AIAA JOURNAL
Vol. 43, No. 6, June 2005

Technical Notes

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Experimental Laser Sensing for Aircraft Vibration Suppression

Ernest D. Shackelford*
Greensboro, North Carolina 27411
Anindya Ghoshal†
United Technologies Research Center, East Hartford, Connecticut 06108
Mannur Sundaresan‡
North Carolina A&T State University, Greensboro, North Carolina 27411
Mark J. Schulz§
University of Cincinnati, Cincinnati, Ohio 45221
C. R. Ashokkumar¶
University of Miami, Coral Gables, Florida 33124-0624
and
Frederick Ferguson**
North Carolina A&T State University, Greensboro, North Carolina 27411

Introduction

AEROELASTICITY is the interaction of inertial, aerodynamic, and elastic forces with and within a structure. In aeroelastic systems, the structure and fluid responses are coupled, hallmark events may occur abruptly and without warning, and the behavior that may evolve often finds parallels in chaotic dynamics.[1–4] During the transition of commonplace flow regimes from subsonic to hypersonic, frequent nonlinearities in the flow require that assumptions[5–8] be made to simplify the mathematical modeling to predict flutter. Advances in nonlinear computational fluid dynamics codes have improved the modeling.[9] Recently, vertical takeoff and landing aircraft and helicopters have introduced challenging aeroelastic modeling problems.[10,11] Smaller vehicles also present challenges in aeroelastic modeling and flutter prediction. These vehicles include unmanned aerial vehicles that provide the possibility of more aggressive in-flight testing without the danger of loss of human lives,[12] and micro or miniature aerial vehicles that mimic biological systems. Other problems in which aeroelasticity and flow instabilities can occur include the near-inelastic fluid dynamics of blood and water,[13] and energy harvesting from the wind.

Received 22 June 2003; revision received 21 September 2004; accepted for publication 22 September 2004.

*Diagnostic Radiologist; retired. Senior Member AIAA.
†Senior Research Scientist, Structural Integrity Group.
‡Associate Professor, Department of Mechanical Engineering.
§Associate Professor, Department of Mechanical, Industrial, and Nuclear Engineering.
¶Research Visiting Scholar, Department of Engineering.
**Professor, Department of Mechanical Engineering.

In all of these areas, undesirable buffet or flutter has been largely repaired for some time by reallocating mass and stiffening the structure of the offending member, adding trailing controllable flaps or tip flaps, and adjusting the shape and position of external stores. More recently, piezoelectric applications and surface shaping have been coupled with refinements in active control theory to alleviate buffet and vibration. Piezoelectric (PZT) actuators and sensors and aircraft morphing are appearing in a variety of conceptual configurations coupled with differing control algorithms and systems.[14,15] Recent studies of aeroelastic phenomena and active control of adverse aeroelastic events have increased remarkably.[16,17]

Aeroelastic phenomena are also a concern in future air vehicles. These highly elastic aircraft will be designed to fly based on shape control, and their increased flexibility will make aeroelasticity, flutter, and buffet become even more critical design parameters. With these needs in mind, it is anticipated that an in situ noncontact movable sensor to check structural integrity and provide a feedback signal for active flutter control could be an important benefit for aircraft and spacecraft. Therefore, the objective of this Note is to investigate a new sensor that may be more effective in a control system to suppress flutter. The sensor is a noncontact laser Doppler vibrometer. This Note outlines preliminary efforts to control buffet of a structurally simplified cantilever lifting surface within unsteady low-Reynolds-number flow.

Control Method

The control technique uses direct velocity feedback from the laser sensor and large piezoceramic patch actuators to reduce the vibration of the scale model wing. The modeling of the wing structure with aerodynamic loading is not discussed in this Note. A filter is necessary to remove noise in the feedback system and to avoid exciting the higher frequency modes. In particular, in the used laser sensor, which generates noise because of speckle pattern motion, and piezoelectric ceramic actuators, which are high-bandwidth transducers that can become unstable because of noise, filtering is almost always necessary to prevent the control system from becoming unstable. The sensors and actuators are not collocated; thus the output feedback control is not guaranteed stable, and the stability depends on the gains and filtering.[18] A low-pass filter is used to remove the high-frequency noise and dynamics in the system. However, the filter introduces a phase lag and the gains must be reduced to maintain stability. The order of the filter is chosen as a compromise to provide an acceptable roll-off rate and acceptable phase delay. In practice, the first two modes of flutter, the bending and torsion modes, are controlled.

