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A Finite Element Model for Structural and Aeroelastic Analysis of Rotary Wings with Advanced Blade Geometry

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Problem statement

Nowadays, crucial issues in rotorcraft design are the reduction of

- Noise
- Vibrations

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- Community acceptance
- Fatigue life of structures
- Maintenance costs

A crucial role is played by rotors as sources of noise and vibrations in rotorcraft

Problem statement

Solutions adopted by designers and researchers are oriented to

- Blade with advanced geometrical and structural properties
- Innovative control devices

BLUE EDGE blade

Since earlier stages of the design process, the availability of accurate tools for prediction of blade dynamics is a crucial issue

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Model Introduction

FEM model for rotor blade structural analysis

Main features

- High flexibility
- Advanced blade geometry (swept and anhedral blade tip)

Application field

- Tiltrotors and helicopters rotor blades design
- Wind turbines blades

Motivations - Why Comsol

- Commercial codes for rotor blades analysis not commonly available
- *Comsol* seems to be the easiest way to implement the model

Mathematical model

Blade structural formulation based on the nonlinear beam-like model developed by Hodges and Dowell in 1974 for straight blades.

It includes:

- Rotating motion of the blades
- Nonlinearities from moderate displacements assumption
- Pre-twist, nonuniform properties

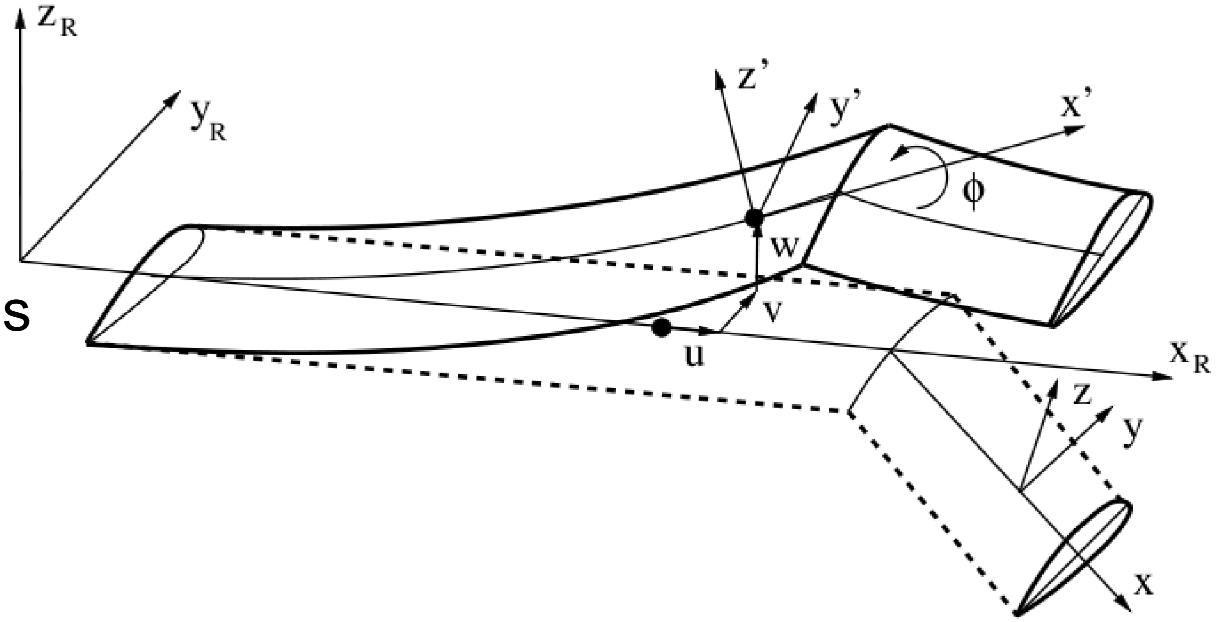
This formulation has been extended to **arbitrary elastic axis** shape to take into account advanced blade geometry as swept and anhedral tip.

