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UAV AEROELASTIC CONTROL USING REDUNDANT MICRO-ACTUATORS

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ABSTRACT

The investigation of trailing edge micro-actuators for aeroelastic control of uninhabited air vehicles (UAVs) has ranged from examining the fundamental aerodynamic effects to demonstrating flutter suppression of a flexible wing. The applicability of aerodynamic prediction methods including CFD and panel methods has been studied. Several generations of actuator concepts have been developed and characterized. Wind tunnel experiments have been completed on a rigid wing to determine the aerodynamic performance of the various actuator concepts including the effects of deflection pattern and rate. Unsteady wind tunnel investigations with Particle Image Velocimetry have been completed to gain insight into the flow physics. An elastically scaled flexible wind tunnel model was fabricated, instrumented, and equipped with several actuators. Active flutter suppression of the flexible model was accomplished using the micro-actuators. This report summarizes the completed research program and highlights potential areas for further investigation.

INTRODUCTION

Motivation

Uninhabited air vehicles (UAVs) are a particularly interesting and important focus for investigating issues of aeroservoelasticity. Many UAV designs, in particular long endurance UAVs, require high aspect ratio wings and are often further constrained by transonic performance considerations to limited section thickness. These factors result in substantial structural deformations. Aircraft such as Dark Star and Global Hawk also fly with small static margins to improve performance, requiring active control to obtain the desired dynamics over the flight regime. Compounding these problems, high aspect ratio UAVs often exhibit substantial coupling between the wing bending modes and the aircraft rigid body modes, requiring the control system to specifically address elastic response. Current UAVs have shown significant aeroservoelastic coupling despite structural designs that are quite stiff, and future UAVs may have greater problems when more efficient structural concepts lead to more flexible wing designs which still satisfy the strength constraints.

Approach

For typical flight vehicles, aeroelastic problems can be solved either by stiffening the structure or altering the mass distribution. These approaches incur a performance penalty, and when coupled with the unique characteristics of UAVs, make active control of the aeroelastic behavior the most promising solution. Recent developments in actuator technology have resulted in many new, small devices, which are capable of generating forces sufficient for flight vehicle and aeroelastic control.[1-3] The approach taken in the current research effort is to utilize large numbers of small, simple, trailing-edge devices to control the flexible vehicle dynamics. This approach has the advantages of utilizing simple devices requiring no accurate servo positioning, robustness due to the large number of devices, and high bandwidth and distributed placement allowing for structural and rigid body mode control. Figure 1 shows an artistic rendition of the proposed approach.

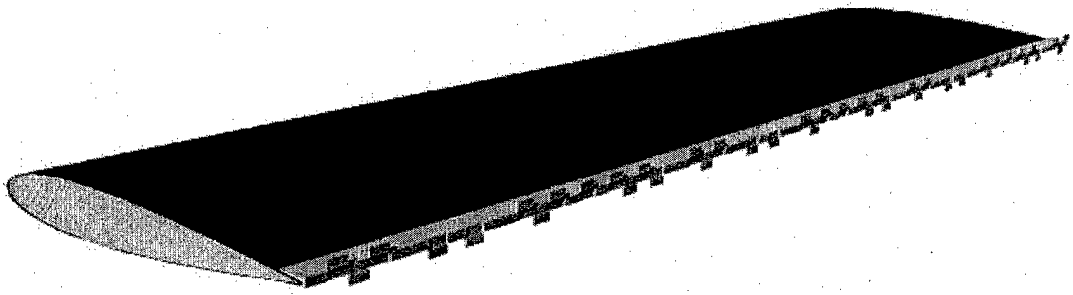

Figure 1. Proposed approach involving a large number of simple trailing edge devices.

The specific device studied, the Miniature Trailing Edge Effector (MiTE), is a small trailing edge device, 1-5% chord, deflected vertically into the flow. The device is inspired by performance enhancing "Gurney flaps", developed for racecars in the 1970s by Dan Gurney and Robert Liebeck.[4] Fundamentally the device results in a stable separation region ahead of flap and a pair of counter-rotating vortices aft. These modifications to the flow field result in significant changes in section forces with small (or negligible) hinge moment and small drag penalty.

