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14. ABSTRACT In this project, quasi-static and flexible trailing edge devices and fins on airfoils were studied for lift enhancement in cruising flight and drag reduction and oscillation suppression in deep stall. The aerodynamics of a NACA0012 airfoil with a static extended trailing edge was studied systematically using a combination of experimental, computational and theoretical methods. Compared with Gurney flap and conventional flap, this device enhanced lift at a smaller drag penalty, indicating a good potential to improve the cruise flight efficiency. Furthermore, drag reduction and low-frequency oscillation suppression of a NACA0012 airfoil model in deep stall were achieved by using a flexible fin attached at a suitable location on the airfoil. Detailed measurements of the velocity fields and fin kinematics revealed the significant effects of the flexible fin on the development of the flow structures in the separated flow region and the physical mechanism of the natural low-frequency oscillation. The coupled computational fluid dynamics and structural dynamics methods were developed and computations were conducted to study the corresponding problems in the experimental studies. The theoretical models were also used to provide insights into the relevant aspects of the problems. The MEMS sensors and actuators embedded on flexible elements were developed and characterized for active flow control.				
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AIRFOIL/WING FLOW CONTROL USING FLEXIBLE
EXTENDED TRAILING EDGE

AFOSR GRANT NUMBER: FA9550-06-1-0187

Tianshu Liu
Department of Mechanical and Aeronautical Engineering
Western Michigan University
Kalamazoo, MI 49008

William W. Liou
Department of Mechanical and Aeronautical Engineering
Western Michigan University
Kalamazoo, MI 49008

Qamar A. Shams
NASA Langley Research Center
Hampton, VA 23681

Abstract

The current study has focused on application of a thin flexible fin attached to the upper surface of a NACA0012 airfoil to passively manipulate flow structures in the separation region for drag reduction in stall. Drag measurements in a water tunnel indicate that both the time-averaged drag and fluctuation of drag are significantly reduced at high angles of attack due to the presence of a flexible Mylar fin. Time-resolved PIV measurements are conducted to investigate interactions between a flexible fin, the surrounding flow and the induced changes of the global flow field. It is found that the dominant spectral components in the separation region on the baseline airfoil are considerably suppressed by a flexible fin and the momentum loss is reduced. The dynamical deformation of a flexible fin is measured, and the interactions between the fin dynamics and the surrounding flow are explored. The fin mainly responds to the dominant modes of the vertical velocity component, and largely suppresses the lower-frequency modes of velocity in the incoming flow direction. In general, a flexible fin is able to dampen velocity fluctuations and suppress highly unsteady separation at high angles of attack. This concept is also useful for passive control of other flows such as cavity flows, free shear layers (mixing layers and jets) and boundary layers. The computational study has simulated the flow/structure interactions (FSI) between a thin flexible plate (e.g. fin) and flow using in-house computational fluid dynamics and computational solid dynamics codes. The computational simulation is directly integrated with the experimental study to explore the physics of airfoil flow control using a flexible fin. The development of instrumentation has focused on implementation of MEMS sensors and piezoelectric actuators on a thin Mylar film for experiments at higher Reynolds numbers in wind tunnels.

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Objective and Concept

A new concept of separation control for airfoils and wings is to use a thin flexible fin attached on the upper surface of an airfoil to passively manipulate flow structures in the separation region for drag reduction in stall. Figure 1 illustrates a thin flexible fin attached to an airfoil at a high angle of attack. The flexible fin used here is a thin Mylar film for passive control, which could be replaced by a polymer or composite sheet embedded with sensors and actuators for active control. To a certain degree, the idea of using a flexible fin is inspired by the fact that the major propulsive elements of birds, insect and aquatic animals like wings, tails and fins are flexible. Nevertheless, a flexible fin used here for drag reduction is not a replica of fish fins that are mainly used for locomotion and maneuver. Morphologically, the flexible fin attached to an airfoil is basically rectangular unlike fish fins.

