Alfred Gessow Rotorcraft Center

UNIVERSITY OF MARYLAND

Aeroelastic Modeling of Trailing-Edge Flap Rotor With Smart Materials Actuation

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Overview

Maryland

1. **Introduction** - *Objective and Scope of Present Research*

2. **Analytic Model** -*Structural model*
   - *Coupled blade-flap-actuator model*

3. **Analytic Results** - *Correlation with CAMRAD II*
   - *Parametric study*

4. **Summary and Conclusions**

UMARC
(University of Maryland Advanced Rotorcraft Code)

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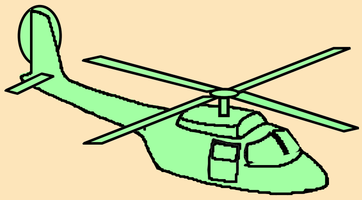
- Finite element methods in space and time
- Nonlinear elastic blade with moderate deflections
- Unsteady flap aerodynamics (Leishman-Hariharan)
- Free wake (Bagai-Leishman)
- Modal reduction
- Coupled trim solution for free flight and wind tunnel conditions



Introduction

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Old UMARC Model: Trailing-edge flap motion was prescribed.

New Model: Blade-flap-actuator as a coupled system, trailing-edge flap motion is calculated along with the blade response.

Smart actuation flap

Analytical model

Objective

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Develop a comprehensive rotorcraft aeroelastic analysis with fully coupled blade-flap-actuator system, and study the effect of this coupling on vibration minimization with trailing edge flap.

Carry out

- Correlation with CAMRAD II predictions
- Parametric studies with coupled blade-flap-actuator model for MD900 rotor

MD900 Explorer: 5-bladed bearingless rotor

Analytical Model

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Coupled blade-flap-actuator equations:

Blade →
Flap →

$$\begin{bmatrix} M_{bb} & M_{bf} \\ M_{fb} & M_{ff} \end{bmatrix} \begin{Bmatrix} \ddot{q}_b \\ \ddot{\delta} \end{Bmatrix} + \begin{bmatrix} C_{bb} & C_{bf} \\ C_{fb} & C_{ff} \end{bmatrix} \begin{Bmatrix} \dot{q}_b \\ \dot{\delta} \end{Bmatrix} + \begin{bmatrix} K_{bb} & K_{bf} \\ K_{fb} & K_{ff} \end{bmatrix} \begin{Bmatrix} q_b \\ \delta \end{Bmatrix} = \begin{Bmatrix} F_b \\ F_f \end{Bmatrix}$$

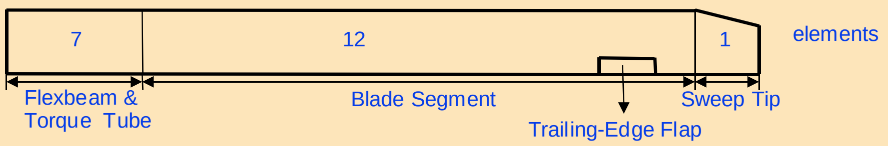
Trailing-edge flap equation contains actuator dynamics

q_b Blade displacement vector

δ Flap angle

Structural Modeling

- **Blade modeling**
  - Flexbeam and torque tube 7
  - Blade segment 12
  - Sweep tip 1
- **Modal analysis**
  - Blade modes 10
- **Flap configuration**
  - Flap Chord 25%
  - Flap length 18%
  - Flap location 83%
- **Wind tunnel trim condition**
  - Advancing ratio 0.2
  - Thrust coefficient (C_T/σ) 0.0774
  - Shaft angle (backward) - 3.5



Coupled Blade-Flap-Actuator

- **Trailing edge flap response**
- **Actuator stiffness**
- **Unlocked and locked flap**

Trailing-Edge Flap Angle

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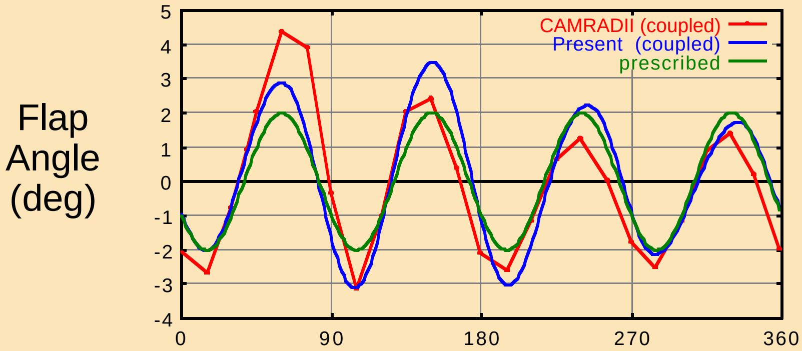
- μ = 0.20
- c_f/c = 25%
- C_T/σ = 0.0774

Flap = 18%R Location = 83%R

Input: $\delta_f = 2\cos(4\psi - 240^o)$



Azimuth Angle

- **Hinge Spring = 81.52 (ft-lb/rad)**
- **Hinge damping = 0.05 (ft-lb/rad/sec)**
- **Flap effectiveness factor = 1**