Overview of Research Program

The completed research program involved many aspects ranging from aerodynamic analyses, actuator development, aerodynamic tests, aeroservoelastic analyses, and aeroservoelastic testing. This report will provide an overview of each of the areas and provide references for more detailed treatments as appropriate. The areas requiring further investigation are highlighted at the end of the report.

AERODYNAMIC ANALYSES

A significant portion of the initial research effort involved aerodynamic analyses to gain insight into the flow physics and confidence in the analysis tools. Only an overview of the scope is provided here while the reader is directed to the previously published summaries for more detail.[5,6]

The aerodynamic analyses utilized steady and unsteady Computational Fluid Dynamics (CFD). The steady analysis results were compared with available experimental results[7,8] to gain confidence in the analysis code, INSD-2D. Figure 2 shows an example result from a steady CFD simulation of a NACA 4412 airfoil. Favorable comparisons were found for a range of MiTE sizes and flow conditions, as seen in Figure 3. These steady analyses also confirmed the effectiveness of the MiTE concept, with large lift coefficient increments resulting from small size Gurney flaps. Unsteady simulations were used to understand the flow physics and to validate the use of lower order models. The unsteady analysis was performed for MiTE movements from the deflected up to the deflected down position. The results indicated that the global forces were well approximated by linear theory although there was also indication of an overshoot which was not captured by linear theory. Figure 4 shows a comparison of unsteady CFD results with predictions from linear theory at two different actuation rates.

The aerodynamic analysis results provided a database for developing the aerodynamic wind tunnel test model and the aeroservoelastic test model.

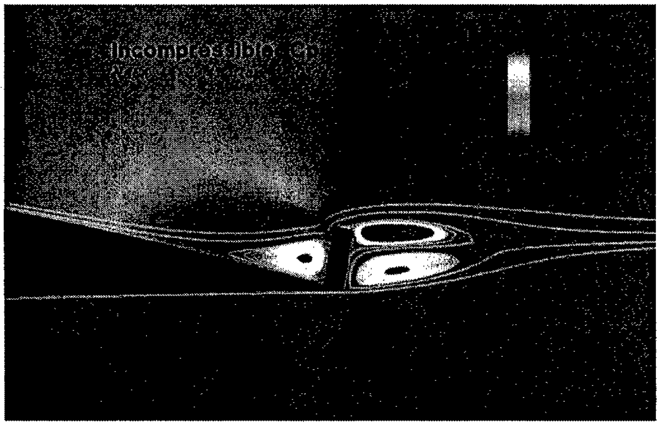

Figure 2. Sample steady aerodynamic analysis result.

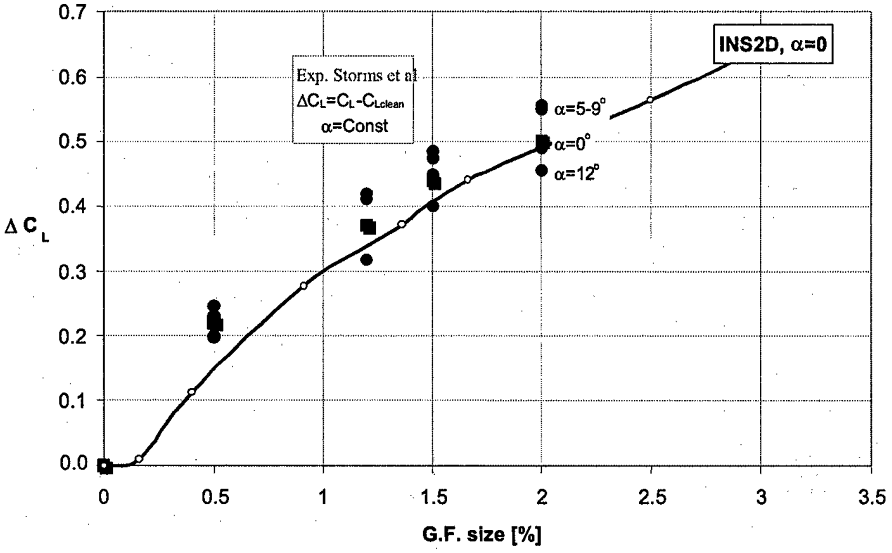

Figure 3. Comparison of CFD with experimental results for lift coefficient increment versus Gurney flap size.

