

Figure 2. This Accelerometer Response shows the onset of flutter.

used to generate computational models for predicting the onset of flutter.

The second phase of the ATW program was a flight test for envelope expansion. In this phase, it was required to analyze experimental data acquired at a series of test points with increasing velocity and dynamic pressure. At each test point, the ATW was excited with a frequency-varying input and its responses were measured by sensors. The resulting flight data were telemetered

to a control room and analyzed by the flutter-prediction methodologies. A total of five flight tests were performed in April 2001.

A flutter instability of the ATW was encountered at approximately mach 0.83 at an altitude 10,000 feet ( $\approx 3$  km). The wing was broken such that the boom and roughly 30 percent of the wing were lost. The pieces fell to the ground without striking the F-15B aircraft or FTF-II testbed. The flutter incident was quite demonstra-

tive of the phenomenon. The instability was encountered during a slow acceleration from mach 0.825 to mach 0.830. The damping changed dramatically during this acceleration. The ATW went from stable, with accelerometer responses going from approximately 3  $g$  (where  $g$  = the standard gravitational acceleration at the surface of the Earth) to unstable during a time interval of only 5 seconds (see Figure 2).

The data from the ATW were analyzed to evaluate the flutter-prediction methodologies. The results indicated that computational models were able to predict the onset of flutter reasonably well, but that small errors in the models could cause large errors in the predictions. The traditional approaches for analyzing flight data were shown to afford a capability to predict the onset of flutter only during operation at flight conditions near the instability. The flutterometer was shown to be somewhat conservative in the worst-case estimates of flutter, but it presented a reasonable prediction of flutter at flight conditions that were far from the instability.

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## Flight-Test Evaluation of Flutter-Prediction Methods

Experiments have demonstrated the accuracy of predictions of instability.

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The flight-test community routinely spends considerable time and money to determine a range of flight conditions, called a flight envelope, within which an aircraft is safe to fly. The cost of determining a flight envelope could be greatly reduced if there were a method of safely and accurately predicting the speed associated with the onset of an instability called flutter.

Several methods have been developed with the goal of predicting flutter speeds to improve the efficiency of flight testing. These methods include (1) data-based methods, in which one relies entirely on information obtained from the flight tests and (2) model-based approaches, in which one relies on a combination of flight data and theoretical models. The data-driven methods include one based on extrapola-

tion of damping trends, one that involves an envelope function, one that involves the Zimmerman-Weissenburger flutter margin, and one that involves a discrete-time auto-regressive model. An example of a model-based approach is that of the flutterometer. These methods have all been shown to be theoretically valid and have been demonstrated on simple test cases; however, until now, they have not been thoroughly evaluated in flight tests.

An experimental apparatus called the Aerostructures Test Wing (ATW) was developed to test these prediction methods. [The ATW is described in the immediately preceding article, "Aerostructures Test Wing" (DRC-01-37)]. The ATW is a small wing-and-boom assembly that has a complicated and realistic structure similar to that of a full-scale airplane

wing. The ATW was flown by use of an F-15 airplane and an associated flight-test fixture. The ATW was mounted horizontally on the fixture and the resulting system was attached to the undercarriage of the F-15 fuselage, as shown in preceding article.

For a flight test of flutter-prediction methods, the ATW was flown on four occasions during April 2001. The flight test involved measuring accelerometer responses as a series of test points. The airspeeds of these test points were increased until the onset of flutter was encountered at 460 knots of equivalent airspeed (KEAS) [ $\approx 237$  m/s equivalent airspeed].

Predictions of the speed associated with flutter were computed at every test point. In each instance, the prediction was based on data from the current test point and any

