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Vibration and Noise Reduction Using Actively Controlled Flaps-Their Evolution and Potential for Improving Rotorcraft Technology

PART 1

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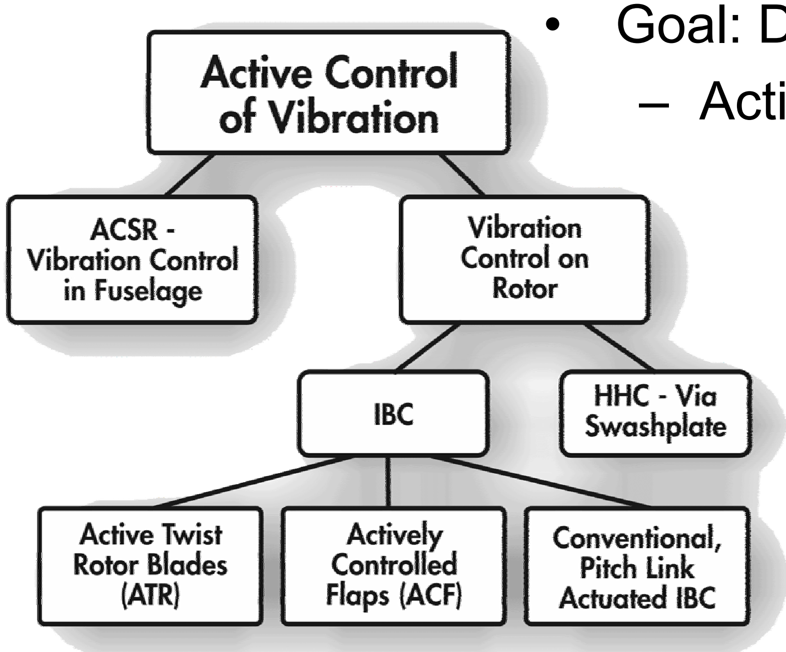
Objectives

- Provide a broad and concise review of active control technology that has been applied primarily to helicopters
- Compare the various approaches
- Describe the evolution of the actively controlled flap and demonstrate its potential for improving rotorcraft technology.

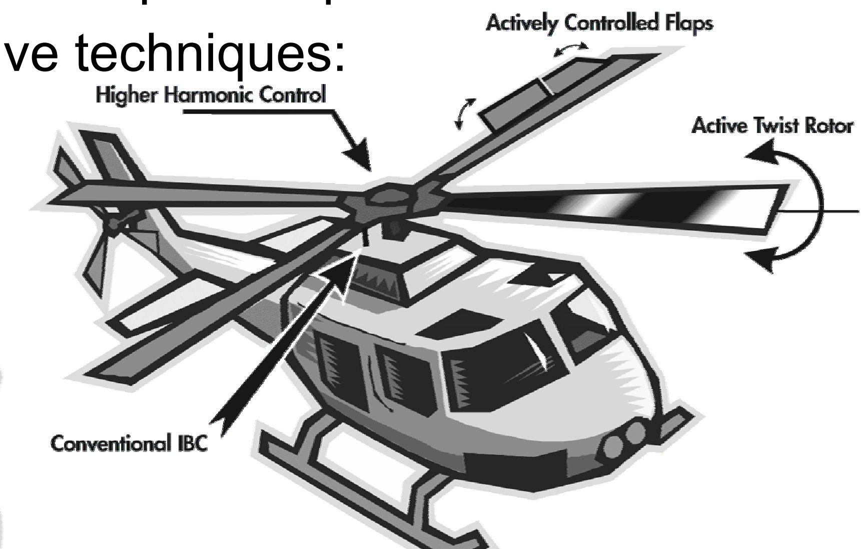
Active Control of Aeroelastic Response (i.e. Vibration) in Rotorcraft

- Desire for “jet smooth” ride combined with stringent vibration requirements (below 0.05g) in rotorcraft has motivated research on active vibration control. Future rotorcraft will probably have an active control system that operates in rotor. Once such a control system is available, it can meet other objectives (noise reduction, performance enhancement and stabilization).
- During the last 25 years various approaches to active vibration control have emerged: (1) higher harmonic control (HHC); individual blade control (IBC), and active control of structural response ACSR).

Introduction: Active Control

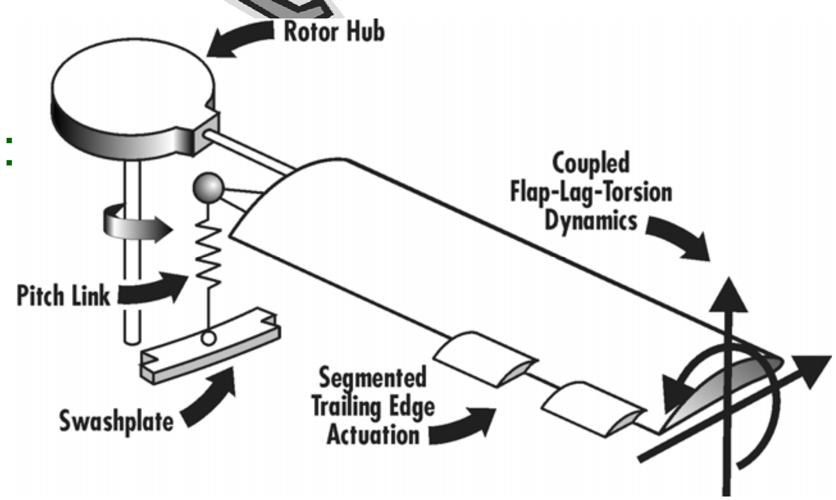


- Goal: Develop helicopters with reduced vibration
  - Active techniques:



Actively controlled trailing edge flaps (**ACF**):

- No adverse affect on helicopter airworthiness
- Lower power consumption than HHC or IBC