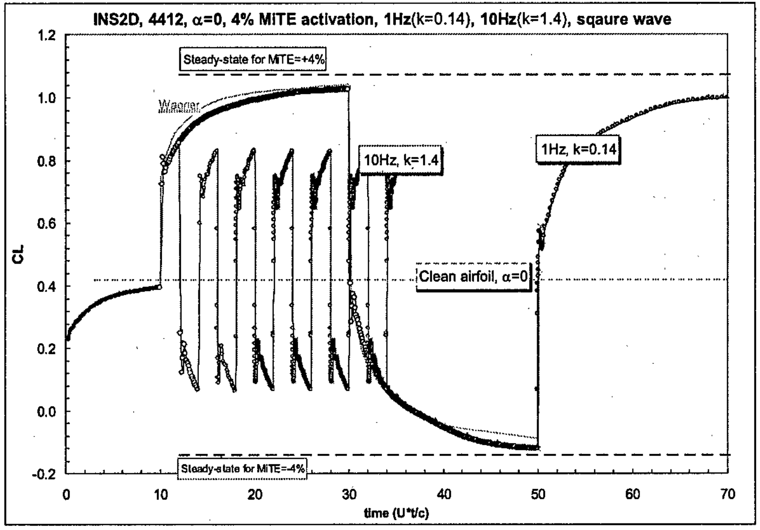

Figure 4. Unsteady CFD predictions compared with linear theory.

ACTUATOR DEVELOPMENT

Several generations of actuators have been developed and their performance characterized. These generations have included rotating pneumatic flaps, Figure 5, and vertical sliding electro-mechanical flaps, Figure 6. Several variants of both types have undergone bench-top and wind tunnel testing to evaluate their performance. The vertical sliding concept resulted in the best performance, achieving actuation rates in excess of 10 Hz while providing the desired aerodynamic forces. The device consists of a small flap deflecting vertically into the flow thereby avoiding the need to overcome the aerodynamic hinge moment. In the undeflected position, the flap is stowed behind the trailing edge, resulting in only a small drag penalty associated with the blunt trailing edge. Vertical sliding MiTEs were incorporated into both the aerodynamic and aeroservoelastic wind tunnel models for further testing.

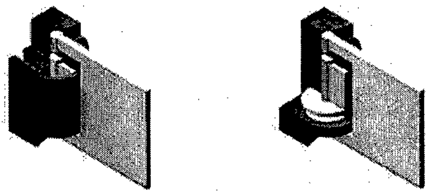

Figure 5. Pneumatic rotating MiTE concept.

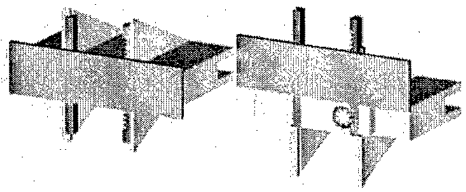

Figure 6. Electro-mechanical MiTE concept.

Several advances have been made in actuator development during the latter portion of the research program. The vertical sliding concept was packaged into pairs of actuators with each actuator behaving in a binary fashion: either deflected or neutral. Combined, the pair of actuators can achieve four total states although only three have been utilized in testing : up, neutral, down. The fourth state, both actuators deflected, results in an in-plane control force applicable for flight control. Previously each actuator had been capable of deflecting in either direction requiring some means of either actively or passively positioning to achieve neutral. Although the refinement reduces the total available actuation authority, it ensures that a true neutral, essential to the control logic, is available. Figure 7 shows four actuators combined into a single mounting bracket as implemented in further wind tunnel testing both on the aerodynamic and aeroservoelastic models.

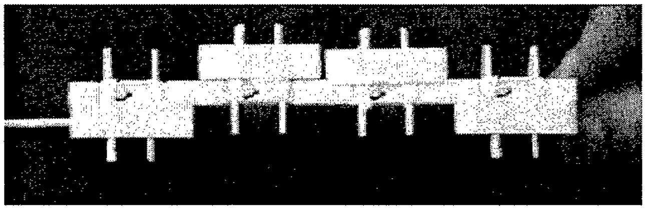

Figure 7. Combination of multiple MiTEs.

