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

## PART-2

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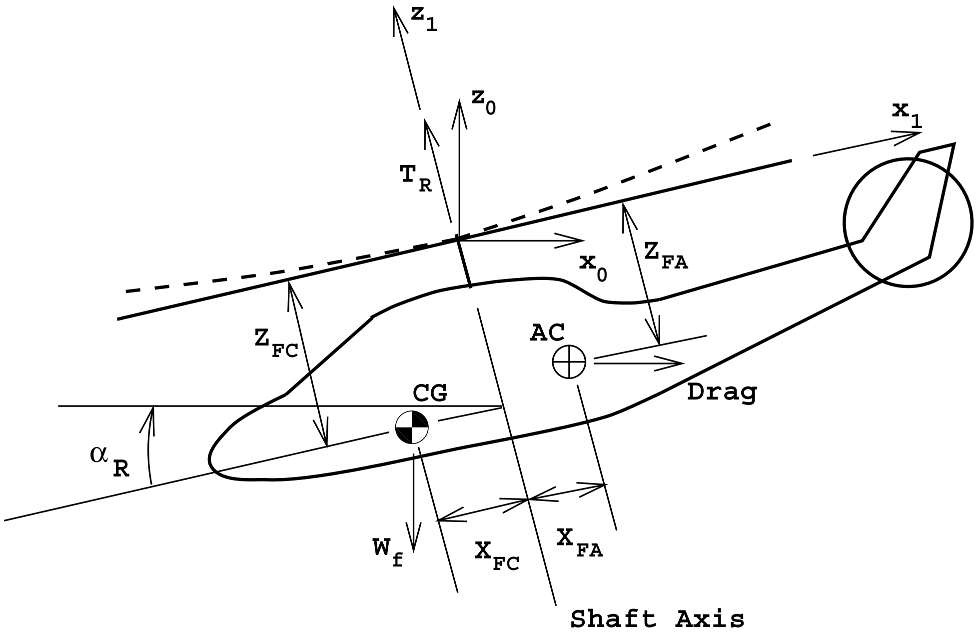
# Complete Aerodynamic Model

- RFA model + free wake used for attached flow loads.
- ONERA dynamic stall model used for separated flow loads.
- Same generalized motion vector in both RFA and ONERA.
- In both RFA and ONERA, attached flow transfer function approximated by a strictly proper rational transfer function.
- Both models are formulated in the time domain, and provide cross-sectional loads.
- State vector consists of:
  - RFA attached flow states
  - ONERA separated flow states
- Drag correction for flap deflection using curve fitted static data applied in a quasi-static manner.

# Method of Solution

- Blade discretization using Galerkin’s method.
- Model reduction based on free vibration modes of the rotating blade, implemented by 3 flapping modes, 2 lead-lag modes, 2 torsion modes
- Coupled trim/aeroelastic solution is obtained, and is used consistently in all parts of the simulation, I.e. flight mechanics and aeroelastic problems are coupled.



- Time-domain integration of the equations of motion using the Adams-Bashfort DE/STEP predictor-corrector algorithm

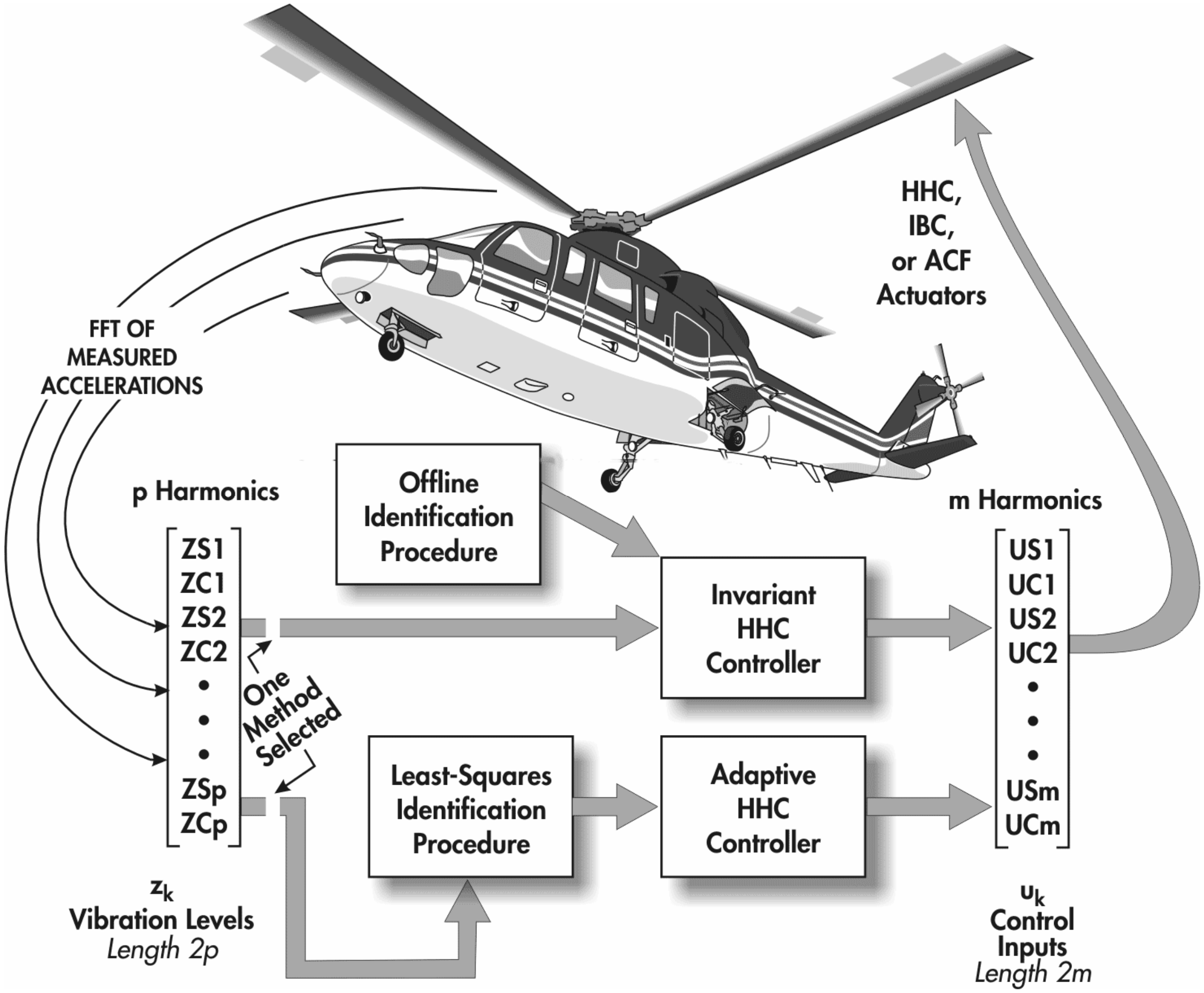
# Higher Harmonic Control Algorithm

Operation of the HHC Algorithm for Vibration Reduction:

Conventional HHC

&

Adaptive HHC



# Variants of the HHC Algorithm

**Three variants of HHC are considered:**

- **Conventional HHC Algorithm**
  Basic fixed-gain controller, can be applied in open or closed loop. Off-line identification. This approach used in the initial portions of the research.
- **Relaxed HHC Algorithm**

  Relaxation coefficient introduced to conventional HHC to enhance robustness. This modification was needed when dealing with dynamic stall.
- **Adaptive HHC Algorithm**
  On-line identification using a least-squares technique. More effective and robust than the previous versions, was needed primarily when pursuing simultaneous vibration and noise reduction.

# Active Vibration Reduction

- Objective: reduce 4/rev vibratory hub loads
- Flap input - combination of 2/rev, 3/rev, 4/rev, 5/rev components

$$\delta(\psi) = \sum_{N=2}^{5} [\delta_{Nc} \cos(N\psi) + \delta_{Ns} \sin(N\psi)]$$

- Conventional control approach (CCA) is a local HHC, where

$$\vec{u} = \left\{\delta_{2c}, \delta_{2s}, \delta_{3c}, \delta_{3s}, \delta_{4c}, \delta_{4s}, \delta_{5c}, \delta_{5s}\right\}^T$$

- 1/rev components would affect helicopter trim
- 6/rev and above would significantly increase 8/rev vibratory loads (Millott and Friedmann, 1994)

# Control Laws

- Conventional control algorithm (CCA) : Minimization of a performance index

$$J = \vec{z}_i^{\,T} W_z \vec{z}_i + \vec{u}_i^{\,T} W_u \vec{u}_i + \Delta\vec{u}_i^{\,T} W_{\Delta u} \Delta\vec{u}_i; \qquad T = \frac{\partial \vec{z}}{\partial \vec{u}}$$

$$\vec{u}_{i+1}^{\,*} = -D_i^{-1}\{T_i^T W_z[\vec{z}_i - T_i \vec{u}_i^{\,*}] - W_{\Delta u}\vec{u}_i^{\,*}\};\; D_i = T_i^T W_z T_i + W_u + W_{\Delta u}$$

- Saturation: limits on flap deflection $-4^{\circ} \le \delta \le 4^{\circ}$
  Cribbs and Friedmann (2001): consider

$$W_u = c_{wu} I$$

when:

$$\begin{cases} |\delta| > 4^{\circ}: & \text{Increase} \quad c_{wu} \\ |\delta| < 4^{\circ}: & \text{Decrease} \quad c_{wu} \end{cases}$$

# Results Generated for Rotor and Flap Properties Shown Below

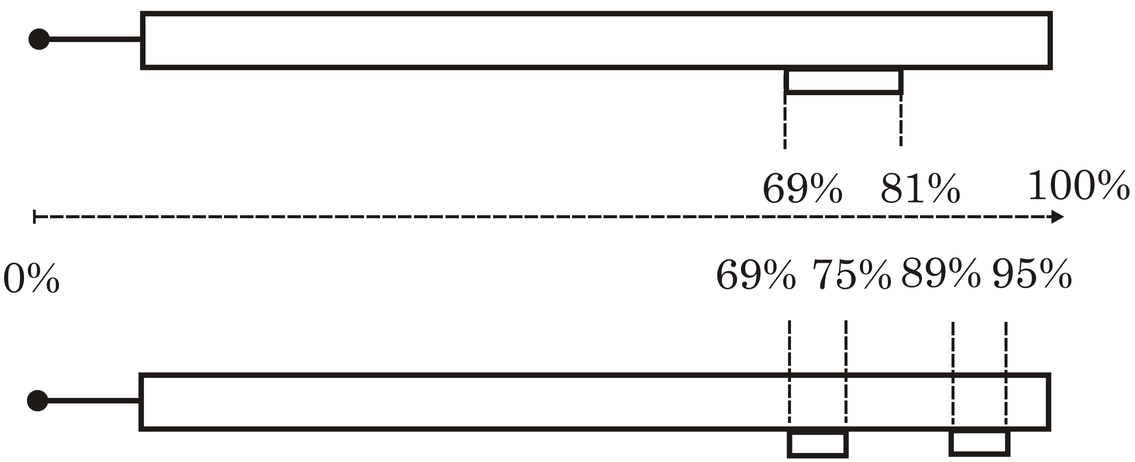
- 4-bladed rotor, similar to MBB BO-105
  $\gamma = 5.5$
  $\sigma = 0.07$
- Flaps:

$\omega_F = 0.727$

$\omega_L = 1.123$

$\omega_T = 3.170$

$C_W = 0.005$



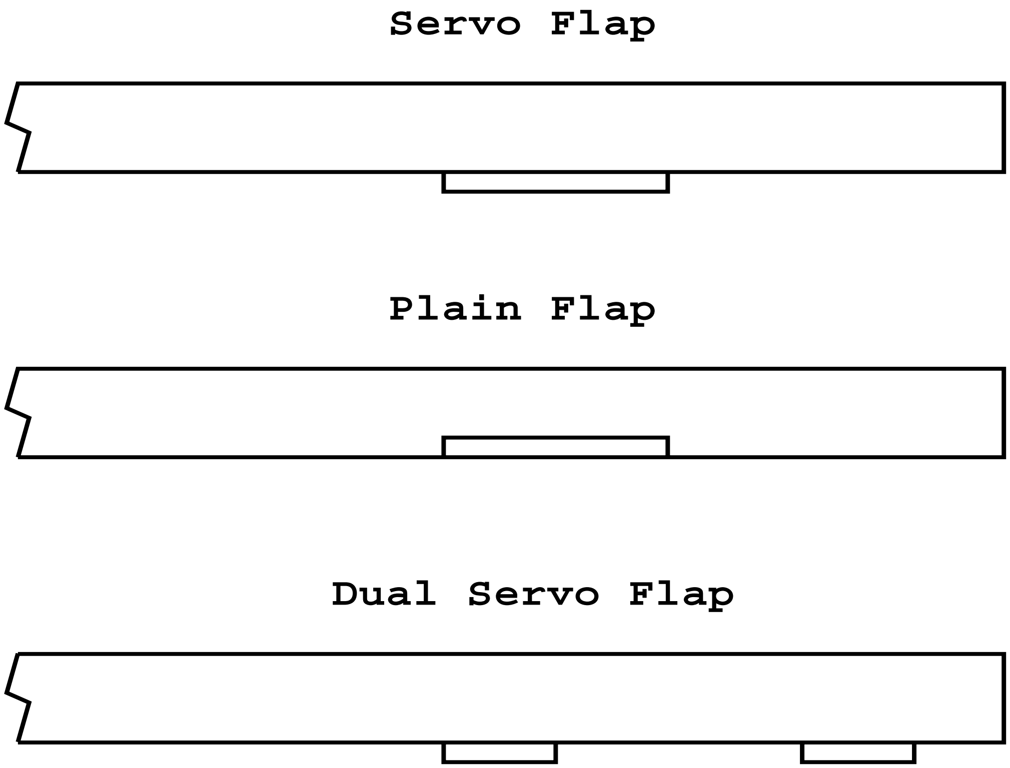
(a) single-flap configuration

(b) dual-flap configuration

# Comparison of Flap Performance

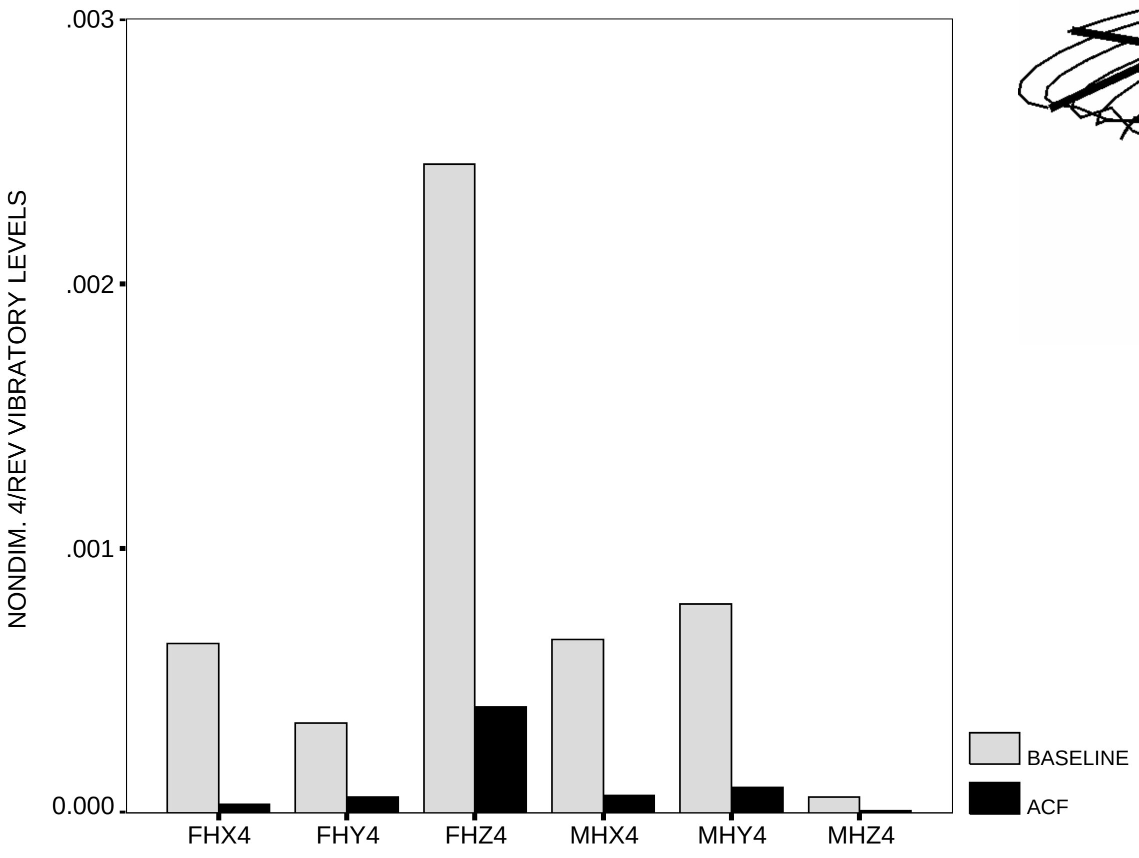
- Three different configurations were considered [Myrtle & Friedmann, 97]: servo flap, plain flap and dual flap.

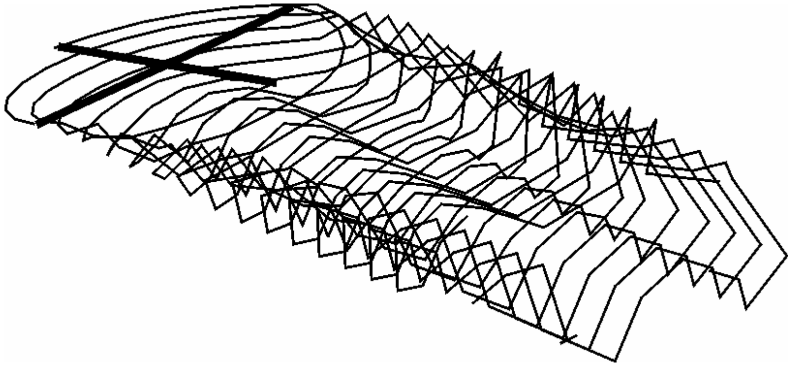
Performance of dual flap best, next the single servo flap, weakest the plain flap.



# Vibration Reduction at Low Advance Ratio BVI

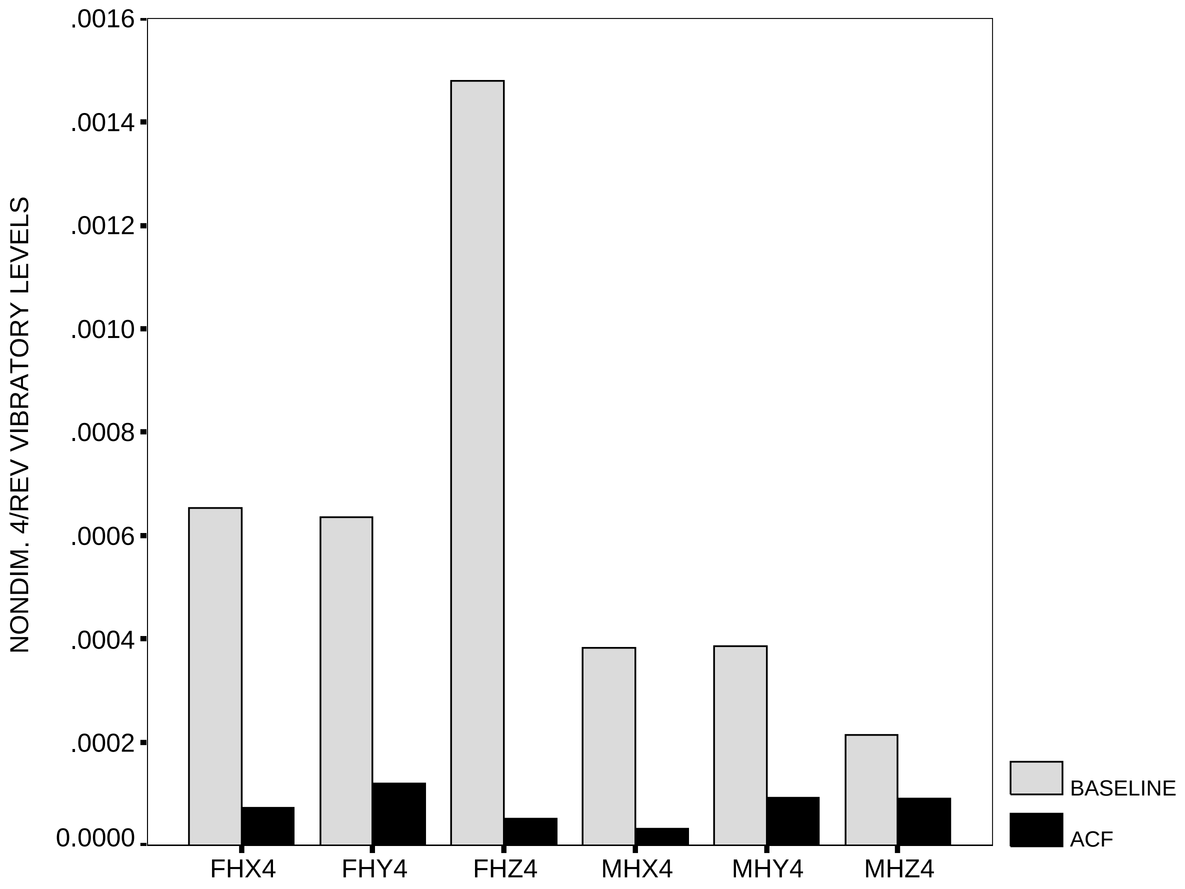
- Vibration reduction at low advance ratio, 0.15, 4/rev hub shears and moments, with RFA aerodynamics and free wake, this represents primarily blade vortex interaction (BVI).