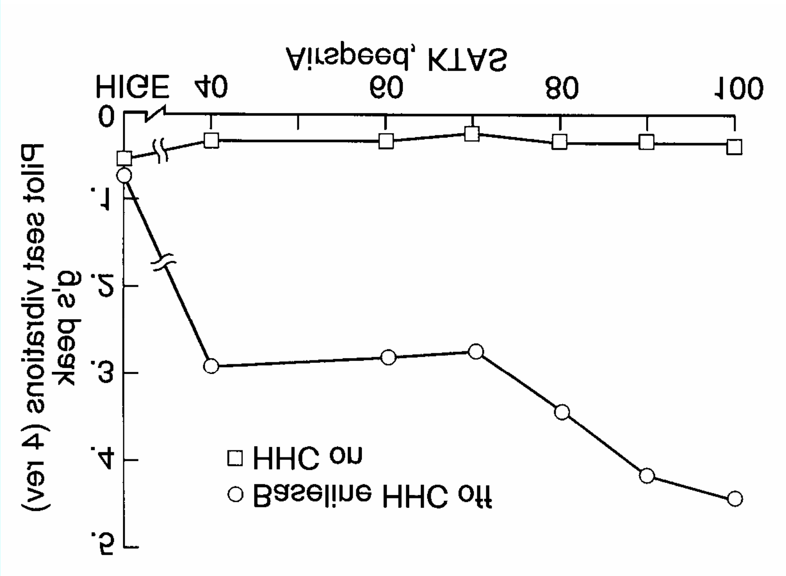


HHC Background and Status

- Inputs in non-rotating system with $\omega_{HH} = N_B / rev$
- Adaptive control strategy combining recursive parameter estimation with linear optimal control theory was used.
- Flight test demonstration on an OH-6A in 1983-84, confirmed 30-90% vibration reduction, in 4P vertical acceleration components at pilot seat, without penalties on loads or performance.

- Despite its demonstrated feasibility HHC has not been implemented on a production helicopter, for three principal reasons:

  (a) cost; (b) limitations on the objectives which can be achieved with control through a conventional swashplate; (c) not very suitable for hingeless and bearingless rotors.

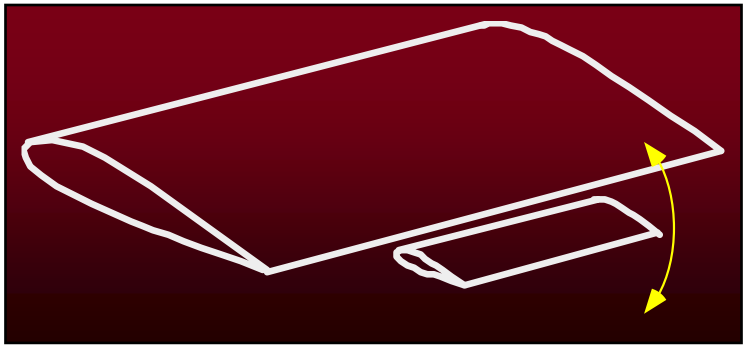


Conventional IBC

- Based on actuating the blade at it's root in the rotating system; leads to a complicated hub which may not be feasible to implement in practice.

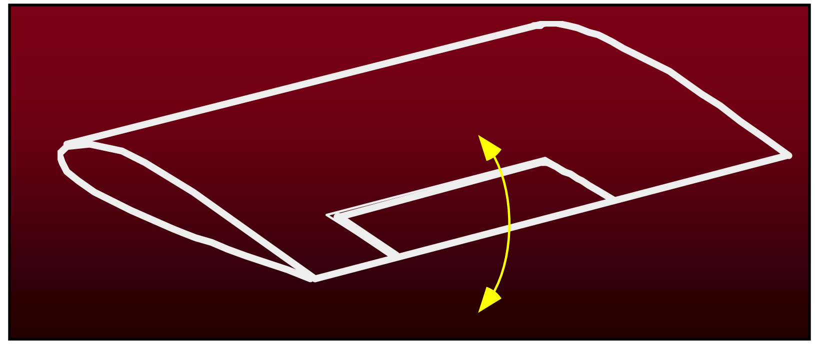
MBB-BO 105 IBC actuators used in WT and Flight Test, note this is a prototype, actual production version will be smaller

Actively Controlled Flap (ACF) Implementation of IBC



Servo Flap

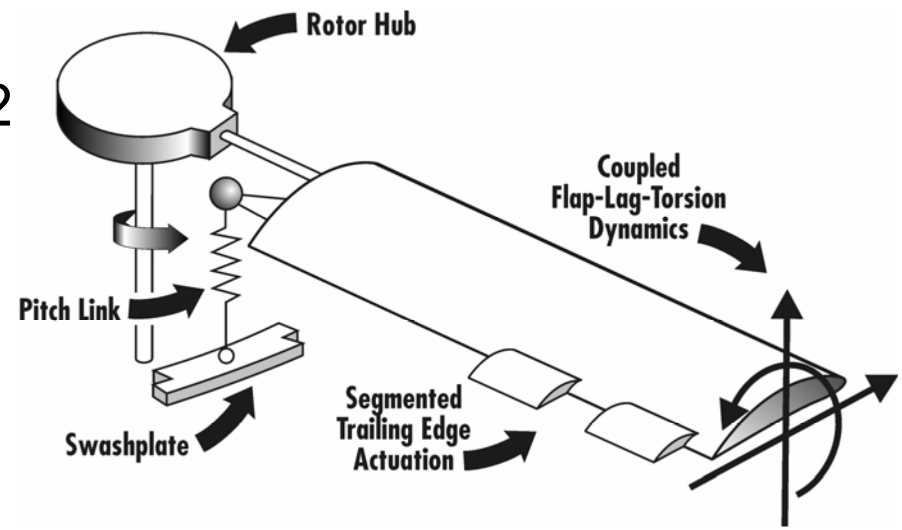
- Large pitching moments
- Exposed linkages
- Reduced effectiveness due to hinge gaps



