Rotorcraft Acoustics and Dynamics

Group Activities

Edward C. Smith, Professor
Director, Penn State Vertical Lift Research Center
CAV Group Leader

Steve Conlon, Res Associate, PSU ARL
Assistant Professor, Aerospace Engineering Dept
Assoc. Director, Vertical Lift Research Center

2011 CAV Workshop
Interaction with Other PSU Research Centers

- Vertical Lift Research Center of Excellence
- ARL Condition Based Maintenance Dept.
- ARL National Center for Advanced Drivetrain Technology
- ARL iMAST
- Institute for Computational Science
- Center for Acoustics and Vibration
- Composites Manufacturing Technology Center
Vertical Lift Center Tech Base

Penn State ARL
NRTC CRI
SBIR Programs

31 Faculty

5 Res Assoc

60 + Graduate Students

100 Undergraduate Students
(Freshman Sem, AHS Chapter, Senior Class, Design projects)

40 Continuing Education Students (Short course)

apply & transition
1. ROTOR AEROMECHANICS & DYNAMICS
2. AIRFOIL DESIGN and TESTING
3. COMPUTATIONAL FLUID DYNAMICS
4. ACOUSTICS
5. STRUCTURES, MATERIALS, and MANUFACTURING
6. CONDITION-BASED MAINTENANCE
7. ICE PROTECTION
8. PROPULSION and DRIVE SYSTEMS
9. FLIGHT CONTROLS and SIMULATION
10. DUCTED FAN AIR VEHICLES
11. VARIABLE SPEED (RPM) & COMPOUND ROTORCRAFT
Presentation Outline

- **Group Highlights (5 min)**
  - Preparation and Submission of 2011-2016 VLRCOE Renewal Proposal

- **Individual Project Highlights**
  - **Multi-State Damper**: Design and Test (5 min)
  - **Ultrasonic Anti-Icing**: Recent progress (5 min)
  - **Airframe Structural Health Monitoring** (15 min)
    (Prof. Steve Conlon)
VLRCOE Renewal Proposal (aka “5 year storm”)

25 Separate Tasks
31 PIs (PSU, PSU ARL, Michigan (1), UT Austin (1))
40 Graduate Students
5 years (20011-2016)
$25M Total (12.5M from sponsor: NRTC = Army + Navy + NASA)

Partners (proposal cost share)

- LORD Corp
- Sikorsky
- Goodrich
- Bell
- Timken Aerospace
- Gyrodyne
- MagCanica Inc
- Penn State University
Group Highlights: VLRCOE Renewal tasks

**Aeromechanics:** More Speed, More fuel efficiency, all weather
- Unsteady Airfoil Design Methods
- Rotor Hub Flows > Drag reduction
- New Rotorcraft Airfoil Design Concepts
- Icing Physics, Modeling, Detection

**Structures:** Lower weight, more reliability, safety
- Nanotailored Composites > Improved Toughness and Thermal Conductivity
- Novel SMA Based Energy Absorbers
- Interfacial Fracture and Functional Grading > Ultrasonic Deicing
- Frequency Selective Rotor Lag Damping

**Flight Dynamics & control:** autonomy, safety, new configs
- Autonomous Multi-Lift Systems
- Load Limiting Flight Controls for Co-axial Rotors
Group Highlights: VLRCOE Renewal tasks

Design Concepts: Speed, range, altitude
Morphing Rotor Blades and Wings
Aeroelastically Tailored wing extensions and Winglets
  > Large Civil Tiltrotors
Control Redundancy> Perf, HQ, and Survivability
Reduced Actuation Reqs and HQ of Swashplateless Rotors

Vibration & Noise Control: active rotors, variable $\Omega$ rotors, speed
Fund Physics of Active Rotors > Perf and Acoustics
Multi-functional Trailing edge Flaps
Tunable Fluidlastic Structures > Vib control & energy harvest
Multifunctional Fluidlastic Picth Links> active rotors, energy harvest, loads control
Group Highlights: VLRCOE Renewal tasks

