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Active Vibration Reduction of Titanium Alloy Fan Blades (FAN1) Using Piezoelectric Materials

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Abstract

The NASA Glenn Research Center is developing smart adaptive structures to improve fan blade damping at resonances using piezoelectric (PE) transducers. In this paper, a digital resonant control technique emulating passive shunt circuits is used to demonstrate vibration reduction of FAN1 Ti real fan blade at the several target modes. Single-mode control and multi-mode control using one piezoelectric material are demonstrated. Also a conceptual study of how to implement this digital control system into the rotating fan blade is discussed.

Objective

Investigate possibility of using an active resonance controller for turbomachinery blade with piezoelectric sensors/actuators.

Outline

I. Introduction
II. Shunt damping and digital control design
III. Experimental test results
IV. Summary

I. Introduction

Previous Activities at GRC

- Developed new damping technologies to reduce excessive vibratory stresses that lead to high cycle fatigue (HCF) failures in aircraft engine turbomachinery.
- Investigated several technologies such as viscoelastic damping (O. Mehmed and J. Kosmatka), passive impact damper, plasma sprayed damping coating, and high temperature shape memory alloy (HTSMA) - (K. Duffy).

Current Efforts at GRC

Develop a damping technology for fan blade incorporating smart structure using materials such as piezoelectric (PE) materials or shape memory alloy (SMA).

- Selected piezoelectric devices due to their fast response to voltage and current signal from controller.
- Demonstrated shunt damping of Ti-alloyed flat plates through bench tests and a *RC* shunt damping in rotating environment (K. Duffy).
- Developed a digital control that replaces equivalent passive-shunt analog circuits with a digital code. Demonstrated its technique to multi-mode control using single PE actuator on titanium-alloyed flat plates (B. Choi, 2009).
- In collaboration with MESA, developed a prototype of power transfer device that transmits control power to the PE actuators in the rotating frame (C. Morrison).

I. Introduction *(continued)*

Smart Fan Blade Technology Pros and Cons

- ❖ <u>Benefits/Payoffs</u>: support the NASA missions

  - Thinner and more efficient blades with shunt damping – fuel burn reduction, noise reduction, HCF failure reduction, etc.

  - Actively controlled blades - real-time health monitoring, aeroelastic control, mistuning problem, active fan distortion control for distributed propulsion system, etc.

- ❖ <u>Drawbacks</u>: structural characteristics degradation, durability and safety issues, added electronics weights, etc.

  - S. Mall (2002) investigated the integrity of the embedded active PZT sensor/actuator under monotonic and fatigue loads – no degradation seen in experimental tests.

  - R. Pickering and K. Barlow (2007) specified the duration (10e+07 cycles) for each vibration mode for durability spin test according to the Goodman diagram.

  - Completed a preliminary durability bench test for 10^9 cycles under *4.6g* at target frequency. Need retest at high speed rotor.

  - On-going system trade study of blade weights reduction vs. added electronics weights.

Literature Survey for Recent Advances

1. <u>Analog Shunt Circuits for Turbomachinery Blades</u>

- Passive control of turbomachine blading flow-induced vibrations (C. Cross, 2002).
  - Synthetic inductor replacing $L = 342\ H$ controlled the first bending mode – real challenge.
- Passive shunt circuit was tested for piezoblade damping (S. Livet, 2008).
  - Virtual inductor (or "gyrator") that consists of op amps, resistors, capacitors, and ext. power supply.
- Numerous papers published for passive shunt for rotorcraft vibration.

2. <u>Active Control of PE Actuator for Turbomachinery Blades</u>

- Cascade flutter control using PE device in subsonic flow (T. Watanabe, 2005).
  - Trailing edge of non-rotating airfoil was oscillated by PE to control the passage shock.
- Low-speed fan noise control using PE actuators mounted on stator vanes (P. Remington, 2003). Reduced fan-stator interaction noise using 210 vane actuators.
- NASA Ames/Boeing developed shape-shifting helicopter blades (2009). PE actuators created a mechanical motion that moves a flap up and down.
- Force excitation control using surface-mounted PE patches on the rotating blades (I. Santos, 2009).
  - First demo in the spin pit. Used Thunder flexible patches covering full blade surfaces.

Full-scale helicopter smart blade in a Ames Res. Ctr. wind tunnel

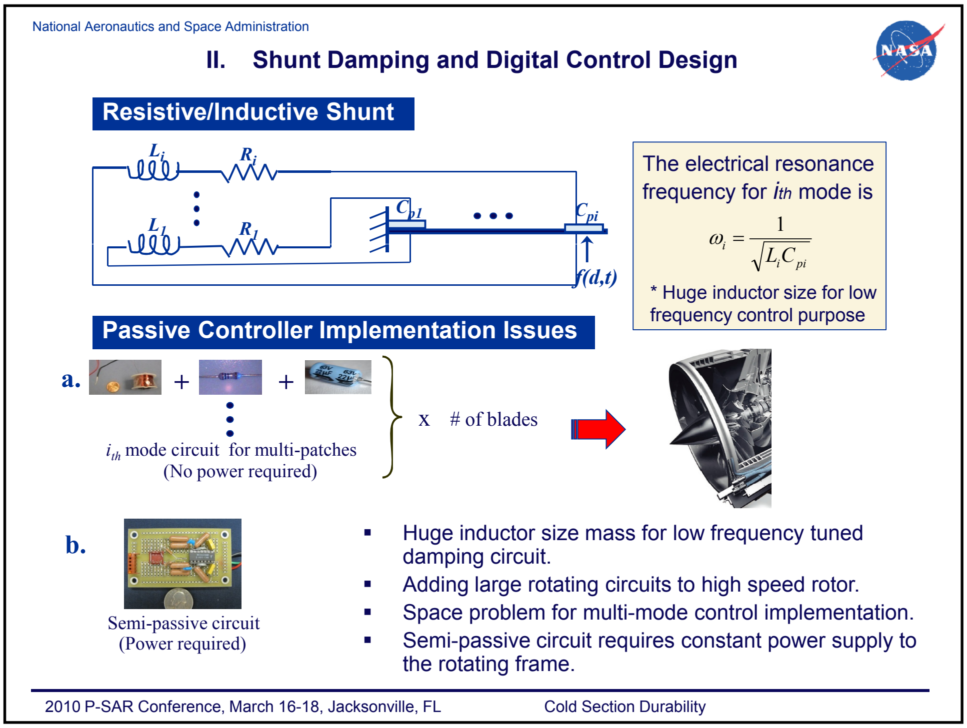
Summary of Conventional Control Approaches

- Wider and thicker patches were used at room temperature, possibly resulting in aerodynamic performance penalty.
- ***For passive damping*** (or shunt damping), semi-passive circuits were used to simulate physical inductors which can be huge size for low frequency.
- ***For active damping cases***, conventional PD control law was used.