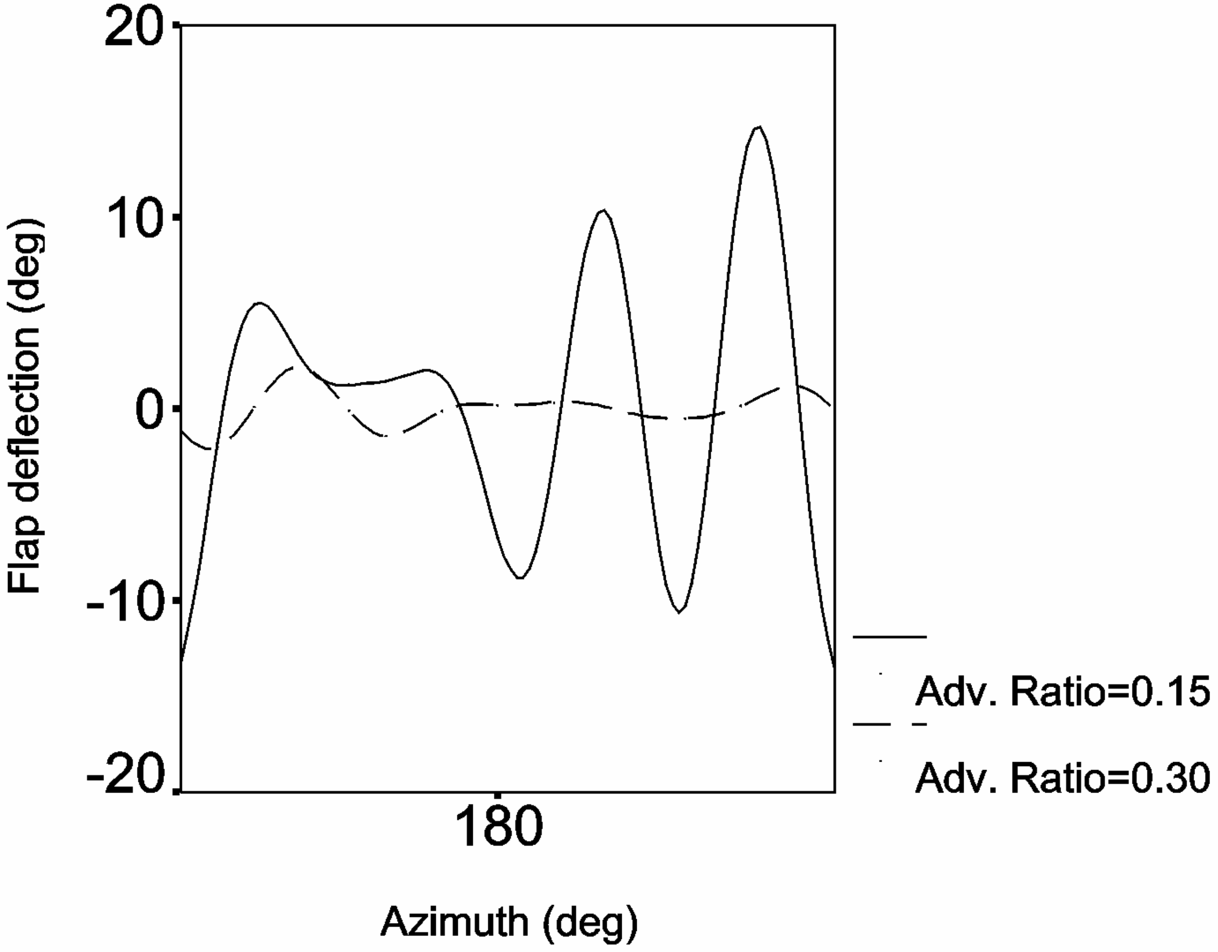
# Vibration Reduction at High Advance Ratio

- Vibration reduction of 4/rev hub shears and moments at high advance ratio, 0.30, with RFA aerodynamics and free wake, shown below.



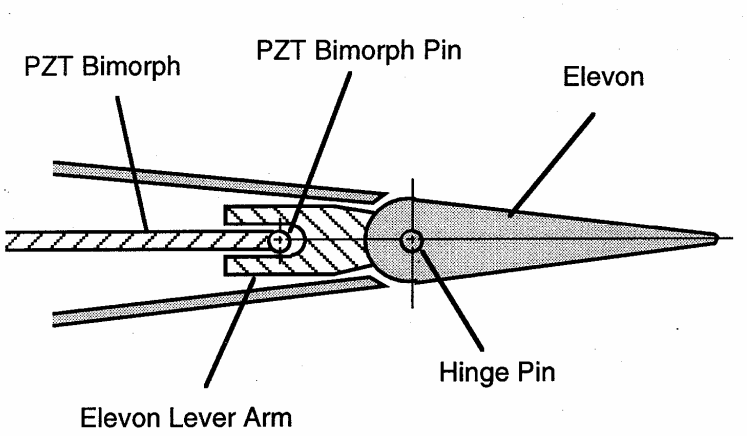
# Flap Deflection Comparison

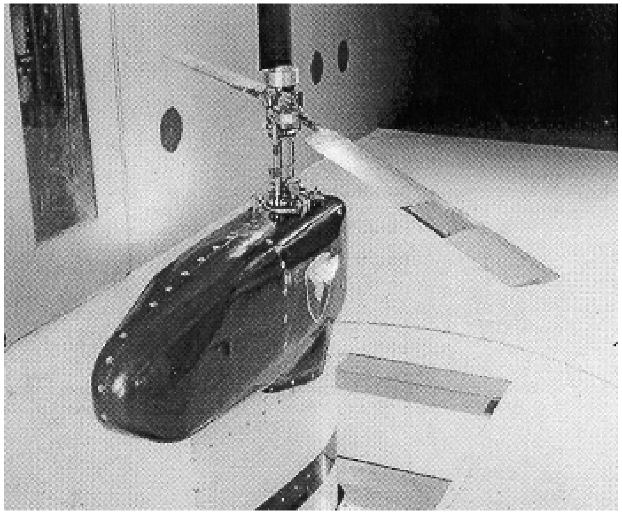
- Flap deflection history at advance ratios 0.15 and 0.30, with RFA aerodynamics and free wake, shown below.

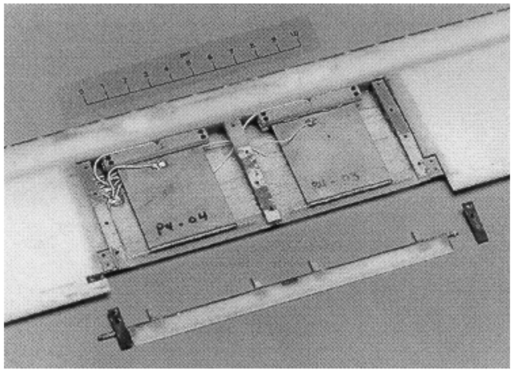


# Experimental Verification

- In a comprehensive study [ Fulton& Ormiston, 1997, 1998] an ACF has been extensively tested in the 7X10 ft. Ames wind-tunnel (open loop mode). The flap chord equal to 10% blade chord, 75% span centered, extends 12% span, V=270 ft/sec, target flap deflection 5 deg, implemented in two bladed, hingeless rotor, 7.5 ft. diameter, 3.4” chord, 760 RPM, tip speed 298 ft/sec.

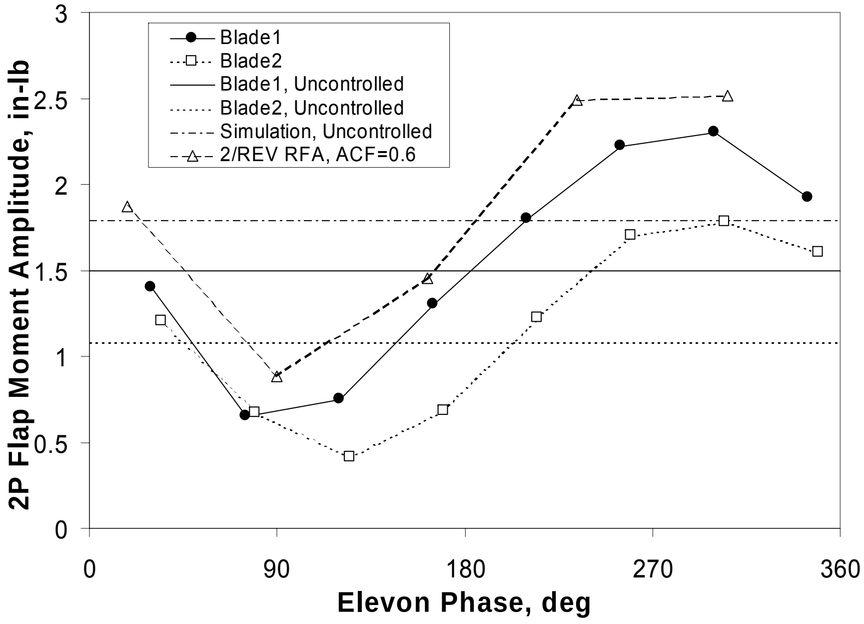




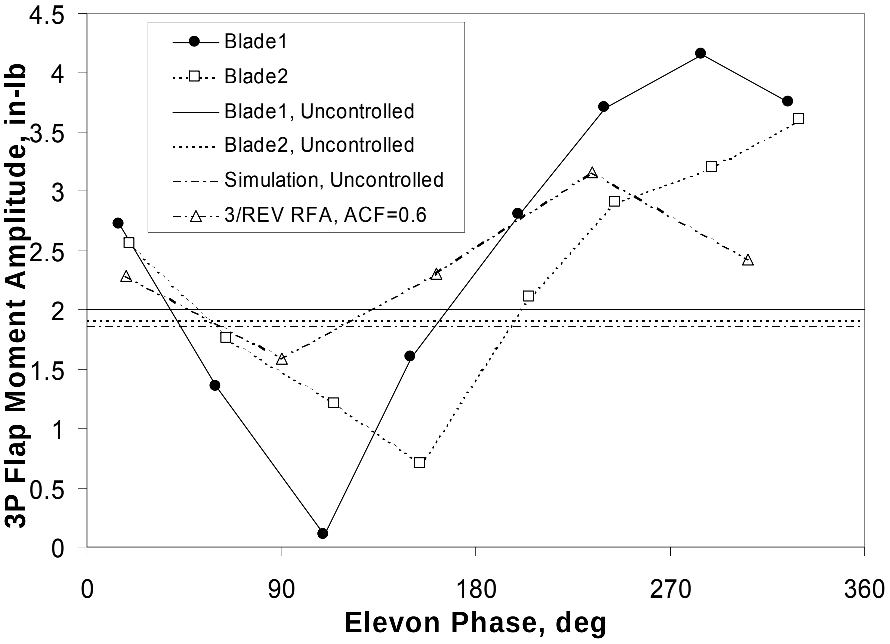


# Experimental Verification (cont.)

- Variation of 2/rev and 3/rev flap bending moment with elevon phase, 760 RPM, $\lambda$=0.20



