Stiff-Inplane Tiltrotor Aeromechanics Investigation Using Two Multibody Analyses

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Outline

1. *Motivation*
    - Simulations Replace Experiments
    - Tiltrotor Aeromechanics with Multibody Codes
    - Previous Work
    - Objectives

2. *Analytical Model*
    - Multibody Dynamics Codes
    - Multibody Tiltrotor Models

3. *Analytical Results*
    - Wind Tunnel Test Used in Model Validation
    - Baseline Results
    - Parameter Study: Pitch-Flap Couplings
    - Parameter Study: Aerodynamic Compressibility

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Cost Saving by Replace Experiments with Simulations

Why uses multibody dynamics simulations in rotorcraft industry?

- Experimental testing routinely performed to verify design
- Experiment, either flight test or wind tunnel test, becomes prohibitively expensive
- Multibody analyses provide high-level of details of complex mechanics in rotor system

Simulation using multibody dynamics codes may become an alternative to expensive experimental verifications.

What is a Tiltrotor?

The Bell-Boeing V-22 Osprey, best known tiltrotor aircraft

Tiltrotor uses tiltable proprotors for lift and propulsion; a combination of helicopter and turboprop aircraft.

- Helicopter mode: proprotor pylon vertical to ground
- Transition mode: proprotor pylon tilts forward
- Airplane mode: proprotor pylon parallels to ground

Tiltrotor has high cruise speed and range, and has also vertical takeoff/landing and hover capability.

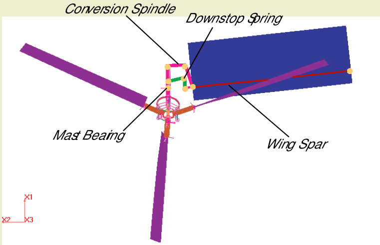
Tiltrotor Whirl Flutter

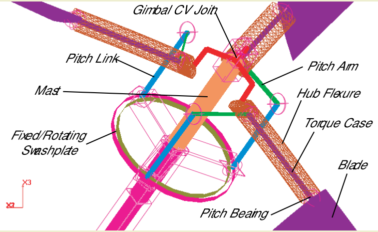
Electra two fatal crashes in 1959 and 1960 due to whirl flutter

- Similar to turboprop aircraft whirl flutter
- Happens in airplane mode
- Aerodynamic forces in rotor plane drive wing beam mode unstable
- Tiltrotor has more degrees of freedom and larger rotor
- A flapping proprotor on a flexibly supported pylon can exhibit whirl flutter

Tiltrotor whirl flutter is an aeroelastic instability phenomenon involving the proprotor, pylon, and wing.

Important Structural Modes in Tiltrotor Whirl Flutter





Fixed System: Wing and Pylon (Pylon Mount: Downstop Spring)

- Wing/pylon beamwise mode
- Wing/pylon torsional mode

Rotating System: Rotor and Hub (Stiff or Soft Inplane Rotor)

- Rotor flap mode
- Rotor lag mode
- Rotor torsional mode

Previous Work

Stiff-inplane tiltrotor

- Ghiringhelli, Masarati, et al.
  Nonlinear Dynamics,
  Vol. 19, No. 4 1999
    - Pioneer work of modeling tiltrotor with multibody analysis
    - Rotor natural frequencies
    - Conversion loads study
    - Lack of whirl flutter study

Soft-inplane tiltrotor

- Masarati, Piatak, et al.
  American Helicopter Society
  Forum, 2004, 2005
    - Using two multibody analyses
    - Whirl flutter study
    - Rotor mast free-play
    - Parameter study

- Soft-inplane rotor has insufficient stability boundaries
- Current production tiltrotor uses stiff-inplane rotor
- Need multibody validation of stiff-inplane tiltrotor model

Objectives

- Develop a sophisticated stiff-inplane tiltrotor model component by component using two multibody dynamics codes
- Carry out correlations of the analytical models with experimental data
- Conduct parametric investigations of key variables that are crucial to the tiltrotor aeromechanical behavior

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DYMORE

- Developed by *Georgia Institute of Technology* team, lead by *Prof. Olivier Bauchau*
- Nonlinear, FEM-based, multibody dynamics code

Nonlinear

- Large deformations
- Free-play/contact
- Geometry
- Aerodynamics

FEM-based

- Beams
- Shells
- Membranes

Multibody

- Rigid bodies
- Joints
    - Revolute
    - Prismatic
    - Spherical
    - Cylindrical

Aerodynamics

- State-space lifting line theory
- Coupling with Computational Fluid Dynamics (CFD) models

MBDyn

- Developed by *Politecnico di Milano* team, lead by *Prof. Paolo Mantegazza*
- Multibody dynamics code with libraries: Mechanical, Hydraulic, Controls, Aerodynamic.

