

taken into account to compute interaction forces accurately. Going beyond computer-graphics collision-detection algorithms, it is necessary to develop algorithms according to a client-server model to provide for synchronization of visual and haptic displays in order to make update rates acceptably high. For example,

by use of multithreading techniques, one can calculate the contact forces at rate of 1 kHz in one thread while updating visual images at 30 Hz in another thread.

*This work was done by Cagatay Basdogan of Caltech, Chih-Hao Ho of Cambridge Research Associates, and Mandayam Srinivasan of MIT for NASA's Jet Propul-*

*sion Laboratory. Further information is contained in a TSP (see page 1).*

*This software is available for commercial licensing. Please contact Don Hart of the California Institute of Technology at (818) 393-3425. Refer to NPO-21191.*

## Σ Modeling and Control of Aerothermoelastic Effects

**This method makes it possible to design controls to compensate for aerothermoelasticity.**

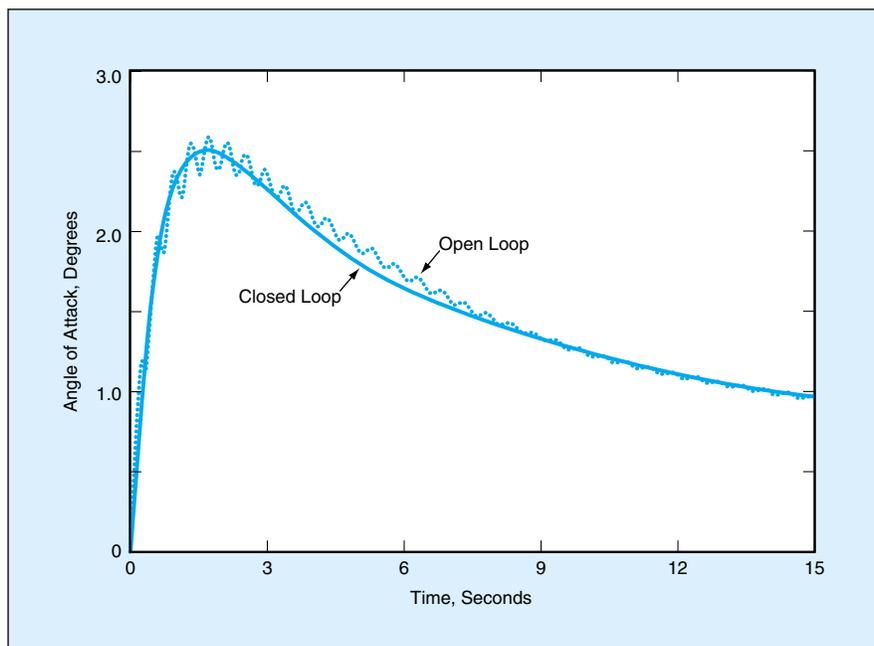
*Dryden Flight Research Center, Edwards, California*

Aerothermoelasticity comprises those aspects of the dynamics of an aircraft that are caused by flexibility and heating during flight. The concept of aerothermoelasticity is particularly important for hypersonic vehicles that operate at extremely high dynamic pressures. The design requirements for such vehicles often introduce long and thin fuselages subject to elastic bending in low-frequency vibrational modes. Furthermore, surface heating can significantly change the stiffness characteristics of these modes. These aerothermoelastic effects must be considered in the synthesis and analysis of control systems.

A method to include the effects of aerothermoelasticity in designing controls has been developed. Heretofore, large, finite-element mathematical models have typically been used to compute the aerothermoelastic effects; however, these models are not suitable for control engineering. The present method makes it possible to incorporate the results of computational analysis into the small linear models that are typically used in designing controls.

In this method, the procedure to include aerothermoelastic effects in linear models begins with noting the relationship between an effect and a temperature. Essentially, computational studies have indicated the changes in the natural frequencies (that is, frequencies of resonance) and damping parameters of structural vibrational modes that occur at various flight conditions and associated temperatures. In the present method, one simply describes the natural frequency and damping parameter of a linear model as functions of temperature that match the variations observed in the computational studies.

The linear models with associated temperature dependence are described by



The Responses of a Hypersonic Vehicle to elevator commands were computationally simulated for an open-loop case and for a case of closed-loop control designed according to the present method.

use of a formulation known as linear parameter-varying systems. This formulation enables the efficient description of systems that contain elements that are functions of such time-varying parameters as temperature. Furthermore, there is a set of previously developed theoretical concepts and associated computer programs that enable the design of control systems that incorporate scheduled-gain compensation for dependences on time-varying parameters.

A generic representation of a hypersonic vehicle has been used to demonstrate this method. A range of natural frequencies and damping parameters for the structural dynamics of the vehicle, based on previous computational studies, was assumed. A linear model including representations of the aerothermoelastic ef-

fects was formulated by describing the parameters of the structural dynamics as functions of temperature. A flight controller to actively damp the bending-mode response of this model was designed. The figure shows the open-loop and controlled (closed-loop) responses to an elevator command during a simulated flight with a fast variation of temperature. The open-loop response includes an oscillatory component from the bending mode, whereas the closed-loop response shows that the controller is able to continuously damp this elastic effect despite the time-varying temperature.

*This work was done by Rick Lind of Dryden Flight Research Center. For further information, contact the Dryden Commercial Technology Office at (661) 276-3689. DRC-01-21*