Full-scale Experimental Validation of Dynamic, Centrifugally Powered, Pneumatic Actuators for Active Rotor Blade Surfaces

Dr. Joseph Szefi, President  
*Invercon, LLC*

Luke Ionno, Aeronautical Engineer  
Brian Cormier, Senior Flight Test & Product Design Engineer  
*Kaman Aerospace Corporation*

NASA Aeronautics Research Mission Directorate (ARMD)  
FY12 LEARN Phase I Technical Seminar  
November 13-15, 2013
Outline

- Background
- The Innovation:
  - Centrifugally Powered Pneumatic Actuators
- Technical Approach / Results
- Planned Future Work
Serious Constraints in Rotorcraft Transportation
- Poor ride quality due to high levels of vibration
- Noise, restricted flight envelope
- Low fatigue life of structural components and high operation cost

Helicopter vibration sources
- Main rotor system – Unique feature of helicopter
- Aerodynamic interaction between rotor and fuselage
- Tail rotor, engine and transmission

Active trailing edge flaps may offer active vibration control solution
- Tailor aerodynamics to counteract harmonic and non-harmonic disturbances
- With sufficient actuation levels, flaps may enable swashplateless rotor
  - No mechanical swashplate, reduced rotor complexity
**Piezoelectric Stack-Based Actuators** – Currently Preferred Actuation Approach
- Straub and Kennedy (2007): Double X-Frame actuator, Boeing
- Leconte and Hofinger (2004): ONERA, DLR, Eurocopter

**Boeing - Double X-Frame Trailing Edge Flap Actuator**
- Whirl tested by Boeing in a fully instrumented MD 900 Explorer rotor in 2007

**Eurocopter – Adaptive Dynamic System (ADASYS)**
- Flight tested by Eurocopter in BK117 in 2005

**Drawbacks:** Added blade weight, complex mechanical motion amplifiers, high voltage slip rings, and no more than ±3°
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Centrifugally Generated Pressure Differentials for Actuation

Pressure Differential Created Across Two Hollow Tubes that Span the Blade

A Pressure Differential of ~7 psi Available for Actuation Along Entire Blade Length for K-MAX

Analysis based on hydrostatic equation:

\[ \frac{dp}{dr} = \rho(r) r \Omega^2 \]

\( p = \text{Pressure}, \ \rho = \text{Density}, \ r = \text{Radius}, \ \Omega = \text{Rotor Speed} \)

Patented by Invercon LLC: “Pneumatic Actuator System for a Rotating Blade”, EFS ID: 9369871, Application Number:13020333
Previous Testing: Full Scale Pressure Generation Test at Kaman

Full-Scale Rotor Test
Pressure Differential Experimentally Demonstrated: 7.5 PSI

2 Pressure Sensors on Root
2 Pressure Sensors on Tip

280 RPM, 24 ft. Radius Rotor
Previous Testing: Full Scale Pressure Generation Test at Kaman

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ROOT
TIP

Pressure Differential vs. Blade Radius

Kmax Blade Pressure Measurements - 280 RPM

- High Pressure Line - Gauge
- Low Pressure Line - Gauge
- Experimental Data - High Pressure Line
- Experimental Data - Low Pressure Line

Gauge Pressure (psi)

0.00 0.20 0.40 0.60 0.80 1.00

% Radius

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Innovation: Centrifugally Powered Pneumatic Actuators

Early Pneumatic Flap Actuator Design Concept

- Opposing Diaphragms Contain Pressure Differential
- Actuator/Flap Links Control Flap Displacements
- Microvalves Control Flow into Diaphragms
- High and Low Pressure Lines
- Precise Flap Displacements Commanded via the Distributed Valves
Innovation: Centrifugally Powered Pneumatic Actuators

- High Pressure Air Inlet
- Distributed Microvalves
- Flap/Actuator Linkages Along Flap
- Actuator Co-located Spanwise with Flap
- Low Pressure Outlet at Blade Tip
Innovation: Centrifugally Powered Pneumatic Actuators

Design Concept Advanced under DARPA’s Mission Adaptive Rotor Program

- Piezoelectric Micro-valves Control Flow to Diaphragms
- Direct Flap Motion Control with no Amplification System
- High and Low Pressure Lines
- Opposing, Actuating Diaphragms
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Phase I Technical Objectives

- Experimentally demonstrate full-scale, centrifugally powered actuation on modified K-MAX blade
  - K-MAX whirl rig at Kaman
  - First full-scale whirl test of actuation concept
  - First demonstration that differential can be used for actuation

