Preliminary Design and Evaluation of an Airfoil with Active Continuous Trailing-Edge Flap

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Presented at the AHS Future Vertical Lift Aircraft Design Conference
San Francisco, CA, January 18 - 20, 2012

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This work is sponsored by the Army Research Lab, Vehicle Technology Directorate, Mechanics Division.

Helicopter Active Vibration and Noise Control

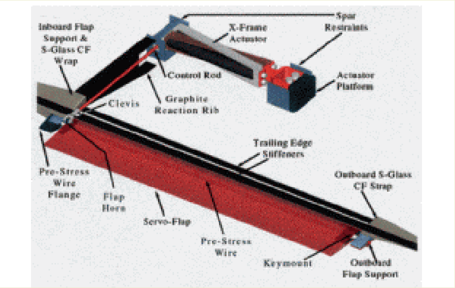
- Helicopters suffer high levels of noise and vibration
- Passive control devices (vibration isolators or absorbers)
  - Effective to a degree
  - Less effective at off-design condition
  - High weight
- Active control device
  - Suppress vibration and noise at the source
  - Adaptive at off-design conditions
  - Multifunctional (rotor performance, in-flight tracking)

Active vibration and noise control systems have been widely recognized as the ultimate to achieve a jet-smooth ride

Discrete Trailing-Edge Flaps (DTEF)

Use piezoelectric stacks as the active driving mechanism, and various hinges and levers to convert and amplify the piezoelectric strain into a DTEF deflection

- Pros
  - Compact: occupy a small portion of the rotor span near the tip
  - Effective: modify the rotor response by changing the rotor pitch angle elastically
- Cons
  - Complex and challenging to fix inside airfoil
  - Brittle piezoelectric stacks tend to break under tensile stress
  - Lever amplification effectiveness is reduced under CF loads

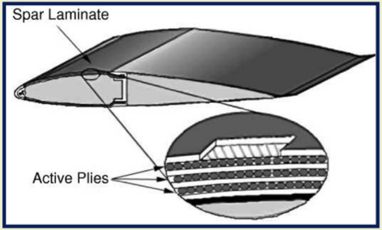


MIT/X-Frame Actuator

Active Twist Rotor (ATR)

Active Macro-Fiber Composite (MFC) layers are built into the blade sectional layout, and the elastic twist is dynamically altered along the blade when MFC layers are activated.

- MFC: active piezoceramic fibers are embedded in a polymeric matrix
- The matrix protects the fibers, and also allows the actuators to be applied to a curved surface such as airfoil skins.
- MFC actuators have to be applied along a major part of the blade to be effective.

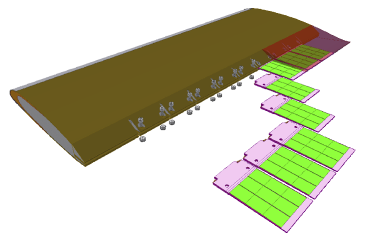


Thornburgh, R. P., Kreshock, A. R., and Wilbur, M. L.,
Structural Optimization of Active-Twist Rotor Blades,
American Helicopter Society 67th Annual Forum Proceedings, Virginia Beach, VA, May 3-5 2011.

Active Trailing-Edge (ATE)

The airfoil trailing edge, which is soft in design, is deformed with a piezoceramic stack bimorph.

- Eliminate the hinges and levers mechanism typically found in a DTEF
- Piezoceramic stacks used in the ATE concept are still exposed to the high stress condition found in a rotor blade.
- In order to protect the piezostacks from breaking under adverse tension loads, the bimorph has to be sliced into small patches along the spanwise direction.



