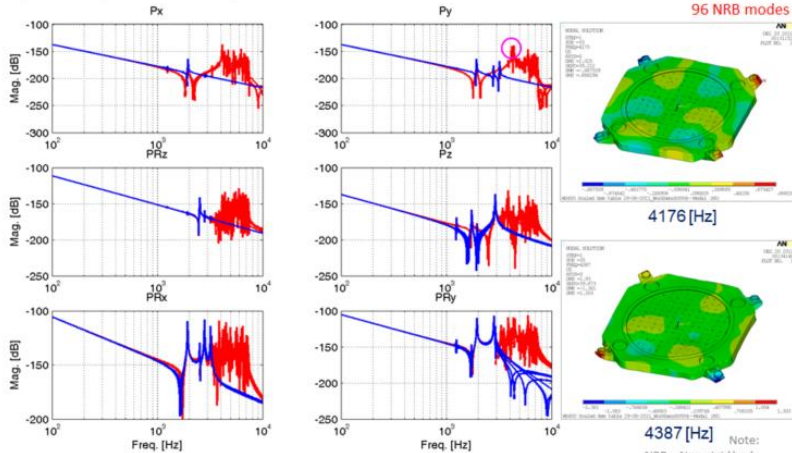


Passive Damping for High Tech Systems

Problem traditional mass-spring approach Performance limited by high-frequency modes, damping opens up solution space

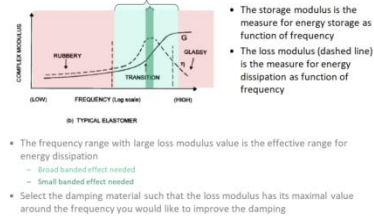


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Passive damping for high tech systems - introduction

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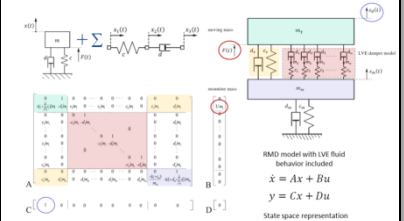
Material damping Linear Viscoelasticity (LVE)



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Material damping Linear Viscoelasticity (LVE)



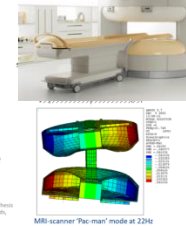
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Case study TMD in MRI scanner

Open structure and low conductance result in low eigen frequencies

- Low stiffness support of superconducting coils and surrounding vessels at 300 K, 40 K and 4 K via rods and cables
- Low frequency eigen modes, e.g. at 'Pac-man' mode at 22 Hz with high amplification
- Eddy currents resulting from vibration negatively influence magnetic field and so image quality

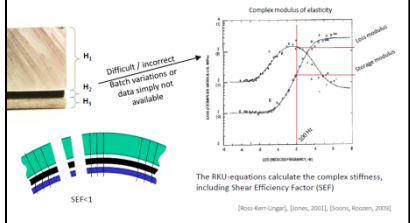


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Constrained layer damper (CLD)

A Linear Viscoelastic (LVE) material is applied as energy dissipating layer



me mechatronics academy B.V. Passive damping for 1

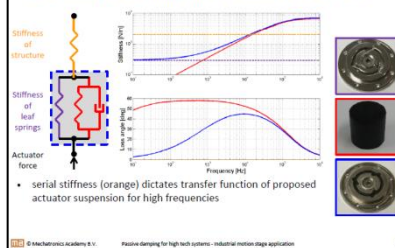
13

Over Actuated Test rig



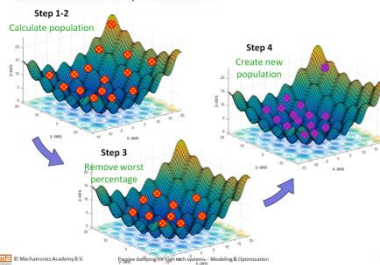
14

Characteristics of design in frequency domain Dimensioning of leaf springs and visco-elastic material is key