- Demonstrate miniature pneumatic valve operation at ~500 g’s CF

- Characterize actuator’s dynamic performance limits

- Compare performance to existing on-blade active rotor technology
K-Max Blade Modifications

Retired K-MAX Blades

High Pressure Tube Installed in Servoflap Control Rod Volume

Low Pressure Tube Installed in Outboard Blade Section

K-Max Control Box Modified
Pneumatic Actuator Design and Fabrication

Actuating Diaphragms

High Pressure Pneumatic Lines

Variable Stiffness Torque Rod

Low Pressure Line

Three way Piezoelectric Valves

High Pressure Input Line

Rotational Output Sensor

High and Low Pressure Sensors

Actuator Readily Installed in Housing

Low Pressure Line

Low Pressure Exhaust Line

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Pneumatic Actuator Design and Fabrication

Fabricated Pneumatic Actuator

Actuator Installed in Blade Shop

Patched Outboard Blade Surface

High Pressure Tube Fed through Inboard Control Rod Channel
Piezoelectric Valve Design, Fabrication and Testing

- Piezoelectric Valves Designed, Fabricated, and Tested at Invercon
- Tested in Modified Centrifuge Test Stand
- Successful Valve Operation Observed up to 500 g’s
Actuator Spin Testing, October 4, 2013

Installed and Hard-Wired Actuator

Piezoelectric Amplifiers and Pneumatic Generator

Miniature Amplifiers

Input:
- +12V Supplied Power
- 0-10V Controller Signal

Output
- 0-250V to Valves

Pneumatic Motor (Generator)
Actuator Spin Testing Results

Realtime PD Feedback
Controller Attempts to Follow Commanded Signal

Pressure Measurements at Actuator

Maximum Pressure Differential
Actuator Spin Testing Results

Pressure Differential, Altitude = 328 ft, RPM = 270, Forward Speed = 0 knots

Analytical Pressure Differential

Experimental Differential at Actuator Location

Gauge Pressure (PSI) vs. Blade Radius (%R)

High Pressure Line
Low Pressure Line

Measured Pressures

Analytical High Pressure

Analytical Low Pressure

Pressure Differential (PSI) vs. Blade Radius (%R)

Pressure Differential Between Lines

Analytical Pressure Differential

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Actuator Spin Testing Results

Actuator Command and Sensor Output

±1° @ 2.5 Hz

High Frequency Slip Ring Noise Filtered Out for Presentation Purposes, Signal Phase Lag Preserved

High and Low Pressure Measurements at Actuator

Commanded
Unfiltered Sensor Output
Filtered Sensor Output

Low Pressure
High Pressure

±1º @ 2.5 Hz
Actuator Spin Testing Results

Actuator Command and Sensor Output

±2° @ 2.5 Hz

High and Low Pressure Measurements at Actuator
Actuator Spin Testing Results

Actuator Command and Sensor Output

±1° @ 30 Hz

Slight Controller Lag at High Frequency ~ 0.009 sec.

High and Low Pressure Measurements at Actuator

Low Pressure
High Pressure
Actuator Spin Testing Results

Actuator Command and Sensor Output

±2° @ 30 Hz

Phase I Actuator Configuration Limited to ± 1° @ 30 Hz

High and Low Pressure Measurements at Actuator

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Actuator Spin Testing Results

Actuator Command and Sensor Output

$\pm 1^\circ$ @ 5 Hz + $\pm 1^\circ$ @ 10 Hz

High and Low Pressure Measurements at Actuator
Actuator Spin Testing Results

Actuator Command and Sensor Output

±1° @ 5 Hz + ±0.5° @ 15 Hz + ±0.5° @ 20 Hz

High and Low Pressure Measurements at Actuator

Actuator Spin Testing Results

Actuator Command and Sensor Output

-4 -2 0 2 4

Time (sec)

±1° @ 10 Hz + ±0.5° @ 15 Hz + ±0.5° @ 20 Hz

High and Low Pressure Measurements at Actuator

Low Pressure

High Pressure

Time (sec)
Actuator Performance Testing

Actuator Command and Sensor Output

Increasing Applied Torque

High and Low Pressure Measurements at Actuator

Supply Pressures Recreated in Lab

Applied Torque Increased using Set Screws to Shorten Effective Torque Rod Length

Pneumatic Actuator Performance

Angular Output (Degrees) vs. Maximum Applied Torque to Output (in-lb)

