Alfred Gessow Rotorcraft Center

UNIVERSITY OF MARYLAND

Analysis of a Swashplateless Rotor With Smart Trailing-edge Flaps

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Overview

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1. **Introduction** - Objective and Scope of Present Research
2. **Formulation** - Aerodynamic model - Response and trim
3. **Results** - Correlation with MDART test data - Analytical results for a swashplateless smart flap rotor
4. **Summary and Conclusions**

Helicopter Primary Control

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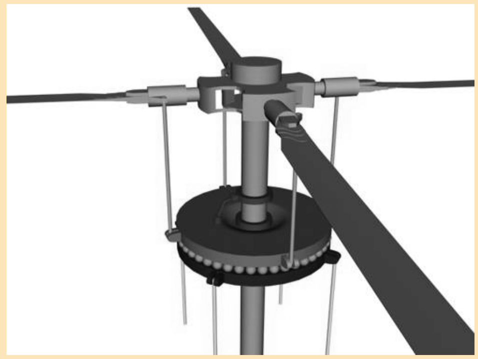
- Primary control mechanism incorporates tilting the resultant rotor thrust vector.
- Conventionally achieved through cyclic pitch change using a swashplate.
- Swashplate system involves pitch links, pushrods, and fixed system hydraulic actuators



Swashplate System

Disadvantages of Swashplate System

Weight, drag, and cost as well as high probability for failure of the mechanical components provide an impetus to search for alternative means to change blade pitch.

Alternative Means

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- **Blade camber control** – achieved by cyclic excitation with embedded material that is applied differently on the top and bottom surfaces of the blade sections. Because of the lack of availability of suitable smart materials with sufficient stroke and stiffness, this concept was found to be infeasible.
- **Blade twist control** – enables blade twist to be generated with embedded active materials and via the application of a cyclic differential voltage over the span of the blade. It requires substantial actuation power and also there is a serious concern of blade structural integrity.
- **Individual blade pitch control** – actuates individual blades in pitch using hydraulic or smart material actuators. For hydraulic actuation, there is an overwhelming complexity of hydraulic slipring whereas for smart actuation there is a barrier of limited stroke of smart materials.

Alternative Means (Cont…)

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- **Tilting shaft concept** – affects a tilt of the control mast in order to reorient the direction of the rotor thrust. This concept was found to be infeasible due to the unacceptably large actuation force and stroke requirement, and due to the complexity and weight of the actuation mechanism.
- **Active servo flaps** – auxiliary airfoil sections that are located behind the main blades as incorporated by Kaman. This design involves linkages exposed in the air, which results in large drag penalties.
- **Active plane trailing edge flaps** – flaps integrated with the main lifting section of the blade are deflected cyclically in order to change the lift and/or moment characteristics of the blade section.

Flap Configurations

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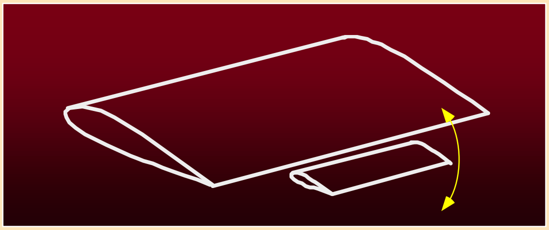
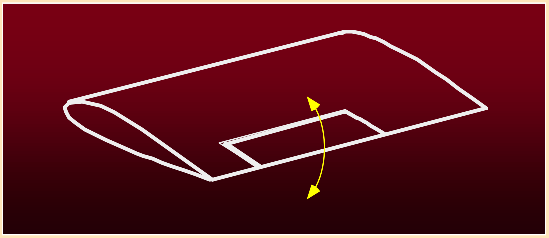


Servo Flap
- Large pitching moments
- Exposed linkages
- Reduced effectiveness due to hinge gaps



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

Active Trailing-edge Flaps

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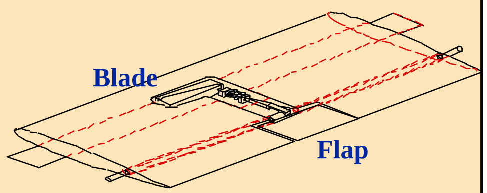
Active Trailing-edge Flap System will involve the integration of smart sensors and actuators, on-blade aerodynamic control surfaces, and integral blade twist.