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Mathematical optimization



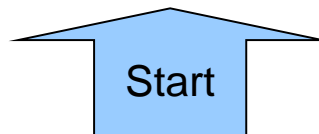
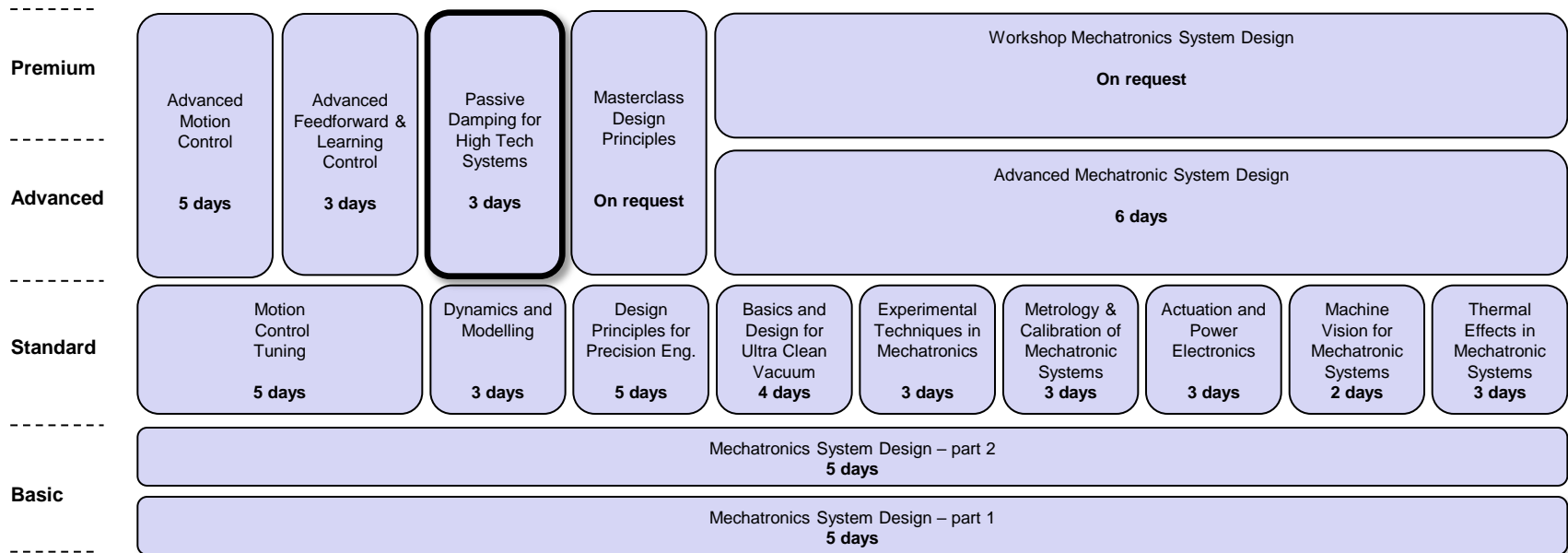
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Contents

- Mechatronics Training Curriculum
- Details of Course *Passive Damping for High Tech Systems*

Mechatronics Training Curriculum



Relevant partner trainings:
 Applied Optics, Electronics for non-electrical engineers, System Architecture, Soft skills for technology professionals, ...

www.mechatronics-academy.nl

Mechatronics Academy

- In the past, many trainings were developed within Philips to train own staff, but the training center CTT stopped.
- **Mechatronics Academy B.V.** has been setup to provide continuity of the existing trainings and develop new trainings in the field of precision mechatronics. It is founded and run by:
 - Prof. Maarten Steinbuch
 - Prof. Jan van Eijk
 - Dr. Adrian Rankers
- We cooperate in the **High Tech Institute** consortium that provides sales, marketing and back office functions.