- Quasistatic
- 2.5 Hz
- 10 Hz
- 20 Hz
- 30 Hz

High Frequency Performance to be Improved in Phase II
Actuator Performance Testing

Interpolated Full Scale Actuator Performance

Full-scale Actuator Configuration would Yield Similar Performance to Piezoelectric Flap Actuator

Goal: Significantly Improve Performance in Phase II

Boeing’s 2X-Frame Piezoelectric Actuator for MD-900

Current Pneumatic Actuator Configuration Extended to Span 30” behind 30” Flap

Angular Output (Degrees)

Maximum Applied Torque to Output (in-lbs)

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Pneumatic Power Harvesting

Inboard Tubing Connected to Pneumatic Generator

Pneumatic Rotary Vane Generator:
- Diameter = 0.86”
- Length = 2.4”
- Weight = 120 g

Tubing Reconfigured within Housing to Bypass Actuator, Resulting in Open Tubing Entire Length of Blade
Pneumatic Power Harvesting

- Variable resistor at generator output used to determine maximum electrical power output
- Maximum of 0.75 Watts can be harvested for given generator size
- Generator type/design can likely be optimized to generate higher power outputs given rotor RPM and radius (~3 Watts)

![Graph showing Pneumatic Generator Power Output]

750 mW of Power Continually Harvested
Conclusions

• Successful experimental demonstration of a full-scale, centrifugally powered pneumatic actuator
  • Centrifugally generated pressures used for actuation
  • Piezoelectric valves operated successfully under 500 g’s CF
  • Higher frequency and multi-frequency control system demonstrated
  • Potential to outperform other on-blade actuation designs
  • Very low complexity, low weight, low power actuation solution

• Experimental demonstration of centrifugal power harvesting
  • In current full-scale test, 750 mW could be continually harvested
  • Sufficient power to run actuator micro-valves
  • Invercon will build on technologies demonstrated in Phase I

Phase II Goal: Self-powered, wirelessly controlled, centrifugally powered actuator that requires no slip ring
• Paper abstract submitted to American Helicopter Society’s Annual Technical Forum

• Invercon currently working Sikorsky on related NASA NFAC wind tunnel test in 2014
  • Pneumatic MiTEs
  • Small transverse surface actuation, not flap actuation
  • Sikorsky active rotor team briefed on project progress

• Invercon currently in talks to license pneumatic flap actuator technology to Bell Helicopter
  • Bell interested in incorporating pneumatic diaphragm technology in future active rotor vehicles
  • Advocates of Invercon’s proposed Phase II work
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Planned Future Work
Future Work: Self-powered, Wirelessly Controlled Actuation System for Rotorcraft

- Improve actuator high frequency performance
- Introduce piloted valve design for flow amplification

Future Work:
- Self-powered, Wirelessly Controlled Actuation System for Rotorcraft
Future Work: Self-powered, Wirelessly Controlled Actuation System for Rotorcraft

Four, Pilot Valves Control Flow Amplifiers

High and Low Pressure Source Volumes Span Length of Main Diaphragms

Piloted, Flow Amplification Valves

Next Generation Actuator:

Piloted Flow Amplification, Enabling High Displacement, High Torque Outputs

Increase in Valve Orifice Area of over 50 Times, Dramatically Improving High Frequency Performance
Future Work: Self-powered, Wirelessly Controlled Actuation System for Rotorcraft

**Predicted Next Generation Actuator Performance**

**Next Generation Pneumatic Actuator**
- 7 psi pressure differential (Higher on Larger Rotors)
- 30” actuator span directly in front of flap
- 2” Flap Lever Arm
- Diaphragms contact area remains constant through stroke

**Goal:** Enable Swashplateless Rotors

**Phase I Pneumatic**

**Force = Pressure * Constant Area**

**Maximum Applied Torque to Output (in-lbs)**

**Angular Output (Degrees)**

Future Work: Self-powered, Wirelessly Controlled Actuation System for Rotorcraft

- Self Powered System
- Wireless Data Transmission
- Miniature Valve Amplifiers

Off-the-Shelf Real Time Wireless Hubs

Planned Phase II Whirl Test

Self-Powered, Wirelessly Controlled, High Displacement, High Torque Pneumatic Actuator

Goal: Enable Self-Powered, Swashplateless, Wirelessly Controlled Active Rotors of the Future

- Fixed Frame DAQ/Controller
- Wireless Data Transmission
Full-scale Experimental Validation of Dynamic, Centrifugally Powered, Pneumatic Actuators for Active Rotor Blade Surfaces

Questions?