Advantages

- Lower the weight, mechanical complexity, drag, and cost by eliminating the swashplate and supporting components.
- Perform multiple functions, primary control as well as active vibration and noise reduction.



Smart trailing-edge flap system

Trailing edge flaps offer potential for effective, lightweight primary control system.

Background (1/2): Blade With Flap Analysis

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- Millott & Friedmann (1992-94)
- Myrtle & Friedmann (1997-98)
  - Analytic Investigation of servo flaps for HHC
- Straub & Charles (1994)
- Hassan & Straub (1995-96)
- Straub & Charles (1999)
  - MD Active Flap Rotor (AFR)
  - Flap/profile design using CFD
  - Comprehensive modeling with CAMRAD/JA and CAMRAD II
- Milgram and Chopra (1996-98)
  - Comprehensive study of plain flaps for vibration reduction
    - Vibratory hub loads, parametric study
    - Flap motion prescribed
- Shen and Chopra (2000-01)
  - Full coupled analysis model for Blade/Flap/Actuator
    - Flap aerodynamics table lookup
    - Aerodynamically balanced flap
    - Actuator dynamics
    - Aeroelastic stability

All these studies focus on vibration reduction

Background (2/2): Swashplateless Rotor

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- Lemnios & Wei (1979-90)
  - Kaman SH-2 Rotor
  - Servo flaps
  - Modeling and correlation with test

- Straub & Charles (1990)
- Phillips & Murphy (1990)
  - Advanced Rotor and Control System (ARCS).
  - Preliminary assessment of control requirement

- Ormiston (2001)
  - Rigid blade model (pitch-flap)
  - Plain trailing-edge flaps
  - Rotor blade aeroelastic characteristics, performance
  - Trailing-edge flap reversal and effectiveness

Objective

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Develop a comprehensive rotorcraft analysis for swashplateless rotor with smart flaps, and evaluate the impact of smart primary control system on rotor loads and performance.

Carry out

- Validation of conventional rotor (without flaps) with wind tunnel test data and CAMRAD II predictions
- Correlation of vibratory loads of T.E. flap rotor with CAMRAD II predictions (Boeing-Mesa)
- Analytical result for a swashplateless rotor with smart flaps

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, Theodorsen)
- Free wake
- Modal reduction
- Coupled trim solution for free flight and wind tunnel conditions

MD900 Explorer: 5-bladed bearingless rotor

Aerodynamics

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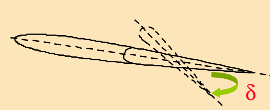
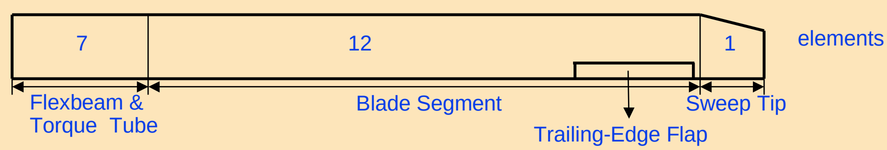
- Blade airfoil with T.E. flap
  - Unsteady trailing edge flap model, indicial method (Leishman and Hariharan)
  - Theodorsen flap theory for aerodynamically balanced flap
  - C81 format table lookup for C_l, C_d, C_m, C_h, and C_{lf}
- Free wake model (Bagai-Leishman)
  - Pseudo-implicit predictor-corrector relaxation scheme



Analytical Model

- **MDART rotor**
  - Pre-production of MD900 rotor
  - 5-bladed bearingless rotor
- **Blade FEM discretization**
  - Flexbeam and torque tube 7
  - Blade segment 12
  - Sweep tip 1
- **Flap configuration**
  - Flap Chord 25% c
  - Flap length 18% R
  - Flap midsection location 83% R
- **Wind tunnel trim condition**
  - Thrust coefficient (C_T/σ) 0.075
  - Shaft angle (prescribed)



Wind Tunnel Trim

Typical wind tunnel experimental procedure involves adjusting the controls to achieve zero first harmonic flapping and prescribed C_T/σ value with prescribed shaft angles.

