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Simultaneous Vibration and Noise Reduction in Rotorcraft -Practical Implementation Issues

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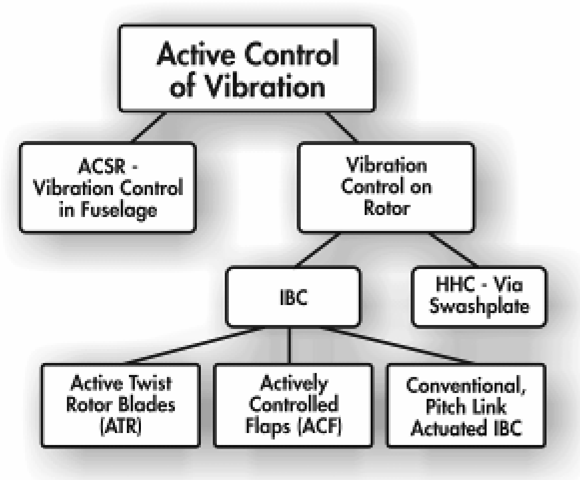
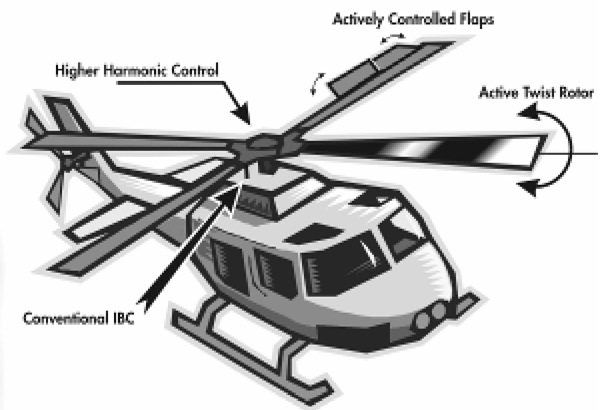
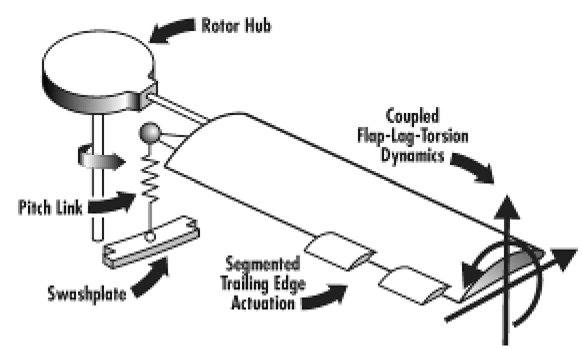
Introduction: Active Control

- Active control of vibration

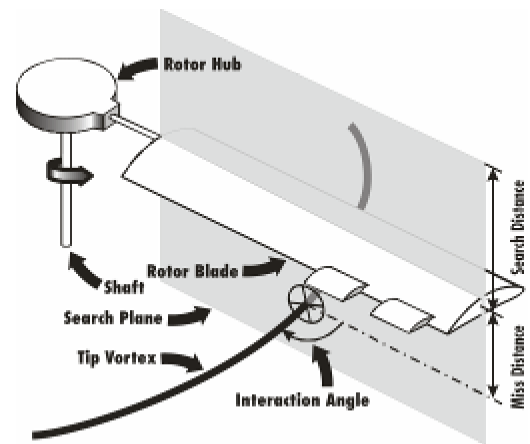






- Actively controlled trailing edge flaps (**ACF**)
  - No adverse effect on helicopter airworthiness
  - Lower power consumption than HHC or IBC

- Blade-vortex interaction (**BVI**)



Introduction: History of the ACF

- Millott and Friedmann (1994)
  - elastic blade model and quasisteady Theodorsen aerodynamics
- Milgram and Chopra (1995)
  - compressible unsteady aerodynamic model (Leishman)
- Myrtle and Friedmann (1997)
  - new compressible unsteady aerodynamics (RFA Aerodynamics)
- de Terlizzi and Friedmann (1999)
  - BVI vibration reduction
- Depailler and Friedmann (2001)
  - reduce vibrations due to dynamic stall
- Experimental studies (open loop and closed-loop)
  - Straub (1995), Fulton and Ormiston(1998), Koratkar and Chopra (2002)
- Boeing Smart Material Actuated Rotor Technology (SMART)
  - MD-900 rotor with piezoelectrically actuated flap
  - Whirl tower tests performed (Oct. 2003)
- BK117/EC145 with three identical adjacent piezoelectrically actuated flaps is scheduled to fly in 2005

Introduction: Noise Control

- **HHC** and **IBC** algorithms developed for vibration reduction have been adapted for noise reduction

- **HHC** For BVI Noise Reduction:
  - HART (1995)
    wind tunnel test, scaled BO-105, open loop, 5-6dB reduction

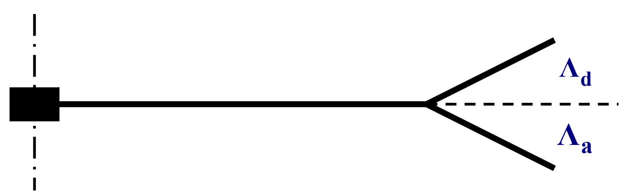
- **IBC** For BVI Noise Reduction:
  - Wind Tunnel
    - BO-105, NASA Ames 40x80’ (Jacklin,1995), open loop, 5-12dB reduction
    - UH-60, NASA Ames 40x80’ (Jacklin,2002), open loop, 5-12dB reduction
  - Flight Test
    - BO-105 (Bebesel, et al. - 2001,2002), open and closed loop, 4-6dB reduction

Introduction: Simultaneous Control

- Brooks et al. (1990) observed increased vibration when using open-loop HHC for noise reduction in the NASA Langley TDT.
- HART with 3/rev HHC
  - 6dB noise reduction, 100% increase in vibratory loads
  - 30% vibration reduction, 3dB noise increase
- NASA Ames BO-105 test with 5/rev IBC
  - Advancing side BVI noise reduced by 4dB
  - Vibratory loads increase by 150%
- Flight Tests of BO-105 with 2/rev IBC
  - 6dB Noise reduction
  - 150% increase in vibratory loads
- Limited cases of simultaneous reduction

Objectives of the Present Study

- Explore the potential of BVI noise reduction as well as simultaneous vibration and noise reduction using the **ACF** approach.
- Determine and compare the effectiveness of the ACF in the closed loop mode for noise and vibration reduction on two different rotor configurations, namely, a four-bladed **MBB BO-105 hingeless** rotor and a five-bladed **MD-900 bearingless** rotor.
- Evaluate the effectiveness of passive methods on the vibration and noise reduction using **advanced geometry tips** with anhedral and dihedral, and compare them with the active approach.



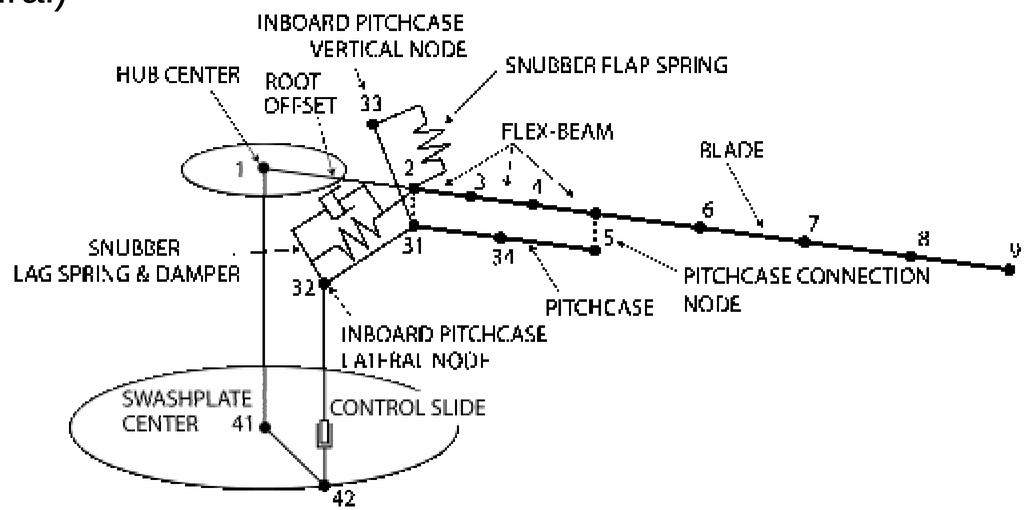
- Examine a number of **practical implementation issues** associated with the ACF system, such as the effects of practical saturation limits, constant and 1/rev pitch inputs, and flap overhang.

Model: Structural Dynamics

- **Isotropic Blade Model** *(Millott & Friedmann, 1995)*
  - Coupled flap-lag-torsion dynamics, with moderate deflections
  - Blade discretization using the Global Galerkin method
  - Free vibration rotating modes (3 flap, 2 lead-lag, 2 torsion)
  - MBB BO-105 hingeless rotor

- **Composite Blade Model** *(Yuan & Friedmann, 1995)*
  - Transverse shear deformation, cross-sectional warping, elastic coupling
  - Finite element discretization
  - Modal reduction based on 8 coupled rotating modes
  - Swept tips (tip sweep and dihedral)
  - MD-900 bearingless rotor