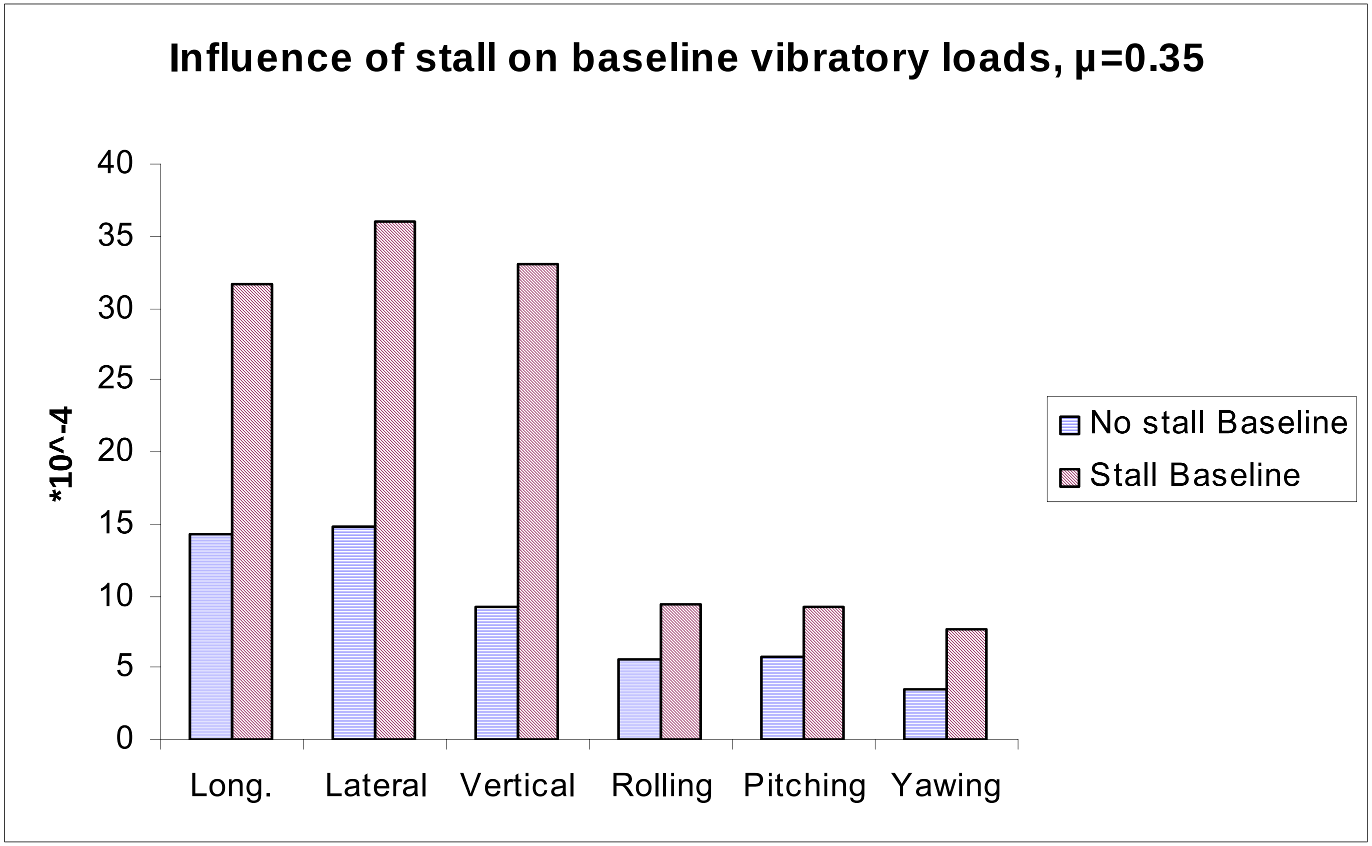
RFA aerodynamics 2/rev



RFA aerodynamics 3/rev

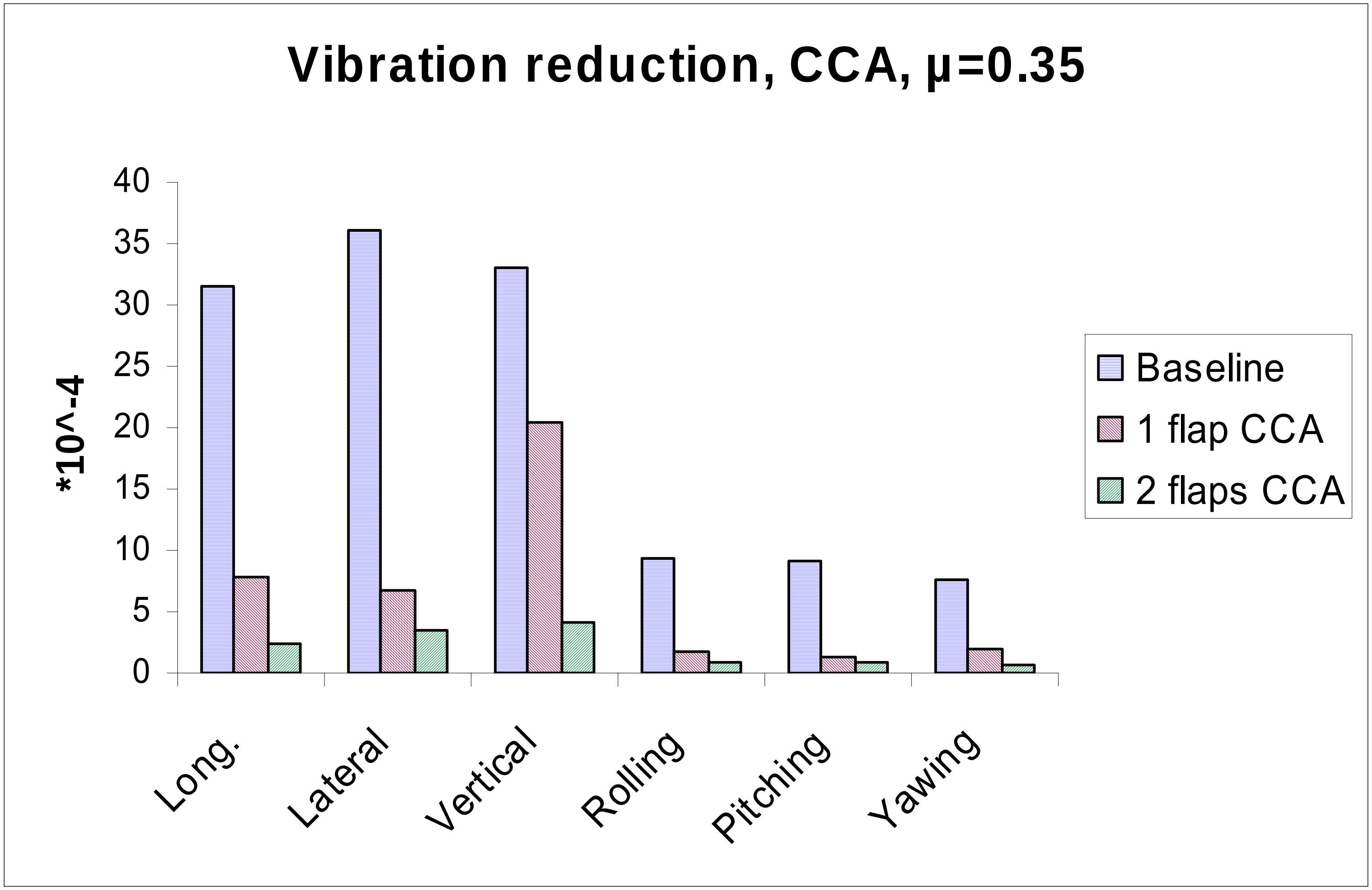
# Effect of Dynamic Stall on Baseline Vibration

- All vibratory loads are much higher when stall is accounted for
- Vertical shear affected most (increases)


Influence of stall on baseline vibratory loads, μ=0.35

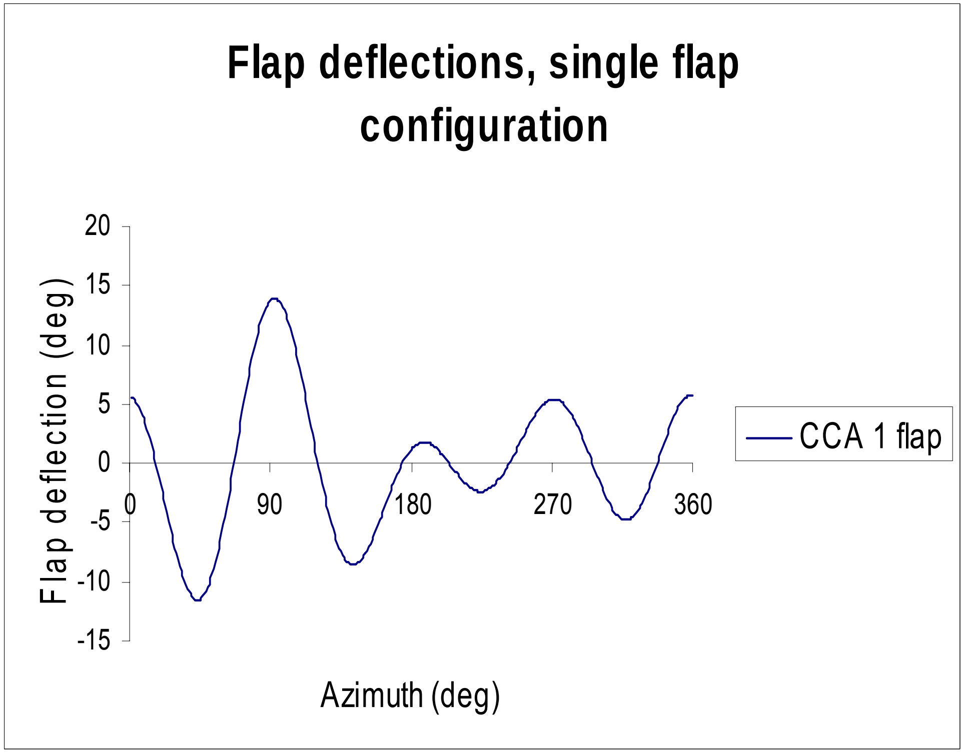
# Vibration Reduction Based on CCA

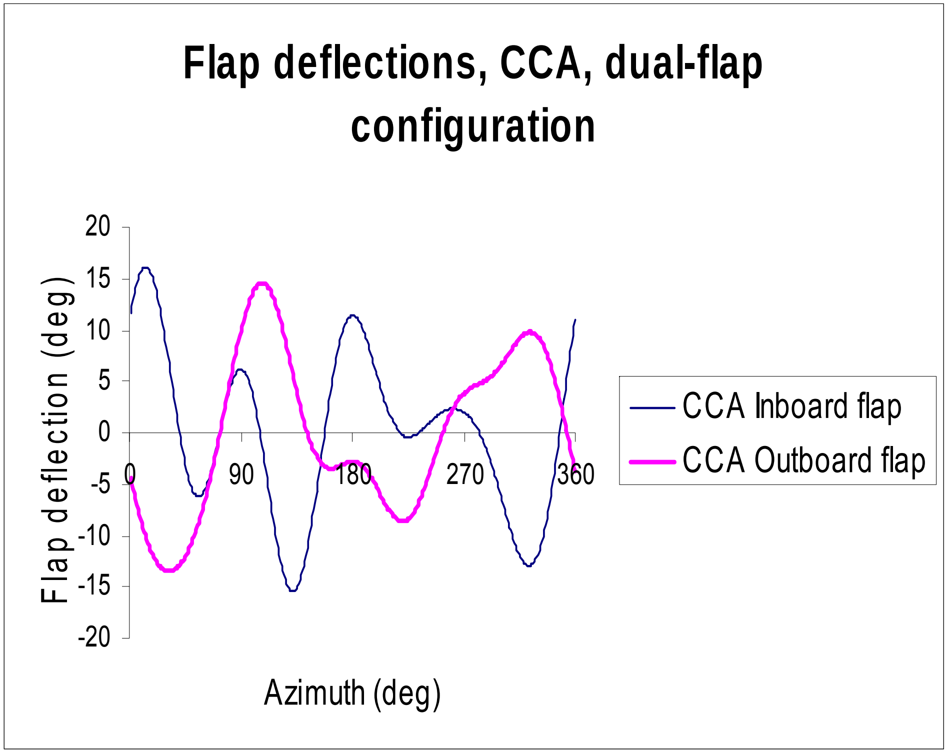
- Reduction of 4/rev hub loads using the ACF



