Experimental Investigation on the vibration Control of a Parallel Manipulator with Multiple Smart Flexible Links

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Abstract

This work presents the experimental investigation of the active vibration control of a 3–PRR parallel manipulator with three flexible intermediate links. Each flexible link is equipped with three collocated PZT sensors and actuators bonded to the flexible link to control unwanted link structural vibration. An active vibration controller is developed and designed in the independent modal space using modal filters. To permit this control to be implemented in real-time, the active vibration control experimental system is developed using a two-CPU programming technology based on LabVIEW Real-Time. Active vibration experiments are conducted, and experimental results validate the effectiveness of the proposed vibration control strategy.

Keywords: Parallel Flexible manipulator, Modal filter, PZT transducers.

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1. INTRODUCTION

There has been increasing interest in the use of smart structures to address the problem of vibration control in flexible structures. A promising smart structure transducer is the surface-embedded lead zirconate titanate (PZT) sensor/actuator. A number of control design techniques have been proposed for active vibration control of flexible structures. Positive position feedback (PPF) [1-2], velocity feedback or strain rate feedback (SRF) [3-4], and resonant control [5] are three typical examples of such control techniques. The presence of uncontrolled modes can lead to the problem of spillover [6]. The independent modal space controller (IMSC) [7-8] was developed and applied to the active vibration control of flexible structures to prevent control spillover. To effectively implement the independent modal space controller, it is very important to sense modal coordinates in real time [9, 10].

There are many simulation and experiment demonstrations of active vibration control in the space-based flexible structures and simple flexible beams [1-10]. A few researchers introduced PZT transducers for the vibration control of manipulators and mechanisms [11-12]. However, most of the early research work involved the active vibration control of manipulators and mechanisms with a single link with a single bonded actuator and sensor. Compared with numerical simulation, few investigations have been conducted towards experimental investigations, especially for parallel manipulators with multiple flexible links, due to their complicated dynamics. Our preliminary work [13-18] conducted the experimental and theoretical investigation of active vibration control of a 3-PRR parallel manipulator with three flexible intermediate links with PZT transducers bonded to these flexible intermediate links during high speed and acceleration manipulator manoeuvres. Previous work [13, 14] presented the dynamic simulation and Strain Rate Feedback control of structural vibrations on a flexible 3-PRR parallel manipulator. Preliminary experimental investigations carried out by these authors in [15] implemented active vibration control experiments of the planar parallel manipulator based on SRF control again on a single link, and experiments in [16, 17] were performed with only one PZT sensor and actuator control pair bonded to each intermediate link at its midpoint. Our results presented in [18] used three PZT sensor/actuator control pairs but active vibration control was only implemented on one flexible link.

To extend our preliminary work, this paper presents an experimental investigation of the active vibration control of a 3-PRR parallel manipulator with three flexible links, with three PZT actuator and sensor pairs bonded to each flexible linkage. To implement the controllers in real time, the vibration control experiments are conducted using parallel processing of the sensing and control algorithms within the LabVIEW Real-Time programming environment. The controller is designed in the modal space based on strain rate feedback control, and the simplified modal filters are used to sense the modal coordinates and velocities in real time. Experimental results demonstrate that the proposed control strategy can achieve effective vibration suppression of a moving parallel manipulator with three flexible links, each of which is equipped with three bonded PZT sensor/actuator pairs.

2. PROBLEM DESCRIPTION

A planar 3-PRR manipulator, as shown in Figures 1, is developed to provide a high-speed and high-accuracy positioning and orienting mechanism. The parallel manipulator is categorized as a 3-PRR type because it has three symmetrical kinematic chains, each of which has one active prismatic (P) joint followed by two consecutive passive revolute (R) joints. The detailed structure and parameters were provided in [13, 19]. To reduce inertia and meet the demands of high speed and acceleration, intermediate links are built to be lightweight. The length of each intermediate link is 200mm, and the cross-sectional dimension of each link is 30$mm\times20mm$. Such lightweight links are more likely to deflect and vibrate due to the inertial forces and external forces from the driving motors.

