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**DAMPING CONTROL OF A LARGE FLEXIBLE
MANIPULATOR THROUGH INERTIAL FORCES
OF A SMALL MANIPULATOR**

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DAMPING CONTROL OF A LARGE FLEXIBLE MANIPULATOR THROUGH INERTIAL FORCES OF A SMALL MANIPULATOR

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Abstract

Damping control is applied to a detailed computer model of a long-reach flexible manipulator test bed. The test bed consists of a long slender link with a dextrous manipulator mounted at its tip. The movement of the dextrous manipulator is controlled to create inertial damping forces on the long link. Parameter identification and sequential loop-closure are used to design a controller that feeds back relative tip position and velocity of the long link to control the azimuth angle of the dextrous manipulator. The controller is designed to be robust to varying manipulator loading conditions and reliable under sensor failures.

1. Introduction

One class of long-reach manipulators being considered for waste remediation at U.S. Department of Energy facilities is configured as a coarse positioning long-reach manipulator (LRM) with a more dextrous, lighter duty short-reach manipulator (SRM) mounted on its tip. A laboratory test bed for this configuration is described in [2]. It consists of a steel beam representing the LRM, which is 15 feet long by 1 foot high by 0.75 inch thick, fixed at one end and free to move horizontally at the other. The free end is supported off the floor by an air bearing. A six-degree-of-freedom hydraulic manipulator (Schilling Titan 7F) is mounted on the beam at the free floating end to represent the SRM.

The control system presented here controls the motion of the azimuth joint of the SRM to generate inertial forces designed to annihilate the oscillations sensed at the tip of the flexible LRM. The controller is designed to be robust and reliable while providing damping. This form of control has received little attention in the literature [1].

Figure 1 shows the structure of the damping control system. The relative tip position and velocity of the LRM are measured and then passed through controllers H_p and H_v , respectively. The outputs of the controllers are subtracted from the desired steady-state azimuth angle (θ_d) and then passed to the SRM as the desired azimuth angle.

The remainder of this paper is organized as follows. System modeling issues are outlined in Section 2. Section 3 addresses the controller design and simulation results, and conclusions are made in Section 4.

Figure 1. Feedback control structure.

2. System Modeling

To design the controllers, linear models are developed using system identification techniques based on Prony analysis. Prony analysis is very well suited for developing models of high-order linear oscillatory systems [3]. The Prony analysis software used here is called IPRONYID and is part of a collection of computer programs used for parameter identification of dynamic systems being developed at PNL with the Bonneville Power Administration. Prony analysis has proven to be a very valuable tool in the measurement-based analysis of power system electromechanical oscillatory dynamics (e.g., see [5]).

A dynamic model of the system was developed using DADS (a nonlinear dynamic modeling and simulation software package). Sixth- to tenth-order linear models are identified for the simulated test bed under two operating conditions: 1) no load on the SRM; and 2) full load on the SRM. The frequency response for the LRM tip position is shown in Figure 2. The responses match the flexible manipulator's true response very closely. Note the change in the mode locations for the different loading conditions

Figure 2. Response from azimuth angle to LRM tip position, open loop.

3. Controller Design

From Figure 2, one sees that the transfer function for the tip position is dominated by the first two modes. Similar analysis indicates that the second and third modes dominate the tip velocity response. Detailed modal analysis shows that the phases of modes 2 and 3 are nearly opposite that of mode 1 (the lowest-frequency mode).

In the no-load case at a nominal SRM configuration, similar phasing occurs as under full load. Therefore, a controller that properly adjusts the phasing for one case will likely do the same for the other.

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One solution to choosing the feedback controllers is to design H_p and H_v to provide damping to different modes. Because the tip-position transfer function has a high gain for mode 1 and requires phase-lag (evident from modal analysis) for adding damping to mode 1, H_p is designed to damp mode 1 while having little or no effect on modes 2 and 3. Controller H_v is used to damp modes 2 and 3 while having very little effect on mode 1. Also, both controllers are required to have significant roll-off properties outside their effective bandwidth. Forcing H_p and H_v to control different modes makes them highly decoupled, which inherently results in a reliable control structure.

Sequential loop-closure [6] is used to design the controllers. First, the parameters of H_v are chosen, and that loop is closed. Then the parameters of H_p are chosen using the system with H_v closed as the design model. The full-load linear models are used to design the control parameters because this represents the highest gain condition. Controllers are required to meet minimum gain and phase margins for each operating condition. The closed-loop system is also required to remain stable under sensor failure conditions. The individual loops are designed using a loop-shaping approach. The design process is iterated several times until acceptable performance is obtained.

After several iterations of design, the following controllers are developed:

$$H_p(s) = \frac{3.2}{(s+0.2)(s+5.0)(s+10.0)} \quad (1)$$

$$H_v(s) = \frac{0.073(s+1.0)}{(s+65.0)(s+15.0)} \quad (2)$$

Figure 3 shows the closed-loop frequency response.

These controllers are very robust and reliable. The worst robustness occurs when the sensor for H_p fails. In this case, the gain margin is guaranteed to be greater than 3.5 db, and the phase margin is greater than 47 degrees (using a Nyquist circle criterion). This means that the gain of the velocity controller could nearly double and the phase could change 47 degrees before mode 1 became unstable. Also, because the controllers are decoupled, failure of H_p has little effect on the damping of modes 2 and 3, and similarly, the failure of H_v has little effect on the damping of mode 1.

Figure 3. Closed-loop frequency response for LRM position.

Time domain simulation results from the closed loop system are shown in Figure 4. Closed-loop responses for other operating conditions also show much improved damping.

Figure 4. Step response of LRM tip position, full load with both H_p and H_v .

4. Conclusions

The results presented here demonstrate that oscillations in a long manipulator can be damped using the inertial forces of a small one attached to its tip. A fixed-parameter damping controller is designed for a detailed computer model of a test bed. The controller is required to be robust in that it provides damping over all loading conditions. It is also required to be reliable in that it must perform well under sensor failures. The controllers are designed based on a set of linear models obtained through a parameter identification scheme which uses measurement test data to construct system models.

5. References

- [1] W. J. Book and S. H. Lee, "Vibration Control of Large Flexible Manipulator by Small Robotic Arm," *Proceedings of the 1989 American Control Conference*, Vol. 2, pp. 1377-1380, June 1989.
- [2] M. S. Evans, D. J. Trudnowski, and C. P. Baker, "Studies in Control of Long Reach Flexible Manipulators," Presented at the American Nuclear Society International Conference, Chicago, Illinois, Nov. 1992, PNL-SA-21136, Pacific Northwest Laboratory, Richland, Washington.
- [3] D. A. Pierre, D. J. Trudnowski, and J. F. Hauer, "Identifying Linear Reduced-Order Models for Systems with Arbitrary Initial Conditions Using Prony Signal Analysis," *IEEE Trans. on Automatic Control*, Vol. 37, No. 6, pp. 831-835, June 1992.
- [4] J. F. Hauer, C. J. Demeure, and L. L. Scharf, "Initial Results in Prony Analysis of Power System Response Signals," *IEEE Trans. on Power Systems*, Vol. 5, No. 1, pp. 80-89, Feb. 1990.
- [5] J. M. Maciejowski, *Multivariable Feedback Design*. New York: Addison-Wesley Publishing, 1989.

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