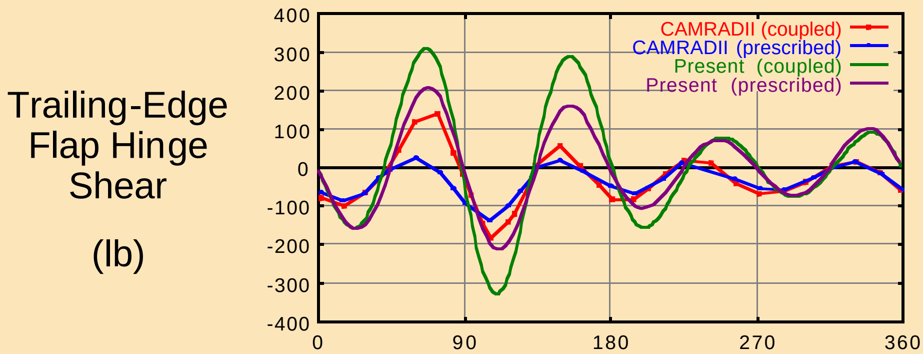
Trailing-Edge Flap Hinge Shear

Maryland

- μ = 0.20
- c_f/c = 25%
- C_T/σ = 0.0774

Flap = 18%R Location = 83%R

Input: $\delta_f = 2\cos(4\psi - 240^o)$



Azimuth Angle

Trailing-Edge Flap Hinge Moment

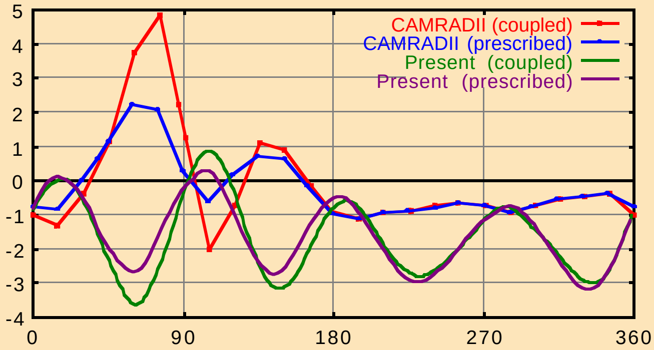
- μ = 0.20
- c_f/c = 25%
- C_T/σ = 0.0774

Flap = 18%R Location = 83%R

Input: $\delta_f = 2\cos(4\psi - 240^o)$

Trailing-Edge Flap Hinge Moment

(ft-lb)



Azimuth Angle

Discrepancy possible because of aerodynamic forces

Actuator Stiffness Effect

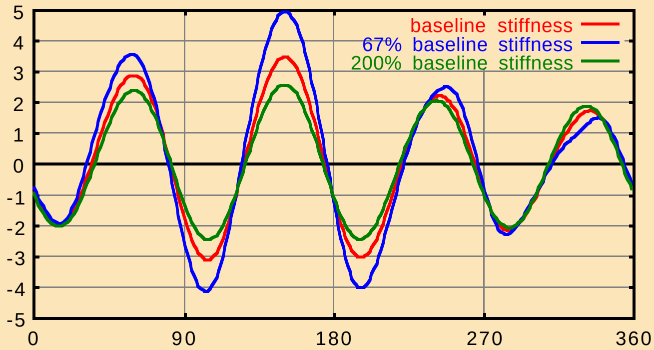
- μ = 0.20
- C_T/σ = 0.0774
- l_f/R= 18%
- r_f/c= 83%
- c_f/c= 25%

Input: $\delta_f = 2\cos(4\psi - 240^o)$

Flap Response

Flap Angle

(deg.)



Azimuth Angle (deg.)

- **Hinge Spring = 81.52 (ft-lb/rad)**
- **Hinge damping = 0.05 (ft-lb/rad/sec)**

Unlocked Flap

Maryland

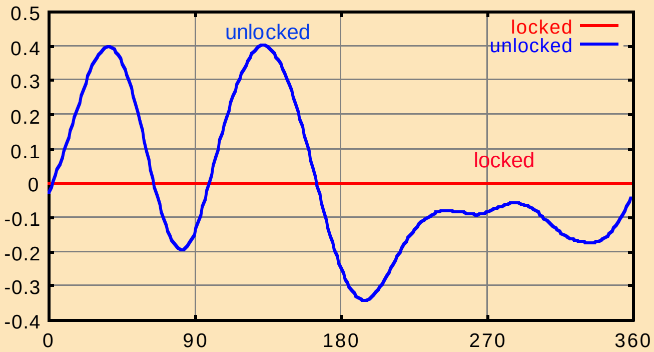
- μ = 0.20
- C_T/σ = 0.0774
- l_f/R= 18%
- r_f/c= 83%
- c_f/c= 25%

Input: $\delta_f = 0$ **(No Actuator Force)**

Flap Response

Flap Angle

(deg.)



Azimuth Angle (deg.)