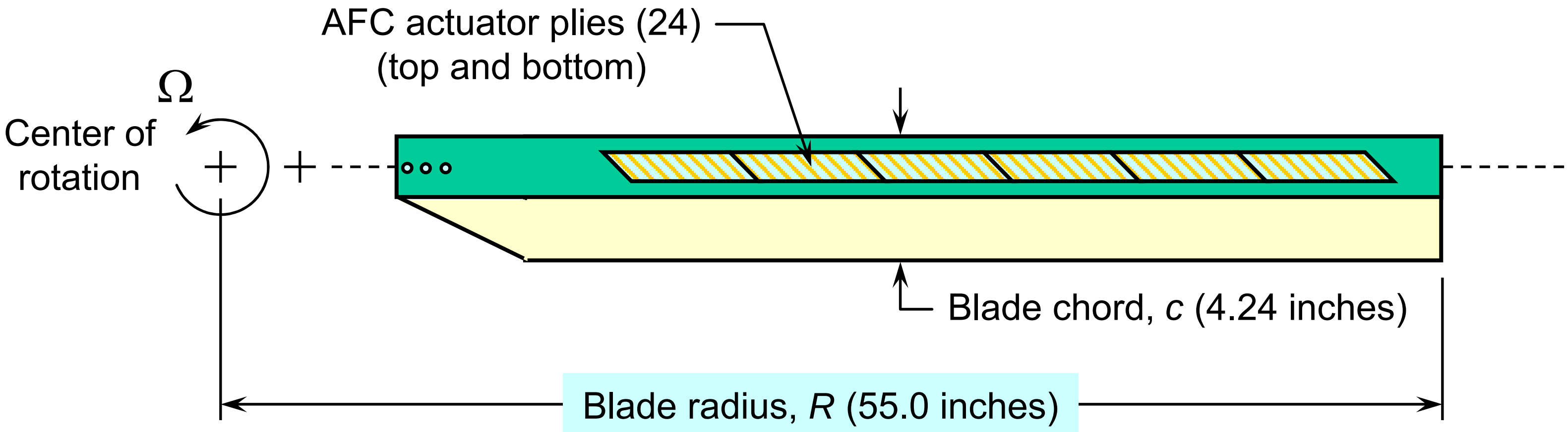
Plain Flap

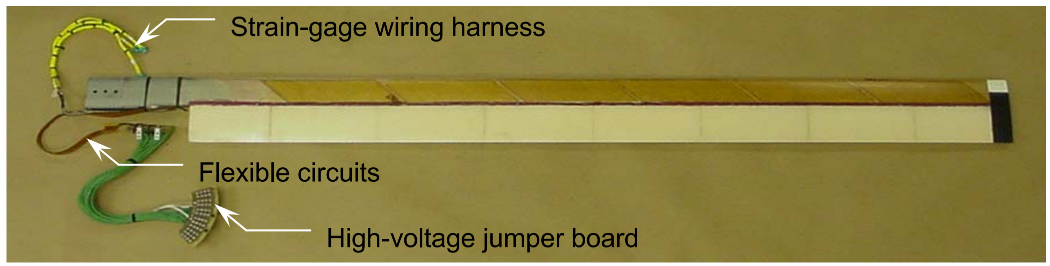
- Modifies lift and pitching moment
- Internally mounted actuator and linkage
- Easier sealing of hinge gaps
- Attractive for smart actuation

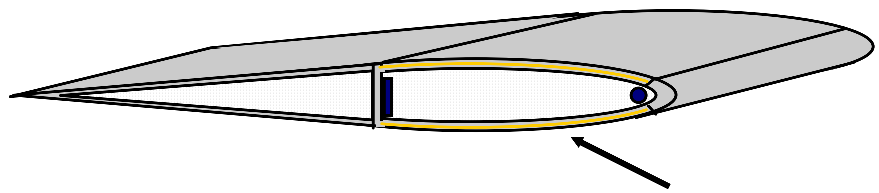
- Inspired by Kaman servo-flap (1972 CTR, Lemnios & Smith)
- Consumes significantly less power than conventional IBC
- Can be implemented with multiple flaps for local control