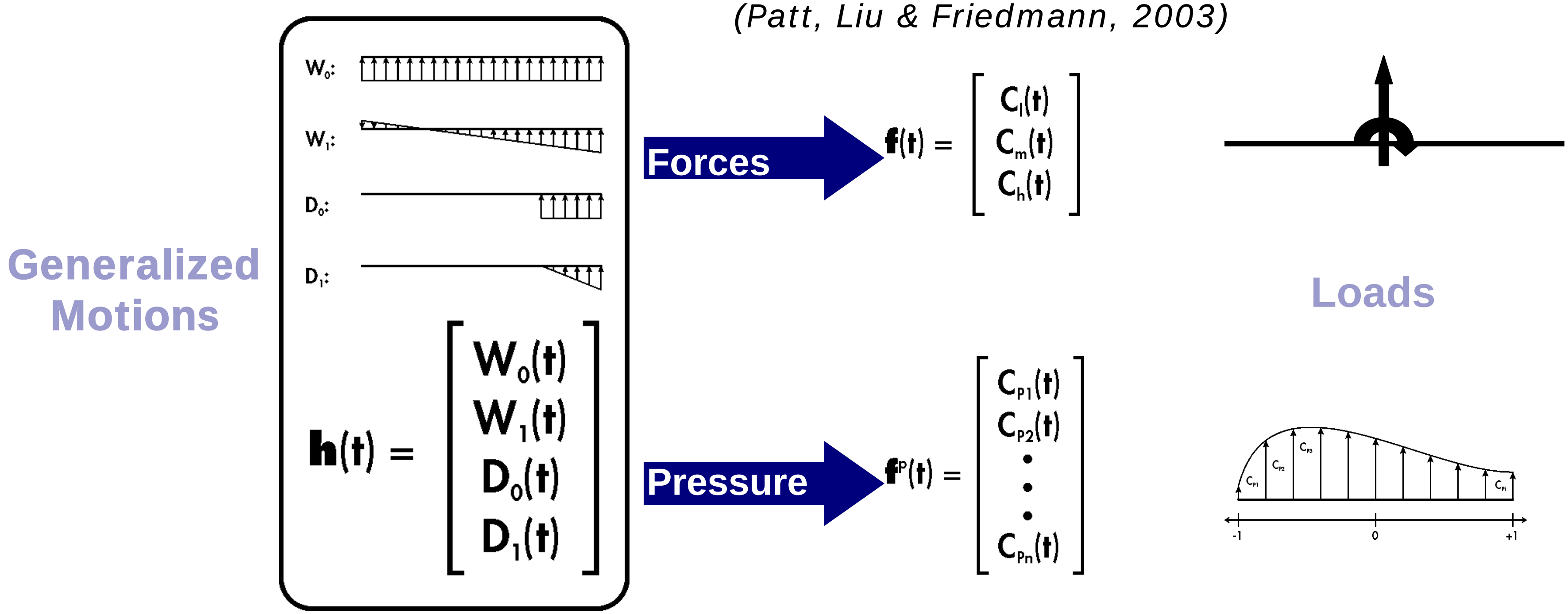
- **Active Flap** incorporated through modification of inertia and aerodynamic loads (assuming structural properties remain unchanged)



Model: RFA Aerodynamics

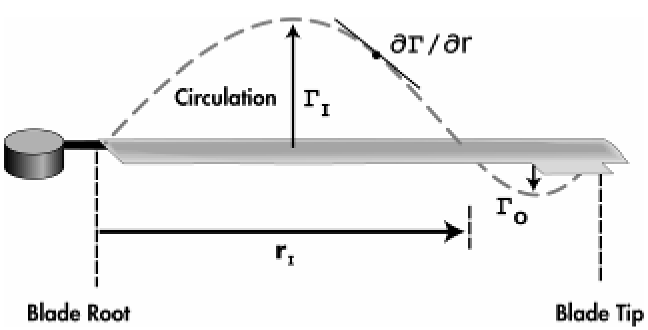
- Blade sectional loads calculated using **rational function approximation (RFA)** *(Myrtle & Friedmann, 1997)*
  - accounts for compressibility, unsteady effects, and time varying freestream effects
  - accounts for the presence of the flap
- Extended for the computation of **chordwise pressure distribution**

(Patt, Liu & Friedmann, 2003)

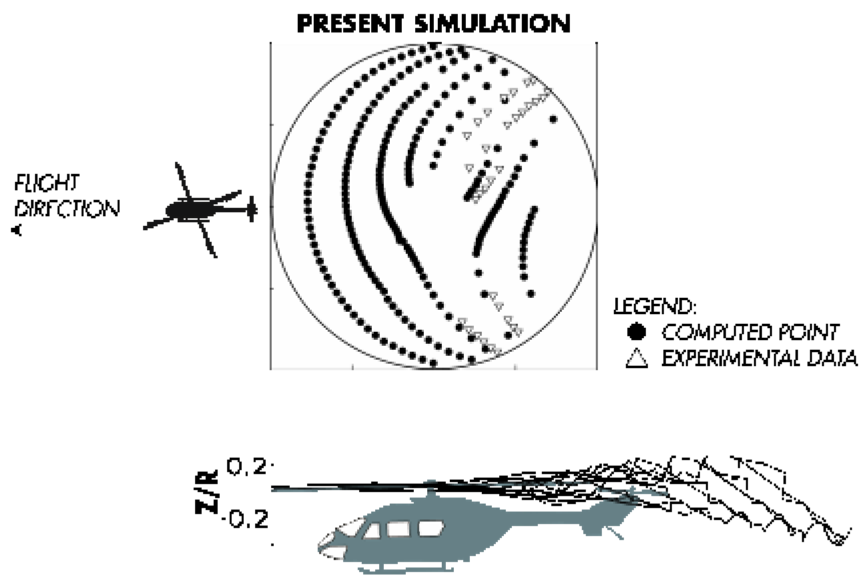


Model: Free Wake

- Wake analysis extracted from CAMRAD/JA *(de Terlizzi & Friedmann,1998)*
- Free wake geometry includes distortion of the wake due to wake self-induced velocity *(Scully, 1975)*
- Fundamental wake resolution restrictions removed
  - 5º azimuthal resolution
- Dual vortex line model with negative blade tip loading
  - experimental evidence (HART)
  - interaction with tip vortices is accounted for

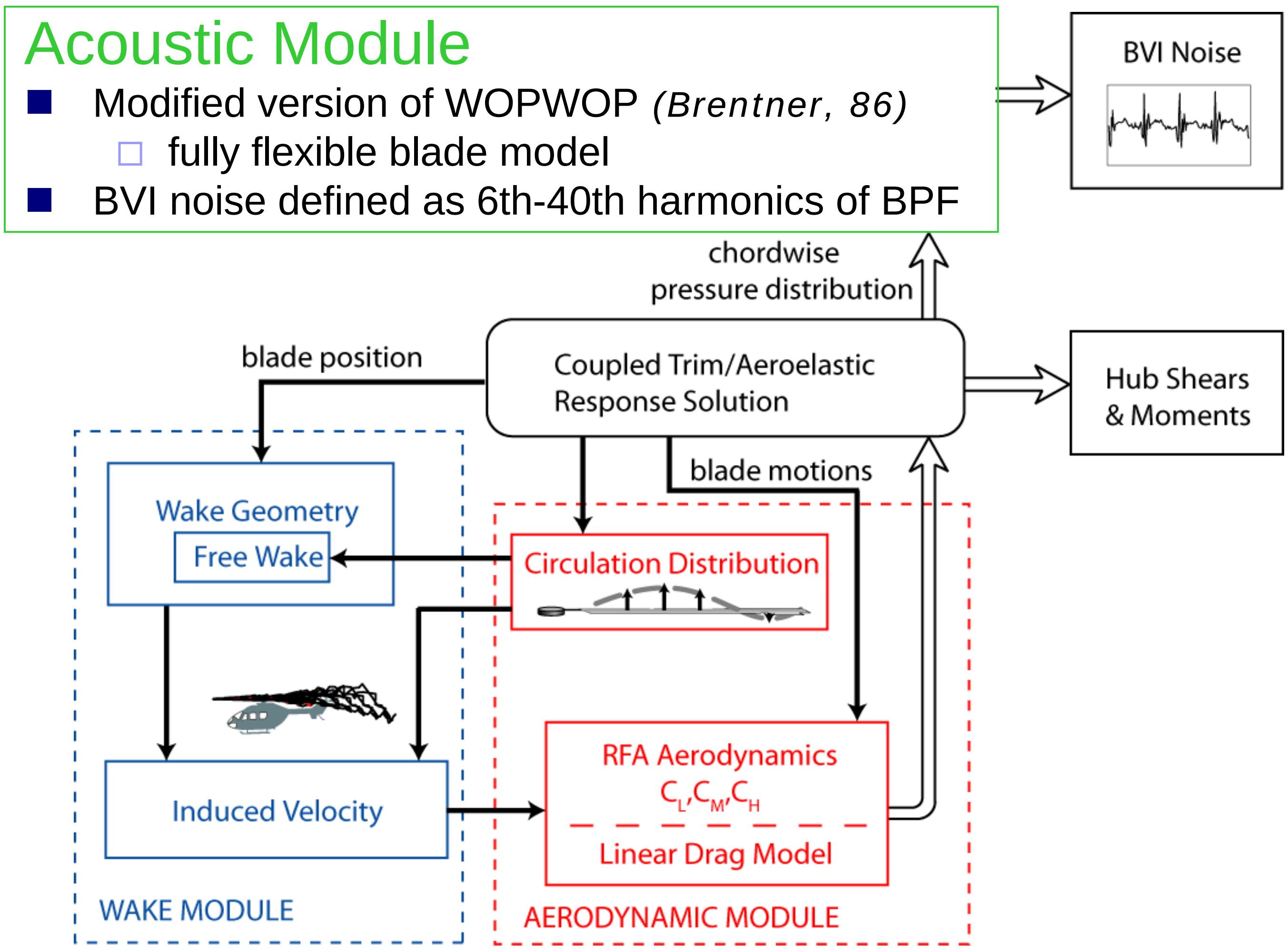


Dual Wake Structure



Free Wake

Model: Solution Procedure



Active Control: Algorithm

Conventional HHC

- Simple, one-step convergence

Relaxed HHC

(Patt, Liu & Friedmann, AIAA 2004-1948)

- Control update is scaled by a relaxation factor
- Improved robustness, slower convergence

Adaptive HHC

- Online identification updates

Saturation Limits on Flap Deflection:

$$-4^\circ \leq \delta \leq 4^\circ \qquad R = c_{wu} I$$

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

(Cribbs & Friedmann, 2001)

Cost Function: $J = \mathbf{z}_k^{\mathrm{T}} \mathbf{Q} \mathbf{z}_k + \mathbf{u}_k^{\mathrm{T}} \mathbf{R} \mathbf{u}_k$

Vibration Reduction:

$$\mathbf{z}_{VR} = \{F_{HX}, F_{HY}, F_{HZ}, M_{HX}, M_{HY}, M_{HZ}\}^T$$

Noise Reduction:

$$\mathbf{z}_{NR} = \{N_{H06}, N_{H07}, \ldots, N_{H17}\}^T$$

Simultaneous Reduction:

$$\mathbf{z}_{SR} = \{\mathbf{z}_{VR}, \mathbf{z}_{NR}\}^T$$

Harmonic Flap Deflection:

- Four-bladed BO-105

  2/rev, 3/rev, 4/rev, 5/rev

- Five-bladed MD-900

  2/rev, 3/rev, 4/rev, 5/rev, 6/rev

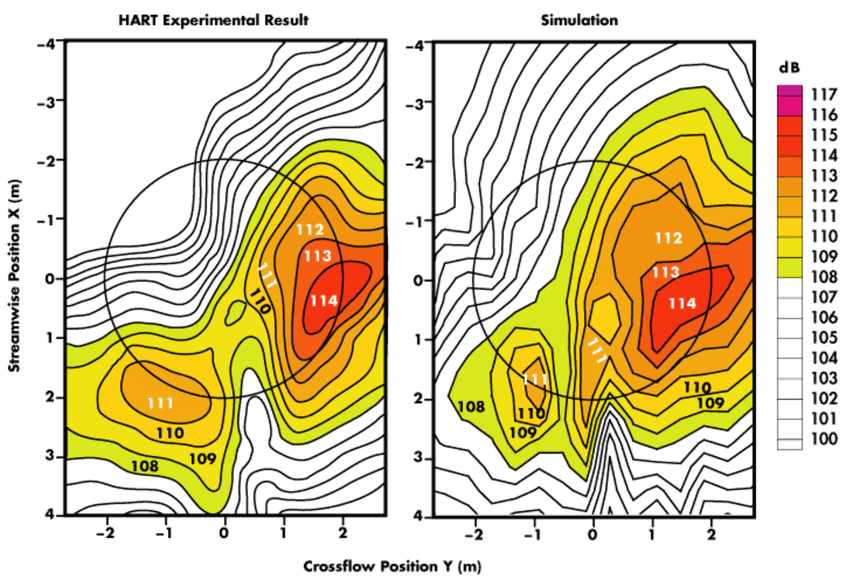
$$\delta(\psi) = \sum_{N=2}^{N_{max}} [\delta_{Nc} \cos(N\psi) + \delta_{Ns} \sin(N\psi)]$$

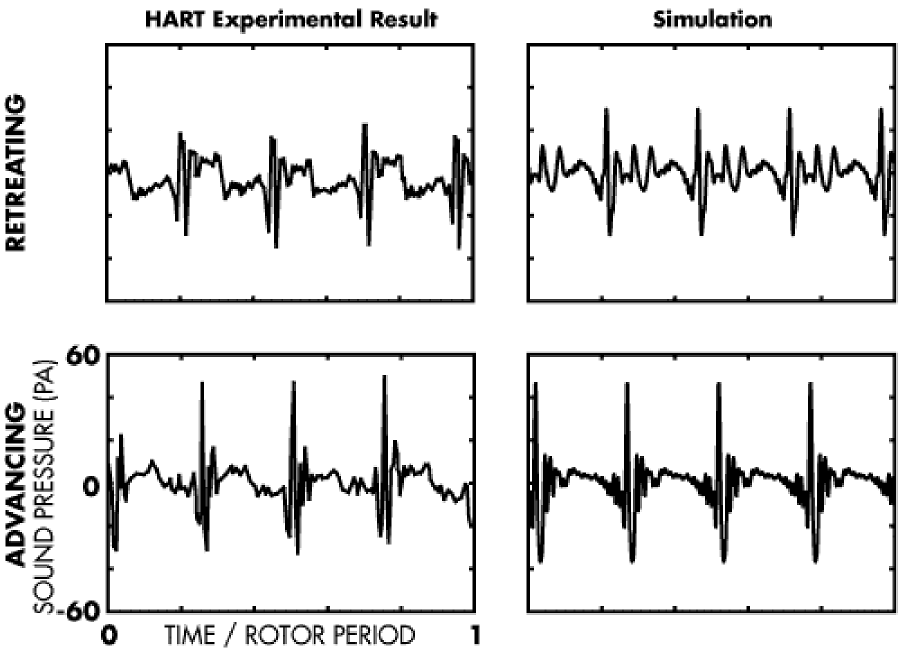
$$\mathbf{u} = \{\delta_{Nc}, \delta_{Ns}\}^T, \text{ N=2-N}_{max}$$

Model Validation: HART

HART (1995)

- Wind tunnel tests of a 40% dynamically and Mach-scaled BO-105 rotor
- BVI Noise carpet plots
  - Noise contour plots at 1.15R below hub
- Acoustic pressure time history

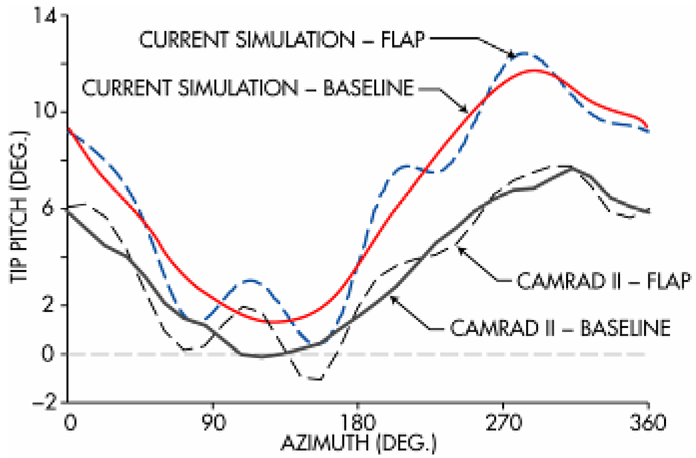




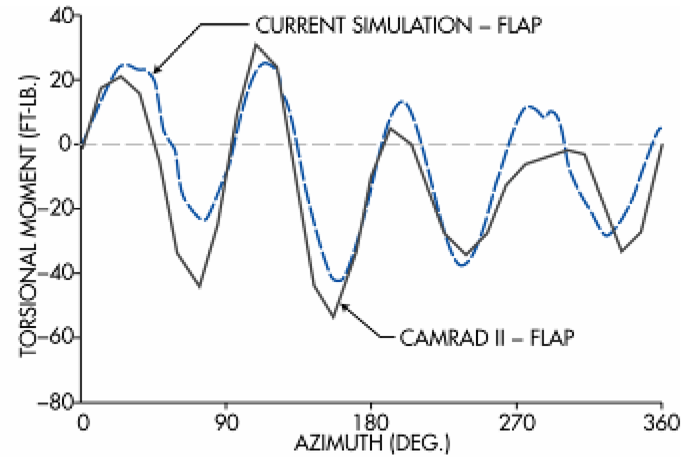
(Liu, Patt & Friedmann, 2004)

Model Validation: MD-900

- Comparison with CAMRAD II *(Straub & Charles, 2001)*
  - Prescribed flap deflection $\delta_f = 2° \cos(4\psi - 240°)$



Tip pitch deflection



Torsional moment @ 0.4R

- Comparison of blade natural frequencies (/rev) with **RCAS** *(**R**otorcraft **C**omprehensive **A**nalysis **S**ystem)*

	ω_{L1}	ω_{F1}	ω_{F2}	ω_{L2}	ω_{F3}	ω_{T1}	ω_{F4}	ω_{A1}
Current Simulation	**0.654**	**1.043**	**2.573**	**3.488**	**4.472**	**5.667**	**7.270**	**25.70**
RCAS	**0.654**	**1.048**	**2.572**	**3.498**	**4.473**	**5.409**	**7.273**	**25.82**

Results: Overview

- MBB BO-105
  - Vibration Reduction
  - Noise Reduction
  - Simultaneous Reduction
  - Effects of Constant and 1/rev Pitch Inputs

- MD-900
  - Effects of Flap Overhang
  - Vibration Reduction
  - Noise Reduction
  - Simultaneous Reduction
  - Effects of Swept Tips

† All results obtained with 4º saturation limits imposed

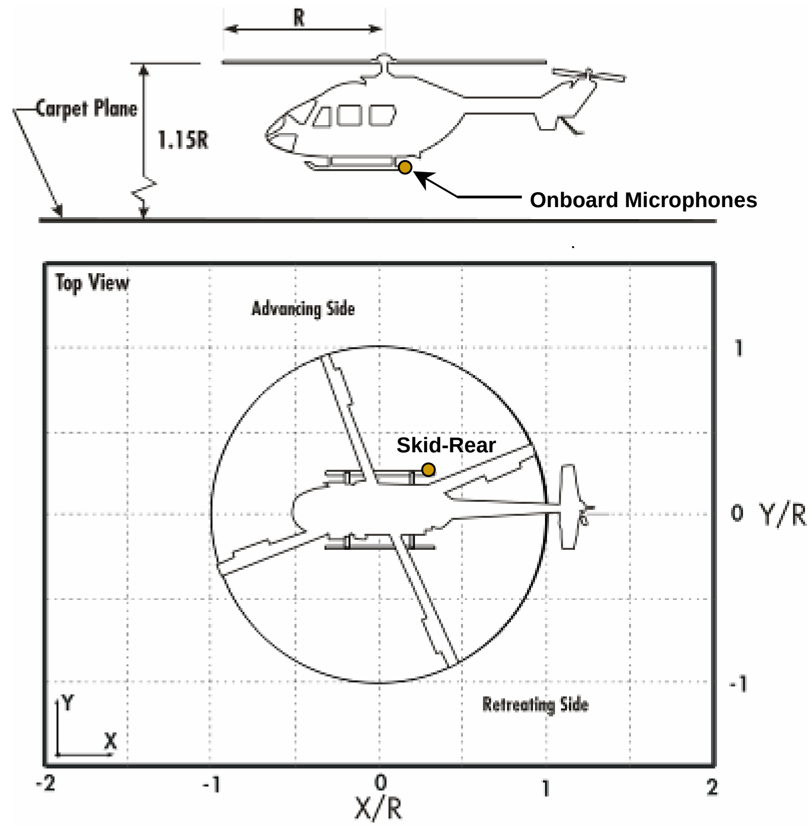
Results: MBB BO-105

- Four-bladed hingeless rotor

N_b	R(m)	μ	Ω(RPM)	C_T	c/R	θ_{FP}
4	4.91	0.15	425	0.005	0.05098	6º

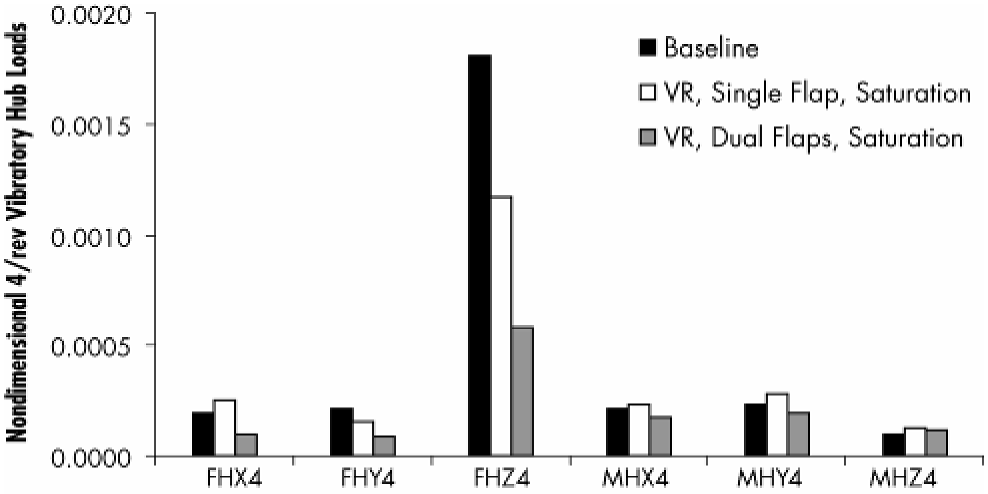
- Propulsive trim
  - 6º descending angle
- Single and dual servo flaps

