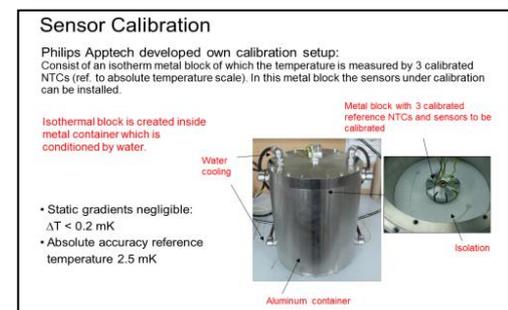
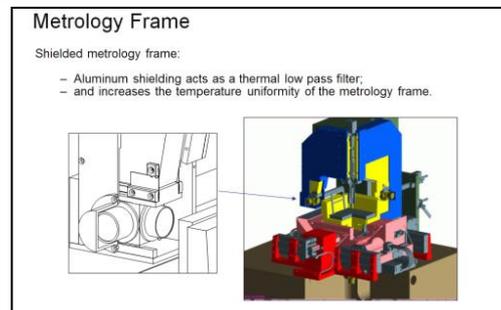
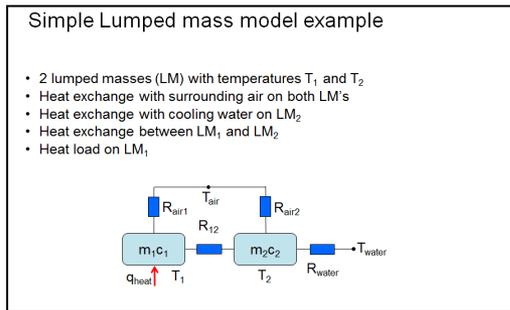
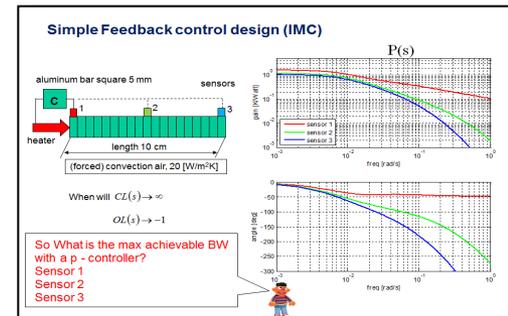
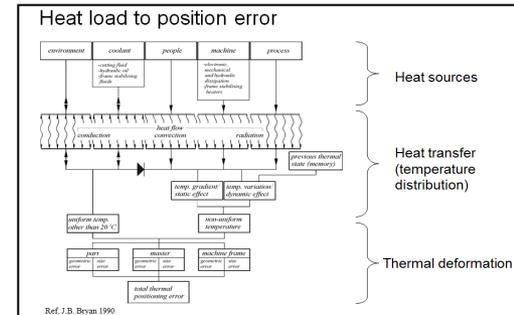
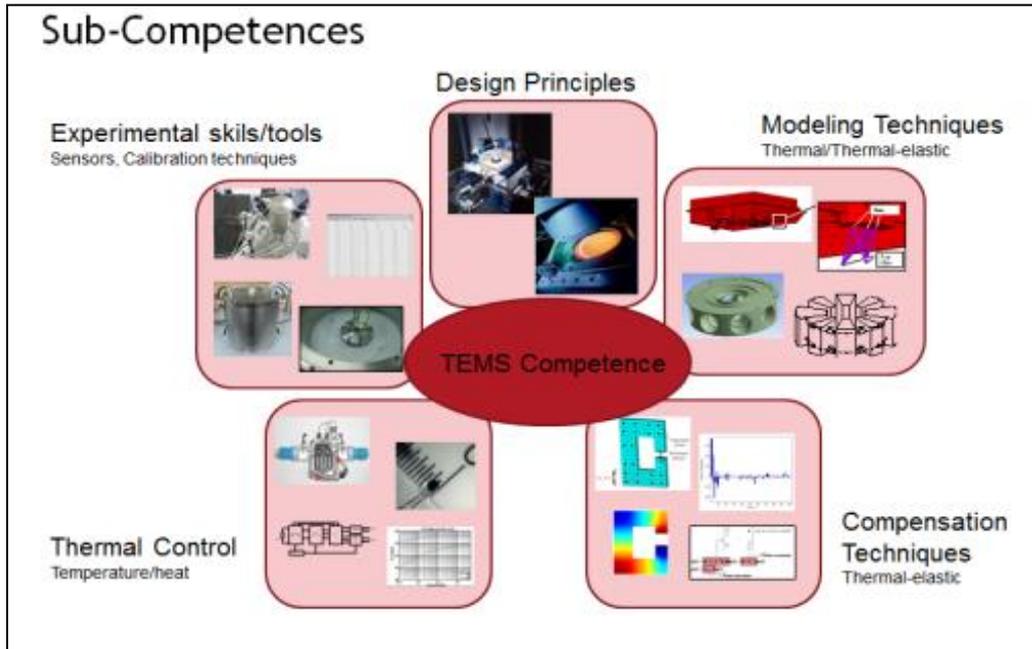