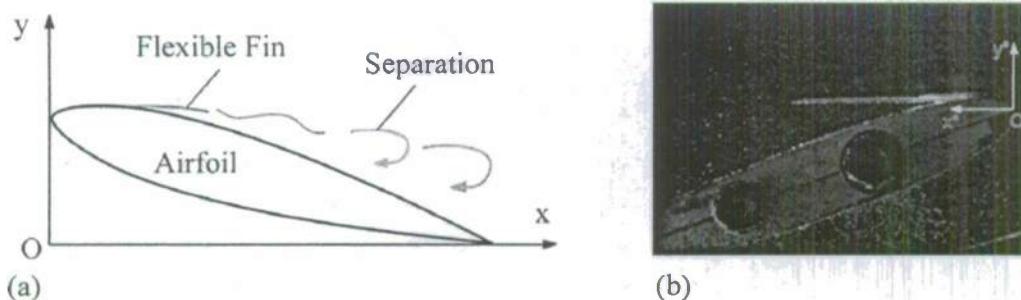


Figure 1. (a) Schematics of a thin flexible fin attached to an airfoil for separation control, (b) Typical PIV image showing a flexible fin attached to the NACA0012 airfoil in a water tunnel

Drag Reduction and Suppression of Separation

A $0.25c$ long rectangular Mylar fin with a thickness of 0.1 mm was first used in preliminary tests, where c is the chord of 10 in (254 mm). To examine how a flexible fin affects the drag of the airfoil, the fin was placed at different locations on the upper surface of the NACA0012 model. In addition, two tandem fins at different locations were tested. The incoming flow velocity was 0.25 m/s, and the Reynolds number based on the chord was $Re_c = 6.3 \times 10^4$. Figure 2(a) shows a significant drag reduction by a $0.25c$ fin located at $0.1c$ for higher AoA. Actually, the drag of the NACA0012 model varies with time due to the highly unsteady nature of separation. The power spectrum of C_D is shown in Fig. 2(b) for the baseline model and model with a $0.25c$ fin located at $0.1c$ at AoA of 18° . The spectral peaks around 0.07 and 0.12 Hz are observed for the baseline model at AoA of 18° . It is indicated that the flexible fin considerably dampens the drag fluctuations.

To understand the physical mechanism of the drag reduction by a flexible fin, PIV measurements of flow fields were conducted and velocity fields were obtained at 15 Hz. The time-averaged velocity vectors and vorticity fields are shown in Fig. 3 for the baseline model and model with a $0.25c$ fin located at $0.1c$ at AoA of 18° . The change of the velocity fields by the flexible fin is appreciable. A time-averaged large vortex is observed on the upper surface near the trailing edge of the airfoil for the baseline model.

Indeed, a time sequence of velocity and vorticity fields indicates that strong large-scale vortices frequently occur in that region. Due to the presence of the flexible fin, the time-averaged large vortex is largely destroyed. Furthermore, the mean vorticity in the shear layer shedding from the baseline model is weaker and more diffused than that from the model with the fin particularly near the trailing edge. Figure 4 shows the profiles of the x -component of mean velocity at $x/c = 0.4, 0.51, 0.66, 0.79$ and 0.91 on the upper surface for AoA of 18° , where x is the coordinate along the incoming flow direction and c is the projected chord onto the x -coordinate. Clearly, the momentum loss is reduced by the flexible fin in the separated region, which corresponds to the drag reduction found in force measurements by the external balance. Further evidence is provided by the momentum thickness development along the x -direction, as shown in Fig. 5. The development of the momentum thickness is significantly suppressed by the flexible fin.

