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Control Engineering Practice 13 (2005) 279–289

CONTROL ENGINEERING PRACTICE

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A hybrid control strategy for active vibration isolation with electrohydraulic actuators

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Received 30 August 2002; accepted 9 March 2004

Abstract

This paper presents a hybrid control approach to circumvent the basic trade-off between performance and robustness from an individual controller. This hybrid control strategy utilizes a robust controller for guaranteed robustness when the plant model is not well known, and employs an adaptive controller for high performance after sufficient plant information has been collected. To avoid a degraded transient after controller switching, a bumpless transfer scheme is designed and incorporated into this hybrid control approach. This bumpless transfer design is an extension from a conventional latent tracking bumpless transfer design for a single-input single-output (SISO) plant with 1 degree of freedom (DOF) controllers to either a SISO plant with multiple DOF controllers or a multi-input multi-output (MIMO) plant. Experimental results implemented on an active vibration isolation testbed demonstrate the effectiveness of the proposed hybrid control strategy.

Keywords: Electrohydraulic systems; Adaptive control; Robust control; Switching algorithms; Active control; Vibration isolation

1. Introduction

Active vibration isolation is a natural evolution of passive vibration isolation. The historical development of theoretical concepts necessary for the design of isolation systems was reviewed by Karnopp (1995) while focusing on a relatively simple idea, the skyhook damper, and its applications to seismic isolation platforms and automotive active and semi-active suspensions. There have been several papers published within the active vibration isolation field and many different control methods have been utilized. Interested readers can refer to Hrovat (1997) and Housner et al. (1997) for surveys of control methods utilized previously.

It is well known that adaptive control and robust control are two popular approaches for the control of uncertain systems. However, either approach has its own advantages and disadvantages. For example, an adaptive controller can achieve high performance for a slowly time-varying or time-invariant uncertain plant after parameter estimation convergence, but it is possible to exhibit poor transient response when the adaptation is initiated. Another disadvantage of adaptive control is that it is sensitive to unmodeled dynamics and disturbances (Ioannou & Kokotovic, 1984). On the other hand, a well-designed robust controller can guarantee robust stability of the closed-loop system under a reasonable class of disturbances and system uncertainties. However, robust controller design is usually conservative because the controller is often based on a worst-case scenario and thus sacrifices part of the achievable performance to guarantee system robustness (Song, Longman, & Mukherjee, 1999). In this work, we propose an alternative hybrid control strategy that switches between a robust controller and an adaptive controller to achieve both controllers' merits and avoid having to choose between either performance or robustness.

When considering switching between controllers, a common problem encountered is the degraded switching transient. One remedy for this is to incorporate a smoothing algorithm to facilitate the transition between

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0967-0661/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.conengprac.2004.03.009

controllers. This type of a process is called Bumpless Transfer, which is defined as the transfer, or switch, between one controller acting in closed loop on a plant and a second controller waiting to take over. Bumpless transfer is often formulated into a tracking problem and the tracking algorithms use an input–output setup to let the second controller track the first one while the first one is active and the second is waiting. The interested reader can examine the work by Edwards and Postlethwaite (1998) where different schemes were compared; additional references can also be found in Zheng and Alleyne (2003). A conventional bumpless transfer design was proposed by Graebe and Ahlen (1996), but its application is limited to a single-input single-output (SISO) plant with 1 degree of freedom (DOF) controllers. An extension is made in the current work to make this latent tracking design also suitable to either a SISO plant with multiple DOF controllers or a multi-input multi-output (MIMO) plant. Experimental results demonstrate the effectiveness of the proposed hybrid control approach including the bumpless transfer design.

The rest of this paper is formulated as follows. In Section 2, the vibration isolation problem will be formulated as a position-tracking problem, which is an improved version of the velocity-tracking approach proposed in Zhang and Alleyne (2001). Section 3 introduces a plant model along with the experimental testbed on which the subsequent controller design methods will be presented. In Section 4, an MRAC controller is designed and Section 5 illustrates an H_∞ controller design. The hybrid control approach is presented in Section 6. Section 7 details a new bumpless transfer design and incorporates it into the hybrid control approach, which is followed by experimental results demonstrating the effectiveness of the overall hybrid control strategy. A conclusion then summarizes the main points and contributions.

2. Problem formulation

The types of isolation systems under consideration here are specifically those that are relatively large, requiring high power actuation with a significant bandwidth. The potential applications include active suspensions, seismic isolation, or shock and vibration isolation for land and sea vehicles. Based on the speed and power requirements, electronically controlled hydraulics, or electrohydraulics, will be the focus of the work presented here. Previous work (Zhang & Alleyne, 2003) contains detailed motivations for the current problem formulation to be outlined below and the reader is referred there for additional background information on the problem under study. This motivation is based on an explanation of inherent system limitations with electrohydraulic actuators for most other vibration isolation problem formulations. In the current paper, a basic single DOF active vibration isolation case shown in Fig. 1 will be studied for focused exposition. However, the insight presented here are applicable to multiple DOF cases.

It has been shown that the inertial or "skyhook" damper illustrated in Fig. 2 can achieve very good overall vibration isolation characteristics (Karnopp, Crosby, & Harwood, 1974). Although it is not possible to find a physical inertial reference to place the skyhook damper in most real applications, it is appropriate to choose a skyhook damper system as the reference system for the real plant in Fig. 1 to emulate. The transfer function relationship from the disturbance position to the absolute position of the isolated mass in Fig. 2 is

$$\frac{x_{des}(s)}{z(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}. \tag{1}$$

The natural frequency and damping ratio in Eq. (1) are $\zeta = b/2\sqrt{Mk}$ and $\omega_n = \sqrt{k/M}$, respectively, and they can be tuned to achieve some desired response.

In most active vibration isolation problems, the measurement of the disturbance acceleration is more feasible than that of the disturbance position. The acceleration measurement can be performed by placing an accelerometer on the base in Fig. 1. Similarly, it is

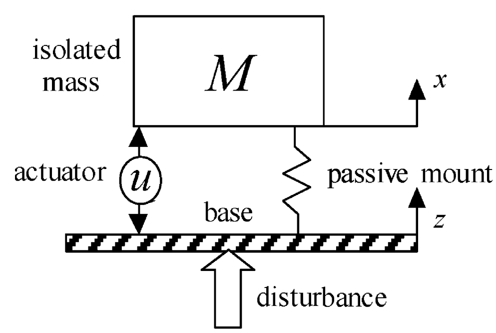

Fig. 1. Disturbance rejection schematic.

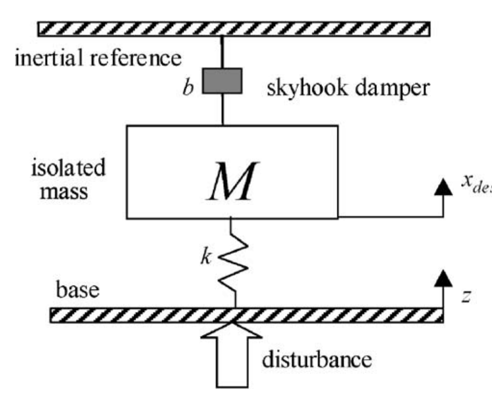

Fig. 2. Skyhook damper representation.