# Vibration Reduction Based on CCA (cont.)

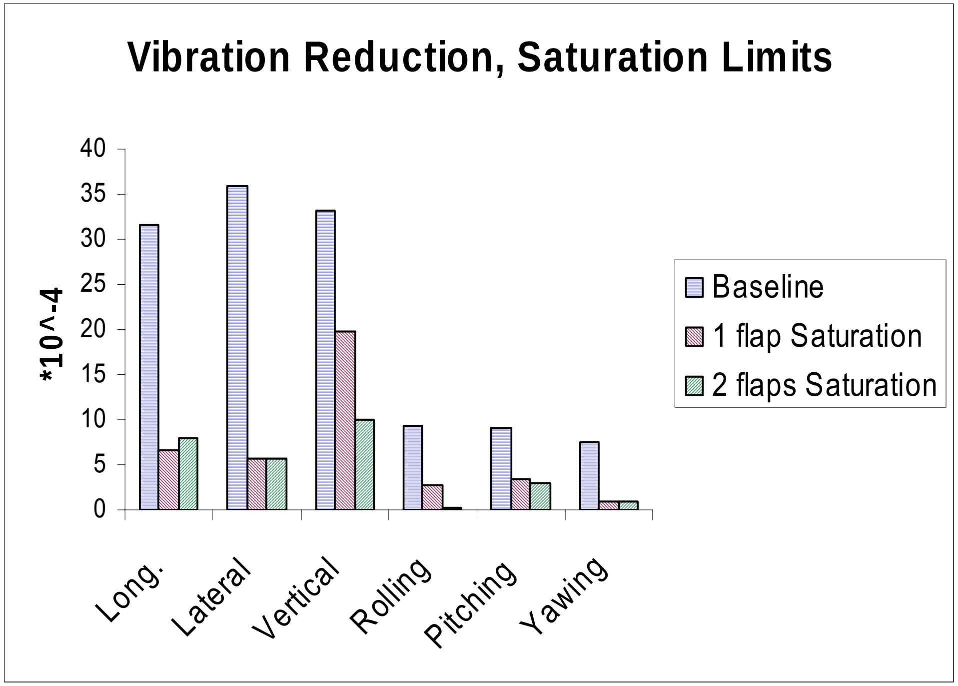
- Flap deflections are significant ($\mu=0.35$); saturation limits (Cribbs & Friedmann 2001) need be considered.



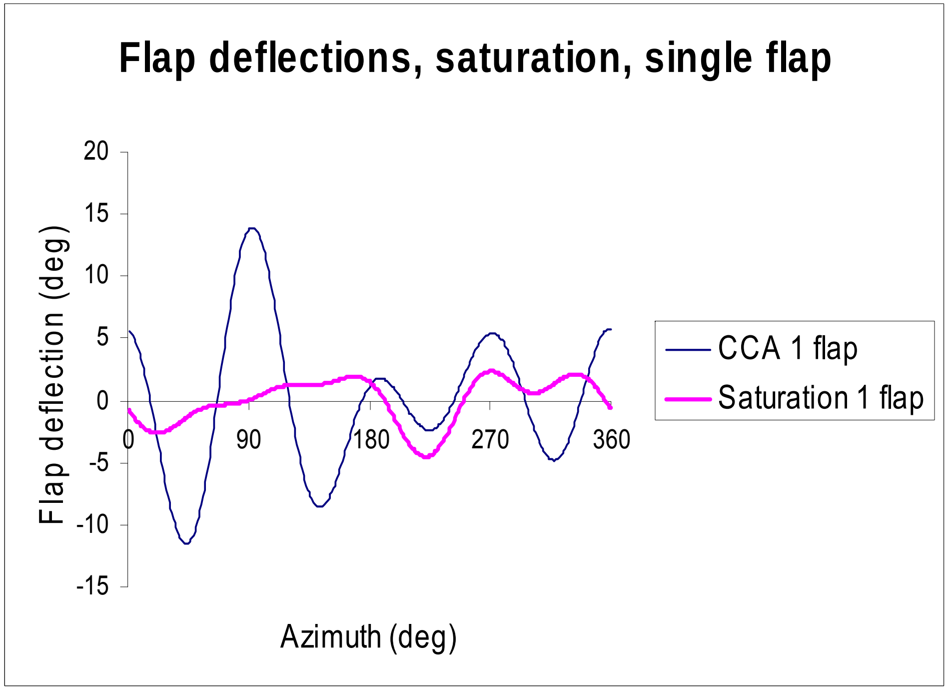


# Saturation Limits

- μ=0.35
- The ACF is a very effective vibration alleviation device even when flap deflection limits are imposed



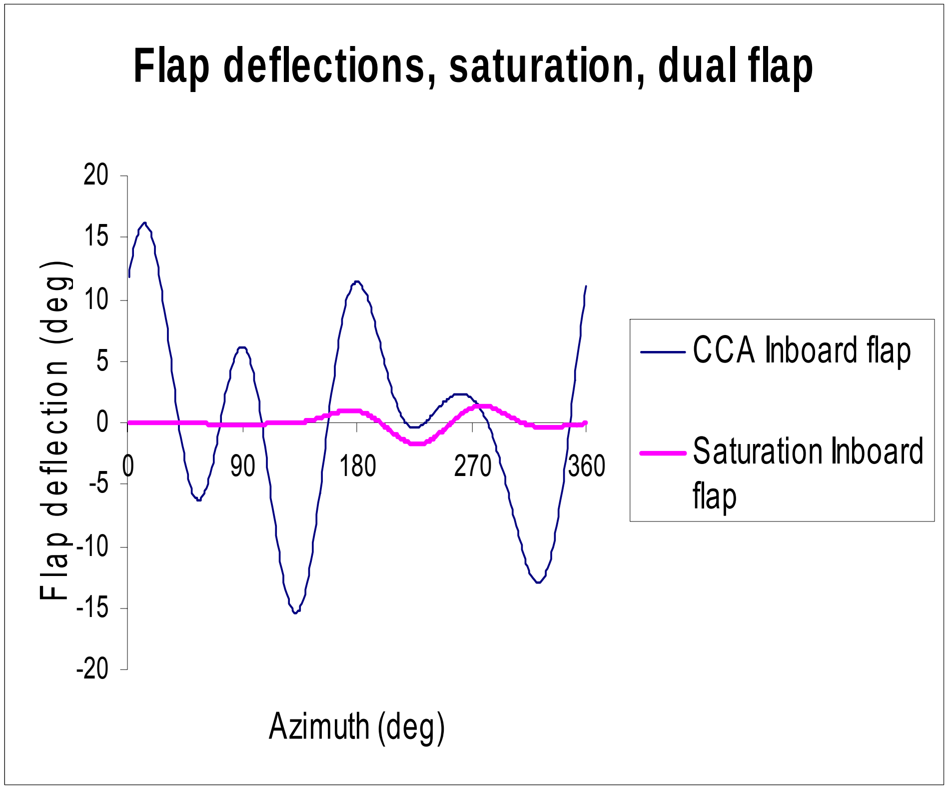
Vibration Reduction, Saturation Limits

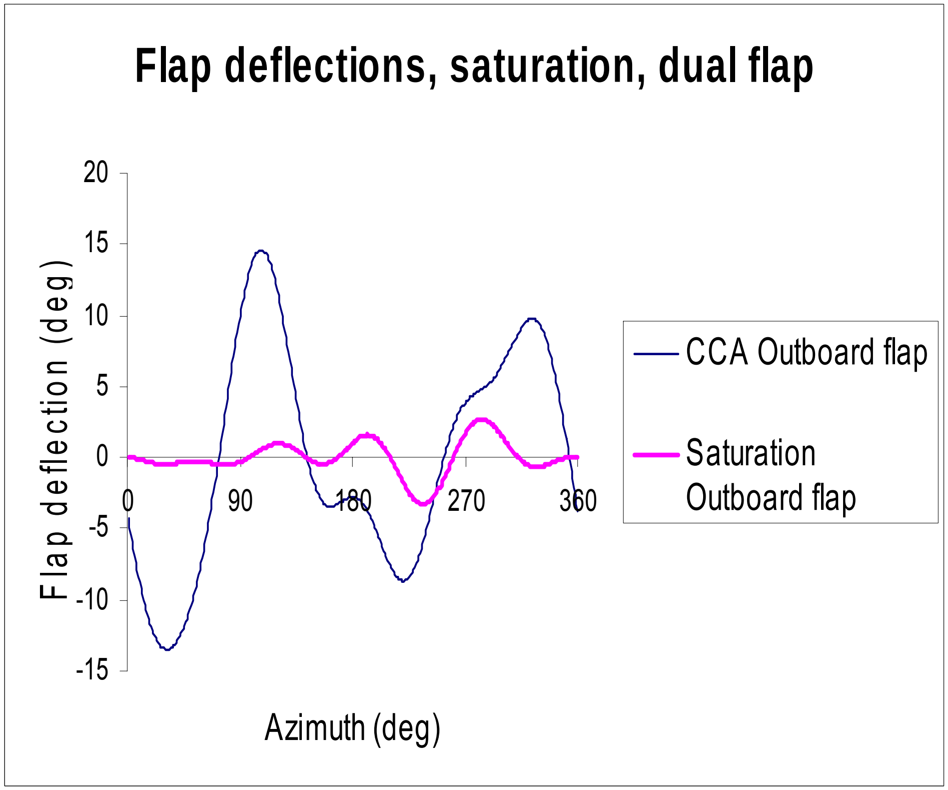


Flap deflections, saturation, single flap

# Saturation Limits (cont.)

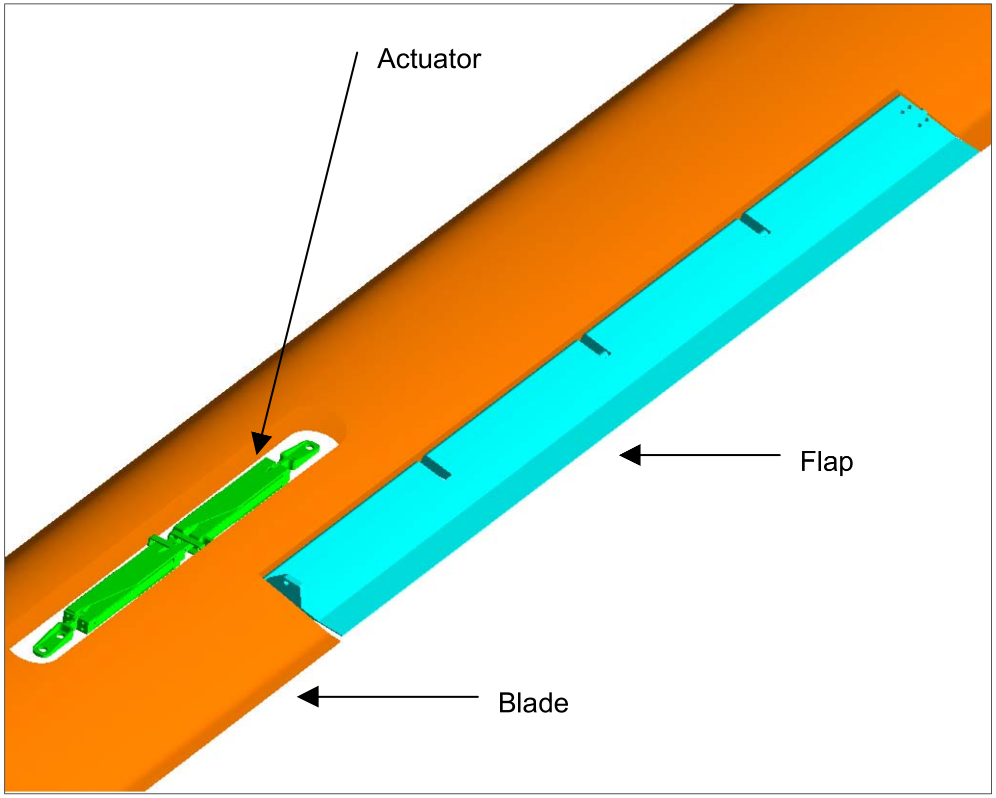
- μ=0.35


Flap deflections, saturation, dual flap


Flap deflections, saturation, dual flap

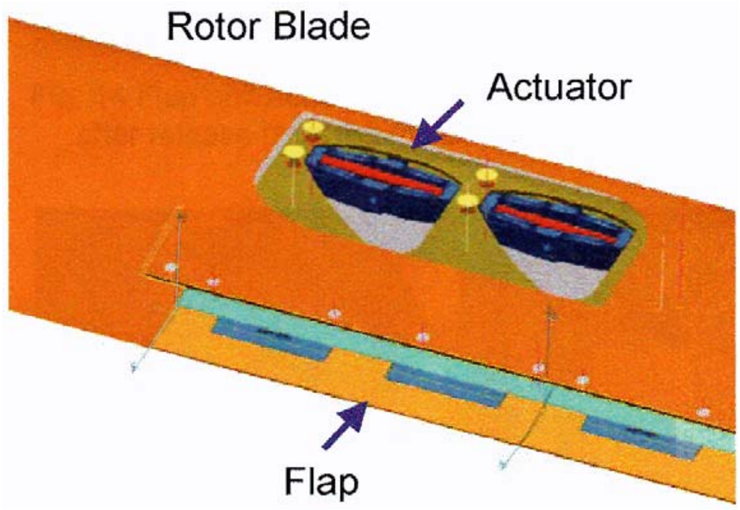
# Test of Piezoelectrically Actuated ACF

