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# Engineering Notes

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## On Active Aeroelastic Control of an Adaptive Wing Using Piezoelectric Actuators

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### I. Introduction

THE application of piezoelectric actuators and sensors for control of aeroelastic response of wing structures has been reported in the literature.[1–6] The material properties of piezoelectrics make them uniquely suited for this task, because they are easily bonded to the surface of the structure on which they are capable of exerting large forces. Piezoelectric ceramics are actuated by passing a current through the thickness of the ceramic wafer, inducing a strain perpendicular to the directional of the electric potential. Piezoelectrics are cable of operation in a frequency range from under 1 Hz up to more than 20 kHz making them ideal for dynamic aeroelastic induced instability control.

The current study is a natural evolution of the research program on active aeroelastic aircraft structures.[7–8] The three-dimensional adaptive wing has its aerodynamic profile made from the primary load-carrying members, the skins of the wing. Piezoelectric sensors and actuators bonded to the inside of the skins then allow for control of the structure. Combining the load-carrying structure of the wing and the aerodynamic exterior makes it possible to realize the full potential benefits of distributed control, which include minimizing weight, control over the aeroelastic behavior of the structure, mitigation of fatigue problems in stressed regions, and reduced component complexity.

The objective of the study is to perform computational and experimental studies of an active aeroelastic wing, using a wing with piezoelectric actuators mounted in the main spar (active spar concept). The characterization and quantification of the improvements on the wing performance was carried out. For the active spar concept, it was found that the actuators were able to suppress significantly the aeroelastic vibrations.

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### II. Methodology

First, the vibration frequencies and modes of the wing were determined using a finite element commercial code ANSYS. Next, the aeroelastic analysis ZAERO¶ program was used to determine the wing flutter and divergence speeds. Next, the experimental wind-tunnel tests were obtained and compared to the computational results. In the wind tunnel, the wing was studied in two different configurations: with control off and with control on. The control was performed using MATLAB® and DSPACE data-acquisition instruments. By monitoring the shape of the wing in real time, the piezoelectric sensors measurements provided real-time information necessary for closed-loop feedback control making it possible to determine the improvements of the wing aeroelastic performance.

The wing has a 2.40-m span and a 0.33-m chord. The wing span was made with a span of 2.40 m because this was a limitation of the horizontal wind-tunnel test section, and the half-model is shown in Fig. 1.

The wing has a modified NACA0012 airfoil. The wing leading-edge skin is made of glass fiber, with distributed balsa ribs along the wing span to ensure that the leading-edge shape is maintained. The wing trailing edge is reinforced balsa. This wing is built conventionally using a carbon-fiber beam that is flat on the upper and lower surfaces. The beam works like the wing spar, and has two sensors near the root, one on the upper and the other on the lower part of the beam. The spar has two pairs of actuators on the adjacent sides of the beam. Figure 2 shows some details of the wing and its internal components.

### III. Computational Structural Modeling

The analysis of free vibration was performed using ANSYS finite element model (FEM) software in order to generate the natural frequencies and mode shapes of the model. The results generated by the ANSYS program are required to generate the input file to the ZAERO program, to perform the wing aeroelastic study. The first six natural frequencies and respective mode shapes are shown in Table 1.

The first, third, fifth, sixth, ninth, and tenth modes are accompanied by the wing bending, whereas the second, fourth, seventh, and eighth modes are mainly characterized by the two carbon plates vibration, without the bending. So, it can be concluded that there are four modes (second, fourth, seventh, and eighth) in which the lower carbon plate and upper carbon plates have deformations in opposite phases. This can be explained because the two carbon plates are only connected with each other at some discrete points, along the leading and trailing edges. These modes are not beneficial to this study because the main objective is to control the vibration of the total wing as a single assembly and not the lower or the upper carbon plates separately.

### IV. Computational Aeroelastic Modeling

The ZAERO program imports the ANSYS results, which consist of an input file containing the nodal deformations of the first 10 modes of the wing, and the aerodynamic wing model has 200 panels. The flutter results are tabulated in Table 2. It can be concluded that the flutter results for the first and second g methods and for the K method are validated. The most important conclusion is that the

¶Data available online at http://www.zonatech.com.