- Active control with 4º saturation
  - Vibration reduction
  - Noise reduction
  - Simultaneous reduction

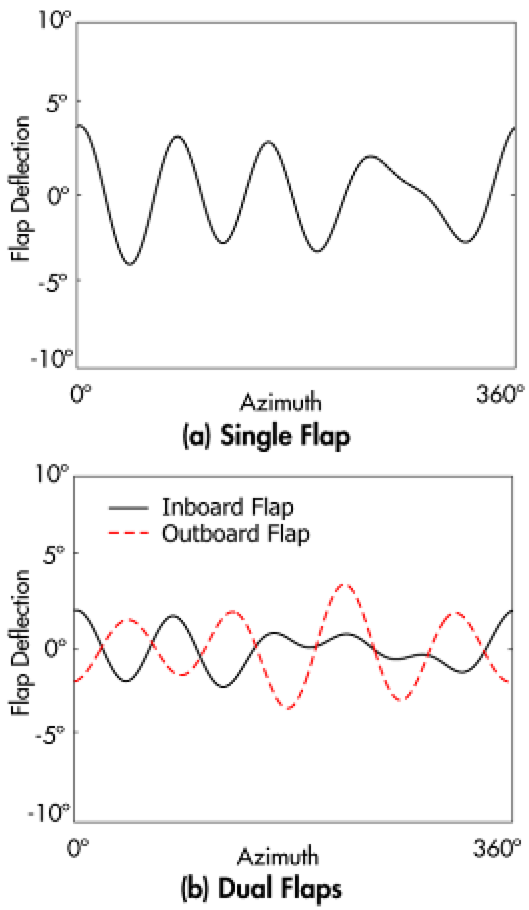


Results: BO-105 Vibration Reduction

- Vibration reduction with conventional HHC algorithm
  - 46% reduction with single flap configuration
  - 86% reduction with dual flap configuration



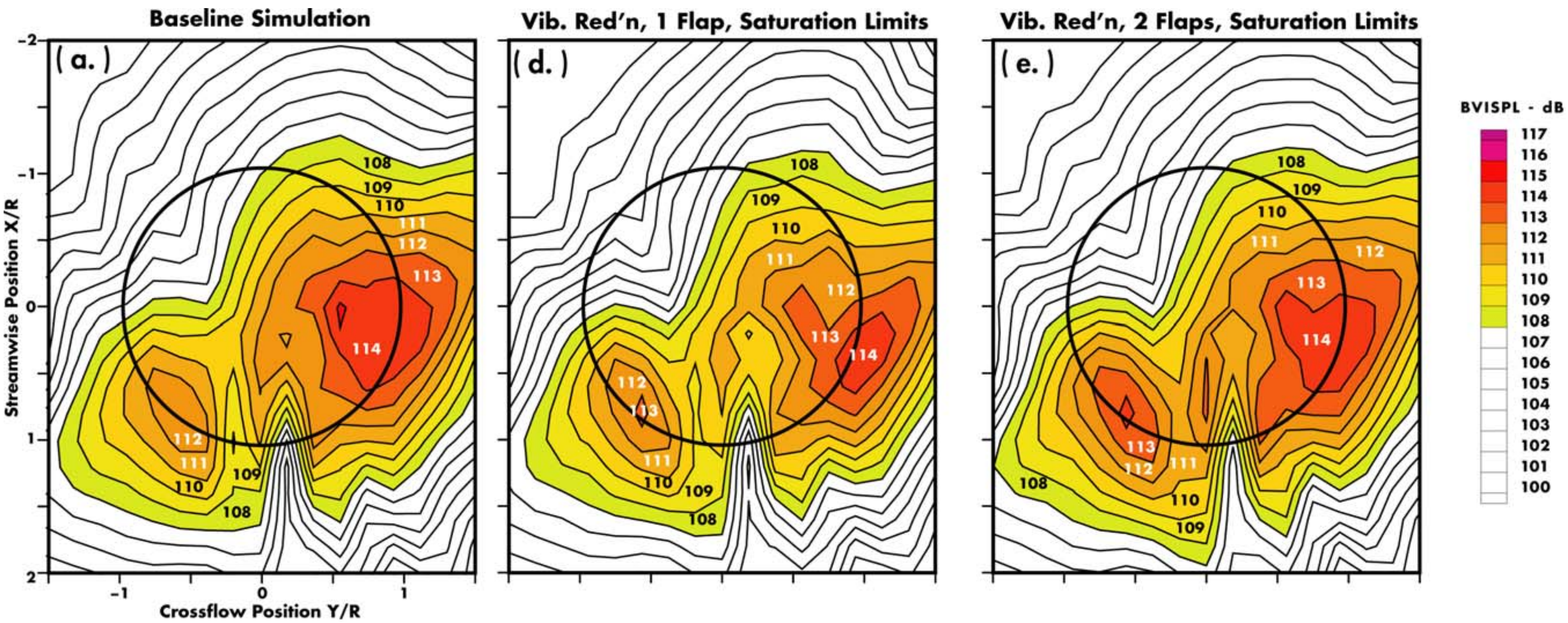
4/rev vibratory loads



Flap deflection

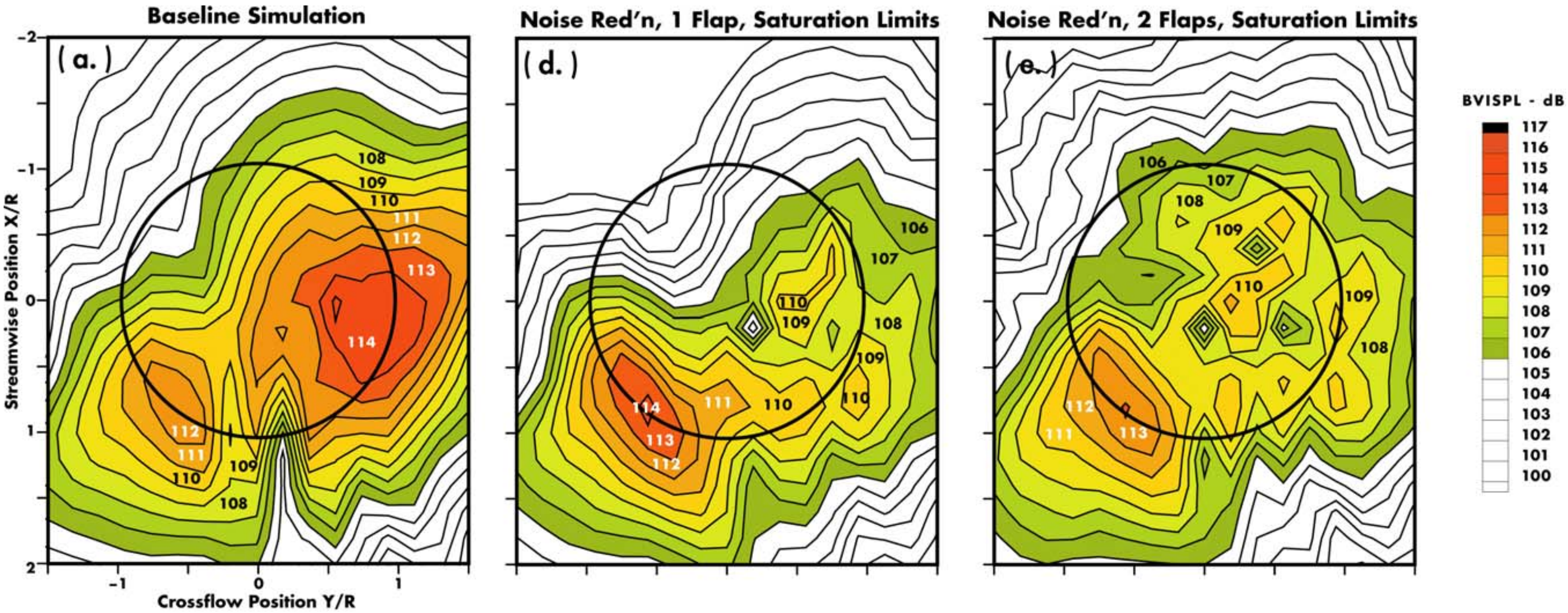
Results: BO-105 Vibration Reduction

- Noise generation during vibration reduction
  - No noise increase on advancing side
  - 1-2dB increase on retreating side



