AEROELASTIC CONTROL OF NON-ROTATING AND ROTATING WINGS USING THE DYNAMIC STIFFNESS MODULATION PRINCIPLE

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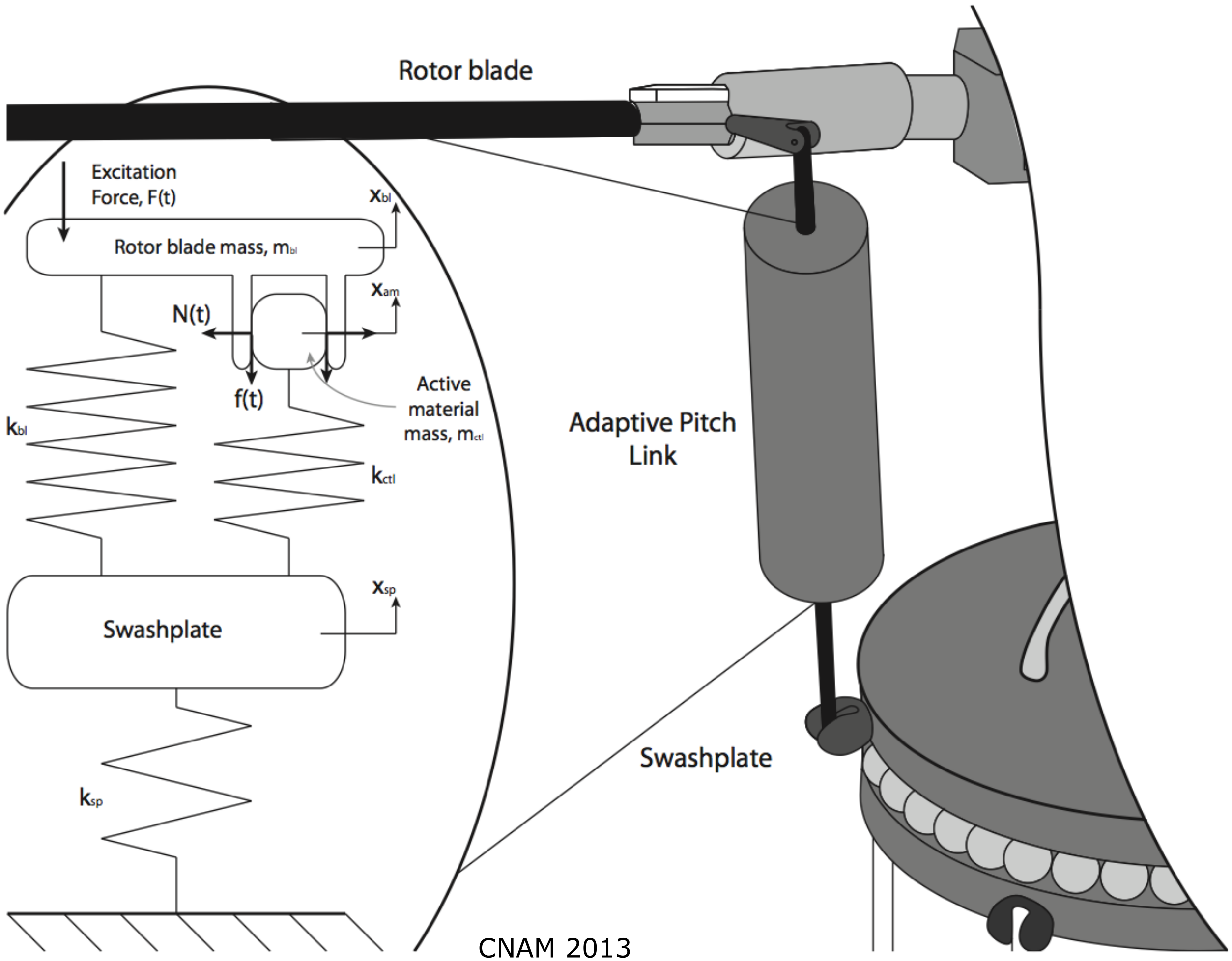
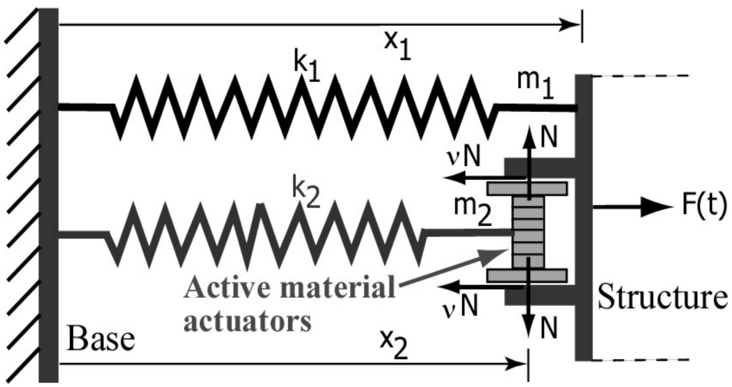
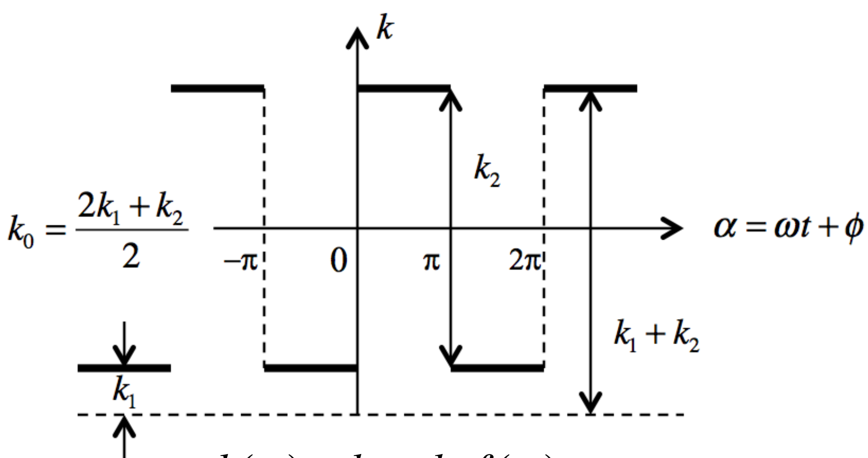
Seminar: December 11, 2013

Adaptive or Active Pitch Link (APL)



Smart Spring parametric excitation reshapes vibration spectrum





$$k(\alpha) = k_0 + k_2 f(\alpha)$$

$$f(\alpha) = \frac{2}{\pi}\left(\sin\alpha + \frac{\sin 3\alpha}{3} + \frac{\sin 5\alpha}{5} + \dots\right)$$

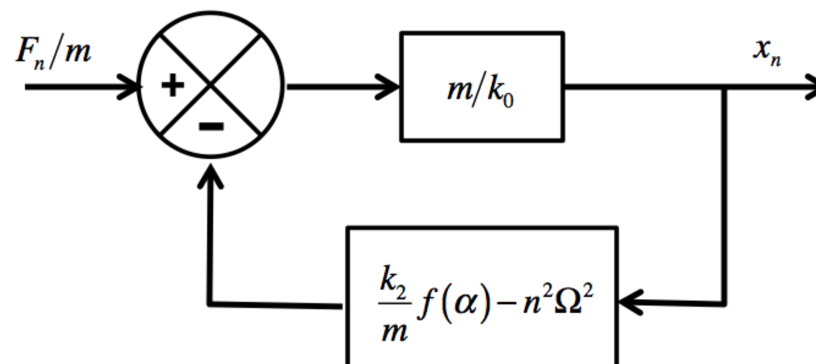
$$m\ddot{x} + k(t)x = F(t)$$

$$F(t) = F_n \sin\left(n\Omega t\right)$$

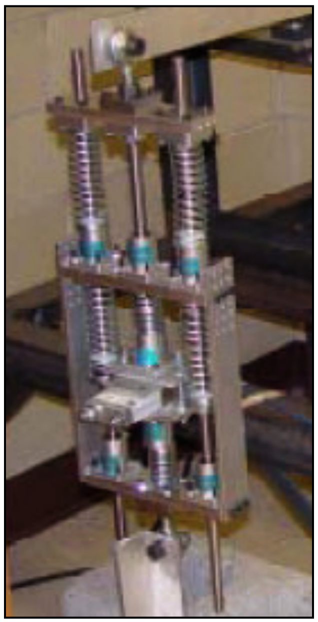
$$x(t) = x_n \sin\left(n\Omega t\right)$$

Neglecting contributions from the other harmonics:

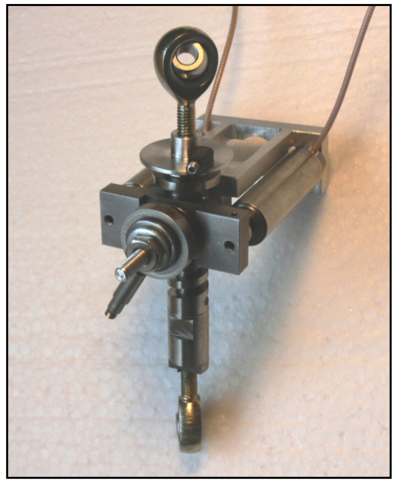
$$x_n = \frac{F_n/k_0}{1+\left(k_2/m\, f(\alpha) - n^2\Omega^2\right)}$$