IBC-Active Twist Rotor Implementation



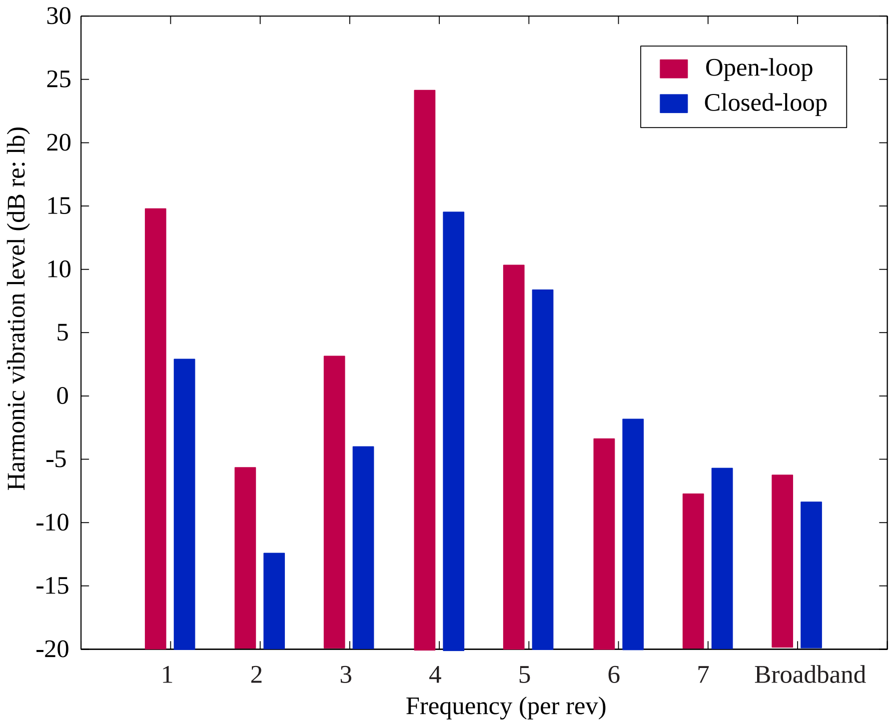




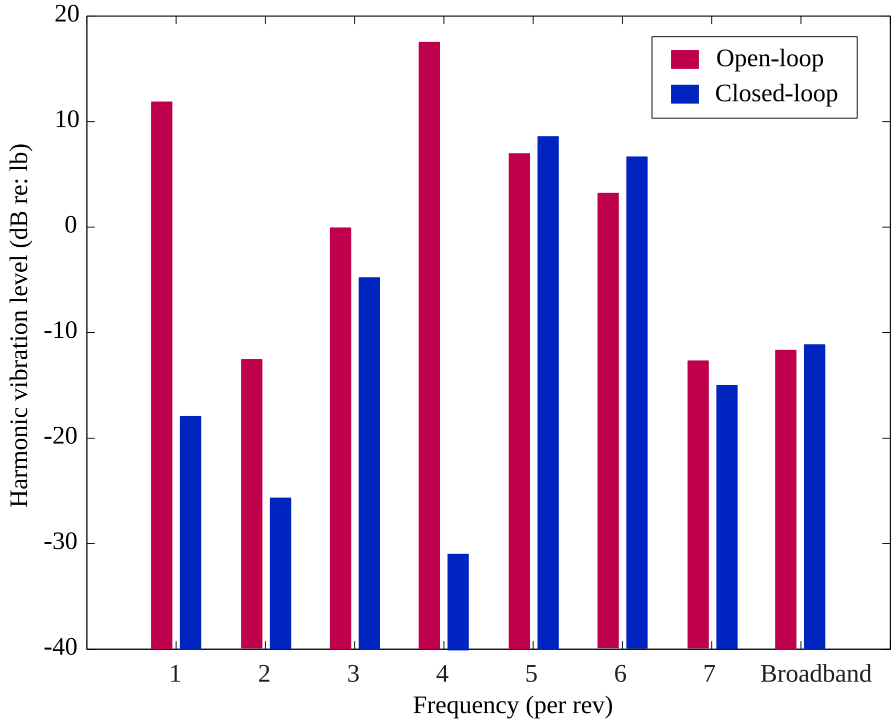
AFC's on the front cell between glass/epoxy layers

ATR Performance in TDT Tests

m=0.333



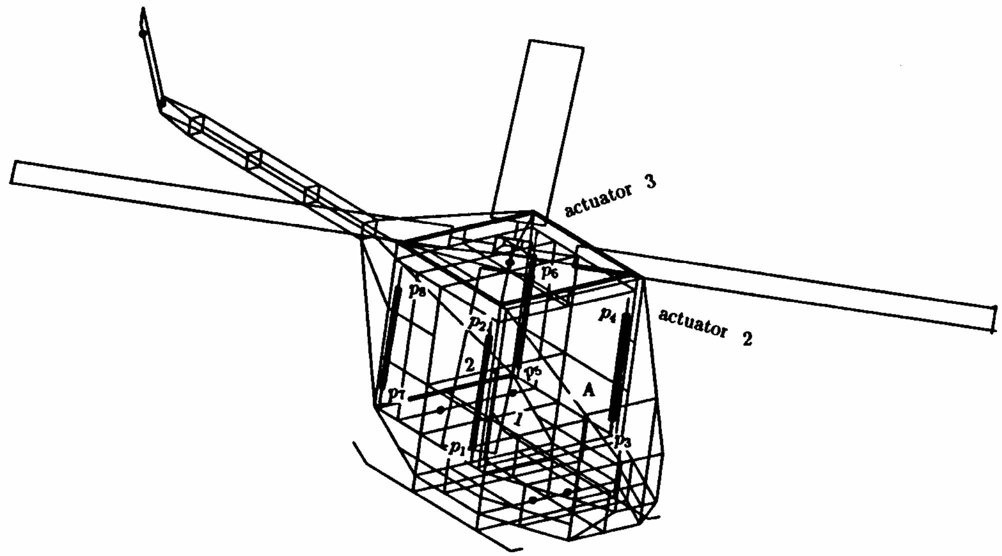
m=0.267



NASA/Army/MIT ATR IBC Closed Loop Test (April 2002) Vertical Hub Force (Cesnik, Wilbur,Hall)

ACSR and Its Implementation

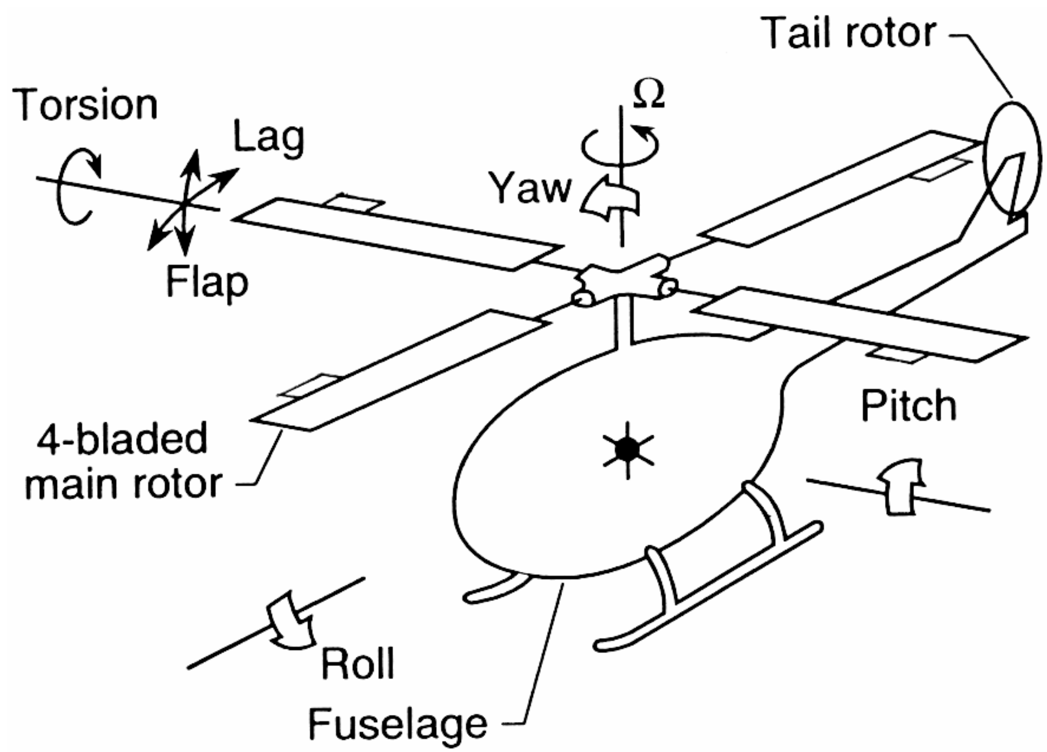
- A third approach known as active control of structural response (ACSR) controls response in the fixed frame. Stiff actuators introduce small amplitude excitation between the rotor and fuselage, such that the sum of the response of the airframe at specific locations, due to rotor loads and excitation due to controls is minimized.
- ACSR implemented on the EH101 (Agusta-Westland).



Coupled rotor/flexible fuselage model showing ACSR platform, rectangle at top supporting rotor, and actuators shown as thick vertical elements.