Figure 6 shows the power spectrums of the x -component of velocity U across the separation region along the y -direction on the baseline model and the model with a $0.25c$ fin located at $0.1c$ at $x/c = 0.9$ for AoA of 18° . For the baseline model, there is a dominant spectral peak at $f = 0.07 \text{ Hz}$ ($St_{\theta_0} = f\theta_0/U_e = 8.4 \times 10^{-4}$). Such a low-frequency component does not directly result from the linear shear-layer instability, and it rather represents a low-frequency large-scale oscillation of the separation region. The effect of the flexible fin on the power spectrums of U indicates that the dominant component and other smaller components are significantly suppressed. Accordingly, the spatial development of all the spectral components along the x -direction in the shear layer is suppressed. For the nearly 2D deformation of the fin observed in our experiments, the first eigenfunction $X_1(x_3)$ is sufficient to describe the fin deformation. Therefore, the normalized displacement of a thin fin is expressed as $w(x_3)/l = \eta_1(t)X_1(x_3)$. Figure 7 shows the time-dependent amplitude $\eta_1(t)$ and its power spectrum for the $0.25c$ flexible fin located at $0.1c$ for AoA of 18° . The magnitude squared coherence indicates a strong correlation between the fin amplitude and the surrounding velocities at 1.3 Hz .

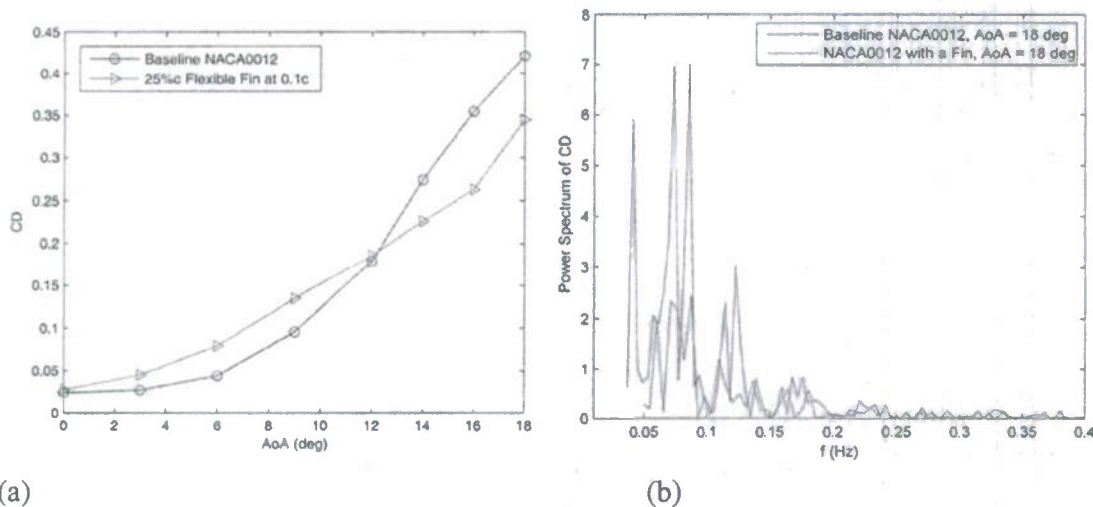


Figure 2. (a) Drag coefficient, and (b) Power spectrums of drag coefficient

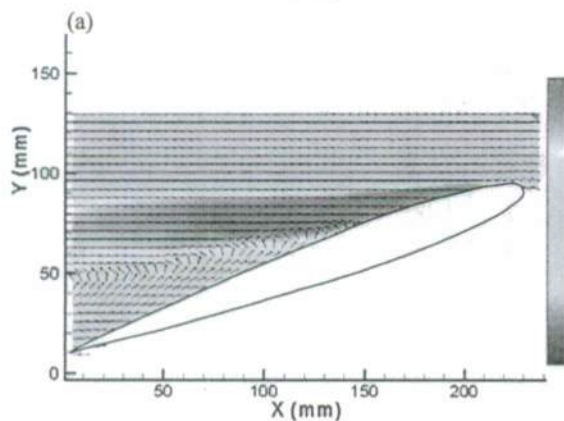
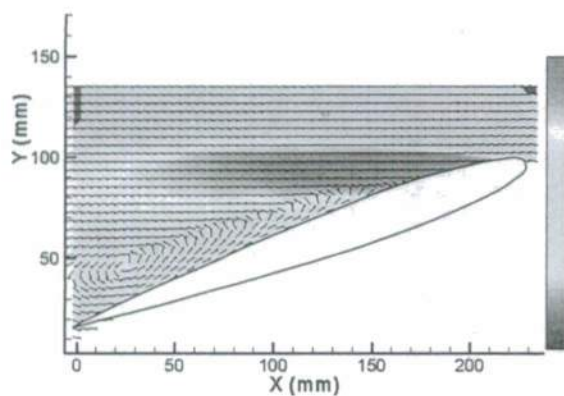