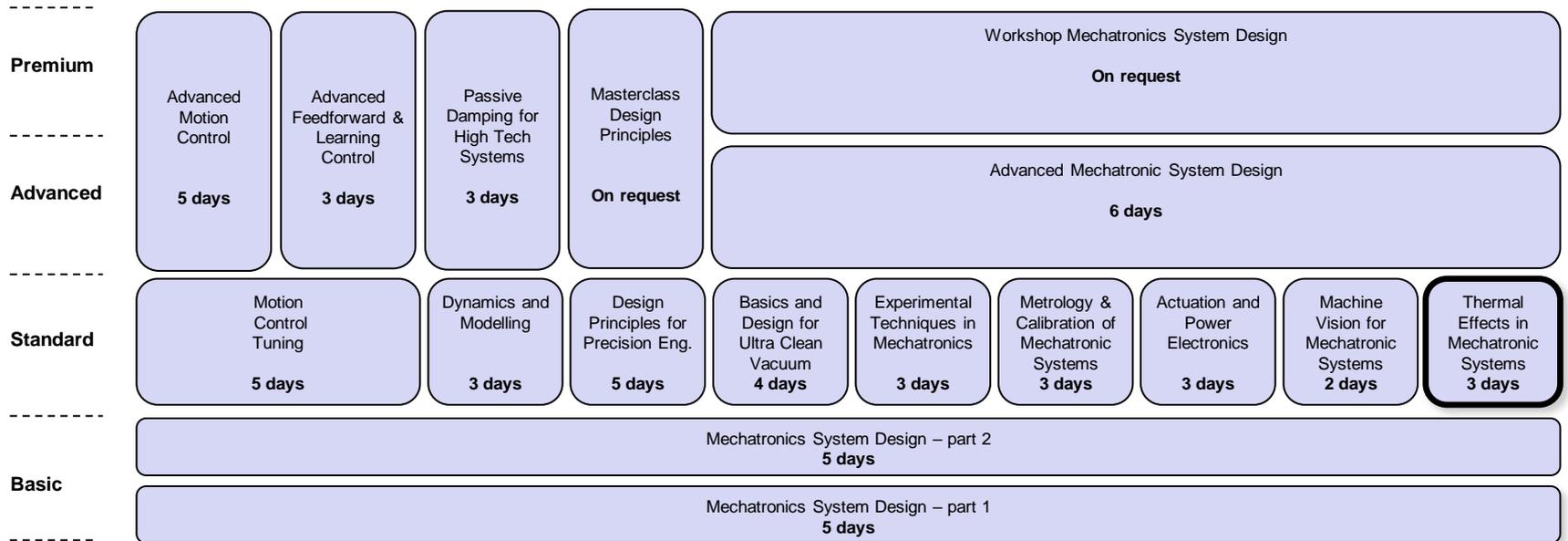
Thermal Effects in Mechatronic Systems



Contents

- Mechatronics Training Curriculum
- Details of Course *Thermal Effects in Mechatronic 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.