- **Peak-to-Peak flap amplitude: 0.75 deg.**
- **Large flap response at azimuth angle 0-180 (deg)**

Unlocked Flap

Maryland

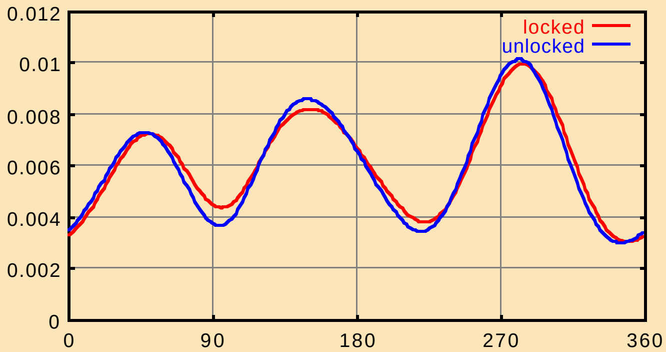
- μ = 0.20
- C_T/σ = 0.0774
- l_f/R= 18%
- r_f/c= 83%
- c_f/c= 25%

Input: $\delta_f = 0$ **(No Actuator Force)**

Blade Tip Flap Response

Blade Tip Flap Fesponse

(w/R)



Azimuth Angle (deg.)

- **Peak-to-Peak tip amplitude increase: 5%**

Unlocked Flap

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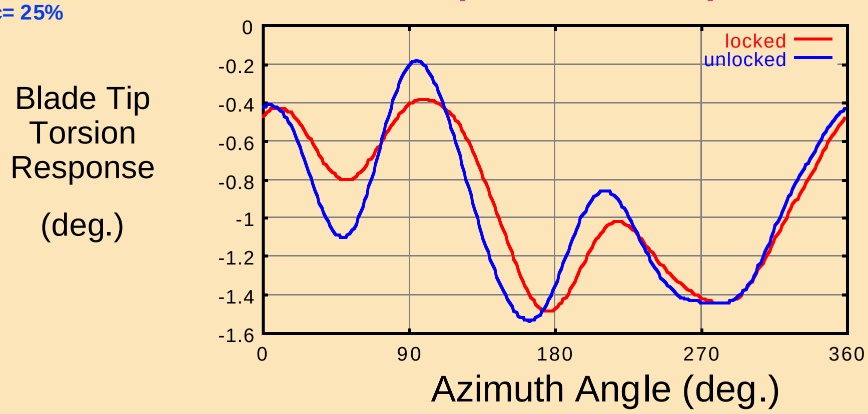
- μ = 0.20
- C_T/σ = 0.0774
- l_f/R = 18%
- r_f/c = 83%
- c_f/c = 25%

Input: $\delta_f = 0$ **(No Actuator Force)**

Blade Tip Torsion Response



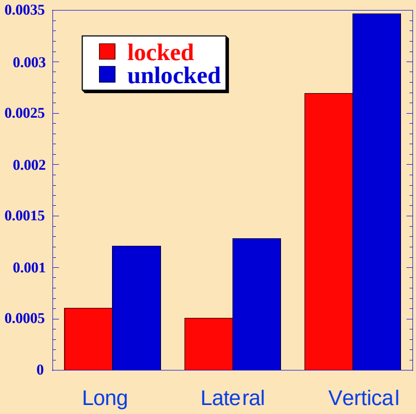
- Peak-to-Peak tip amplitude increase: 15%

Unlocked Flap

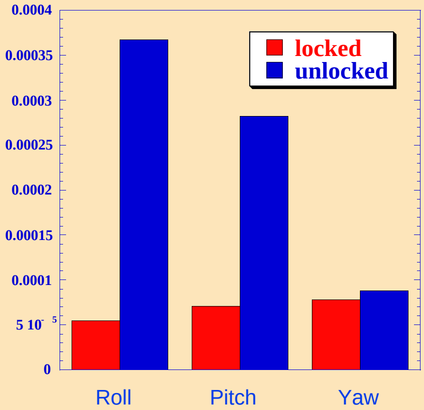
Input: $\delta_f = 0$

Maryland

5/Rev Hub Forces



5/Rev Hub Moments



Uncontrolled hub forces increase due to flap/actuator dynamics

Parametric Study
(with coupled system)

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- **Design Parameters**
  - *Flap span-wise location*
  - *Flap span-wise size*
  - *Blade pitch link stiffness*
  - *Advancing ratio*

- **Trend Studies**
  - *Objective function (5/rev hub loads)*
  - *Optimal flap peak-to-peak angle*
  - *Actuation power*

Study coupling effect due to blade-flap-actuator dynamics

Multicyclic controller

Maryland

- **Objective function**

$$J \equiv Z_n^T W_z Z_n + \theta_n^T W_\theta \theta_n$$

- **Local linearization**

$$Z_n = Z_{n-1} + T(\theta_n - \theta_{n-1})$$

Z : 5/Rev hub loads
(3 forces + 2 moments)
W: Weighting matrix
θ : 4,5 and 6/Rev flap angles
T : Transfer function