• Conventional Rotor

Blade pitch (Control inputs)

- **Blade collective pitch (θ_0) → C_T/σ**
- **Blade cyclic pitch (θ_{1c}, θ_{1s}) → β_{1c}, β_{1s}**

• Swashplateless Rotor

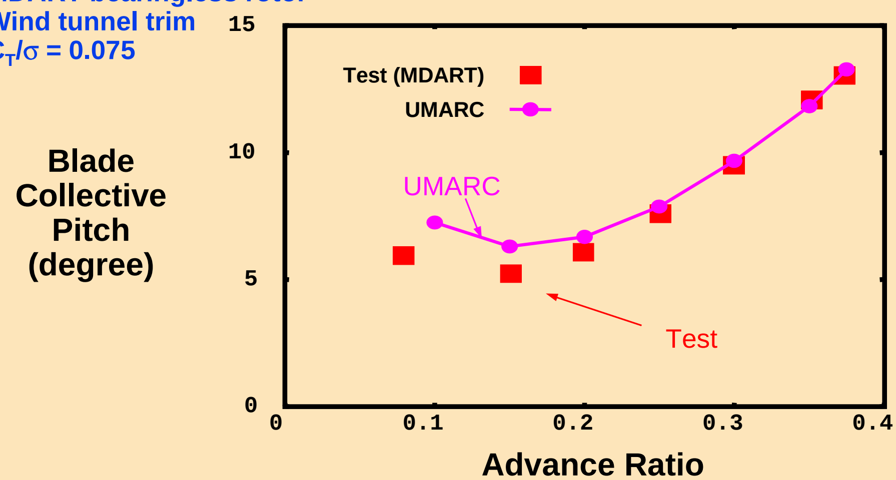
Smart flap deflection (Control inputs)

- **Smart flap collective (δ_0) → Blade twist (ϕ_0) → C_T/σ**
- **Smart flap cyclic (δ_{1c}, δ_{1s}) → Blade twist (ϕ_{1c}, ϕ_{1s}) → β_{1c}, β_{1s}**

Validation Study
For Conventional Rotor
(Without Trailing-Edge Flap)

Baseline Results (without T.E. Flap): Blade Collective Control

- MDART bearingless rotor
- Wind tunnel trim
- $C_T/\sigma = 0.075$



- UMARC result shows good correlation with test data.

Baseline Results (without T.E. Flap): Blade Cyclic Control

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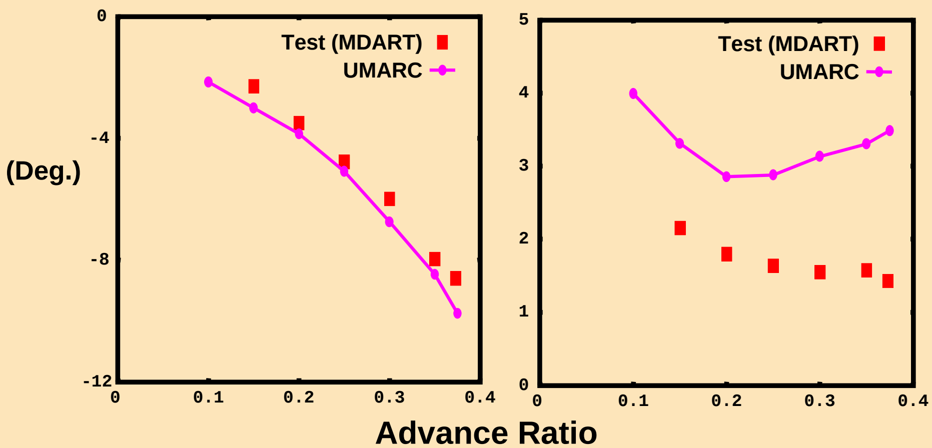

- UMARC result shows good correlation longitudinal cyclic and poor correlation lateral cyclic.