Thermal Effects in Mechatronic Systems

Course Director(s) / Trainers

Teachers

- Dr.ir. T.A.M. Ruijl (MI-Partners)
- Ing. J. van der Sanden (ASML)
- Ir. Marco Koevoets (ASML)
- Dr.ir. Rob van Gils (Philips Innovation Services)

Course Director(s)

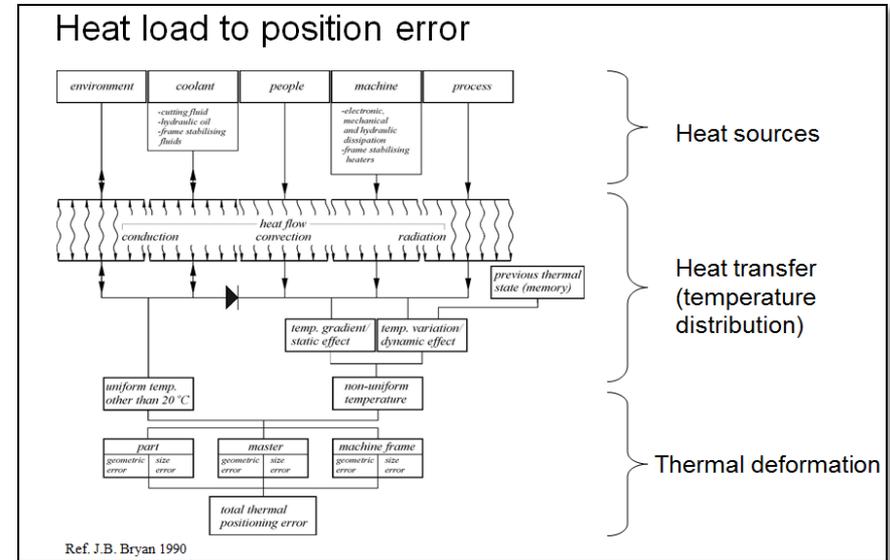
- Dr.ir. T.A.M. Ruijl (MI-Partners)
- Dr.ir. A.M. Rankers (Mechatronics Academy)

Program

Day	Contents
1	Basic Theory
	Lunch
	Basic Theory - continued
	Introduction to modeling techniques: building lump-mass models part
2	Recap day
	Precise temperature measurements
	Case Cryo
	Lunch
	Case, Cryo - continued
	Design for Thermal Stability + Case Shielding
3	Active Thermal Control
	Lunch
	Advanced Topics - model reduction / thermal modes / compensation & sensor placement

Day 1 (morning): Basic Theory

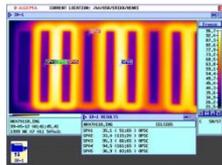
- Heat loads
- Theory of heat transfer
- Theory fluid flow
- Theory thermal deformations
- Transient effects
- Vacuum aspects



Common heat loads in Mechatronic Systems

- Motors, actuators, measurements systems, sensors and additional electronics close to the machine

Example: LIMMS motor



2 of 3 windings powered

Thermal issues:

- Internal temperature → lifetime, degradation of insulation
- Heat load to frame → accuracy, heat "loss" to structure

Summary: Heat transfer mechanism

ΔT is driving potential for energy flow.

