II. Damping Control of Vibrating Systems

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The topics covered

- General Feedback Control
- Active Control of S&V

1. PID, Lead-Lags, Notch filters
2. EDA (Electrical Dynamic Absorber)
I. Principle

Background & Concept

II. Application Examples

1. Active Vibration Isolation (IEEE TCST 2008)
2. Transducer Damping (JSV1 2011)
3. Multi-Modal Control (SMS1 2011)
4. PPF v.s. NPF (SMS2 2011)
5. Broadband Vibration Control (SMS3 2011)
6. Non-collocated Control (JSV2 2013)
7. Time Delay Control (SMS4 2013)
8. Vibration Control of a Flexible Manipulator (SMS5 2013)

III. Potential Applications
Background: Mechanical Damper v.s. Mechanical Dynamic Vibration Absorber

**Parallel Form**

- **Coefficient:** $c_a$
- **Damping:** $v$
- **Force:** $F$

**Serial Form**

- **Coefficient:** $k_a$
- **Stiffness:** $v$
- **Force:** $F$

**Contributor:** Hartog (1947)

**Impedance**

$$Z_a = c_a$$

$$Z_a = \frac{1}{j\omega m_a} + \frac{1}{c_a} + \frac{j\omega}{k_a}$$

**Graphs:**

- Velocity vs. Frequency
- Impedance vs. Frequency

**Equivalent Form**
Background: Mechanical Damper v.s. Mechanical Dynamic Vibration Absorber

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<th>Tools</th>
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<th>Dynamic Absorber</th>
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<td>Mechanism</td>
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<td>Narrowband Skyhook Damper</td>
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<td>Advantage</td>
<td>• Installation (ex. Vehicles)</td>
<td>• Vibration Isolation &amp; Transmission</td>
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![Car and damper diagram](image)

**Examples of DVA**

- Simple cantilever form
- Buildings
- Automobiles
- Engine break

![Examples of DVA](image)
Examples of DVA

- Harmonic Dampers for Engines
- Helmholtz Resonator
- Suction Resonator
- Muffler

Piezo Actuator

Electromagnetic Actuator

Background: Passive Electrical Dynamic Absorber
Background: 

**Electrical Damper (ED)** v.s. **Electrical Dynamic Absorber (EDA)**

**ED**

- Electrical Damper
- Control Force
- Mechanical System
- Controller
- Response
- Equivalent Model

**EDA**


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**Development of Electrical Dynamic Absorber (EDA)**

- Electrical Damper
  \[ H(j\omega) = c_a \]
- Electrical Dynamic Absorber
  \[ H(j\omega) = c_a \frac{j2\zeta\omega_d\omega}{\omega^2 - \omega_d^2 + j2\zeta\omega_d\omega} \]

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**Equivalent Model**
Comparison between ED and EDA

- \( H(j \omega) \)

**Tools**

- **Electrical Damper**
  - Broadband Device
  - Narrowband Skyhook Damper

- **Electrical Dynamic Absorber**
  - Narrowband Device

**Performance**

- Broadband Device
- Narrowband Device

**Mechanism**

- Narrowband Skyhook Damper

**Advantage**

- Robustness
  - Effectively in the control bandwidth & Ineffectively otherwise.

"EDA is ALWAYS better than ED."

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Advantages of **Electrical Dynamic Absorber (EDA)**

Most eminent advantages come from the fact that it is a narrowband controller.

If it is tuned to a mode, it simply becomes a modal controller controlling only a single target mode.

1. multi-modal control is feasible.
2. Non-collocated control is feasible for multiple modes of mixed phases
3. Time delay system control is feasible
   - by compensating each of multiple modes of different phases.
Summary

Passive Tools
<table>
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Active Tools
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Three General Tools for Noise & Vibration Control

Performance

Advantages:
1. Effective
2. Convenient to design
3. Very stable
II. Applications

1. Active Vibration Isolation
2. Transducer Damping
3. Multi-Modal Control
4. PPF vs. NPF
5. Broadband Vibration Control
6. Non-Collocated Control
7. Time Delay Control
8. Vibration Control of a Flexible Manipulator

Design Rules – using Den Hartog’s Fixed-Point Theory

Obtain maximally flat response.

Frequency tuning \( \omega_d = \omega_p \sqrt{\text{mass ratio}/2} \)

Normalized Frequency

Velocity (dB) vs. Position

Three Ways to realize the same EDA

1. Active Vibration Isolation
2. Transducer Damping
3. Multi-Modal Control
4. PPF vs. NPF
5. Broadband Vibration Control
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Methods

Position

Velocity

Acceleration

PPF (position acceleration feedback)

VVF (velocity velocity feedback)

APF (acceleration position feedback)

2nd order HP filter

2nd order BP filter

2nd order LP filter

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Normalized Frequency

2. Electrical Transducer Damping (JSV 2011)

3. Modal Control using strain sensors (SMS 2011)

4. Multi-modal Control using Acc. (SMS 2011)

5. Broadband Control (SMS 2011)

6. Non-collocated Control (JSV 2013)

7. Time Delay Control (SMS 2013)

8. Flexible Manipulator (SMS 2013)

1. Active Vibration Isolation: Background (1/3)

Commercial product by multiprobe

Test rig

Construction

Performance

4-mount experimental rig

Kinetic energy

Frequency
1. Active Vibration Isolation: Goal (2/3)

- Task: Improve Stability and Performance
- Solution: EDA
- Method: Comparison between ED and EDA

Isolator
Primary shaker
Equipment and secondary shaker

Digital EDA filter using an x-PC Target

\[ H(j\omega) = \frac{j2\zeta\omega_a\omega}{\omega_a^2 - \omega^2 + j2\zeta\omega_a\omega} \]

1. Active Vibration Isolation: Performance (3/3)

EDA works as well as ED.