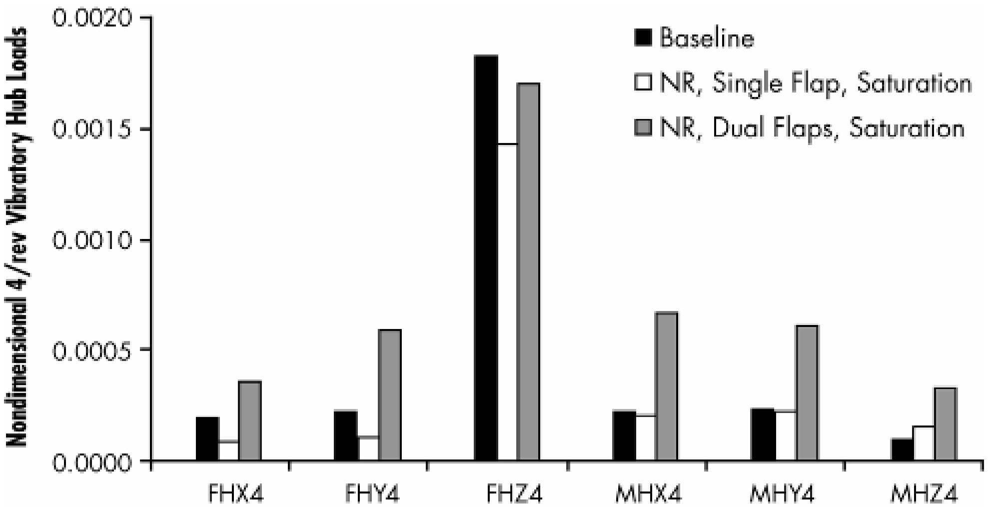
Results: BO-105 Noise Reduction

- Noise reduction with adaptive HHC algorithm
  - 5-6dB reduction on advancing side
  - 2dB increase on retreating side

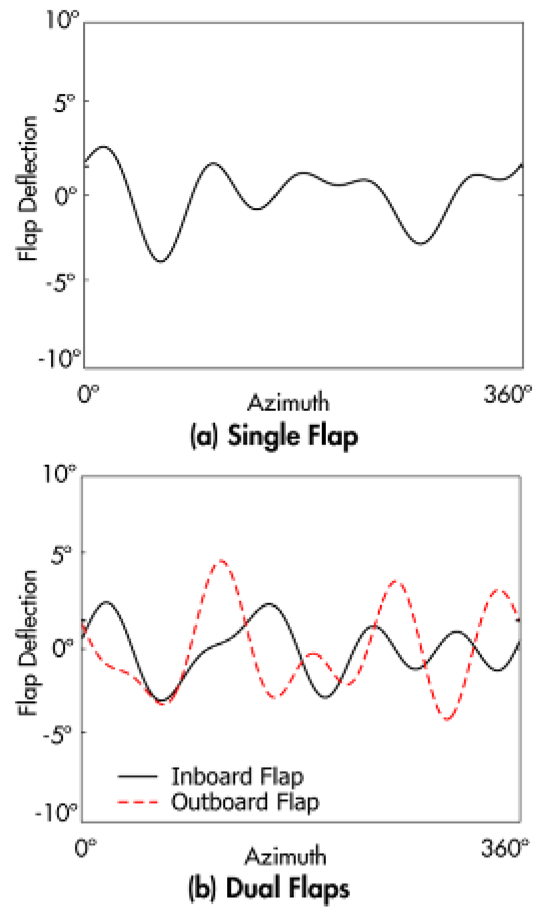


Results: BO-105 Noise Reduction

- Vibration levels during noise reduction
  - Unchanged for single flap configuration
  - 130% increase for dual flap configuration
  - Vertical shear always reduced



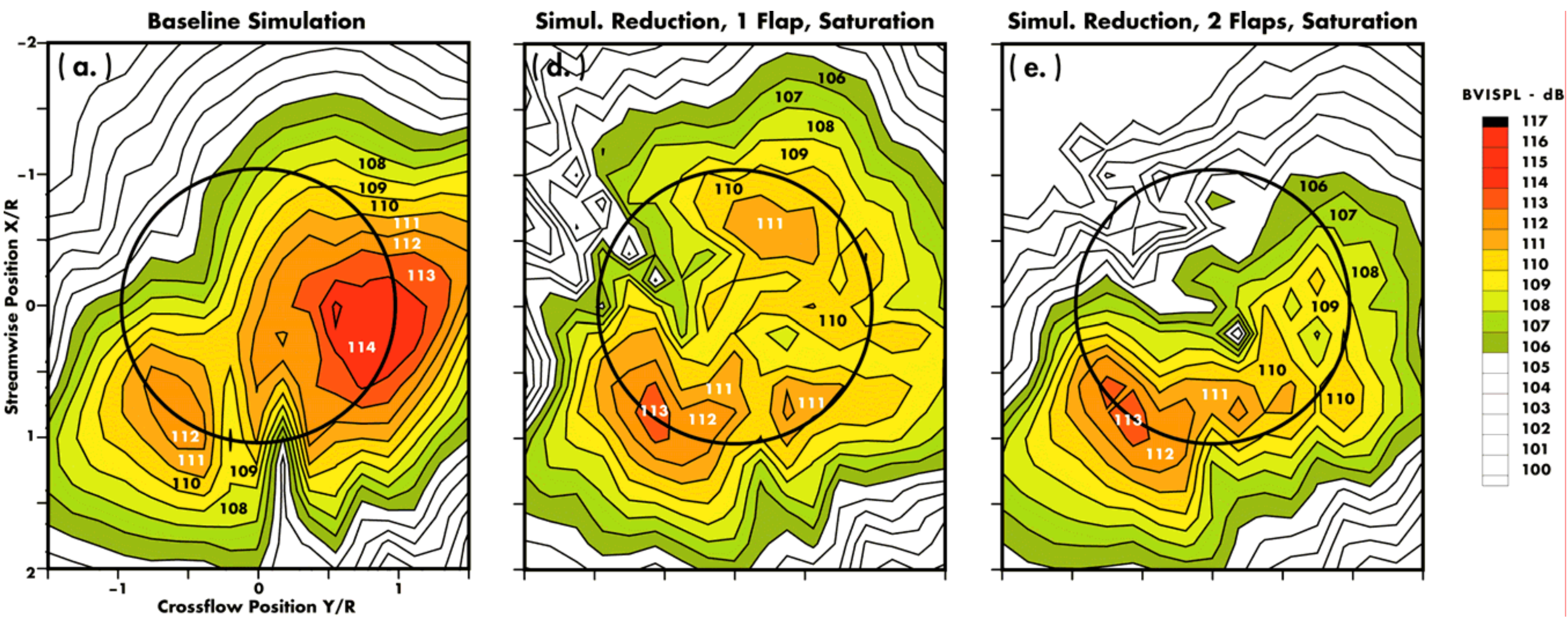
4/rev vibratory loads



Flap deflection

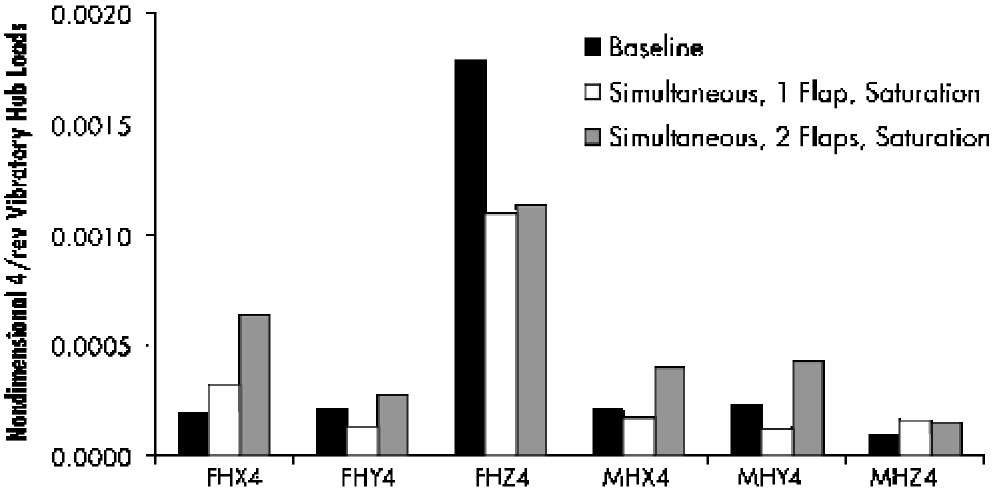
Results: BO-105 Simultaneous Reduction

- 3-5dB noise reduction and 40% vibration reduction
- Demonstrates the potential for simultaneous reduction
  - Deliberately instead of coincidently

