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Dynamic modeling and adaptive vibration suppression of a high-speed macro-micro manipulator

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ABSTRACT

This paper presents a dynamic modeling and microscopic vibration suppression for a flexible macro-micro manipulator dedicated to high-speed operation. The manipulator system mainly consists of a macro motion stage and a flexible micromanipulator bonded with one macro-fiber-composite actuator. Based on Hamilton's principle and the Bouc–Wen hysteresis equation, the nonlinear dynamic model is obtained. Then, a hybrid control scheme is proposed to simultaneously suppress the elastic vibration during and after the motor motion. In particular, the hybrid control strategy is composed of a trajectory planning approach and an adaptive variable structure control. Moreover, two optimization indices regarding the comprehensive torques and synthesized vibrations are designed, and the optimal trajectories are acquired using a genetic algorithm. Furthermore, a nonlinear fuzzy regulator is used to adjust the switching gain in the variable structure control. Thus, a fuzzy variable structure control with nonlinear adaptive control law is achieved. A series of experiments are performed to verify the effectiveness and feasibility of the established system model and hybrid control strategy. The excited vibration during the motor motion and the residual vibration after the motor motion are decreased. Meanwhile, the settling time is shortened. Both the manipulation stability and operation efficiency of the manipulator are improved by the proposed hybrid strategy.

1. Introduction

Currently, macro-micro manipulators are essential and popular devices in the fields of microassembly and micromanipulation, such as microcomponent assembly [1], biological cell manipulation [2,3], and minimally invasive surgery [4]. Generally, a macro-micro manipulator is constructed by mounting a flexible micromanipulator onto a macro motion stage. Initially, the macro stage is used to produce a large-scale motion between the pick and place areas, and the distance is several millimeters or even tens of millimeters. Meanwhile, the micromanipulator is employed to accomplish a high-precision manipulation and its resolution can be up to micro level or nanometer level. However, micro-operation objects also

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exhibit a limited life span and a huge quantity in various high-through applications [5]. Accordingly, both high speed and large scale are desirable in these manipulation systems. On the other hand, micromanipulators are usually actuated by piezoelectric actuators, and their precision motion is delivered by flexible components using elastic deformations [6,7]. This is because piezoelectric actuators have several merits including ultrahigh-resolution motion, large bandwidth and fast response [8]. In fact, flexible systems have been widely used in many practical engineering applications, such as flexible manipulators for multiple degrees of freedom (DOFs) manipulation [9,10], automated assembly systems for micro-object operation [11,12], scanning stations for nanocharacterization [13], positioning system for micro/nano environment [14], cables for positioning the payload [15,16], industrial moving strips for metal sheeting [17], and robotic arms [18,19]. The flexible components exhibit certain advantages in terms of high resolution, lightweight, efficiency and repeatable motion [20].

However, the structural flexibility of micromanipulators also results in the presence of unwanted vibrations during and after the macro motion. In a typical 6-DOF manipulation system, the undesirable residual vibration has a maximum amplitude of 25.9 μm, and a long settling time of 173 ms [2]. The vibration amplitude is approximately 43.2%–64.8% of the micro-operation object (40–60 μm). Moreover, the settling time accounts for 49.4% of the total positioning time (350 ms). Therefore, the positioning accuracy and the manipulation efficiency are significantly reduced by the excited vibration. Meanwhile, the system state becomes unstable and it is relatively difficult to control such a manipulator system [21]. Accordingly, vibration suppression in the microscopic scale is desirable but difficult. Moreover, the dynamics of a flexible system is essentially a distributed parameter system, which has an infinite-dimensional state space. Generally, the dynamic model of a flexible system can be derived using coupled partial differential equations (PDEs) and ordinary differential equations (ODEs) [22]. For the control of flexible systems, one effective method is to design a control based on the original PDEs without any model discretization. In particular, a boundary control using sensors and actuators at the boundary draws a lot of attention [23]. This is because the dynamic model of the flexible system is not affected, and the spillover problem is avoided. In the past, many papers about boundary control have been reported, making great contributions to the vibration suppression of flexible systems. Based on the Lyapunov approach, reference [24] developed an output feedback boundary control for a flexible beam with an input disturbance. In Refs. [25,26], a boundary control based on Lyapunov's method is proposed for the vibration control of flexible structures. In Ref. [27], a boundary control for both wing twist and bending is proposed, and the control stability is proved by introducing a suitable Lyapunov function.

Another popular control method is based on the discretization or simplification of the PDEs into a finite number of ODEs [28]. To date, many vibration suppression techniques based on ODEs have been reported. These methods contain the feedforward control (i.e., the input command shaping [6,29] and trajectory planning [21,30]) and feedback control (e.g., the linear velocity feedback [31], proportional-integral- derivative (PID) control [32], fuzzy control [33,34], positive position feedback (PPF) control [35,36] and neural network control [28]). The feedforward control does not need additional sensors and the system structure is more compact. However, the input command shaping requires many calculations and it cannot reduce the existing vibrations [18]. On the other hand, the trajectory planning approach is advantageous owing to its effectiveness and simplicity. However, this approach suppresses the elastic vibrations in open loop and its control results are determined by the system model. As a result, large unwanted vibrations would occur because system disturbances and model uncertainties are inevitable [30]. To solve the drawbacks of the feedforward control, various researchers develop feedback control techniques to suppress the elastic vibration. However, most studies focus on the improvement of the control performance and the feedback control usually responds after the vibration appears [6,37]. Therefore, the feedback control alone cannot suppress the vibration before it occurs, resulting in poor reactive performances. Alternately, it will be more efficient and promising if a hybrid control strategy combining the feedforward control and feedback control is considered. In particular, the feedforward control can be responsible for the rough vibrationless motion of the manipulator through the trajectory planning approach of the macro stage. Meanwhile, the feedback control can be used to deal with vibrations that may arise from modeling errors and external disturbances during and after motor motion using the active control of the piezoelectric actuators. Thus, a preliminary vibration suppression is performed by the trajectory planning approach and the feedback control can decrease any remaining vibration.

One challenge of the hybrid strategy is designing the motion trajectory reasonably. Although various trajectories have been proposed, most of them are only effective for residual vibrations after the motor motion. Few trajectories can decrease the excited vibration during motor motion, not to mention the simultaneous vibration suppression during and after the motor motion. Another challenge arises from the limited actuation capability of conventional piezoelectric actuators, but this can be avoided by using macro-fiber-composite (MFC) actuators [38]. The MFC actuator is composed of piezoelectric ceramic fibers embedded in epoxy layers. Thus, it contains several unique merits including large output, high precision, flexible nature and damage tolerance [39]. Nevertheless, similar to other types of smart actuators (e.g., the conventional piezoelectric actuator [6–8,20], shape memory alloy [40], and ionic polymer metal composite [41,42]), the MFC actuator also exhibits a severe nonlinear hysteresis phenomenon. To investigate the hysteresis property, many hysteresis models including operator-based models (e.g., Preisach model [43] and Prandtl–Ishlinskii model [44,45]) and differential-equation models (e.g., Dahl model [46], Duhem model [47] and Bouc–Wen model [48,49]) were proposed. Typically, the operator-based models can be very accurate when the number of hysteresis operators is high enough. However, increasing the hysteresis operators also brings difficulties in practical implementation. On the other hand, differential-equation models outperform the operator-based ones in terms of fewer model parameters [38,50]. As a result, the differential-equation model especially the Bouc–Wen model is promising. However, most reported hysteresis models deal with the precision positioning of compliant mechanisms [51]. In the fields of vibration suppression, the hysteresis effect is generally ignored or modeled with a fixed long beam in macro scale.