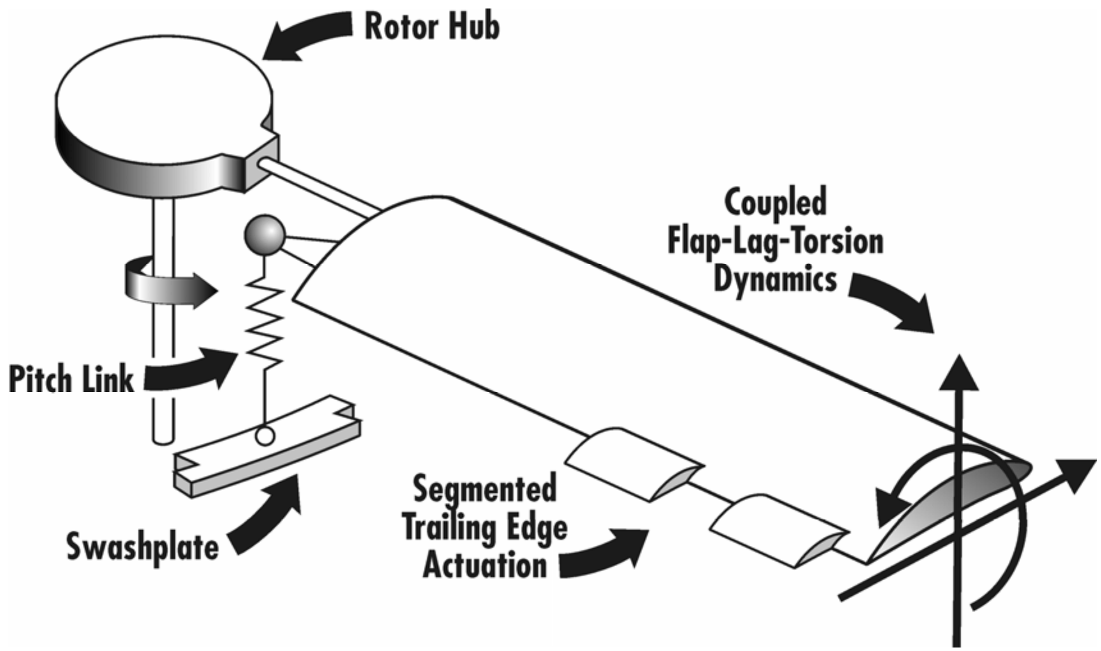
Vibration Reduction in Rotorcraft Using ACF

- Research carried out in the last 15 years, has shown that the ACF may have a significant edge compared to the other approaches.
- Several Ph.D. dissertations:
  - Dr. T. Millott, UCLA 1993
  - Dr. T. Myrtle, UCLA 1998
  - Dr. M. de Terlizzi, UCLA 1999
  - Dr. G. Depailler, UM 2002
  - Dr. R. Cribbs, UM, post-doc, 1999-2000
  - Dr. Dan Patt, UM, Oct. 2004
  - Li Liu, UM, May 2005



Vibration Reduction in Rotorcraft Using ACF (cont.)

- Principal advantages of ACF are:
  - Only a small portion of the blade needs to be actuated, less than 5% of the blade area, consisting of less than 18% of the span, less than 25% of the chord, and the flap is usually centered between 75%-85% of the blade span, where the aerodynamic loading is most effective.
  - Conventional swash-plate retained, flaps have limited influence on vehicle airworthiness.
  - Multiple flaps can be accommodated.
  - Can be used for vibration reduction, noise alleviation, performance enhancement.



Vibration Reduction in Rotorcraft Using ACF (cont.)

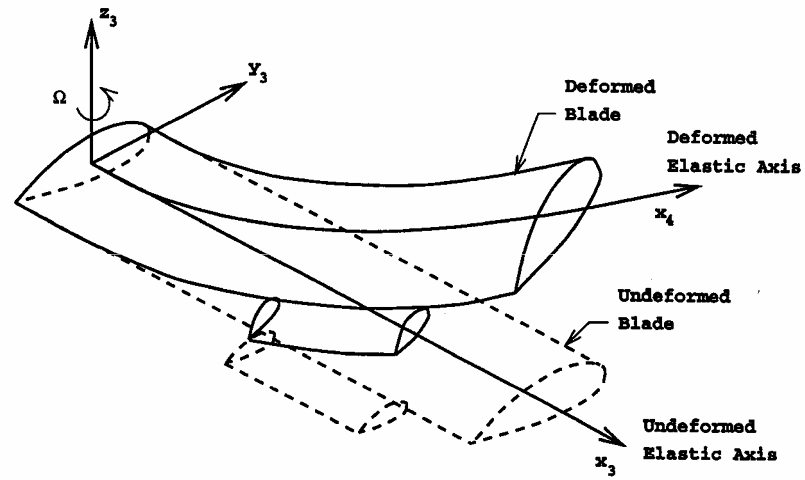
- Concept first studied by Millott and Friedmann [1992-95] where the feasibility and potential of ACF was demonstrated. Subsequently studied by Milgram and Chopra [95-97] using UMARC. Studied analytically by Straub et al [1996] and also tested in wind tunnel at NASA Langley [1995]. Refined aeroelastic simulation capability developed by Myrtle and Friedmann [1996-98].
- A number of ACF designs have been developed using piezo-electric bi-morph actuation [Spangler& Hall, 1990; Hall & Prechtl, 1996, 1998, 1999; Koratkar & Chopra, 1997], Bernhard and Chopra [1997-99]. In a comprehensive study [Fulton& Ormiston, 1997, 1998] an ACF has been extensively tested in the 7X10 ft. Ames wind-tunnel(the open loop mode).
- Application to BVI studied by deTerlizzi and Friedmann (1998,1999), including correlation with Fulton & Ormiston experiment.
- Application to alleviation of dynamic stall induced vibrations [Depailler & Friedmann, 2002].
- Application to noise reduction studied first by [Patt, Li & Friedmann, 2003] including correlation with HART data.
- Application to simultaneous vibration and noise reduction [Patt, Li & Friedmann 2004, 2005].