Propulsion and Drive Systems: weight, reliability, interior noise reduction

Comprehensive Anal of Gearbox Loss of Lube

Gearbox Health Monitoring and Loads Management via Piezo-magneto-elastic control systems

Multifunctional Radial Isolator > bearing HUMS and Noise Red

Affordability: condition-based maintenance, SHM, etc

Health Monitoring for Joints in Composite Structures

Structural Tailoring for High Sens Robust Damage Detection

Maritime Operations: shipboard ops, dynamic interface, slung loads, etc

Advanced Response Types and Cueing Systems for Naval Ops

Autonomous Shipboard Take-Off and Landing
Presentation Outline

• Group Highlights

• Individual Project Highlights
  - **Multi-State Damper**: Design and Test
  - **Ultrasonic Anti-Icing**: Recent progress
  - **Airframe Structural Health Monitoring**
    (Prof. Steve Conlon)
Multi-State Lead-Lag Damper Development and Validation

Conor Marr, PhD Candidate, Penn State
Zach Fuhrer, Senior Engineer, LORD Corporation
Edward C. Smith, Professor, Penn State
George A. Lesieutre, Professor, Penn State

AHS International 67th Annual Forum and Technology Display
Test and Evaluation I
Tuesday, May 3, 2011
Objectives

Design, construct, and **experimentally validate** a first generation prototype of a passive or semi-active LORD Fluidelastic™ **bypass damper** that greatly reduces damper forces when damping is not required.

An **adaptable lag** damper could greatly reduce the forces seen both by the damper and the blade and hub attachment points.

Longer damper life, smaller lower drag parts, lighter dampers.
Approach: Experiment

- Design damper to meet damping requirements for a generic light helicopter
- Reduce damper force by at least 50% via a bypass feature
- Conduct a series of experimental bench tests to evaluate the damper performance with bypass channels open and closed
Approach: Analysis

- Predict damper behavior using **basic analytical fluid flow** equations
- **Develop a CFD model** of the bypass damper
- Validate models with experimental data
- Use findings to work towards ultimate goal of developing a first-principles model that incorporates CFD correction factors
Experimental Prototype

- Adjustable number of orifices (max of 2) and orifice diameter
- Bypass channels able to be open or closed
- Adjustable number of bypass channels (max of 3)
- Bypass inlet diameter alterable up to 0.4 inches in diameter
- Closed state meets light helicopter damper requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>English</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piston Diameter</td>
<td>2.74 in</td>
<td>0.07 m</td>
</tr>
<tr>
<td>Bypass Diameter</td>
<td>3 x 0.4 in</td>
<td>3 x 0.01 m</td>
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CFD Model

- Ansys Workbench meshing utility used to create geometry and mesh
- Full 3 dimensional model
- Fluent used to calculate fluid flow
- Transient flow and dynamic meshing utilized
- Carreau equation for shear thinning captures nonlinear fluid behavior:

\[ \mu_{act} = \left( \mu_{\text{inf}} + (\mu_0 - \mu_{\text{inf}})\left(1 + (\gamma \lambda)^2\right)^{\frac{n-1}{2}} \right) \]
CFD Results: Bypass Closed

- Velocity Magnitude pictured over a single cycle for 2.5 Hz at 0.06” dynamic displacement

- Closed bypass channel case

- 2D cross section of 3D calculation

- Flow is almost exclusively through the orifice
CFD Results: Bypass open

- Velocity vectors at orifice and bypass entrance/exit
- Flow is split between bypass channel and orifice
- 3 bypass channels with a diameter of 0.1 inches reduce damper force by approximately 50%
Results: Comparison with CFD

4 Hz at 0.06” Bypass Closed

CFD Model: **10% error** for Peak Force, **15% error** for Loss Stiffness

Analytical Model: **45% error** for Peak Force, **82% error** for Loss Stiffness
Both CFD and Analytical models predict a near elimination of damping when three 0.4” diameter bypass channels are opened.
Results: Comparison with CFD

2.5 Hz at 0.06” Bypass Open

Main source of error due to lack of damping from the elastomer in the CFD and analytical models
Piezoelectric actuators used to create ultrasonic waves which generate transverse shear stresses at the ice interface.
Piezoelectric actuators used to create ultrasonic waves which generate transverse shear stresses at the ice interface.
### Ultrasonic De-Icing Issues