Grohmann, B., Muller, F., Achci, E., Pfaller, R., Bauer, M., Maucher, C., Dieterich, O., Storm, S., and Janker, P., *Design, Evaluation and Test of Active Trailing Edge,* American Helicopter Society 67th Annual Forum

Continuous Trailing-Edge Flaps (CTEF)

Distort the trailing edge section dynamically with MFC layers embedded into airfoil layout

- Combines the advantages of the ATR and ATE concepts
- Eliminating moving parts typically found in a discrete trailing-edge flap: such as hinges and levers
- Avoid complex arrangement of protecting piezoceramic stacks with partitioning
- Simplify structural design, potentially lead to reduction in rotor weight and maintenance requirements
- More efficient in generating aerodynamic excitation than discrete flap (no leaks of air due to gap)

Potential CTEF applications are active control of helicopter rotor vibration and noise, performance improvements, and in-flight rotor blade tracking, similar to the widely studied discrete trailing-edge flap and active twist rotor concepts.

Objective

- Carry out a preliminary design of an airfoil with active continuous trailing-edge flap with MFC actuators
- Develop an analytical framework to predict active CTEF deformation with a fluid and structure interaction procedure, and evaluate the 2D aerodynamic characteristics of the CTEF by comparing to the conventional DTEF

Outline

1. *Introduction*
   - Helicopter Active Vibration and Noise Control
   - Active Control Designs
   - Continuous Trailing-Edge Flaps (CTEF)
   - Objective
2. *Analytical Model*
   - CTEF Model Cross-Sectional Layout
   - Structural Cross-Sectional Analyses
3. *Analytical Results*
   - Structure Analysis
   - Aerodynamics
   - 2D Static Coupling of Structure and Aerodynamics
4. *Summary and Conclusions*

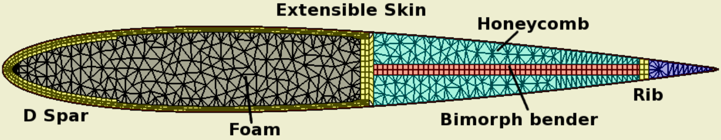
Scaled Model

- Baseline airfoil is a NACA 0012, selected for its simplicity and its symmetry which facilitates validations of analytical models
- Design and evaluation procedure presented in this study can be readily applied to modern helicopter asymmetric airfoils
- Airfoil chord size was chosen as a sub-scale representation of the main rotor blade of a general utility helicopter

Scale parameters

Parameter		Full-scale	Sub-scale
Scale factor		1	0.234
Chord length	(mm)	531	124
Tip speed	(m/s)	221	107
Tip Mach number	(Air)	0.65	0.31
Tip Reynolds number	(Air)	8e+6	0.9e+6

CTEF Cross-Sectional Layout



- E-glass D-shaped nose spar, main load-carrying element
- MFC bimorph bender between two ribs, deforms trailing edge
- Extensible airfoil skin
- Rohacell foam inside the “D” spar
- Nomex Honeycomb in the trailing edge region; easy to bend but hard to shear

MFC bender parameters

Bender location	50%c
Bender length	40%c
MFC layers	3+3
MFC layer thickness	0.3 mm
MFC-PZT d33	4.0e-10
MFC-PZT stiffness	30.3 GPa
MFC-PMN d33	5.6e-10
MFC-PMN stiffness	12.4 GPa

Analysis Codes

Multidisciplinary analyses are required to calculate the aeroelastic deformation of an airfoil with active continuous trailing-edge flaps.

Structural Analyses

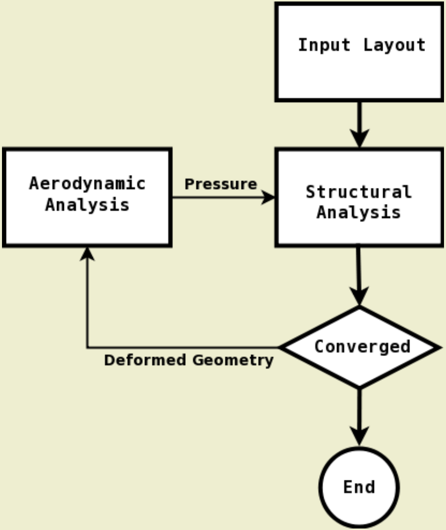
- MSC/NASTRAN: an industry-standard FEM analysis
- UM/VABS (Variational-Asymptotic Beam Cross-Sectional) developed in University of Michigan