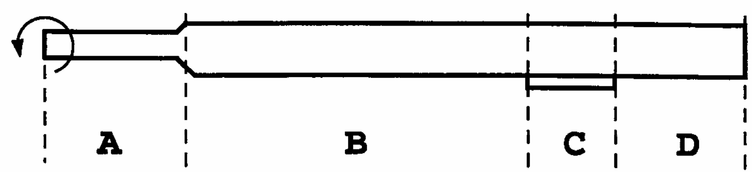
Development of a Refined Aeroelastic Simulation Capability for Vibration Reduction Using ACF

- Refined structural structural dynamic model capable of representing composite blades with advanced geometry tips.
- Comprehensive aerodynamic model capable of representing unsteady aerodynamic loads on the blade/flap combination, free wake, drag due to flap deflection and dynamic stall.
- Robust control algorithm for vibration reduction including provision for limiting flap deflections (to practical values) while avoiding saturation.
- Validation of the code with experimental data.

Structural Dynamic Model

- Most important requirements are: transverse shear deformation, cross-sectional warping, elastic coupling due to material anisotropy, geometric nonlinearities (moderate deflections), and advanced geometry tip.
- Model combines the geometrically nonlinear, span-wise one dimensional beam theory, with a FE CS analysis to determine the CS constants and warping. The CS analysis capable of modeling anisotropic, arbitrary cross-sections, with multi-cell construction and arbitrary wall thickness.
- Flap incorporated in the model using only inertia and aerodynamic loads, structural effect neglected.



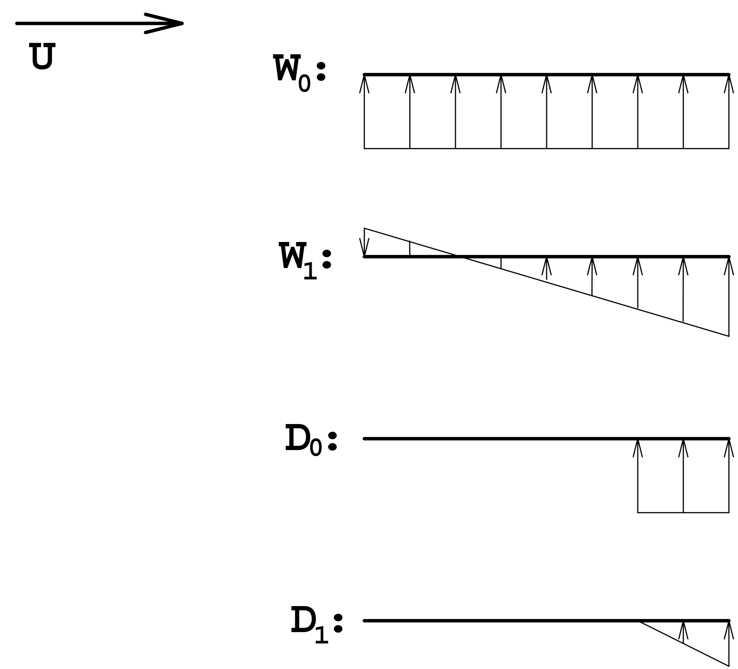


Compressible Time Domain Aerodynamic Model for Blade/Flap Combination

- **Unsteady aerodynamic model of airfoil/flap combination modeled using rational function approximation (RFA), includes compressibility and unsteady freestream effects (Myrtle & Friedmann, 98, 01).**
- **Based on Roger's approximation (1977)**

$$\tilde{Q}(\bar{s}) = C_0 + C_1\bar{s} + \sum_{n=1}^{n_L} \frac{\bar{s}}{\bar{s}+\gamma_n} C_{n+1}$$

•Compressible oscillatory response quantities are generated numerically using a doublet lattice approach to obtain solutions to the Possio integral equation, for a set of fundamental airfoil and flap motions.



Compressible Time Domain Aerodynamic Model for Blade/Flap Combination (cont.)

- Transformation to the time domain produces a state space aerodynamic model

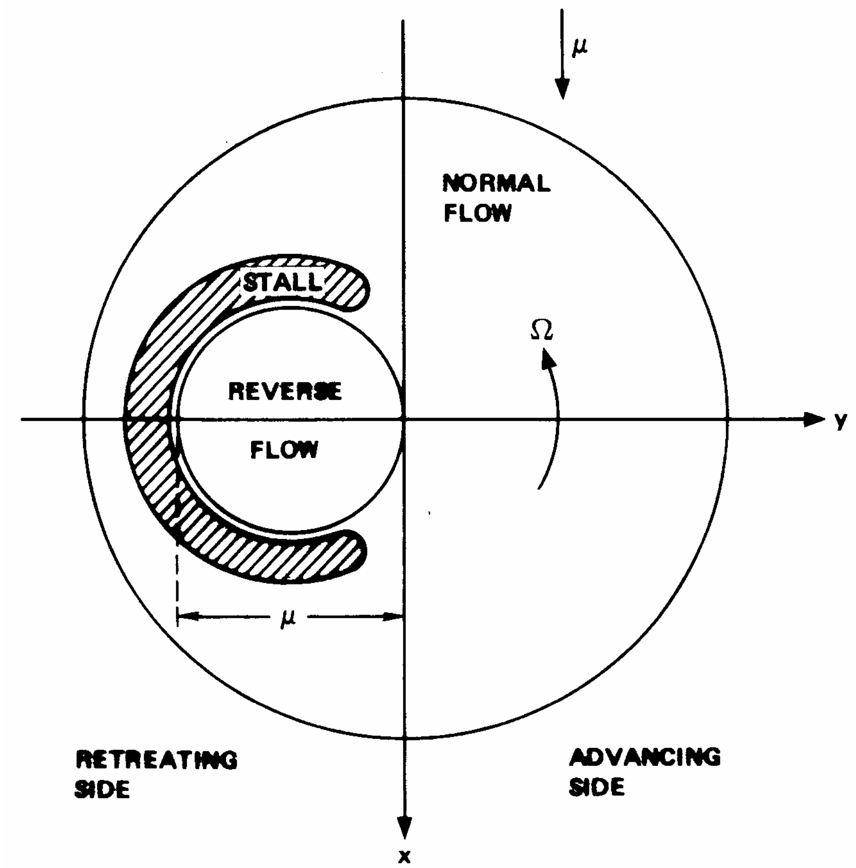
$$\mathbf{f}(t) = \frac{1}{U(t)}\left(\mathbf{C}_0\mathbf{h}(t) + \mathbf{C}_1\frac{b}{U(t)}\dot{\mathbf{h}}(t) + \mathbf{D}\mathbf{x}(t)\right)$$