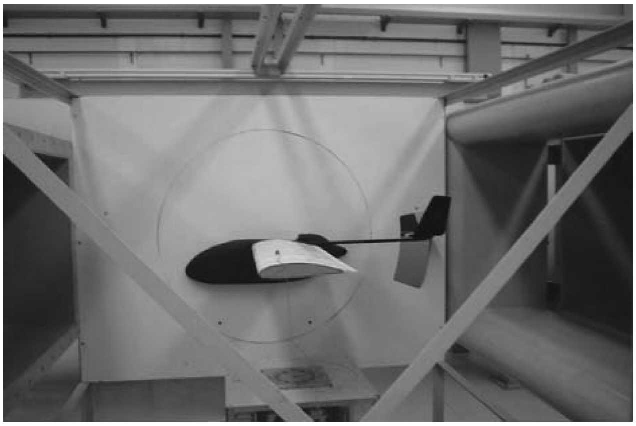

Fig. 1 Wind-tunnel configuration of the active wing.

flutter results for the first modes are similar using the three different methods. Figure-3 shows the first three flutter modes using the g-method results. Note that the flutter modes are numerated in crescent order of the speed values at which they will occur.

## V. Wind-Tunnel Test Results

The wing was tested in a range of speeds between 10 and 30 m/s. The angle of attack of the remotely piloted vehicle (RPV) was

**Table 1 First six wing natural frequencies**

| Mode | Natural frequency, Hz |
|---|---|
| 1 | 16.435 |
| 2 | 30.944 |
| 3 | 38.512 |
| 4 | 53.153 |
| 5 | 56.663 |
| 6 | 63.723 |

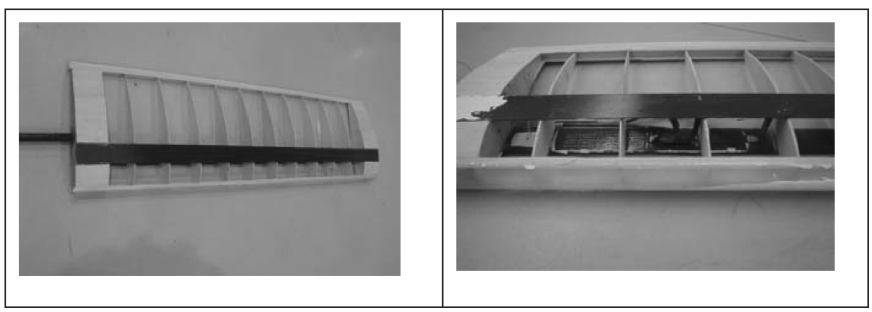

Fig. 2 Internal structure of the wing with active spar with the piezoelectric sensors and actuators.