APL evolution along the SHARCS project



1st Generation (2003)

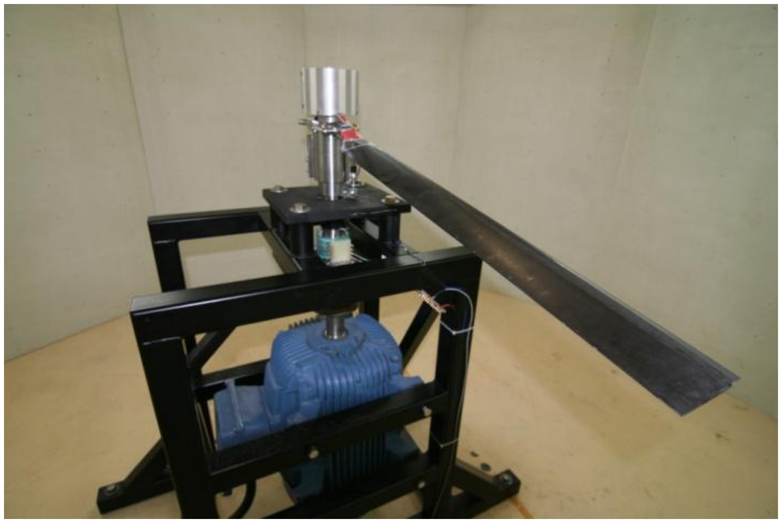


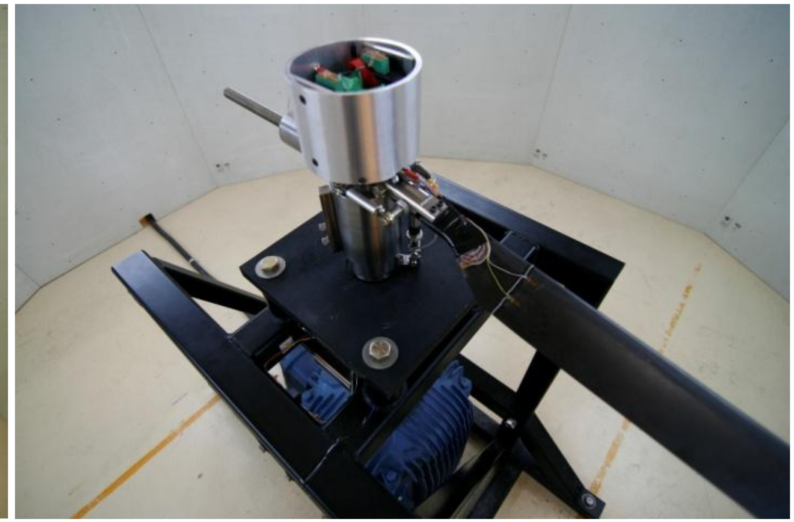
2nd Generation (2006)

3rd Generation (2010)

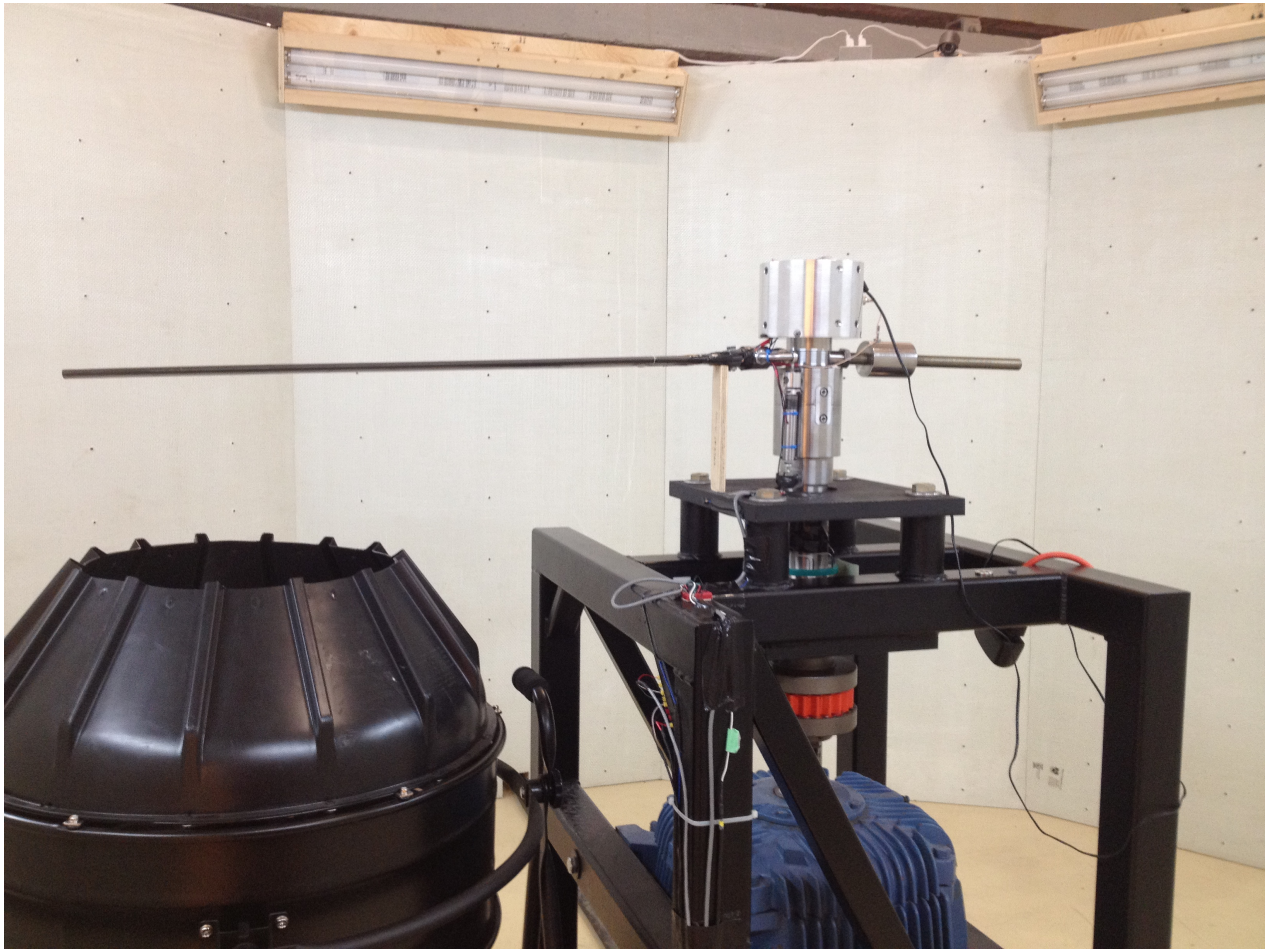
Carleton University rotorcraft

APL rotating tests





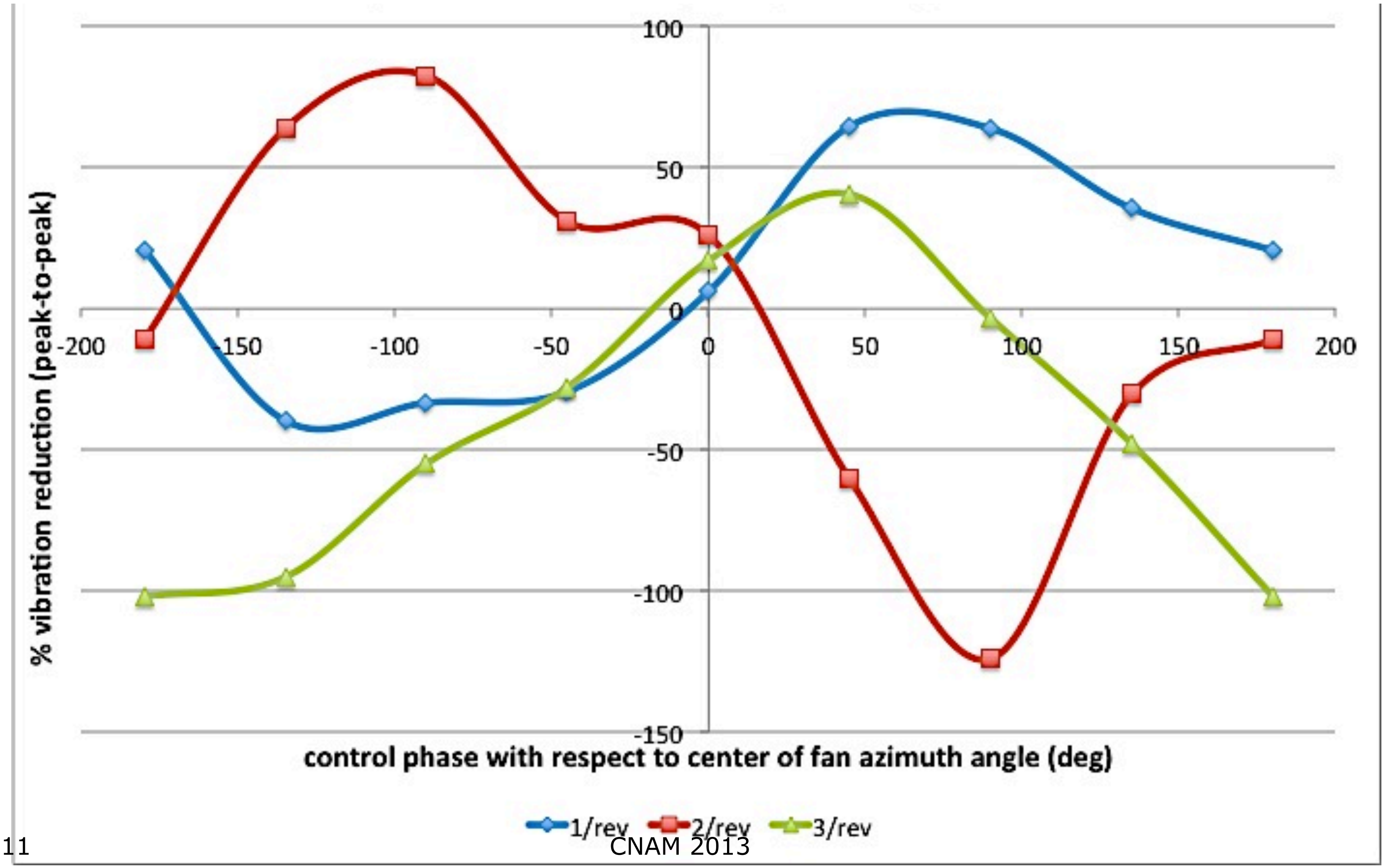
Fan excitation (transversal flow)