As experimental experience was gained with the MiTEs over the past year, additional actuation concepts were developed. Motivating these developments were the goals of reducing the exposed wetted area and simplifying the manufacturing requirements. One of the resulting concepts is shown in Figure 8. This concept consists of a rotating arm which still avoids the aerodynamic hinge moment and now has no exposed surfaces in the undeflected position. Stops to ensure the binary deflection limits are manufactured integrally with the housing. Further refinement of the concept is required based upon additional aerodynamic investigations since the effective deflection angle is now greater than 90 degrees and the aspect ratio has been increased. Several of the devices have been manufactured using the same process as that for the vertical sliding MiTEs.

More details on the manufacturing process and bench-top testing for the various actuator concepts are contained in Reference 14.

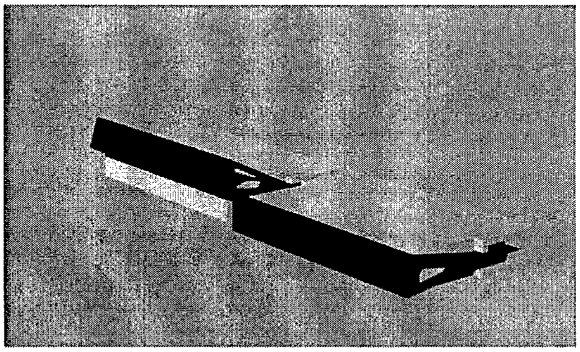

Figure 8. Next generation electro-mechanical MiTE.

AERODYNAMIC TESTING

Only a general overview of the aerodynamic testing is provided in this report. A thorough description is provided in Reference 9.

The aerodynamic testing consisted of two components, steady and unsteady experiments. The steady testing was used to compare the as-built MiTE performance with predicted. These comparisons included section forces as well as pressure distributions. Figure 9 provides an example of these measurements and shows the measured pressure profiles for three different positions of the MiTEs. This portion of the testing also explored the effect of different actuator configurations, as shown in Figure 10. This result demonstrated the linearity of lift coefficient increment with percentage deflection for various deflection patterns. Results of these tests have also been published previously in more detail.[5,6,10]

The unsteady testing utilized Particle Image Velocimetry (PIV) to examine the evolution of the flow structure near the trailing edge as the MiTEs were actuated. Since the results of this work have not been previously published, they are attached as Appendix A to this report and are taken directly from Chapter 5 of Reference 9. As an example of the results, Figure 11 shows the measured mean flow field behind the deflected MiTE. Figures 12 and 13 show the flow pattern behind the MiTEs just as they have reached the deflected position for two different flow speeds. These latter results provide a qualitative confirmation of the potential overshoot for high actuation rates.

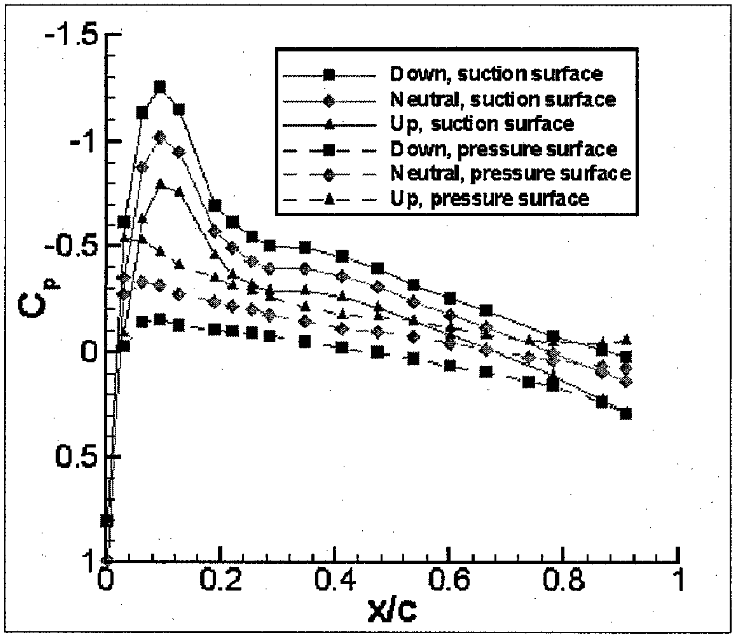

Figure 9. Pressure profile measurements for different MiTE positions.