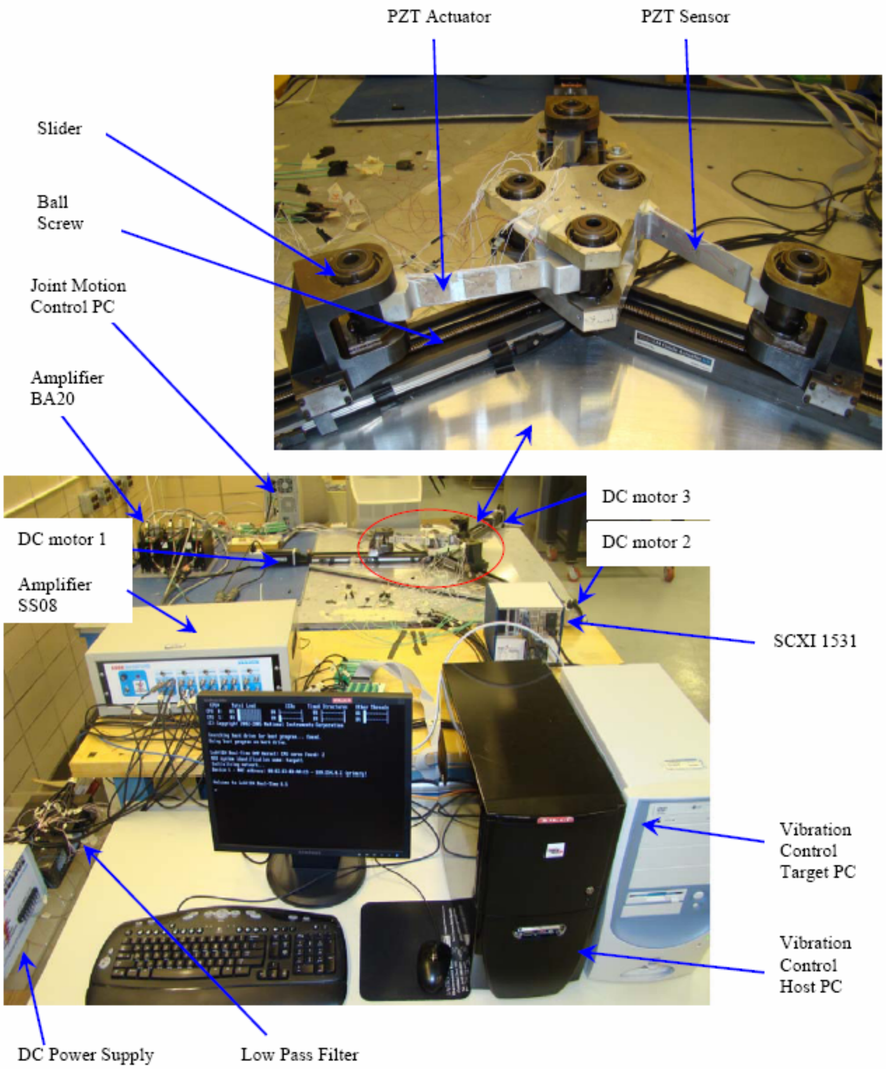

Fig. 1. Photograph of the active vibration control system setup

3. DYNAMICS AND CONTROLLER DESIGN

Dynamic modeling and strain rate feedback control design are presented in detail in our previous work [13], and therefore, this part of work is only briefly introduced in this section.

3.1 Dynamic Equations

Using the assumed mode method based on pinned-pinned boundary conditions, the dynamic equations of the parallel manipulator with three flexible links were developed and given as [13]

$$M\ddot{\overline{\eta}} + D\dot{\overline{\eta}} + K\overline{\eta} = F_d + F_a \tag{1}$$

where M is the system modal mass matrix, D is the modal damping matrix, K is the structural modal stiffness matrix, $\overline{\eta} = [\eta_1 \quad \eta_2 \quad \cdots \quad \eta_r]^T$, F_d reflects the modal force from the effect of the rigid-body motion on the elastic vibration of the flexible links, and the coupling between the rigid-body motions and the elastic motions. The detailed expressions for M, K and F_d are given in [13]. F_a is the modal control force vector and is dependent on the bending moment created by the PZT actuators.

3.2 Smart Structure

The "smart" structure aspects of the system proposed here refers to the use of PZT sensor and actuator system and corresponding active control system. A smart structure was built by bonding PZT sensors/actuators to the two sides of the intermediate linkage as shown in Figure 1. The PZT patches on one side of the link acts as sensors, while the PZT patches on the opposite link face acts as actuators. One sensor and one actuator constitute a PZT control pair based on the strain rate feedback control strategy, and are located at the same position along the length of each intermediate link.

A PZT actuator in a smart structure functions as a bending moment, $M_a(t)$, applied on the linkage over the length of the actuator, expressed as

$$M_a(t) = K_a V_a(t) \tag{2}$$

where $V_a(t)$ is control voltage applied to the PZT actuator. The detailed expression is given in [13].