- **Weighting matrix (diagnal)**

$$W_z = [0.040 \quad 0.023 \quad 1.000 \quad 0.440 \quad 0.136]$$

Long	Lateral	Vertical	Roll	Pitch

Controller Works for both coupled system and prescribed system

Effect of Flap Location

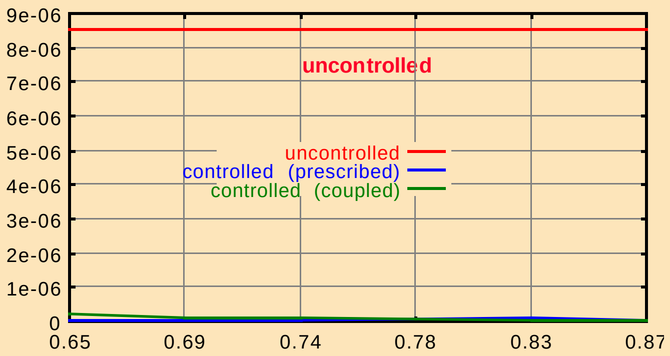
Maryland

- μ = 0.30
- c_f/c = 25%
- C_T/σ = 0.0774

Flap = 18%R

Hub Loads (3 forces + 2 moments)

Vibration Objective Function J_0 and J



Flap Location, r_{mid}/R

- **Complete minimization with prescribed and coupled flap**

Effect of Flap Location

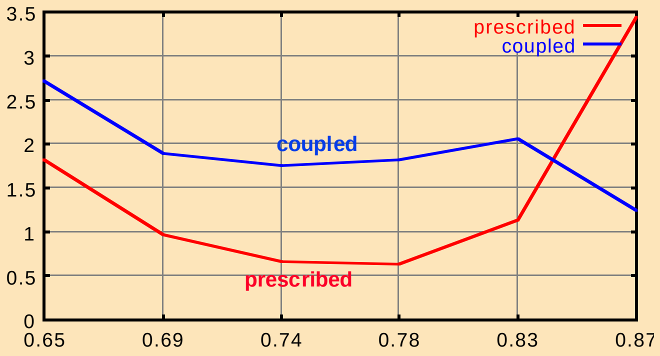
Maryland

- μ = 0.30
- c_f/c = 25%
- C_T/σ = 0.0774

Flap = 18%R

Flap Deflections

Peak-to-Peak Flap Deflection $||\delta||$ (deg.)



Flap Location, r_{mid}/R

- **Peak-to peak flap deflection for coupled system increase: 100%**

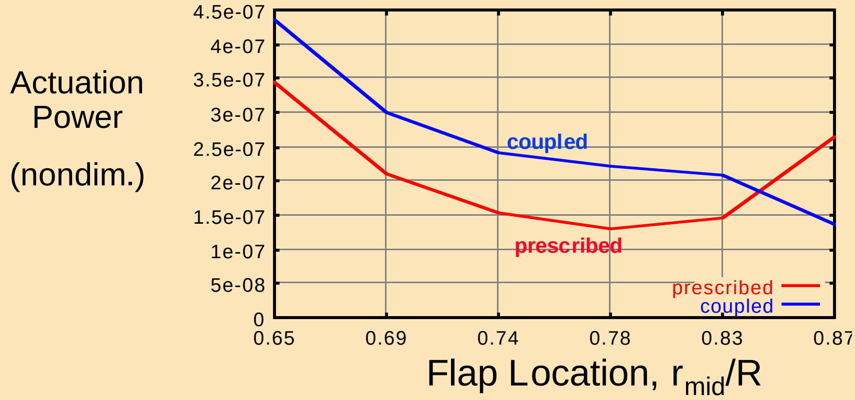
Effect of Flap Location

Maryland

- μ = 0.30
- c_f/c = 25%
- C_T/σ = 0.0774

Flap = 18%R

Actuation Power



- **Power for coupled system increase: 40%**

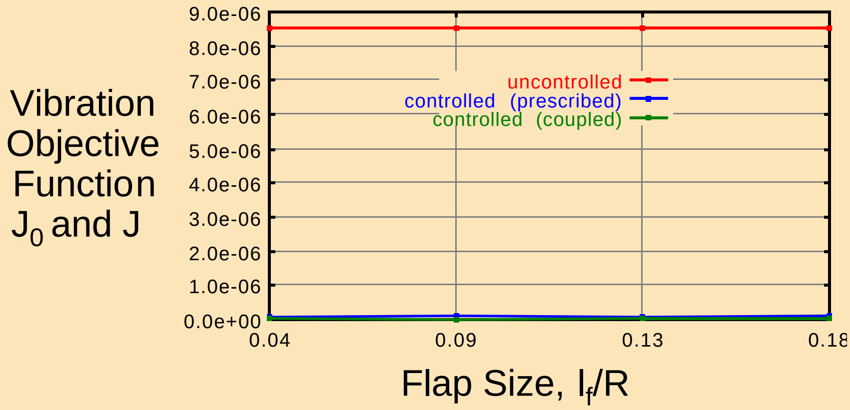
Effect of Flap Size

Maryland

- μ = 0.30
- c_f/c = 25%
- C_T/σ = 0.0774

Flap location = 83%R

Hub Loads (3 forces + 2 moments)