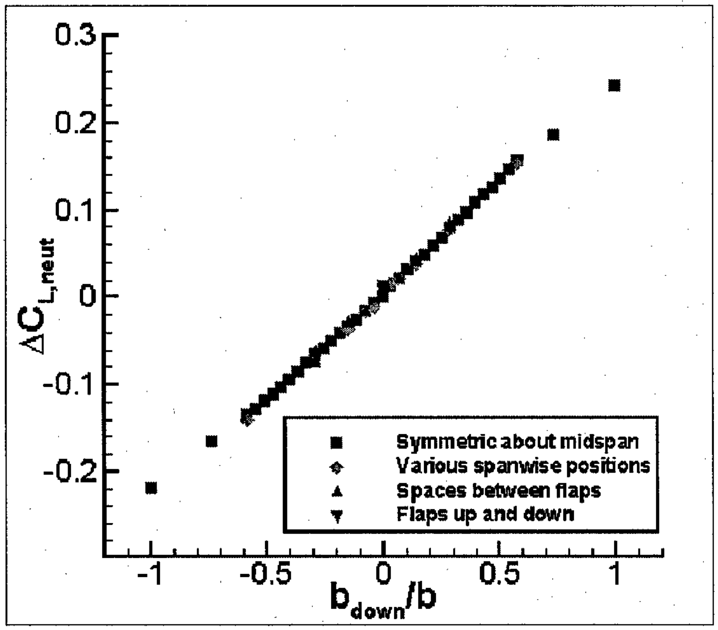

Figure 10. Effect of percentage MiTE actuation versus lift coefficient increment for various actuation patterns.

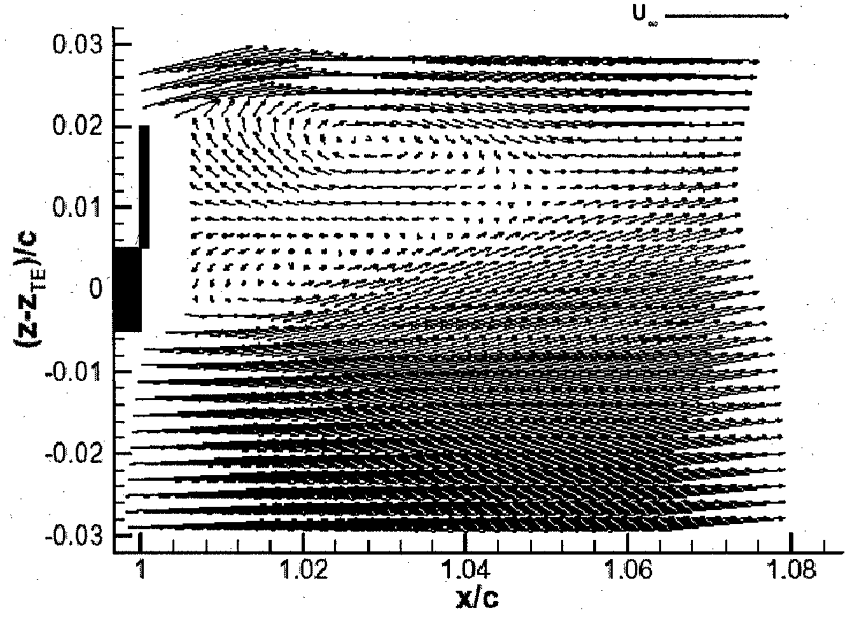

Figure 11. Mean flow field behind deflected MiTE measured with Particle Image Velocimetry (PIV).