Passive Damping for High Tech Systems

Course Director(s) / Trainers

Teachers

- Prof.Dr.ir. Hans Vermeulen (Eindhoven University of Technology & ASML)
- Dr.ir. Kees Verbaan (NTS Group)

Industrial Guest Speaker

- Dr.ir. Stan van der Meulen (ASML)

Course Director(s)

- Prof.Dr.ir. Hans Vermeulen (Eindhoven University of Technology & ASML)
- Dr.ir. A.M. Rankers (Mechatronics Academy)

Program

Day	Contents
1	• Introduction
	• Basics of Damping (energy dissipation, modal damping, exponential decay, other application domains)
	Lunch
	• Materials & Damping
	• Tuned Mass Dampers (Basics, Design Considerations, Case Study TMD in MRI Scanners)
2	• Case TMD Design for Ceramic Tool Slides
	• Constrained Layer Damping (Modelling, Case Flexures & Frames)
	Lunch
	• Demo & Exercise CLD
	• CLD for Discontinuous Surfaces
3	• Robust Mass Damping (design, testing & semiconductor wafer stage case)
	• Integral Modelling & Optimization (approach, algorithms, over-actuated wafer chuck case)
	Lunch
	• Industrial Case Semiconductor Industry (modelling approach, design & analysis)
	• Special Topics

Day 1 (morning): Intro & Basics

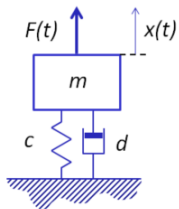
- Introduction
- Basics of Damping

Discrete system response – Stiffness, mass and damper

Resonant behavior combined with transient behavior, damping leads to decreasing amplitudes over time after excitation

Decay in time is a function of **modal damping** and **natural frequency** (saves time too!!)

Stiffness
Mass
Damper

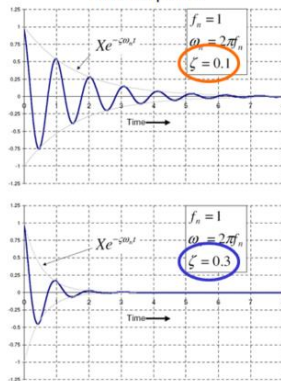


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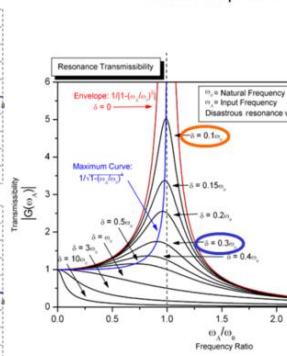
Passive damping for high tech

Free vs. forced response

Free response



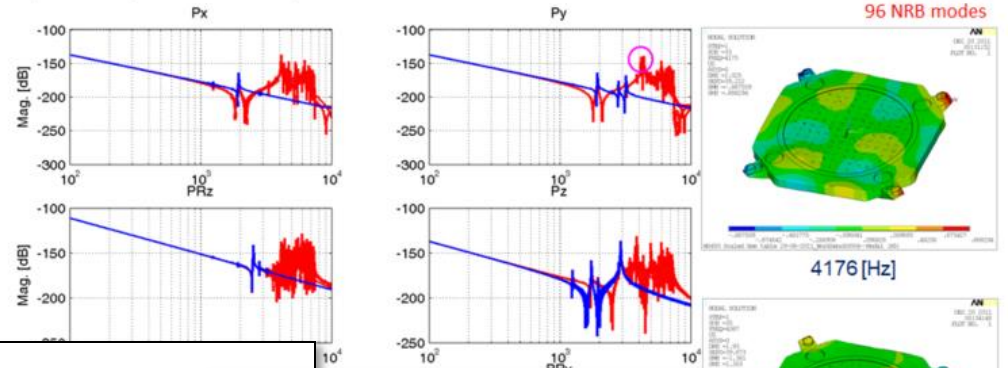
Forced response



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Design principles for precision engineering – Design for damping

Problem traditional mass-spring approach
Performance limited by high-frequency modes, damping opens up solution space