Aerodynamic analyses

- 2D OVERTURNS (Overset Transonic Unsteady Rotor Navier-Stokes) developed in University of Maryland
- XFOIL: a 2D airfoil analysis using vortex panel method developed in Massachusetts Institute of Technology

2D Static Fluid and Structure Interaction

- Linear interpolation is used to map the aerodynamic loads from the fluid grids to the structure grids
- FSI solution using XFOIL is obtained first
- FSI using OVERTURNS starts from converged XFOIL solution so that fewer CFD iterations are needed
- Convergence criterion is difference of CTEF deflections between iterations approaches zero



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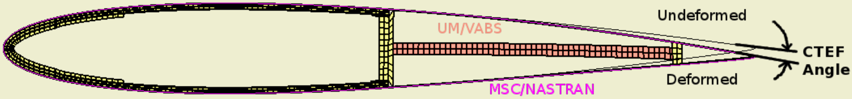
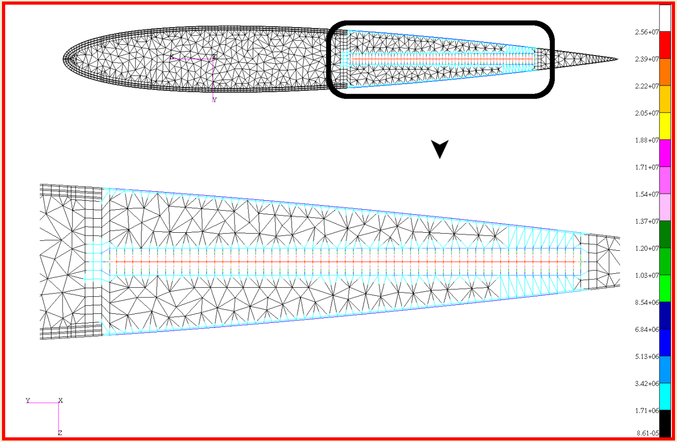
CTEF Deformation



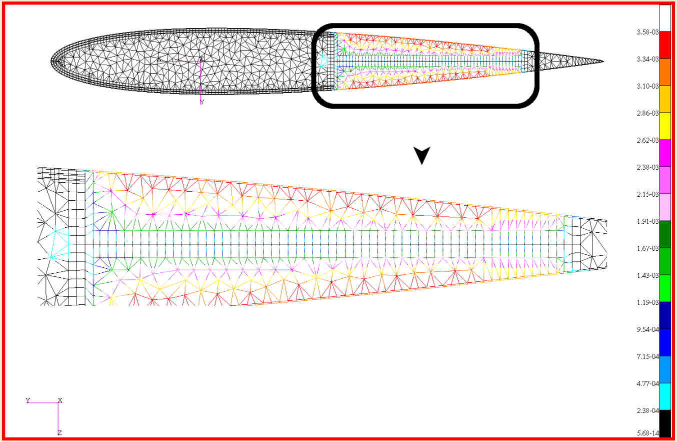
- CTEF angle defined as rotation of the trailing edge (calculated as the rotation angle of a segment formed by the trailing-edge node and its adjacent node on the upper surface)
- CTEF angle about two degrees with the MFC-PZT bimorph bender in the absence of aerodynamic loads

Stress Distribution



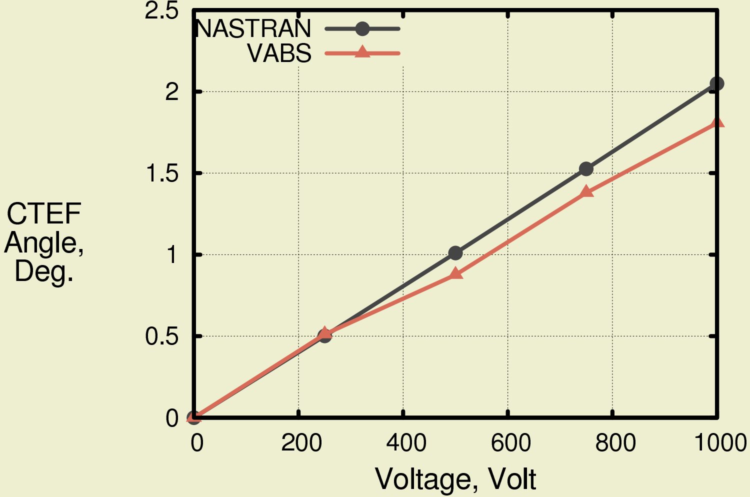
- Mid plane of the MFC bender has the maximum stress
- Top and bottom surface of the bender have almost zero stress
- Block force and free strain relationship of piezoelectric materials