Our Unique Approach Extends To

1) Rotating fan blades under high centrifugal loads /g-loads
2) High temperature environment
3) Adaptive features to follow change in blade frequencies vs. the rotor speed
4) Ultimate goal of "Smart blade" - thinner and more efficient, fuel burn reduction, noise reduction, HCF failure reduction, real-time health monitoring, aeroelastic control, mistuning problem, active fan distortion control for distributed propulsion system.

In this presentation, a digital resonant control technique is demonstrated to reduce blade vibration at several target modes. Notice that the control feedback is effective only at targeted vibration frequencies.



II. Shunt Damping and Digital Control Design

Resistive/Inductive Shunt

The electrical resonance frequency for i_{th} mode is

$$\omega_i = \frac{1}{\sqrt{L_i C_{pi}}}$$

* Huge inductor size for low frequency control purpose

Passive Controller Implementation Issues

- Huge inductor size mass for low frequency tuned damping circuit.
- Adding large rotating circuits to high speed rotor.
- Space problem for multi-mode control implementation.
- Semi-passive circuit requires constant power supply to the rotating frame.

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Digital Control Design

Digital Control Approach

- Transfer function of *LRC* shunt circuit is expressed in S-domain so that it can be programmed in a digital code.
- As opposed to analog shunt circuit, a real-time adaptive control for change in blade frequencies in Campbell Diagram is possible.
- Adaptive capability to aged blade dynamics change is possible.
- Effective for multi-mode control because a few coding lines are necessary, as opposed to analog circuit approach.
- Control feedback is effective only at targeted blade frequencies.

Digital Controller Implementation Issues

- Added weights of power electronics in the rotating frame.
- Durable power electronics surviving high centrifugal loads/g-loads.
- Operational overhead of transducing high voltage power to the blades.
- Potential cross-talk between high voltage control signals and blade sensor signals.
- Safety and durability issues of power electronics, etc.

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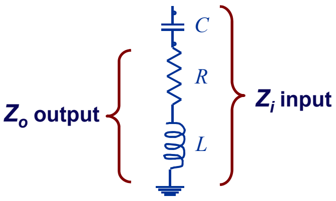
Digital Control Design *(continued)*

Transfer Function of Analog *LRC* Circuit



General feedback control *LRC* network.

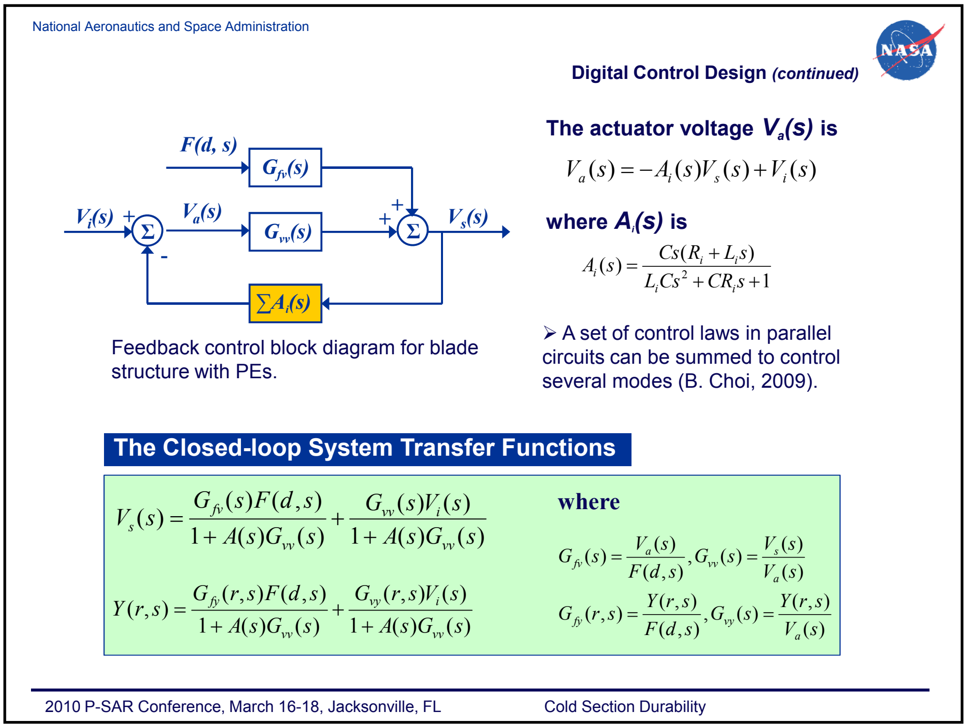
$$Z_i = R + i\omega L - i/(\omega C)$$
$$Z_o = R + i\omega L$$
$$\frac{V_o}{V_i} = \frac{Z_o}{Z_i}$$
$$= \frac{R + i\omega L}{R + i\omega L - i/(\omega C)}$$
$$= \frac{Cs(R + Ls)}{LCs^2 + CRs + 1}$$

➡ The controller is expressed in terms of passive circuit components (***LRC***) regardless of modal shape.

PID (proportional-integral-derivative) Control Law

$$u(t) = \mathrm{MV}(t) = K_p e(t) + K_i \int_0^t e(\tau)\,d\tau + K_d \frac{de}{dt}(t)$$

K_p: proportional gain, K_i: integral gain, K_d: derivative gain



Digital Control Design *(continued)*

Feedback control block diagram for blade structure with PEs.

The actuator voltage $V_a(s)$ is

$$V_a(s) = -A_i(s)V_s(s) + V_i(s)$$

where $A_i(s)$ is

$$A_i(s) = \frac{Cs(R_i + L_i s)}{L_i C s^2 + CR_i s + 1}$$

➢ A set of control laws in parallel circuits can be summed to control several modes (B. Choi, 2009).