Legend:
10 NRB modes
96 NRB modes

Energy dissipation – Spring and damper

Forced cycles with constant amplitude:

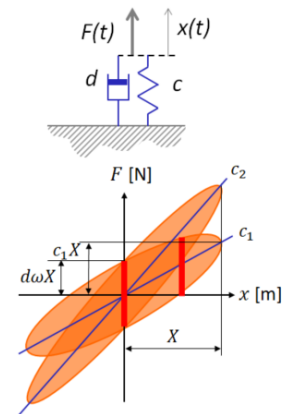
$$x(t) = X \sin(\omega t)$$

$$F(t) = F_c(t) + F_d(t) = cx(t) + d\dot{x}(t)$$

$$= cX \sin(\omega t) + d\omega X \cos(\omega t)$$

Angle of ellipsoid depends on the stiffness c

REMARK: Moving the same mechanical system twice as fast results in a wider ellipsoid, and therefore, the ellipsoid is not a system characteristic



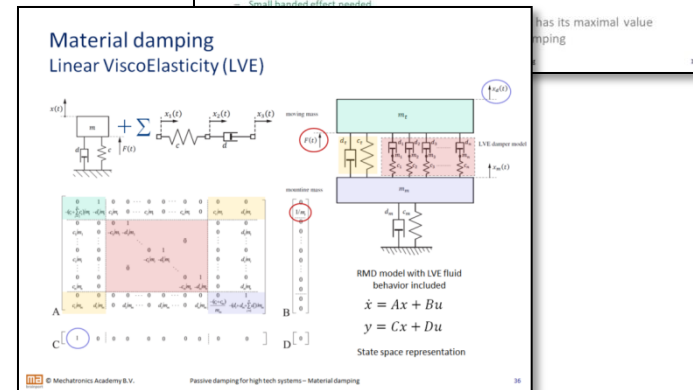
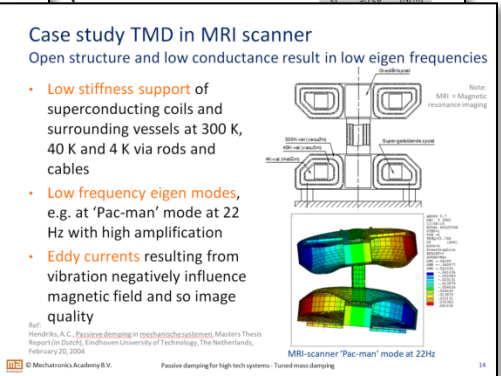
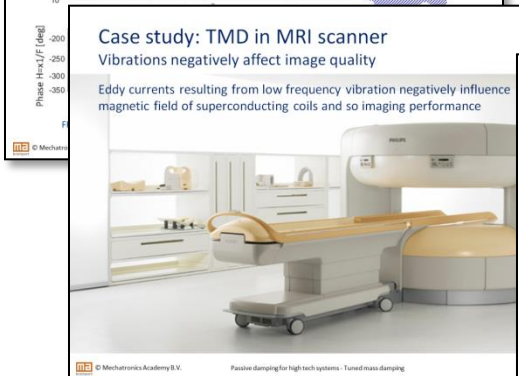
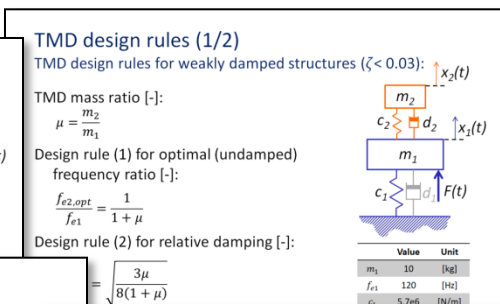
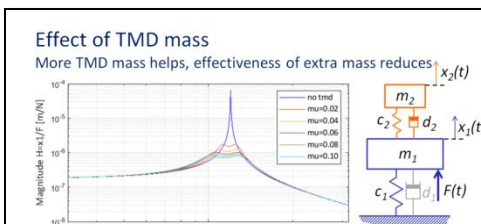
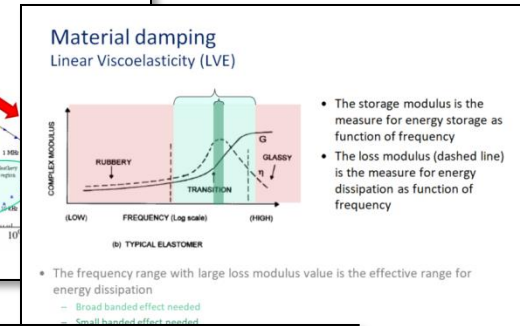
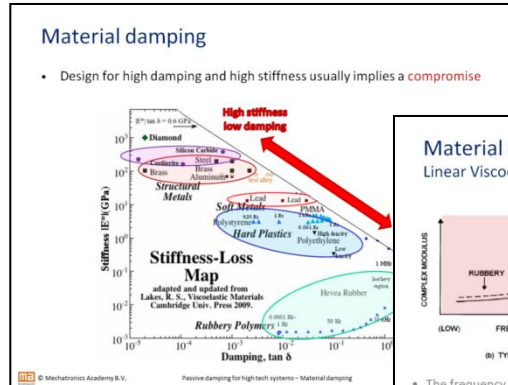
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Passive damping for high tech systems - Introduction

