Institute of Fundamental Technological Research

ul. Pawińskiego 5B, 02-106 Warsaw, Poland

Structural vibration mitigation by means of semi-active adaptation of structural stiffness

Grzegorz Mikułowski

Discipline: mechanical engineering

Department of Intelligent Technologies,
Division of Safety Engineering

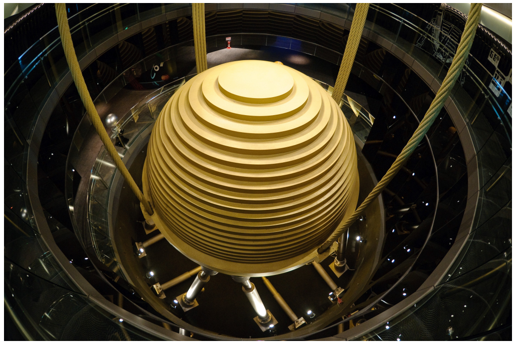
e-mail: gmikulow@ippt.pan.pl

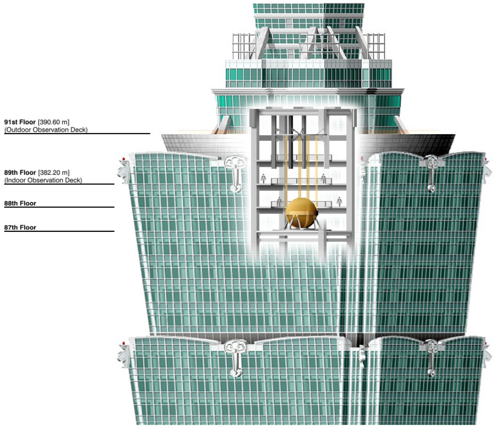
Contents

- Vibration control - challenges
- Stiffness modulation for vibration mitigation
  - Semi-active pneumatic isolation
  - Semi-active piezoelectric isolation
  - Semi-active local stiffness modifications in frames
- Habilitation achievement, professional activities

Vibration control – contemporary challenges

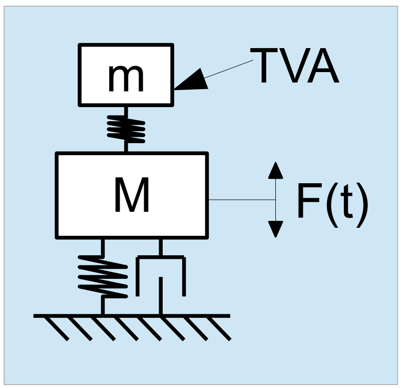
- Types of vibration control actuators:
  - hydraulic,
  - pneumatic,
  - elastomeric.
  - ceramic.



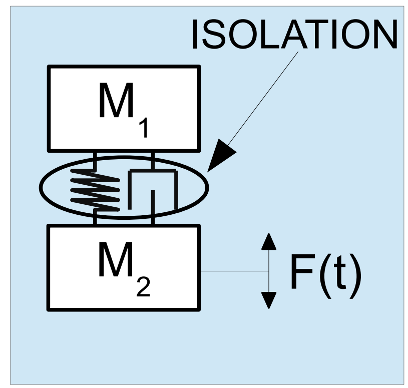


Vibration mitigation – classification

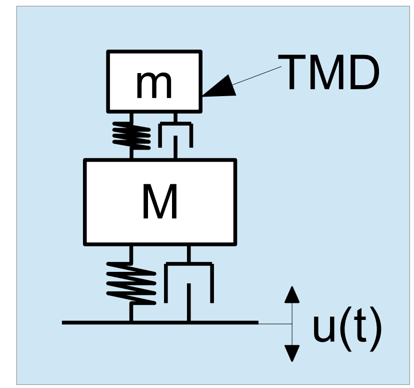
- **Source mitigation**



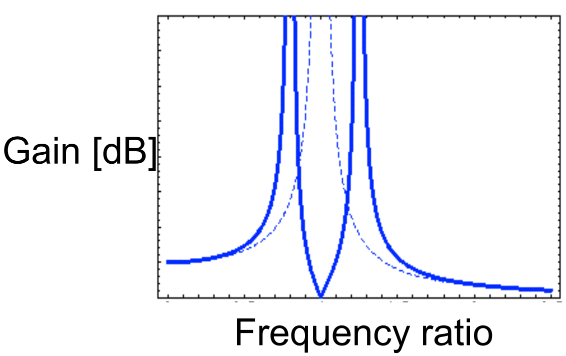
- **Isolation**

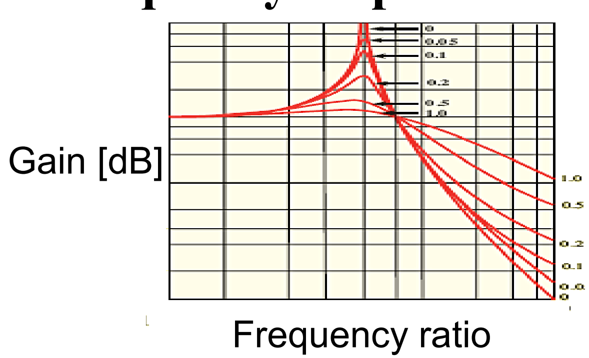


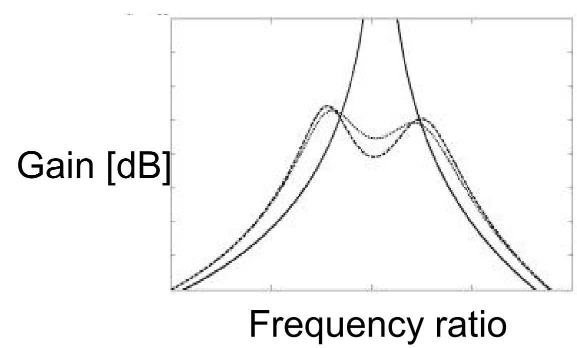
- **Absorption**



- **Frequency response functions:**



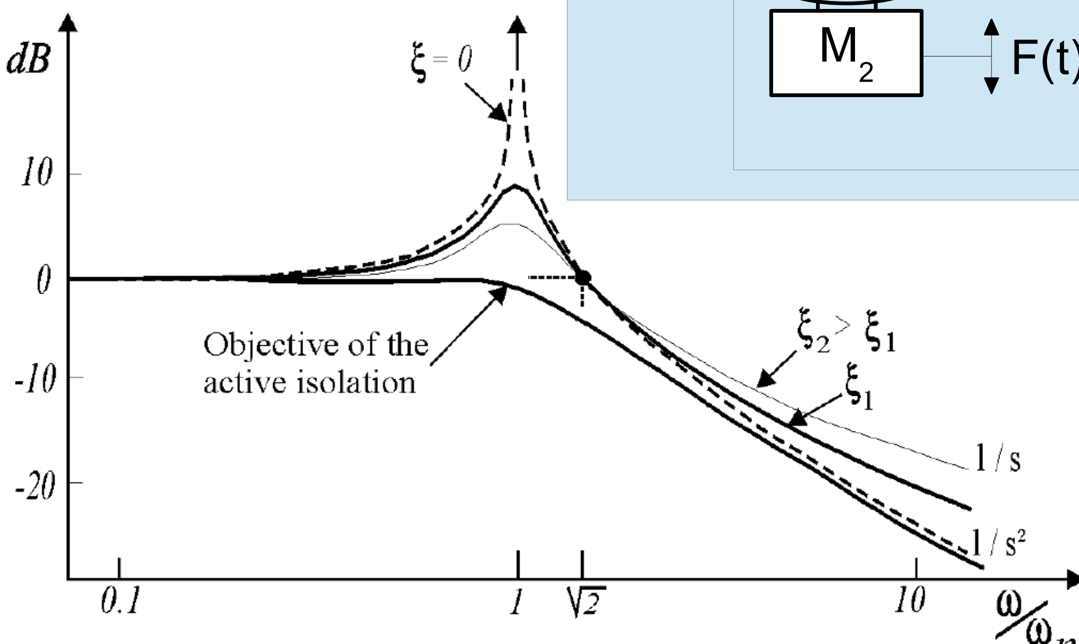




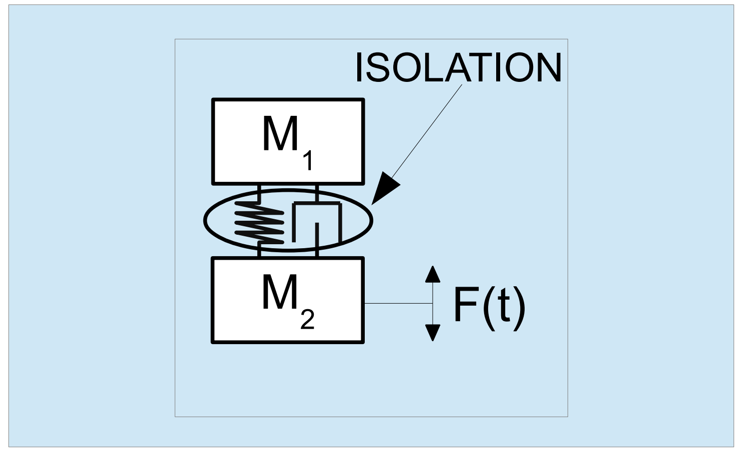
- **Passive, active, semi-active systems**
  - **Demands:** adaptivity within a certain bandwidth (e.g. resistance to temperature variations) by system's stiffness, inertia and damping modification

Vibration isolation – objectives

Transmissibility

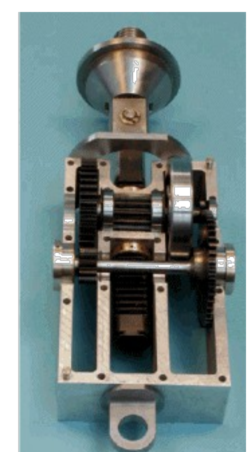


Frequency ratio



Requirements:

- system stiffness tuning
- system inertia increase



Inerter demonstrator

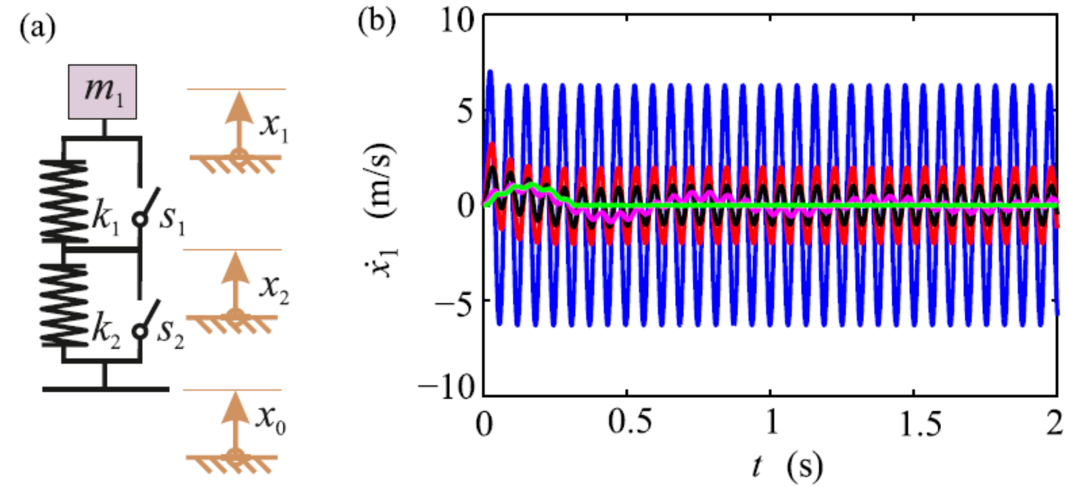
A. Preumont, Vibration Control of Active Structures, Kluwer Academic, London, 2002

Vibration isolation by switching stiffness and negative stiffness

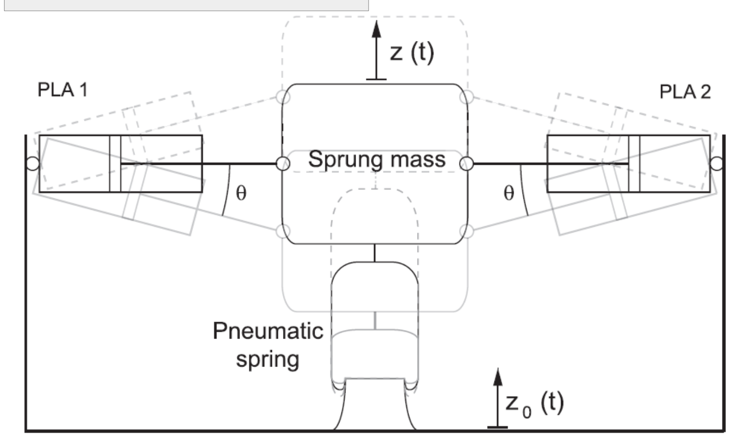
2017 Min et al.