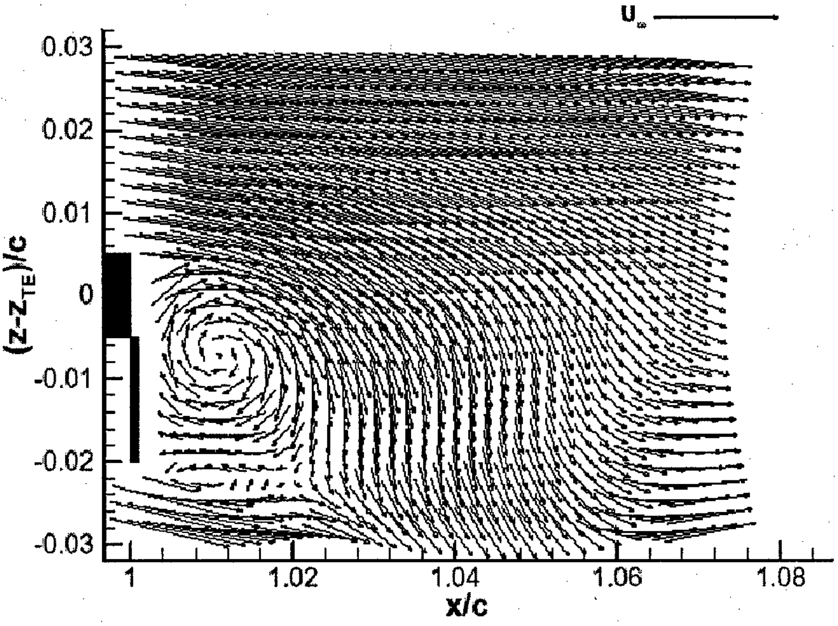

Figure 12. Averaged instantaneous flow field as deflected MiTE reaches lower stop for low flow speed.

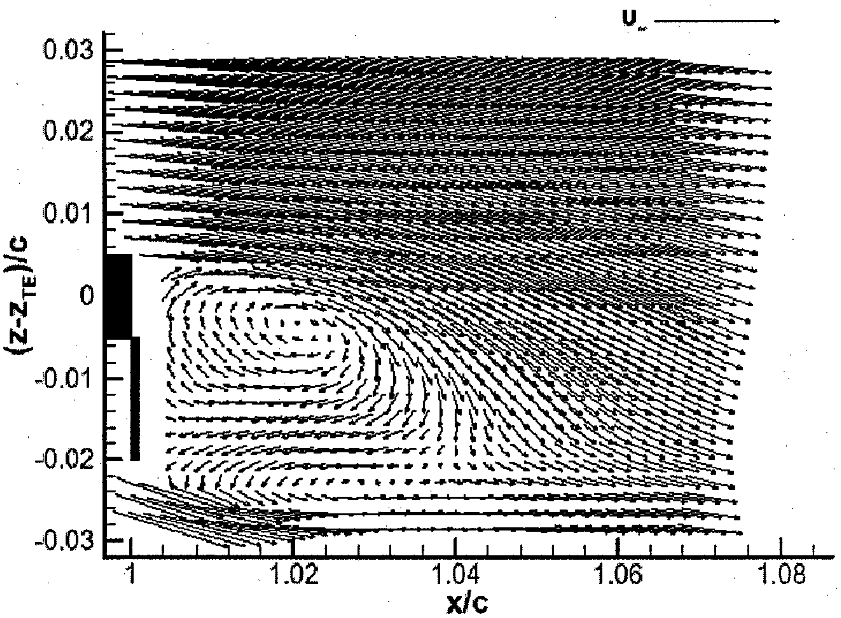

Figure 13. Averaged instantaneous flow field as deflected MiTE reaches lower stop for high flow speed.

AEROSERVOELASTIC ANALYSES & TESTING

To demonstrate the aeroelastic control capabilities of the MiTEs, an aeroservoelastic model was designed, fabricated, and tested. Several different structural concepts were explored and analytical models for the design and analysis of each developed. The design included aeroelastic constraints, flutter frequency and speed, that were within the capabilities of the MiTE actuators and experimental facilities, respectively. The testing included initial structural characterization and baseline aeroelastic response to select the preferred structural concept. Open and closed loop testing was then completed with the selected concept.

The first structural concept consisted of two spars utilizing differential bending to achieve the desired aeroelastic behavior. The spars were covered with a foam airfoil shape for the aerodynamics. Reference 11 describes the design of the aeroelastic model based upon this structural concept. The second concept consisted of a laminated fiberglass plate. Reference 12 describes the analytical model used for this concept. This reference also contains the experimental results for both structural concepts, including the successful closed loop testing which demonstrated flutter suppression with the MiTEs. Reference 12 is attached as Appendix B to this document.

Both structural concepts are depicted side by side in Figure 14. The laminated plate concept including sensors, MiTE actuators, and aerodynamic foam covering is shown in Figure 15. This configuration was used for both the open and closed loop testing. Figure 16 shows a result of the closed loop testing performed just above the flutter speed. The measured sensor responses along with the commanded actuation are shown. The controller is clearly seen to initiate at 32.5 seconds and suppress the response within 2 seconds.