Strain Distribution



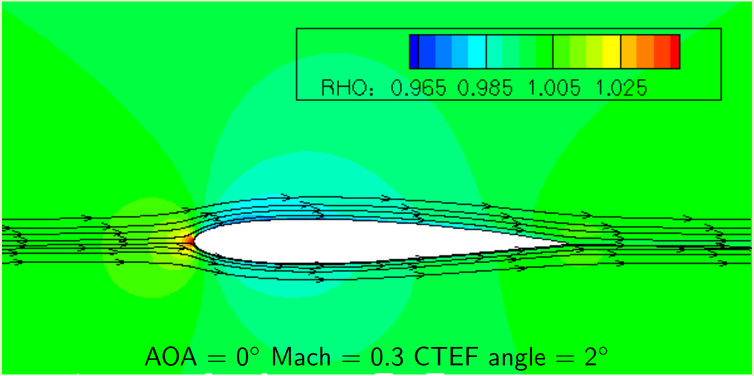
- Strain at bender top and bottom surfaces approaches free strain
- Add more MFC layers will not increase CTEF deflection because required active strain is beyond maximum active piezoelectric strain

CTEF Deflection Comparison



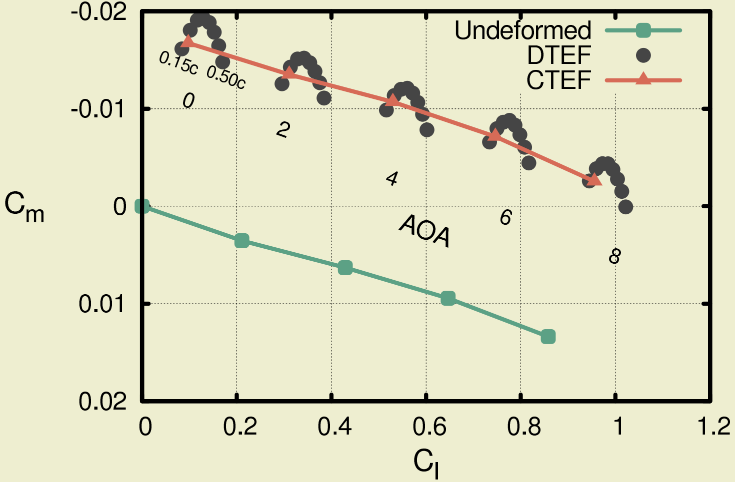
Good agreement is observed between the analyses except that the NASTRAN predictions are slightly larger than those of UM/VABS.

2D OVERTURNS Density Contour of CTEF Airfoil



- Air flows off airfoil parallel to deformed trailing edge, and changes the circulation in a manner similar to a deflected DTEF
- Although MFC bender starts at 0.5c, major CTEF deformation happens rather close to the trailing edge. CTEF is not equivalent to a 0.5c DTEF. Instead, it matches a DTEF with a much shorter chord

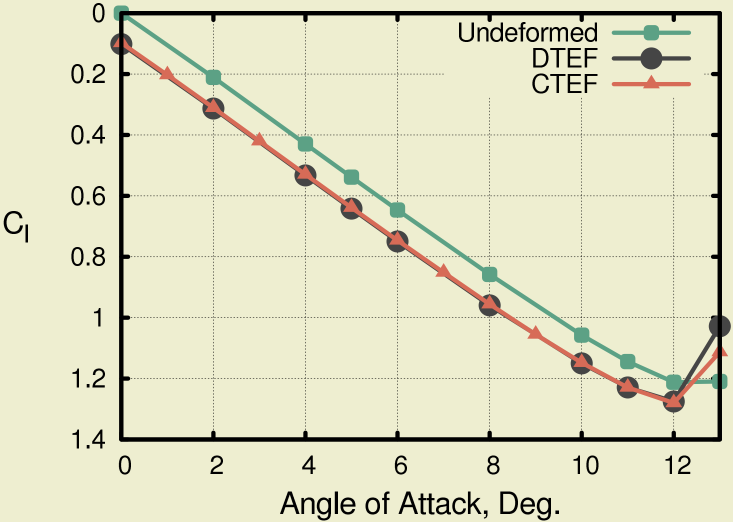
Compare CTEF & DTEF of Different Flap Chord Sizes



