Modeling and Control of Marine Cable Systems

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LONG-TERM GOALS

This project develops modeling, analysis, and control techniques for distributed cable systems coupled with rigid bodies, sensors, actuators, and fluids.

OBJECTIVES

- Develop, analyze, and experimentally verify coupled mechanical/fluid models for marine cables that can be used for control system design. Although there has been significant research in this area, most of the models are too complex to be used for model-based control system development. This research distills and combines the important physics of current models.
- Design and experimentally implement robust control algorithms for accurate position control of cable systems. Complex, nonlinear cable system models have distributed displacement variables, complicating the theoretical development of asymptotically stabilizing controllers. Also, practical control implementation requires a minimum number of implementable, robust sensors and actuators.
- Develop disturbance-rejecting controllers that reduce the forced response of cable systems resulting from fluid loading or boundary motion.

APPROACH

When flexible cable structures are excited by external disturbances such as vortex shedding or boundary motion, it is often desirable to isolate quiet parts of the structure (*e.g.*, sensors) from the disturbances. Confinement of vibrations to relatively unimportant areas in the structure allows high precision pointing and/or positioning in the presence of unknown disturbances. Active control using forces applied to the cable via control surfaces has the potential to actively isolate sensing equipment from cable vibration-induced errors. In this work we focus on developing isolation controllers for discrete models of flexible structures such as cable systems that can be modeled by the generic matrix differential equation

$$M\ddot{\mathbf{q}} + D\dot{\mathbf{q}} + K\mathbf{q} = \mathbf{f}$$

where M, D, and K are the mass, stiffness, and damping matrices, respectively, $\mathbf{q}(t)$ is the structural displacement vector, and $\mathbf{f}(t)$ is the vector of control and disturbance forces. The control objective is to use the control forces to isolate a set of “quiet” coordinates from the disturbances acting on the “noisy” coordinates. For marine cable systems, an active breaker ball could be used to isolate hydrophones from vortex-shedding disturbances on another part of the cable. In addition, we assume that the system

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parameters (*e.g.* cable tension) are unknown. Thus, we seek adaptive controllers that learn the system parameters on-line and asymptotically regulate the quiet coordinates to zero.

WORK COMPLETED

In Ertur *et al.* (1998), we show that under assumptions of inertially decoupled quiet and noisy coordinates, a symmetric and positive definite mass matrix for the quiet subsystem, asymptotically stable eigenvalues for the noisy subsystem, and bounded disturbances, an adaptive regulator asymptotically drives the controlled coordinates to zero.

To test the effectiveness of the proposed control approach, the algorithm is implemented on the simple three-mass/spring system shown in Figure 1. The control objective is regulate the positions of Mass 1 and Mass 2 (quiet coordinates) despite the disturbances applied to Mass 3 (noisy coordinate) via an impact hammer. The control force from an actuator motor is applied to Mass 2. Regulation and tracking experiments demonstrating the robust performance of the adaptive controllers have been successfully completed.

