difficult to establish accurate mathematical models for long flexible arms. Considering the computational efficiency, we use the equivalent section moment of inertia to simplify a flexible arm to the Euler-Bernouli beam as shown in Fig. 1(b). The model can approximately describe the rotation dynamics characteristics. Therefore, by studying the relation between the input signal and the residual vibration, we find that the starting and stopping signals are closely related with the residual vibration. Thus, the vibration suppression could be achieved by conditioning the input signals to make the residual vibration be close to zero.

The position vector of a point P in a flexible arm is $\mathbf{r_p} = \mathbf{A}[x, \omega]^T$, and the rotation speed vector in the inertial coordinate system XOY is as follows:

$$\dot{\mathbf{r_p}} = \begin{bmatrix} -x\dot{\theta}\sin\theta - \dot{\omega}\sin\theta - \omega\dot{\theta}\cos\theta \\ x\dot{\theta}\cos\theta + \dot{\omega}\cos\theta - \omega\dot{\theta}\sin\theta \end{bmatrix}, \dot{x} = 0, \tag{1}$$

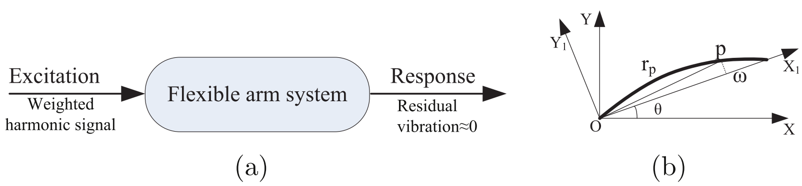

Fig. 1. (a) The excitation and response of a rotary flexible arm and (b) the basic description of the rotation dynamics of the flexible arm.