Open-loop control performance (APL transmitted axial load)

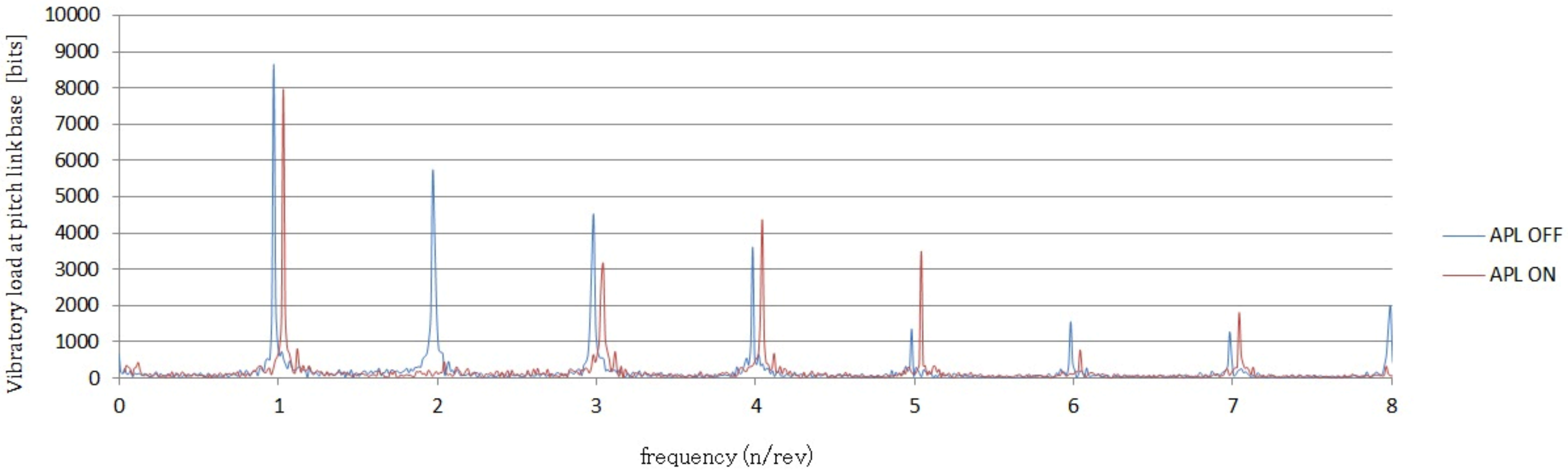
Carleton University rotorcraft

1/rev control signal



Open-loop control performance (APL transmitted axial load)

Best result so far – 100 % reduction at 2/rev with little effect at 1/rev:



1/rev control signal

Conclusions (1)

- Smart Spring concept was proved in experimental rotating blade tests
  - Open-loop parametric stiffness modulation of the blade torsion showed almost 100% vibration reduction for axial transmitted load in one case!
  - Repeatable results were obtained
  - No degradation on the Smart Spring performance was noticed after more than 10 hours of tests
  - Indirect-active device (low power requirement)
  - Reshapes the transmitted load vibration spectrum
    - Simulations indicate that closed-loop control can be designed to attenuate target frequencies – such as 4/rev in a 4-blade helicopter

Synchronized Switch Methods

- Originally presented by Richard *et al.* (1999, 2000)*

- Nonlinear treatment of the electrical output of electromechanical system increases the mechanical to electrical conversion and consequently the shunt damping effect

SSDS (*Synchronized Switch Damping on Short*):

- Leaves piezoelectric element in open-circuit, except when a local maximum voltage is detected and the system is switched to short-circuit for a short period of time

SSDI (*Synchronized Switch Damping on Inductor*):

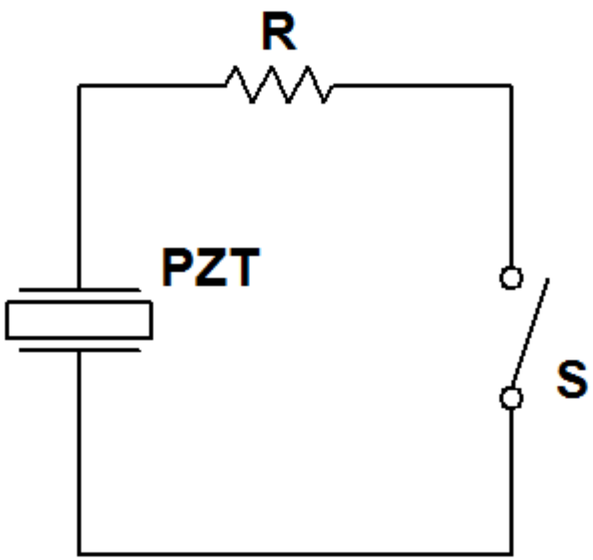
- Similar process but the piezoelectric voltage is inverted due to brief switch to a resonant electrical circuit

**RICHARD, CLAUDE; GUYOMAR, DANIEL; AUDIGIER, D.; CHING, G. Semi-passive damping using continuous switching of a piezoelectric device. Proceedings of SPIE, v. 3672, pp. 104–111, Newport Beach, CA, USA, 1999.*

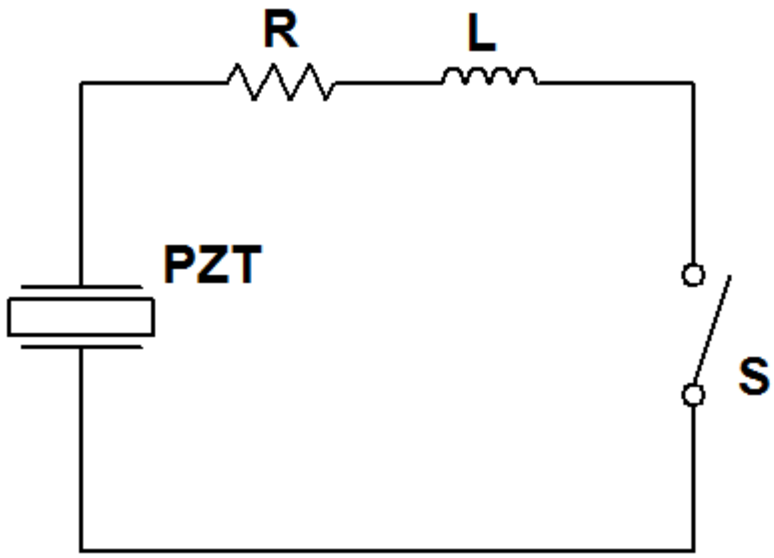
**RICHARD, CLAUDE; GUYOMAR, DANIEL; AUDIGIER, D.; BASSALER, H. Enhanced semi passive damping using continuous switching of a piezoelectric device on an inductor. Proceedings of SPIE, v. 3989, pp. 288–299, 2000.*