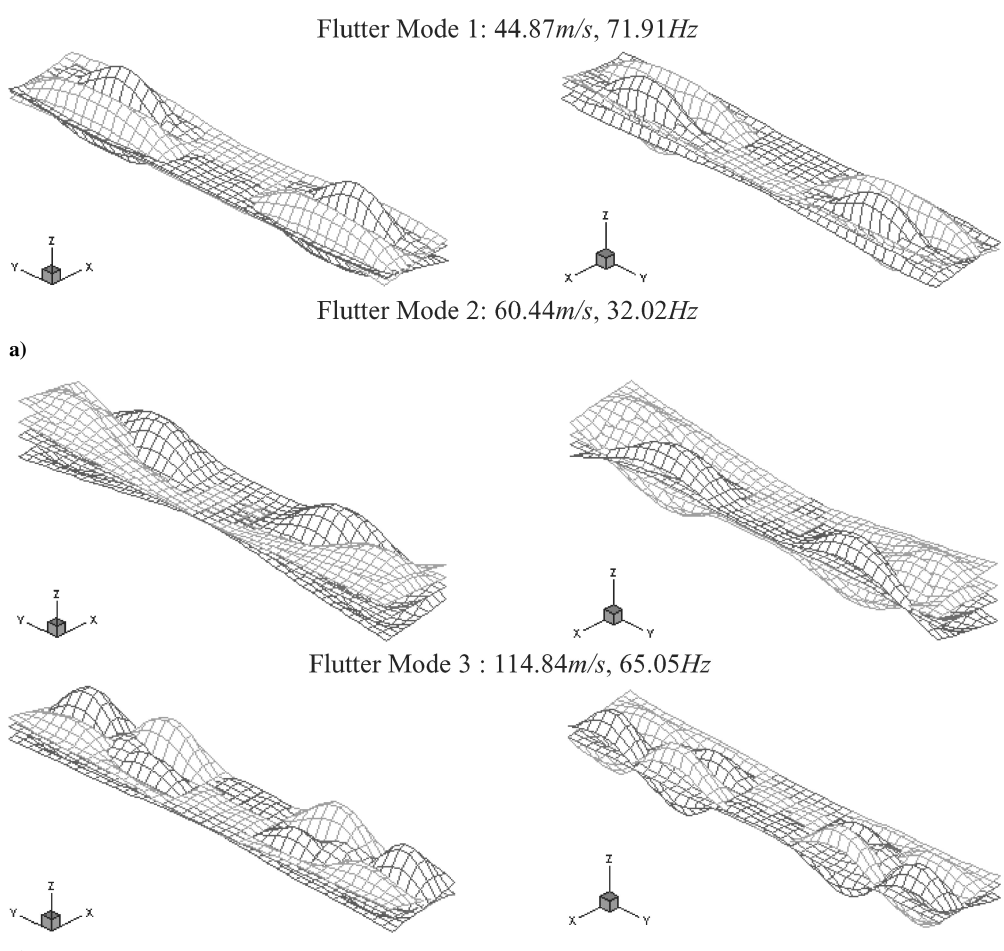


Fig. 3 First three flutter modes using the g method results.

**Table 2 Flutter speeds for the three analyses**

| First g method | K method | Second g method |
|---|---|---|
| 1st flutter mode: 44.87 m/s, 71.91 Hz | 45.1 m/s, 71.90 Hz | 45.69 m/s, 71.94 Hz |
| 2nd flutter mode: 60.44 m/s, 32.02 Hz | 60.5 m/s, 31.937 Hz | 60.74 m/s, 32.18 Hz |
| 3rd flutter mode:: 114.84 m/s, 65.05 Hz | 112.4 m/s, 61.45 Hz | —— |
| 4th flutter mode: 131.92 m/s, 86.96 Hz | 131.6 m/s, 86.96 Hz | —— |
| 5th flutter mode: 144.39 m/s, 31.46 Hz | —— | 145.36 m/s, 31.15 Hz |
| 6th flutter mode: 194.97 m/s, 44.71 Hz | —— | 184.51 m/s, 44.22 Hz |
| 1st divergence: 50.00 m/s | 55.32 m/s | 50.76 m/s |
| 2nd divergence: 170.00 m/s | 171.4 m/s | 175.67 m/s |

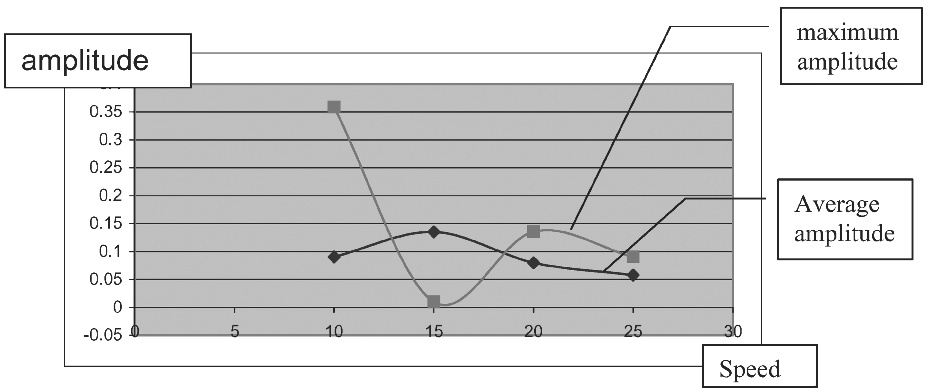


**Fig. 4 Improvement of the amplitude of the wing.**

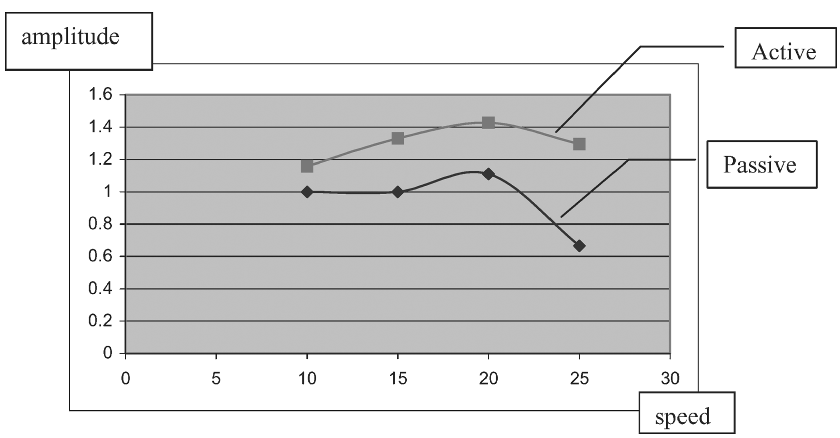


**Fig. 5 Wing damping at 5 Hz.**

calibrated for each speed, and the signals of displacements were recorded for each flying condition. With the angle of attack of the airplane calibrated for each speed, the signals of displacement of the wing were recorded for each flying condition. This displacement signal was then measured for average and maximum displacements.