Baseline Results (without TEF): Blade Flap Bending Moment

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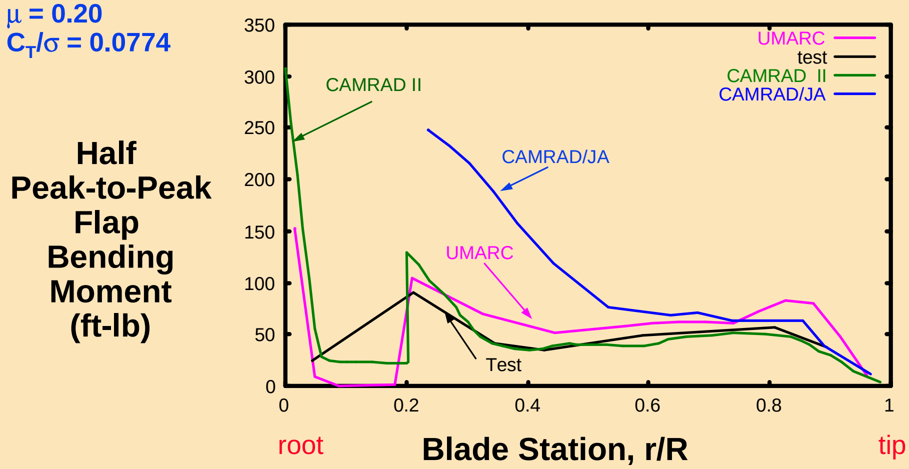
- MD900 bearingless rotor
- $\mu = 0.20$
- $C_T/\sigma = 0.0774$



- UMARC result shows good correlation with test data and CAMRAD II prediction

Baseline Results (without TEF): Blade Chord Bending Moment

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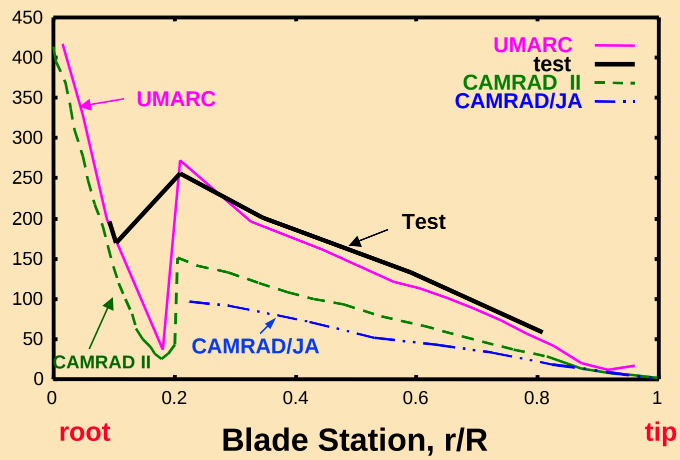
- MD900 bearingless rotor
- $\mu = 0.20$
- $C_T/\sigma = 0.0774$

Half Peak-to-Peak Chord Bending Moment (ft-lb)



- UMARC result shows good correlation with test data.

Baseline Results (without TEF): Blade Torsion Moment

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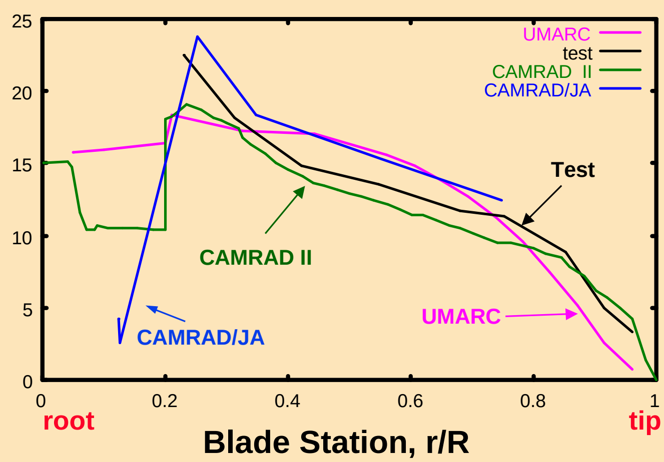
- MD900 bearingless rotor
- $\mu = 0.20$
- $C_T/\sigma = 0.0774$

Half Peak-to-Peak Torsion Moment (ft-lb)



- UMARC result shows good correlation with test data and CAMRAD II prediction.