The Closed-loop System Transfer Functions

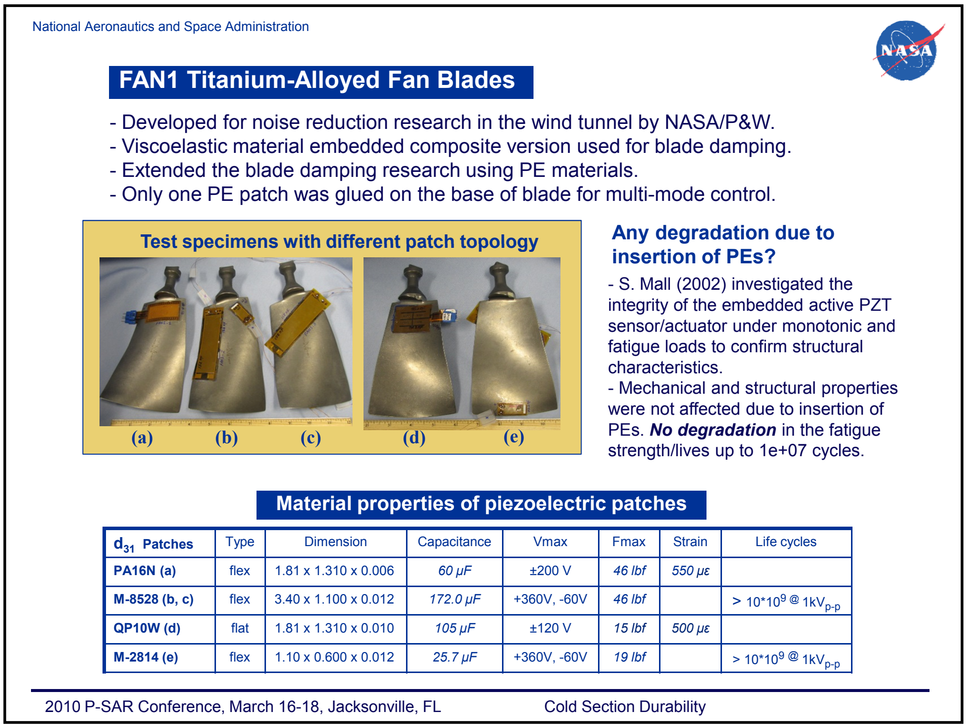
$$V_s(s) = \frac{G_{fv}(s)F(d,s)}{1 + A(s)G_{vv}(s)} + \frac{G_{vv}(s)V_i(s)}{1 + A(s)G_{vv}(s)}$$

$$Y(r,s) = \frac{G_{fy}(r,s)F(d,s)}{1 + A(s)G_{vv}(s)} + \frac{G_{vy}(r,s)V_i(s)}{1 + A(s)G_{vv}(s)}$$

where

$$G_{fv}(s) = \frac{V_a(s)}{F(d,s)}, G_{vv}(s) = \frac{V_s(s)}{V_a(s)}$$

$$G_{fy}(r,s) = \frac{Y(r,s)}{F(d,s)}, G_{vy}(s) = \frac{Y(r,s)}{V_a(s)}$$



FAN1 Titanium-Alloyed Fan Blades

- Developed for noise reduction research in the wind tunnel by NASA/P&W.
- Viscoelastic material embedded composite version used for blade damping.
- Extended the blade damping research using PE materials.
- Only one PE patch was glued on the base of blade for multi-mode control.

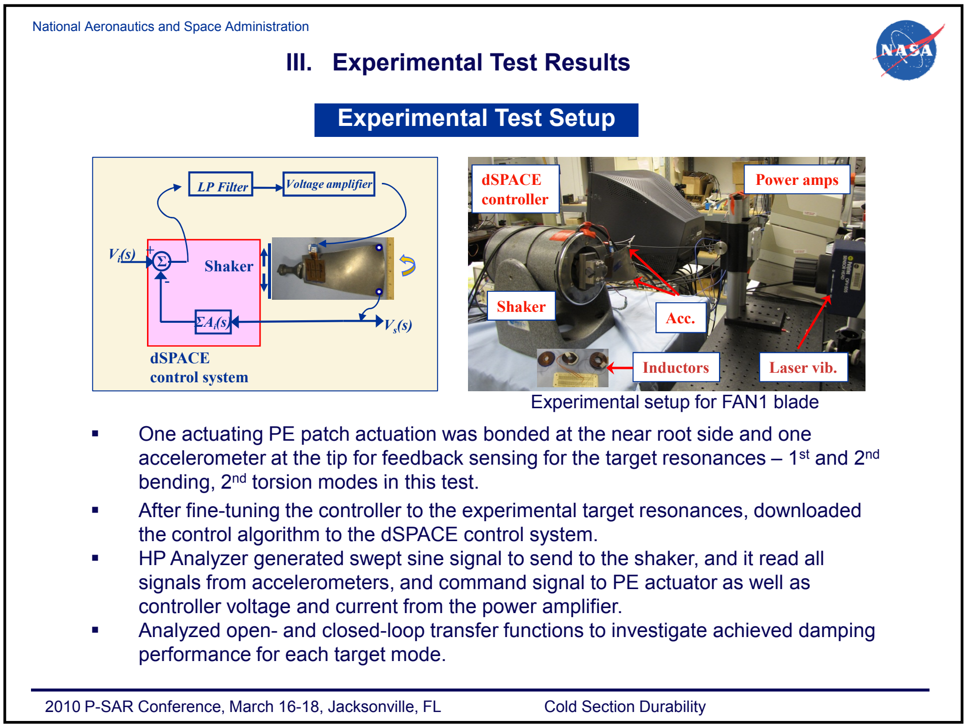
Test specimens with different patch topology

Any degradation due to insertion of PEs?

- S. Mall (2002) investigated the integrity of the embedded active PZT sensor/actuator under monotonic and fatigue loads to confirm structural characteristics.
- Mechanical and structural properties were not affected due to insertion of PEs. ***No degradation*** in the fatigue strength/lives up to 1e+07 cycles.