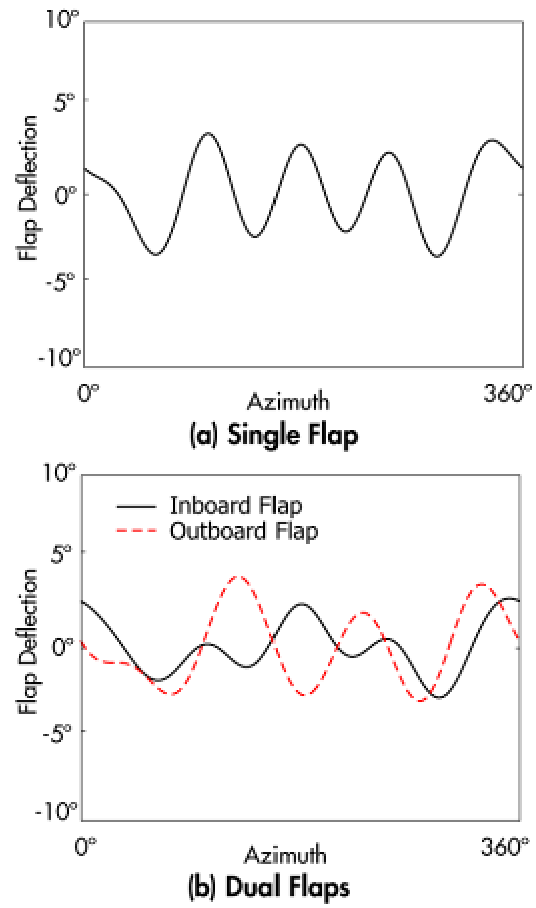


Results: BO-105 Simultaneous Reduction

- 40% vibration reduction



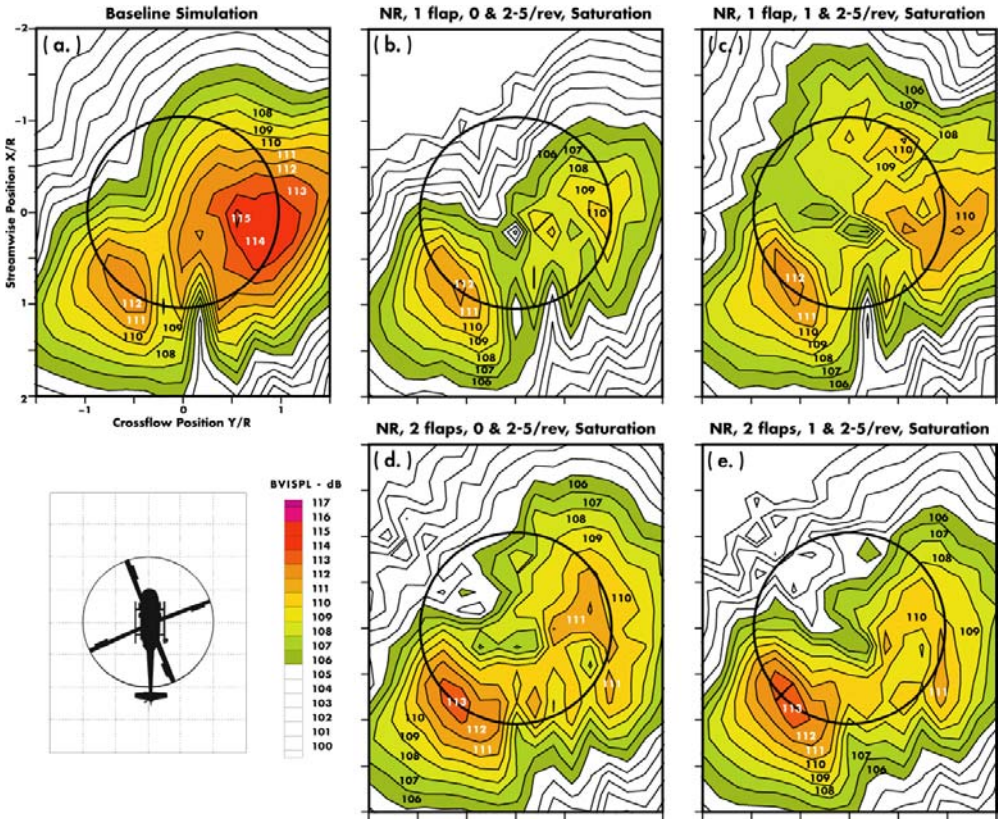
4/rev vibratory loads

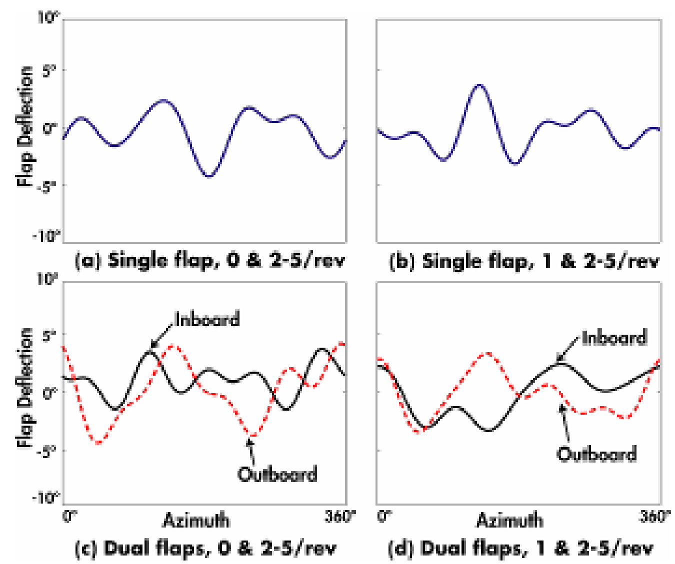


Flap deflection

Results: BO-105 Additional Flap Inputs

- Traditionally the flap harmonic inputs are taken to be a combination of 2-5/rev components
- The effects of constant (0/rev) and 1/rev flap harmonic inputs for BVI noise reduction are examined
  - Not appear to have significant effects





Results: MD-900

- Five-bladed bearingless rotor

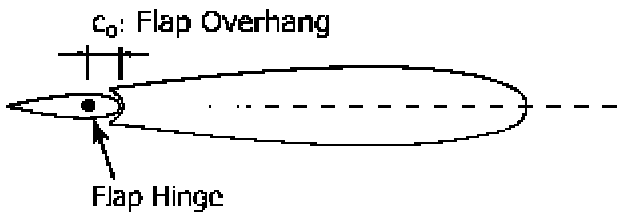
N_b	R(m)	μ	Ω(RPM)	C_T	c/R	α'
5	5.16	0.20	392	0.006	0.04924	-3.5º

- Wind tunnel trim
  - Simulated descent condition
- Flap configuration
  - Developed in Boeing **SMART** program

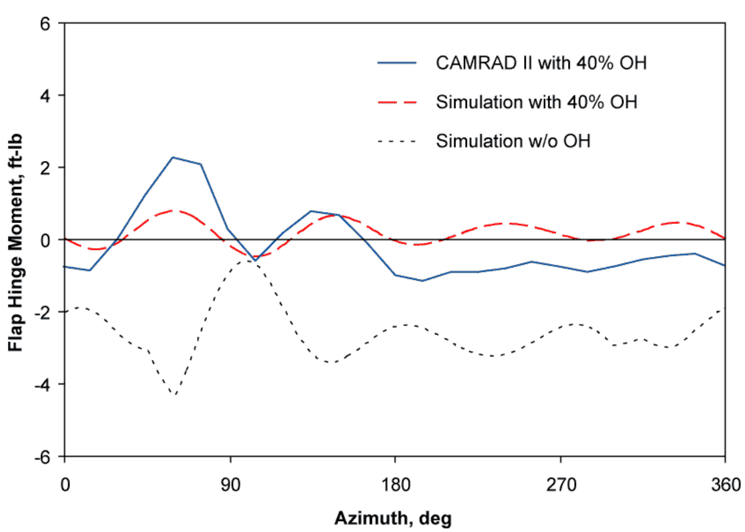
- Active control with 4º saturation
  - Vibration reduction
  - Noise reduction
  - Simultaneous reduction

Results: MD-900 Flap Overhang

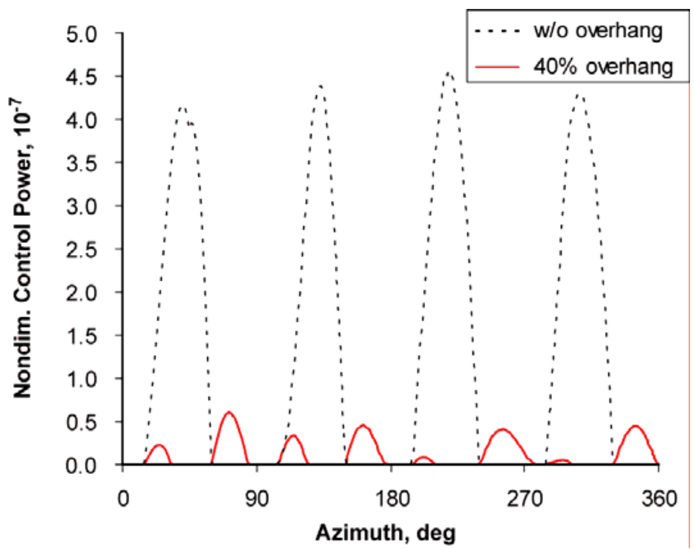
- Flap overhang (aerodynamic balance)



- Flap hinge moment reduced using 40% overhang
- Control power requirement reduced by an order of magnitude