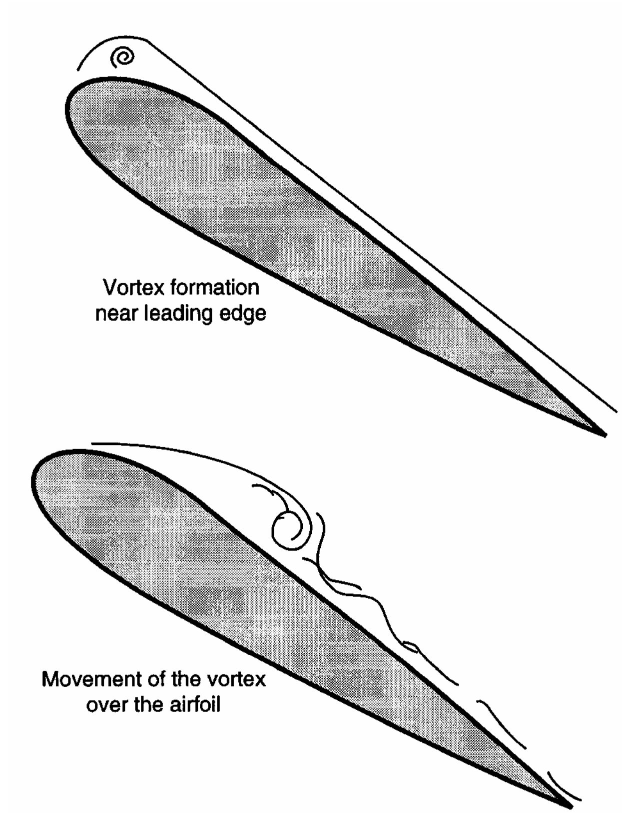
$$\dot{\mathbf{x}}(t) = \frac{U(t)}{b}\mathbf{R}\mathbf{x}(t) + \mathbf{E}\dot{\mathbf{h}}(t)$$

- Aerodynamic states combined with the state space representation of the physical dof's.
- The combined structural and aerodynamic equations form a coupled system of nonlinear ordinary differential equations, for which the solution is obtained by direct numerical integration.

Dynamic Stall

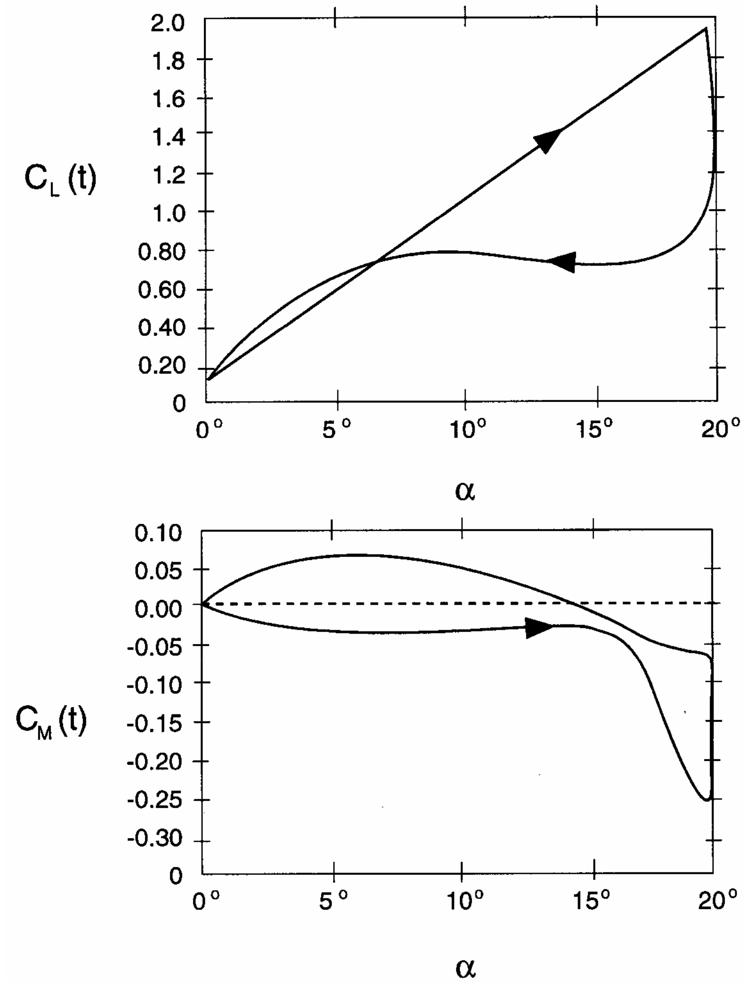
- Dynamic stall (DS) is a strong, nonlinear aerodynamic effect. DS is associated with the retreating blade and borders on the reversed flow region.
- Affects helicopter performance at high μ ; hysteretic air loads, large pitching moments, and large increases in pitch-link vibratory loads.





Dynamic Stall (cont.)

- DS is incorporated using 2-D semi-empirical model, which captures the nonlinear hysteretic nature of lift, drag and moment.
- The ONERA model, that describes US behavior in both attached and separated flow using a set of nonlinear differential equations (in time). Developed in 1984, it has undergone improvements, the most recent version [Petot 89]. Model contains 22 empirical coefficients determined by parameter identification from experimental measurements on oscillating airfoils.
- It is completely compatible with our compressible time domain theory, since it is based on the same set of generalized motions.



Hysteretic behavior with ONERA DS NACA0012, M=0.379, k=0.075

Dynamic Stall (cont.)