Material properties of piezoelectric patches

d_{31} Patches	Type	Dimension	Capacitance	Vmax	Fmax	Strain	Life cycles
PA16N (a)	flex	1.81 x 1.310 x 0.006	*60 μF*	±200 V	*46 lbf*	*550 με*	
M-8528 (b, c)	flex	3.40 x 1.100 x 0.012	*172.0 μF*	+360V, -60V	*46 lbf*		> $10{*}10^9$ @ 1kV$_{p\text{-}p}$
QP10W (d)	flat	1.81 x 1.310 x 0.010	*105 μF*	±120 V	*15 lbf*	*500 με*	
M-2814 (e)	flex	1.10 x 0.600 x 0.012	*25.7 μF*	+360V, -60V	*19 lbf*		> $10{*}10^9$ @ 1kV$_{p\text{-}p}$



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III. Experimental Test Results

Experimental Test Setup

Experimental setup for FAN1 blade

- One actuating PE patch actuation was bonded at the near root side and one accelerometer at the tip for feedback sensing for the target resonances – 1st and 2nd bending, 2nd torsion modes in this test.
- After fine-tuning the controller to the experimental target resonances, downloaded the control algorithm to the dSPACE control system.
- HP Analyzer generated swept sine signal to send to the shaker, and it read all signals from accelerometers, and command signal to PE actuator as well as controller voltage and current from the power amplifier.
- Analyzed open- and closed-loop transfer functions to investigate achieved damping performance for each target mode.

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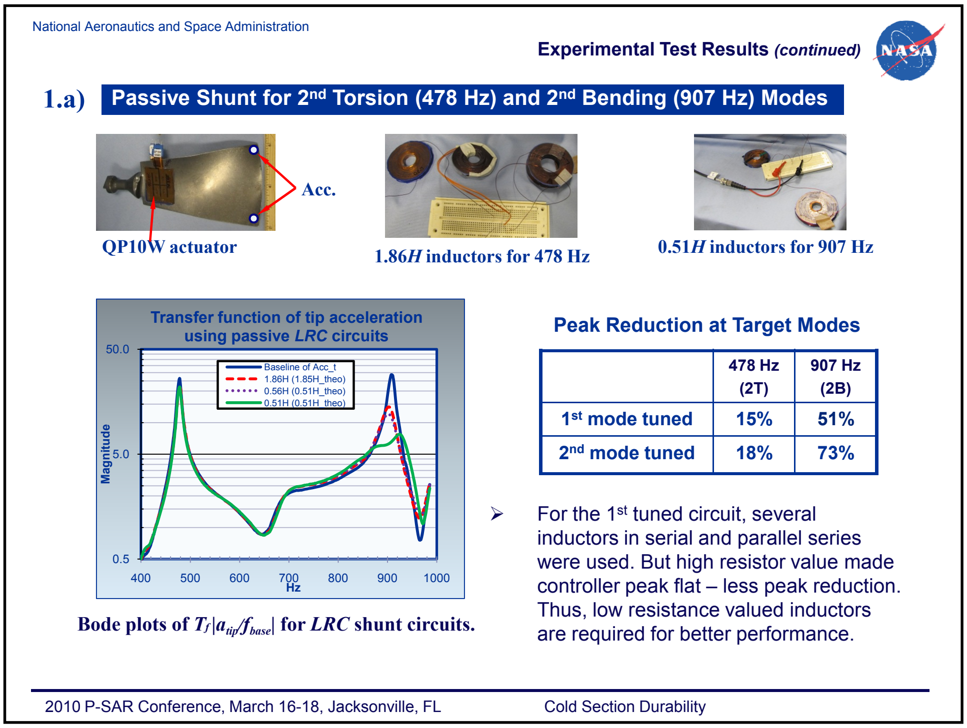

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Experimental Test Results *(continued)*

1.a) Passive Shunt for 2nd Torsion (478 Hz) and 2nd Bending (907 Hz) Modes

1.86*H* inductors for 478 Hz

0.51*H* inductors for 907 Hz

Bode plots of $T_f|a_{tip}/f_{base}|$ for *LRC* shunt circuits.

Peak Reduction at Target Modes

	478 Hz (2T)	907 Hz (2B)
1st mode tuned	15%	51%
2nd mode tuned	18%	73%

- For the 1st tuned circuit, several inductors in serial and parallel series were used. But high resistor value made controller peak flat – less peak reduction. Thus, low resistance valued inductors are required for better performance.

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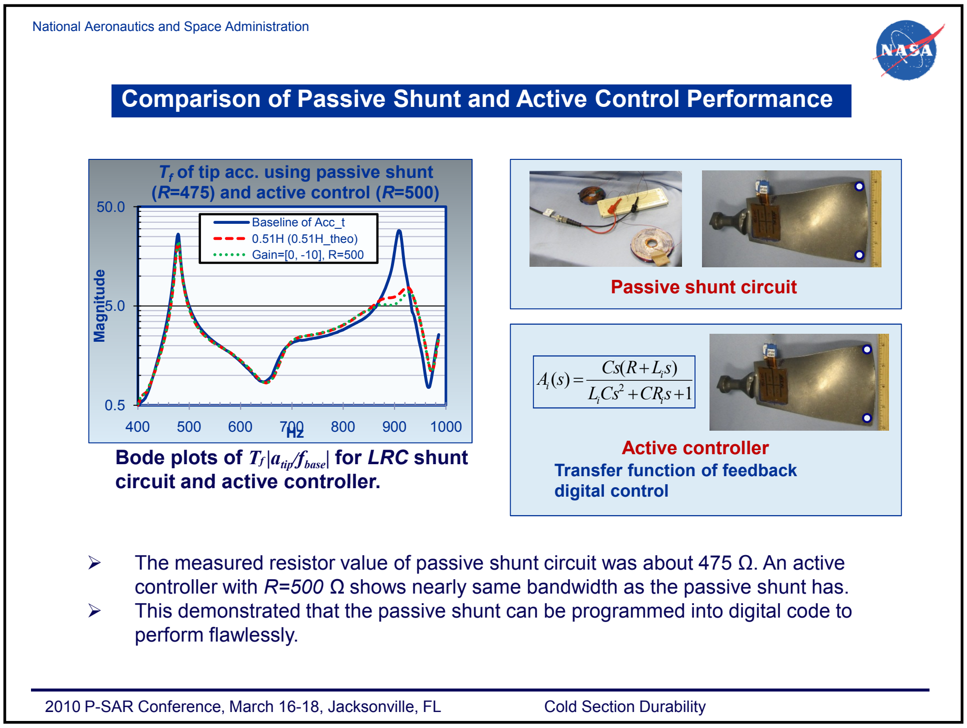


Comparison of Passive Shunt and Active Control Performance

Bode plots of $T_f|a_{tip}/f_{base}|$ for *LRC* shunt circuit and active controller.