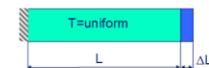
$$\Delta T = R_{th} \cdot Q$$

1. Conduction $R_{th} = \frac{d}{\lambda A}$
 λ : thermal conductivity (W/(m.K))
material parameter, see handbooks
2. Convection $R_{th} = \frac{1}{h A}$
 h : heat transfer coefficient (W/(m².K))
= f(type of fluid, geometry, velocity, ...)
3. Radiation $R_{th} = \frac{1}{h_{rad} A}$
 h_{rad} : effective heat transfer coefficient for radiation (W/(m².K))
dependent on absolute temperature of both objects, geometry (view factors), emissivity's

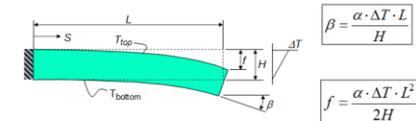
Summary: Deformations

Linear thermal expansion:

$$\Delta L = L \cdot \alpha \cdot \Delta T$$



Thermal bending:

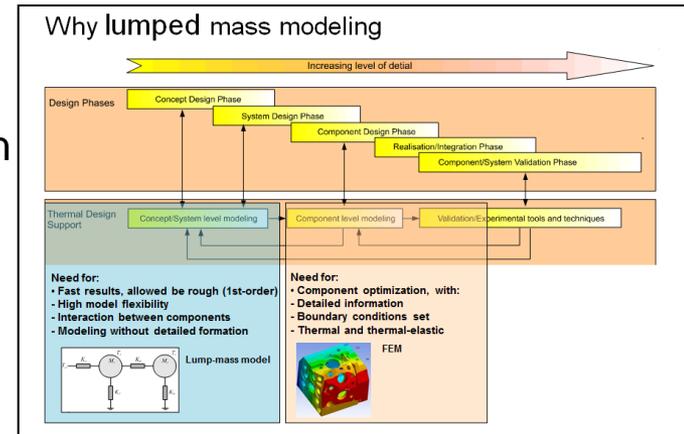


$$\beta = \frac{\alpha \cdot \Delta T \cdot L}{H}$$

$$f = \frac{\alpha \cdot \Delta T \cdot L^2}{2H}$$

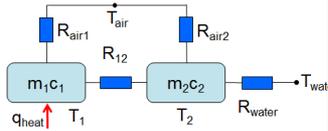
Day 1 (afternoon): Modelling

- Why lumped mass modeling
- Simple Lumped mass model example
- Analysis and simulation using a state space description
 - Stationary solution
 - Transient simulation
 - Frequency domain analysis
- Exercises
 - simple lumped mass model (deriving system matrices)
 - effects of cooling water
 - analyzing a temperature sensor



Simple Lumped mass model example

- 2 lumped masses (LM) with temperatures T_1 and T_2
- Heat exchange with surrounding air on both LM's
- Heat exchange with cooling water on LM₂
- Heat exchange between LM₁ and LM₂
- Heat load on LM₁



Thermal lumped mass equations in state space description

- General thermal equation:
$$\mathbf{E} \dot{\vec{T}} + \mathbf{K} \vec{T} = \mathbf{L} \vec{u}$$
- Thermal state space:
$$\dot{\vec{T}} = \mathbf{A} \vec{T} + \mathbf{B} \vec{u}$$
 with:
$$\vec{T} = \mathbf{C} \vec{T}$$
 - $\mathbf{A} = -\mathbf{E}^{-1}\mathbf{K}$
 - $\mathbf{B} = \mathbf{E}^{-1}\mathbf{L}$
 - $\mathbf{C} = \mathbf{I}$
 - $\mathbf{D} = 0$

Unity matrix if all temperatures are desired as output
- In Matlab:


```

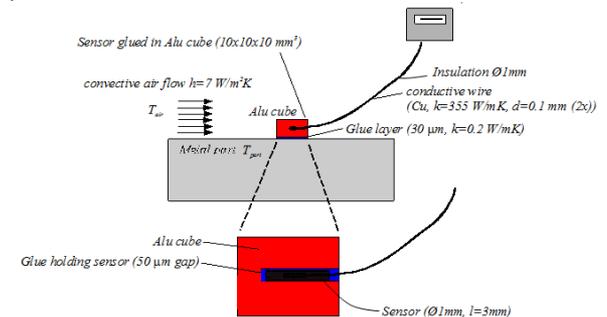
%% state space model
A=-inv(E)*K; % A=-E^-1*K
B=inv(E)*L; % B=E^-1*L
C=eye(n,m); % UNITY MATRIX size n (if you are interested in all temperatures)
D=zeros(n,m); % DEEPS size n,m
sys=ss(A,B,C,D); % create state space variable "sys", Control System Toolbox required!
            
```

Create system

Sensor model

How well is temperature of metal part measured ?