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Day 1 (afternoon): Materials & TMD

- Materials & Damping
- Tuned Mass Damping (TMD)
 - Basics
 - Design Considerations
 - Case Study MRI Scanner



Day 2 (morning): TMD case & CLD

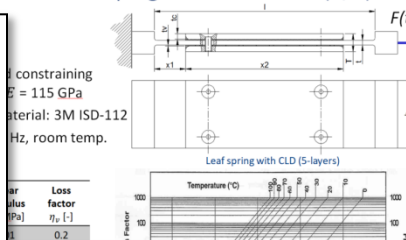
- TMD Case
- Constrained Layer Damping (CLD)
 - Modelling
 - Case Flexures & Frames

Constrained layer damping – Three-layer beam RKU (Ross, Kerwin and Ungar) method for optimal layer thickness

- Assumptions to make the problem solvable in closed-form:
1. Beam simply-supported, which leads to purely sinusoidal mode shapes
 2. Beam is comprised of only three layers (other approximate techniques available for multi-layer configurations)
 3. Viscoelastomer is modeled by a complex shear stiffness $G^* = G(1 + j\eta_v) = G' + jG''$
 4. Elastic layers are maintained at constant spacing by viscoelastic layer
 5. Beam has wavelength sufficiently larger than its thickness
 6. Deflections small enough such that slope of the neutral axis is much less than unity

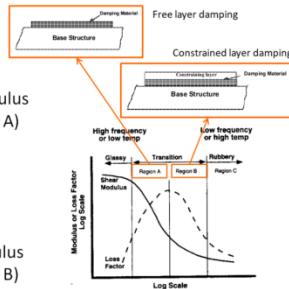
Source: Marsh, E.R., An Integrated Approach to Structural Damping, PhD Thesis, 1998
© Mechatronics Academy B.V. Passive damping for high tech systems - Constrained layer damping

CLD in flexures – Damping of axial motion (1/6)



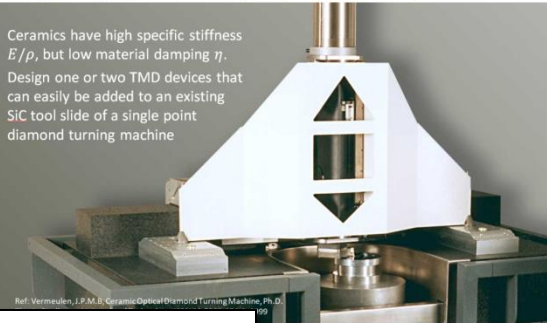
Viscoelastic layer damping Broad band damping in structural components