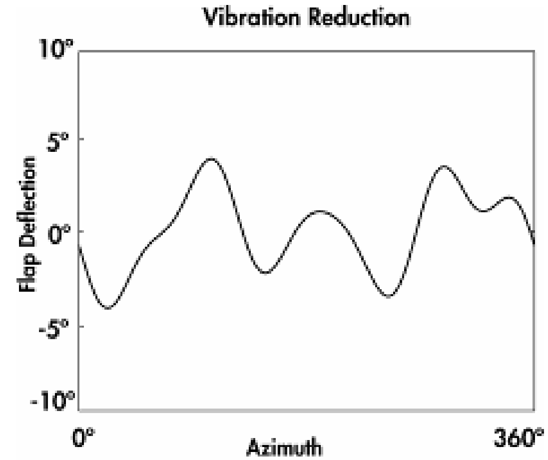
Flap hinge moment



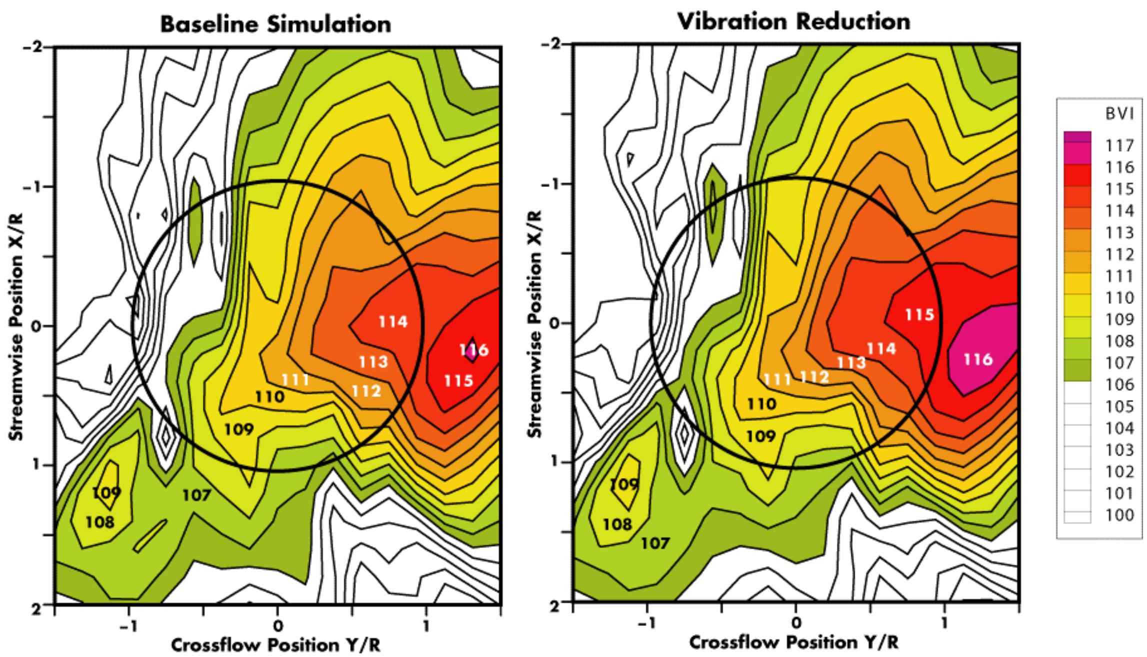
Instantaneous control power

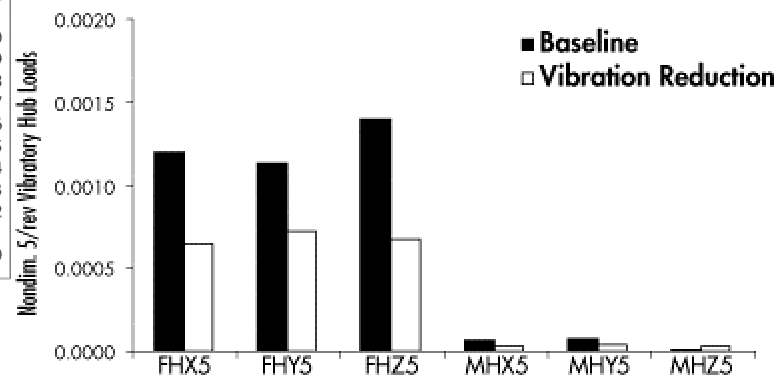
Results: MD-900 Vibration Reduction

- 60% vibration reduction
- 1dB noise increase



Flap deflection

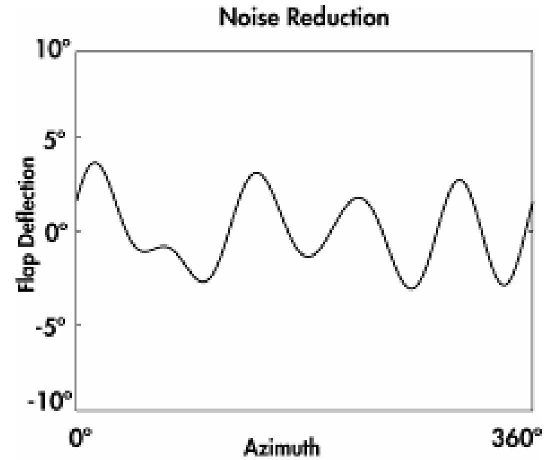




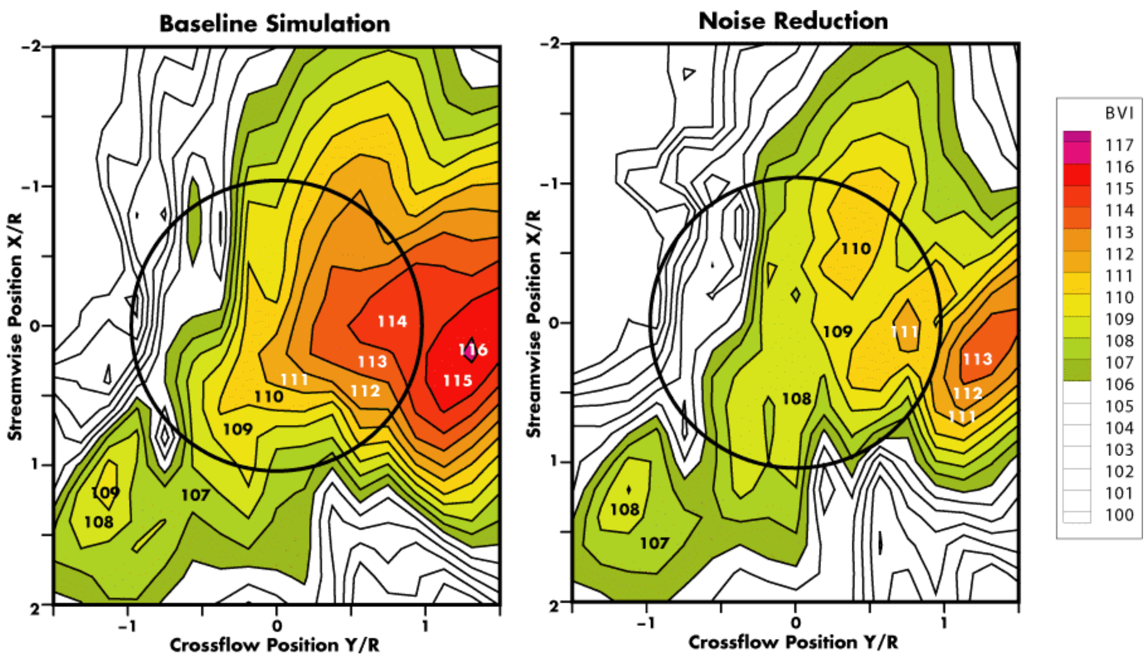
5/rev vibratory loads

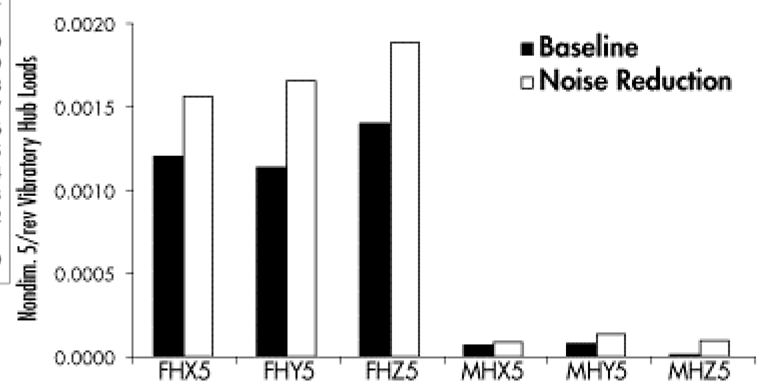
Results: MD-900 Noise Reduction

- 3dB BVI noise reduction
- No noise penalty on retreating side
- 150% vibration increase



Flap deflection

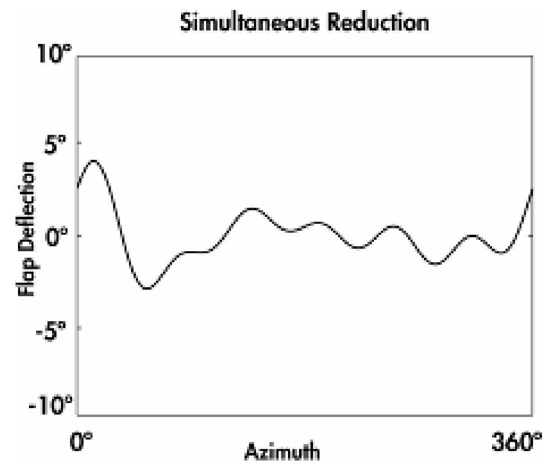




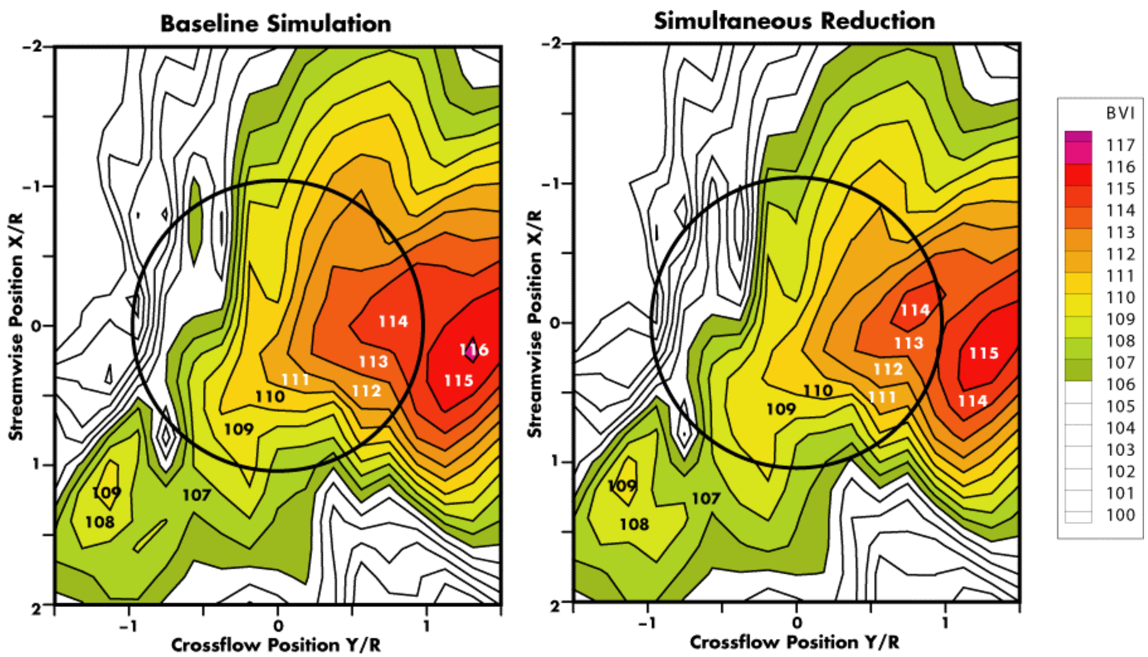
5/rev vibratory loads

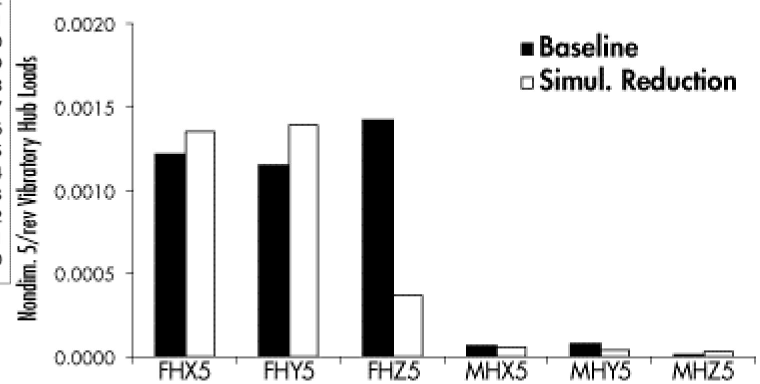
Results: MD-900 Simultaneous Reduction

- 74% reduction in vertical shear
- 1dB noise reduction
- ACF appears less effective in simultaneous reduction than in the MBB BO-105 case