The analysis tools mentioned above both utilized low order aerodynamics in the form of unsteady strip theory. A more detailed aeroelastic model utilizing an unsteady vortex lattice formulation for the aerodynamics and a finite element approach for the structures was also developed. This analytical model was verified using the experimental results from the laminated plate concept and was used to explore some alternative control architectures. The model formulation and results are provided in Reference 13

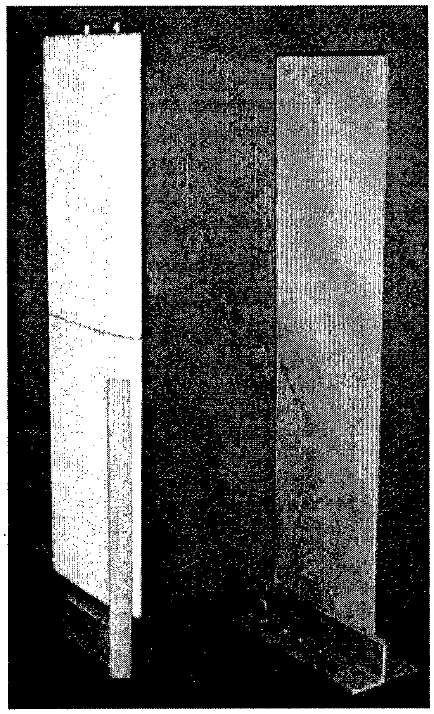

Figure 14. Structural concepts explored for aeroservoelastic testing.

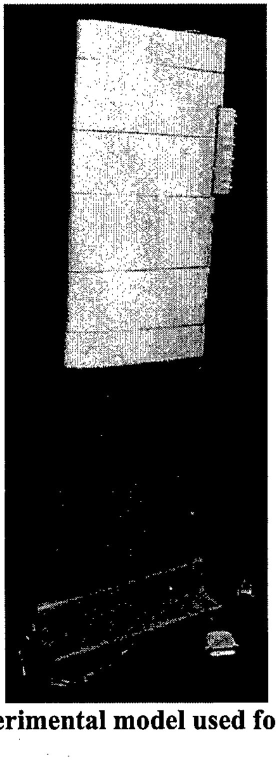

Figure 15. Aeroservoelastic experimental model used for open and closed loop testing.

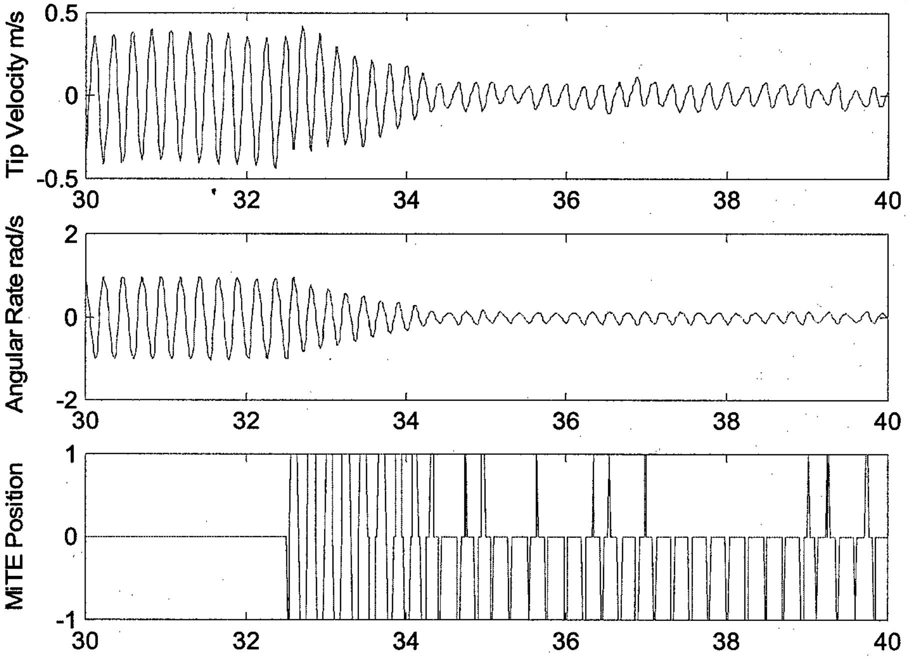

Figure 16. Experimental aeroservoelastic result demonstrating the MiTE capability.