Experimental Setup

The experimental setup described here is shown in Fig. 1. The control algorithm is implemented by using MATLAB® SIMULINK and a dSpace Controller. The SIMULINK diagram is downloaded to the dSpace controller for hardware-in-the-loop experimentation. A computer is used to host MATLAB and to operate the dSpace system. The dSpace system uses a fast alpha DEC processor and has two input A/D channels and two output D/A channels. The output feedback signal goes to a two-channel PCB Piezotronics amplifier and then to the piezoceramic patches. The piezoceramic actuator patches are Cymer QP40W, which are two-layer patches with four piezoceramic elements[19] and are shown as A1 and B1 in Fig. 1. One patch is used on each side of the wing structure. In addition, a small

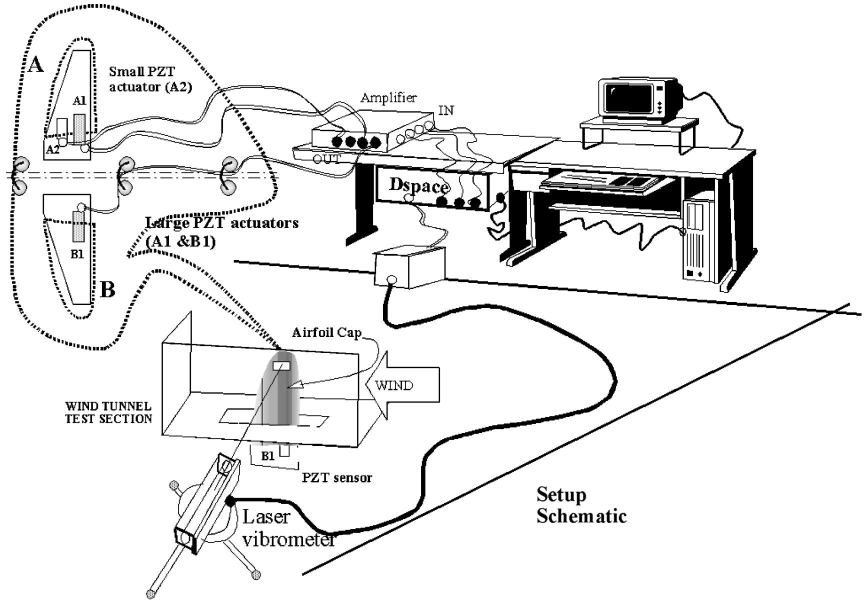

Fig. 1 Vibration-suppression experiment.

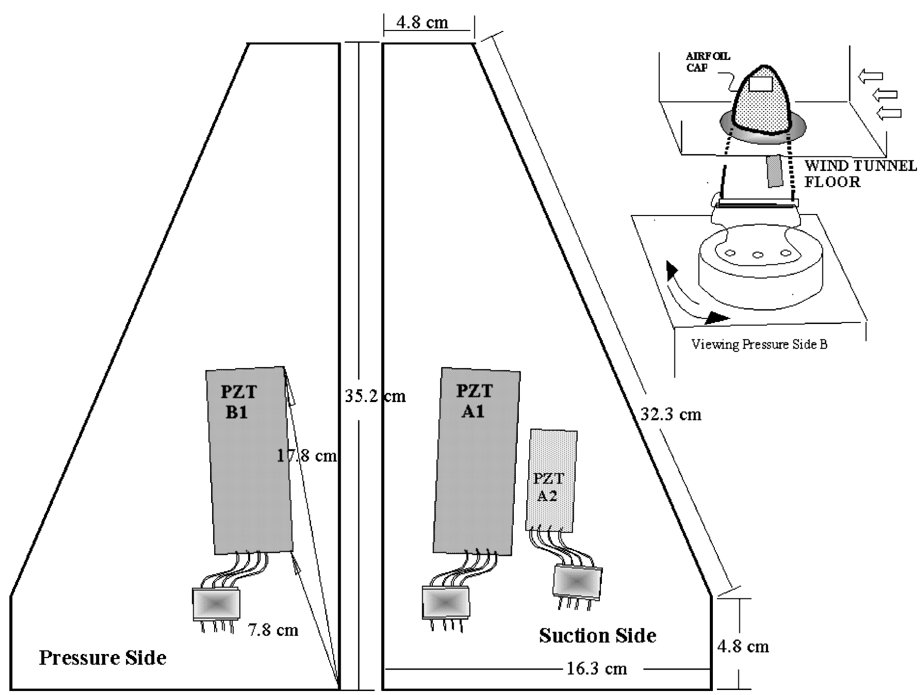

Fig. 2 Detail of the aluminum spar with PZT actuators attached.

PZT patch QP10N is used on top of the large patch A1. One actuator patch is used on each side of the wing structure.