- Free layer damping:
- Viscoelastic layer loaded in tension / compression
 - Typically high Young's modulus and high loss factor (region A)
- Constrained layer damping:
- Viscoelastic layer loaded in shear → very effective
 - Typically low Young's modulus and high loss factor (region B)



Case: TMD design for ceramic tool slide Design an optimum absorber (TMD) within boundary constraints

Ceramics have high specific stiffness E/ρ , but low material damping η .
Design one or two TMD devices that can easily be added to an existing SiC tool slide of a single point diamond turning machine



Ref: Vermeulen, J.P.M.B. Ceramic Optical Diamond Turning Machine, Ph.D. Thesis, 1995

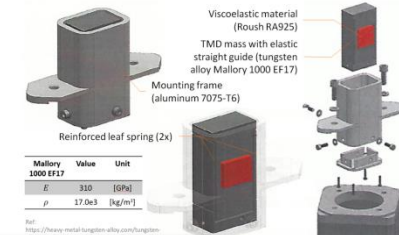
TMD boundary conditions and specifications (2/3) Goal: Provide maximum amount of damping via TMDs

TMD interface
Upper tool slide bearing
Tool slide (SiC)
Encoder measurement system
Lower tool slide bearing
Diamond tool and TMD interface



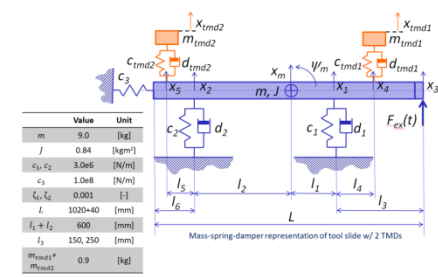
Passive damping for high tech systems - TMD case

TMD design – Implementation examples (1/2)



Mallory 1000 EF17	Value	Unit
E	310	[GPa]
ρ	17.0e3	[kg/m³]

Dynamic model of tool slide w/ 2 TMDs

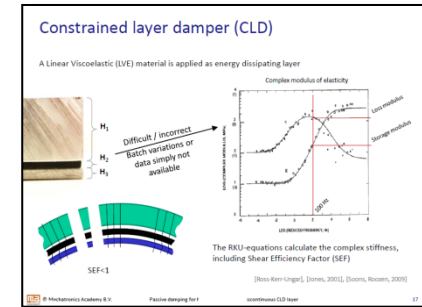


Value	Unit
m	9.0 [kg]
J	0.84 [kgm²]
c_1, c_2	3.0e5 [N/m]
d_1, d_2	1.0e8 [Ns/m]
l_1, l_2	0.001 [-]
l_3	1020-40 [mm]
$l_4 + l_5$	600 [mm]
l_6	150, 250 [mm]
m_{TMD1}, m_{TMD2}	0.9 [kg]

Passive damping for high tech systems - TMD case

Day 2 (afternoon): CLD

- Demo & Exercise CLD
- CLD for Discontinuous Surfaces



Day 3 (morning): RMD & Modelling

- Robust Mass Damping
 - design, testing, semiconductor wafer stage)
- Integral Modelling & Optimization
 - approach, algorithms, over-actuated wafer chuck)