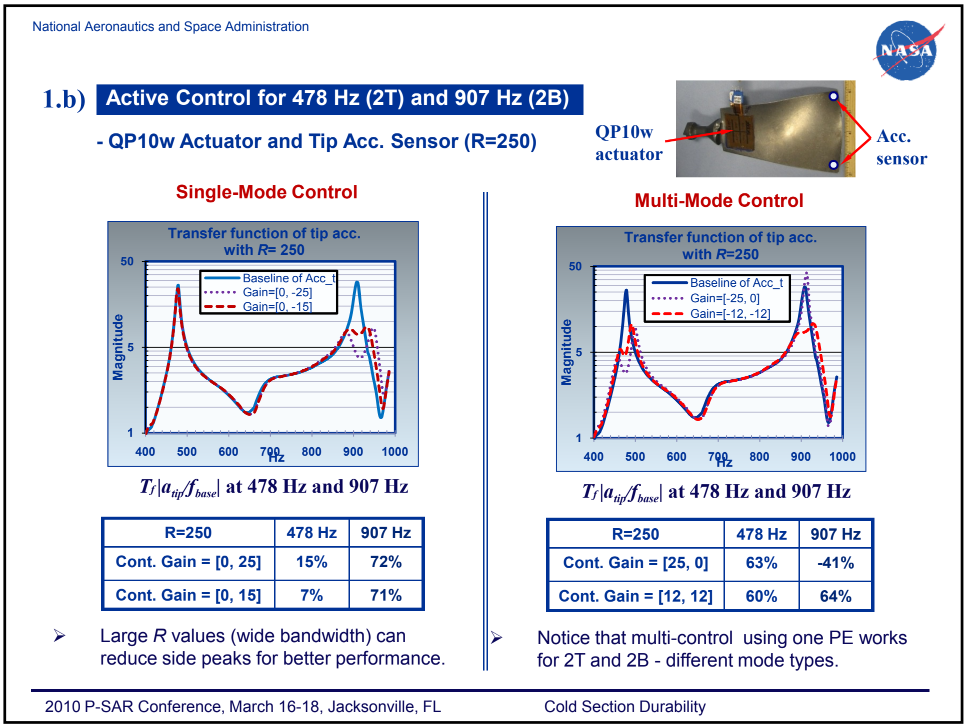
Passive shunt circuit

$$A_i(s) = \frac{Cs(R + L_i s)}{L_i C s^2 + CR_i s + 1}$$

Active controller

Transfer function of feedback digital control

- The measured resistor value of passive shunt circuit was about 475 Ω. An active controller with *R=500* Ω shows nearly same bandwidth as the passive shunt has.
- This demonstrated that the passive shunt can be programmed into digital code to perform flawlessly.



1.b) Active Control for 478 Hz (2T) and 907 Hz (2B)

- QP10w Actuator and Tip Acc. Sensor (R=250)

Single-Mode Control

$T_f|a_{tip}/f_{base}|$ at 478 Hz and 907 Hz

R=250	478 Hz	907 Hz
Cont. Gain = [0, 25]	15%	72%
Cont. Gain = [0, 15]	7%	71%

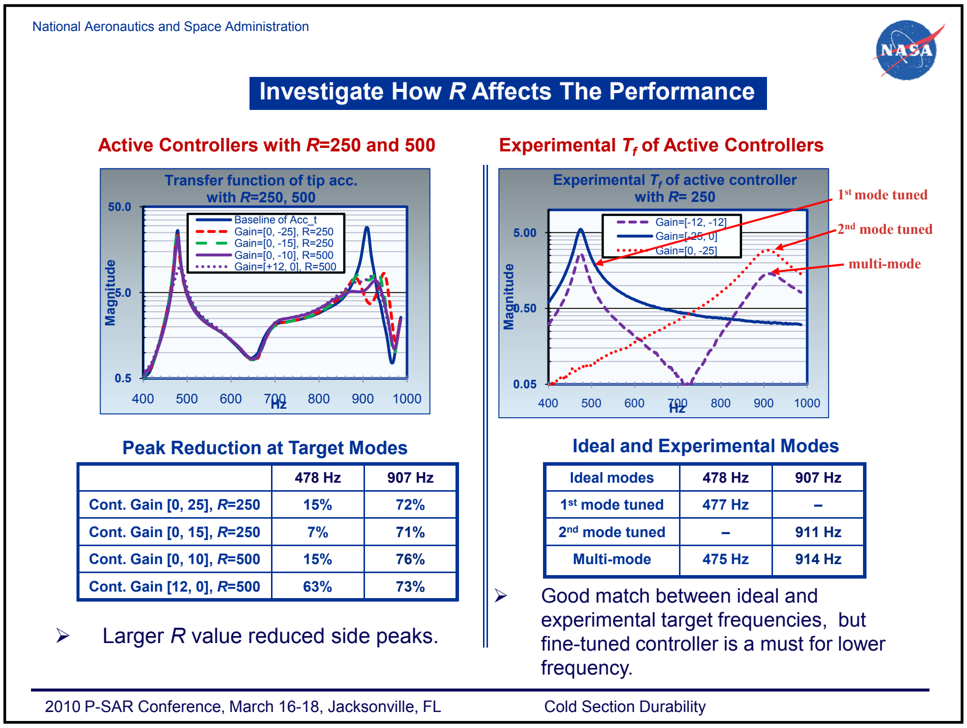
- Large *R* values (wide bandwidth) can reduce side peaks for better performance.

Multi-Mode Control

$T_f|a_{tip}/f_{base}|$ at 478 Hz and 907 Hz

R=250	478 Hz	907 Hz
Cont. Gain = [25, 0]	63%	-41%
Cont. Gain = [12, 12]	60%	64%

- Notice that multi-control using one PE works for 2T and 2B - different mode types.