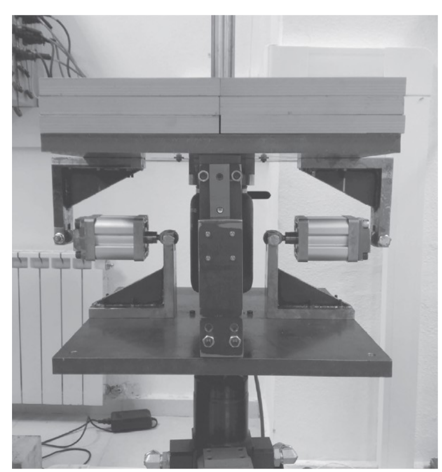
Demands:

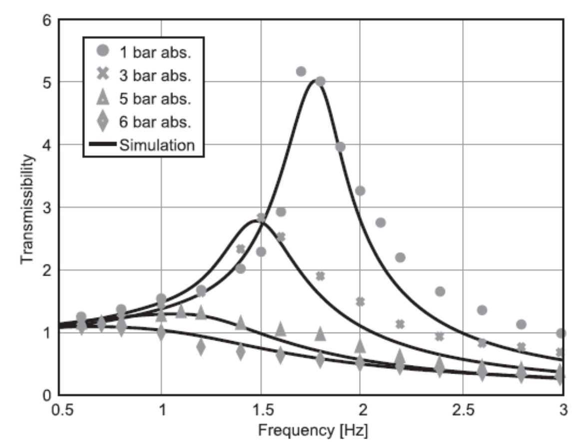
- Stiffness control
- Low weight
- Efficiency in low frequency range
- Increased stroke solution



2018 Palomares et al.



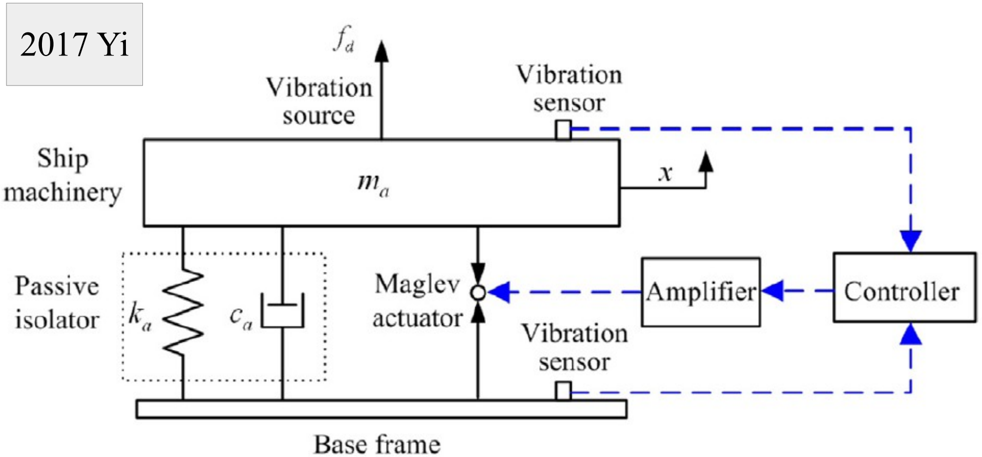


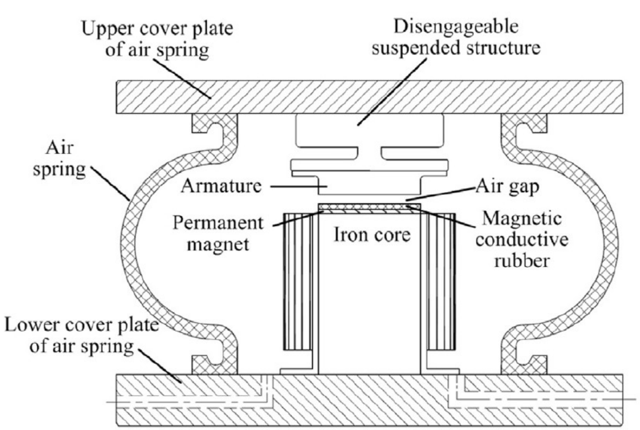


2017 C. Min et al., A concept for semi-active vibration control with a serial-stiffness-switch system, Journal of Sound and Vibration 405,
2018 E. Palomares et al., Numerical and experimental analysis of a vibration isolator equipped with a negative stiffness,Journal of Sound and Vibration, 414.

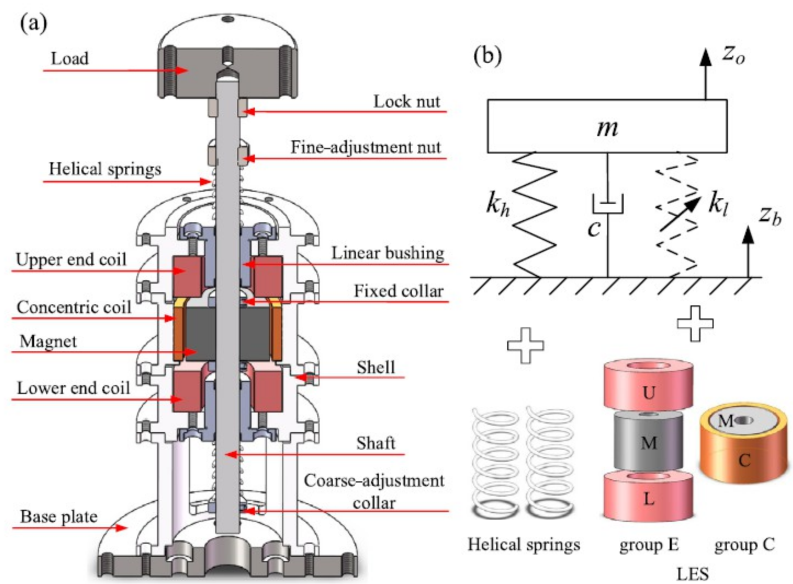
Vibration isolation via stiffness modulation in magnetic field

2017 Yi



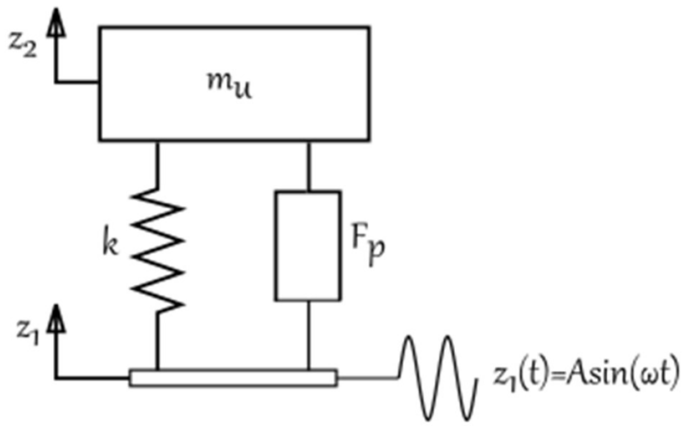


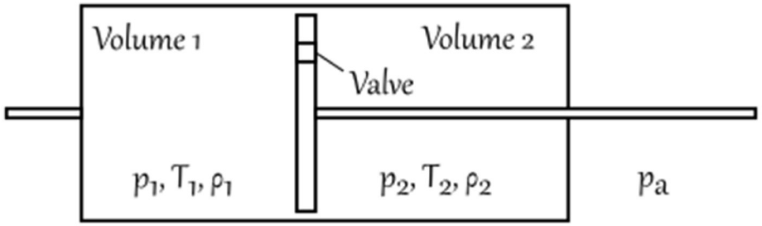
2020 Yuan

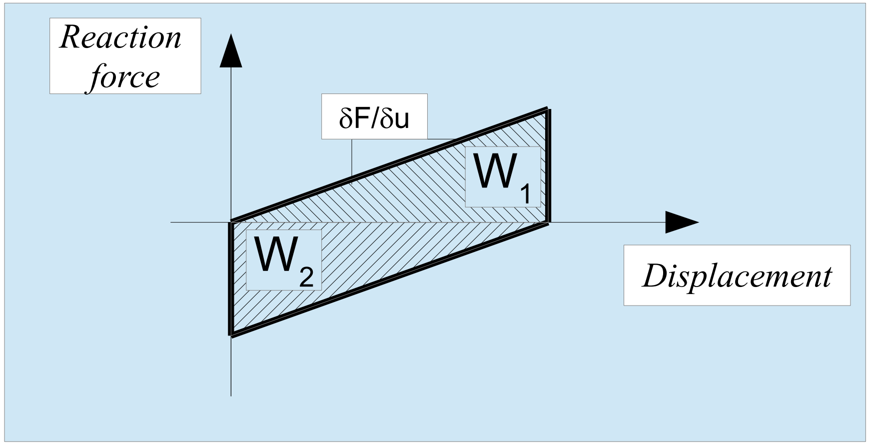


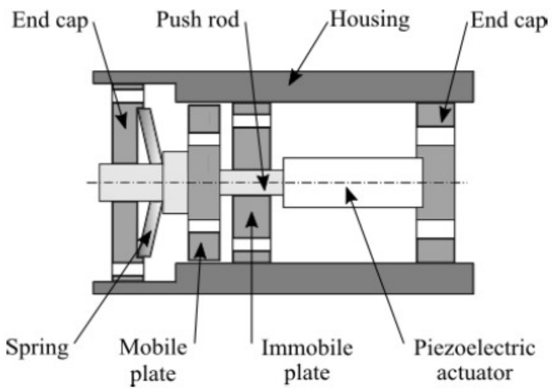
2017 Y. Li et al., Improved hybrid isolator with maglev actuator integrated in air spring for active-passive isolation JSV 407, pp. 226−239
2020 S. Yuan et al., A tunable quasi-zero stiffness isolator based on a linear electromagnetic spring

Part 1: Switching stiffness on pneumatics – thermodynamic approach









- Switching stiffness concept
- Dissipation via a thermodynamic process
- Semi-active actuator
- Increased stroke solution

2021 G.Mikułowski, *Vibration isolation concept by switchable stiffness on a semi-active pneumatic actuator*, SMART MATERIALS AND STRUCTURES, Vol.30, No.7

Mathematical modelling

Force equilibrium

$$F_e(t) + F_{pC}(z, T_C, m_C) - F_{pD}(z, T_D, m_D) + F_a - F_f(\dot{z}) = 0$$

Ideal gas law

$$pV = mRT$$

Mass continuity

$$\frac{dm_C}{dt} + \dot{m}_{Ce} - \dot{m}_{Ci} = 0, \quad \frac{dm_D}{dt} + \dot{m}_{De} - \dot{m}_{Di} = 0$$