Figure 3. Mean velocity vectors and vorticity, (a) baseline and (b) fin

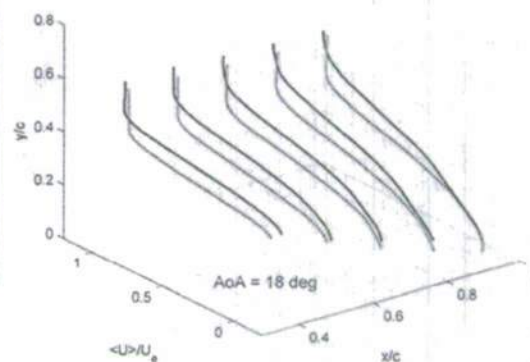


Figure 4. Mean velocity profiles

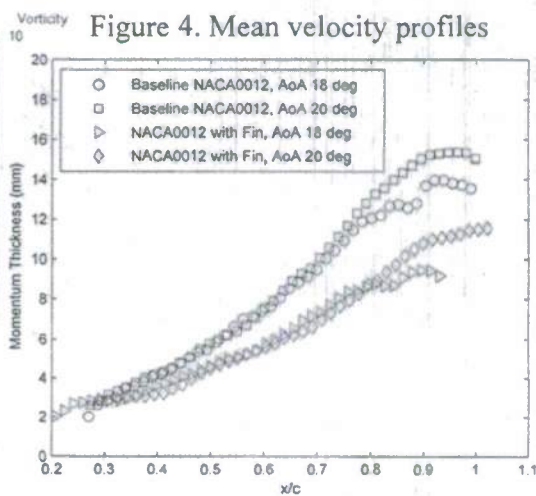
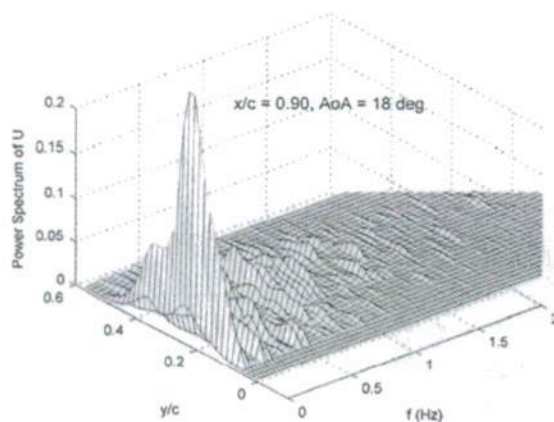
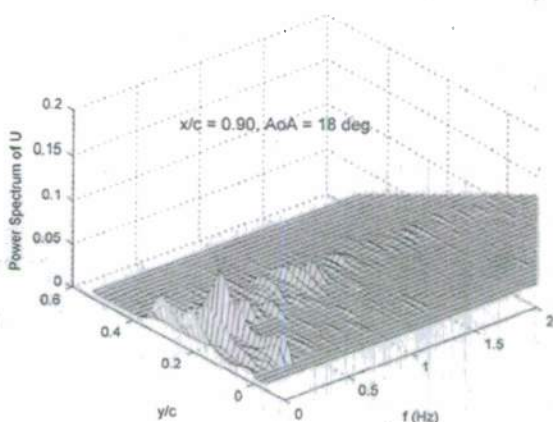