- **The ACF was tested on a MD-900 Explorer Rotor, on a whirl tower, by Boeing, Mesa, AZ, in 2003, under the Smart Material Actuated Rotor Technology (SMART) Program funded by DOD/ARPA ( more than $10M).**



# European Tests

- Full scale rotor based on hingeless BK 117/EC145 is under development by a European consortium with several partners.
- Whirl tower tests to confirm the basic design have been carried out
- Flap system consists of three identical flaps adjacent to each other, they span 16% of blade radius, flap chord is 15%, centered at 0.718; 0.773; 0.827.
- Piezoelectric stack actuation (10 degrees deflection).
- Flight tests scheduled for 2005.



# The *Simultaneous* Noise & Vibration Problem

- Experimental data shows that it is difficult to

**Reduce Noise**

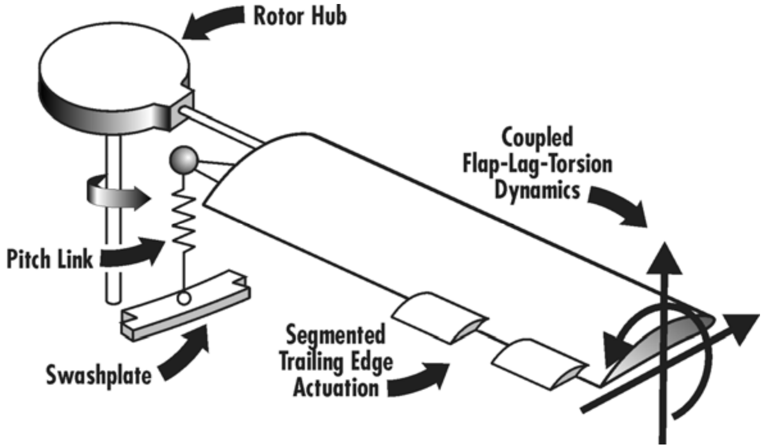
and

**Reduce Vibration**

at the same time on a helicopter using active control:

**- HART (**Higher-Harmonic Aeroacoustic Rotor Test, Splettstoesser, et al. 1996**):** Applies a 3/rev input: **6dB Noise reduction**, but 100% **Increase in vibratory loads**

**- NASA Ames BO-105 (**Jacklin, et al. 1995**):** Applies 5/rev IBC **4dB Noise Reduction** (advancing side) **Vibratory loads increase** by 150%



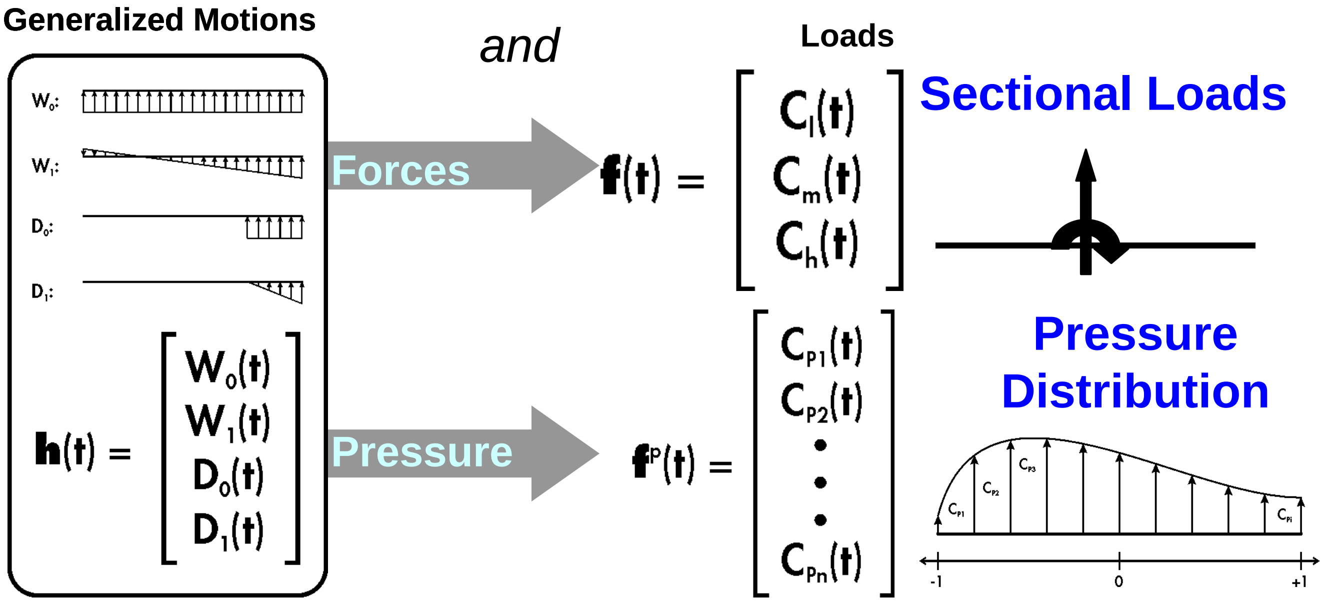
- Explore the reasons for this, and develop a framework for performing simultaneous noise and vibration reduction using Actively Controlled Trailing Edge Flaps (ACF)

# A *High-Resolution* Aerodynamic Model

**Blade Pressure Distribution is Required for Acoustic Computation**

- Extended the RFA (Rational Function Approximation) approach (Myrtle and Friedmann, 1997).
  - Unsteady time-domain aerodynamics accounting for compressibility and presence of flap
- Computed pressures are only used in noise computation, not in aeroelastic analysis

RFA constructs relations between:



**Generalized Motions**

$$\mathbf{h}(t) = \begin{bmatrix} W_0(t)\\ W_1(t)\\ D_0(t)\\ D_1(t)\end{bmatrix}$$

Forces

Pressure

*and*

**Loads**

$$\mathbf{f}(t) = \begin{bmatrix} C_l(t)\\ C_m(t)\\ C_h(t)\end{bmatrix}$$

**Sectional Loads**

$$\mathbf{f}^P(t) = \begin{bmatrix} C_{P1}(t)\\ C_{P2}(t)\\ \bullet\\ \bullet\\ \bullet\\ C_{Pn}(t)\end{bmatrix}$$

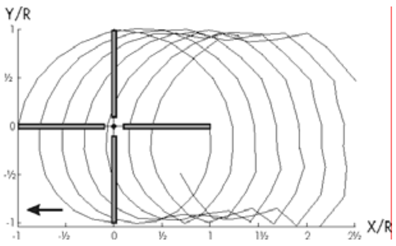
**Pressure Distribution**

Improved **wake** Model:

Free wake model based on Scully ('76), Johnson – CAMRAD/JA ('88)

-Improved Resolution (Steps as fine as 2° azimuthally)

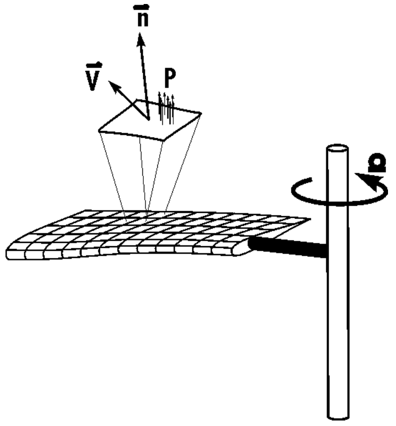
-Improved Multiple-Trailer Vortex and Rollup models



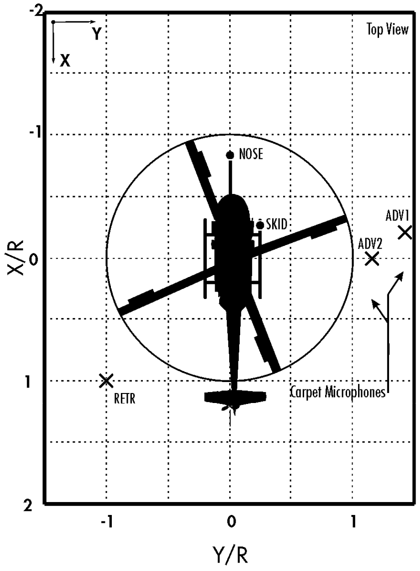
# An *Efficient* Acoustics Computation Procedure

- Modified version of WOPWOP aeroacoustic code (Brentner, ’86).
  - Ffowcs-Williams Hawkings Equation without the quadrupole term.