A PZT sensor monitors the strain or stress of the linkage and responds by outputting a voltage $V_s(t)$. $V_s(t)$ is given

$$V_s(t) = K_s[\frac{\partial^2 w}{\partial x^2}(x_k, t)] \tag{3}$$

where K_s is the sensor constant (the detailed expression is given in [13]), w is the lateral deformation of the link (m), and x_k is the distance from the PZT sensor to the link base join close to the slider.

3.3 Strain Rate Feedback Control

The strain rate feedback is adopted for the vibration controller. Using strain rate feedback, the control voltage applied a PZT actuator is given

$$V_a(t) = -g_a \dot{V}_s(t) = -g_a K_s[\frac{\partial^2 \dot{w}}{\partial x^2}(x_k, t)] \tag{4}$$

where g_a is feedback gain. Using modal transformation $w(x,t) = \sum_{i=1}^{r} \psi_i(x)\eta_i(t)$, the modal force vectors produced by the PZT actuator is expressed

$$F_a = -g_a K_s K_a \begin{bmatrix} (\psi_1'(x_{k2}) - \psi_1'(x_{k1}))\psi_1''(x_k) & \cdots & (\psi_1'(x_{k2}) - \psi_1'(x_{k1}))\psi_r''(x_k) \\ \vdots & \vdots & \vdots \\ (\psi_r'(x_{k2}) - \psi_r'(x_{k1}))\psi_1''(x_k) & \cdots & (\psi_r'(x_{k2}) - \psi_r'(x_{k1}))\psi_r''(x_k) \end{bmatrix} \begin{pmatrix} \dot{\eta}_1 \\ \vdots \\ \dot{\eta}_r \end{pmatrix} = -C\dot{\overline{\eta}} \tag{5}$$

Substituting equation (5) into equation (1), the equation (1) is rewritten

$$M\ddot{\overline{\eta}} + (C + D)\dot{\overline{\eta}} + K\overline{\eta} = F_d \tag{6}$$

Equation (6) clearly shows that the essential contribution of the strain rate feedback control is to introduce the additional damping C into the flexible manipulator system, and hence suppress the vibration of the flexible links.

3.4 Independent Modal Space Control Implementation

To prevent control spillover and decouple the control system, it is desirable to design the feedback controller in the independent modal space so that each targeted mode is controlled by one independent modal controller. In practice, the output voltage of a PZT sensor corresponds to the physical coordinate, not the modal coordinates. Therefore, to implement IMSC control, the modal coordinates must be extracted from the output voltages of discrete PZT sensors in real time. Modal filters provide a solution to this problem. The modal filter expression for the i^{th} smart link is expressed as

$$\overline{\eta}_i(t) = \Phi \overline{V}_s(t) \tag{7}$$

where $\overline{\eta}_i = \left(\eta_{i1}(t) \quad \eta_{i2}(t) \quad \cdots \quad \eta_{ir}(t)\right)^T$ is modal coordinate vector of the i^{th} intermediate link, $\overline{V}_s = \left(V_{s1}(t) \quad V_{s2}(t) \quad \cdots \quad V_{sm}(t)\right)^T$ is the output vector of the m sensors bonded to the i^{th} intermediate link, and Φ is a $r \times m$ modal coordinate transformation matrix or modal analyzer. Matrix Φ is given as

$$\Phi = \frac{1}{K_s}(\psi^T \psi)^{-1} \psi^T \tag{8}$$

The matrix ψ is calculated with the values of the mode shape function at the discrete sensors. Note that it assumed the effect of PZT actuators and sensors on the mode shapes is negligible in this work.

Using the modal synthesizer, the modal control voltages are then transformed to the control voltages in physical space and then used as inputs to the PZT actuators. A compensator is included in series with each modal SRF controller to cut off amplified noise and unmodeled vibration signal at high frequencies due to the differentiation operations [3, 16].

4. EXPERIMENTAL SETUP

The experimental setup consists of a three-axis joint control system, a parallel manipulator with three flexible links, and a real time active vibration control system.

The three-axis motion control system is a PC/DSP based hybrid control system. The hardware architecture consists of a joint motion control PC, a MCX-DSP-ISA 120Mflop/sec DSP controller, three Aerotech BM200 DC brushless motors, and three corresponding BA20 SineDrive amplifiers. The details about the joint motion control system were presented in our preliminary work [19].

