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A general dynamics and control model of a class of multi-DOF manipulators for active vibration control

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ABSTRACT

A general dynamic model of a class of parallel platforms for vibration control applications based on Kane's method is presented. A general parallel platform is composed of a moving platform, a base platform, and i limbs with identical kinematic structure. Each limb connects the mobile platform to the base platform by $j+1$ hinges and j struts, where the prismatic actuator is fixed at one of the struts. The hinges can be replaced by any other kind of conventional hinges or flexure hinges. The control system architecture based on mixed H_2/H_∞ synthesis method is introduced for a class of parallel platforms as a multiple-input/multiple-output (MIMO) problem for the purpose of active vibration isolation. A case study is illustrated and the theoretical analysis is validated at last.

1. Introduction

In recent years, many precision industrial and experimental processes cannot work normally if the instruments are affected by internal or external vibrations, since more and more vibration sensitive components in terms of lightweight flexure materials and structures are used in modern mechanism, which are ease of causing vibrations. Many applications in precision engineering, e.g. wafer stepper lithography machines, atomic force microscopes, space telescopes and interferometers, laser communication systems, space experiments of crystal growth and some other sensitive optical applications would be impossible without a careful isolation of the process from the environmental vibrations. It will strongly require a careful isolation from the vibration environment to provide a sufficiently quiescent gravity environment. Thus a precision process can be maintained on a platform that is essentially vibration-free. Parallel mechanisms are employed in many active vibration isolation systems because the multiple DOF mechanical vibrations isolations always need multiple DOF mechanisms for effective attenuation [1–4]. Active vibration isolation by a parallel mechanism is an active application of generating multiple DOF anti-vibration forces in an equal module and opposite phase to the forces imposed by external vibration, which can achieve a very low remaining vibration level. Hence, a system designed to meet the requirements of precision industrial and experimental processes is an integration of robotics, control technique, material science, actuator and sensor technology. The key issues involved in multiple DOF active vibration isolation problems are [1]: (1) Optimal geometry for the mechanism to generate multiple DOF anti-vibration forces; (2) Development of active elements (actuators and sensors); and (3) Control system design and implementation.

This paper will focus on the dynamics modeling and control strategy investigation of a class of parallel manipulators using conventional hinges or flexure hinges for active vibration isolation. The remainder of the paper is organized as follows. First, the task will be described in details in Section 2. In Section 3, the dynamics modeling will be built up by using Kane's method for a class of parallel manipulators. The analysis results will be presented as a state-space, analytical set of linearized equations of motion. In Section 4, the control system architecture based on mixed H_2/H_∞ synthesis method will be introduced for a class of parallel

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platforms as a multiple-input/multiple-output (MIMO) problem. Finally, a case study is illustrated in Section 5 to verify the theoretical derivations.

2. Task description

The process of an active vibration isolation system designed for this purpose is shown in Fig. 1. Several sensors are located on the moving platform of a designed multi-DOF mechanism. The sensors will measure the motion in three degrees of freedom, then the signals are amplified and converted by electronic amplifier and A/D signal converter. The digital signals are fed back to the controller to calculate the driving forces which will be sent to actuators, and finally the active vibration isolation is realized.

2.1. Multi-DOF mechanism design

Micro/nano positioners and active vibration control devices are increasingly being made of parallel manipulators due to their characteristics of high precision, low inertia, and high speed capability. Meanwhile, it is very important to select actuators that offer such merits as smooth motion, high accuracy, and fast response, which make them much suitable for active vibration isolation in precision engineering applications.

As shown in Fig. 2, a class of parallel platforms consists of a moving platform, a base platform, and i limbs with identical kinematic structure. Each limb connects the mobile platform to the base platform by $j+1$ hinges and j struts, where the prismatic actuator is fixed at one of the struts. As a prerequisite, to ensure the DOF for end-effector, the hinges shown in Fig. 2 can be replaced by any other kind of flexure hinges (such as those shown in Fig. 3). This kind of parallel manipulators can achieve a 3-DOF movement such as 3-PUU [5](Fig. 2(a)) or 3-UPU [6] (Fig. 2(b)), 6-DOF such as 6-SPS [7] (Fig. 2(c)), 6-UPS, and even can be a redundant mechanism with more than six limbs such as 8-SPS [8] (Fig. 2(d)). Voice coils, piezo-electric (PZT), hydraulics, pneumatics, or other motors may provide with the active forces. PZT actuators offer the advantages of sub-nanometer resolution, several thousands of large force generation, sub-millisecond response, no magnetic fields and so on. Thus the PZT actuators can be utilized to actuate the mechanism for vibration isolation. In addition, voice coil motors can also be selected as the active absorbers since they owe the advantages of higher speed and higher track resolution than stepper motors and have been widely utilized in active vibration isolation systems. But the payload of the motor should be of low mass. Passing too big current through the coils may cause them to overheat.

2.2. Dynamics modeling

Active vibration isolation based on parallel manipulators aims at crossing the bridge between the structural dynamics and control communities, meanwhile providing a potential application of smart materials for sensing and actuating purposes in active vibration control domain. In order to provide effective model-based isolation, the task of controller design requires a priori development of an adequate dynamics model for the isolation system. There are fundamentally two ways for deriving system dynamical equations of motion: vector methods and energy methods [3]. Both methods lead to scalar equations, but they have different starting points. Vector methods begin with vector equations proceeding from Newton's law of motion such as momentum principles, D'Alembert's principle, or Kane's method. Energy methods begin with scalar energy expressions which use Hamilton's canonical equations, the Boltzmann–Hamel equations, the Gibbs equations, or Lagrange's equations. Kane's method, which appears in general to be distinctly advantageous for complex problems, leads to simple and intuitive dynamical equations. In this approach, Kane's method is exploited to obtain the equations of motion in terms of independent variables without using Lagrange multipliers for a multi-body system, and the computational complexity and labor will be reduced significantly.

2.3. Control method

A suitable control strategy plays a very important role in multi-DOF active vibration control. In order to provide a quiescent acceleration environment to an experiment, an active isolation system always uses an acceleration feedback control system to sense the motion of the acceleration sensitive experiment and apply forces to reject the unwanted motions. By sensing the

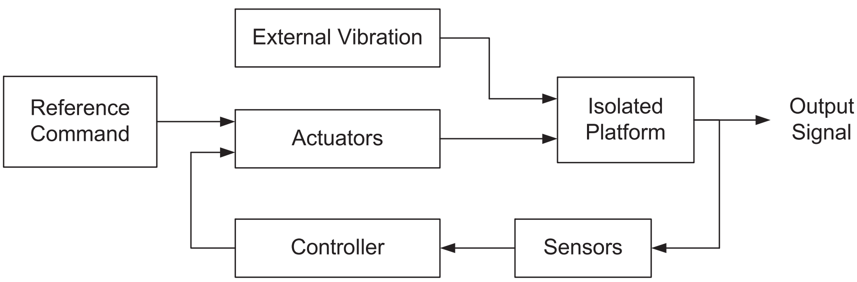

Fig. 1. Process of the active vibration control.