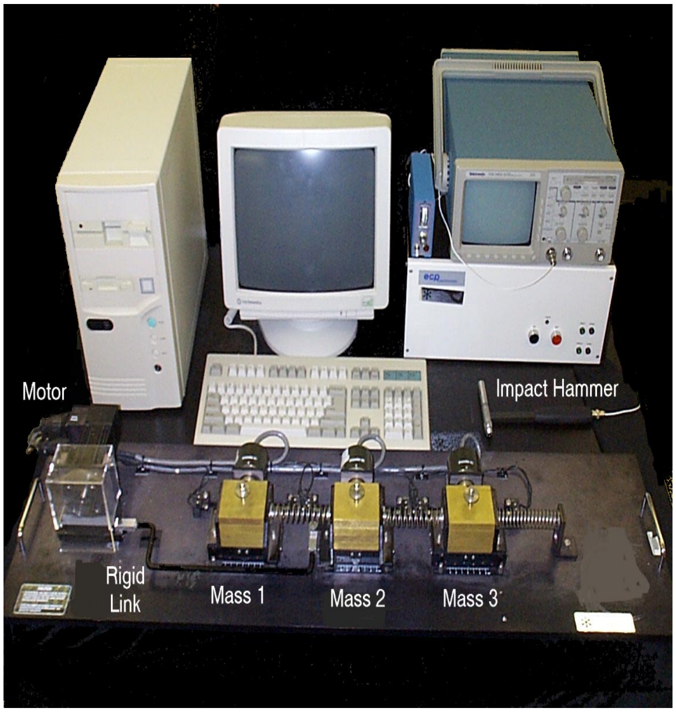

Figure 1. Experimental Adaptive Vibration Isolation Testbed

RESULTS

Figure 2 shows the open loop response of the system to repeated impulsive inputs $f_3(t)$ on Mass 3 (Fig. 2(D)). The quiet coordinate response $x_1(t)$ and $x_2(t)$ shown in Figures 2 (A) and (B) closely mirror the noisy coordinate response $x_3(t)$, producing a steady, oscillatory error of approximately ±10 mm.

The adaptive regulation experiment starts and ends with impulse inputs on mass 1 $f_1(t)$ to demonstrate the damping provided by the control law. The mass 1 transient resulting from impulse $f_1(t)$ inputs decays 30% more quickly than open loop. Repeated impulse inputs to mass 3 between $t = 2$ seconds and $t = 15$ seconds show the disturbance rejection provided by the controller. After a transient period when the adaptive parameters increase from zero to steady values, the responses for mass 1 and 2 are less than $\pm$ 0.1 mm to the impulse $f_3(t)$ inputs. This factor of 100 reduction in the response uses a relatively small control effort of ±1 V. The on-line integration of the adaptive update laws propagate the estimates of the spring stiffness $\hat{k}_3$ and damping $\hat{d}_3$ between masses 2 and 3. The stiffness estimate $\hat{k}_3$ converges from an initial value of zero to near the measured value of 800 *N/m*. No dampers are inserted between masses 2 and 3, so $\hat{d}_3$ converges from zero to a small 17 *Ns/m*.

The results clearly show that vibration isolation control effectively regulates quiet parts of a flexible structure from noncolocated disturbances. In Li *et al.* (1999), we apply the vibration isolation concept to a distributed parameter string model and show good experimental performance. We plan experiments on sagged cables in air this year. In Zhang *et al.* (1998), we show how the Lyapunov-based control ideas used in the vibration isolation work can be applied to a pinned string with large amplitude vibration and the associated nonlinear tension and displacement effects.

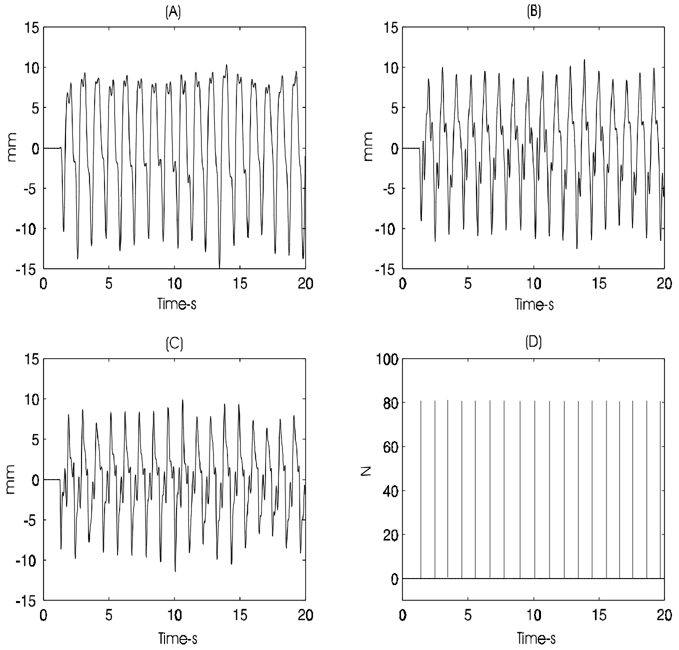

Figure 2. Open Loop Response: (A) Quiet coordinate, $x_1(t)$; (B) Quiet coordinate, $x_2(t)$; (C) Noisy coordinate, $x_3(t)$; (D) Disturbance input, $f_3(t)$.