Semi-active shunt schemes for vibratory energy harvesting

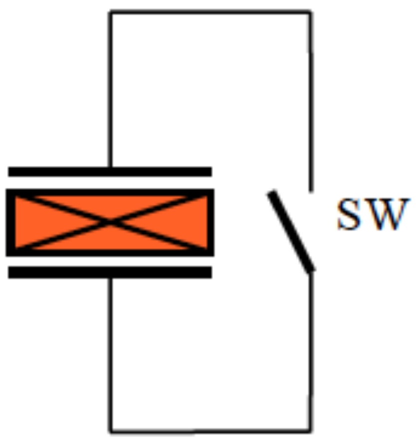
SSDS



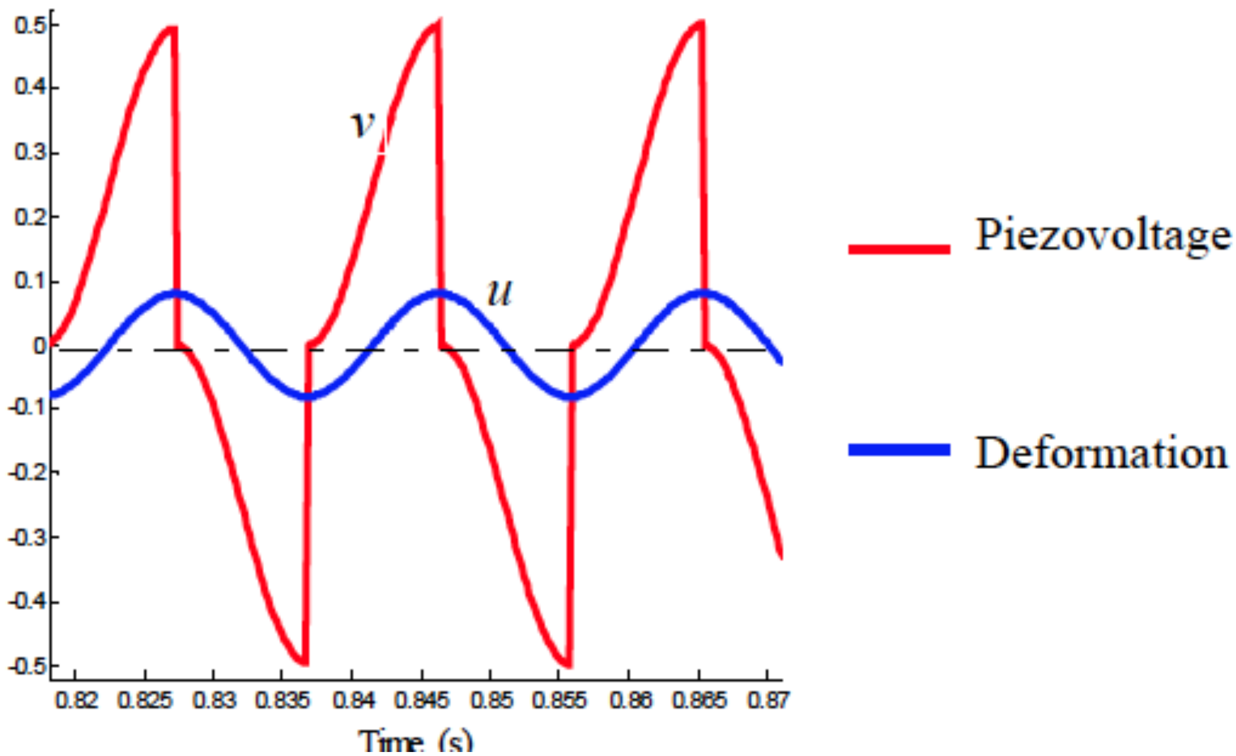
SSDI



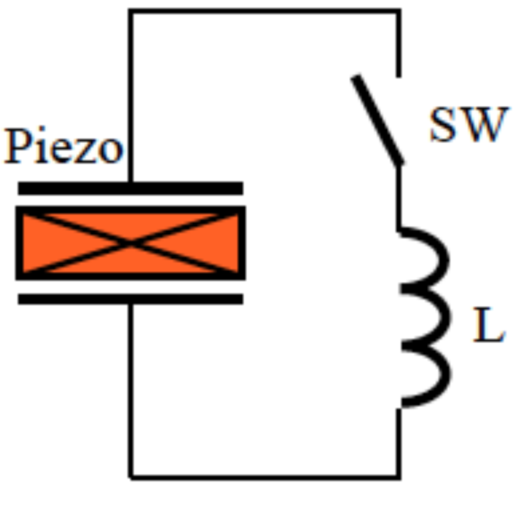
SSDS scheme



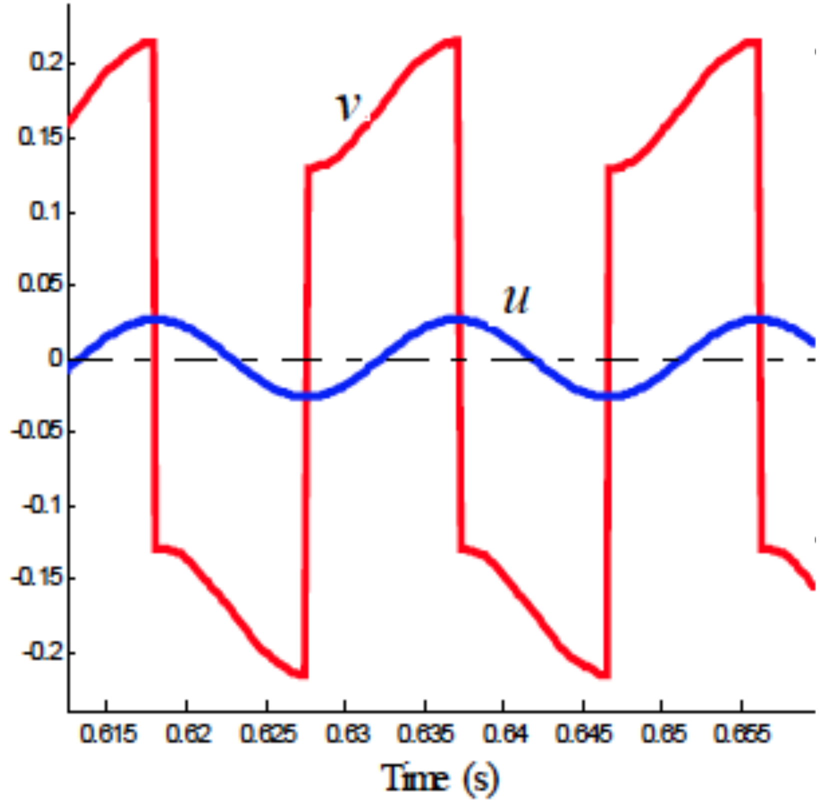
(a) SSDS



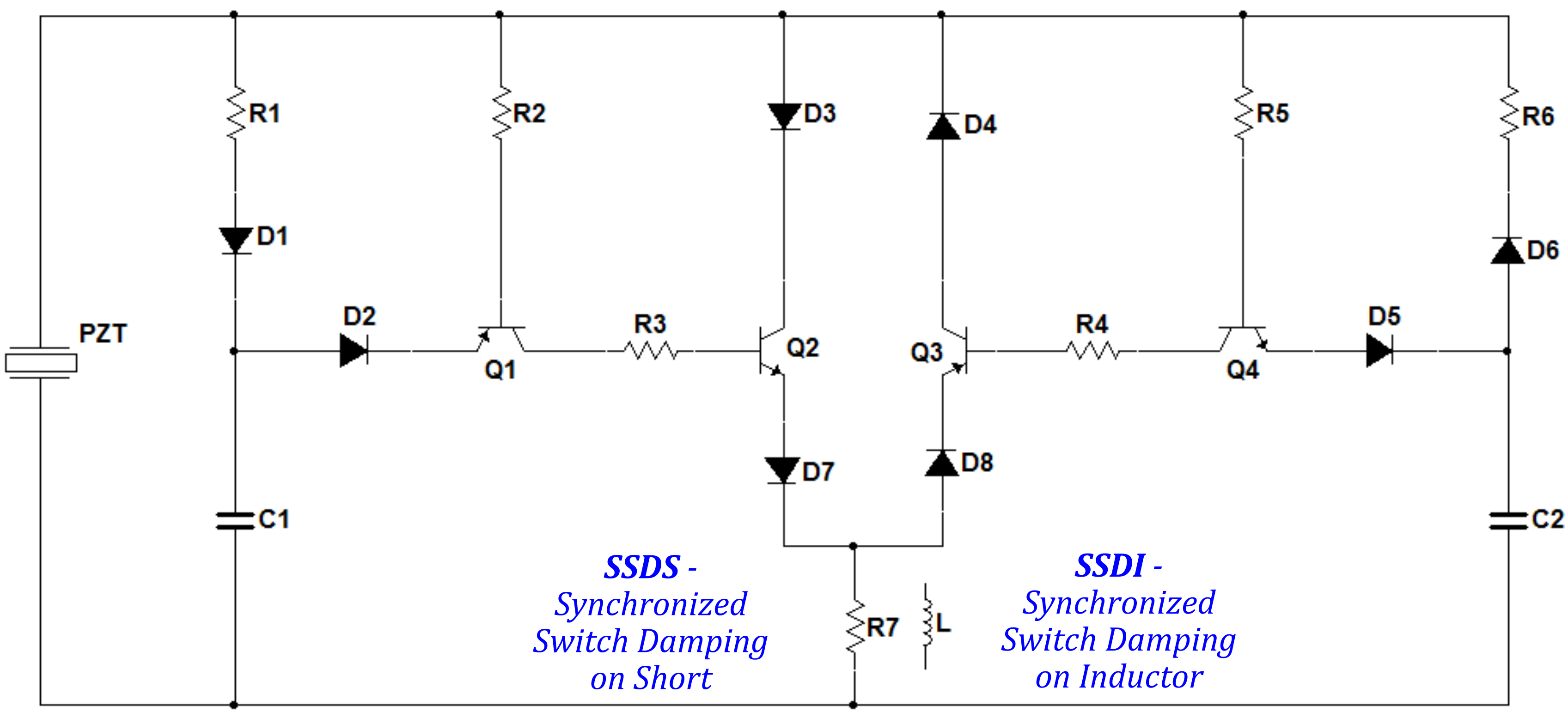