The improvement in displacement supression results of the analyzed displacement signals (average and picks) with control on (active wing) and control off (passive wing) are shown in Table 3.

Graphically that can be observed as in Fig. 4.

These tests prove that the proposed approach for active aeroelastic control significantly decreases both the maximum amplitude and the average amplitude that a wing sustains during flight. This way the fatigue life will increase leading to a much safer structure. The damping of the wing was also studied. The damping influence was studied with two objectives: to determine the amount of damping that the controller can induce in vibration modes caused by external excitation (like turbulence or other vibration of the fuselage that also excites the wing) and the added damping to the vibration modes associated with the flutter. The aerodynamic shape of the tail in conjunction with the vibration modes of the aircraft fuselage generate a steady vibration at around 5 Hz and that shifts to almost 10 Hz as the speed increases. After validating the mode shapes, the signals of the sensors of the wing were transformed to frequency vs amplitude in order to calculate the damping of the wing at several speeds and in the active and passive mode. For the 5-Hz vibration, we found the dampings as tabulated in Table 4.

It can be concluded that the controller increases the damping of the wing in modes that are excited by external vibrations. Once again the dynamic characteristics of the wing are improved. The flutter tests were conducted in order to verify the predicted flutter speed for the wing working in the passive mode and then to investigate the maximum attainable speed increase without fluttering the wing with the controller working. The flutter speeds (controller on an off) were determined experimentally by calculating the damping of the vibration modes that will induce flutter (first flexing mode at 17 Hz and the first torsion mode at 33 Hz), plotting them in a damping vs speed graph (Fig. 5), and then extrapolating to zero damping for each case.

The damping of the first torsion mode is the most important to determine the flutter speed because this wing flutters conventionally. With a predicted frequency of 33 Hz of the first torsion mode, a flutter speed of 29.1 m/s was calculated.

This test was conducted in the following order: the speed was increased in steps of 5 m/s starting at 10 m/s. At each speed the sensor signals were recorded with and without the controller. Above 28 m/s

**Table 3 Displacements improvement**

| Speed, m/s | Suppression of the average amplitude, % | Suppression of the maximum amplitude,% |
|---|---|---|
| 10 | 9.0 | 35.9 |
| 15 | 13.5 | 1.0 |
| 20 | 8.0 | 13.6 |
| 25 | 5.8 | 9.0 |

**Table 4 Dampings for 5 Hz, tested with 10, 15, 20, and 25 m/s**

| Speed, m/s | Damping passive | Damping active |
|---|---|---|
| 10 | 1 | 1.158 |
| 15 | 1 | 1.33 |
| 20 | 1.111 | 1.428 |
| 25 | 0.666 | 1.296 |

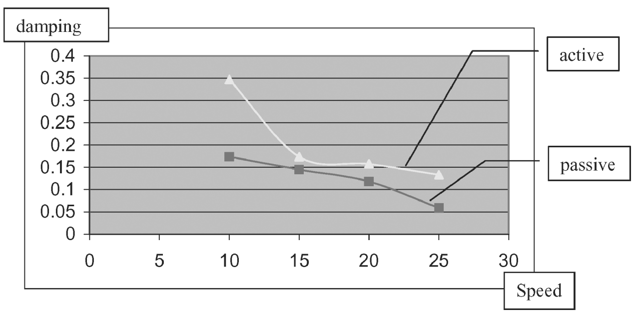


**Fig. 6 Wing damping for the first torsion model.**

the speed was increased with the controller on. After recording all of the data, the wing was taken to approximately 33 m/s with the controller on, and no flutter was observed. After that the speed was decreased to 30 m/s and the controller was turned off, then the wing fluttered, and it was destroyed. This proved beyond any doubt that the real flutter speed is between 28 and 30 m/s and that with the controller on we can fly above this speed with no structural damage. Later we estimated the flutter speed with controller on of 36 m/s. At 10 m/s the average amplitude decreased 9%, and the maximum amplitude peaks decreased by 36%. At 25 m/s the average amplitude decreased 6%, and the maximum amplitude peaks decreased by 9%.