A sketch of the flat-swept wing is shown in Fig. 2. The wing is made of aluminum, and a light airfoil is used to cover the wing for wind-tunnel testing. The large PZT patches A1 and B1 shown in Fig. 2 are used for actuation, and a small piezoceramic patch A2 is used on the wing as a sensor or actuator.

A lightweight sheath is fitted over the sturdy but flexible aluminum wing structure to which the piezoelectric actuators are attached. Within the tunnel flow, the wing profile induces bending moments and lifting forces. The piezoelectric patches are affixed so as to maximize their bending signals and are spaced a sufficient distance from the wing root to avoid cracking the actuators at high strains. The wing profile is shown in Fig. 3.

A laser Doppler vibrometer[20] is used as the velocity sensor to measure the vibration of the wing near the tip. The laser Doppler vibrometer works based on the Michelson interferometer. In this method, a coherent He–Ne laser beam is divided into an object beam and a reference beam by a beam splitter. The object beam strikes a point on the vibrating wing and the light reflected from the wing travels back to the laser head and through a lens to a beam splitter and interferes with the reference beam. The vibration of the wing produces an intensity fluctuation in the light. A detector converts this signal into a voltage fluctuation. The velocity of the wing is proportional to the frequency of this sinusoidal signal based on the equation $\nu = \lambda f_0/2$, where ν, f_0, and λ are the velocity of the wing, the Doppler frequency, and wavelength of the laser light, respectively. A Bragg cell in the laser head is used to frequency-shift the reference beam to determine whether the velocity signal is positive or negative. The velocity signal is connected to an input channel of the dSpace controller and runs through an A/D converter (to be used in the SIMULINK control loop where the signal is low-pass filtered), and the feedback signal to the piezoceramic actuators is computed.

Fig. 3 Model wing used in the experimentation: a) back side of the wing showing a large PZT actuator and a smaller PZT sensor or actuator and b) front side of the airfoil covering the aluminum wing in a wind tunnel; retroreflective tape and the laser spot are visible.

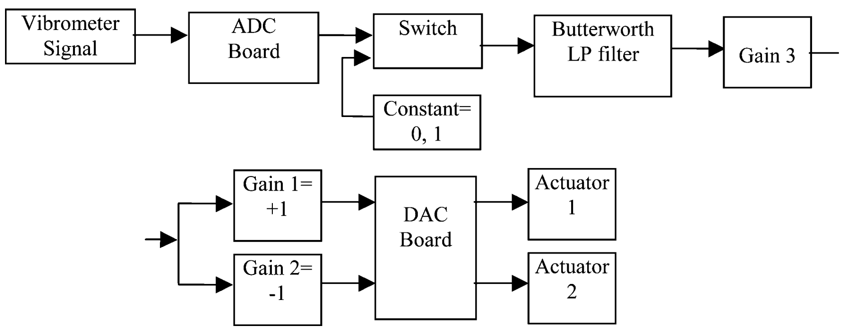

Fig. 4 SIMULINK block diagram used for the experimentation: the vibrometer signal is an input and the two actuator control signals are outputs. A Butterworth low-pass filter (cutoff frequency = 16 Hz; order 3) is used for all of the cases.

Advantages of using the laser sensor are as follows: 1) direct velocity measurements can be made without significant time delay or the need to integrate acceleration measurements, 2) the laser can be scanned over the structure to measure the velocity at different points, 3) the laser is noncontact and no wires or power are needed for the sensor on the wing, and 4) damage to the ailerons and wing structure can be detected by measuring the higher-frequency vibration. The main disadvantages of using the laser are the high cost and the requirement for a line of sight to the structure.

The wind tunnel used in the experiment is located at North Carolina A&T State University, is a closed-return variety similar to the Gottingen and Prandtl tunnels used in very early aerodynamic study, and is highly turbulent. There is a 30.5 cm × 30.5 cm × 38.1 cm test section with sealable Plexiglas® doors. The experiment was performed in the subsonic range with an estimated Mach number $M = 0.03$ and Re of approximately 2.5×10^4. The tunnel controller gives about 1.3–1.8 in. (3.3–4.6 cm) of water at stagnation.