Mathematical model

Equations of motion derived in a weak form, starting from *Hamilton* principle

$$\int_{t_1}^{t_2} [\delta(U-T)-\delta W]\,dt=0$$

U = strain energy
T = kinetic energy
W = work of external loads



Degrees of freedom:
axial displacement, *u*, bending displacements *v*, *w*, torsion ϕ

Mathematical model

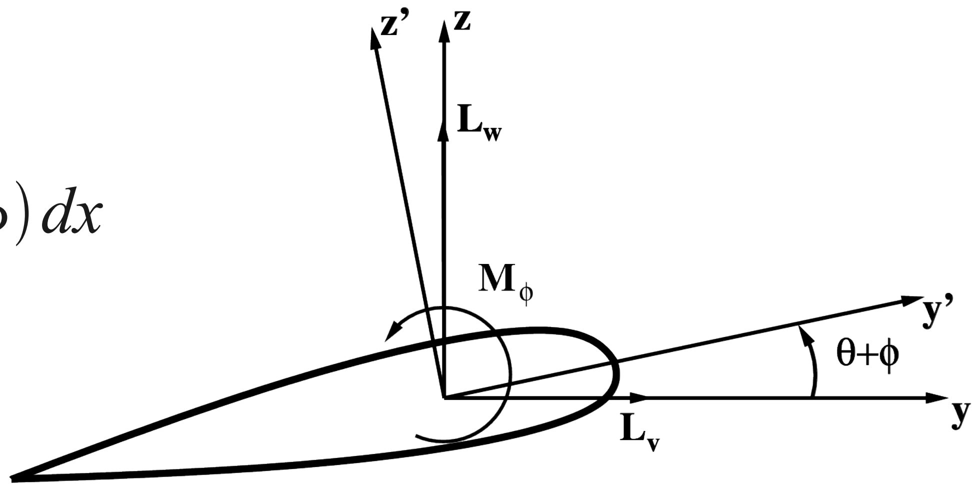
- Since moderate displacements assumption, strain-displacements relations are nonlinear and a second order approximation scheme is applied

- Inertial loads due to the rotary motion of the blade are derived considering arbitrary orientation of each beam element.

For aeroelastic applications:

$$\delta W = \int_0^R (L_v \delta v + L_w \delta w + M_\phi \delta \phi)\, dx$$

L_v, L_w and M_ϕ are the sectional loads from quasi-steady airfoil theories



Implementation in *Comsol*

Starting point: the 3D Euler-Bernoulli beam model

Why

- Same dofs of the rotor blade model
- Availability of transformation from local to global variables

How

Equations of motion written in beam local reference and:

- *weak* terms = δU
- *dweak* terms = δT

Implementation in *Comsol*

Starting from the transient solver it is possible to determine:

- Stationary analyses
- Parametric analyses
- Eigenvalue analyses

Since the nonlinearities of the problem, the last solution requires a solution sequence:

step 1: Stationary solution

step 2: Eigenvalue solution of equations perturbed about step 1 solution

Results – Model validation

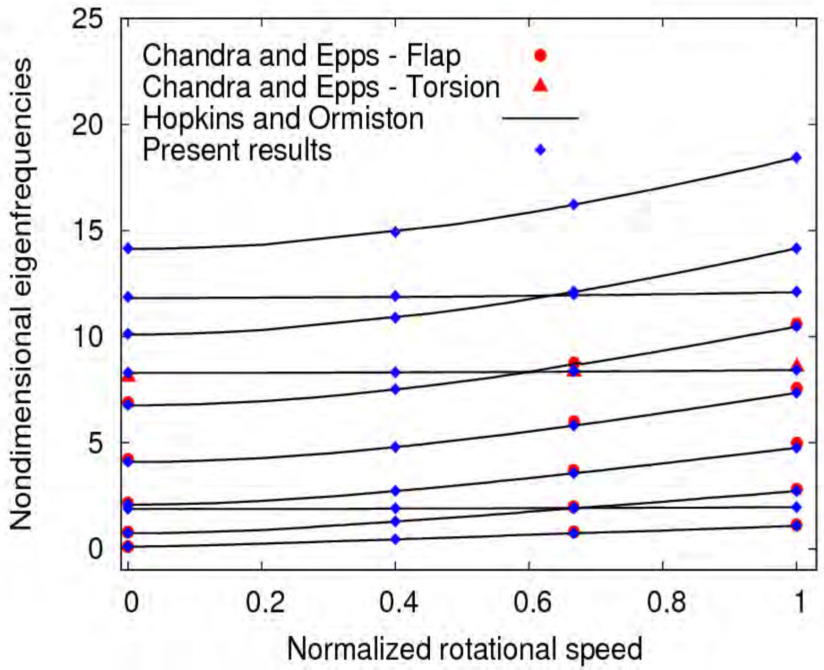
Model validation through comparisons with numerical and experimental literature data for rotor blades with sweep and anhedral angles at the tip.