- Make a schematic sensor model (masses and thermal resistances)
- What questions could be answered with this model?



Day 2 (morning): Temp. Measurement

Spot Sensor types:

- Thermocouples
- Resistance based sensors
 - RTD (Resistance Temperature Detector)
 - Thermistor: NTC (Negative Temperature Coefficient)

Performing Real Measurements

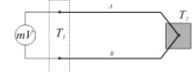
- From True to Observed value
- Real Ideal Sensor Model
- Temperature measurement of Solids/Liquids/Gas
- Dynamic behaviour, general remarks
- Sensor Calibration

IR Temperature Meters:

- Principle and limitations
- IR spot meters
- IR scanners/imaging system

Output voltage is given by ΔT , not only by T_2 :

- So, T_1 should be hold constant and known
- Or, T_1 is measured differently (e.g. RTD)



- Dedicated temperature indicator
 - Cold junction reference inside equipment
 - Suited for several types (K, J and T)
 - Much easier to use
 - Direct read out of temperature
- Data loggers (Agilent, Fluke Hydra etc.) work the same, but can read more channels



Resistance Based Sensors

Source US Sensor

Features for Ultra Precision Interchangeable NTC Thermistors

- High accuracy
- Fast thermal response
- Long life
- R/T Curve-matched
- Easy encapsulated
- High stability
- Small size

Options for Ultra Precision Interchangeable NTC Thermistors

- Special bead materials and lengths
- Special encapsulations or probe housings
- Non-standard resistance values and tolerances

Specifications for Ultra Precision Interchangeable NTC Thermistors

- Thermal time constant: 1 second max. in a well stirred oil bath, 10 seconds max. in air
- Dissipation constant: 1 mW/°C
- Maximum power rating: 30 mW at 25°C de-rated to 1 mW at 125°C
- Interchangeability tolerance of $\pm 0.05^\circ\text{C}$ from 0-50°C
- Operating temperature: -55°C to +400°C
- Storage and operation temperatures for best long term stability: -55° to +50°C

Philips Apptech design

Main problems:

- Noise (e.g shielded cables)
- Self heating of sensor
- Use low currents, $P=I^2R$ (PT100 typical 1mA so 0.1 mW; thermistor typical 10 uA, so 1..10 uW;)
- Use intermitted currents (used in Agilent 34970A)
- Typical heating coefficient 1mW/K in air

Use of sensor in control loop

You need a relatively high speed data sampling rate with intermitted very low currents

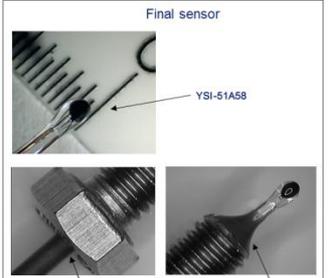
Performing Real Measurements

Sensor for measuring fast and accurately in water

First → Evolution → Final



Final sensor



- YSI-51A58
- Shrink-on tube extending in side bolt
- Very good water resistant

TC 100K Ω I-51A58 ending a by bolt ble at ss rod with ie

Sensor Calibration

Philips Apptech developed own calibration setup: Consist of an isotherm metal block of which the temperature is measured by 3 calibrated NTCs (ref. to absolute temperature scale). In this metal block the sensors under calibration can be installed.

Isothermal block is created inside metal container which is conditioned by water.