<table>
<thead>
<tr>
<th>Issue</th>
<th>Proposed Solution</th>
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<tbody>
<tr>
<td>Limited control of matching ultrasonic modes</td>
<td>PZT Actuation Controller</td>
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<tr>
<td>Actuator Cracking Failure</td>
<td>Drive Actuators in Compression</td>
</tr>
<tr>
<td>Actuator Debonding</td>
<td>Optimal Thickness Actuators</td>
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[Images of actuator failures and de-icing process]
**PZT Actuation Controller Design**

**Design Goal:** Develop a program to autonomously check the ultrasonic modes of a PZT actuator and drive the actuator at the optimum ultrasonic mode.

**Variations in Ultrasonic Modes due to:**
- Loading Conditions
- Ambient Temperature
- Actuator Temperature
- Boundary Conditions
Thickness Reduction

Predicted thinner actuators would not delaminate due to lower inertia forces.

Modeled 0.10” vs. 0.05” Thick Disk Actuators to compare transverse shear stresses at the PZT/Glue interface.

- **PZT-4 Disk 1.5” Diameter**
- **Ti Plate 6” x 6” x 0.04”**
- **Applied Voltage**
  - 70 V
  - 140 V

**EP 21 Adhesive - 0.01” Thick**
- \( \rho = 1078 \text{ kg/m}^3 \)
- \( E = 2240 \text{ MPa, } v = 0.3 \)
Thickness Reduction


Step: Step-3
Increment 9: Frequency = 6.4000E+04
Primary Var: S, S12   Complex: Real
Thickness Reduction

ODB: Thick_Disk_Results.odb  Abaqus/Standard 6.9-2  Mon Jan 10 15:09:15 EST 2011
Step: Step-3
Increment 9: Frequency = 6.4000E+04
Primary Var: S, S12  Complex: Real
Rotational Test Setup

Ultrasonic Deicing System Tested on Representative Leading Edge Erosion Cap

- Thin PZT-4 Disk
  - 1.5” Diameter, 0.05” Thickness (x12)
  - Total Volume = 1.07 in²
  - Radial Mode Frequency = 65-66 kHz

Test Specimen:
- 12” Span, 16” Chord, NACA 0015 Airfoil
- Interchange leading edge cap/actuation systems
Finite Element Model Setup

NACA 0015 Ti
Leading
Edge Erosion Cap

Ice Accretion
(2mm)

10.6 cm
Finite Element Results

Transverse shear stresses at the ice interface exceed published results for the adhesion strength of Ice-Ti (250kPa-875kPa)
Finite Element Results

Transverse shear stresses at the ice interface exceed published results for the adhesion strength of Ice-Ti (250kPa-875kPa)
Rotational Test Matrix

• A total of 4 Impact Icing Test Conducted
  – Tested at 2 Temperatures (-12 °C, -18 °C)

• Constants
  – RPM: 320
  – MVD: ~25 μm
  – LWC: ~3.5 g/m³

• Total icing time dictated by the rotor imbalance load limitations

• The Ice Thickness measured on Blade without ultrasonic deicing system
Rotational Test Matrix
Sample Results: Case 4

Icing Conditions
- Temp: -18.2 °C
- MVD: ~25 μm
- LWC: ~3.5 g/m³
- RPM: 320

No Ultrasonic De-Icing System
Ice Thickness: 0.431”

Ultrasonic De-Icing System
Power: 1.48 W/in²
Deicing Time: 139 s
Sample Results: Case 4

Icing Conditions
• Temp: -18.2 °C
• MVD: ~25 μm
• LWC: ~3.5 g/m³
• RPM: 320

No Ultrasonic De-Icing System

Heaters to Prevent Ice Bridging to Test Section

Ultrasonic De-Icing System
Power: 1.48 W/in²
Deicing Time: 139 s
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• Individual Project Highlights

  - Multi-State Damper: Design and Test
  - Ultrasonic Anti-Icing: Recent progress

  - Airframe Structural Health Monitoring
    (Prof. Steve Conlon)
Overview of Recent Rotorcraft