Mechanical

- Rigid bodies, Deformable: Lumped, Beams, Modal elements
- Joints: Absolute/relative position, orientation, velocity, acceleration.

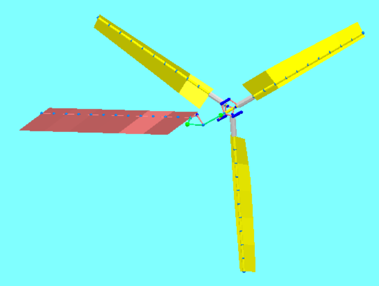
Controls

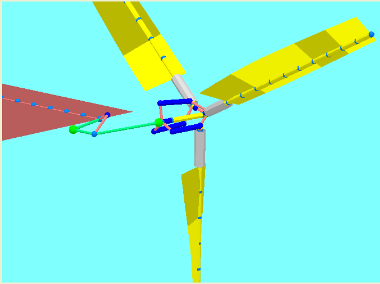
- Electric motors
- Strain, displacement, acceleration
- Programmable elements

Aerodynamics

- Blade element on rigid bodies, beams
- Coupling with CFD models

DYMORE & MBDyn Tiltrotor Models





Structural modeling

- Beams: Wing, blades
- Rigid bodies: rotor hub, control system, pylon
- Springs: control system stiffness, pylon mount (downstop springs)

Aerodynamic modeling

- Aerodynamic forces on wing and rotor
- Aerodynamic interaction between wing and rotor neglected

Beam Discretization

	DYMORE		MBDyn	
Beam	Number	Order	Number	Order
Wing	10	3	6	2
Flex-beam	5	3	10	1
Blade	10	3	15	2

Beam discretization?

Degrees of freedom

- DYMORE: 3554
- MBDyn: 1873

Real/Simulated time

- DYMORE: 700:1
- MBDyn: 70:1

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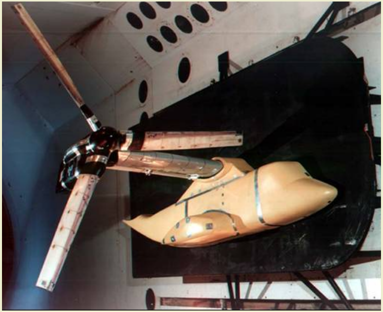
Wind Tunnel Model and Test

WRATS stiff-inplane tiltrotor in NASA Langley TDT tunnel tested in 2000



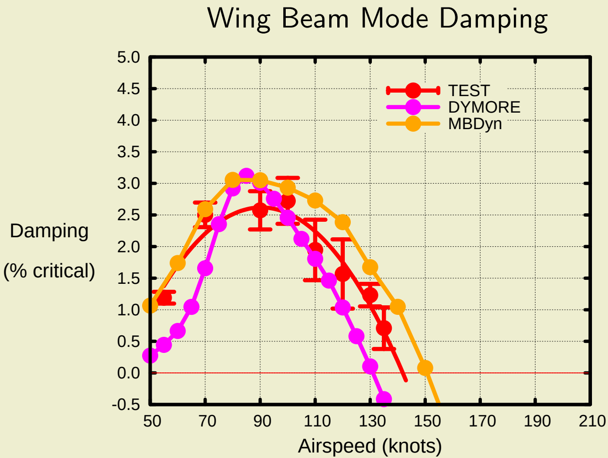
Test Procedure

- Trim: adjust blade pitch angle to trim rotor speed in windmilling
- Excitation: excite wing/pylon mode
- Stability: process wing transient response to obtain damping
- Sweep: increase air speed until low damping or flutter

"Virtual Experiment"

Analytical models use the same procedure to predict wing damping.

Baseline Stability Boundary (1/3)



Parameters

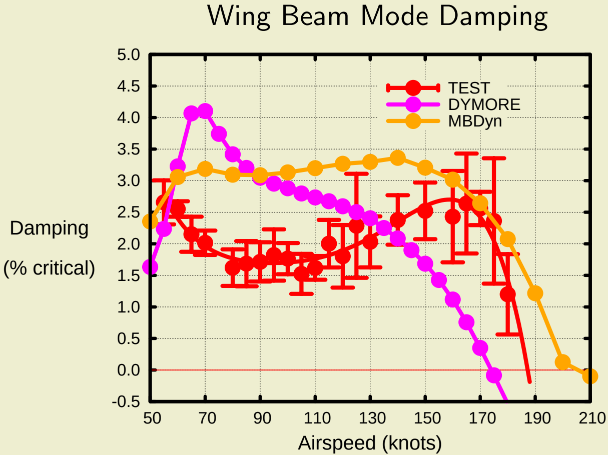
- Pylon: Off-Downstop
- Rotor Speed: 742 RPM

Flutter Speed (kts)