SSDI scheme



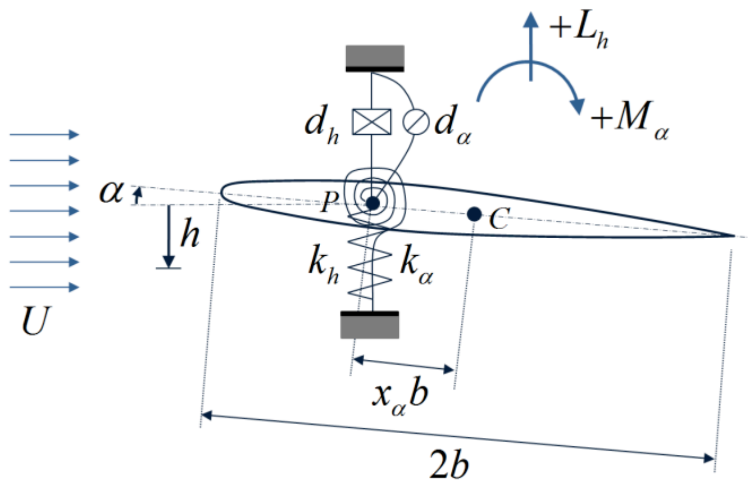
(b) SSDI



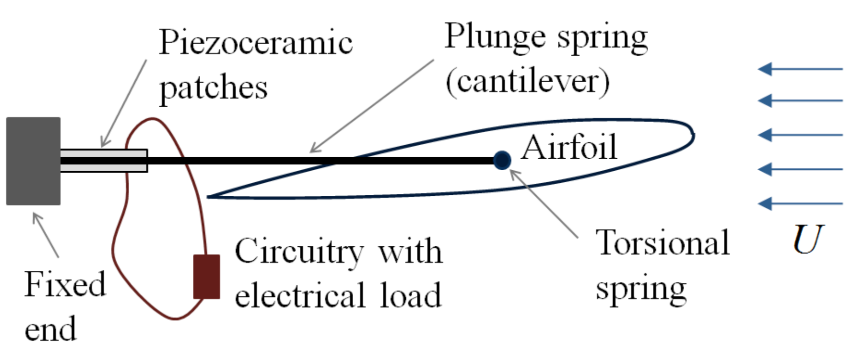
Electronic breaker circuit



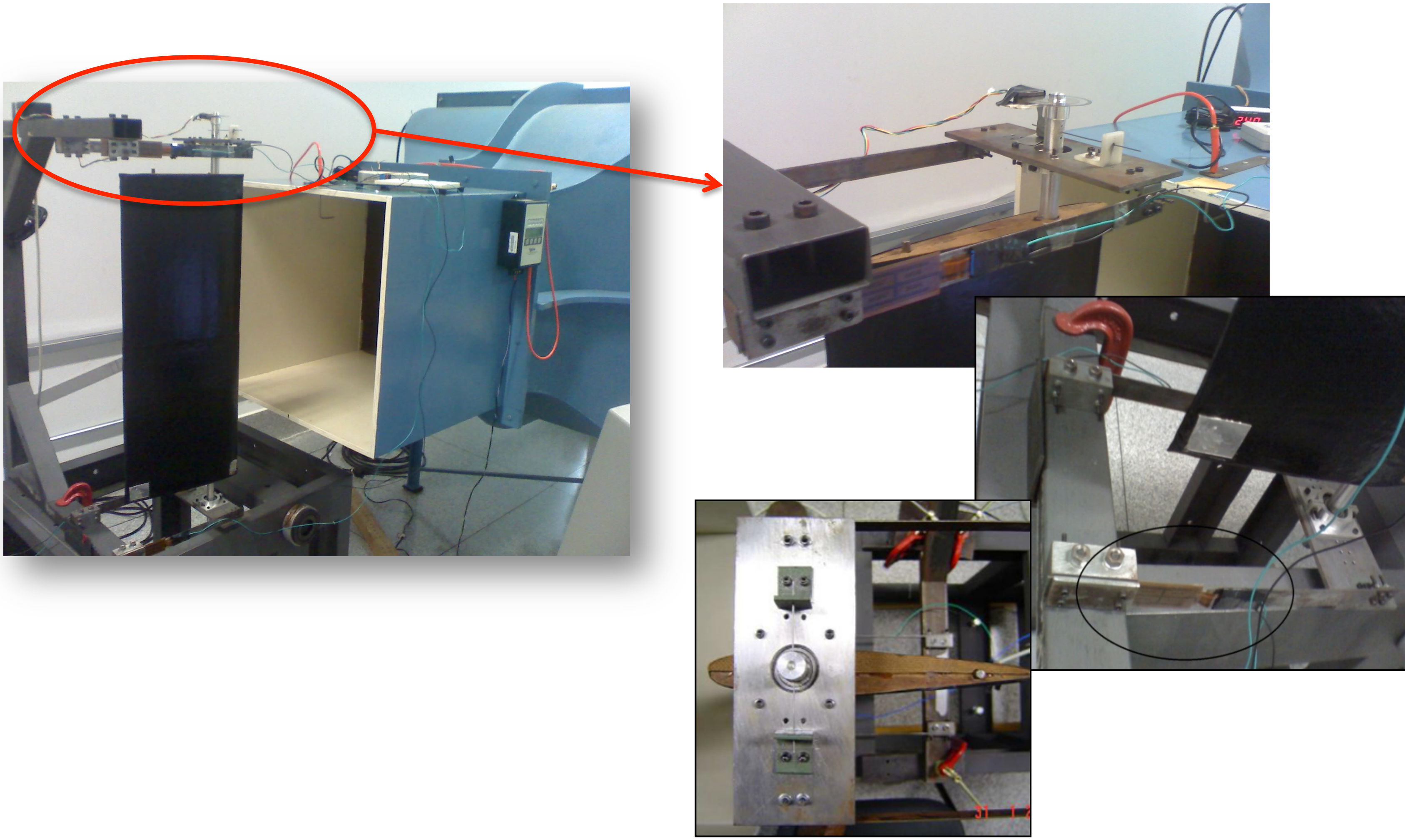
Semi-active method to damp aeroelastic oscillations of a typical section



Piezoelectric coupling is considered for the plunge DOF:

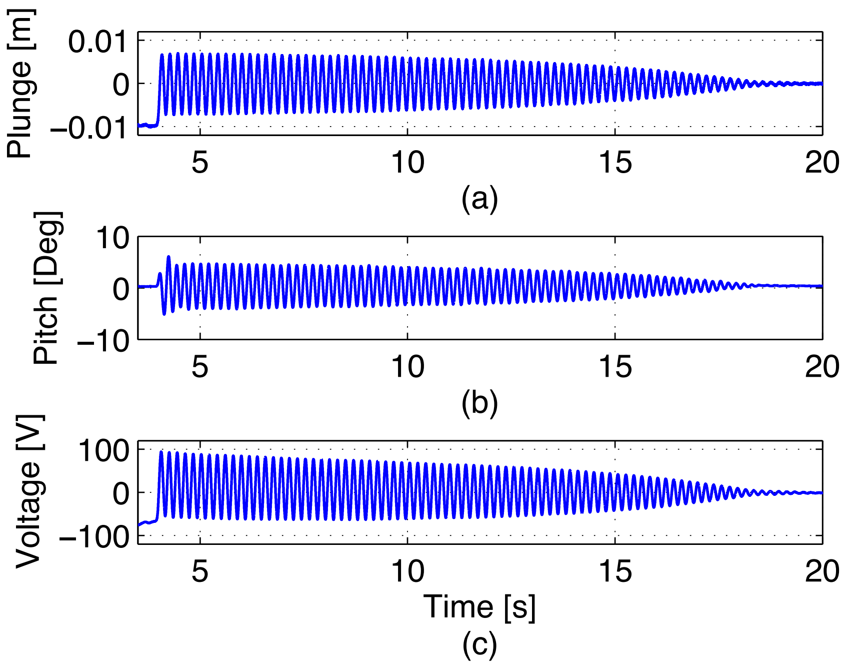


Wind tunnel tests

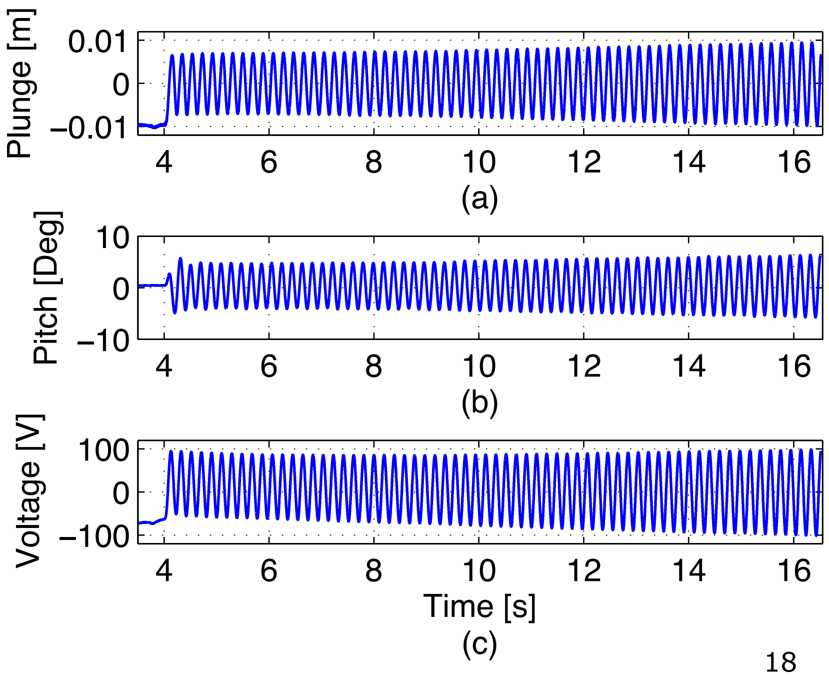


Flutter speed of the electromechanical system experimentally verified

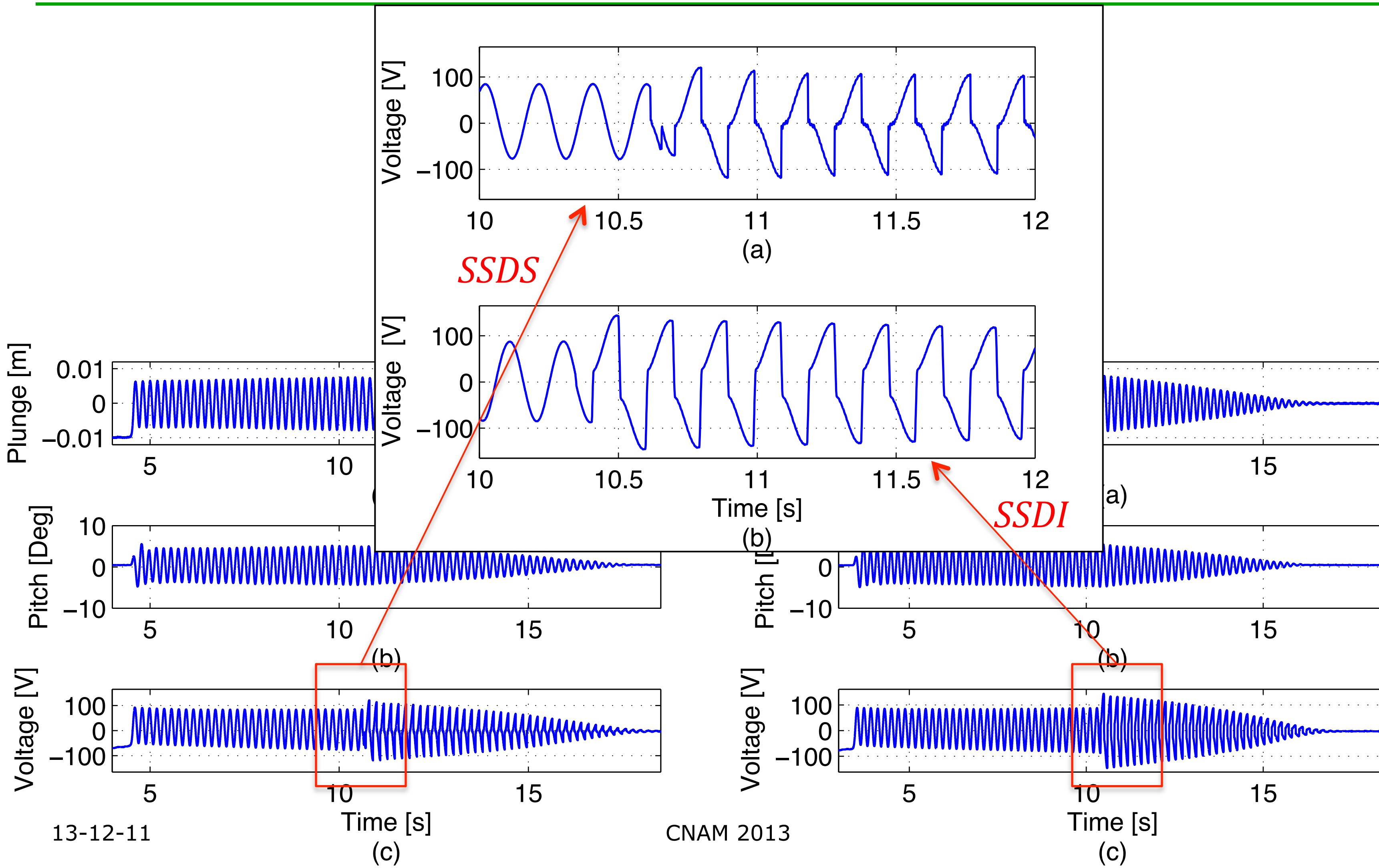
Airflow speed of 11.5 m/s



Airflow speed of 12 m/s



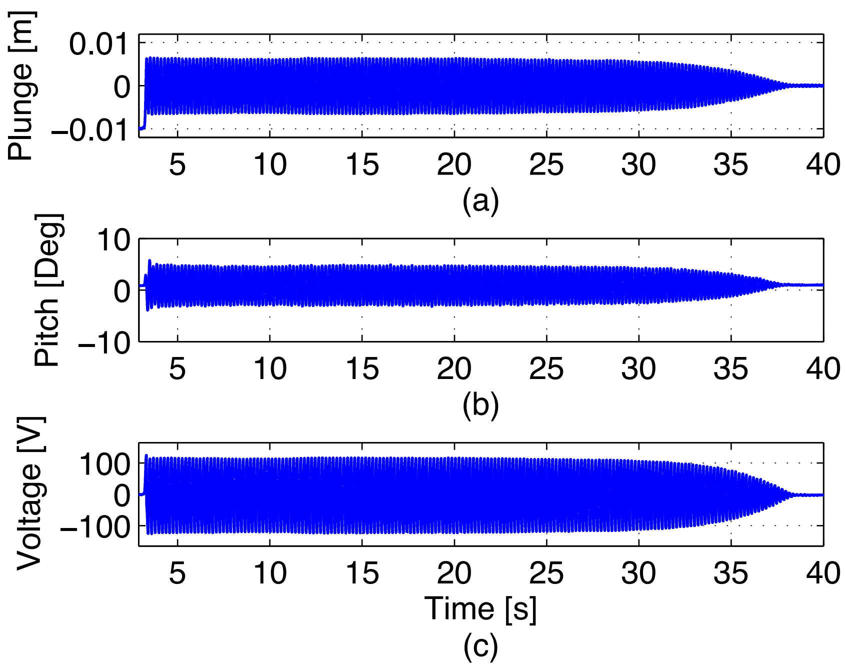
SSDS vs SSDI flutter control



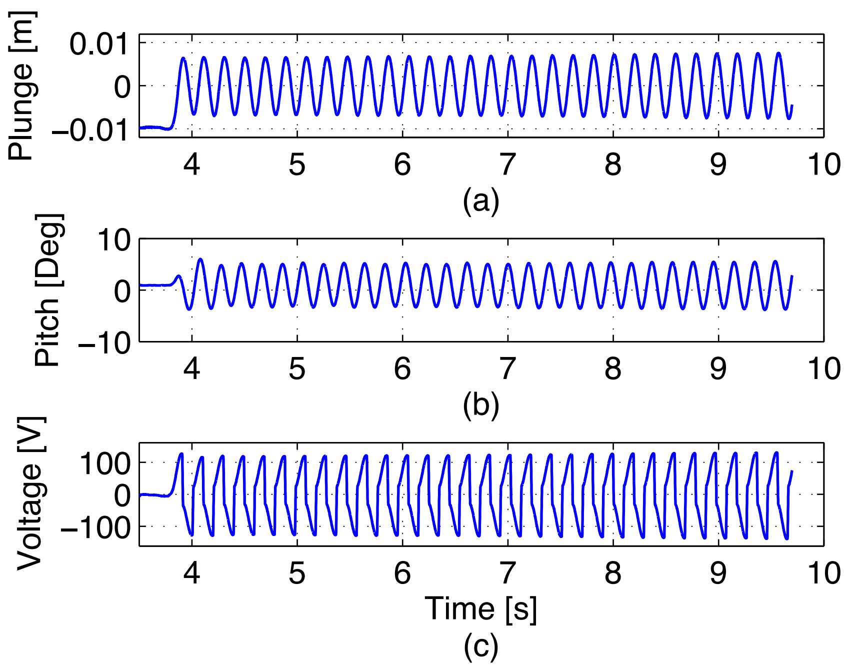
Performance of SSDI controller