*Structural Health Monitoring / Damage Detection*

Research Activity

9 May 2011

Center for Acoustics & Vibration

20th Annual Spring Workshop

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Penn State Vertical Lift Research Center of Excellence
Recent & Ongoing SHM / CBM Projects

• 6.1 (SHM / Damage Detection)
  ▪ Rotor blade damage detection (CRI, 3 yrs)
  ▪ SI based damage detection (CRI, 2 yrs)

• 6.2 (SHM / Damage Detection)
  ▪ Intensity based airframe SHM (AATD, 2 yr)

• 6.2+ (SHM)
  ▪ OH-58D Tailboom damage detection study (PEO, 6 mo)
Airframe SHM Technology Development Overview:


Considering a cracked rod subjected to an external dynamic axial load:

Subharmonics and Ultra-subharmonics

The Subharmonics components are characterized by a threshold behavior; they are not generated below a certain amplitude of the external driving force.

Structural Intensity Based Damage Detection

SI maps of plate driven at resonance frequencies

- Frequency sweep from 135 Hz to 695 Hz, color bar indicated SI magnitude in dB, unit vectors indicate SI direction

For SHM implementation local sensors / sensor arrays will detect damaged induced changes to SI magnitude and direction
Nonlinear Structural Intensity Based Damage Detection

Damaged Structure: Sub-harmonic vs Super-harmonic Vibration

The resonance growth of the modes is affected by the amplitude and frequency hysteresis & instability

Contact Acoustic Nonlinearity (CAN)

Issue:
- Rotorcraft airframe elements can experience critical fatigue loading during their usage life. The development and implementation of enhanced structural diagnostics techniques will directly support the Army Aviation S&T Mission.

Objectives:
- Structural intensity based SHM approach for airframe structural damage detection was investigated.

Program Solution:
- Study the fundamental energy flow mechanisms of vibrating structures.
- Develop simulation & experimental techniques to determine sensitivities for detecting and localizing structural damage.
- Apply techniques to representative rotorcraft airframe structure / typical damage flaws for detection performance validation.
Structural Intensity Based SHM System Overview

(Airframe Vibration – Active / Passive)

raw sensor signals: strain, acceleration

SSI features (acceleration & strain data fusion)

active interrogation

NSSI sensor array (non-linear)

active / passive

SSI magnitude / phase feature trending
single / multiple sensors (linear)

Passive

automated advanced pattern recognition technique, (AR / ARX)

Damage:
- detection
- (possible limited) localization via multiple sensor use

Baseline-free techniques
- Damage:
  - detection
  - localization
  - sizing (extent)

Baseline required techniques
- Damage:
  - detection
  - (possible limited) localization via multiple sensor use

Hybrid (model based) techniques
- SSI Models
  - enhanced local / global detail

Loads & Usage
- Damage:
  - detection
  - localization
  - sizing (extent)
Why Airframe Structural Health Monitoring?

Goal of SHM development:
Develop technologies to provide critical actionable information, enabling a shift to airframe CBM

UH-60 Corrosion & Crack Locations
UH-60 Transmission Frame
Primary Structural Element Cracking

UH-60 Cabin Upper Deck
Main Transmission Frame
FS360/BL 16.5 Joint

Typical application of interest for Intensity Based SHM

- Damage precursors – fastener (rivets) loosening / damage, load / stress redistribution
- Structure (frame strap) fatigue crack initiation & growth

(J. Cycon, SHM Activities and Needs for Sikorsky Products, PSU SHM Center of Excellence Meeting, Nov 2007)
Development and Verification / Validation Test Beds

- **Plate & stiffened plate**
  - Study/insight SI for healthy & damaged structures
  - Discrete sensor development / implementation
  - Algorithm development
  - Detection performance V&V

- **Transmission frame joint mock-up**
  - Technology transition to more complex substructure
  - Detection performance V&V

- **UH-60 upper cabin structure**
  - Technology transition to airframe complex structure
  - Detection performance V&V

