Active Flutter Control with V-Stack Piezoelectric Flap Actuator

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Aeroelastic control of wings using distributed, trailing-edge control surfaces is of interest for maneuvers, gust alleviation, and flutter suppression. The use of high-energy-density, piezoelectric materials as motors provides an appealing solution to the problem of flutter suppression. A new piezoelectric actuator, the V-stack piezoelectric actuator, was designed and bench tested at Duke University. This actuator meets the requirements for trailing-edge flap actuation in both stroke and force. It is compact, simple, and sturdy and leverages stroke geometrically with minimum force penalties while displaying linearity over a wide range of stroke. Integration of the actuator inside a structure requires minimal modifications. The shape of the actuator makes it extremely suitable for trailing-edge flap actuation, eliminating the need for a push rod. A typical section prototype was constructed and tested experimentally in the wind tunnel at Duke University. This experiment was designed for preliminary evaluation of the actuation concept. During bench tests the desired flap deflection of \( \pm 5 \) deg was obtained. Wind-tunnel experiments showed that air flow has little influence on flap deflection, suggesting good actuation authority. Actuator-flap frequency bandwidth achievable for this experiment, in the context of \( \pm 5 \) deg flap deflection, was sufficient and facilitated control design. Positive position feedback (PPF) control was used to add damping to the unstable flutter mode. Operating in closed loop, the flutter was suppressed at the speed at which the flutter occurred open loop, and the flutter speed was increased by more than 30%.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a )</td>
<td>position of the elastic axis with regard to midchord point in fractions of the semichord</td>
</tr>
<tr>
<td>( b )</td>
<td>semichord</td>
</tr>
<tr>
<td>( c )</td>
<td>position of the hinge line with regard to midchord point in fractions of the semichord</td>
</tr>
<tr>
<td>( I_{CG} )</td>
<td>moment of inertia of the wing model with regard to its center of mass</td>
</tr>
<tr>
<td>( I_{CGf} )</td>
<td>moment of inertia of the flap with regard to its center of mass</td>
</tr>
<tr>
<td>( I_{wCG} )</td>
<td>moment of inertia of the wing model without flap with regard to its center of mass</td>
</tr>
<tr>
<td>( K_p )</td>
<td>plunge stiffness</td>
</tr>
<tr>
<td>( K_r )</td>
<td>pitch stiffness</td>
</tr>
<tr>
<td>( K_f )</td>
<td>flap stiffness</td>
</tr>
<tr>
<td>( m )</td>
<td>total mass of the wing model</td>
</tr>
<tr>
<td>( m_{bl} )</td>
<td>mass of the lower mounting block</td>
</tr>
<tr>
<td>( m_{bu} )</td>
<td>mass of the upper mounting block (including the sensor)</td>
</tr>
<tr>
<td>( f )</td>
<td>mass of the flap</td>
</tr>
<tr>
<td>( s )</td>
<td>actuator stroke</td>
</tr>
<tr>
<td>( U_{\infty} )</td>
<td>airflow speed</td>
</tr>
<tr>
<td>( x_{CGf} )</td>
<td>position of the center of mass of the flap with respect to hinge line</td>
</tr>
<tr>
<td>( x_{CGw} )</td>
<td>position of the center of mass of the wing without flap with regard to the elastic axis</td>
</tr>
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</table>

Introduction

In real-life applications aerelastic control is done using discrete control surfaces because of practical aspects (thus are easy to manufacture, actuate, and maintain). Discrete trailing-edge control surfaces (flaps and ailerons) are widely used for aeroelastic control because of simplicity, inherent stability, and effectiveness of the solutions. Various solutions exist for trailing-edge flap actuation; however, flutter alleviation requires actuation systems capable of producing large force and large stroke (up to \( \pm 6 \) deg flap deflection) over a wide frequency range (up to 25–30 Hz). Conventional hydraulic systems, widely used for actuation of conventional aeroelastic control systems, are relatively slow (limited bandwidth) and complicated.

Recent developments of new piezoelectric actuator systems have made flutter alleviation using trailing-edge flaps more feasible for small aircraft such as unmanned aerial vehicles (UAVs). The latest results are encouraging in spite of the fact that the piezoelectric transducers are not well developed for large stroke applications; they are used in numerous other applications.\(^1\)\(^6\)

At Duke University, as part of an effort to build an adaptive high-aspect-ratio wing, a new actuator, called V-stack piezoelectric actuator, was developed.\(^6\) Preliminary tests performed on the actuator indicated that integration of the actuator into a wing model for driving a trailing-edge flap should give good results.\(^7\) The actuator uses two stacks of high-performance piezoceramic as active elements. The stacks are symmetrically positioned with respect to a central element (lever) and work complementarily. The shape of the actuator facilitates its integration into an airfoil, requiring very few additional elements. This helps to make the structure simple and efficient (mass, stiffness, construction, etc.).