1) **In-vacuo structural dynamics analysis**

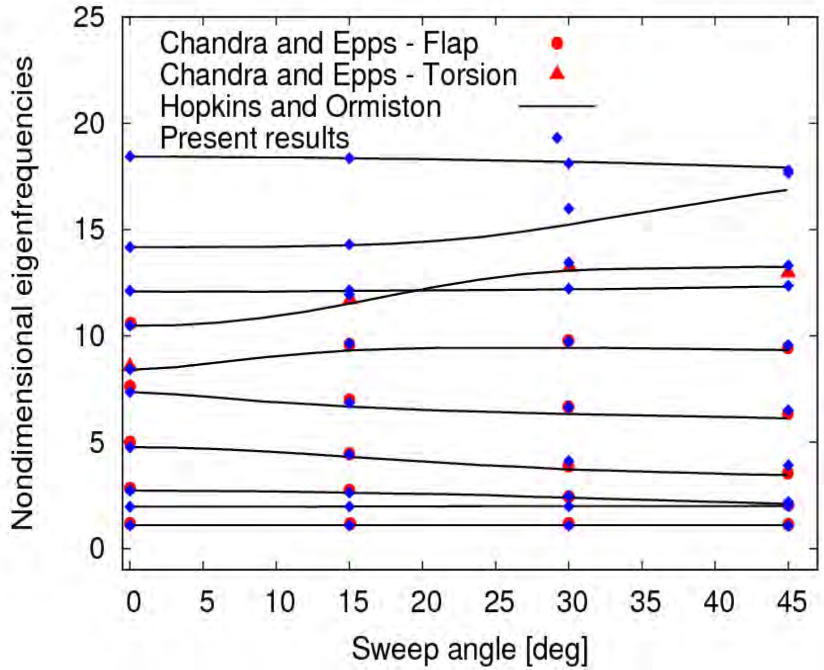
2) **Aeroelastic analysis**

Results – Model validation
eigenanalysis in vacuo

Rotating straight blade



Rotating swept tip blade

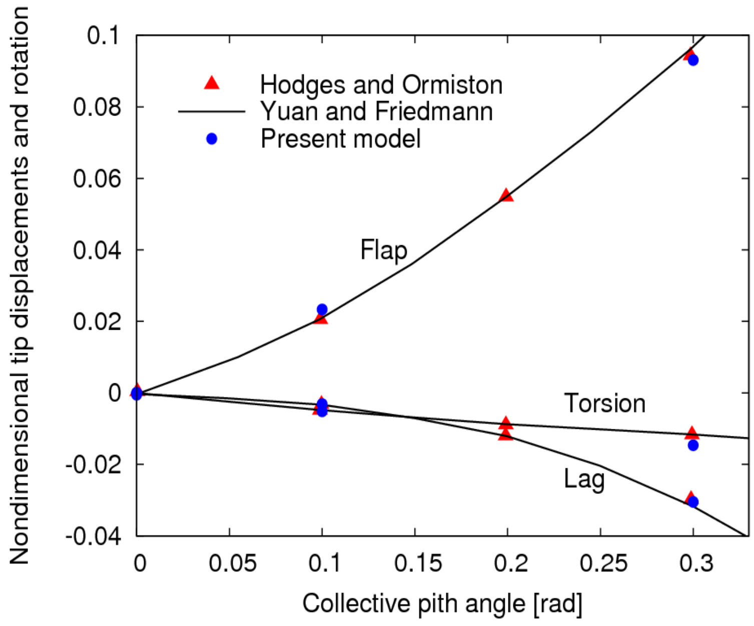


Hopkins and Ormiston (numerical)
Chandra and Epps (experimental)