- **Complete minimization with prescribed and coupled flap**

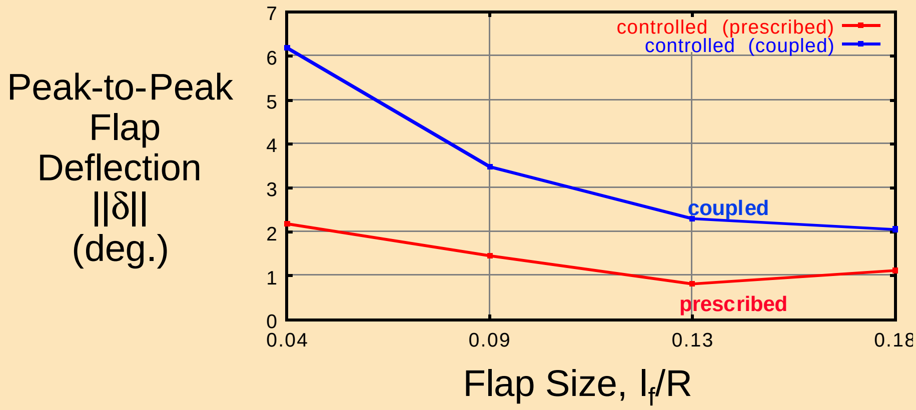
Effect of Flap Size

Maryland

- μ = 0.30
- c_f/c = 25%
- C_T/σ = 0.0774

Flap location = 83%R

Flap Deflections



- **Peak-to-peak flap deflection for coupled system increase: 200%**

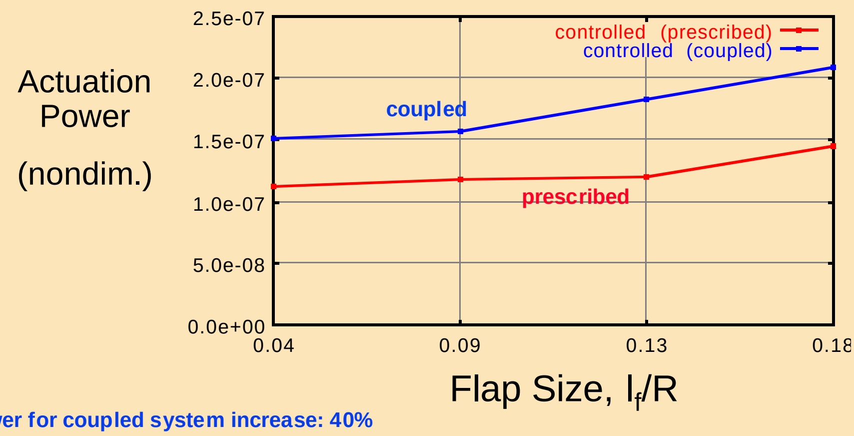
Effect of Flap Size

Maryland

- μ = 0.30
- c_f/c = 25%
- C_T/σ = 0.0774

Flap location = 83%R

Actuation Power



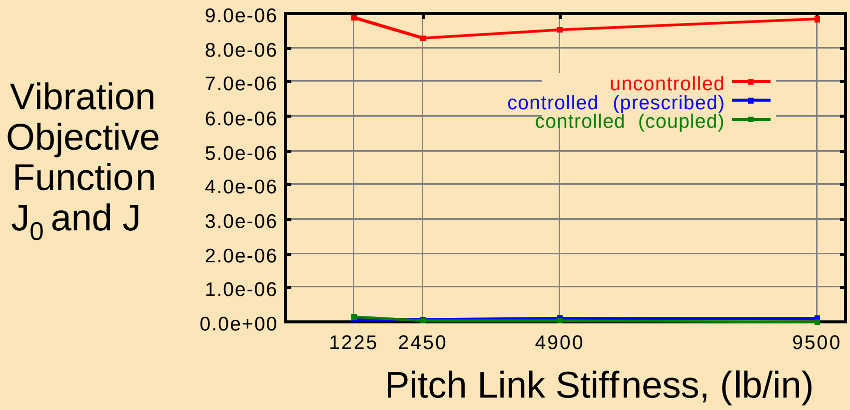
- **Power for coupled system increase: 40%**

Effect of Pitch Link Stiffness

Maryland

- μ = 0.30
- c_f/c = 25%
- C_T/σ = 0.0774

Flap = 18%R location = 83%R
Hub Loads (3 forces + 2 moments)