The active vibration control system is developed using National Instruments LabVIEW Real-Time [20]. The control system consists of two PCs: a host PC and a target PC, as shown in Figure 1. Using LabVIEW programming, a LabVIEW Real-Time embedded control application is developed on the host PC, and then downloaded to, and run on the target PC. The two PCs communicate over Ethernet using TCP/IP. Two individual loops, namely the deterministic loop (the time-critical loop or control loop), and the nondeterministic loop (the communication loop) are programmed with the LabVIEW Real-Time Module. These loops run in separate threads at different priorities. The highest execution priority is set to the deterministic loop which contains deterministic control codes. The normal priority is set to the communication loop, which contains the network communication codes and logging data codes. Therefore, the real-time execution of the closed-loop controller can be guaranteed by prioritizing control tasks so that the most critical task always take control of the processor when needed. The two-CPU programming technique is used to further improve the real-time property of the control system by assigning one CPU for control and calculation, the other CPU for data logging. The active vibration controller is developed with the identical architecture for each intermediate link with bonded PZT transducers. The voltage signal from a PZT sensor is filtered and amplified using an NI signal conditioner SCXI 1531, and then sampled by a NI A/D board PCI 6031E, which is installed inside the target PC. The generated voltage from the controller is sent to a low pass filter through a NI D/A board PCI 6733. To achieve higher actuation ability, the filtered voltage signal is amplified by an actuation amplifier SS08 (manufactured by Sensor Technology). Finally, the amplified voltage is fed back to the corresponding actuator to control the vibration of the corresponding intermediate link.

5. EXPERIMENTAL RESULTS

To excite the vibration of intermediate links, a circular motion was assigned as a desired trajectory for the mass center point of the moving platform. The radius of the circular trajectory was set to be 30mm.The maximum velocities and accelerations of three sliders were experimentally set to be $0.1\, m/s$ and $50\, m/s^2$, respectively. The positions of the three axes were obtained through the inverse kinematics with the desired pose of the end-effector of the manipulator.

Three PZT sensors and actuators are bonded to each intermediate link at its quarter point, midpoint and three-quarter point, as shown in Figure 1. The PZT actuators and sensors are BM 532, manufactured by Sensor Technology. The piezoelectric constant d_{31} is $-270\times10^{-12} C/N$, and Young's modulus is $6.3\times10^{10} N/m^2$. The dimensions of each PZT actuator are $25.4mm\times25.4mm\times0.254mm$ and the dimensions of each PZT sensor are $6.35mm\times6.35mm\times0.254mm$. The sampling rate for each channel of the A/D and D/A is configured to be 1000 *Hz*, and the input and output voltage range of each channel of the A/D and D/A is set to be ±10 volts. The voltage gain for each channel of the Sensor Technology SS08 amplifier is set to be 30.