Energy balance

$$\dot{Q}_C + \dot{m}_{Ci}\, h_D = \dot{W}_C + \dot{m}_{Ce}\, h_C + \frac{d}{dt}(m_C\, u_C),$$

$$\dot{Q}_D + \dot{m}_{Di}\, h_C = \dot{W}_D + \dot{m}_{De}\, h_D + \frac{d}{dt}(m_D\, u_D),$$

Enthalpy change

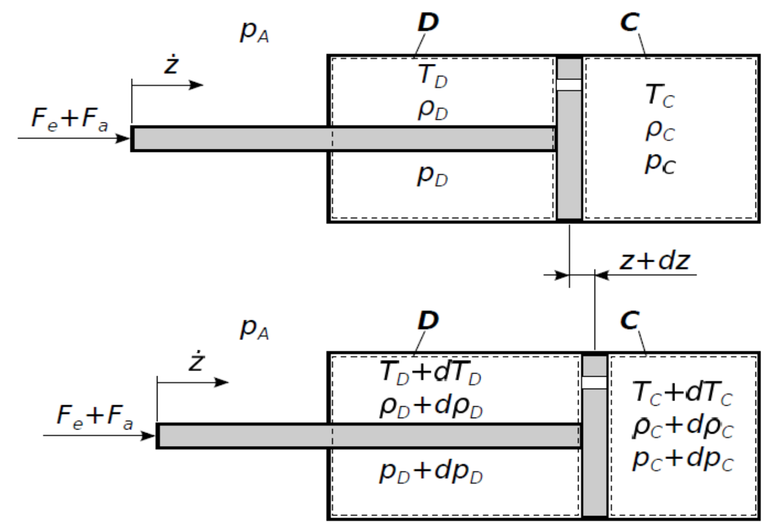
$$h_C = c_p T_C, \quad h_D = c_p T_D,$$

Work delivered to the system

$$\dot{W}_C = p_C(z)\frac{dV_C}{dt}, \quad \dot{W}_D = p_D(z)\frac{dV_D}{dt}.$$

Heat transfer

$$\dot{Q} = \alpha \cdot (T_{gas} - T_{ambient})$$



Mass flow rate on the valve

$$\dot{m}_t = \begin{cases} C_d \dfrac{Ma\, A\, p_0 \sqrt{\frac{\kappa}{RT_0}}}{\left[1 + \frac{(\kappa-1)Ma^2}{2}\right]^{\frac{\kappa+1}{2(\kappa-1)}}}, & \text{if } Ma < 1 \\ C_d\, A\, p_0 \sqrt{\dfrac{\kappa}{RT_0}} \left(\dfrac{2}{\kappa+1}\right)^{\frac{\kappa+1}{2(\kappa-1)}}, & \text{if } Ma = 1 \end{cases}$$

Assumptions: *ideal gas, uniform-state process, uniform-flow process, uniform state of the mass entering the valve, changes in kinetic energy, inertia and gravity forces were negligible.*

G. Mikułowski, Wiszowaty R., Pneumatic Adaptive Absorber..., MATHEMATICAL PROBLEMS IN ENGINEERING, Vol.2016

Numerical algorithm for the thermodynamic process calculation

During each time step the following analysis is conducted:

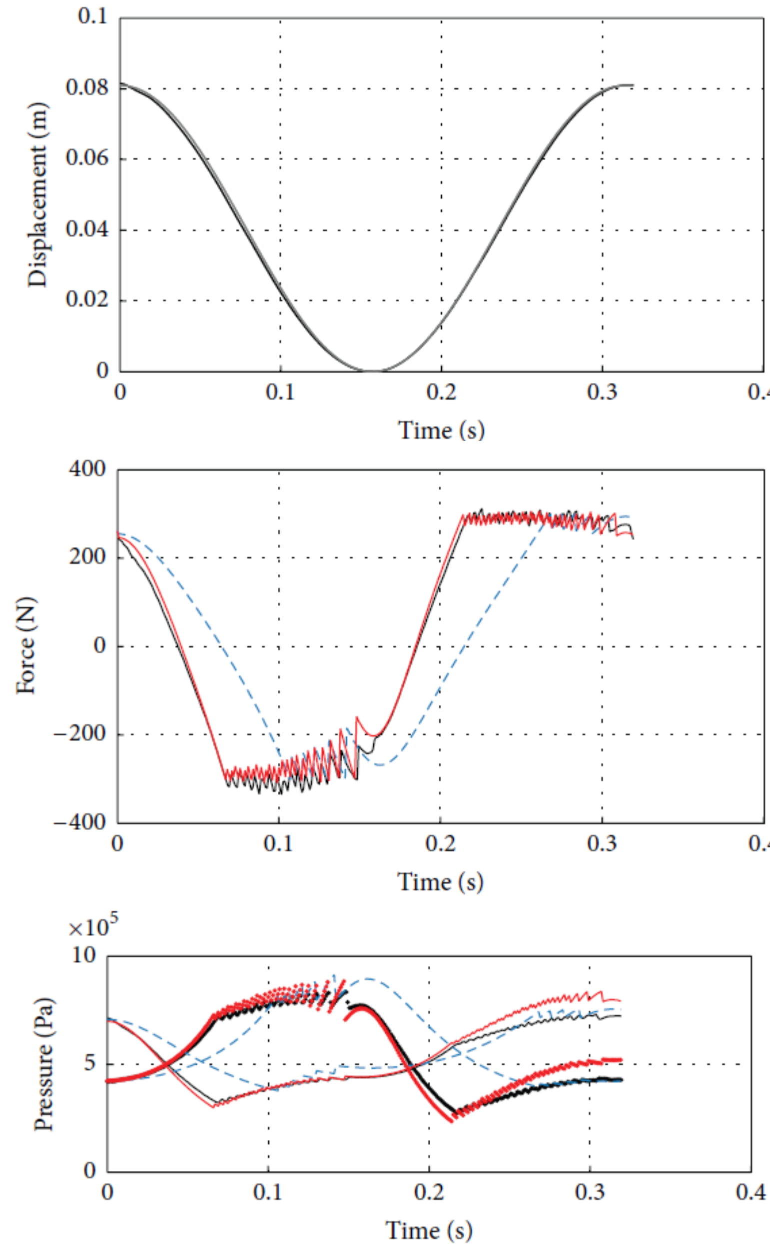
(i) determination of the gas state change due to the volume change on the basis of the adiabatic model,

(ii) determination of the internal energy of the gas,

(iii) determination of the heat exchange between the control volume and the surroundings (with the actual area of the cylinder walls interfacing the gas computed),

(iv) determination of the energy balance in the control volume with the mass and heat exchange taken into consideration,

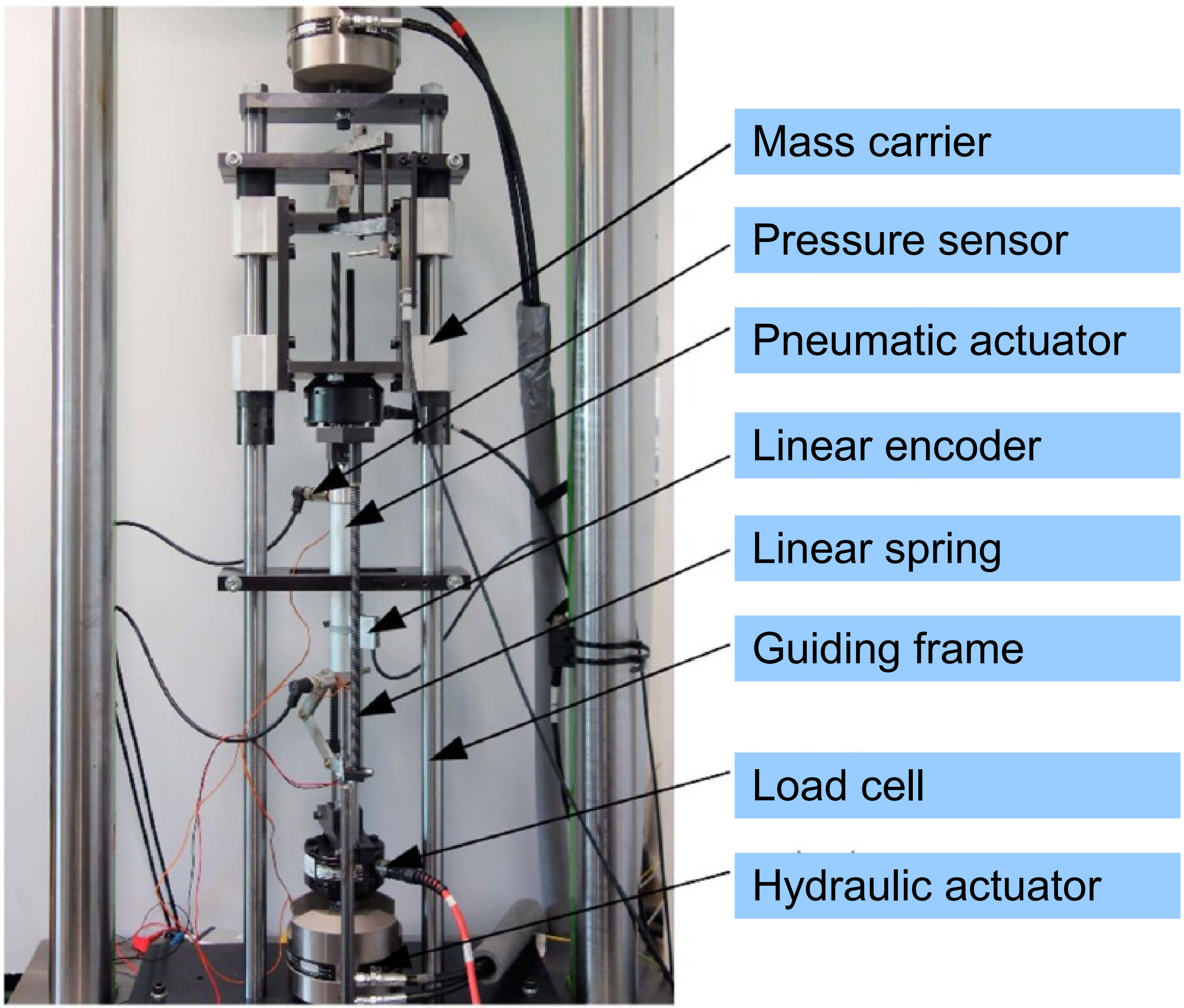
(v) recalculation of the gas state parameters on the basis of the energy balance equation.