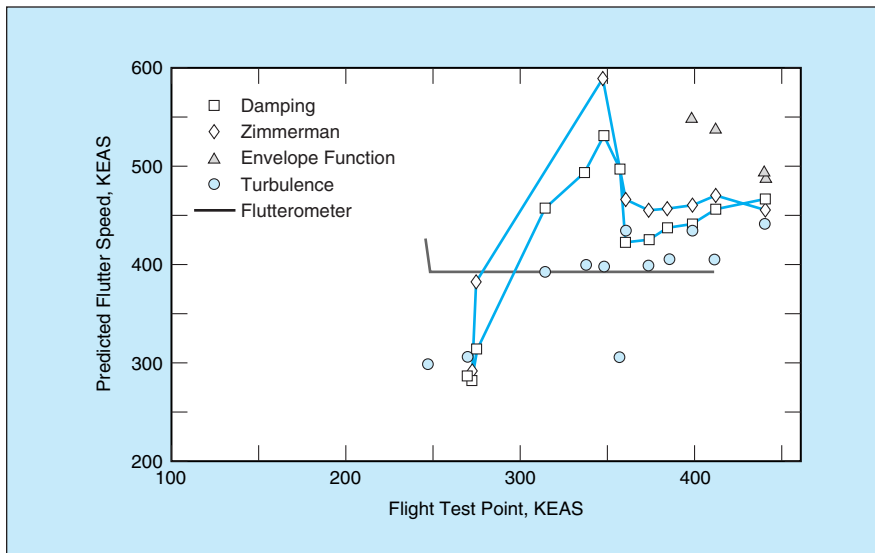


Figure 1. Flutter Speeds were predicted during envelope expansion by five different methods.

previous test points. The predicted speeds at the test points are plotted in Figure 1.

The predictions depicted in Figure 1 can be easily summarized. The data-based methods yield poor predictions for low-speed data but produce reasonable predictions that converge on the correct answer as the envelope is expanded to include high-speed test points. The flutterometer

produces a reasonable worst-case prediction of flutter speed immediately and remains conservative throughout the envelope expansion.

An analysis of Figure 1 reveals the nature of the prediction methods. In the data-driven methods, one attempts to compute the exact speed associated with the onset of flutter. In the flutterometer

(model-based) method, one attempts to obtain a conservative prediction of the worst-case flutter speed. It is expected that the data-driven methods should yield highly accurate predictions at test points close to flutter and that the particular implementation of the flutterometer should not reduce conservatism despite the analysis of data from high-speed test points.

The nature of the prediction methods indicates a method for efficient envelope expansion. A flight test should be initiated at low-speed test points and the flutterometer should be used to obtain a conservative estimate of the flutter speed. As the test proceeds, the airspeed should be increased until the system nears the speed of instability predicted by the flutterometer. At this point, the envelope should be expanded to high-speed test points by relying heavily on the data-based methods to finalize an accurate prediction of the exact speed at which flutter will be encountered.

*This work was done by Rick Lind and Marty Brenner of Dryden Flight Research Center. Further information is contained in a TSP (see page 1). DRC-01-57*

## ⊕ Piezoelectrically Actuated Microvalve for Liquid Effluents

Power consumption and size would be reduced.

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Modifications have been proposed to effect further improvement of the device described in "Improved Piezoelectrically Actuated Microvalve" (NPO-30158), *NASA Tech Briefs*, Vol. 26, No. 1 (January 2002), page 29. To recapitulate: What is being developed is a prototype of valves for microfluidic systems and other microelectromechanical systems (MEMS). The version of the valve reported in the cited previous article included a base (which contained a seat, an inlet, and an outlet), a diaphragm, and a linear actuator. With the exception of the actuator, the parts were micromachined from silicon. The linear actuator consisted of a stack of piezoelectric disks in a rigid housing. To make the diaphragm apply a large sealing force on the inlet and outlet, the piezoelectric stack was compressed into a slightly contracted condition during assembly of the valve. Application of a voltage across the stack caused the stack to contract into an even more compressed

condition, lifting the diaphragm away from the seat, thereby creating a narrow channel between the inlet and outlet. The positions of the inlet and outlet, relative to the diaphragm and seat, were such that the inlet flow and pressure contributed to sealing and thus to a desired normally-closed mode of operation.

The basic principles of design and operation of the proposed improved valve would be the same as those of the prior valve. However, there would be important differences in design details, leading to improvements, as summarized below:

- The piezoelectric stack would be highly miniaturized (only 0.9 by 0.9 by 10 mm) and manufactured with high precision. The interior volume of the valve would be only 0.1 cm<sup>3</sup>.
- Whereas the prior valve consumed a power of 2 W when actuated at a frequency of 100 Hz, the proposed improved version would consume only 0.1 W at 100 Hz. The combination of minia-

turization and decreased power demand would be made possible by, among other things, utilization of a mode of piezoelectric actuation known in the art as d<sub>31</sub>. (The term "d<sub>31</sub>" signifies one of three independent moduli of piezoelectricity as well as the mode of actuation to which this modulus applies. In the d<sub>31</sub> mode, the application of an electric field along one axis produces a longitudinal contraction along a perpendicular axis.)

- Unlike in the prior valve, the piezoelectric stack would be isolated from the fluid to be controlled. Hence, it would not be necessary to take special measures to protect the stack against the fluid and, even more specifically, it would not be necessary to coat the stack with a dielectric material for protection against an electrically conductive liquid.
- The design would include several features that would increase the ability of the valve to control a fluid at high pressure.

Like the prior valve, the proposed im-