**Structural Complexity**

- Homogeneous plate
- Plate + stiffener
- I-beam frame structure
  - Joint strap w/ fasteners
- Real aircraft structure
  - Skin
  - Stiffeners / ribs
  - Riveted joints
Verification and Validation Test Beds: Transmission Frame Mock-up

Electrodynamic shaker (out-of-plane excitation)

PZT actuator (in-plane excitation)

Straps – loose fastener progression and strap crack progression for damage detection measurements

Example - critical region of interest: FS360 / BL 16.5

Transmission Support and Attachment Structure
Verification and Validation Test Beds: UH-60 Upper Cabin Structure

- Technology transition to airframe complex structure
- Detection performance V&V

Example - critical region of interest: FS360 / BL 16.5
NSSI exploits the nonlinear response characteristics of certain types of defects such as fatigue cracks and loose riveted joints.

*The interrogation signal (single tone continuous excitation) triggers the damage nonlinear dynamic response at subharmonic frequencies.*
Structural Intensity Based SHM System: Application Results

Transmission Frame Test Structure

Damage detection loose fasteners, BW 1.75 to 1.85 kHz

Damage discrimination, loose fastener vs crack, BW 5.5 to 5.8 kHz

UH-60 Upper Cabin Test Structure

NSSI Feature
(Contact Indicator)

Damage detection at all 4 corner joints on frame using single SSI sensor location, drive frequency approx. 2.48 kHz

Issue:
- Fleet OH-58’s are experiencing tailboom cracking / damage which requires inspections every 10 hrs

Objectives:
- **Nonlinear intensity based SHM** approach for airframe structural damage detection is being investigated

Program Solution:
- **Transition / enhance** NSSI techniques developed under 6.2 AATD effort
- **Apply** & adapt experimental techniques to laboratory test beds for demonstrating detection capability (NSSI sensors & actuators)
- **Assess** (1) use of current HUMS sensors/locations for damage detection use, (2) in-flight passive SHM
- **Define** system technology transition plan / aircraft integration requirements for 6.3 Phase II effort
- **(Phase II) Deploy** techniques to OH58 airframe structure / typical damage flaws for detection performance validation and system flight qualification
Tailboom SHM Testbeds
Damage grouped around several “hot spots” - hanger bearing mounts, tailboom mounts, gearbox mount.

Designated inspection area captures 10% of cracks.

Inspection area is one inch either side and 3 inches above and below golden rivet.
Honeywell CBM for KW has 15 Accelerometers and 5 Tachometers covering all the rotating drive train components.

Existing HUMS accelerometers potential for use / integration with embedded Tailboom SHM system.
**SHM Technology Development and Verification / Validation Test Beds**

- **Plates & Connected Plates**
  - Discrete sensor & algorithm development / implementation
  - Fatigue crack detection performance

- **OH-58 Tailboom Structures**
  - Technology transition to airframe complex structure
  - Algorithm development
  - Detection performance V&V

**Structural Complexity**

- Homogeneous plate
- Plate + lap joint / fastener line
- Real aircraft structure
  - Skin, conical shell
  - Stiffeners / ribs
  - Riveted joints

**Increasing Complexity**
Structural Intensity Based SHM System
Damage Detection: APPLICATION RESULTS

OH-58D Test Structure

Aluminum Skin (Fatigue Crack) Test Structures

- High damage detection sensitivity - loose HB bracket: NSSI (bulkhead sensors), NLS (skin mounted), NLA (“HUMS” accels at brackets)
- Good vibration response from skin & bulkhead mounted PZT actuators

- Damage detection, exposed and hidden small fatigue cracks
- Detection with actuator position both local & remote (through lap-joint)
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F. Semperlotti (Ph.D., UMich), P. Romano (M.S., Bell), W. Schmidt (M.S., Sikorsky), B. Grisso (Post Doc, NSWC Carderock), K. Brennan (M.S.)

M. Shepherd (ARL), J. Hines (ARL), A. Barnard (ARL), K. Reichard (ARL/Acoustics), S. Hambric (ARL/Acoustics)

J. Cote (B.S., Pratt & Whitney), P. DiBiase (B.S., NAVAIR Pax River), Justin Long (B.S.)