- CTEF: 0.5c
- DTEF: 0.15-0.50c
- TEF: 2°
- Mach: 0.31

- CTEF equivalent to a DTEF with flap size between 0.15c and 0.20c
- DTEF with small flap chord preferable in rotorcraft application

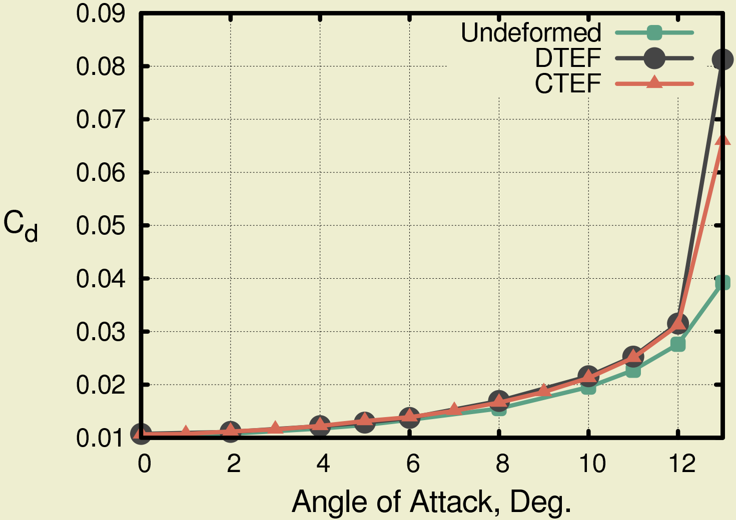
Comparison of Lift Coefficient of CTEF and DTEF



- CTEF: 0.5c
- DTEF: 0.2c
- TEF: 2°
- Mach: 0.31

The 0.5c CTEF shows virtually the same variations of lift coefficient with the angle of attack as those of the 0.2c DTEF.

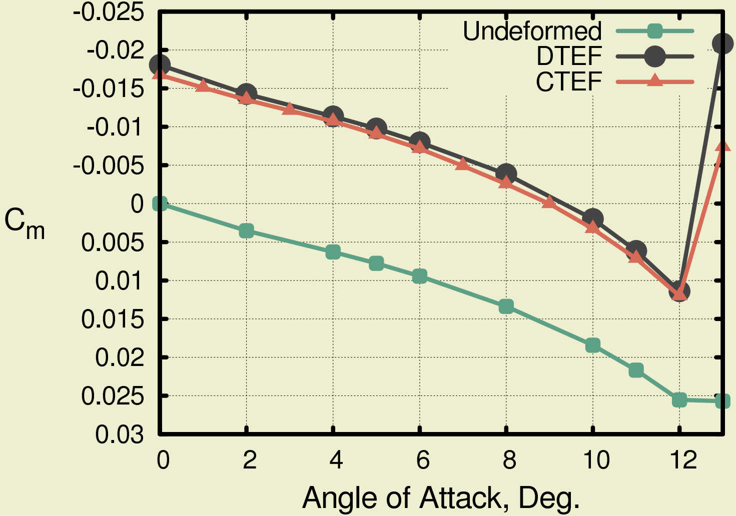
Comparison of Drag Coefficient of CTEF and DTEF



- CTEF: 0.5c
- DTEF: 0.2c
- TEF: 2°
- Mach: 0.31

CTEF and DTEF airfoils have the same 12 degree stall angle although CTEF airfoil shows a milder stall than DTEF airfoil