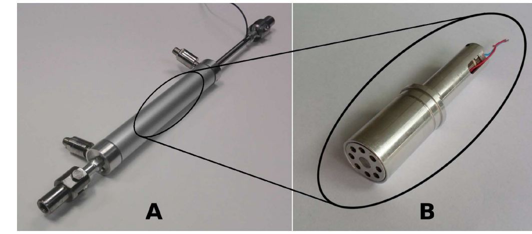


- politropic model
- author model
- experiment

G. Mikułowski, Wiszowaty R., Pneumatic Adaptive Absorber...MATHEMATICAL PROBLEMS IN ENGINEERING, Vol.2016

Experimental setup





Measured signals:

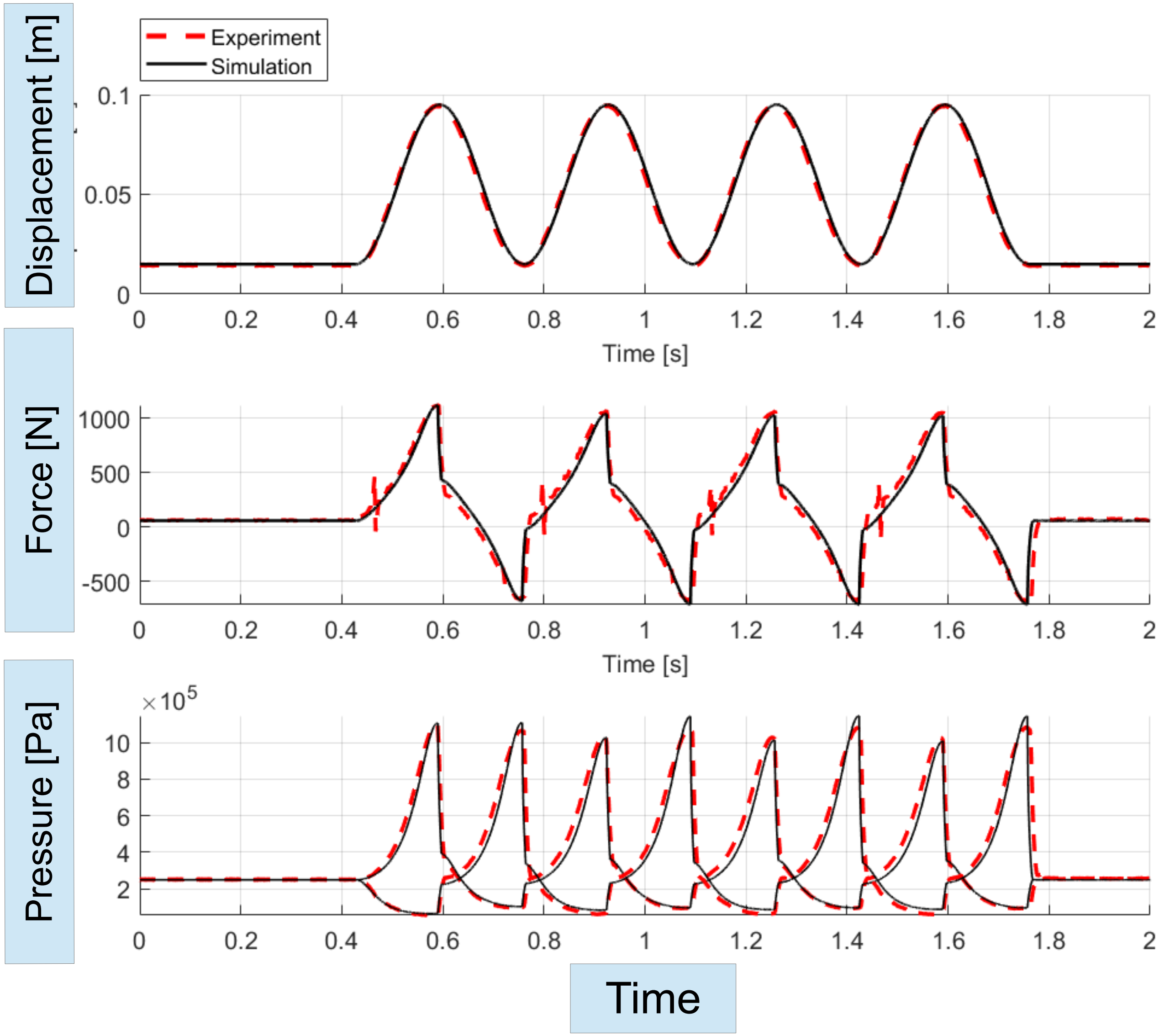
- **Force:** excitation, response
- **Displacement**: excitation, response
- **Gas pressure:** Vol. 1 and Vol. 2
- **Gas temperature**: Vol. 1 and Vol. 2

2021 G.Mikułowski, *Vibration isolation concept by switchable stiffness on a semi-active pneumatic actuator*, SMART MATERIALS AND STRUCTURES, Vol.30, No.7
2013 G. Mikułowski, W. Rogożnicki, R. Wiszowaty, *Plate Valve*, Patent, WUP 08/2013

Time response: model vs experimental results

Modelling vs
Experiment results

- Frequency 3 Hz
- Amplitude **80 mm**

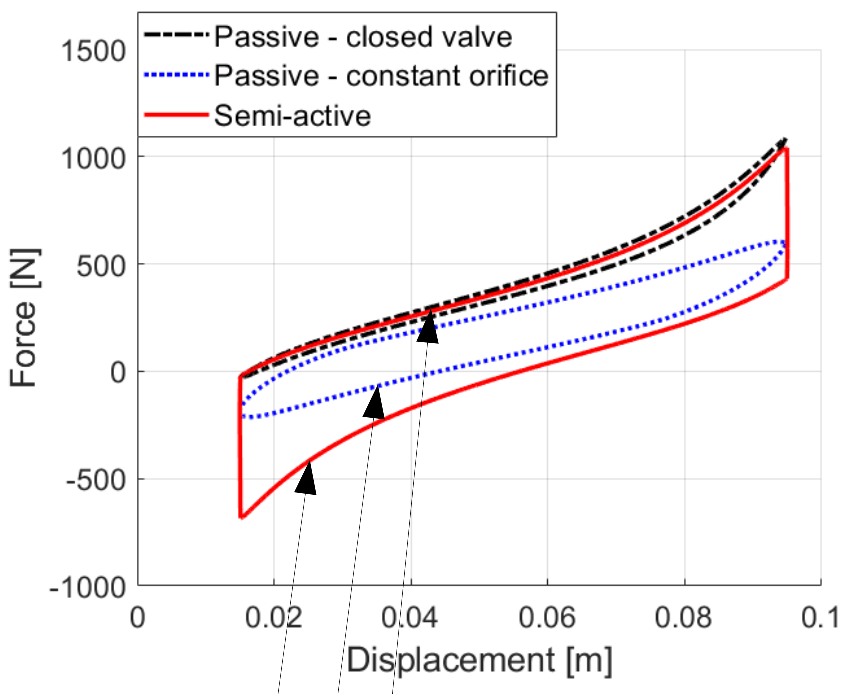


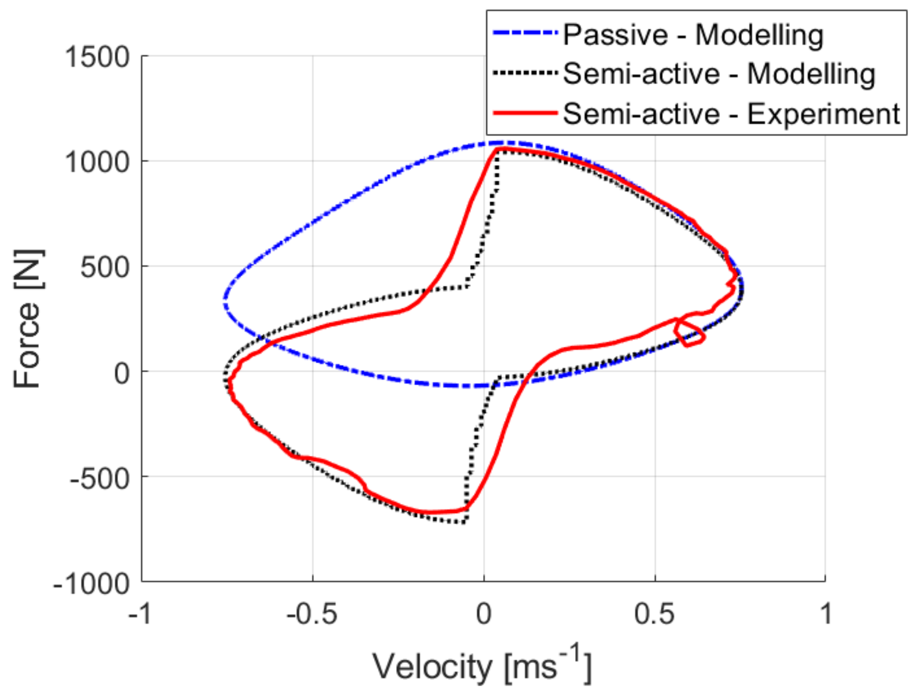
2021 G.Mikułowski, *Vibration isolation concept by switchable stiffness on a semi-active pneumatic actuator*, SMART MATERIALS AND STRUCTURES, Vol.30, No.7

Displacement and velocity response: model and experiment

Control algorithm

$$C_{\text{ctrl}} = \begin{cases} = 0 & \text{when} \quad \dot{z} < u_{c1}, \\ = 1 & \text{when} \quad u_{c1} < \dot{z} < u_{c2}, \\ = 0 & \text{when} \quad \dot{z} > u_{c2}, \end{cases}$$



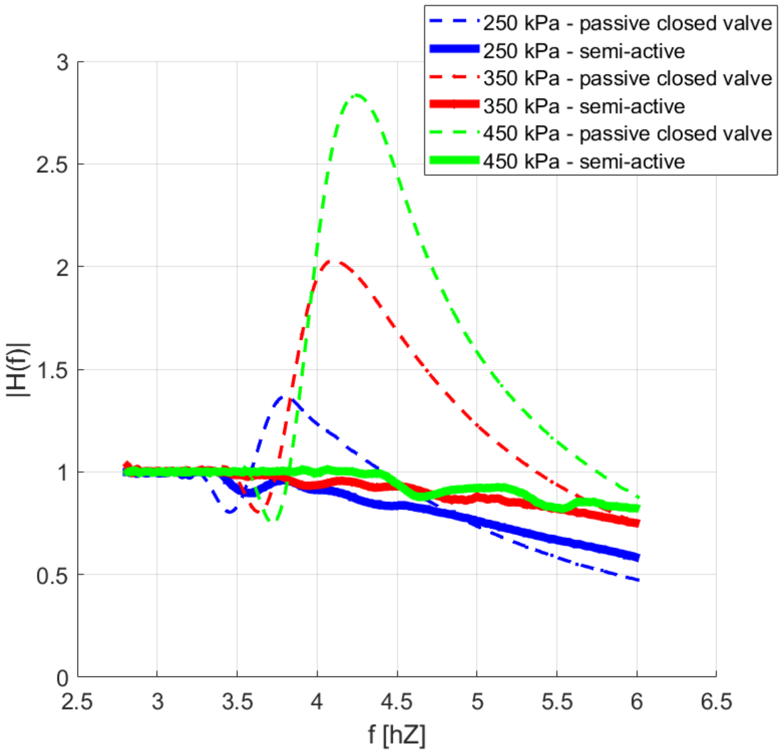


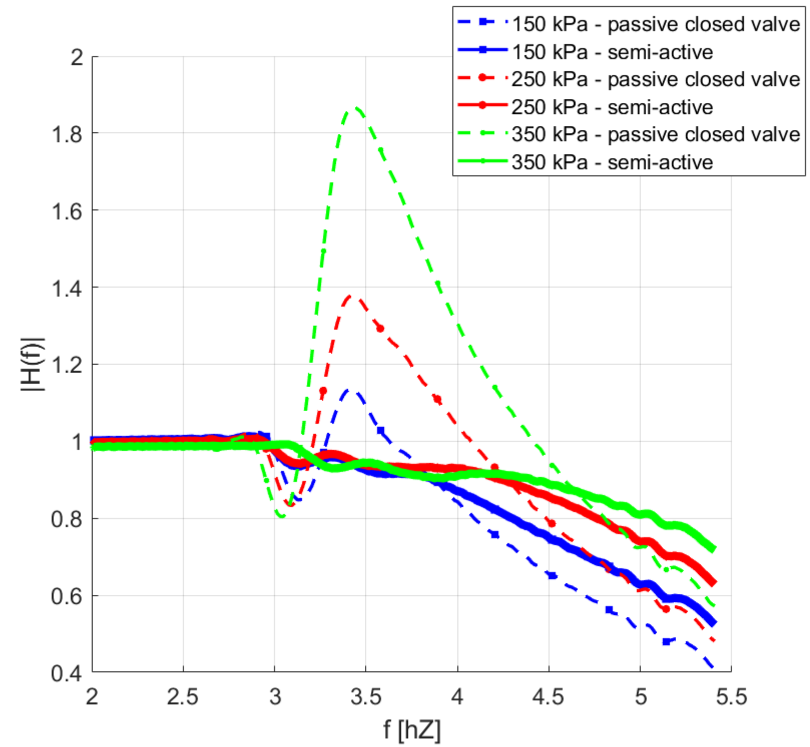
Energy dissipated – 28% (4.33 J)