EDA is more robust to undesirable effects outside the control bandwidth.
2. Transducer Damping: Background (1/3)

Inertial Actuator

![Inertial Actuator Image]

Accelerometer

![Accelerometer Image]

Figure 2: Typical actuator response. Actuator with 100 gram inertial mass is attached to 20 kilogram ground.

2. Transducer Damping: Construction (2/3)

![Construction Diagram]

Passive shunt circuit

EDA
2. Transducer Damping: Performance (3/3)

Contributions

1. Exact mechanical analogy

2. Optimal absorber damping \[ \omega_a = \omega_s \quad \zeta_a = \sqrt{\text{(mass ratio)}/2} \]

3. Multi-Modal Control: Experimental Setup (1/3)

Plant description

Digital EDA filter

Task: Suppress the first three modes

Plant Response

1st Mode

2nd Mode

3rd Mode

Contributions

- Optimal and robust control methodology;
- Optimal because the controller maximally flattens the mobility;
- Robust because it does not allow the control spillover any more than 2 dB.
4. Comparison between PPF and NPF: Plant (1/2)

Using PZT + PVDF

Digital EDA filter using an x-PC Target

Plant Response

(a) Generalized Stability Response (dB)

\[ H(j \omega) = \frac{-k_a \omega_a^2}{\omega_a^2 - \omega^2 + j2\zeta \omega_a \omega} \]

(b) Imaginary

\[ \text{Lowpass Filter} \quad H_{PPF}(j \omega) = \frac{-k_a \omega_a^2}{\omega_a^2 - \omega^2 + j2\zeta \omega_a \omega} \]

\[ \text{Highpass Filter} \quad H_{NPF}(j \omega) = \frac{k_a(j \omega)^2}{\omega_a^2 - \omega^2 + j2\zeta \omega_a \omega} \]

4. Comparison between PPF and NPF: Performance (2/2)

Contributions

1. NPF = eDVA
2. NPF is useful for multi-modal control
5. Robust Broadband Vibration Control: Setup (1/4)

Plant: The same as for 3. the Modal Control using an Accelerometer

Task: Suppress all the vibrations in the frequency bandwidth of two decades from 10 Hz to 1 kHz

5. Robust Broadband Vibration Control: Analog Control Filter (2/4)

\[
C(j\omega) = m_2 \left( \frac{\omega_a^2}{\omega_a^2 - \omega^2 + jb\omega_a\omega} \right) \left( \frac{\omega_c}{\omega_c + j\omega} \right)
\]
5. Robust Broadband Vibration Control: Performance (3/4)

Original plant

![Graph showing Original plant performance.]

Perturbed plant

![Graph showing Perturbed plant performance.]

5. Robust Broadband Vibration Control: Robustness (4/4)

Original plant

![Graph showing Original plant robustness.]

Perturbed plant

![Graph showing Perturbed plant robustness.]

Conclusions

It is possible to control broadband vibrations using a single EDA. This has been possible because it have been implemented electrically.
6. Non-Collocated Control: Setup (1/3)

Concept: negatively FB for in-phase modes and positively FB for out-of-phase modes.

Task: Suppress both in- and out-of-phase modes.

6. Non-Collocated Control: Concept (2/3)

Concept: negatively FB for in-phase modes and positively FB for out-of-phase modes.

Plant mobility

Controller

Loop Gain

(a) 

(b) 

(c)
6. Non-Collocated Control : Results (3/3)

Original plant

Perturbed plant

7. Time Delay Control : Setup (1/3)

Task : Suppress the first two modes that are time delayed
7. Time Delay Control: Plant (2/3)

7. Time Delay Control: Results (3/3)
Figure 1. Experimental setup for both motion and vibration control of a flexible beam.

Figure 2. Measured Nyquist plot of the plant, where numbers 1–6 indicate the vibration mode orders.
8. Vibration Control of a Flexible Manipulator (3/3)

Figure 4. Control of a random disturbance without (dash-dot lines) and with (solid lines) the vibration control circuit: (a) the hub displacement, and (b) the tip displacement.

Figure 5. Control performance for a step input of 2° without (dash-dot lines) and with (solid lines) the vibration control circuit: (a) the hub displacement, and (b) the tip acceleration.

II. Potential Applications

1. Vibrations
2. Dynamics
3. Acoustics
**Summary**

- **EDA** is an electrical realization of mechanical dynamic vibration absorber.

- It is stable and robust as it realizes a physically existing mechanism.

- It is rather a general method that has many applications: ex. multi-modal control, non-collocated control, time delay control.

- Prospect: It may survive for a long time as we can not think of any simpler and more effective method to control a mode than using the dynamic absorption mechanism.

- Hot Challenges: Adaptive EDA, Non-resonance control
References

- S M Kim, M J Brennan, Active vibration control using delayed resonant feedback, Smart Materials and Structures 22, 095013 (7pp) (2013)

Those recommendable to read in blue.