- Our approach to coefficient selection (Depailler & Friedmann, 01;02):
  - Use of optimization routine (Powell's method) for curve-fitting
  - Emphasis on the reproduction of the downward moment peak

•Separation criterion

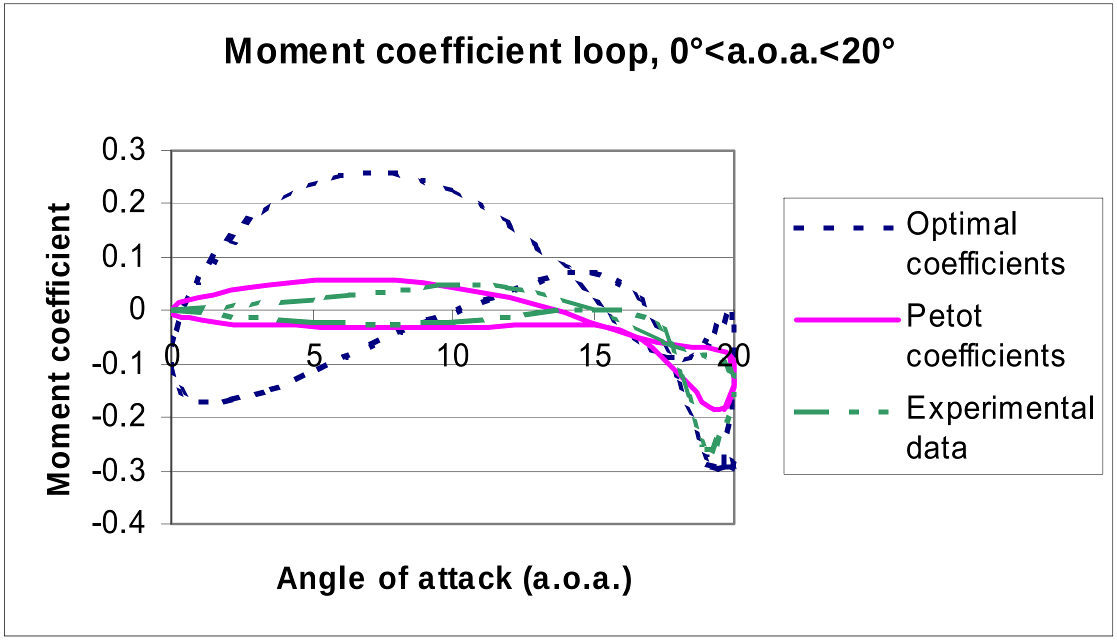
based on α :

$$\alpha \geq \alpha_{cr} = 15^0\left(1 - M^2\right)$$

and after time delay, reattachment

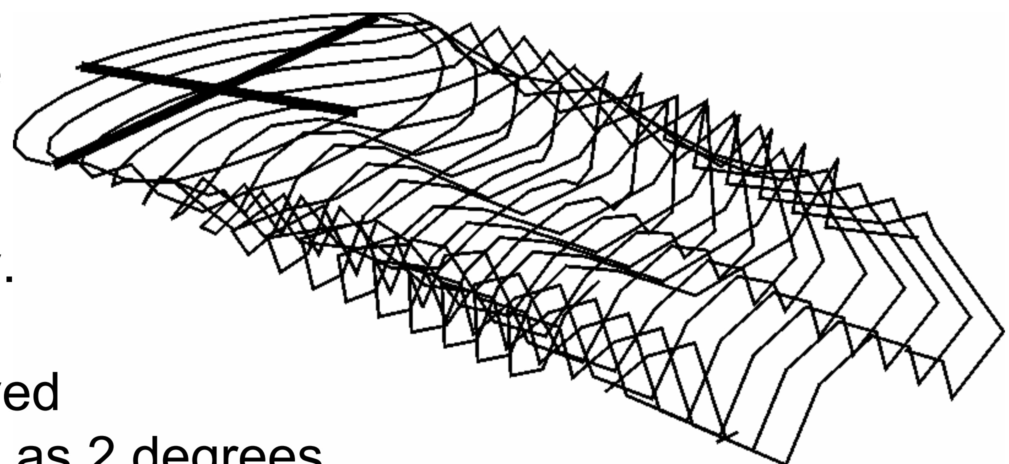
$$\alpha \leq \alpha_{cr} = 15^0\left(1 - M^2\right)$$

•Attached, separated air loads are combined in an appropriate manner.



Free Wake Model

- Wake analysis extracted from CAMRAD/JA (de Terlizzi & Friedmann,98). Consists of a wake geometry calculation procedure, developed by Scully (1975) and an induced velocity calculation procedure developed by Johnson (1988).
- Wake geometry includes distortion of the wake due to wake self-induced velocity.
- During the last five years the wake model has undergone a number of improvements which have increased its accuracy significantly.

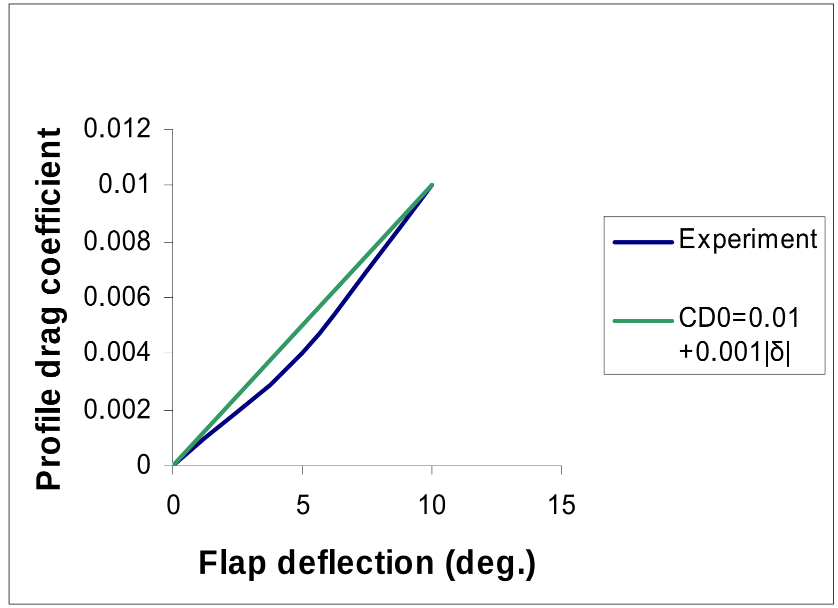


- Wake resolution restrictions removed by allowing azimuthal steps as fine as 2 degrees. Dual vortex line model with negative blade tip loading also introduced.

Static Drag Corrections for Partial Span Trailing Edge Flaps

- Curve-fitting of experimental data (Wenzinger & Harris): for c_{cs} / c_b =0.2,

$$C_{D0} = 0.01 + 0.001|\delta|$$



- Modification of C_{D0} due to flap chord ratio:
  – Based on McCormick's semi-empirical relation between drag increase and flap chord ratio
- Final model for c_{cs} / c_b =0.25:

$$C_{Do} = 0.01 + 0.001225|\delta|$$