Energy dissipated – 100% (15.26 J)

Energy dissipated – **247%** (37.64 J)

Frequency response - experiment





suspended mass: 17 kg
initial pressure = 250,350, 450 kPa
excitation: sine sweep

|H(f)| =<1

suspended mass = 27 kg
initial pressure = 150, 250, 350 kPa
excitation: sine sweep

|H(f)| =<1

2021 G.Mikułowski, *Vibration isolation concept by switchable stiffness on a semi-active pneumatic actuator*, SMART MATERIALS AND STRUCTURES, Vol.30, No.7

Remarks on the switching stiffness isolation research – original contribution

- Swithing Stiffness principle for a pneumatic system was formulated and studied
- A mathematical model of the system was formulated including an original numerical algorithm for system energy balance
- Development, patenting and analysis of a gas valve suitable for an advanced flow control

Part 2: Semi-active approach for vibration control in space

- Challenges in vibration control systems for space applications

- Specific features of piezoelectric ceramics

- Amplified Piezo Actuator as semi-active vibration isolation system

Vibration control in space applications

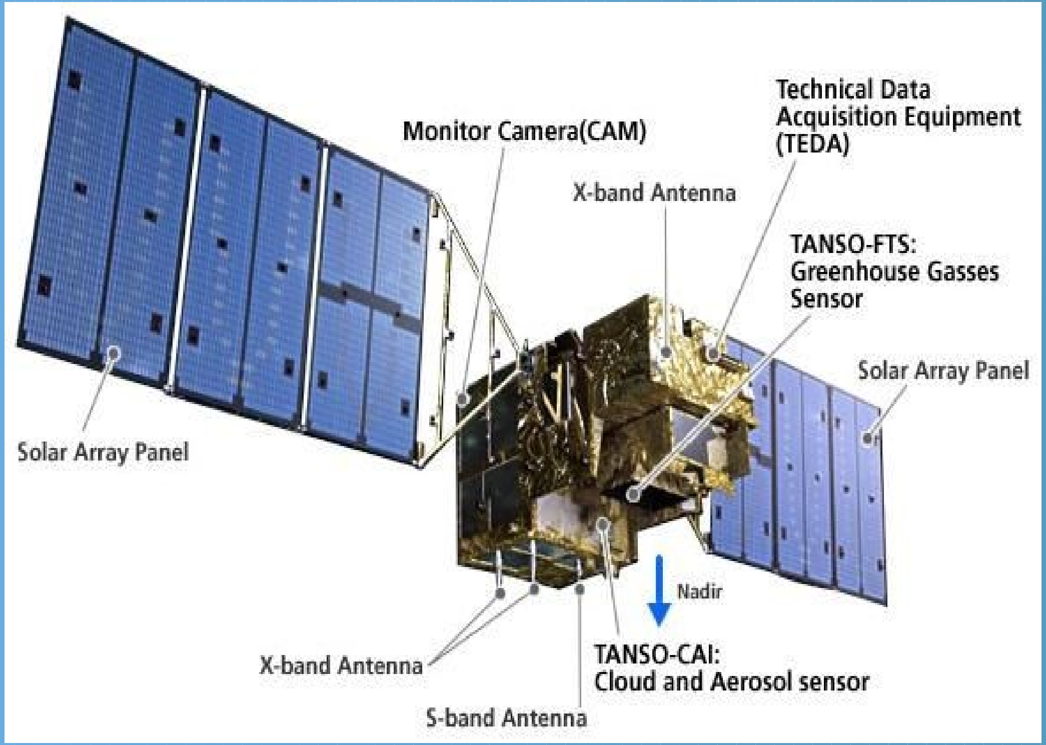
Source of vibration → Mechanical energy transmission path → Structural interface

Characterization:

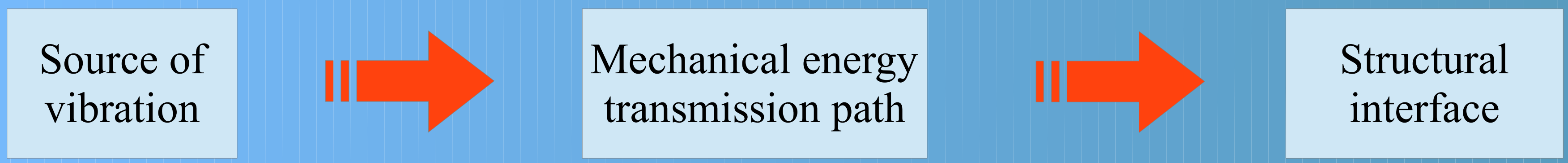
- Slender structures:
  - Low level structural damping (high quality factor)
  - Low level of environmental damping
  - Vacuum conditions

Excitations:

- Cryo pumps,
- Piro actuators
- Temperature variations



Vibration control in space applications



Requirements for vibration control in space applications:

- low mass added to the system

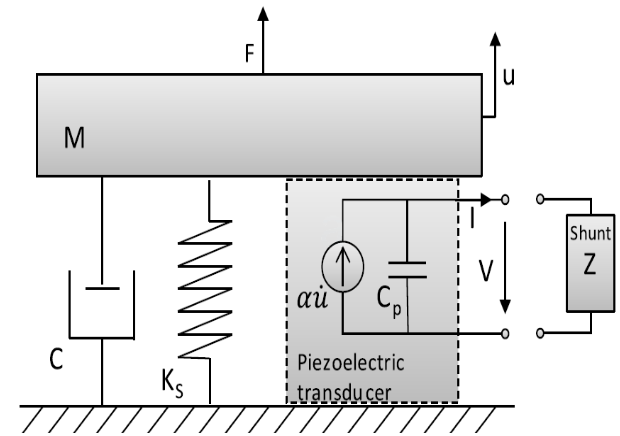
- embedded into structure

- resistant to temperature variations

- resistant to outgasing

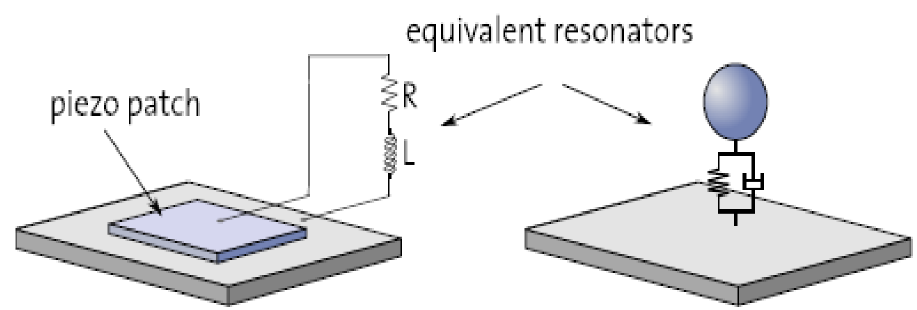
- passive or semi-active solution with low power requirement

Modifiable mechanical properties of piezoelectric actuators

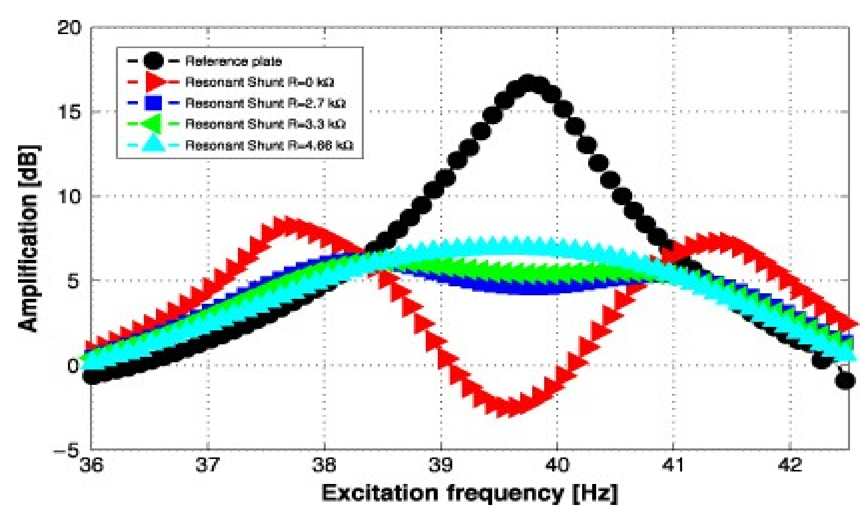


Stiffness:
Capacitive shunt: a capacitive element in the shunt network will change the apparent stiffness of the piezoelectric element without affecting the damping properties of the structure.

Damping:
Resistive shunt: shunting a resistive element to the piezoelectric element means that some of the electrical energy is lost in the circuit through Joule heating. This virtually works as augmenting the structural damping



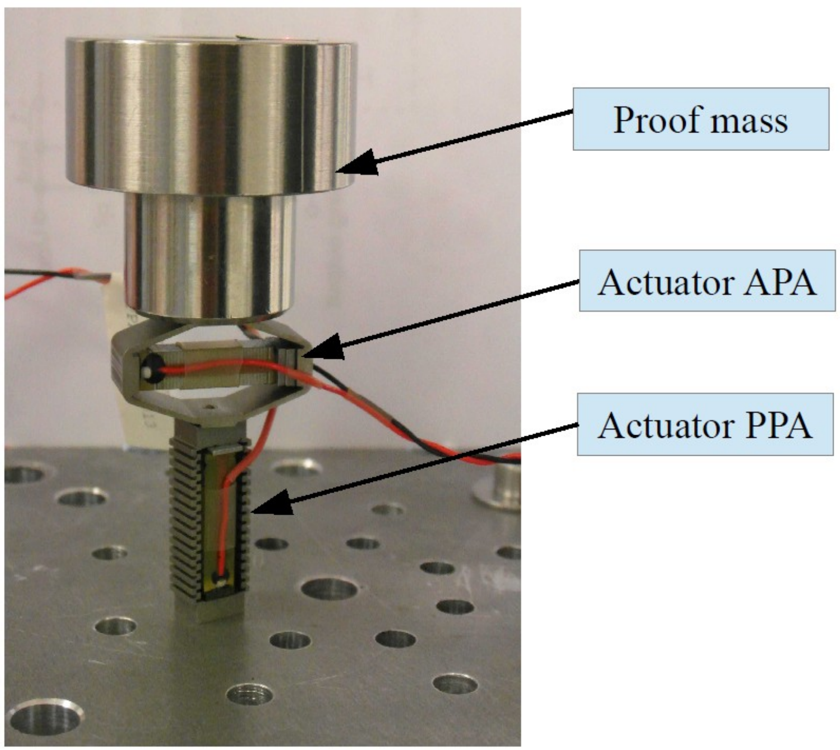
Resonant system:
Inductive shunt: since the piezoelectric element behaves electrically as a capacitor, shunting an inductive element will result in a resonant LC circuit.