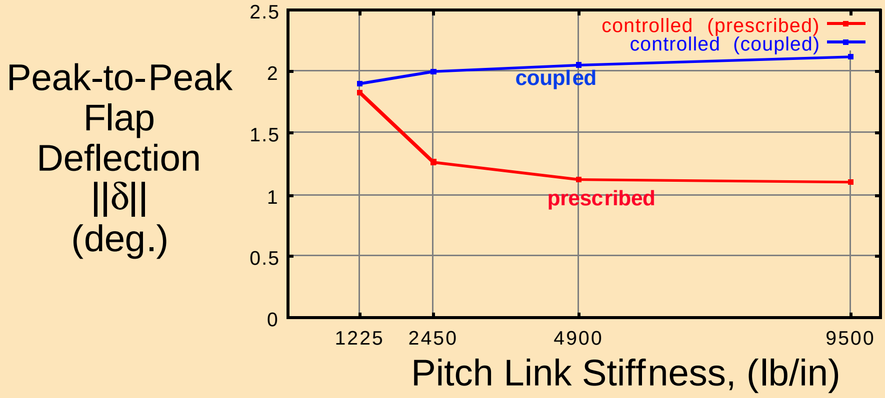
- **Complete minimization with prescribed and coupled flap**

Effect of Pitch Link Stiffness

Maryland

- μ = 0.30
- c_f/c = 25%
- C_T/σ = 0.0774

Flap = 18%R location = 83%R
Flap Deflections



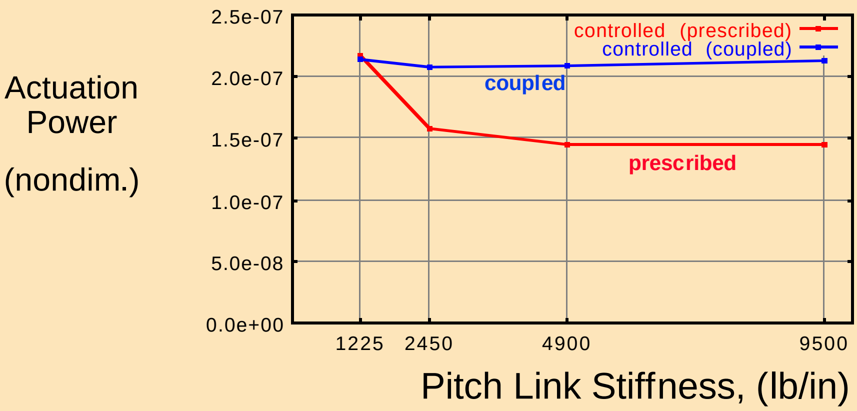
- **Peak-to-peak flap deflection for coupled system increase: 90%**

Effect of Pitch Link Stiffness

Maryland

- μ = 0.30
- c_f/c= 25%
- C_T/σ = 0.0774

Flap = 18%R location = 83%R
Actuation Power



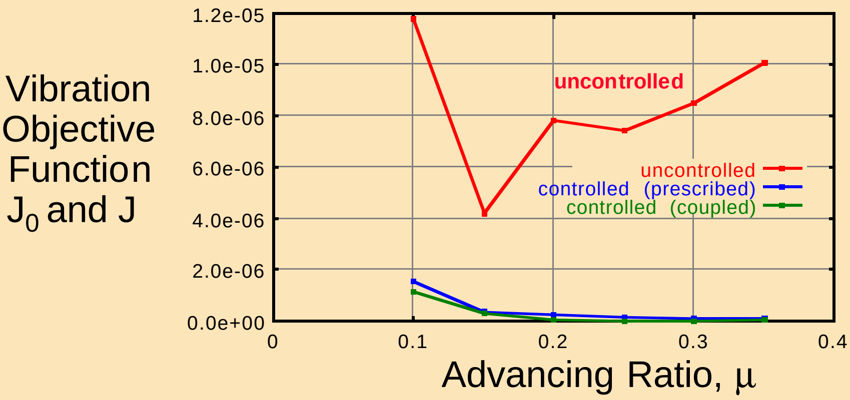
- **Power for coupled system increase: 30%**

Forward Speed Effect

Maryland

- μ = 0.30
- c_f/c= 25%
- C_T/σ = 0.0774

Flap = 18%R
Hub Loads (3 forces + 2 moments)



- **Vibration objective function was minimized to less than 10%**

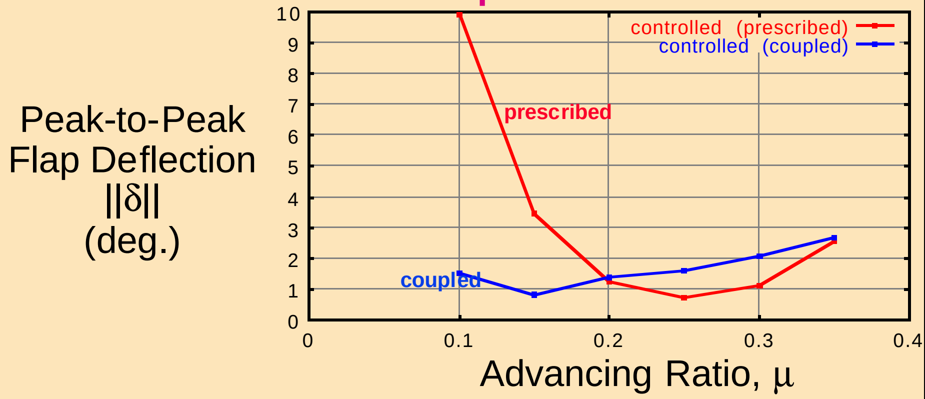
Forward Speed Effect

Maryland

- μ = 0.30
- c_f/c= 25%
- C_T/σ = 0.0774

Flap = 18%R

Flap Deflections



- For prescribed system, peak-to-peak flap deflection: 0.8 degree to 10 degree
- For coupled system, peak-to-peak flap deflection: 0.9 degree to 2.6 degree