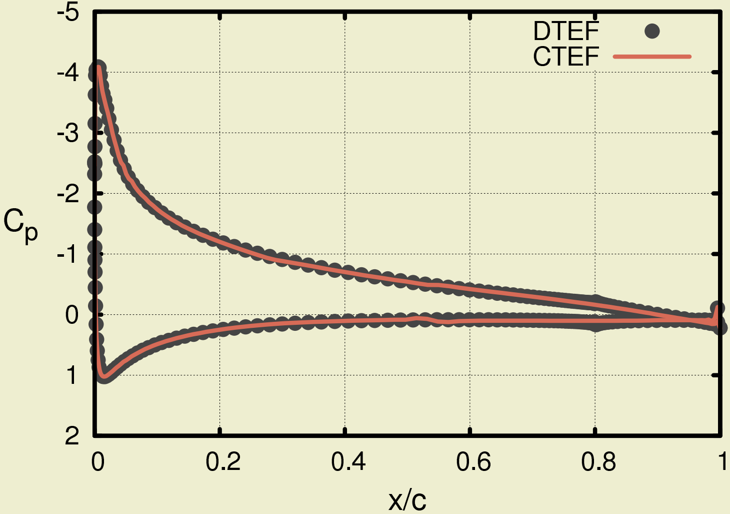
Comparison of Moment Coefficient of CTEF and DTEF



- CTEF: 0.5c
- DTEF: 0.2c
- TEF: 2°
- Mach: 0.31

The magnitude of CTEF pitching moments is slightly less than that of the DTEF for all the angles of attack shown.

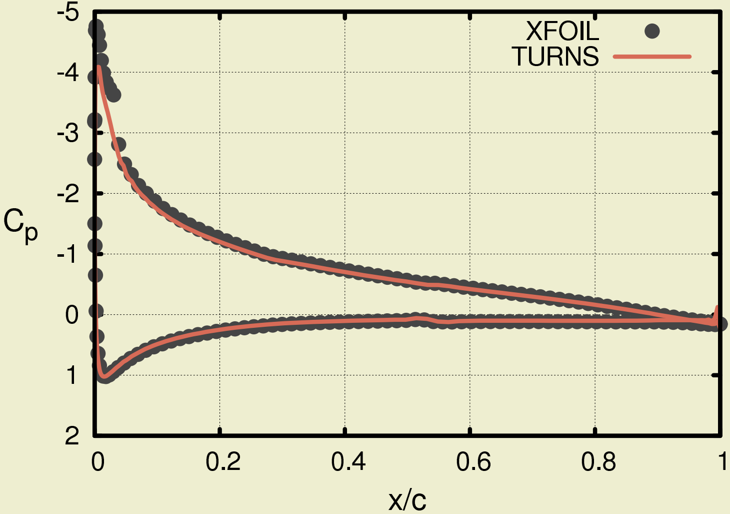
Comparison of Pressure Coefficient of CTEF and DTEF



- CTEF: 0.5c
- DTEF: 0.2c
- TEF: 2°
- AOA: 8°
- Mach: 0.31

- Similar pressure distribution between CTEF and DTEF
- CTEF angle, defined as rotation of trailing edge, meaningful

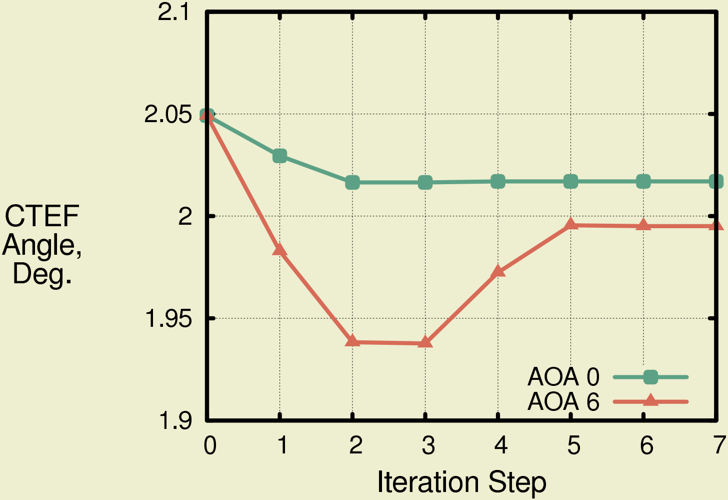
Compare C_p predictions by XFOIL and OVERTURNS



- TEF: 2°
- AOA: 8°
- Mach: 0.31

XFOIL provides sufficient accuracy to supplement CFD where high computation efficiency is required.