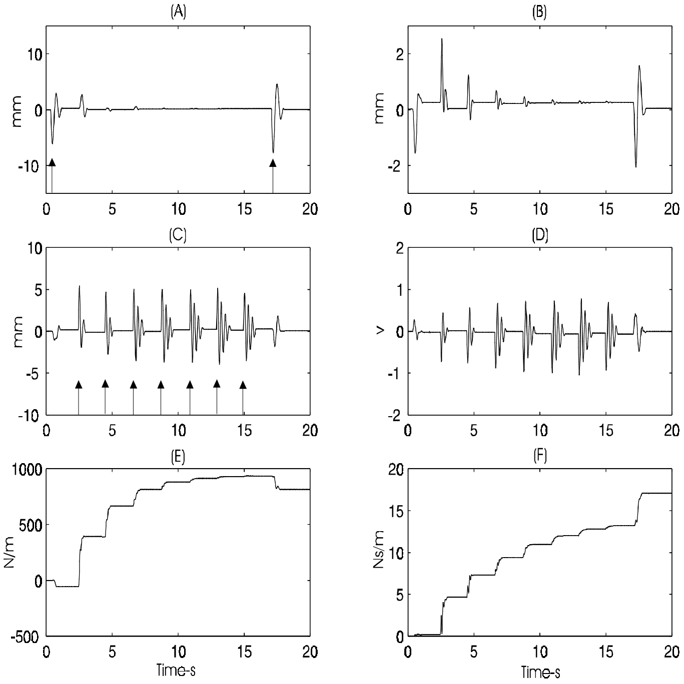

Figure 3. Adaptive Regulation Response: (A) Quiet coordinate, $x_1(t)$ (solid), quiet side disturbance, $f_1(t)$ impulses (arrow); (B) Quiet coordinate, $x_2(t)$; (C) Noisy coordinate, $x_3(t)$ (solid) and noisy side disturbance $f_3(t)$ impulses (arrow); (D) Control voltage, $f_2(t)$; (E) Stiffness estimate, $\hat{k}_3(t)$; (F) Damping estimate, $\hat{d}_3(t)$.

IMPACT/APPLICATIONS

There are many Navy applications of advanced vibration control systems for marine cable structures, including towed vehicles, buoys, and remotely operated vehicles. Active vibration control has been successfully applied to many flexible systems. The motion of flexible robots, for example, can be tightly regulated with active control. Flexible wing vibration can be stabilized by flight control systems. Active control also allows precise motion control despite flexible drivetrains. Vibration control algorithms provide for large angle motion of flexible space structures. There are also many examples of complex electromechanical systems operating in marine environments. Towed vehicles, for example, have rate gyros, inclination sensors, actuated control surfaces, and control equipment. These systems are robust enough to work for long periods of time in harsh marine environments without maintenance. Sealants and insulation have been developed to isolate the systems from corrosion and temperature variations. This research combines recent advances in vibration control with mechatronic implementation for marine environments. The vibration isolation technology presented in this report provides a key building block in the development of smart cable systems with increased agility, performance, robustness, and insensitivity to disturbances.

RELATED PROJECTS

Cable vibration can reduce the performance of a variety of civil and military structures. This research directly impacts the problems caused by cable vibration in four important Navy systems: moorings, towed arrays, remotely operated vehicles, and towed vehicles.

In related work for the Coastal Systems Center (Jaffar and Rahn, 1998), we have developed partial differential equation models of the whisker sensor proposed for the surf-zone project autonomous underwater vehicle. We are currently working with Chuck Bernstein’s group to develop computer models of contact sensors.

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