TEST:	140
DYMORE:	130
MBDyn:	150

- Low flutter speed when pylon is off downstop-lock
- Good agreements among analytical predictions and test data

Baseline Stability Boundary (2/3)



Parameters

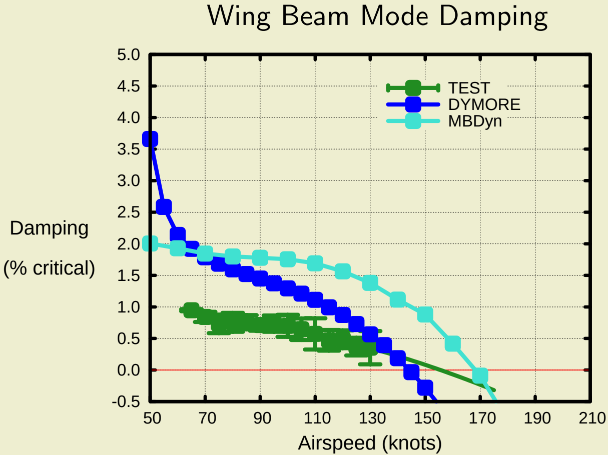
- Pylon: On-Downstop
- Rotor Speed: 770 RPM

Flutter Speed (kts)

TEST:	190
DYMORE:	175
MBDyn:	200

- Higher flutter speed when pylon locked on-downstop
- Fair agreements among analytical predictions and test data

Baseline Stability Boundary (3/3)



Parameters

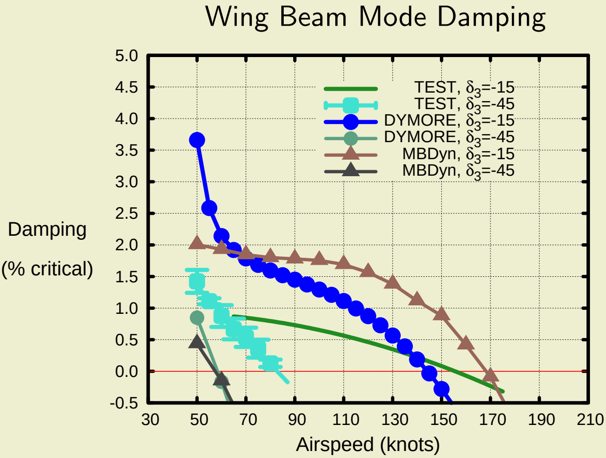
- Pylon: On-Downstop
- Rotor Speed: 888 RPM

Flutter Speed (kts)

- TEST: 155
- DYMORE: 145
- MBDyn: 170

- Flutter speed reduces when increasing rotor speed
- Fair agreements among analytical predictions and test data

Parameter Study: Pitch-Flap Couplings (δ_3)



Parameters

- Pylon: On-Downstop
- Rotor Speed: 888 RPM

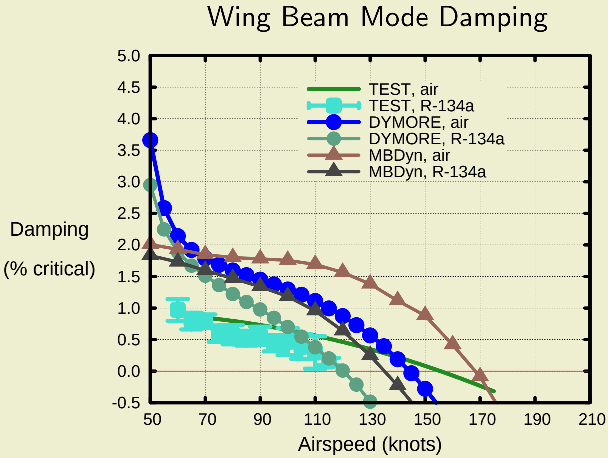
Flutter Speed (kts)

With $\delta_3 = -45°$

- TEST: 80
- DYMORE: 60
- MBDyn: 60

- Flutter speed reduces when increasing pitch-flap coupling
- Analytical models capture the flutter speed reduction

Parameter Study: Aerodynamic Compressibility



Parameters

- Pylon: On-Downstop
- Rotor Speed: 888 RPM

Flutter Speed (kts)

Test gas R-134a

TEST:	120
DYMORE:	120
MBDyn:	135

- Aerodynamic compressibility reduces whirl flutter speed
- Analytical models capture the flutter speed reduction

Summary

- Develop analytical models of WRATS stiff-inplane tiltrotor using two multibody dynamics codes
- Multibody dynamics analyses show consistent capabilities in predicting tiltrotor whirl-flutter stability
- Parameter study using multibody dynamics analyses shows same trend as experimental investigation

- Outlook
  - Further improve analytical correlations
  - Detailed comparisons of the two multibody models in sub-component level and in the computational aspects