A typical section (NACA 0015) suitable for testing in the wind tunnel at Duke University, referred to as the wing model in the
following, was constructed and tested. The primary objective of
the experiment was to increase the flutter boundary by controlling
the flap in a closed-loop fashion. Aeroelastic analysis of the wing
predicted the flutter free stream velocity of 19 m/s and a flut-
ner frequency of 4.2 Hz. The wing was first tested on the bench and
then tuned for testing in the wind tunnel. The tuning was related
primarily to the actuator-flap system because of issues addressed in
the following sections.

Experimental Model

The shape of the actuator (V) triggered the idea that the actuator
could be mounted in the direction of the chord. In this case, the
actuator plane would be perpendicular to the wing plane and the
direction of the actuator output would be also perpendicular to the
wing plane. By positioning the actuator chordwise, the output point
could be located very close to the hinge of the flap, eliminating
the need for a push rod. Without a push rod, the actuation mechanism
can be simpler, lighter, and stiffer. Also, the internal structure of a
particular wing would be minimally disturbed. A design analysis
revealed that a crank-slider-like mechanism would be a better solu-
tion than a floating link. As a result, the design of the actuator tip
was modified to accommodate a slider.

Figure 1 presents a cross-sectional view of the design of the ac-
tuator integration into a wing model. The actuator, 3, is attached to
the ribs, 1, through the support, 2, designed such that it will mount
on existing elements of the structure. Two bolts are used to secure
the actuator in place. For sophisticated constructions, one would
use an adjustable support to tune the desired position of the actuator
(chordwise and spanwise). However, for the purpose of this work a
careful machining of the parts was preferred.

The necessary torque for flap actuation is realized by applying the
actuator output force at an offset distance, \( r_f \), from the flap hinge.
Upon applying voltage to the actuator piezoelectric stacks, the tip
of the actuator moves up and down and pushes the slider (mounted
on a pin), causing the flap to rotate about the hinge line, 5. There
is a very low-clearance fit between the actuator tip and the slider to
avoid undesirable nonlinearities (free play) and, at the same time,
to allow free motion of the slider along the slot. The motion of the
slider along the slot is required to compensate for the change in
distance between the pivot point of the lever and the axis of the
flap-actuation pin during operation. To minimize friction between
the slider and the actuator tip, the slider is made of bronze and the
actuator tip is made of high-strength steel. The slider is mounted
(tight fit) on a pin that is supported on two ball bearings mounted in
a support, 6. The flap is mounted on ball bearings for minimal
friction losses.

The support, 6, can slide along a slot machined in the flap rib, 7,
and this permits tuning of the actuator-flap system: flap deflection
and flap bandwidth. A trade-off between the two exists because for
large flap deflection one would obtain smaller bandwidth and vice
versa. Tuning is realized by adjusting the distance, \( r_f \), between the
flap hinge and slider pivot axis.

The typical section model was designed and constructed to fit in
Duke’s low-speed wind tunnel, using a testing rig used by other Duke
researchers for aeroelastic experiments on typical sections. The
geometric, inertia, and stiffness parameters for the test section are
given in Table 1. The rig consists of two almost-identical assemblies
(mechanisms), mounted above and below the testing section of the
wind tunnel. The schematic of the mechanisms is presented in Fig. 2.

The typical section is mounted on two bearings (top and bottom)
using two short shafts that fit in the aluminum tube at quarter chord.
The bearings allow the shafts to rotate freely, thus permitting pitch
degree of freedom. The housings of the bearings are fixed on moving
support plates that are further supported, each on two leaf springs.
The leaf springs are clamped in the fixed support block and allow
plunge degree of freedom and provide plunge stiffness at the same
time. Pitch stiffness is provided by a steel wire subjected to bending
(upper support only). The wire runs through a hole drilled in the
upper mounting shaft and is pinned at both ends on the moving
support plate. Stiffness in both plunge and pitch can be adjusted
by adjusting the length of the leaf springs and distance between
support points of the steel wire respectively. Angular displacement
sensors (Lucas Shaevitz) are used to directly measure displacement
for pitch and flap and indirectly for plunge. The testing rig brings
additional mass into the system to be tested in the wind tunnel. The
added mass is significant only for plunge motion and does not affect
pitch-support plates, only translate, as shown in Fig. 2.