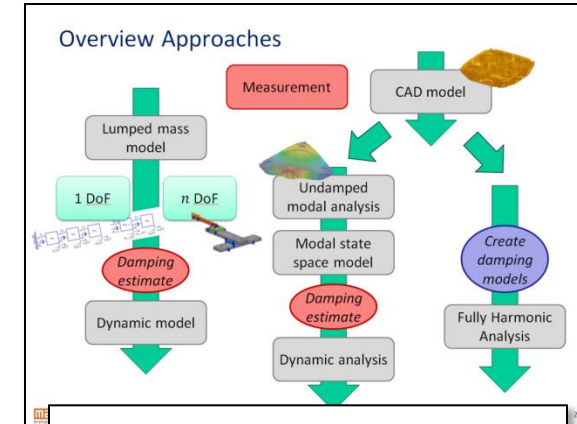
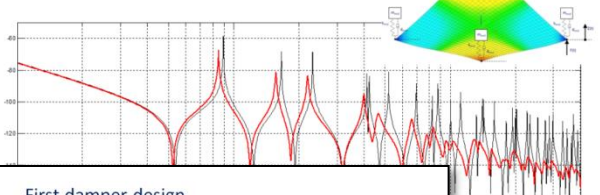
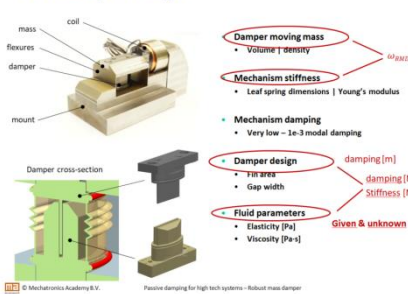


Plate model – damper application

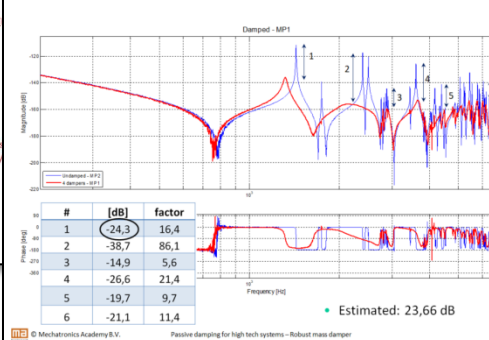
- Robust Mass Damper design - $\zeta > 1$ -



First damper design

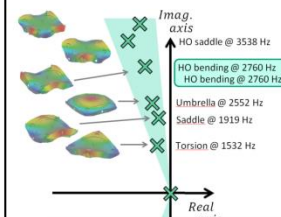


Measurements – Transfer function



System poles

In real mechanical systems, resonances are very under-critically damped



ZPK model

A ZPK model is build from a list of poles and zeros. This is a very quick and intuitive way of creating a dynamic model without the book keeping of transfer functions

SIISO system

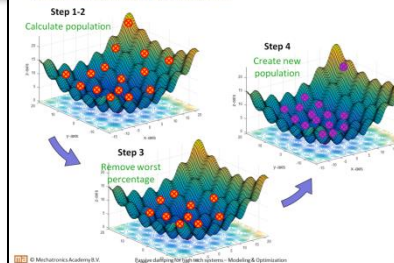
- Vector with poles
- Vector with zeros
- Single gain

Zeros				Poles			
ZPK.Zeroes_Hz				ZPK.Poles_Hz			
12.2	35e-2			12.2	1e-2		
24.7	5e-2			24.7	35e-2		
98.9	2e-2			98.9	60e-2		
101.3	4e-3			101.3	99.2	5e-2	
110.4	3e-2			110.4	109.9	5e-2	
114.2	1e-4			114.2	110.9	3e-2	
124.9	4e-2			124.9	126.6	5e-2	
134.9	7e-2			134.9	134	7e-2	
151	3e-3			151	150	5e-2	
155	1e-4			155	154	7e-2	
168	1e-3			168	162	9e-2	
509.5	5e-3			509.5	214	15e-2	
222	12e-2			222	314	7e-2	
516.5	5e-3			516.5	529.5	1e-2	