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Investigate How *R* Affects The Performance

Active Controllers with *R*=250 and 500

Peak Reduction at Target Modes

	478 Hz	907 Hz
Cont. Gain [0, 25], *R*=250	15%	72%
Cont. Gain [0, 15], *R*=250	7%	71%
Cont. Gain [0, 10], *R*=500	15%	76%
Cont. Gain [12, 0], *R*=500	63%	73%

- Larger *R* value reduced side peaks.

Experimental T_f of Active Controllers

Ideal and Experimental Modes

Ideal modes	478 Hz	907 Hz
1st mode tuned	477 Hz	–
2nd mode tuned	–	911 Hz
Multi-mode	475 Hz	914 Hz

- Good match between ideal and experimental target frequencies, but fine-tuned controller is a must for lower frequency.

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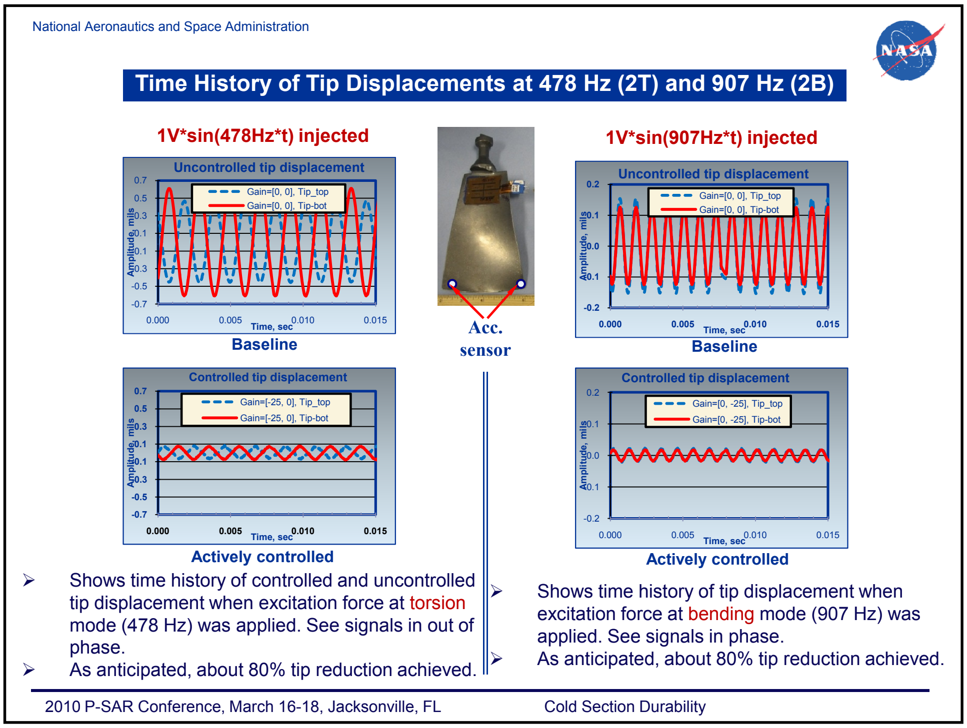

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Time History of Tip Displacements at 478 Hz (2T) and 907 Hz (2B)

1V*sin(478Hz*t) injected

Baseline

Actively controlled

- Shows time history of controlled and uncontrolled tip displacement when excitation force at torsion mode (478 Hz) was applied. See signals in out of phase.
- As anticipated, about 80% tip reduction achieved.

1V*sin(907Hz*t) injected

Baseline

Actively controlled

- Shows time history of tip displacement when excitation force at bending mode (907 Hz) was applied. See signals in phase.
- As anticipated, about 80% tip reduction achieved.

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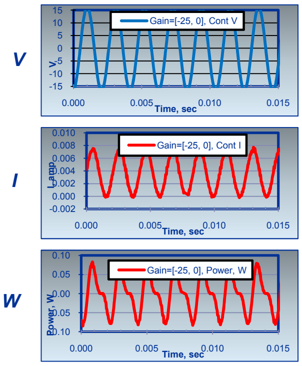
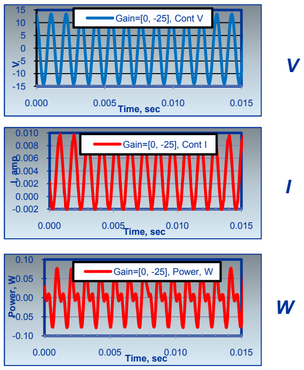
Power Measurement of Using Active Controller

Active Damping at 478Hz (2T)



- Shows time history of control *V, I*, and *W* required to achieve about 80% reduction.
- Notice that *V* and *I* are not in phase, resulting in about 0.09 $W_{peak\text{-}peak}$

Active Damping at 907Hz (2B)

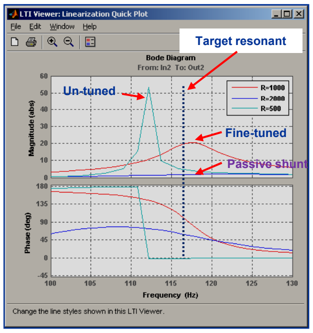


- Shows required power for about 80% damping. Needed about 0.08 $W_{peak\text{-}peak}$ which is well within the capability of a slip ring for the spin test.
- Double checked with the average power formula over a complete cycle

$$P_{avg} = \frac{V_{peak}}{\sqrt{2}} \frac{I_{peak}}{\sqrt{2}} \cos \varphi$$

1.c) 1st Bending Mode Control at 116 Hz – Technical Challenge

-1st Bending control is explored by fine-tuning controller transfer function

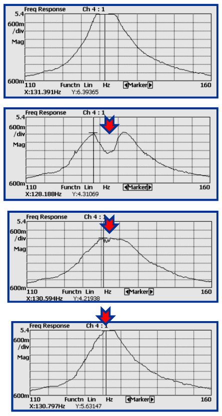


Change the line styles shown in this LTI Viewer.

Bode plot of *controller* transfer function

- Controller has to have high peak. If un-tuned controller with *R*=500 Ω is used, no peak reduction can be achieved at the target resonance.
- For the passive *LRC* circuit, the inductors' *R* value is 2.77 kΩ which makes controller's peak flat – near zero peak reduction.