Preliminary Tests

Preliminary tests were conducted to verify the experimental
rig before the wind-tunnel experiments. During the design of the

![Fig. 1 Actuator integration into the wing (SolidWorks model): 1, rib; 2, actuator support; 3, actuator; 4, slider; 5, hinge line; 6, ball-bearing support; and 7, flap rib.](image1)

![Fig. 2 Schematic of the testing rig.](image2)

| Table 1 Parameters of the typical section model and testing rig |
|---------------------------------|-----------------|----------------|
| Parameter | Unit | Value |
| **Dimensions** |
| Span | m | 0.525 |
| Chord | m | 0.360 |
| b | m | 0.180 |
| a | — | 0.5 |
| c | — | 0.5 |
| **Inertial characteristics** |
| \( m \) | kg | 2.610 |
| \( m_f \) | kg | 2.258 |
| \( m_f \) | kg | 0.352 |
| \( x_{CG} \) | m | 0.050 |
| \( x_{CGw} \) | m | 0.026 |
| \( x_{CGf} \) | m | 0.025 |
| \( I_{CG} \) | kg m² | 2.439 \times 10^{-2} |
| \( l_{wCGw} \) | kg m² | 1.5 \times 10^{-2} |
| \( l_{wCGf} \) | kg m² | 2.604 \times 10^{-4} |
| \( S_w \) | kg m | 0.1305 |
| \( S_f \) | kg m | 0.0088 |
| \( m_{bu} \) | kg | 0.644 |
| \( m_l \) | kg | 0.392 |
| **Stiffness characteristics** |
| \( K_y \) | N/m | 1055.12 |
| \( K_w \) | N/m | 32.28 |
| \( K_f \) | N/m | 13.06 |


Experimental model two main objectives were targeted, namely, quasi-static angular deflection of the flap in excess of ±5 deg and bandwidth of the actuator-flap system exceeding natural frequencies in pitch and plunge. A large angle of deflection gives good control authority and a large bandwidth of the actuator-flap system will facilitate control design because the dynamics of the actuator flap will not influence the aeroelastic system dynamics.

Figure 3 presents the frequency response of the actuator-flap system in the absence of flow along with frequency responses obtained for flow speeds of 20 and 35 m/s. Observe that, regardless of the flow speed, flap response is flat up to about 10 Hz. Also observe that as the flow speed increases more damping is added to the system.

To analyze the fully coupled dynamic of the aeroelastic system in the absence of flow, the wing model was placed in the wind tunnel in the position it would be eventually tested under flow conditions, and all three degrees of freedom were allowed. The excitation of all three degrees of freedom was provided by exciting the flap with 100-Hz white noise. Resonant frequencies were found at 3.1, 5.9, 9, and 31 Hz. Because the connection between the upper and lower mounting blocks was not perfectly rigid, a plunge natural mode at 9 Hz is present.

Open-Loop Characteristics

The main objective for open-loop experiments was to determine flow speed and frequency at flutter. To this end, frequency-domain system identification of the aeroelastic system was performed for flow speeds from zero to a value close to the flutter speed. For $U_{\infty} < 10$ m/s, the reference flap motion was commanded using a white-noise excitation signal. However, for $U_{\infty} \geq 10$ m/s, the ambient wind-tunnel “noise” was significant compared to the motion generated by white noise to the flap. To obtain a satisfactory signal-to-noise ratio above 10 m/s, the frequency response was measured using a swept-sine analysis. Frequency responses from commanded flap deflection to pitch and plunge displacements were estimated by commanding a sinusoidal flap deflection of 2 deg. Continuous-time state-space models were then fit to estimated frequency responses using frequency-domain system-identification software. Parameters of interest, namely damping ratios and pole locations, were then obtained from these models.

Flutter speed $U_f$ can be determined by representing the damping factor as a function of the flow speed. The speed for which the damping factor becomes zero is the flutter speed. Damping factors associated with the two poles of interest for different flow speeds can be found from the continuous-time models obtained as described previously. Figure 4 presents the variation of the damping factor with flow speed. Because system identification for an unstable system is not possible, $U_f$ can be found by extrapolating experimental data. For this case it is $U_f \simeq 23$ m/s, which is ~21% greater than the theoretical value. This difference is likely to be due to model simplicity because effects of the wind-tunnel walls, air temperature, and humidity were not taken into account.

Figure 5 presents migration of the two complex conjugate pairs of poles of interest for flow from 0 to 22 m/s. Note that the poles associated with pitch tend to become unstable, migrating toward the imaginary axis and eventually crossing into the right-hand-side plane, whereas damping of the plunge poles increases. The experimental flutter frequency is 4.3 Hz, accurately predicted by the aeroelastic model.