Neubauer et.al., 2012, Shunted piezoceramics for vibration damping – modelling, applications and new trends

Research program – vibration isolator based on piezoelectric actuator

Objective: Semi-active isolator by shunted piezoelectric amplified actuator



Excitation: PPA actuator
Acquisition system – Dynamic Signal Analyzer

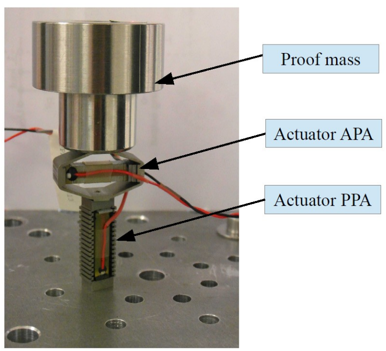
Sensing system - Laser vibrometer,

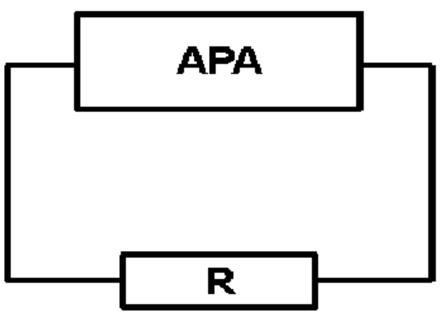
Test configurations:
- resistive
- capacitive
- inductive

Amplified piezo actuator
APA 40SM
40 um stroke

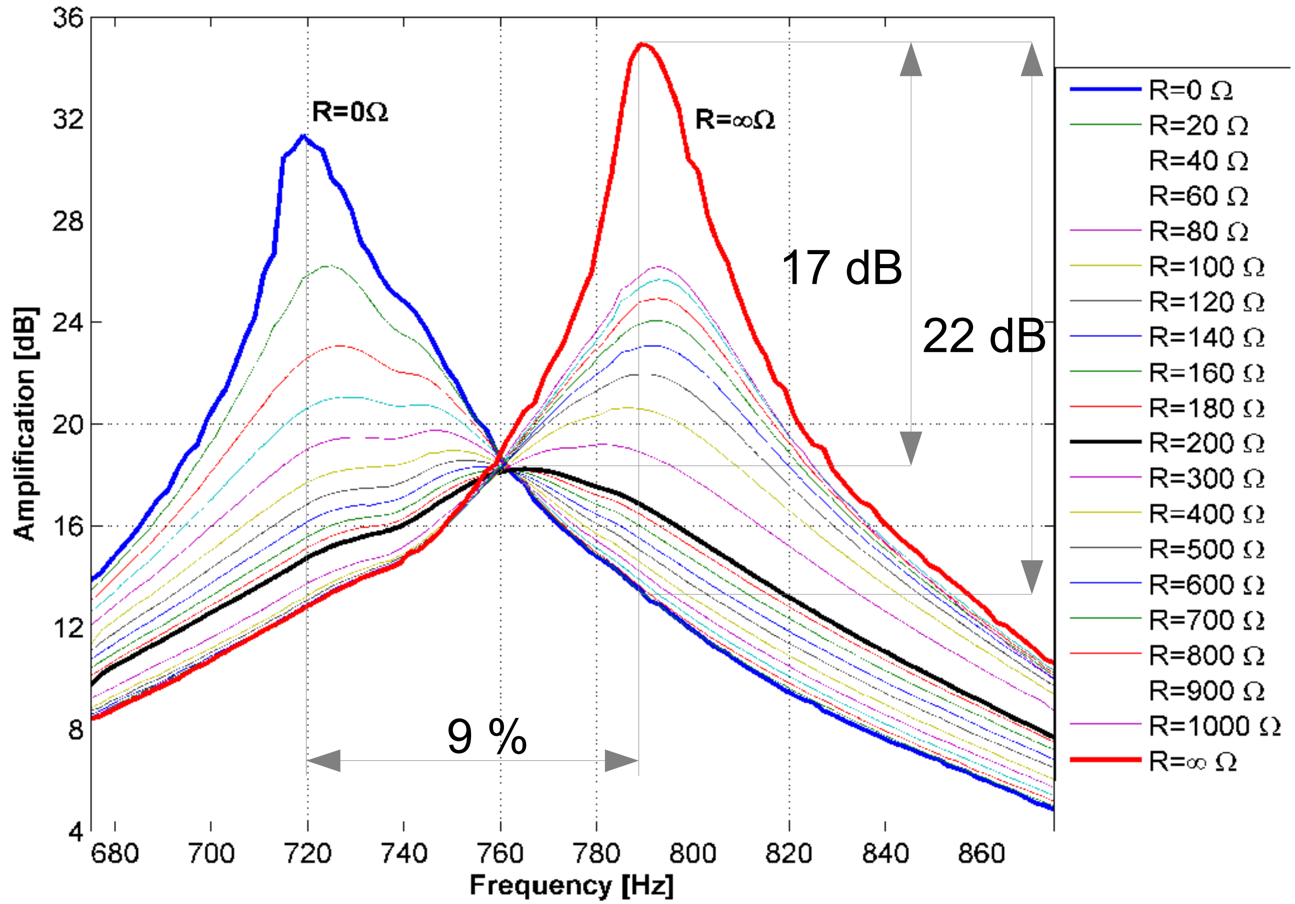
Mikułowski G., Fournier M.♦, Porchez T.♦, Belly C.♦, Claeyssen F.♦, Semi-Passive Vibration Control Technique via Shunting of Amplified Piezoelectric Actuators, ACTUATOR 2016 International Conference

Resistive shunting – damping tuning



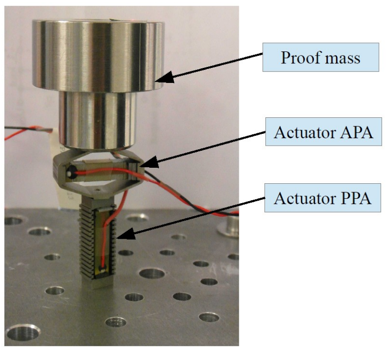


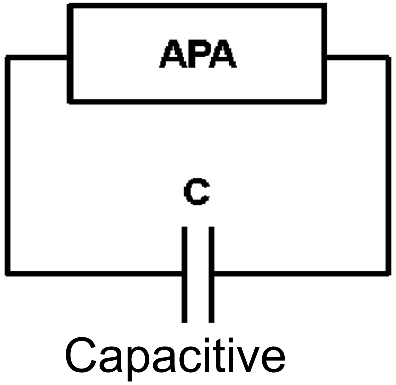
Resistive

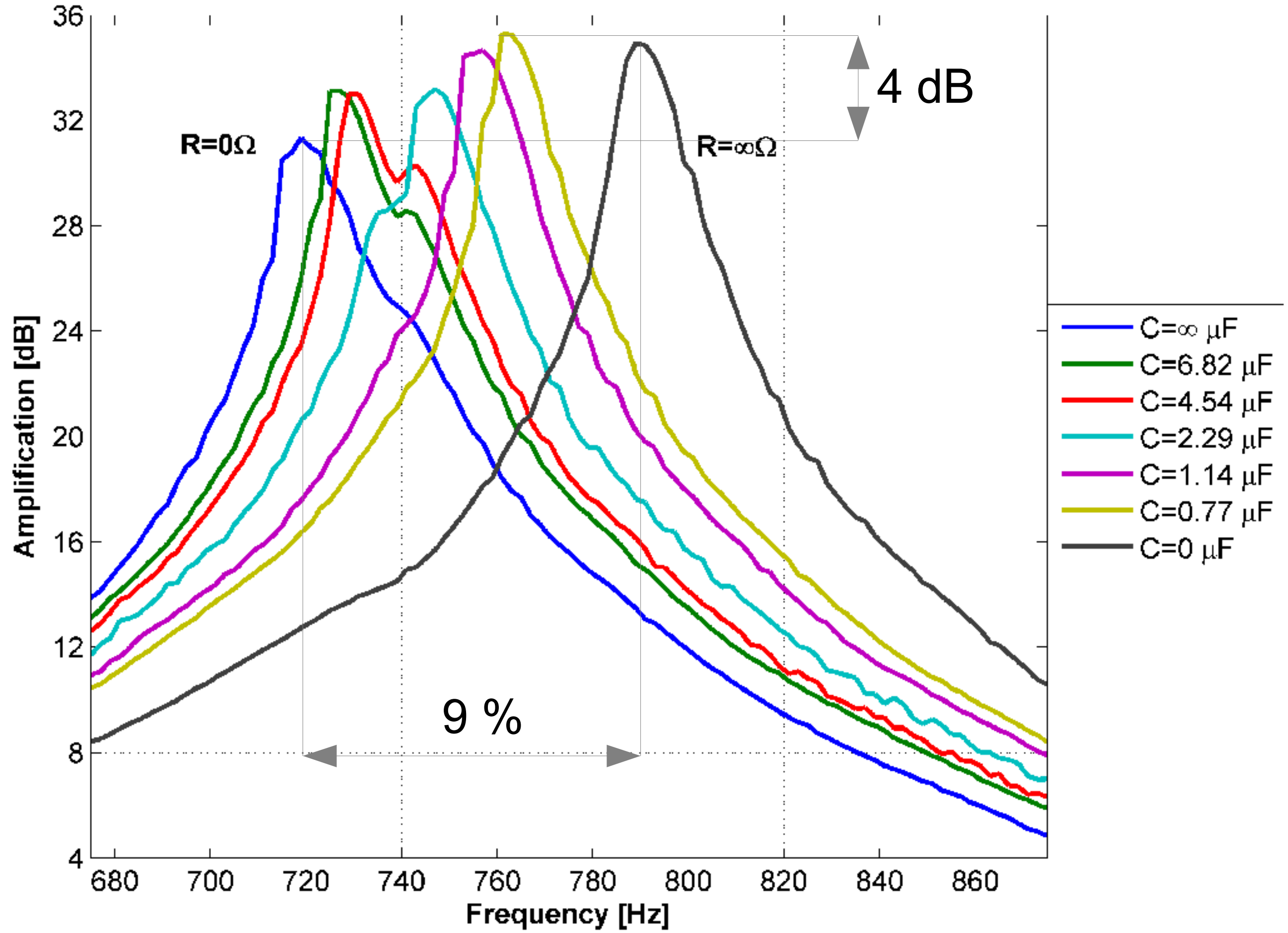


Mikułowski G., Fournier M.♦, Porchez T.♦, Belly C.♦, Claeyssen F.♦, Semi-Passive Vibration Control Technique via Shunting of Amplified Piezoelectric Actuators, ACTUATOR 2016 International Conference