Bode plots of $T_f|a_{tip}/f_{base}|$ at 116 Hz



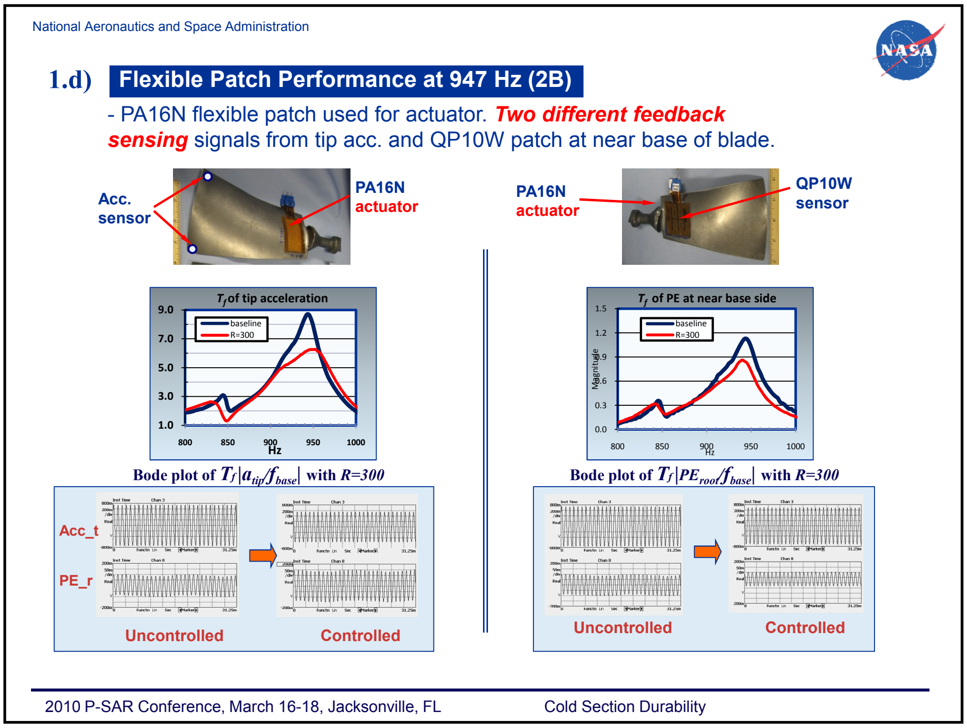
Baseline

***R*=500 Ω, 33%**

***R*=1 kΩ, 35%**

***R*=2 kΩ, 12%**

- With *R* between .5 and 1 kΩ, better peak reduction anticipated.



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1.d) Flexible Patch Performance at 947 Hz (2B)

- PA16N flexible patch used for actuator. ***Two different feedback sensing*** signals from tip acc. and QP10W patch at near base of blade.

Bode plot of $T_f|a_{tip}/f_{base}|$ with $R=300$

Bode plot of $T_f|PE_{root}/f_{base}|$ with $R=300$

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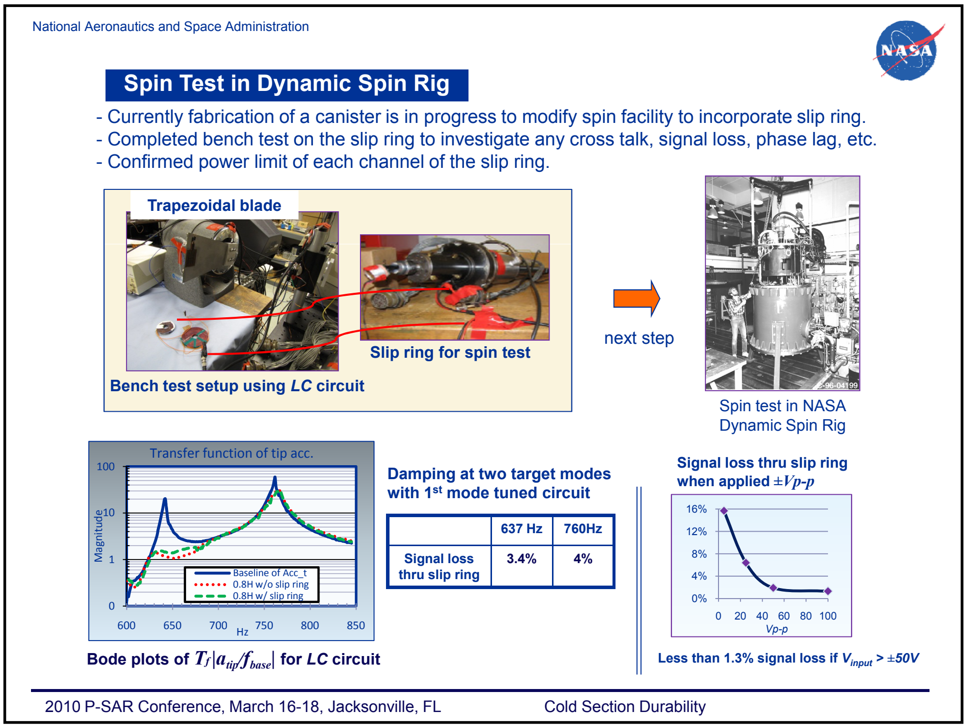

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Spin Test in Dynamic Spin Rig

- Currently fabrication of a canister is in progress to modify spin facility to incorporate slip ring.
- Completed bench test on the slip ring to investigate any cross talk, signal loss, phase lag, etc.
- Confirmed power limit of each channel of the slip ring.