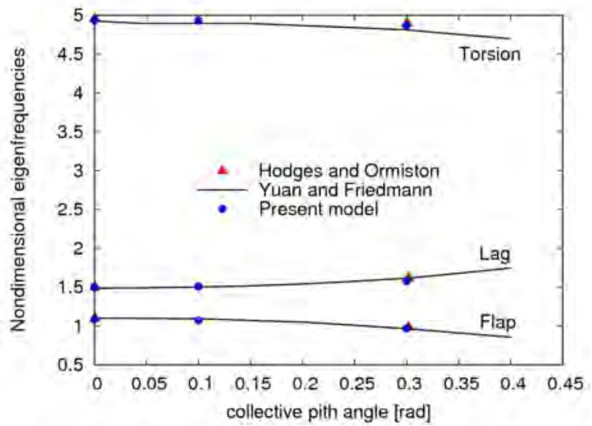
Results – Model validation
hovering aeroelastic analysis

Straight blade
(lag = in-plane bending)

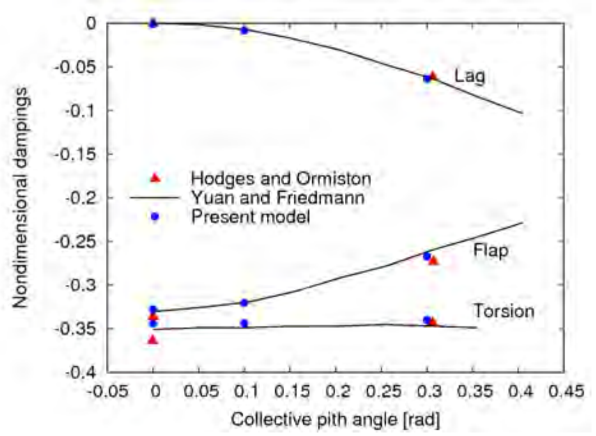
Stationary solution



Eigenfrequencies



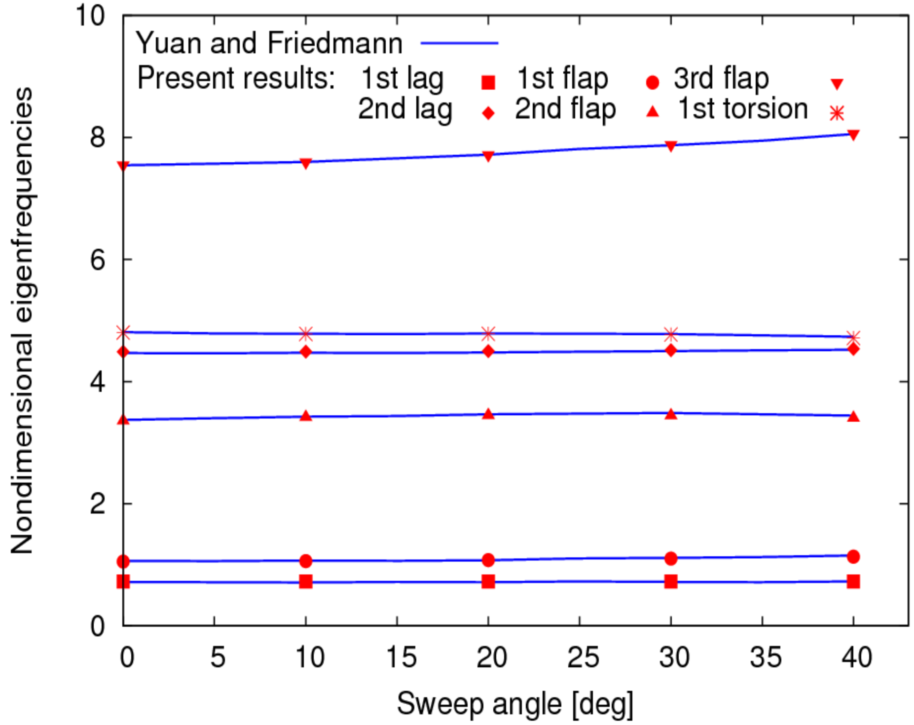
