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Simultaneous Vibration and Noise Reduction in Rotorcraft - Practical Implementation Issues

Li Liu
PhD Candidate

Peretz P. Friedmann
François-Xavier Bagnoud Professor

Dan Patt
Postdoctoral Researcher

Department of Aerospace Engineering
University of Michigan
Ann Arbor, MI 48109-2140

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Introduction: Active Control

- Active control of vibration

  - Active Control of Vibration
    - ACSR - Vibration Control in Fuselage
    - Vibration Control on Rotor
      - IBC
      - HHC: Via Swashplate
    - Active Twist Rotor Blades (ATR)
    - Actively Controlled Flaps (ACF)
    - Conventional, Pitch Link Actuated IBC

- 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)
- 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** \(^{(Patt, Liu \& Friedmann, 2003)}\)

\[
\mathbf{f}(t) = \begin{bmatrix}
C_1(t) \\
C_m(t) \\
C_h(t)
\end{bmatrix}
\]

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

\[
\mathbf{f}^p(t) = \begin{bmatrix}
C_{p1}(t) \\
\vdots \\
C_{pn}(t)
\end{bmatrix}
\]
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
  - 5° azimuthal resolution
- Dual vortex line model with negative blade tip loading
  - Experimental evidence (HART)
  - Interaction with tip vortices is accounted for
Model: Solution Procedure

Acoustic Module
- Modified version of WOPWOP (*Brentner, 86*)
  - fully flexible blade model
- BVI noise defined as 6th-40th harmonics of BPF

![Diagram of Acoustic Module]

- Wake Geometry
- Free Wake
- Induced Velocity
- Coupled Trim/Aeroelastic Response Solution
- Circulation Distribution
- RFA Aerodynamics $C_L, C_M, C_D$
- Linear Drag Model
- Blade motions
- Chordwise pressure distribution
- BVI Noise
- Hub Shears & Moments

WAKE MODULE

AERODYNAMIC MODULE
Active Control: Algorithm

Conventional HHC
- Simple, one-step convergence

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

Adaptive HHC
- Online identification updates

Saturation Limits on Flap Deflection:
\[-4^\circ \leq \delta \leq 4^\circ\]
\[R = c_{wu} I\]
\[\begin{align*}
|\delta| > 4^\circ : & \quad \text{Increase } c_{wu} \\
|\delta| < 4^\circ : & \quad \text{Decrease } c_{wu}
\end{align*}\]

(Cribbs & Friedmann, 2001)

Cost Function:
\[J = z_k^T Q z_k + u_k^T R u_k\]

Vibration Reduction:
\[z_{VR} = \{F_{HX}, F_{HY}, F_{HZ}, M_{HX}, M_{HY}, M_{HZ}\}^T\]

Noise Reduction:
\[z_{NR} = \{N_{H06}, N_{H07}, \ldots, N_{H17}\}^T\]

Simultaneous Reduction:
\[z_{SR} = \{z_{VR}, z_{NR}\}^T\]

Harmonic Flap Deflection:
- Four-bladed BO-105
- Five-bladed MD-900

\[\delta(\psi) = \sum_{N=2}^{N_{max}} [\delta_{Nc} \cos(N\psi) + \delta_{Ns} \sin(N\psi)]\]
\[u = \{\delta_{Nc}, \delta_{Ns}\}^T, N=2-N_{max}\]
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 $\delta_f = 2^\circ \cos(4\psi - 240^\circ)$

- Comparison of blade natural frequencies (/rev) with RCAS *(Rotorcraft Comprehensive Analysis System)*

<table>
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<th></th>
<th>$\omega_{L1}$</th>
<th>$\omega_{F1}$</th>
<th>$\omega_{F2}$</th>
<th>$\omega_{L2}$</th>
<th>$\omega_{F3}$</th>
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<th>$\omega_{F4}$</th>
<th>$\omega_{A1}$</th>
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<td>Current Simulation</td>
<td>0.654</td>
<td>1.043</td>
<td>2.573</td>
<td>3.488</td>
<td>4.472</td>
<td>5.667</td>
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<td>RCAS</td>
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<td>1.048</td>
<td>2.572</td>
<td>3.498</td>
<td>4.473</td>
<td>5.409</td>
<td>7.273</td>
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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 4° saturation limits imposed
Results: MBB BO-105

- Four-bladed hingeless rotor

<table>
<thead>
<tr>
<th>N_b</th>
<th>R(m)</th>
<th>μ</th>
<th>Ω(RPM)</th>
<th>C_T</th>
<th>c/R</th>
<th>θ FP</th>
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<tr>
<td>4</td>
<td>4.91</td>
<td>0.15</td>
<td>425</td>
<td>0.005</td>
<td>0.05098</td>
<td>6º</td>
</tr>
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- 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

Flap deflection

4/rev vibratory loads

- Baseline
- NR, Single Flap, Saturation
- NR, Dual Flaps, Saturation
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
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

<table>
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<tr>
<th>$N_b$</th>
<th>$R(m)$</th>
<th>$\mu$</th>
<th>$\Omega$(RPM)</th>
<th>$C_T$</th>
<th>$c/R$</th>
<th>$\alpha'$</th>
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<td>5</td>
<td>5.16</td>
<td>0.20</td>
<td>392</td>
<td>0.006</td>
<td>0.04924</td>
<td>-3.5°</td>
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- Wind tunnel trim
  - Simulated descent condition

- Flap configuration
  - Developed in Boeing SMART program

- Active control with 4° 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
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.
Results: MD-900 Passive Approach

- Advanced geometry tips
  - 10° sweep
  - 10° dihedral (tip up)
  - 10° 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)
Results: MD-900 Swept Tip – Descent

- -3.5° tip path plane angle, simulating descending flight
- 10° dihedral
  - 40% reduction in vertical shear
- 10° anhedral
  - 34% increase in vertical shear
- 10° 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 4°.
- 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.