CONCLUSIONS

The potential of Miniature Trailing Edge Effectors for aeroelastic control has been studied and demonstrated. Experimental and computational investigations of these small large-deflection devices has improved our understanding of the underlying flow physics and has led to the development of low order methods that approximate their global influence in steady and unsteady flows. The application of this concept to aeroelastic control was successfully demonstrated in a wind tunnel experiment, suggesting that the high bandwidth and low inertia of the devices may be useful in controlling dynamic aeroelastic phenomena. These results have been very promising and indicate that the present application may be just one of many roles for such control concepts. Application to vehicle flight control for enhanced maneuverability and improved performance is one area that may warrant further study. The present program has also highlighted specific areas for continued basic research, especially with respect to some of the details involved in the nonlinear unsteady aerodynamics. These areas of future work are described in further detail in the next section and could yield valuable information for further development of these devices and the computational methods needed for their design. Work to date does provide sufficient information to pursue application of the concept in practical flight vehicles, however, and we are actively working with industry and government agencies to identify promising applications.

FUTURE WORK

Aerodynamic Analyses

The aerodynamic analyses performed for this research program were the first known attempts to understand the unsteady flow physics resulting from the motion of the MiTEs or any similar device. Further areas for examination have been identified following the aerodynamic testing and aeroservoelastic testing.

Critical to the application of the MiTEs for aeroelastic control is the need for a neutral position where no control effort is applied. As a result, a detailed understanding of the aerodynamic behavior as the MiTEs are deflected from neutral to either the up or down position is required. The aerodynamic studies, as well as the aerodynamic testing completed to date, have all considered motion from the deflected up to deflected down positions. Experience gained with the aeroservoelastic model, in which a neutral was required and implemented, indicate a potentially important non-linear effect. The unsteady flow-field structure and forces, resulting from MiTE deflection to and from neutral, need to be understood through further study.

As mentioned in the aerodynamic analysis summary, the unsteady results indicated an overshoot in the section forces which was not captured by linear theory. Subsequent experimental investigations have qualitatively confirmed this behavior for deflection timescales comparable to the flowfield timescales[9]. The aerodynamic test results are, however, localized and at specific flow conditions. Since the unsteady aerodynamic analyses were the first of their kind, further investigation of these phenomena are required. In particular, the questions of whether a low order approach can model this effect and under what flow and actuator conditions the effect appears need to be addressed.

Actuator Development

As more experience is gained with the MiTE actuators, and in particular the newly manufactured next generation electro-mechanical MiTE, more refinements and improvements will result. During the discussion of the aerodynamic analysis, the possibility of a high frequency overshoot in the forces was suggested. Further investigation into increasing the actuator bandwidth to take advantage of this result should be explored. Finally, general improvements in manufacturing time and complexity should be explored.

Aerodynamic Testing

The scope of suggested future efforts is well described in Chapter 6 of Reference 9, included as Appendix C to this report.

Aeroservoelastic Analysis and Testing

As described in Reference 12, closed loop flutter testing was only completed to speeds just above the uncontrolled flutter speed. The analysis suggests, however, that suppression to higher speeds is possible and should be explored to demonstrate the full aeroelastic control capability of the MiTEs. The testing also revealed the importance of understanding the unsteady aerodynamics as the MiTEs are actuated to and from the neutral position. This was evident during the testing when the actuator motion was reversed (neutral corresponding to deflected for each MiTE rather than neutral being stowed behind the trailing edge). It was only in this configuration that flutter suppression was achieved. Reversing the motion to the more conventional configuration was unable to achieve flutter suppression with the originally designed controller. This was partially due to the analysis model used for the controller design. The analysis model approximates the aerodynamics as linear and apparently better predicts the reversed actuator configuration. Clearly this indicates some aerodynamic non-linearity is present which must be understood before more refined control designs can be attempted.

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APPENDICES

APPENDIX A : Chapter 5 from Reference 9.

APPENDIX B : Reference 12.

APPENDIX C : Chapter 6 from Reference 9.