Dampings



Results – Model validation
hovering aeroelastic eigenanalysis

Swept tip blade

Eigenfrequencies



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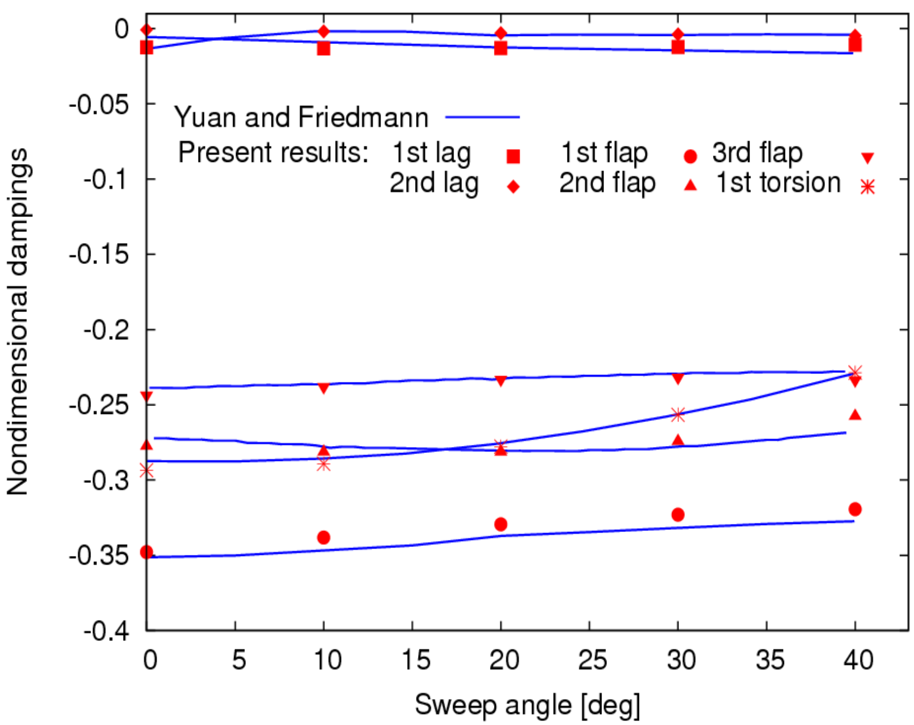
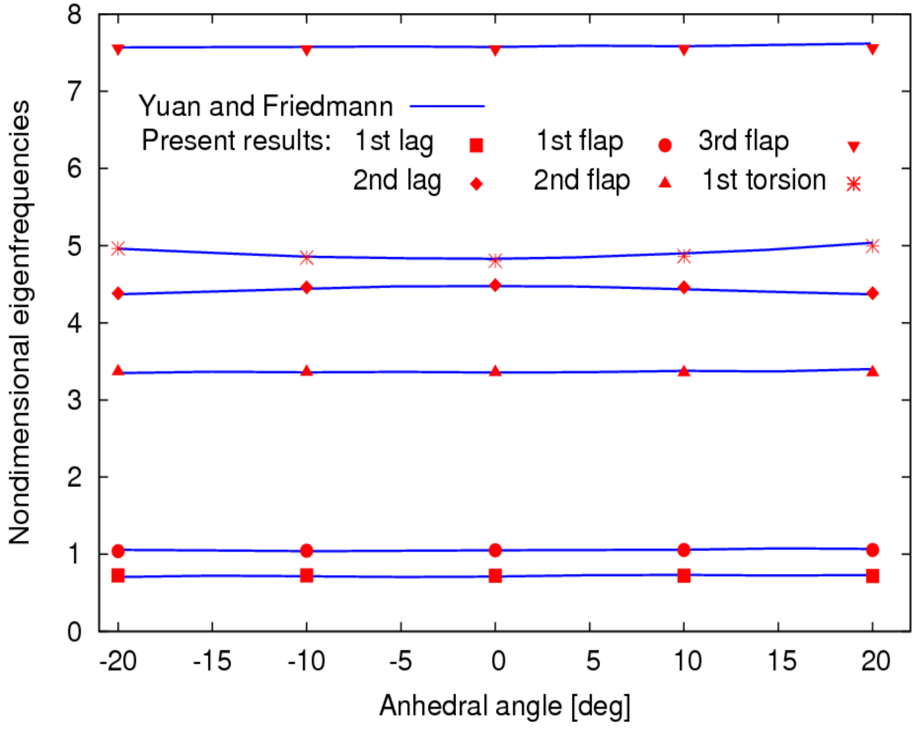