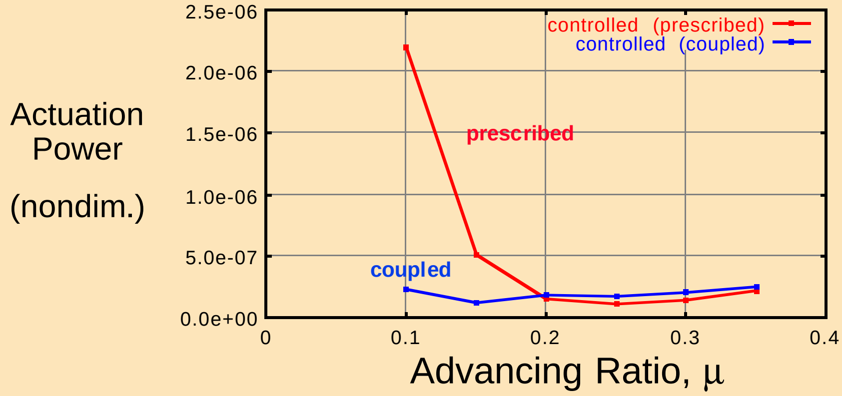
Forward Speed Effect

Maryland

- μ = 0.30
- c_f/c= 25%
- C_T/σ = 0.0774

Flap = 18%R

Actuation Power

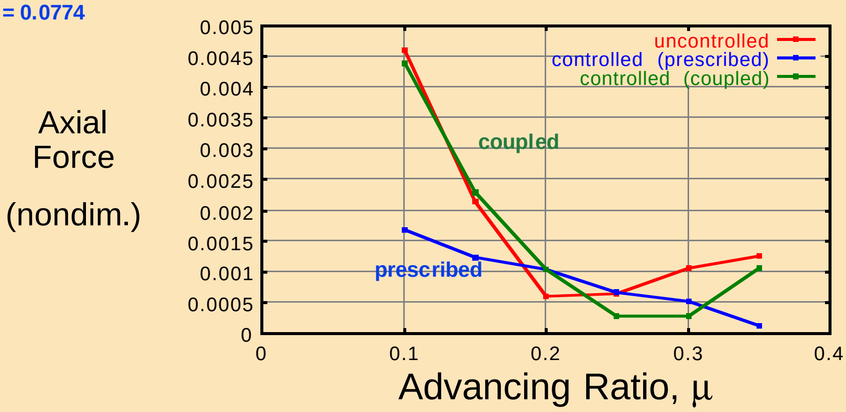


Forward Speed Effect

Maryland

- l_f/R = 18%
- c_f/c = 25%
- r_f/R = 83%
- C_T/σ = 0.0774

5/rev Hub Axial Force



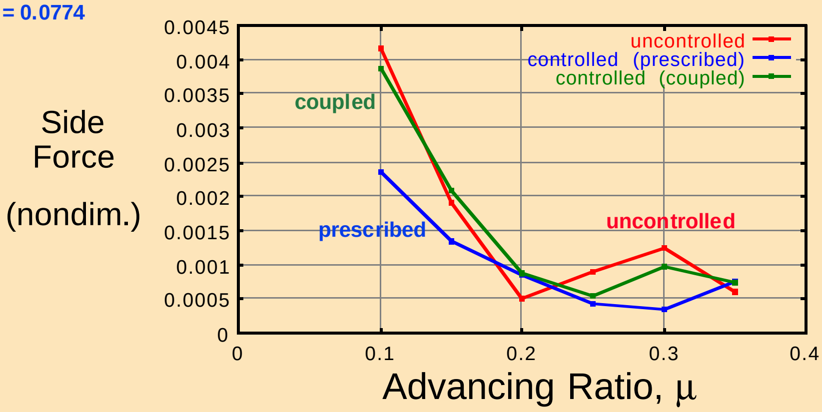
- Small reduction or small increment for axial force because of its small weight in objective function