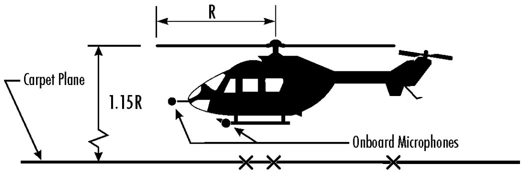
$$4\pi a_0^2 \rho(x,t) = \underline{\frac{\partial^2}{\partial x_i \partial x_j}\iiint\left[\frac{T_{ij}}{r|1-M_r|}\right]dV} - \frac{\partial}{\partial x_i}\iint\left[\frac{P_{ij}n_j}{r|1-M_r|}\right]dS + \frac{\partial}{\partial t}\iint\left[\frac{\rho_o v_n}{r|1-M_r|}\right]dS$$



- Aimed at predicting BVI noise
  - 6th-40th Harmonics of blade passage frequency
- Input to WOPWOP:
  - Blade discretized into panels (identical to pressure computation)
  - Includes ***fully flexible blade model with trailing edge flaps***
  - ***Coupled flap-lag-torsional dynamics***
  - Unsteady pressure distribution calculated with RFA and wake model

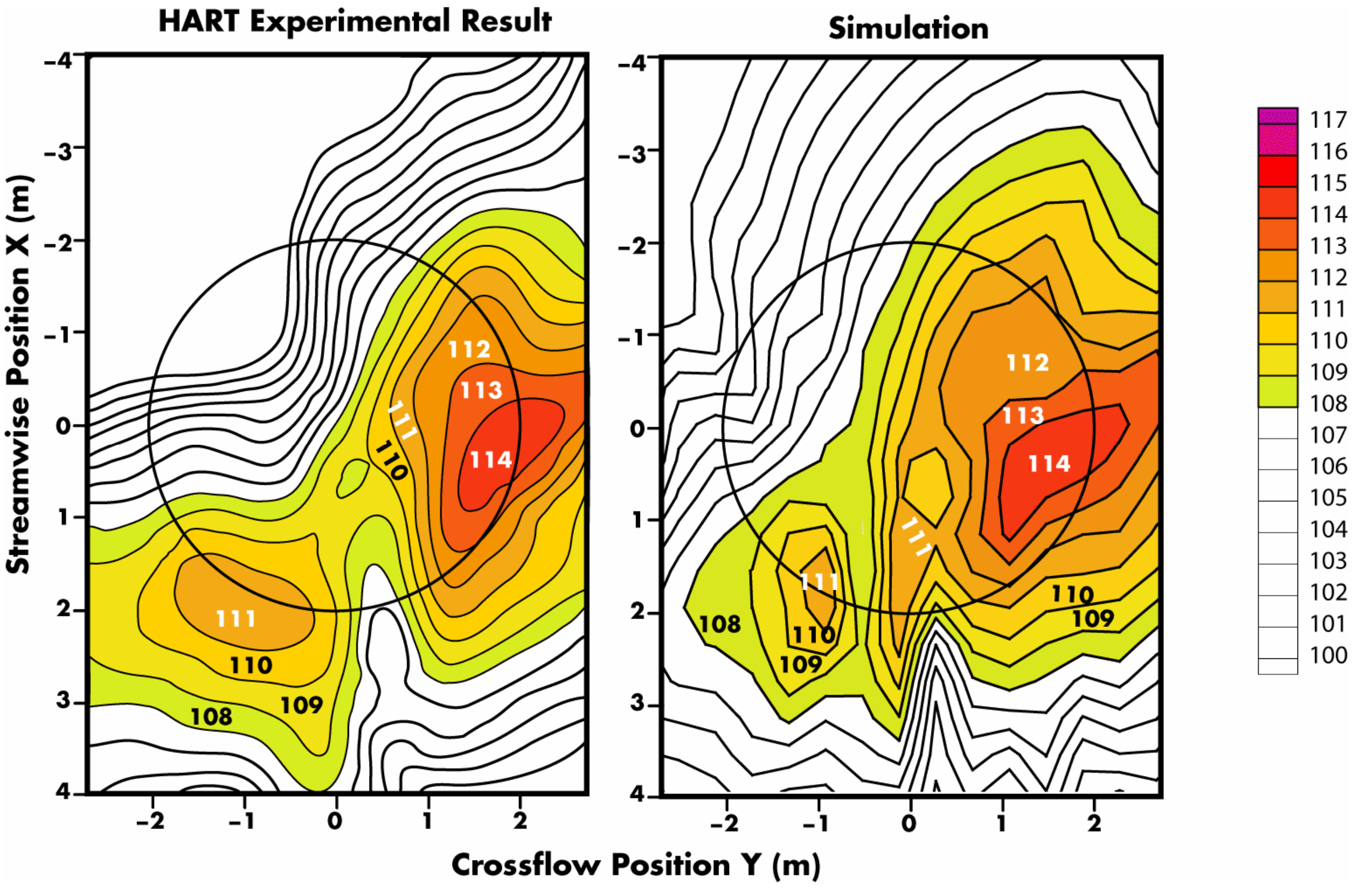


- During Simulation, Noise is tracked onboard helicopter and on carpet plane beneath rotor
- **Noise Levels can be fed back into controller**



# Simulation Validation

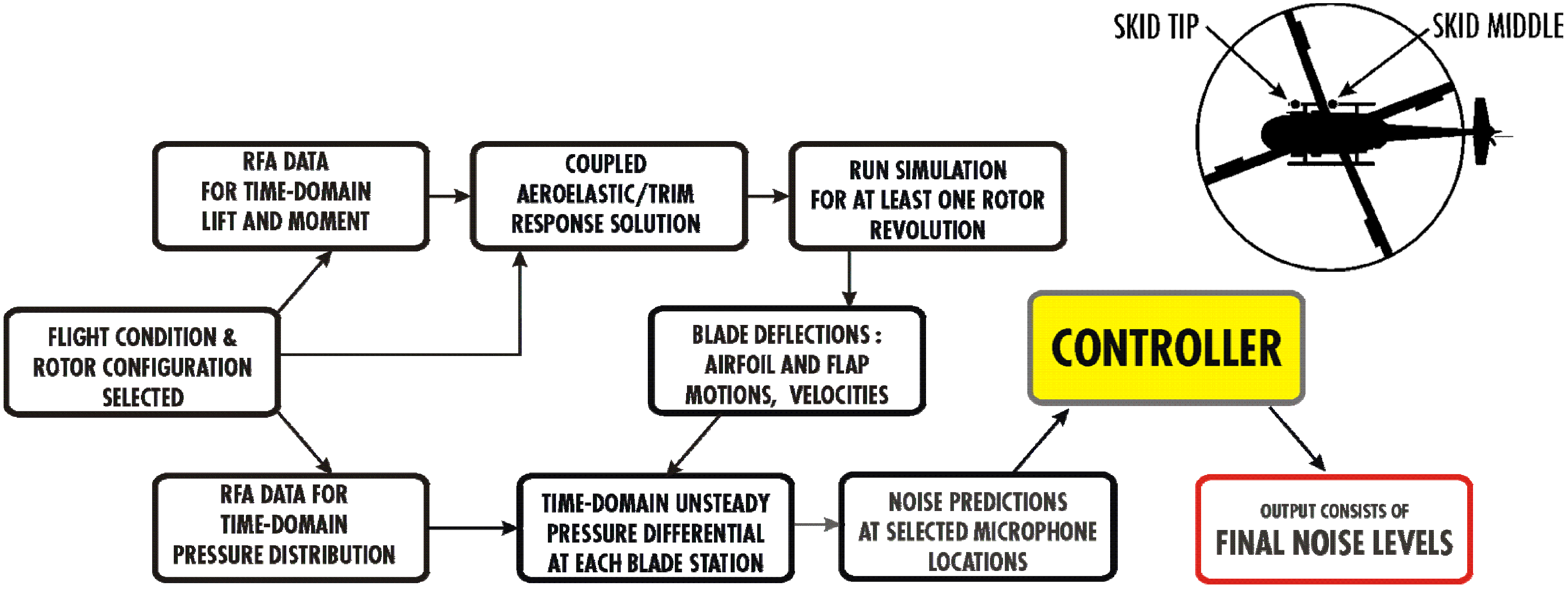
- Comparison with the HART test (1995)
  - wind tunnel tests of a 40% Geom. & Elast. scaled BO-105 rotor



- $C_W = 0.0044$
- 2m blade radius
- m = 0.15
- -8° linear pretwist
- 6° descent
- s = 0.077

# Simultaneous Noise and Vibration Reduction

- Active noise reduction is achieved by placing a feedback microphone: on the right landing skid, at the tip
- Active control is implemented using a modified version of the Adaptive HHC controller used for vibration reduction:
  - Objective: reduce the 6th-17th harmonics of the overall noise spectrum together the vibrations in combined objective function



FLIGHT CONDITION & ROTOR CONFIGURATION SELECTED

RFA DATA FOR TIME-DOMAIN LIFT AND MOMENT

COUPLED AEROELASTIC/TRIM RESPONSE SOLUTION

RUN SIMULATION FOR AT LEAST ONE ROTOR REVOLUTION

BLADE DEFLECTIONS : AIRFOIL AND FLAP MOTIONS, VELOCITIES

RFA DATA FOR TIME-DOMAIN PRESSURE DISTRIBUTION

TIME-DOMAIN UNSTEADY PRESSURE DIFFERENTIAL AT EACH BLADE STATION

NOISE PREDICTIONS AT SELECTED MICROPHONE LOCATIONS

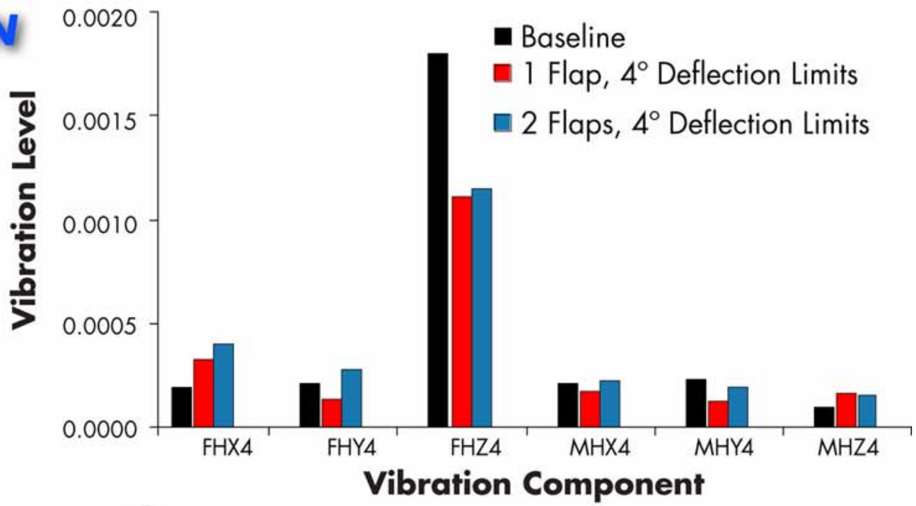
**CONTROLLER**

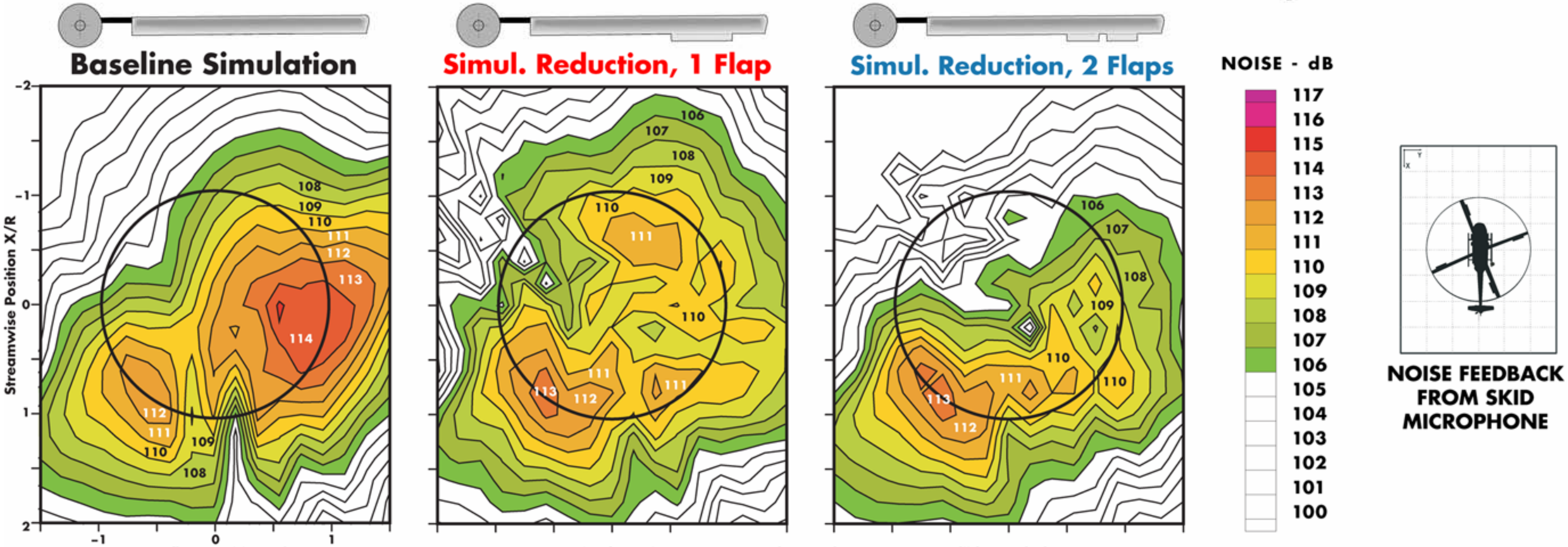
OUTPUT CONSISTS OF FINAL NOISE LEVELS

# Simultaneous Reduction

## SIMULTANEOUS NOISE & VIBRATION REDUCTION RESULTS

- Possible to achieve 4-6dB of Noise Reduction and 40% Vibration Reduction simultaneously.
- Results are for low-speed descent flight in heavy blade-vortex interaction. Rotor is similar to that of the MBB BO-105.
- The rotor is moderately loaded and has an advance ratio of 0.15.