Correlation
For Flap Analysis
(Response & Loads Result)

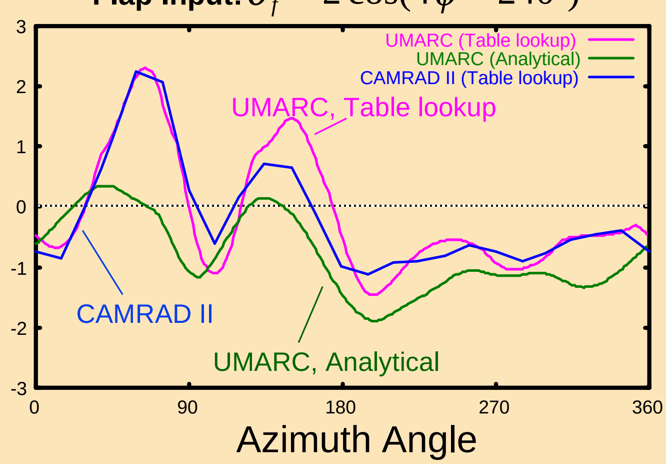
T.E. Flap Hinge Moment

- 0.18R Flap Located at 0.83R
- μ = 0.20
- C_T/σ = 0.0774

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

Trailing-Edge Flap Hinge Moment

(ft-lb)



- Results of UMARC and CAMRAD II both using table lookup agree with each other
- Result of UMARC using Theodorsen model qualitatively agree with the other two predictions

Torsion Moment at .60R

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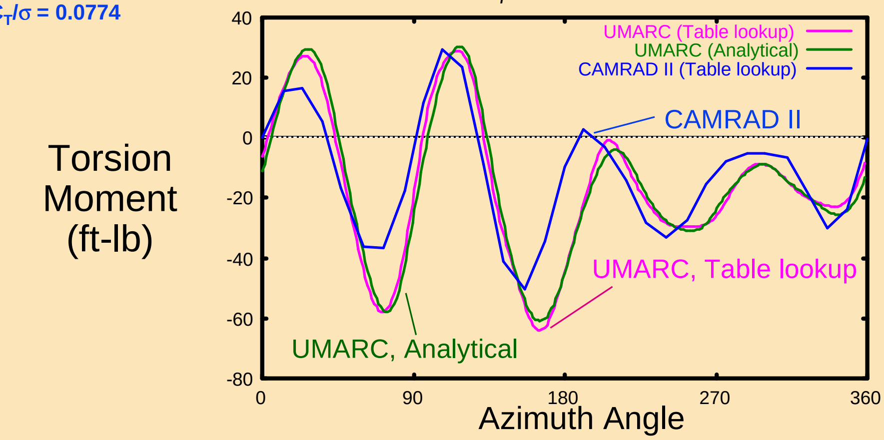
- .18R Flap Located at .83R
- μ = 0.20
- C_T/σ = 0.0774

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



- **UMARC result agree with CAMRAD II predictions.**

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Loads Result for Swashplateless Rotor With Smart Trailing-edge Flaps

Rotor & Flap Configuration

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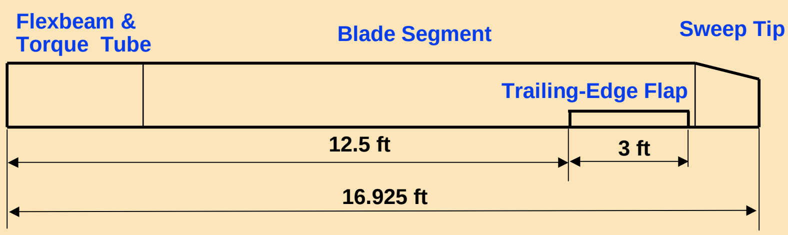
- **Blade structural properties**

  (Modified MD900 rotor blade)

- Flap frequency	1.03/rev
- Lag frequency	0.67/rev
- Torsion frequency	2.10/rev
- Blade pitch indexing	16 deg.