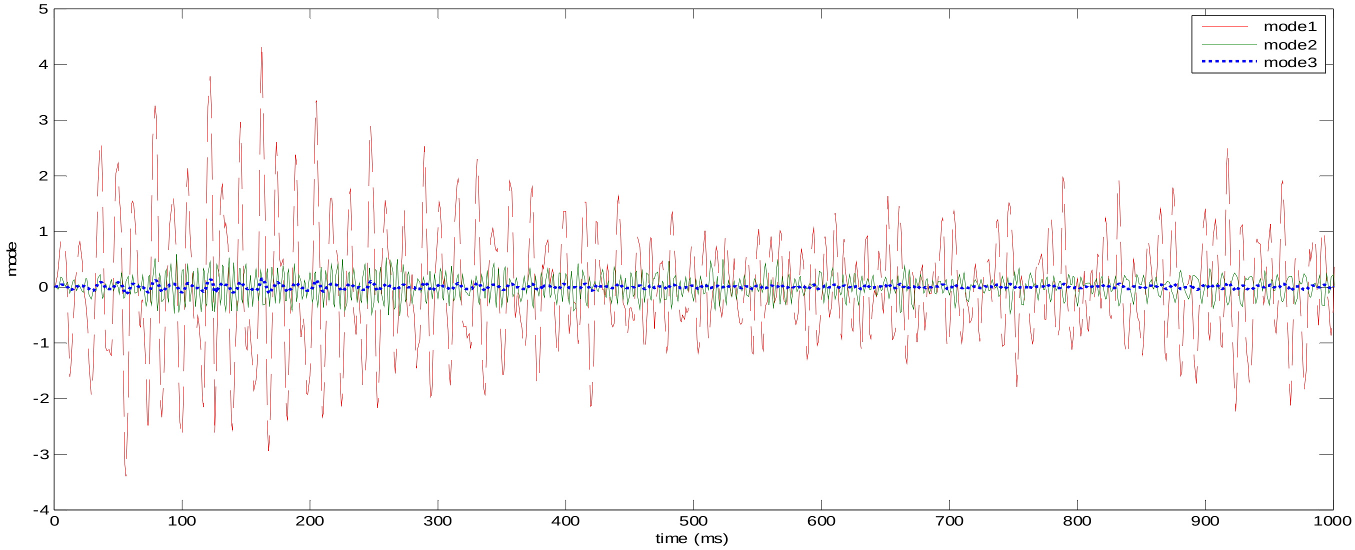

Fig. 2.First three modes of the 2^{nd} intermediate link

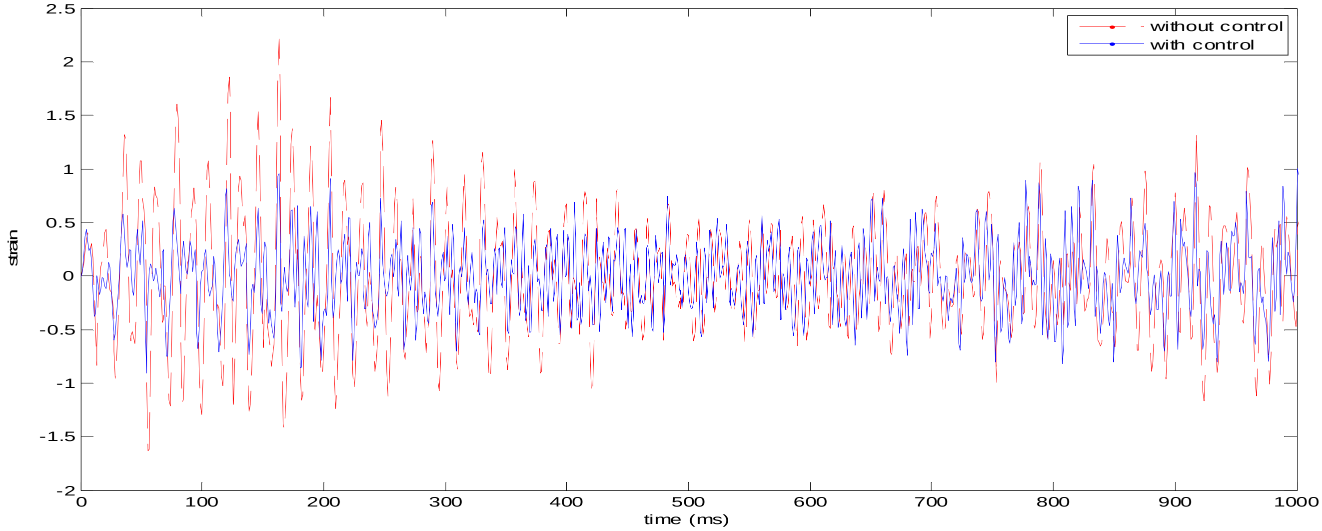

Fig. 3. Strain at the midpoint of the 2^{nd} intermediate link

In all the experimental results presented here, only the first vibration mode is targeted for control. Figure 3 presents the strain at the midpoint of the second intermediate link. With the implementation of the proposed control strategy, the first mode vibrations of all three intermediate links are effectively reduced. The experimental results show that the power spectral density (PSD) of the first vibration mode is effectively suppressed by 38% for the first link, by 41% for the second intermediate link, and by 70%

for the third link. The experimental results also demonstrate that the structural vibrations are better suppressed in the third intermediate link than in the first and second intermediate link. In the experiments, the path of the platform is not symmetric about the coordinate origin, and hence the dynamic behavior of each intermediate link is different.

Figure 2 shows the first three modes of the 2nd intermediate link. It clearly illustrates that the first order mode is much larger than the second and third order mode. Therefore, it is reasonable to design the active vibration controller targeting at the first mode for the proposed manipulator system.

6. CONCLUSIONS

Smart structures are developed and built with three collated PZT sensors and actuators bonded at the quarter point, midpoint, and three quarter point of each intermediate link. Independent modal space controllers are designed for each mode of each intermediate link so a complicated and coupled vibration control system with physical coordinates is simplified to be a series of uncoupled sing-degree-freedom vibration control systems with modal coordinates in parallel. Modal filters are developed to monitor modal coordinates in real time, and a second order compensator is added to cut off the high-frequency unmodeled vibration signal and noise due to the derivative operations. The proposed control strategy is implemented experimentally to the 3-PRR parallel manipulator with three flexible links when the manipulator is moving. The experimental results verified the effectiveness of the proposed control method.

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