Figure 5. Momentum thickness development

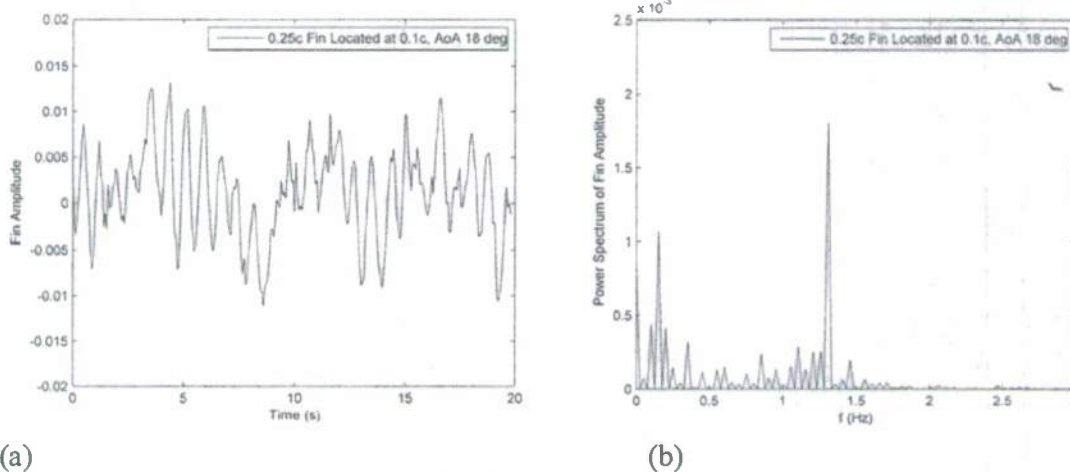


(a)



(b)

Figure 6. Power spectrums of U across the separation region at $x/c = 0.9$ for (a) the baseline and (b) model with a flexible fin



(a) (b)
Figure 7. Fin dynamics, (a) fin amplitude and (b) power spectrum of fin amplitude

Development of Computational Tools

Simulations of the time-dependent deformation of elastic elements are studied using several numerical solution methods. The major challenge for the current problem with a flexible fin attached to an airfoil arises from the fact that the dynamics of the elastic fin interacts strongly with the dynamics of the fluid flows. This results in a highly unsteady, multi-physics flow/structure interaction (FSI) problem, involving computational fluid dynamics (CFD) and computational structural dynamics (CSD).

CFD: The capabilities of two commercial software, Fluent 6.2 and CFX 10.0, are examined for simulating unsteady aerodynamics over moving bodies, particularly on their fundamental numerical behavior such as accuracy and grid convergence under deformed mesh conditions. This also provides validation to using the software as computational tools to complement experimentation. A test problem has been examined for the flow over a flapping thin flat plate. As shown in Fig. 8, three kinematical models are used to mimic the flapping thin plate: Model I for the motion of a solid flapping plate, Model II for deformation of a simple cantilever beam, and Model III for a standing wave deformation. Figure 9 shows the pressure distributions on the plate for the same three time instances for Model II and III.

An immersed boundary method (IBM) has been incorporated into an in-house three-dimensional, unsteady, finite difference Navier-Stokes equations solver. The code is used to compute the flow around a NACA0012 airfoil with and without a static extended trailing.