Slip ring for spin test

Bench test setup using *LC* circuit

Spin test in NASA
Dynamic Spin Rig

Bode plots of $T_f|a_{tip}/f_{base}|$ for *LC* circuit

Damping at two target modes with 1st mode tuned circuit

	637 Hz	760Hz
Signal loss thru slip ring	3.4%	4%

Signal loss thru slip ring when applied $\pm Vp\text{-}p$

Less than 1.3% signal loss if $V_{input} > \pm 50V$

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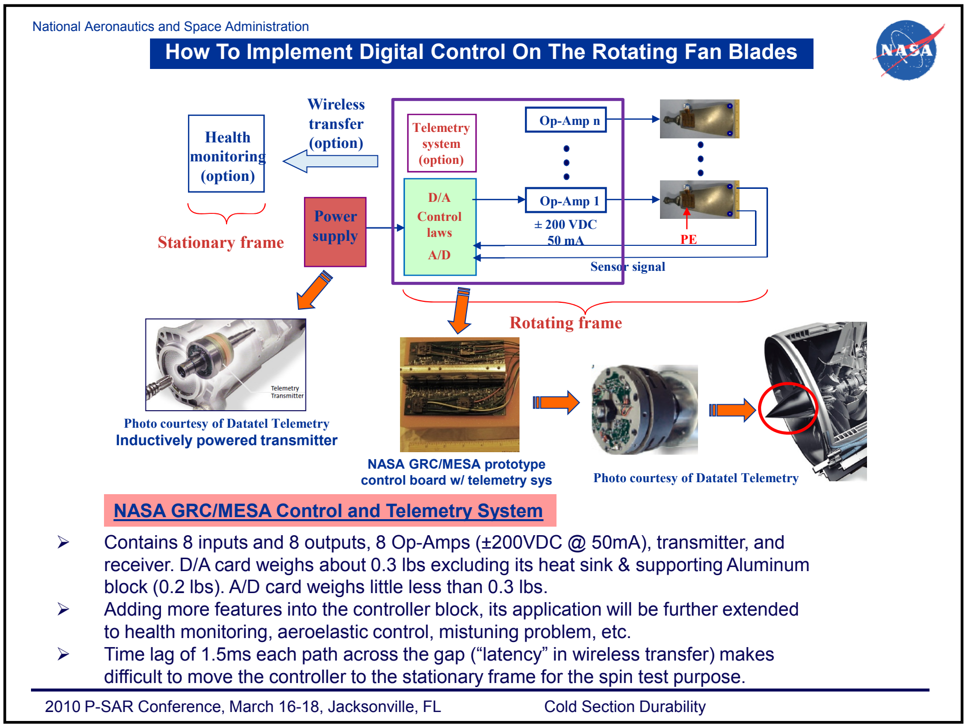

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How To Implement Digital Control On The Rotating Fan Blades

Photo courtesy of Datatel Telemetry

Inductively powered transmitter

NASA GRC/MESA prototype control board w/ telemetry sys

Photo courtesy of Datatel Telemetry

NASA GRC/MESA Control and Telemetry System

- Contains 8 inputs and 8 outputs, 8 Op-Amps (±200VDC @ 50mA), transmitter, and receiver. D/A card weighs about 0.3 lbs excluding its heat sink & supporting Aluminum block (0.2 lbs). A/D card weighs little less than 0.3 lbs.
- Adding more features into the controller block, its application will be further extended to health monitoring, aeroelastic control, mistuning problem, etc.
- Time lag of 1.5ms each path across the gap ("latency" in wireless transfer) makes difficult to move the controller to the stationary frame for the spin test purpose.

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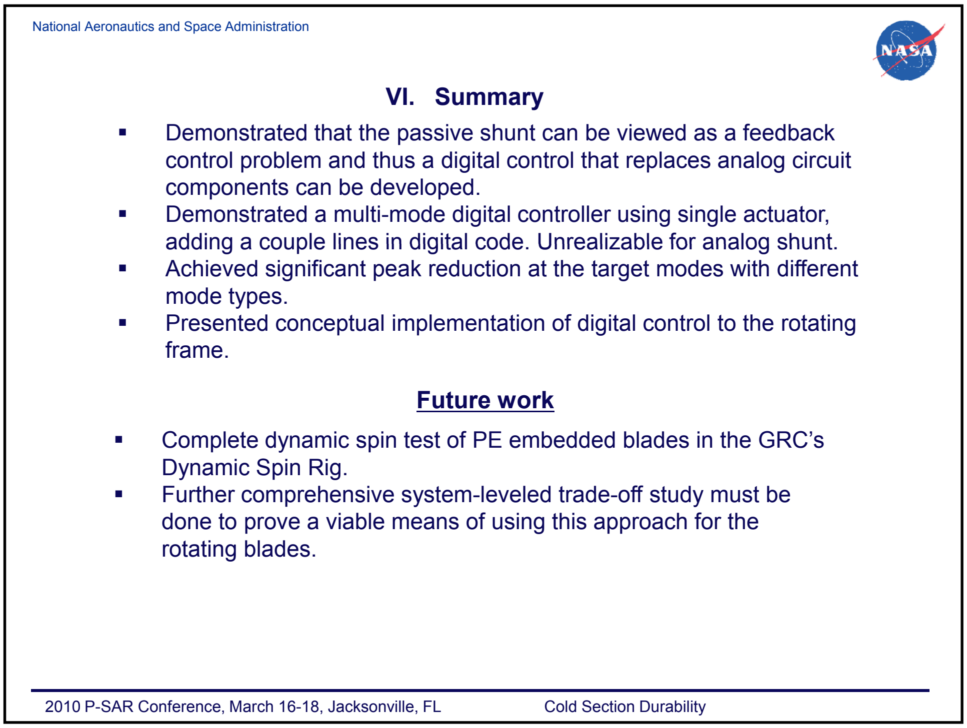

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VI. Summary

- Demonstrated that the passive shunt can be viewed as a feedback control problem and thus a digital control that replaces analog circuit components can be developed.
- Demonstrated a multi-mode digital controller using single actuator, adding a couple lines in digital code. Unrealizable for analog shunt.
- Achieved significant peak reduction at the target modes with different mode types.
- Presented conceptual implementation of digital control to the rotating frame.

Future work

- Complete dynamic spin test of PE embedded blades in the GRC's Dynamic Spin Rig.
- Further comprehensive system-leveled trade-off study must be done to prove a viable means of using this approach for the rotating blades.

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14. ABSTRACT
The NASA Glenn Research Center is developing smart adaptive structures to improve fan blade damping at resonances using piezoelectric (PE) transducers. In this paper, a digital resonant control technique emulating passive shunt circuits is used to demonstrate vibration reduction of FAN1 Ti real fan blade at the several target modes. Single-mode control and multi-mode control using one piezoelectric material are demonstrated. Also a conceptual study of how to implement this digital control system into the rotating fan blade is discussed.

15. SUBJECT TERMS
Piezoelectric transducer; Active control; Damping tests; Fan blades; Vibration damping; Shunt damping

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