Experimental Results

The control gains for the wing were determined experimentally by trial and error. The SIMULINK[18] diagram used for the experimentation is shown in Fig. 4. GAIN1, GAIN2, and GAIN3 are gain variables, which can be adjusted or set to zero. It is also possible to have a hybrid control in which feedback from the laser and from a piezoceramic patch are used simultaneously,[21] or a reconfigurable control law is used for laser scanning.[22] In this Note, a simple velocity-feedback control law, filtering, and buffet suppression using a wind tunnel are investigated. A Butterworth filter is used to remove the high-frequency vibration signals and noise caused by speckle-pattern motion from the laser feedback signal. The filter is shown on the diagram in Fig. 4. In this experiment, trial-and-error optimization of the filter parameters showed that a third-order filter with a 16-Hz cutoff frequency provided the best performance to suppress the low-frequency vibration of the wing. Three cases of vibration suppression are considered and are 1) free vibration from a tip displacement, 2) excitation by cross flow from a fan, and 3) wind-tunnel flow.

The experimentation is performed first for the free-vibration response of the wing. In this case, the wing is displaced against a fixed stop and released. The free response is measured without control first and is shown in Fig. 5a. The damping of the aluminum wing is small, as shown by the free response. The second experiment performed is the controlled free response of the wing. In this case, the wing is again displaced against a fixed stop and released. The free response is measured with control and is shown in Figure 5b (different scale). The free response is damped to near zero in two cycles of vibration. The performance of the free response depends on the control authority, which depends on the size of the piezoceramic patches. The logarithmic decrement technique[23] was used to compute the damping ratio of the wing from the free vibration response. The equations used are

$$\delta = (1/n)\,\ln(x_o/x_n) \tag{1a}$$

$$\zeta = \delta/(4\pi^2 + \delta) \tag{1b}$$

where δ is the logarithmic decrement, x_o and x_n are the vibration amplitudes after n cycles of vibration, and ζ is the damping ratio.

The third and fourth experiments performed are the uncontrolled and controlled response of the wing because of fan-wind loading. The fan is a common four-blade low-speed cooling fan that is arranged at an angle to the wing. The response is measured first with no control (not shown). The response has random amplitude and mostly occurs at the fundamental natural frequency of the wing, which is about 20 Hz. Active control was performed with large PZT collocated actuators on each face of the prototype blade and with one small PZT actuator on one side. Approximately 46% amplitude suppression was obtained.

The fifth and sixth experiments involve the wind tunnel. In Fig. 6a the free vibration of the blade under subsonic flow in a wind tunnel with wind speed of about Mach 0.1 is shown. The response is random

Table 1 Results of the buffet control experimentation

Test condition	Vibration of wing		
	No control	Controlled	Percent reduction
Damping ratio of wing free vibration; response shown in Figs. 5 and 6	$\zeta = 0.002$	$\zeta = 0.025$	——
Vibration velocity of the wing due to fan excitation; response not shown	Peak = 0.023	Peak = 0.0124	46%
	RMS = 0.0084	RMS = 0.0045	46%
Vibration velocity of the wing due to wind-tunnel excitation; Figs. 7 and 8	Peak = 0.0727	Peak = 0.0448	38%
	RMS = 0.0220	RMS = 0.0149	32%

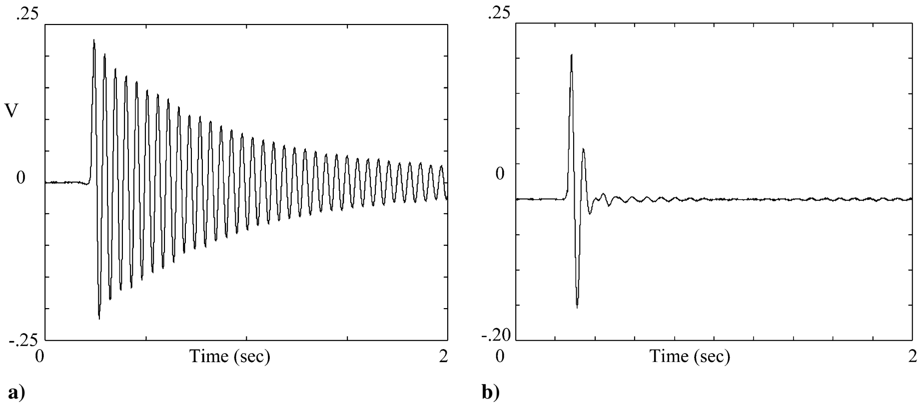

Fig. 5 Free vibration of the model blade because of initial tip displacement. The vibrometer signal is shown a) for no control −0.25–0.25 V and b) with control −0.2–0.25 V.