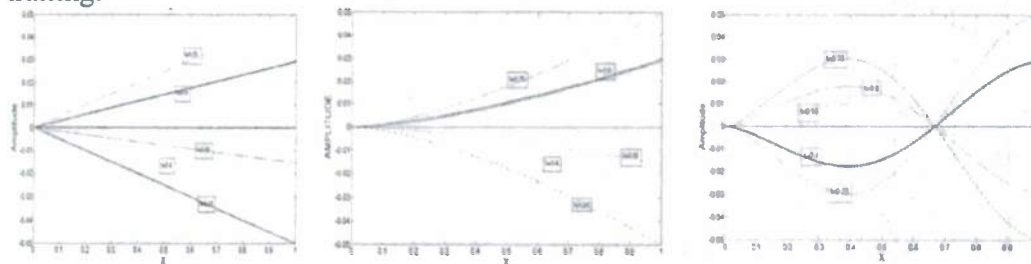


Figure 8. Three kinematical models for fin motion

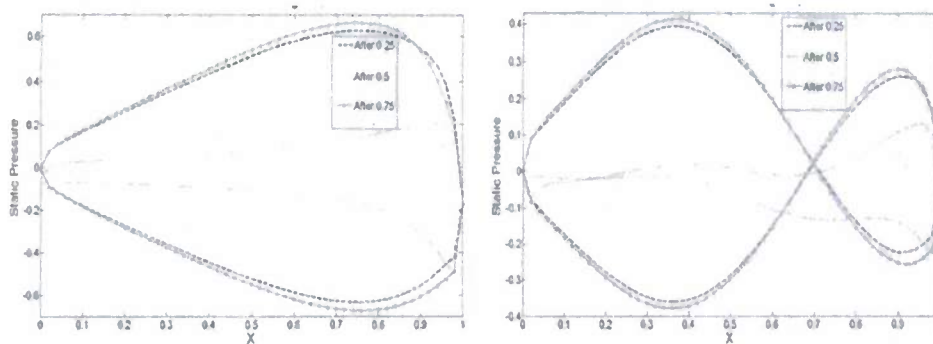


Figure 9. Surface pressure distribution given by CFX for (a) Model II and (b) Model III

CSD: The Kirchhoff-Love thin shell theory has been used in the development of a finite element code to simulate the dynamic responses of thin flapping element under aerodynamics loading. High-order triangular subdivision using Loop's rule has been implemented.

FSI: The CFD and the CSD codes developed in-house have been successfully coupled and the FSI solver is being validated.

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Personnel Supported During Duration of Grant

Javier Montefort

Assistant Professor, Western Michigan University

Srinivasa R. Pantula

Graduate Student, Western Michigan University

Publications

"Lift enhancement by static extended trailing edge," T. Liu, J. Montefort, W. Liou, S. R. Pantula, and Q. Shams, *Journal of Aircraft*, Vol. 44, No. 6, pp. 1939-1947, 2007

"Thin-airfoil-theoretical interpretation for Gurney flap lift enhancement," T. Liu and J. Montefort, , *Journal of Aircraft*, Vol. 44, No. 2, pp. 667-671, 2007

"Weight criterion on flow control in level flight," T. Liu, *Journal of Aircraft*, Vol. 44, No. 1, pp. 348-351, 2007

"Unsteady flow calculation for flexible thin plate," W.W. Liou and S. Pantula, 37th AIAA Fluid Dynamics Conference and Exhibit, Miami, Florida, 25-28 June 2007, AIAA-2007-4339

"Static extended trailing edge for lift enhancement: Experimental and Computational Studies," T. Liu, J. Montefort, W.W. Liou, and S. Pantula, 3rd International Symposium on Integrating CFD and Experiments in Aerodynamics, Colorado Springs, 20-21 June 2007

"Extended Trailing Edge: Experimental and Computational Studies," (Invited Talk) W.W. Liou, T. Liu, J. Montefort, S. Pantula, and Q. Shams, 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, 7-10 January 2008, AIAA-2008-0683

"Flow past a cylinder with a flapping element attached to its end," W.W. Liou, S. Pantula, T. Liu, and J. Montefort, 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 8-11 January 2007, AIAA paper 2007-1309

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9. Archival Publications (published) during reporting period:

T. Liu, J. Montefort, W. Liou, S. R. Pantula, and Q. Shams, "Lift enhancement by static extended trailing edge," *Journal of Aircraft*, Vol. 44, No. 6, pp. 1939-1947, 2007
 T. Liu and J. Montefort, "Thin-airfoil-theoretical interpretation for Gurney flap lift enhancement," *Journal of Aircraft*, Vol. 44, No. 2, pp. 667-671, 2007
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 W.W. Liou, S. Pantula, T. Liu, and J. Montefort, "Flow past a cylinder with a flapping element attached to its end," 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 8-11 January 2007, AIAA paper 2007-1309
 S. Pantula, M. H. Lu, W. W. Liou, "Calculations of Turbulent Flow around Airfoils with Attached Flexible Fin using an Immersed Boundary Method," 2009 AIAA Paper 2009-721, Orlando, FL

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