As illustrated in Fig. 6, if we extrapolate the lines of damping to the zero damping we conclude that the flutter speed of the wing with no controller is 30 m/s and with the controller on approximately 36 m/s. This means that the active beam enables an increase in maximum speed of the wing of 20% with no structural damages.

An important consideration in the design of active aeroelastic control solutions is to know the savings in weight possible in relation to an equivalent passive wing. Thus, knowing the flutter speed of the active wing, a new spar was designed in order to obtain a passive wing with the same flutter speed, that is, 36 m/s at 40 Hz was obtained. The objective is to compare the active wing with an equivalent (in flutter speed) passive wing. The weight of the wing with no controller equals 690 g. The weight increase as a result of the controller equals 57.8 g, giving a total weight of the active wing equal to 747.8 g, which translates to a percentage increase in structural weight equal to 8.3%.

On the other hand, the beam weight increase in order to obtain an aeroelastically equivalent wing equals 180 g for a total weight of equivalent passive wing of 870 g. This implies a percentage increase in structural weight using a equivalent wing equal to 26.08%. Thus the weight saving by using an active beam wing results in a reduction of 122.2 g or 17.7% of the initial wing. To summarize, it is possible to increase the flutter speed of the wing by 20% with a savings of 17% in weight.

## VI. Conclusions

As a preliminary remark, it can be stated that the active spar concept has produced excellent results in active aeroelastic control, and significant savings in weight were achieved using the distributed and adaptive structures approach. In a posterior phase, it is proposed to use wings with both active spar and skin: the active span to control bending vibrations and the active skin to control the twist vibrations.

## Acknowledgments

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## References

[1]Lin, C. Y., and Crawley, E. F., "Towards Optimal Strain Actuated Aeroelastic Control," Ph.D. Dissertation, Dept. of Aeronautics, Massachusetts Inst. of Technology, Cambridge, Aug. 1996.

[2]Antcliff, R. R., and McGowan, A.-M. R., "Active Control Technology at NASA Langley Research Center," *Proceedings of the NATO Symposium on Active Control Technology for Enhanced Performance Operational Capabilities of Military Aircraft, Land Vehicles and Sea Vehicles*, Braunschweig, Germany, 8–11 May 2000.

[3]Heeg, J., McGowan, A., Crawley, E., and Lin, C., "The Piezoelectric Aeroelastic Response Tailoring Investigation: A Status Report," *Proceedings of the SPIE Smart Structures and Materials*, Vol. 2447, edited by C. Robert Crowe and Gary L. Anderson, May 1995, pp. 2–13.

[4]McGowan, A. R., Heeg, J., and Lake, R. C., "Results of Wind-Tunnel Testing from the Piezoelectric Aeroelastic Response Tailoring Investigation," AIAA Paper 96-1511-CP, April 1996.

[5]Weisshaar, T. A., Nam, C., and Batista-Rodriguez, A., "Aeroelastic Tailoring for Improved UAV Performance," *Proceedings of the 39th Structures, Structural Dynamics and Materials Conference*, AIAA, Reston, VA, April 1998.

[6]Kudva, J. N., Appa, K., Martin, C. A., Jardine, A. P., Sendeckyj, G., Harris, T., McGowan, A., and Lake, R., "Design, Fabrication and Testing of the DARPA/WL Smart Wing Wind Tunnel Model," *Proceedings of the 38th AIAA/ASME/AHS/Adaptive Structures Forum*, AIAA, Reston, VA, April 1997.

[7]Suleman, A., Moniz, P. A., and Costa, A. P., "Experimental Flutter and Buffeting Suppression Using Piezoelectric Actuators and Sensors," *Proceedings of the ASME International Mechanical Engineering Congress and Exposition*, Adaptive Structures and Material Systems, AD-Vol. 59, MD-Vol. 87, edited by G. Washington and J. Redmond, New York, 1999, pp. 293–299.

[8]Suleman, A., Crawford, C., and Costa, P., "Experimental Aeroelastic Response of Piezoelectric and Aileron Controlled 3-D Wing," *Journal of Intelligent Materials Systems and Structures*, Vol. 13, No. 2/3, Feb. 2002, pp. 75–83.