Flap deflection

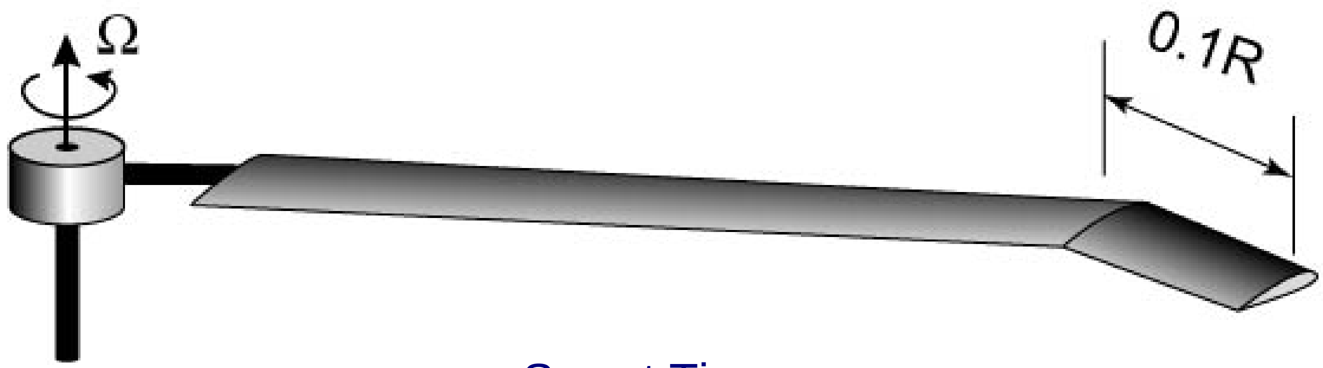




5/rev vibratory loads

Results: MD-900 Passive Approach

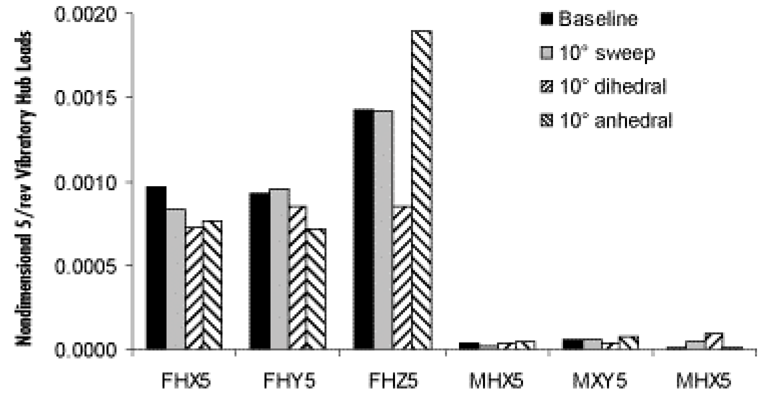
- Advanced geometry tips
  - 10º sweep
  - 10º dihedral (tip up)
  - 10º anhedral (tip down)
- Alleviation of BVI effects through increased separation distance
- BVI effects are alleviated for anhedral and enhanced for dihedral for level flight condition *(de Terlizzi & Friedmann,1999)*

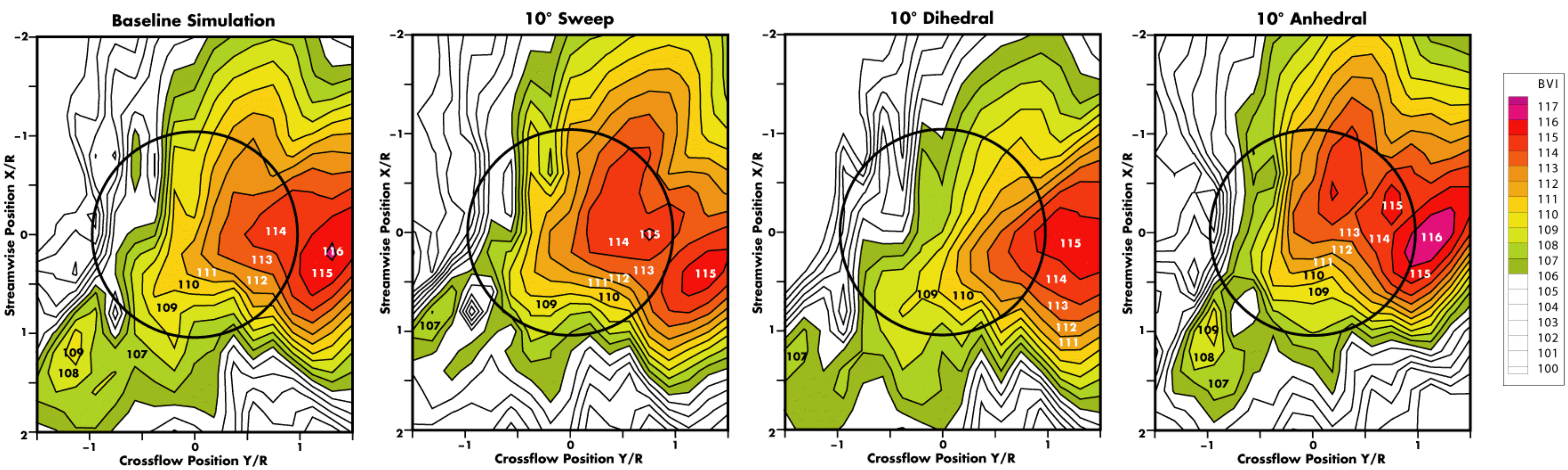


Swept Tip

Results: MD-900 Swept Tip – Descent

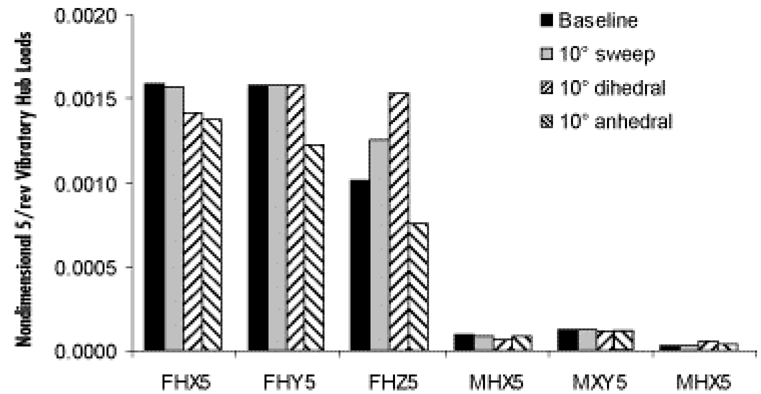
- -3.5º tip path plane angle, simulating **descending flight**
- 10º dihedral
  - 40% reduction in vertical shear
- 10º anhedral
  - 34% increase in vertical shear
- 10º sweep
  - Negligible effects

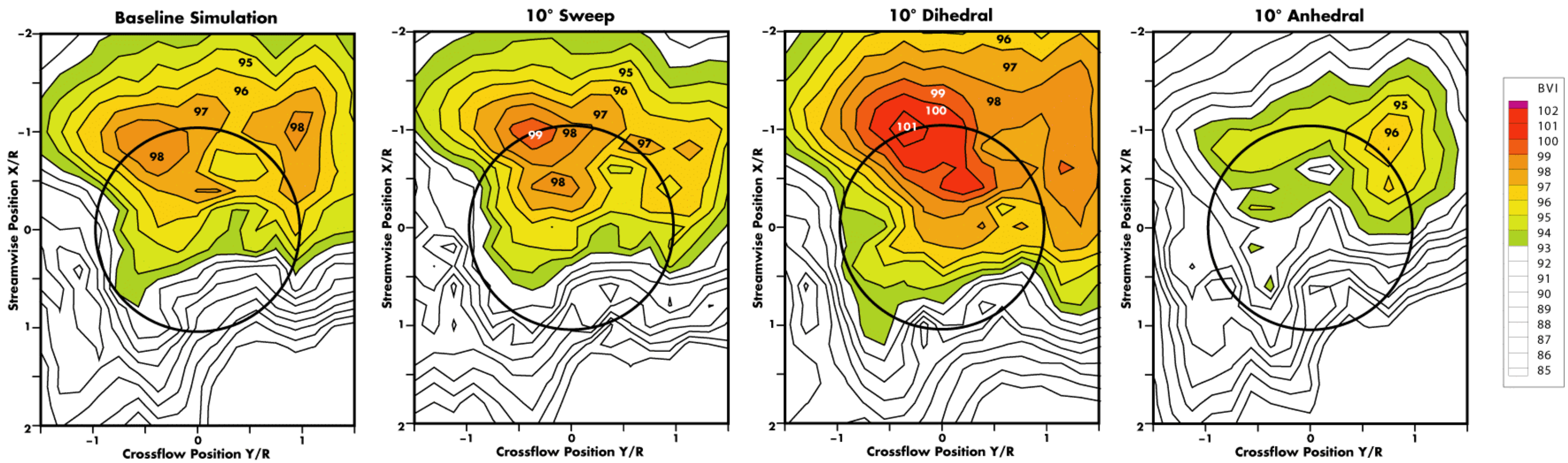




Results: MD-900 Swept Tip – Level Flight

- 2º tip path plane angle, simulating **level flight**
- 10º dihedral
  - 50% increase in vertical shear
  - 3dB noise increase
- 10º anhedral
  - 25% reduction in vertical shear
  - 2dB noise reduction
- Agrees with the results in *de Terlizzi & Friedmann, 1999*





Conclusions

- The ACF is an effective device for vibration and BVI noise reduction in rotorcraft, for different types of rotors and different helicopter configurations.
- The effectiveness of the ACF system has been clearly demonstrated despite imposing a practical flap saturation limits of 4º.
- The addition of constant and 1/rev flap harmonic input to the harmonic content of flap deflection does not have significant effects on BVI noise reduction, for the active flap systems employed on a rotor that resembles the MBB BO-105 rotor.
- Using a substantial flap overhang is a very effective means of reducing the flap hinge moment, thus further reducing the actuation power requirement for the ACF system.
- A passive approach employing tip anhedral or dihedral is effective at alleviating the BVI effects. However, this reduction depends on the flight condition.
- The ACF provides superior vibration and BVI noise reduction compared to the passive approach.