Capacitive shunting – stiffness tuning

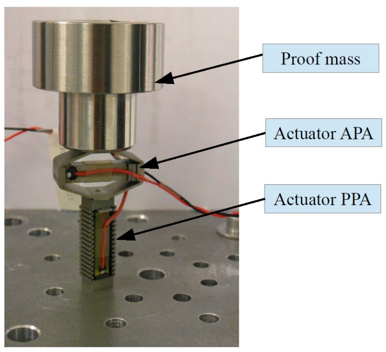


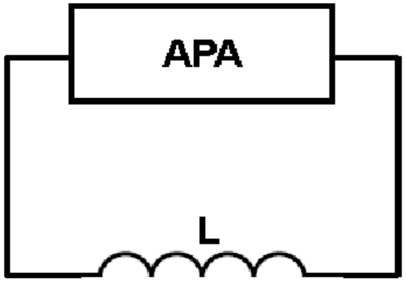




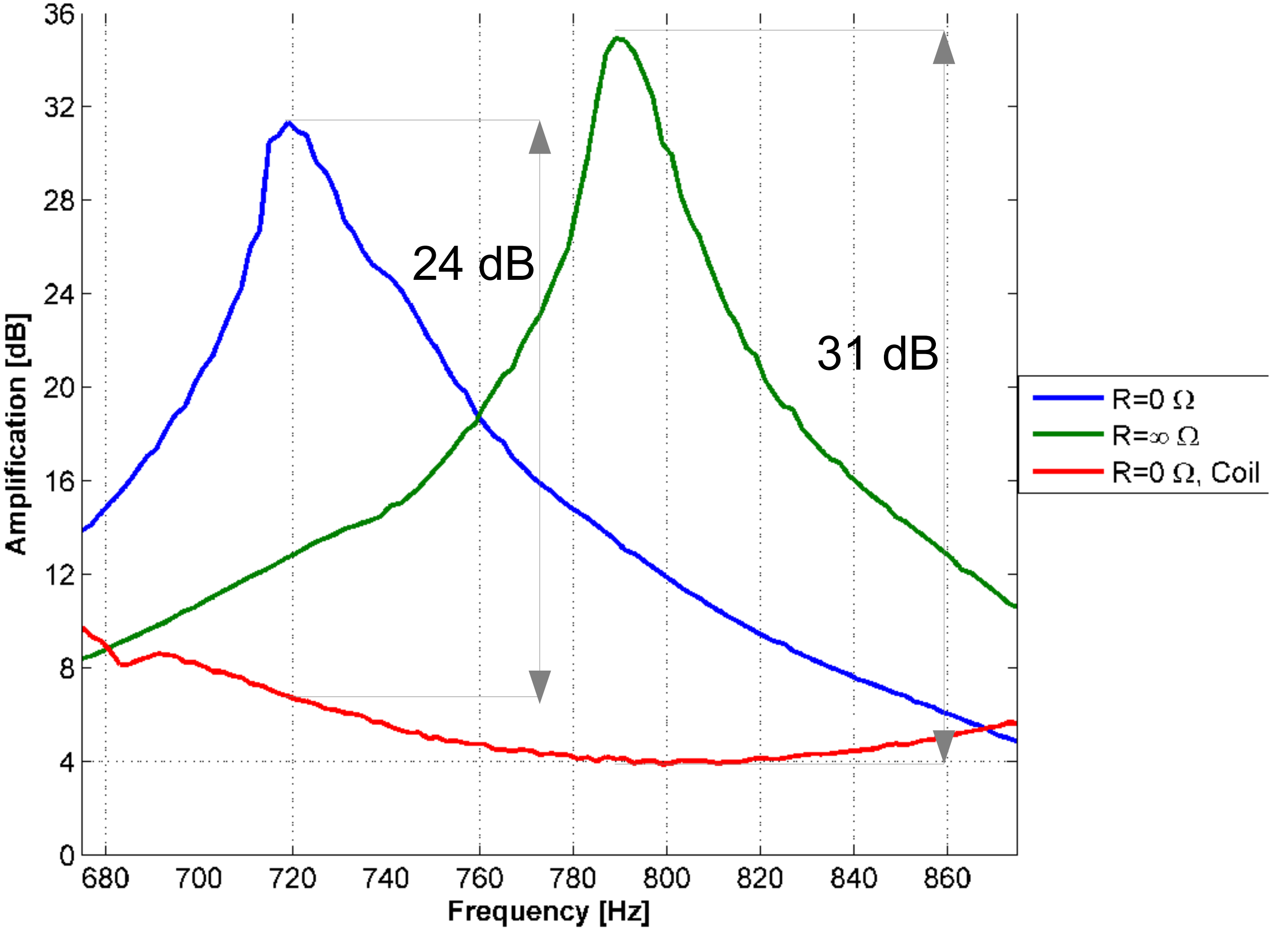
Mikułowski G., Fournier M.♦, Porchez T.♦, Belly C.♦, Claeyssen F.♦, Semi-Passive Vibration Control Technique via Shunting of Amplified Piezoelectric Actuators, ACTUATOR 2016 International Conference

Inductive shunting – tuned resonant response





Inductive



Mikułowski G., Fournier M.♦, Porchez T.♦, Belly C.♦, Claeyssen F.♦, Semi-Passive Vibration Control Technique via Shunting of Amplified Piezoelectric Actuators, ACTUATOR 2016 International Conference

Remarks on piezo based vibration isolation study

- Key features:
  - Adaptivity, high effectiveness
  - Low power requirement, potential for self-powering
  - Vacuum compatibility
  - Low complexity, low number of mechanical elements
- Original contribution: a new concept of a vibration isolation system was proposed and studied.

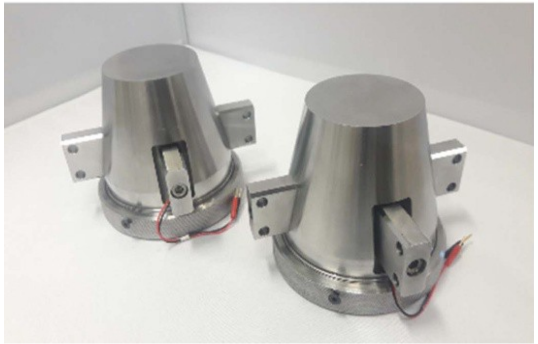
Mikułowski G., Fournier M.♦, Porchez T.♦, Belly C.♦, Claeyssen F.♦, Semi-Passive Vibration Control Technique via Shunting of Amplified Piezoelectric Actuators, ACTUATOR 2016 International Conference

Part 3: Local vibration absorption dedicated to frame structures

- Vibration absorption concept
- Considered modes of operation

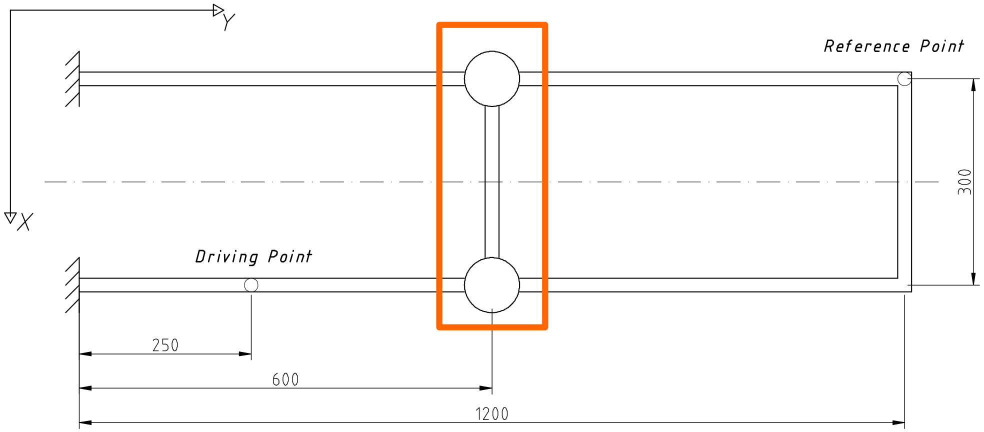
  centralised, decentralised
- Laboratory demonstrators
- Frequency domain results

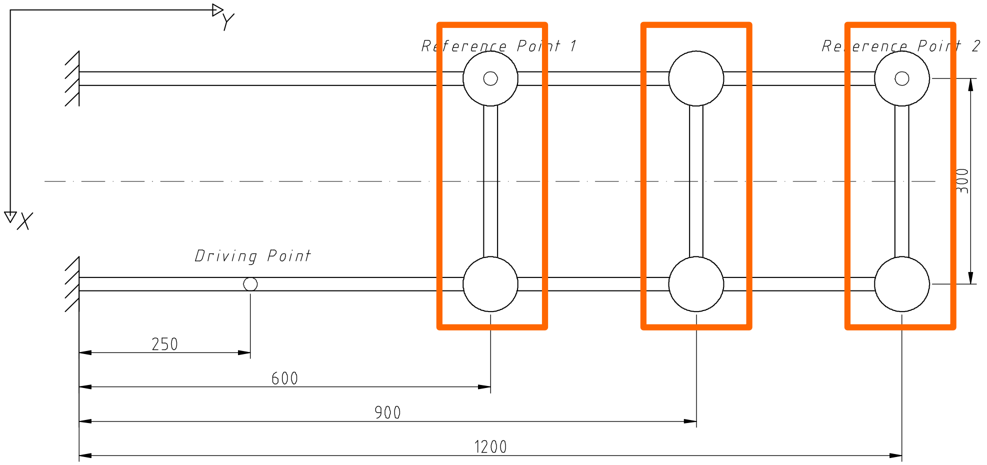
Vibration control concept



Controllable joints

Designed and manufactured by Adapronica Ltd
(www.adaptronica.pl)





Demonstrator frame

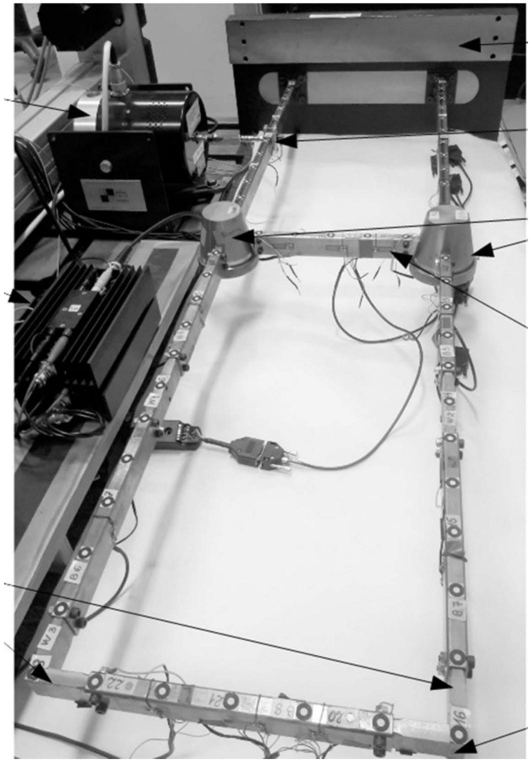
Mróz A., Orłowska A., Holnicki-Szulc J., Semi-active damping of vibrations. Prestress Accumulation-Release strategy development, SHOCK AND VIBRATION, Vol.17, pp.123-136, 2010

Control approach

Control algorithm I

$$\alpha_i = \begin{cases} 0 & \text{at } \max(E_{\text{strain}}) \\ \alpha^{\max} & \text{otherwise} \end{cases}$$

Centralised + Decentralised

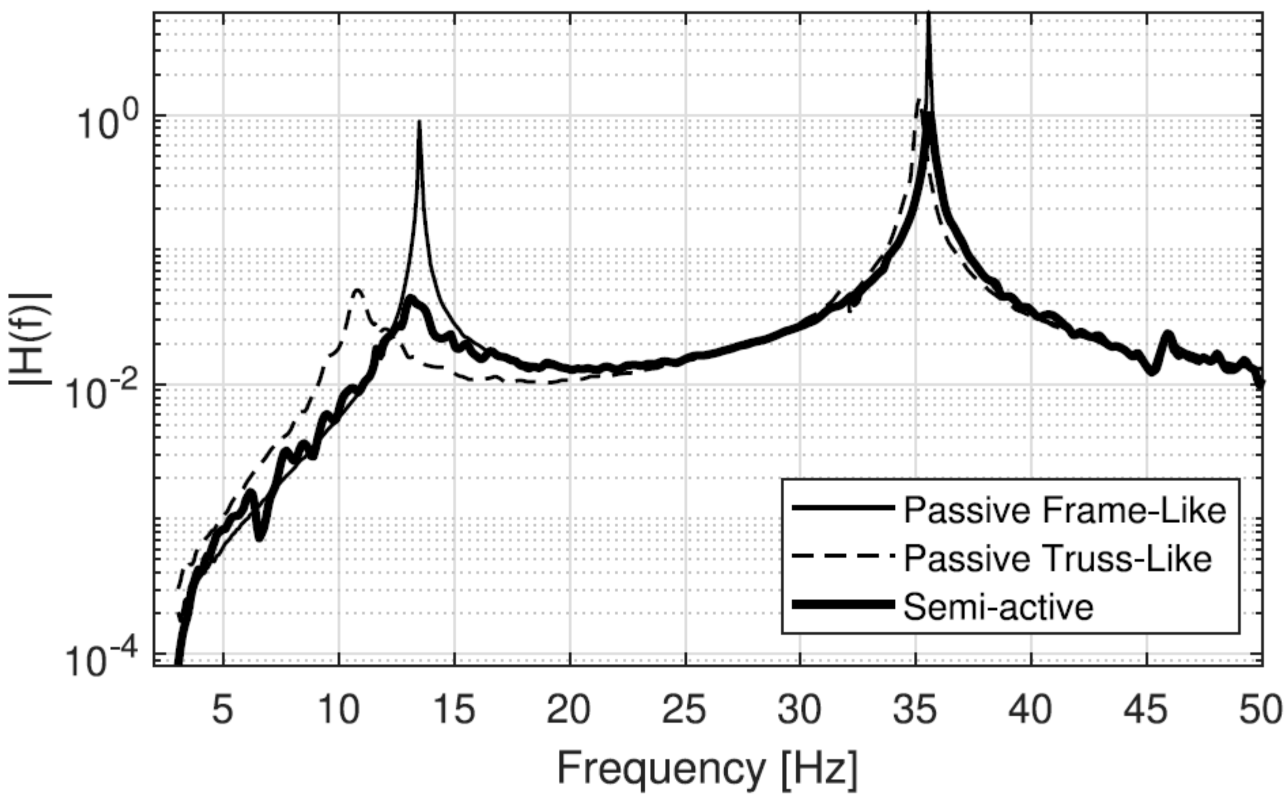


- Research tasks
  - Verification of the control algorithms
  - Analysis of potential malfunctioning of the structure due to the bending moments modification