Flutter speed 11.4% larger than in the original case

Airflow speed of 13.1m/s

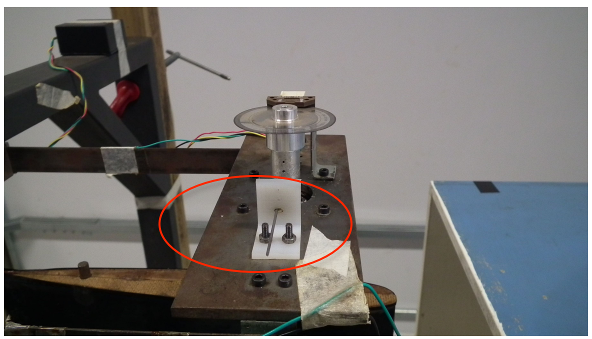


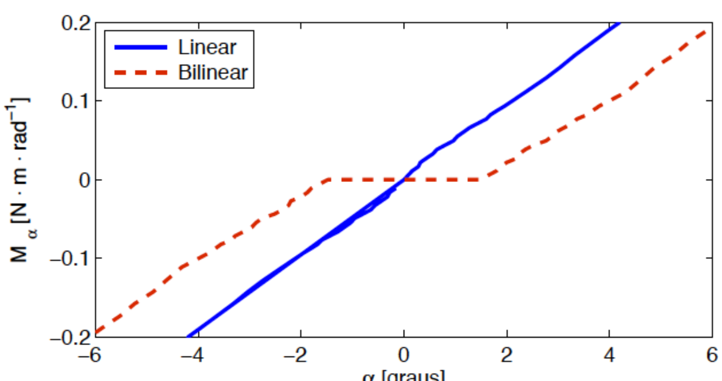
Airflow speed of 13.5m/s

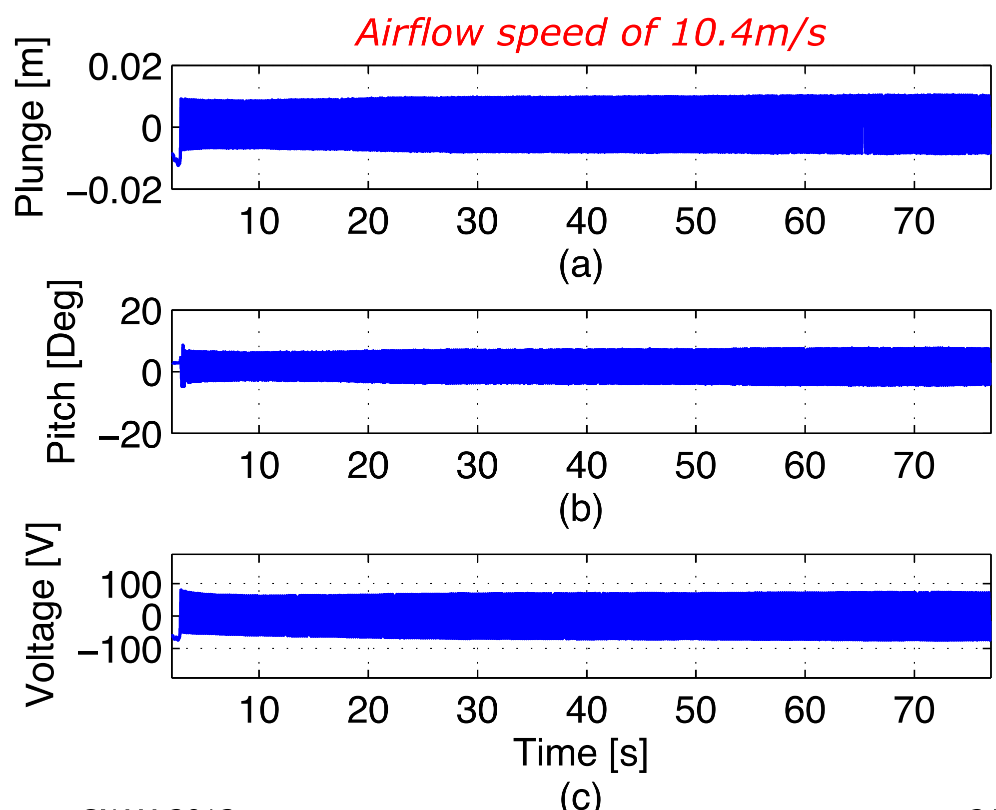


Limit-cycle oscillations

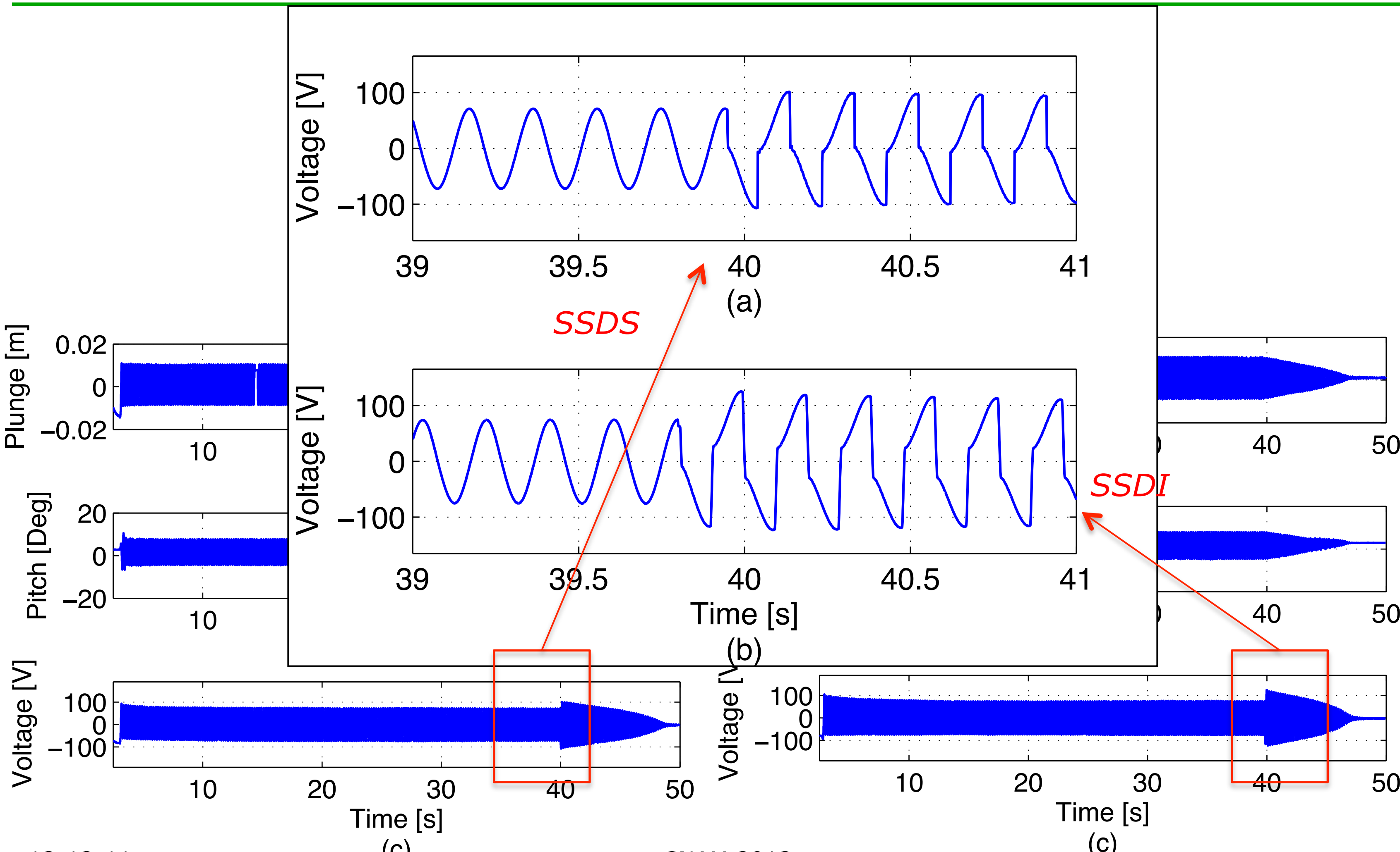
- Free-play nonlinearity was added to the pitch DOF
- LCOs are observed below the flutter speed