Over Actuated Test rig



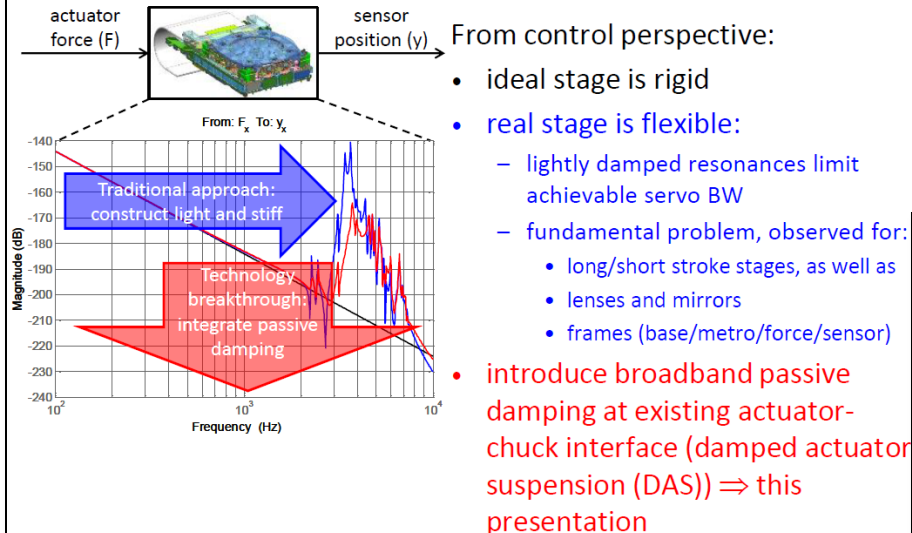
Mathematical optimization



Day 3 (afternoon): Ind. Case & Specials

- Industrial Case 450mm wafer stage
- Special Topics

Idea behind passive damping in motion stages Establish servo bandwidth increase



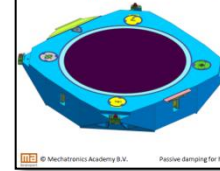
mechatronics academy

Passive damping for high tech systems - Industrial motion stage application

Concept for 450mm lithography

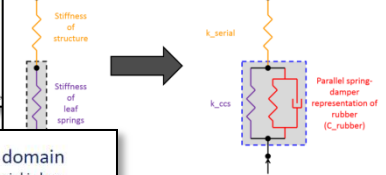
Design comprises 4 horizontal actuators and 4 position sensors

- wafer stage short stroke (WSSS) encoder block (EB) for wafer size transition from 300 to 450 [mm] (0.4% modal damping)
- 4 horizontal reluctance actuators for in-plane motion (red arrows: x-actuators; green arrows: y-actuators)
- 4 stage position(ing) measurement (SPM) encoders in square configuration at EB corners (black dots)



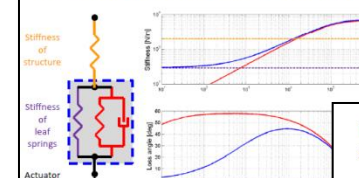
Modeling of actuator-chuck interface

Apply visco-elastic material in parallel to metal leaf springs



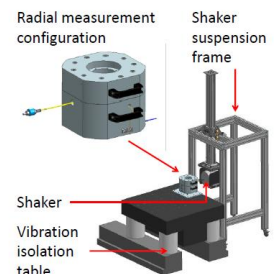
Characteristics of design in frequency domain

Dimensioning of leaf springs and visco-elastic material is key



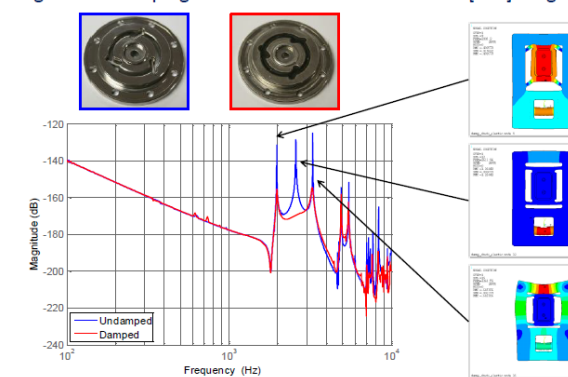
Experimental validation on component level

Split functionality between force frame and measurement table



Experimental validation in system environment

Significant damping of actuator-chuck modes in 1-4 [kHz] range



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High Tech Institute