Forward Speed Effect

Maryland

- l_f/R = 18%
- c_f/c = 25%
- r_f/R = 83%
- C_T/σ = 0.0774

5/rev Hub Side Force



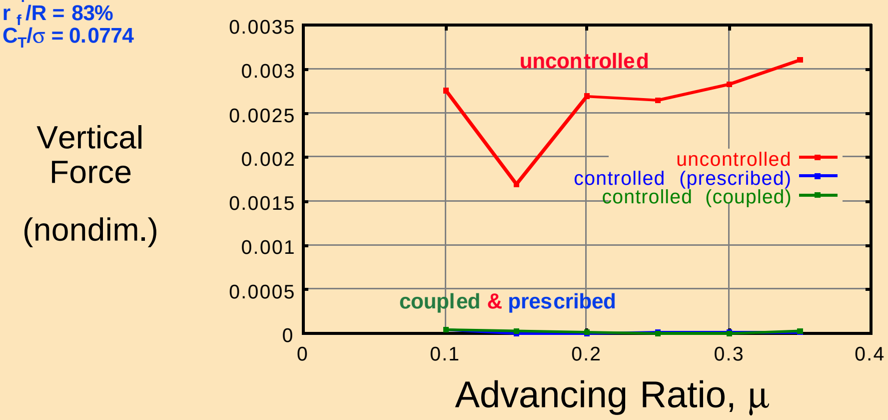
- Small reduction or small increment for side force because of its small weight in objective function

Forward Speed Effect

Maryland

- l_f/R = 18%
- c_f/c= 25%
- r_f/R = 83%
- C_T/σ = 0.0774

5/rev Hub Vertical Force



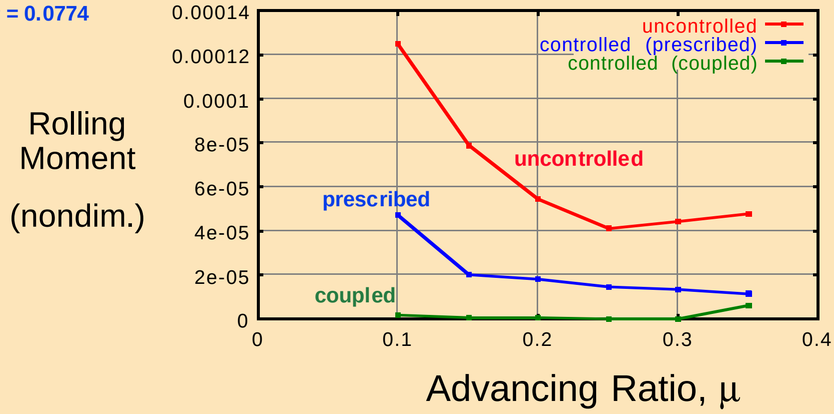
- Complete reduction for vertical force because of its dominant weight in objective function

Forward Speed Effect

Maryland

- l_f/R = 18%
- c_f/c= 25%
- r_f/R = 83%
- C_T/σ = 0.0774

5/rev Hub Rolling Moment



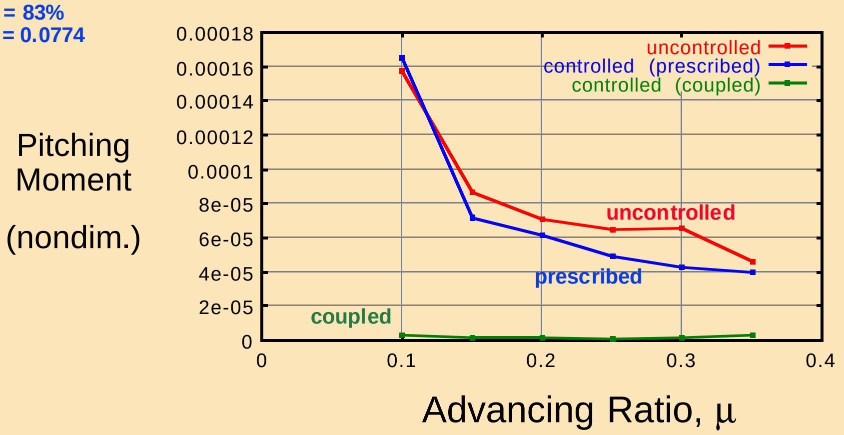
- For prescribed system, rolling moment reduced to 40%
- For coupled system, rolling moment reduced to 1% to 5%

Forward Speed Effect

Maryland

- l_f/R = 18%
- c_f/c= 25%
- r_f/R = 83%
- C_T/σ = 0.0774

5/rev Hub Pitching Moment



- For prescribed system, rolling moment reduced to 90%
- For coupled system, rolling moment reduced to 1% to 3%

Summary

Maryland

- **Coupled blade-flap-actuator modeling was formulated .**
- **Coupling effect due to actuator dynamics on blade response and loads was examined.**
- **Correlation with CAMRAD II predictions was fair.**
- **Parametric study with coupled blade-flap-actuator system was carried out.**

Conclusions

Maryland

- Flap/Actuator dynamics increases the vibratory hub loads if flap is unlocked in uncontrolled condition.
  - 5/Rev hub forces increase 50 %
  - 5/Rev hub moments increase 400%

- The optimal flap location, size and pitch link stiffness are same for both coupled and prescribed system, however, the required flap peak-to-peak deflection and actuation power increase due to flap/actuator dynamics.
  - flap peak-to-peak deflection increases 90% to 200%
  - flap actuation power increases 30% to 40%

- Vibration objective function can be minimized to less than 10% for advancing ratios from 0.1 to 0.35