- **Flap configuration**

- Flap Chord	25% c
- Flap length	18% R
- Flap midsection location	83% R



Blade Pitch Indexing

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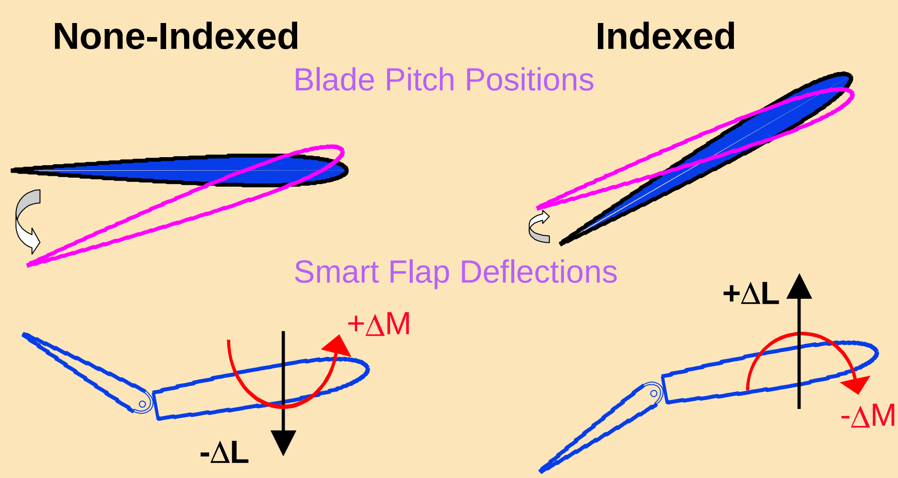

- **Smaller blade pitch travel with blade pitch indexing.**
- **Selection of blade indexing is key to low actuation power.**

Blade Pitch/twist Controls

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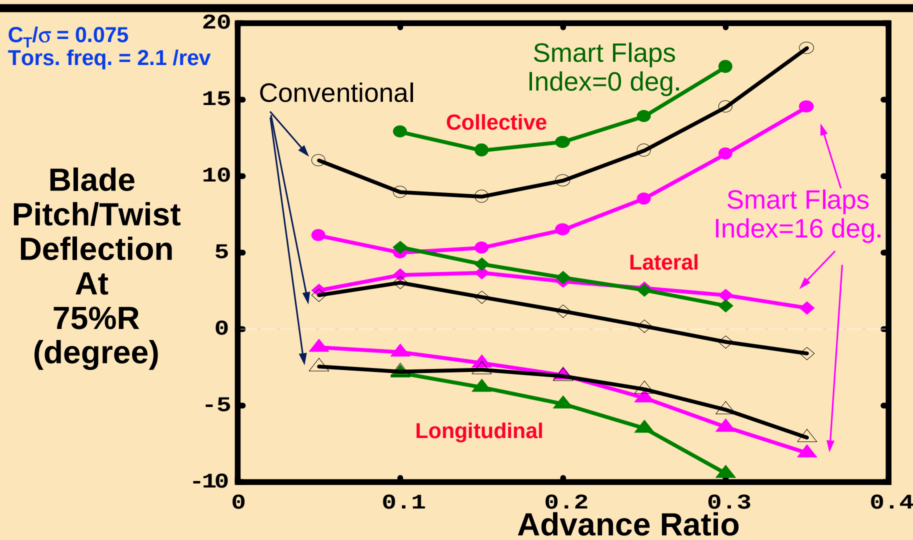
- C_T/σ = 0.075
- Tors. freq. = 2.1 /rev



- Smaller collective pitch for swashplateless rotor due to incremental lift of trailing-edge flaps

T.E. Flap Deflections

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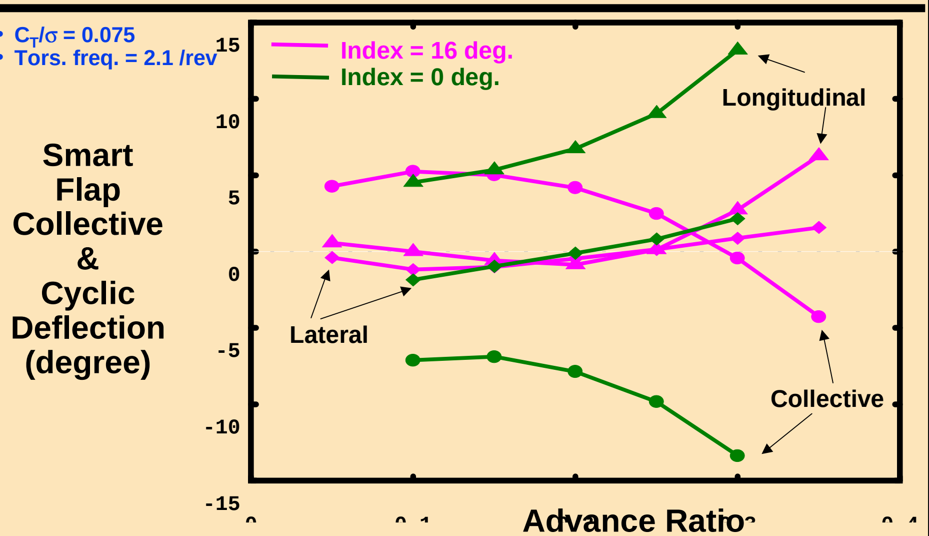
- C_T/σ = 0.075
- Tors. freq. = 2.1 /rev



- For advance ratios below 0.3, positive flap deflections result in favorable incremental lift.