Results – Model validation
hovering aeroelastic eigenanalysis

Anhedral tip blade

Eigenfrequencies



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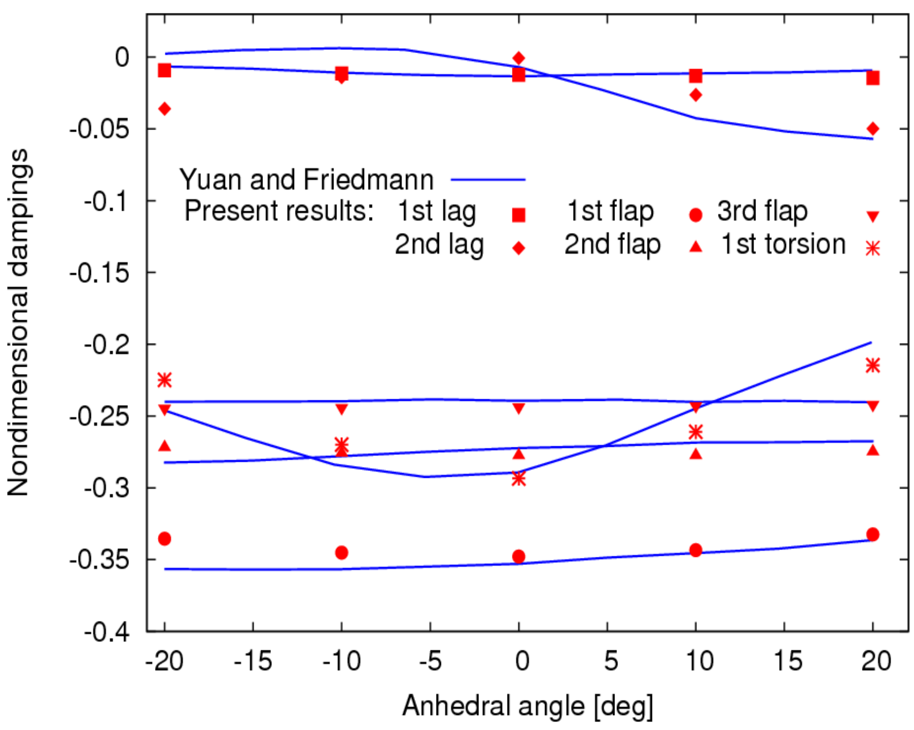
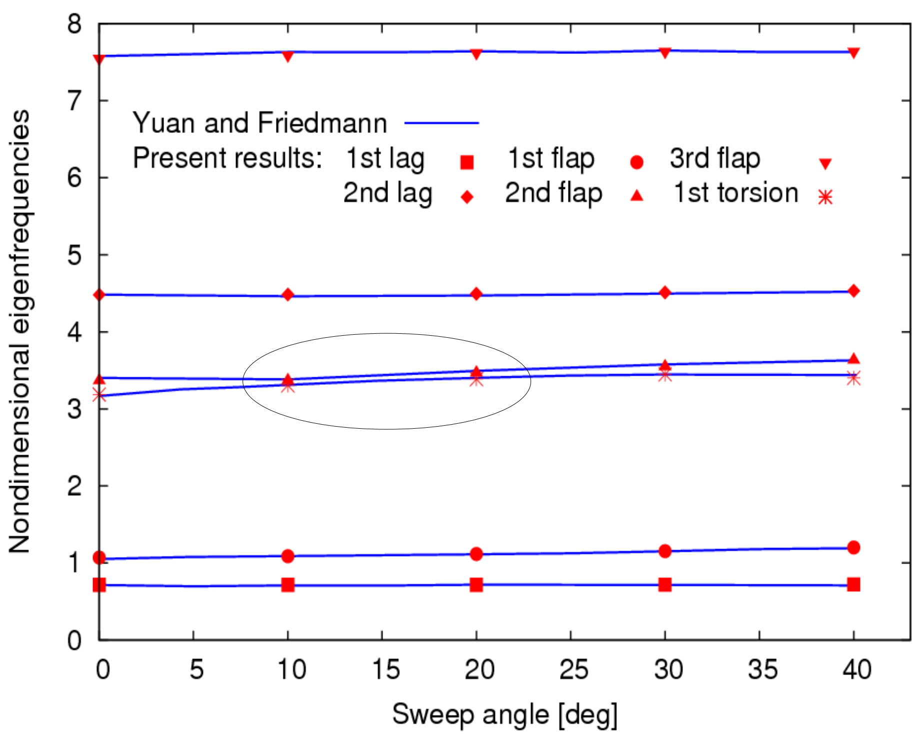