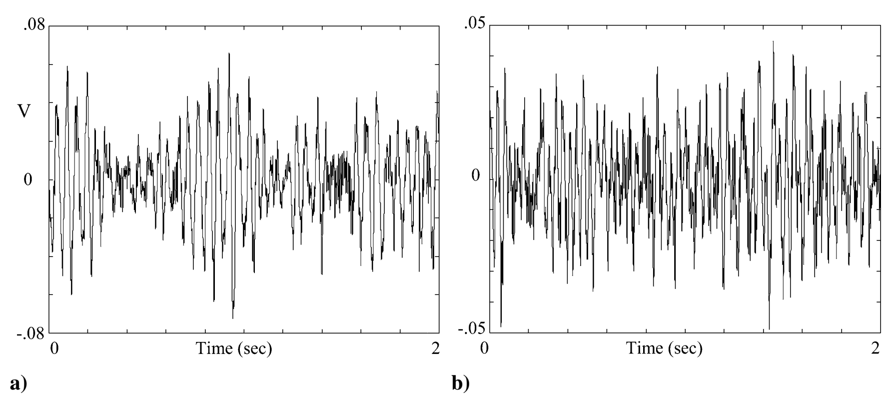

Fig. 6 Vibration of the model blade during subsonic wind in a wind tunnel. The vibrometer signal is shown a) for no control, −0.08–0.08 V and b) with control, −0.05–0.05 V.

in amplitude and frequency with the dominant frequency in the response at the first natural frequency of the wing, which is about 20 Hz. In Fig. 6b (different scale) vibration buffet suppression is shown for the prototype blade in a wind tunnel. Vibration amplitude suppression of 38% peak and 32% rms is obtained. Because the loading is greater and the frequency of the loading is varying in the wind tunnel, larger actuators and a higher bandwidth controller could further reduce the vibration level.

The results of the vibration suppression study are summarized in Table 1. The percent reduction in the vibration level is computed as

$$R = [(\dot{x}_{\text{no control}} - \dot{x}_{\text{control}})/\dot{x}_{\text{no control}}]100 \qquad (2)$$

Practical Use of a Laser Sensor in a Flight Environment

The practical issues with using a laser sensor in a flight or space environment are discussed here. The key requirement for making measurements through clouds and rain is that the backscatter light intensity from the surface of interest should dominate any light backscattered from other media. As long as the cloud is not too dense and the wing top is painted with retroreflective paint, meeting this requirement should not be a problem. Rain droplets may be more of a problem and cause dropouts on the signal, but signal processing might be used to extract the information from the velocity signal between the droplets, especially if the frequencies at which the wing will vibrate are known beforehand. Another approach regarding the rain problem is to use more than one conventional out-of-plane laser vibrometer, targeting the wing from slightly different points. By recording the velocity and Doppler signals (light intensity reaching the detector, a signal available at the back of the laser controller), it may be possible to extract from the velocity signals only the signals corresponding to the strongest Doppler signals, that is, when the laser reaches the retroreflective paint or tape. When a rain droplet interferes with one laser, the other laser might reach its target and vice versa. Darkness has no influence on the ability to make measurements whatsoever. Regarding the angle of the laser with the structure, a conventional out-of-plane laser vibrometer will measure the velocity vector in the laser direction and a cosine correction must be made to calculate the out-of-plane vibration. Larger-diameter laser beams may be needed to accomplish this, and the power of each beam may need to be higher than the standard class 2, 1-mW laser. The use of the single out-of-plane laser for scanning at small angles of incidence is a subject for future investigation. To maximize signal level, the wing would be painted with retroreflective paint. Vibration of the laser mount will also affect the readings and must be considered. Online diagnostics of incipient mechanical failure of critical aircraft systems by remotely sensing aircraft vibrations using a laser was studied in Ref. 24. Other applications where this technique of in situ scanning laser vibrometry could work for control and damage detection include launch vehicles, the space station, satellites, and large civil structures such as bridges, towers, and tall buildings.

Conclusions

This Note has demonstrated the possibility of using a laser sensor and piezoceramic patches for vibration suppression on aircraft. The control technique significantly increased the damping ratio and reduced the steady-state vibration of a model wing in a low-speed wind tunnel. The performance could be improved by using actuators that have a larger force and a filter with less phase lag. The advantages of this approach are that the laser can be scanned over the structure to measure the velocity at different locations on an aircraft and no wires, contact, or power are needed for the sensor. The laser can operate in clouds, and darkness has no affect on the laser. However, because of reflection, the amplitude of the laser beam is reduced each time it passes through a different medium, which would occur when flying through rain, for example. Sensing during rain and at low angles of incidence need further investigation.

Acknowledgment

This work was supported by the NASA Center for Aerospace Research at North Carolina A&T State University under Grant NCC-1-255. Instrumentation was partly from an AFOSR Instrumentation Grant. David E. Oliver of Polytec PI provided information on the operation of the laser vibrometer. This support is gratefully acknowledged.

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E. Livne
Associate Editor