Control Design

The problem of flutter suppression is one of the most important objectives in aeroelastic control. The goal is stabilization of an unstable plant and delaying the onset of flutter until a higher speed. Instability occurs when damping associated with a pole of the aeroelastic system (a dynamic system in general) becomes negative; that is, the pole migrates into the right-hand plane. To prevent the pole from crossing into the right-hand plane, damping has to be added to the pole by using a suitable controller, therefore moving the pole into the stable region. By stabilizing an aeroelastic system that would otherwise encounter instability, the operational envelope of that system is increased.

Significant effort has been devoted to the subject of active flutter control using control strategies including classical, modern, LQR, LQG, robust $H_\infty$, and $H_\infty$ (see Refs. 5, 10–21). Although many researchers presented successful experimental demonstrations, in most cases performances are rather modest. Significant increase of the flutter speed (~50%) for a rectangular HAR wing (AR = 10) was obtained by Borglund and Kutsenko. Using robust control design, Vipperman et al. extended the flutter boundary of a typical section model by roughly 10%. Heeg reported a 20% increase of flutter speed for an experimental model using piezoelectric actuation.
and simple SISO feedback control. Cox also reported a 20% increase of the flutter boundary of a typical section by successfully using a gain-scheduled multiobjective controller.

**Positive-Position-Feedback (PPF) Control Design**

Because the aerodynamics, wing structure, and controller are interconnected dynamic systems, it is possible to control flutter by feeding back an observable state of the system. Of the two measured aeroelastic states, pitch was chosen as a suitable measure of the system because of its high interaction with the air flow and higher coupling with flap deflection.

Positive-position-feed back (PPF) control is used to add damping to the unstable flutter mode. This technique was originally introduced by Goh and Caughey as alternative to collocated-direct-velocity feedback. The control approach consists of feeding back a structural displacement through a second-order filter and is analogous to the tuned-mass vibration damper.

**Closed-Loop Results**

Models of the plant calculated from system-identification data were used to compute overall damping factors at flow speeds ranging from 10 m/s to 28 m/s. Figure 6 presents plots of the damping factor vs the flow speed for open-loop and closed-loop aeroelastic systems. At speeds greater than 28 m/s, the ambient wind-tunnel noise caused a poor signal-to-noise ratio; thus, identification of the plant did not supply reliable data sets for model computation. Although Fig. 6 presents data up to 28 m/s during the experiment, the system remained stable for flow speeds exceeding 30 m/s. The closed-loop flutter boundary, considered to be 30 m/s, represents an increase by more than 30% over the open-loop flutter boundary.

Figure 7 presents pole migration for open- and closed-loop cases. It can be observed that just as for the open-loop case, the high-frequency pole (pitch) tends to become unstable; however, closed-loop pole frequencies are lower than in the open-loop case for the same flow speed.

**Conclusions**

This work investigated the feasibility of aeroelastic flutter control using trailing-edge control surfaces (flaps) powered by a V-stack piezoelectric actuator. The actuator was integrated into an experimental wing to articulate the trailing-edge flap. The objective was to control the onset of flutter by altering the aerodynamics of the wing by deflecting the trailing-edge flap in a controlled fashion.

By taking advantage of the actuator’s shape (V), the actuator was placed chordwise with the output point close to the flap hinge; thus, a simple crank-slider mechanism was used for flap actuation. The mechanism is adjustable and facilitates tuning of the actuator-flap mechanism for desired flap deflection and bandwidth. The actuator produces the desired flap deflection and the response of the flap (angle of deflection), with respect to the voltage applied across the piezoelectric stacks, exhibits the desired linearity, and the actuator-flap system exhibits a bandwidth in excess of 10 Hz.

High control authority and bandwidth facilitated control design. A simple PPF controller was used to add damping to the resonant mode. Operating in closed-loop fashion, the flutter boundary was extended by more than 30%, from 23 to more than 30 m/s. Control authority was remarkable, evidenced by the fact that the unstable wing can be stabilized by closing the loop even while in strong flutter. Reduction of oscillation amplitude was achieved for all flow speeds. Further increase of the flutter speed is deemed possible by using a more sophisticated control approach such as adaptive, Q-parametrization, and gain scheduling approaches. However, this is a topic for future research because the main goal of this work was to investigate the effectiveness of the actuation solution.

Through appropriate changes in design, the flap-actuation solution presented here could be successfully used at smaller or larger scales and for significantly higher flow speeds. For example, in the case of a larger wing, multiple control surfaces, which are individually powered by one V-stack actuator, can be distributed along the trailing edge. One could also conceive of a solution in which multiple actuators power a single control surface and so on. Although this was a demonstration of flutter control of a two-dimensional wing model situated in low aerodynamic pressure, it demonstrated that piezoelectric actuators have the potential for use in real-life applications.

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**References**