Main Rotor Shaft Power

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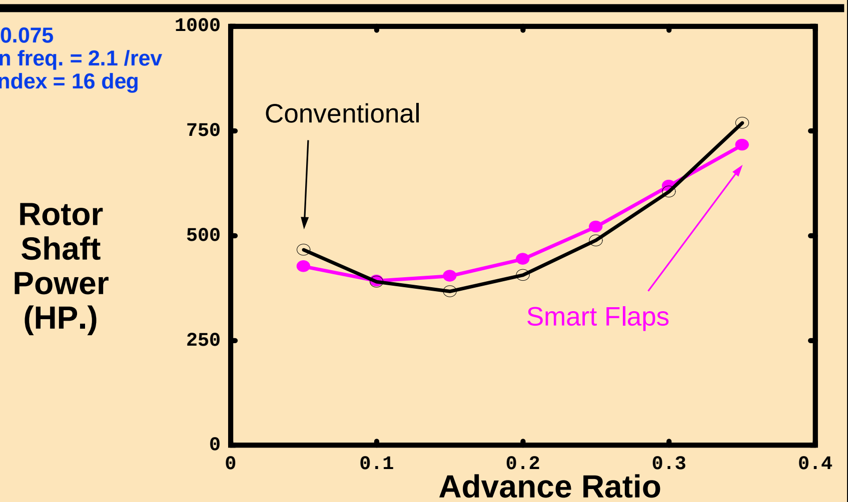
- $C_T/\sigma = 0.075$
- Torsion freq. = 2.1 /rev
- Pitch index = 16 deg



- Swashplateless rotor show larger rotor shaft power than that of conventional at most advance ratios except 0.1 and 0.35.

Actuation Requirement

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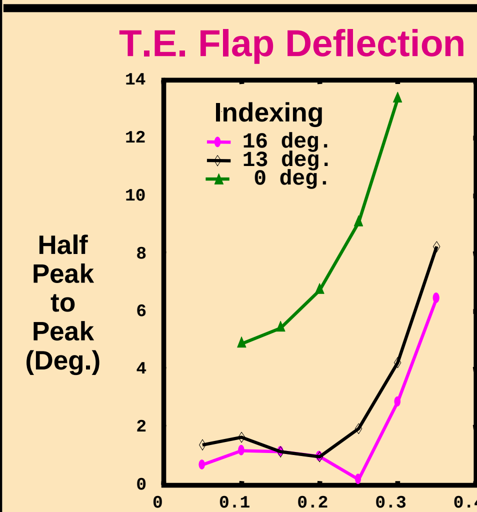

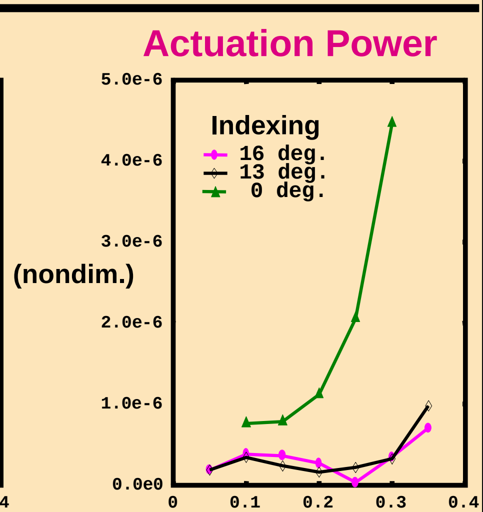

Advance Ratio

- Requirement increase largely after advance ratio 0.3 for indexed blade.