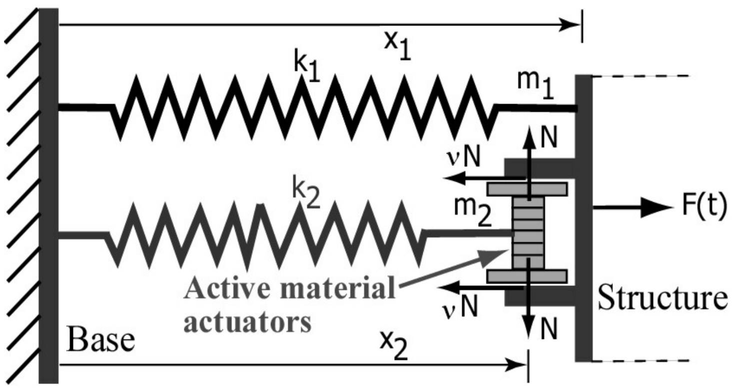
SSDS vs SSDI LCO control

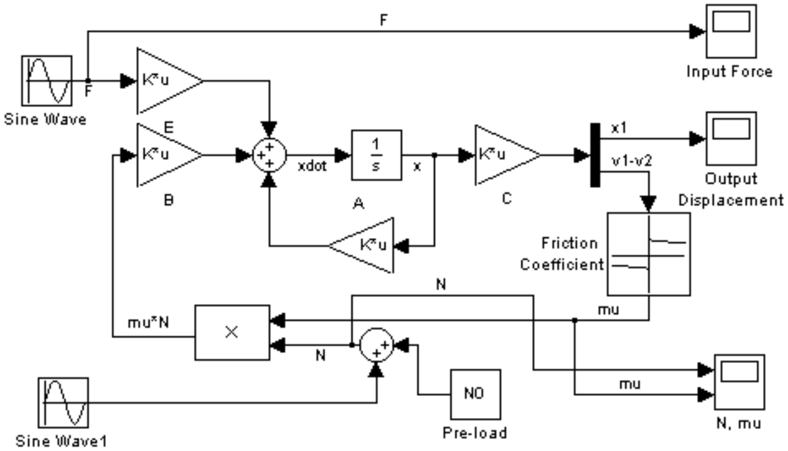


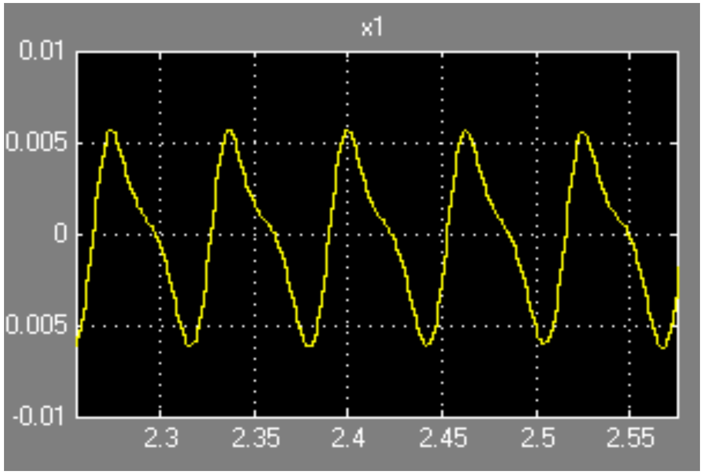
Conclusions (2)

- A self-powered piezoelectric flutter controller was experimentally investigated
  - Flutter oscillations were suppressed when either SSDS or SSDI techniques were used
  - The flutter speed was 8.5% larger when SSDS technique was used
  - The flutter speed was 11.4% larger when SSDI technique was used
- Nonlinear aeroelastic oscillations (LCOs) were observed when free play nonlinearity was added to the pitch DOF
  - LCOs were suppressed when either SSDS or SSDI techniques were employed

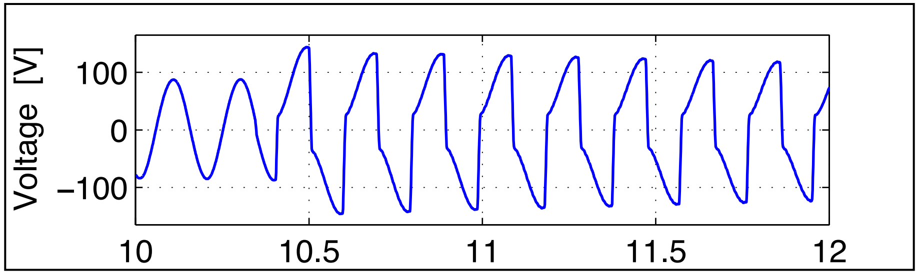
Mechanical vs electromechanical systems: Is the Smart Spring the mechanical realization of the SSDI?





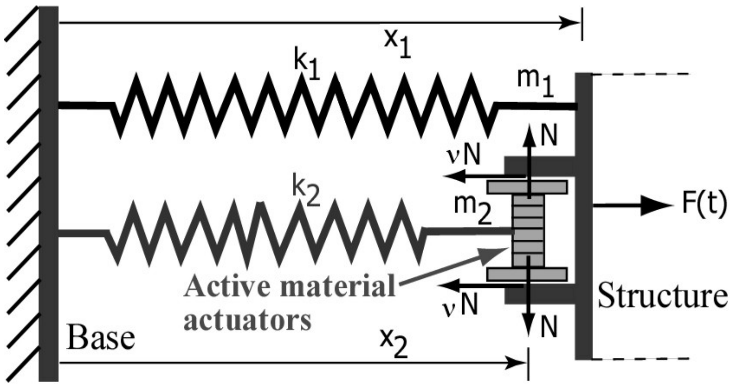


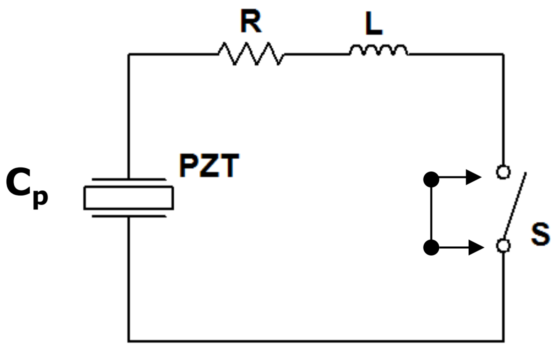
SSDI technique for typical wing aeroelastic control:



$$\ddot{x}+\frac{c}{m}\dot{x}+\frac{k}{m}x=0 \quad \text{versus} \quad \ddot{I}+\frac{R}{L}\dot{I}+\frac{1}{LC}I=0$$

During switching process:





SSDI

$$k=\mathrm{Re}\{k\}+i\,\mathrm{Im}\{k(N,\omega,\nu)\}$$

$$\mathrm{Re}\{k\}=k_1+k_2$$

$$\omega_n=\sqrt{(k_1+k_2)/m_2}\cong\sqrt{k_2/m_2}$$

$$\omega_n=1\Big/\sqrt{LC_p}$$

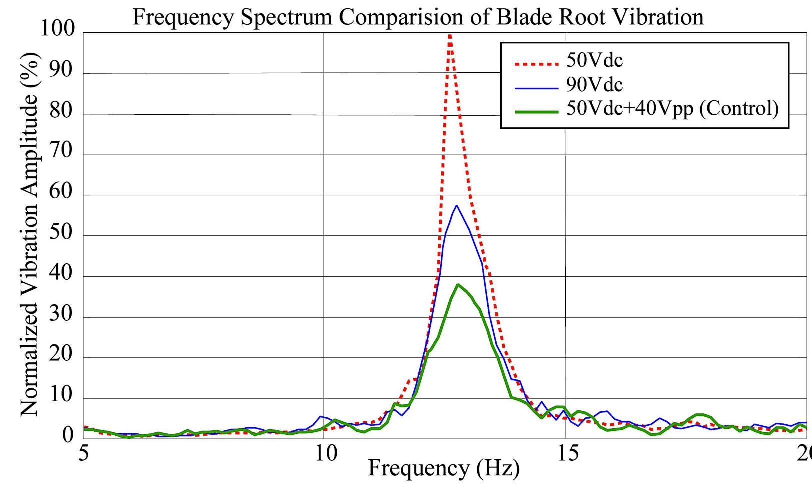
$$\frac{1}{-\omega^2m_2+\mathrm{Re}(k)+i\,\mathrm{Im}(k)}=g(i\omega)=\frac{1}{-\omega^2m_2+i\omega c_2+k_2}$$

$$\zeta=\tfrac{1}{2}\mathrm{Im}(k)\Big/\omega\sqrt{m_2k_2}$$

$$\zeta=\tfrac{1}{2}R_i\sqrt{C_p/L}$$

Parallel between the "Smart Spring" and SSDS / SSDI control methods

- Practical realization of the SSDI calls for a resonance electrical system that is 10 to 50 times the control target frequency of the associated mechanical system
- In a good "Smart Spring" design, the resonance frequency associated with the secondary path (internal resonance frequency) is high, well above the target control frequency
  - "Smart Spring" is called a *stiffness* modulation system where, by definition, the resonance frequency is much higher than the exciting frequency ($\omega_n >> \omega$) and, thus, the system is defined as *stiffness dominated*



Resonance frequency >> 13 Hz
(stiffness dominated system)

Conclusion

- The Smart Spring is the mechanical realization of the SSDI (or SSDS) systems
  - For the “Smart Spring a real variation in the structural stiffness is introduced by the piezoelectric-driven switching mechanism
  - For the SSDS and SSDI techniques, the *apparent* stiffness variation of the coupled electro-mechanical system, introduced by the piezoelectric elements between their closed- and open-circuit conditions (shunt effect), is explored to control vibrations
    - Both SSDS and SSDI can be seen as a class of *stiffness* modulation (or control) methods
  - The objective of the “Smart Spring”, SSDS and the SSDI methods are to artificially increase the operative damping of electro-mechanical systems at a range of relatively low frequencies where the dynamics is primarily stiffness dominated