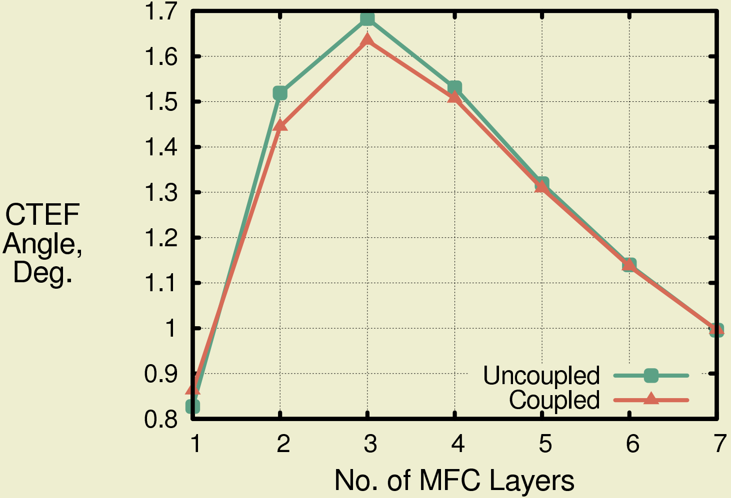
FSI Convergence History



- Mach: 0.31

The reduction magnitude due to aerodynamic pressure is small: the largest reduction with OVERTURNS is 2.6% at AOA of 6 degrees.

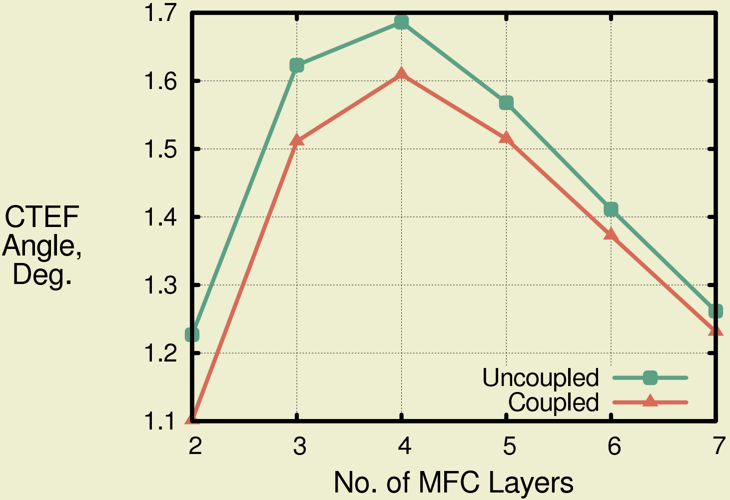
CTEF Deflection with Different MFC-PZT Layers



- AOA: 8°
- Mach: 0.31

CTEF angle reaches maxima with three layers of MFC-PZT layers for both the uncoupled and FSI coupled cases.

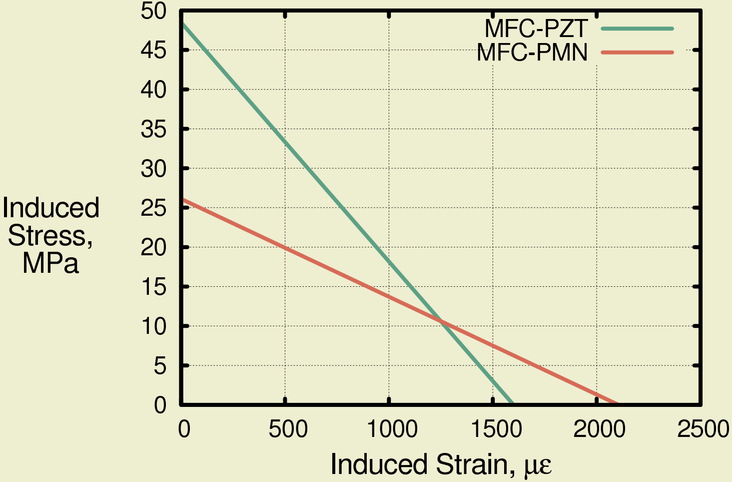
CTEF Deflection with Different MFC-PMN Layers