Note: Noise footprints are measured on a plane 1.5 rotor radii beneeth the rotor

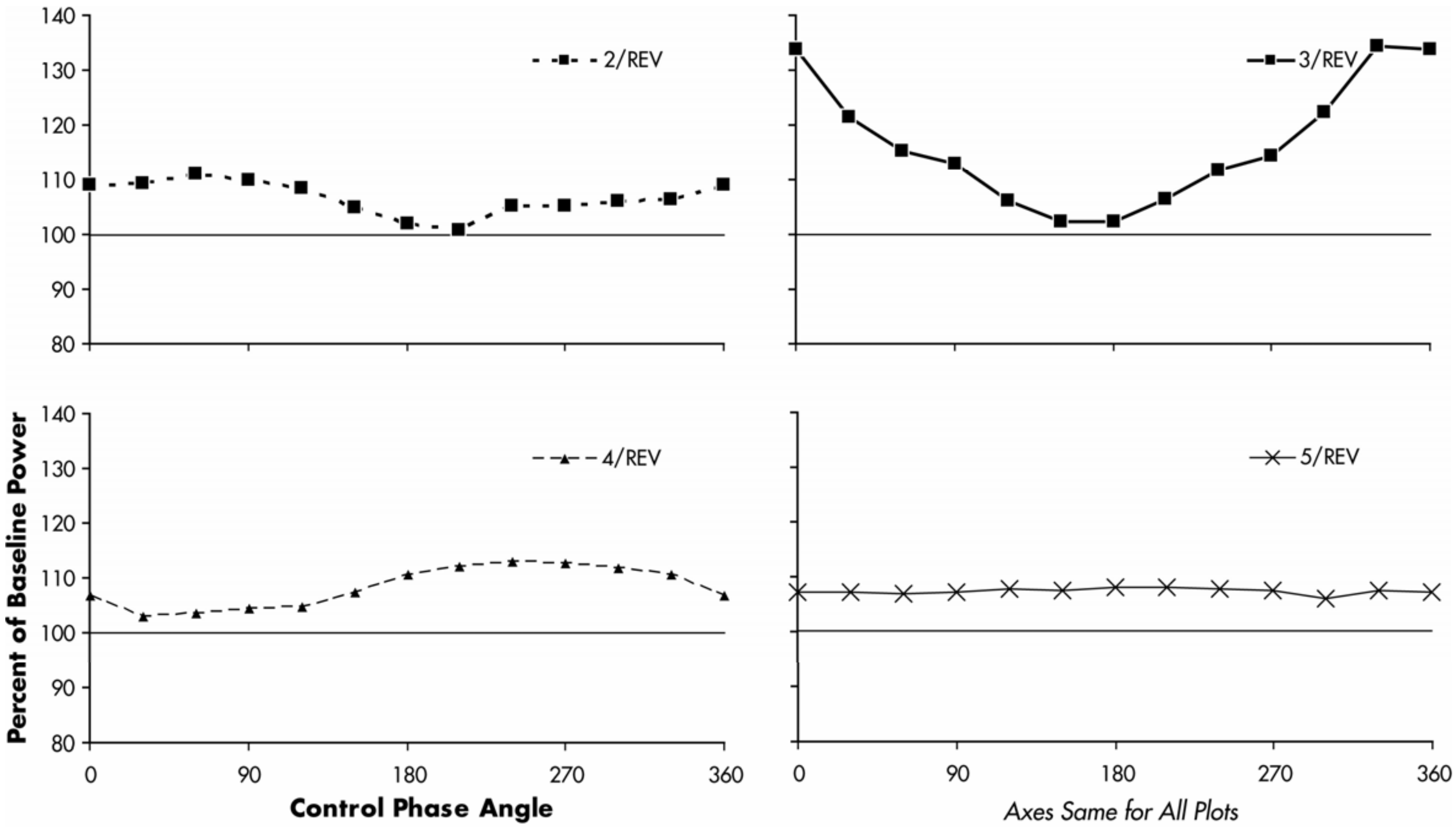
# Power Reduction in Open Loop Mode

- Power computed from $$C_P = \frac{\Omega}{2\pi}\int_0^{2\pi} -C_{M_{Hz1}}(\psi)d\psi$$
- Open loop control input is $$\delta(\psi) = \delta_n \cos(n\psi - \varphi)$$

MBB BO-105
Torsion 3.17/rev

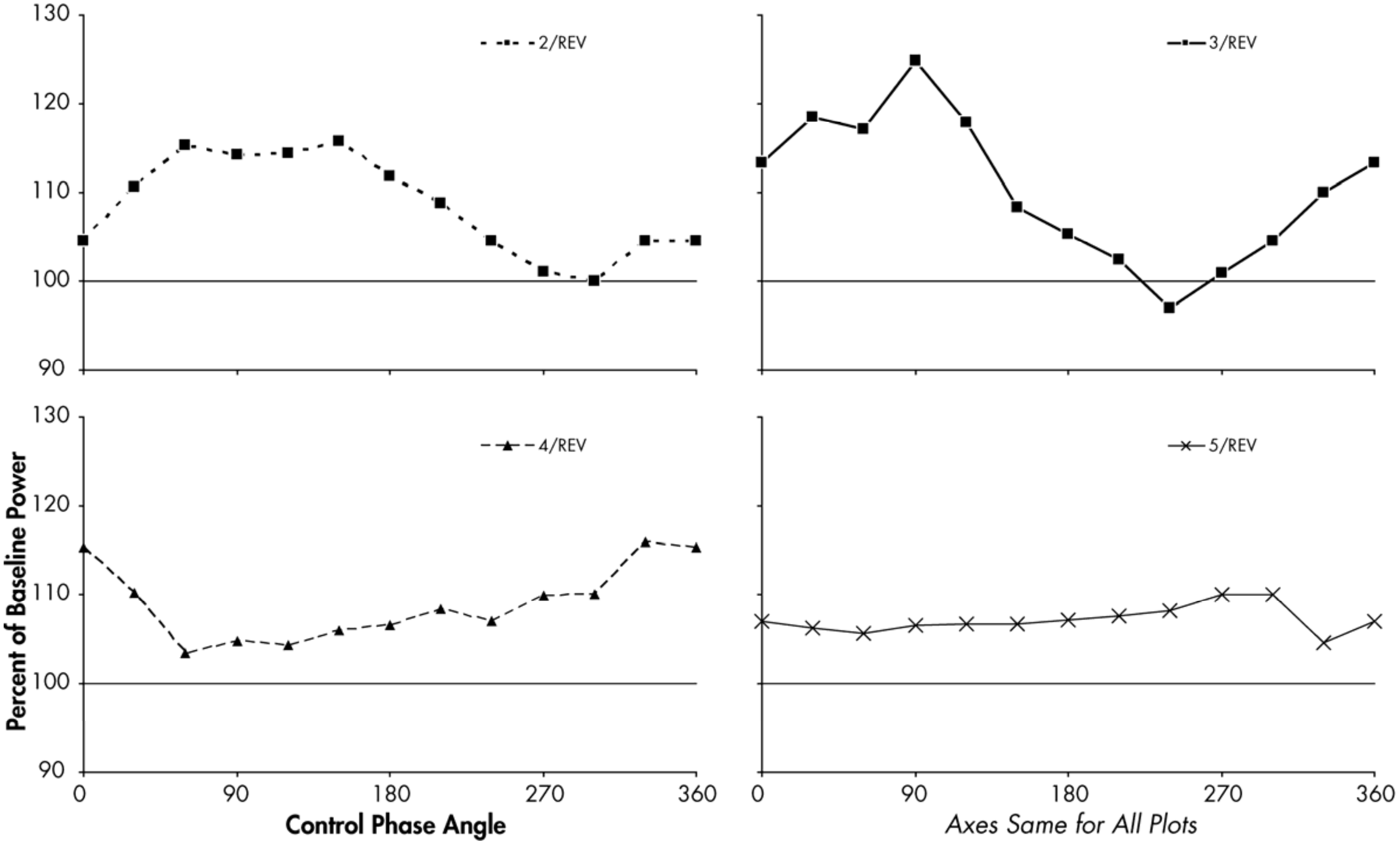
$\mu = 0.15\ descent$

$\delta_n = 4^0$



# Power Reduction in Open Loop Mode (cont)

- Soft rotor, torsional frequency 2.5/rev, advance ratio=0.15, small power reduction at 2/rev; more substantial at 3/rev



# CONCLUDING REMARKS

- The computational research conducted at UCLA/Umich has contributed substantially towards establishing the ACF from a preliminary concept to an effective device for vibration reduction in helicopter rotors. This has been also augmented substantially by experimental research done at MIT and U. of Maryland.
- Have demonstrated its feasibility and low power requirements.
- Have developed a new compressible unsteady aerodynamic theory capable of modeling blade/flap combinations operating at relatively high frequencies in oscillatory oncoming flow.
- Have established the force, moment, flap angle and power requirements for reducing **(by over 90%)** 4/rev vibrations (hub shears and moments) due to forward flight.
- Have developed a composite swept tip aeroelastic blade model with an actively controlled flaps capable of simulating BVI and its control.

# CONCLUDING REMARKS (cont.)

- Have demonstrated BVI vibration alleviation **(in excess of 80%)** with an actively controlled flap. **The different physical mechanisms of vibration reduction in high speed flight, and BVI alleviation have been identified, for the first time.**
- Simulation model provides **good** correlation with experimental data obtained in wind tunnel tests (by Fulton and Ormiston).
- Have demonstrated vibration alleviation in presence of **dynamic stall** and developed algorithm for saturation control.
- Have developed a remarkable capability to simulate BVI induced noise generation that produces very good correlation with the experimental results obtained in the HART test.
- Have demonstrated simultaneous vibration and noise reduction: 3-5 db noise and 40% vibration .

# CONCLUDING REMARKS (cont.)

- ACF has been tested with piezoelectric actuation (X-frame actuator-Prechtl & Hall) on a **full scale MD-900 rotor** on a whirl tower in 2003. Flight test of a BK117 equipped with three flaps is imminent in Germany.
- The ACF appears to be the most viable active control concept for helicopter rotors, and it has significant potential not only for vibration reduction, but also for noise reduction and possibly performance enhancement. Therefore it clearly has remarkable potential for improving rotorcraft technology.