Results – Model validation
hovering aeroelastic eigenanalysis

Swept tip blade: torsional stiffness effects

Eigenfrequencies



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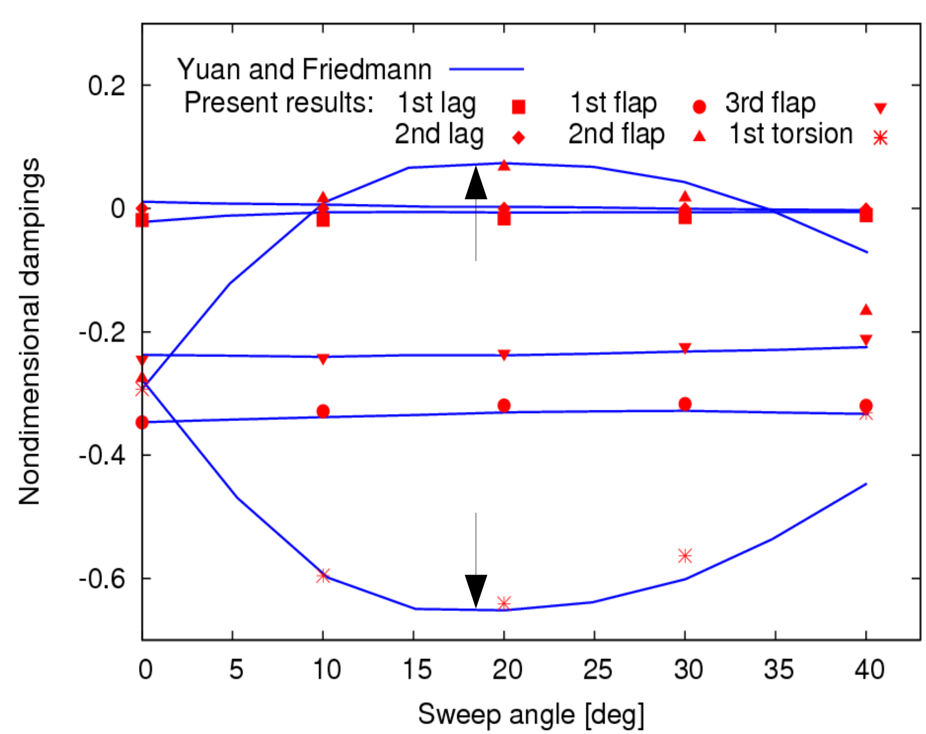

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Conclusions

1. A FEM model suited for structural and aeroelastic analyses of rotors blades with advanced geometry has been developed and implemented in *Comsol Multiphysics*

2. The model has been validated through comparisons with numerical and experimental literature data, for in vacuo free vibrations and aeroelastic analyses

3. Results show the capability of the formulation to predict with good accuracy the structural dynamics and aeroelastic behavior of rotating blades with advanced geometry

4. The developed FEM model seems to be a reliable tool for analysis and design of helicopter and tiltrotor rotor blades.

Future work

Present formulation will be extended to include:

- Non isotropic (composite) blade materials
- Rotor forward flight conditions