- AOA: 8°
- Mach: 0.31

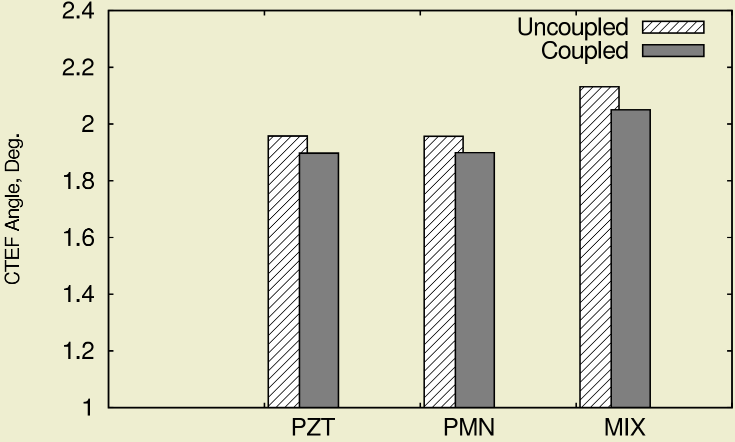
- Maximum CTEF deflection is achieved with four layers
- Larger reductions with aerodynamic pressure than MFC-PZT

Stress vs. Strain of MFC-PZT and MFC-PMN



- MFC-PZT generates higher stress than MFC-PMN for same strain
- MFC-PMN has higher free strain than MFC-PZT

CTEF Deflections with Different MFC Constituents



Mixed MFC-PZT and MFC-PMN bender generates 8% more CTEF deflection than an MFC-PZT or an MFC-PMN only bender.

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Summary and Conclusions

- The preliminary design and evaluation of an airfoil with active continuous trailing-edge flap (CTEF) has been presented as a potential rotorcraft active control device.
- The development of structural CTEF cross-section models was described. Its deformations with MFC actuation are predicted by NASTRAN and UM/VABS, and showed good agreement.
- The 2D aerodynamic characteristics of CTEF were evaluated using the CFD analysis OVERTURNS. The comparison of the aerodynamic efficiency of a continuous trailing-edge flap to a conventional discrete trailing-edge flap was also performed.
- A fluid structure interaction procedure was implemented, and used for predicting deflection of the continuous trailing-edge flap under aerodynamic pressure.

Summary and Conclusions, Cont'd

- MFC bender of small numbers of layer achieves maximum CTEF deflection for the sub-scale model: three layers of MFC-PZT (six for top and bottom sides) obtains two degrees of CTEF deformation.
- The aerodynamic characteristics of CTEF and DTEF with the same deformation angle, where the CTEF angle is defined as the rotation angle of the trailing edge, are similar.
- The equivalence of CTEF and DTEF is for different flap chord sizes: the aerodynamic characteristics of a 0.5c CTEF is comparable to a DTEF with a flap chord size between 0.15c and 0.20c with the same deflection angle.
- The reductions in CTEF deflection are relatively small when the aerodynamic pressure is applied: 2.6% reduction for CTEF deflection two degrees and angle of attack of six degrees.
- A mixed MFC-PZT and MFC-PMN bender generates 8% more CTEF deflection than an MFC-PZT or an MFC-PMN only bender under aerodynamic loads.

Acknowledgements

The authors gratefully acknowledge Prof. Carlos Cesnik and his research group at the University of Michigan for assistance on running UM/VABS analysis, and Prof. James Baeder and his group at the University of Maryland on using 2D OVERTURNS.