Smart Flap With Multiple Roles

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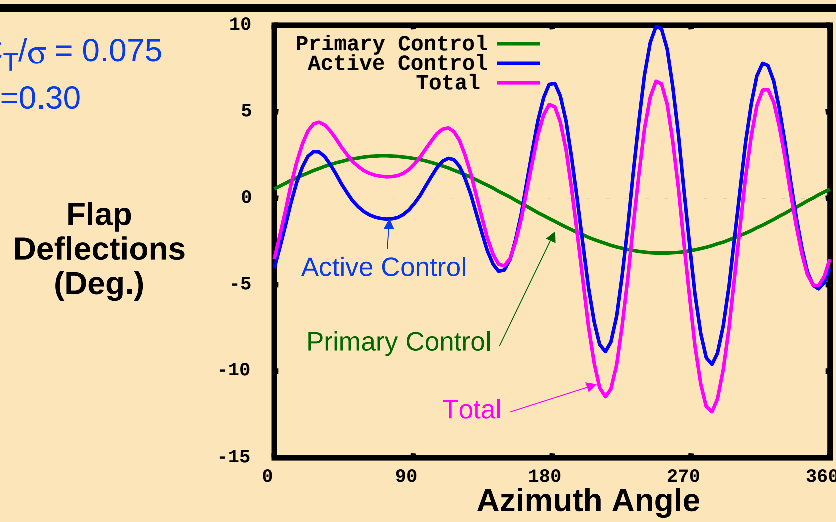
- $C_T/\sigma = 0.075$
- μ=0.30



- **Smart flap can play multiple roles with primary control (1/rev input) and active vibration control (high harmonics input).**

Rotor 5/rev Vibratory Hub Loads

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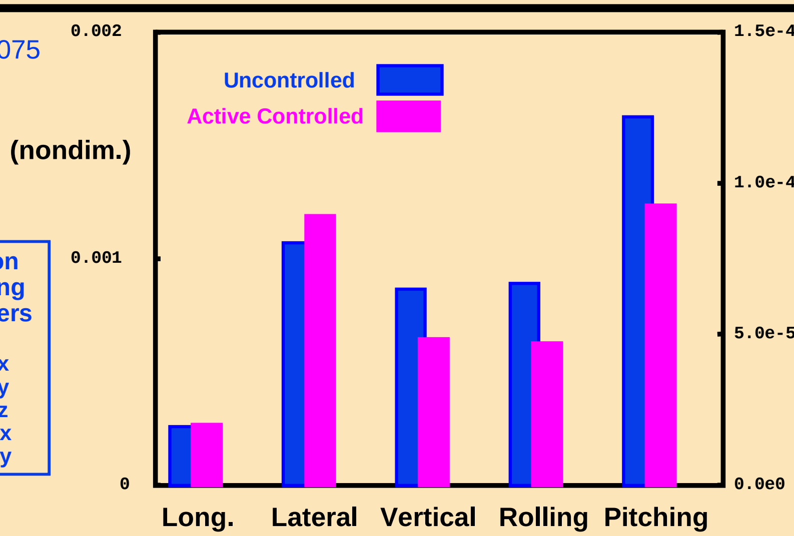
- $C_T/\sigma = 0.075$
- μ=0.30

Vibration Weighting Parameters

0.040 Fx
0.023 Fy
1.000 Fz
0.440 Mx
0.136 My



- **About 30% vibratory hub loads reduction with smart flaps playing both the roles of primary control and vibration control.**

Summary & Conclusions (1/2)

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- Correlation with MDART test data for conventional rotor showed fairly good agreement.
- Trailing-edge flap hinge moments and blade torsional moment were compared between UMARC and CAMRAD II calculations; good agreement is seen.
- Comprehensive rotorcraft analysis for swashplateless rotor with smart flaps was developed, and the actuation requirement of smart primary control system was evaluated.

Summary & Conclusions (2/2)

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- Blade pitch indexing is key to achieve a feasible swashplateless rotor system with smart flaps.
  - Flap half peak-to-peak deflection was reduced about 2~4 times with 16 deg blade indexing.
  - Actuation power was reduced about 5~20 times with 16 deg blade indexing.
- Smart flaps are capable to play both the roles of primary control and active control.
  - For advance ratio 0.30, about +/- 3 deg (1/rev) flap inputs for primary control, and +/- 10 degree (4,5,6/rev) flap inputs for active vibration control
  - Vibratory hub loads was reduced 30%.

Acknowledgements

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