G. Mikułowski, B. Popławski, Ł. Jankowski, Semi-active vibration control based on switchable transfer of bending moments: study and experimental validation of control performance, Smart Materials and Structures, Vol. 30, no. 4, 2021

Random excitation response

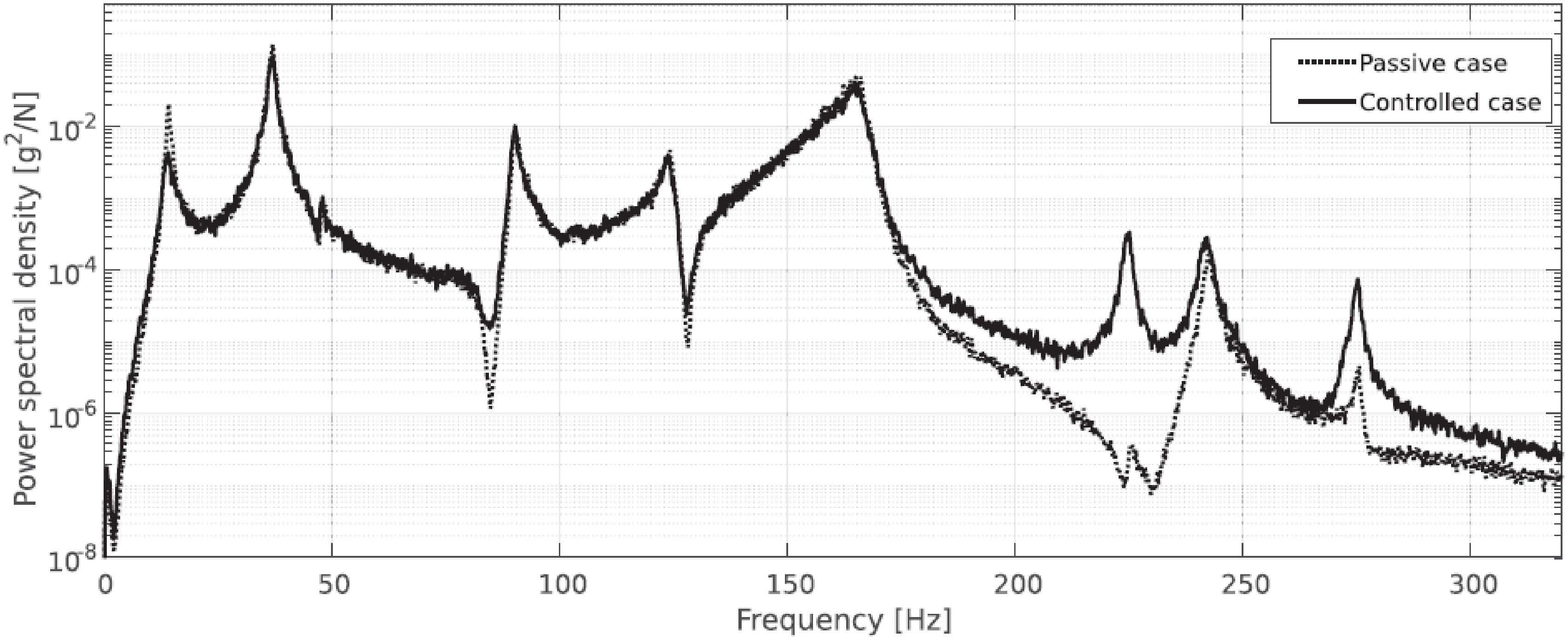
Accelerance of the demonstrator structure



G. Mikułowski, B. Popławski, Ł. Jankowski, Semi-active vibration control based on switchable transfer of bending moments: study and experimental validation of control performance, Smart Materials and Structures, Vol. 30, no. 4, 2021

Random excitation response

Power spectral density of the structure in wider bandwidth

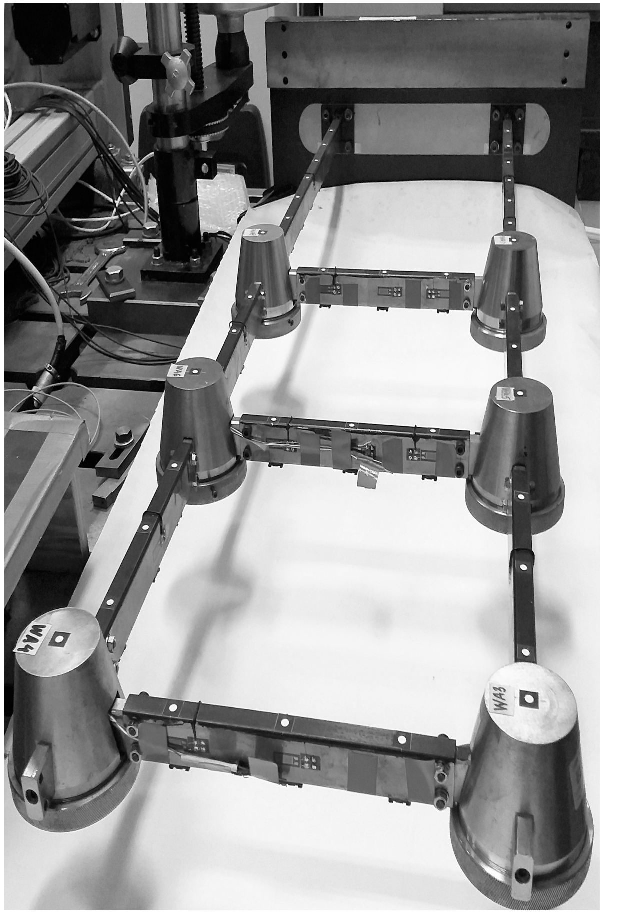


Popławski B., Mikułowski G., Mróz A., Jankowski Ł., *Decentralized semi-active damping of free structural vibrations by means of structural nodes with an on/off ability to transmit moments*, MECHANICAL SYSTEMS AND SIGNAL PROCESSING, Vol.100, pp.926-939, 2018

Popławski B., Mikułowski G., Wiszowaty R., Jankowski Ł., *Mitigation of forced vibrations by semi-active control of local transfer of moments*, MECHANICAL SYSTEMS AND SIGNAL PROCESSING, Vol.157, pp.107733-1-16, 2021

Concluding remarks

- The theoretically developed control strategies were experimentally verified
- Forced random vibration cases were shown to be effectively mitigated
- The concept is further studied with modal control algorithms and machine learning approach



Professional activities

Employment

2007 – currently – Instytut Podstawowych Problemów Techniki, PAN

(assistant, assistant professor, senior researcher)

International experience

2014 - France – CEDRAT Technologies – scientific-engineering contract – development and design of an eddy current rotary damper – Marie-Curie Fellowship Program - 2 months

2015 - Germany – I-deal Technologies – scientific-engineering contract – research on scanning system for non-destructive testing of pipelines – Marie-Curie Fellowship Program – 2 months

2015 - France – CEDRAT Technologies – scientific-engineering contract – research and development on piezoelectric Tuned Mass Dampers – Marie-Curie Fellowship Program – 4 months

Professional activities

Publication achievements

Author and co-author of:

31 publications indexed in Web of Science Core Collection

1 monograph,

3 chapters in monographies,

5 patents,

Participation in 24 international conferences and co-author of 59 conference papers.

Bibliometric data:

Acc. Web of Science Core Collection	Acc. Scopus
Times cited – 298	Times cited – 358
Without self citations – 245	H-index - 12
H-index - 11	

Habilitation achievement

[A1] **Mikułowski G.**, *Vibration isolation concept by switchable stiffness on a semi-active pneumatic actuator*, SMART MATERIALS AND STRUCTURES, Vol.30, No.7, 2021, **100 pk**t MNISW, **4.131** Impact factor

[A2] **Mikułowski G.**, Wiszowaty R., *Pneumatic Adaptive Absorber: Mathematical Modelling with Experimental Verification*,MATHEMATICAL PROBLEMS IN ENGINEERING, Vol.2016, 2016, **40 pkt** MNISW, **1,43** Impact Factor

[A3] **Mikułowski G.**, Wiszowaty R., Holnicki-Szulc J., *Characterization of a piezoelectric valve for an adaptive pneumatic shock absorber*, SMART MATERIALS AND STRUCTURES, Vol.22, No.12, 2013, **100 pkt** MNISW, **4.131** Impact factor

[A4] Faraj R., **Mikułowski G.**, Wiszowaty R., *Study on the state-dependent path-tracking for smart pneumatic shock-absorber,* SMART MATERIALS AND STRUCTURES, Vol.29, No.11, 2020, **100 pkt** MNISW, **4.131** IF

[A5] Popławski B., **Mikułowski G.**, Mróz A., Jankowski Ł.,*Decentralized semi-active damping of free structural vibrations by means of structural nodes with an on/off ability to transmit moments*, MECHANICAL SYSTEMS AND SIGNAL PROCESSING, Vol.100, 2018, **200 pkt** MNISW, **8,934** Impact Factor

[A6] Popławski B., **Mikułowski G.**, Wiszowaty R., Jankowski Ł.,*Mitigation of forced vibrations by semi-active control of local transfer of moments*, MECHANICAL SYSTEMS AND SIGNAL PROCESSING, Vol.157, 2021, **200 pkt** MNISW, **8,934** Impact Factor

[A7] **Mikułowski G.**, Popławski B., Jankowski Ł., *Semi-active vibration control based on switchable transfer of bending moments: study and experimental validation of control performance*, SMART MATERIALS AND STRUCTURES, Vol.30, No.4, 2021, **100 pkt** MNISW, **4.131** Impact factor

Didactic, popularization and organizational activities

- Function of co-supervisor in 3 PhD procedures

- Member of organizational comitee of 7th Europen Conference on Structural Control (EACS 2022)

- Author and co-organizer of lessons for school children in frame of Science Festival (2012 - 2022)

Meritorical patron and co-organizer of Laboratory of Safety Engineering in Department of Intelligent Technologies

Scope of the laboratory:

- Modal analysis for structures (classical, operational, optical)

- Structural kinematics measurements by optical methods

- Advanced control systems prototyping for semi-active actuators

- Impact testing

- Tension, compression, rotary component testing

- DIC technique for strain measurements

Thanks

- Prof. Jan Holnicki-Szulc – initiator of the Safety Engineering Laboratory in IPPT PAN
- Prof. Łukasz Jankowski – head of the Safety Engineering Division
- Dr Rafał Wiszowaty – for fruitful scienific cooperation

Thank you for your attention. :)