- Water cooling
- Metal block with 3 calibrated reference NTCs and sensors to be calibrated
- Aluminum container
- Isolation

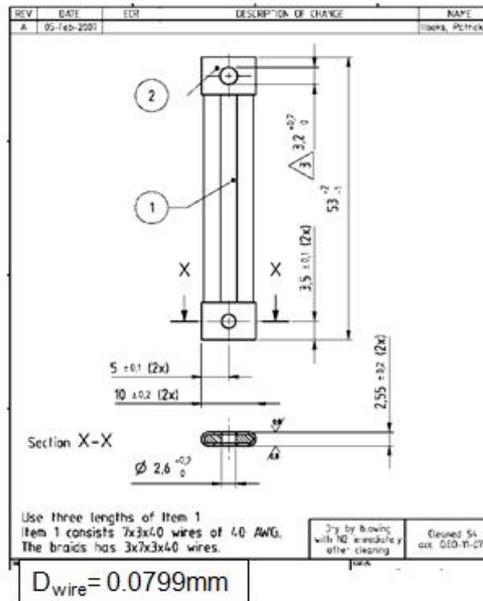
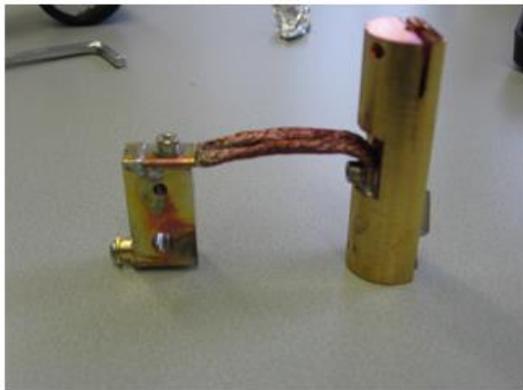
- Static gradients negligible: $\Delta T < 0.2 \text{ mK}$
- Absolute accuracy reference temperature 2.5 mK

Day 2 (morning/afternoon): Case

Exercise: Determine thermal resistance of braid

This braid is used in an electron microscope to cool a sample, which is positioned on a TEM stage, down to cryogenic temperatures (e.g. 100 K).

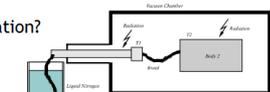
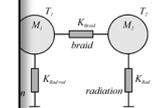
Braid between cooling rods



Dynamic versus static measurements

Dynamic or transient excitation?

Thermal model



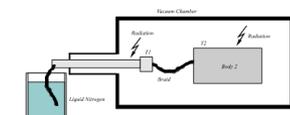
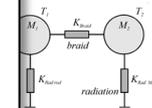
$$\frac{T_2}{T_1} = \frac{K_{\text{Braid}}}{K_{\text{Braid}} + K_{\text{Rad}M_2}} = \frac{K_{\text{Braid}}}{K_{\text{Braid}} + K_{\text{Rad}M_2} s + 1}$$

$$\left. \frac{T_2}{T_1} \right|_{s \rightarrow 0} = \frac{K_{\text{Braid}}}{K_{\text{Braid}} + K_{\text{Rad}M_2}} \approx \frac{K_{\text{Braid}}}{K_{\text{Braid}}} = 1$$

$$\tau_2 = \frac{M_2 c_p s^2}{K_{\text{Braid}} + K_{\text{Rad}M_2}}; (K_{\text{Braid}} \gg K_{\text{Rad}M_2}) \Rightarrow \tau_2 \approx \frac{M_2 c_p s^2}{K_{\text{Braid}}}$$

Dynamic versus static measurements

Thermal model



to M_2 :

$$\sum Q_2 = K_{\text{Braid}}(T_1 - T_2) + K_{\text{Rad}M_2}(T_{\text{amb}} - T_2) = M_2 c_p \frac{dT_2}{dt}$$

Laplace's:

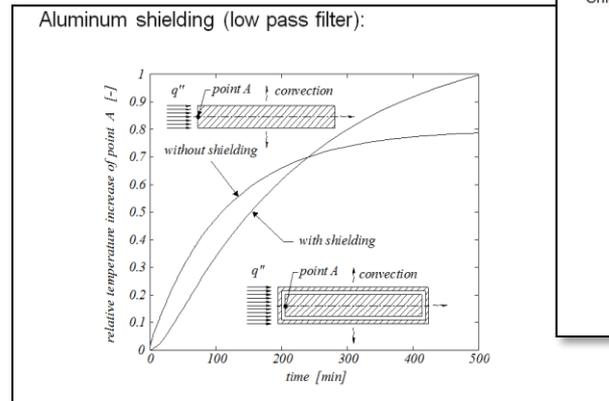
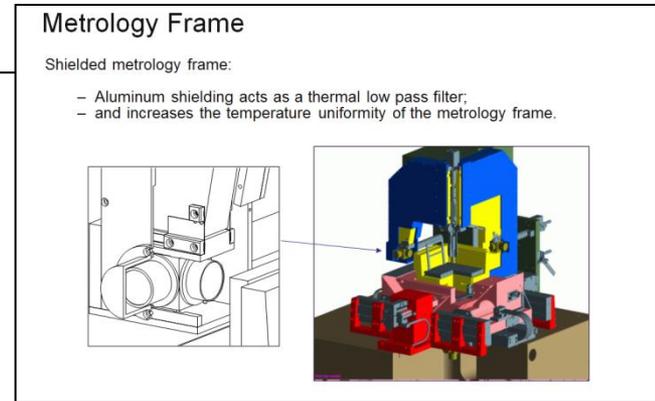
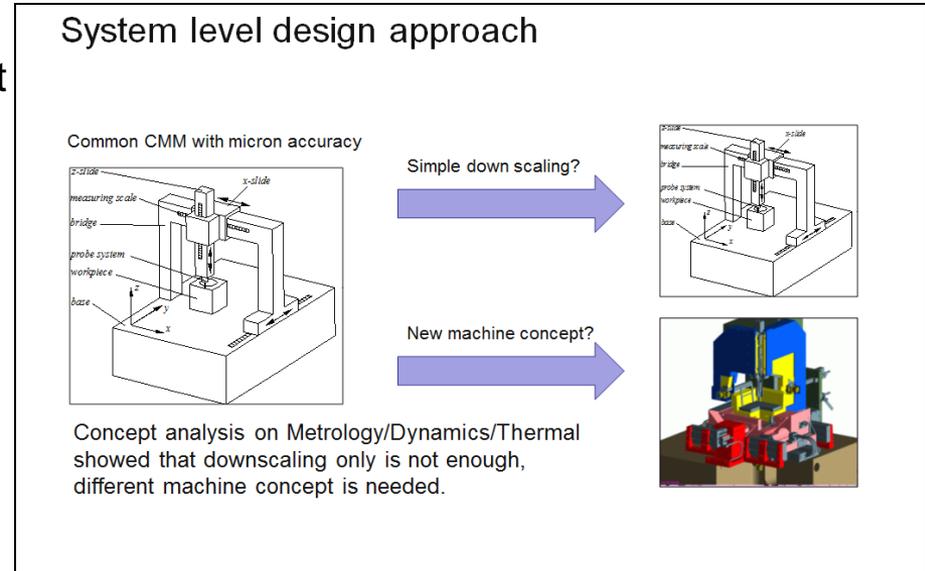
$$K_{\text{Braid}}T_1 - (K_{\text{Braid}} + K_{\text{Rad}M_2})T_2 = M_2 c_p s T_2$$

Transferfunction:

$$\frac{T_2}{T_1} = \frac{K_{\text{Braid}}}{K_{\text{Braid}} + K_{\text{Rad}M_2}} = \frac{K_{\text{Braid}}}{K_{\text{Braid}} + K_{\text{Rad}M_2} s + 1} = \frac{1}{\tau_2 s + 1}$$

Day 2 (afternoon): Design for TEMS

- Basic design rules for precision equipment
- Structural and metrology function
- Thermal design considerations
- Example case: Ultra precision CMM
 - System level design approach
 - Structural and metrology function
 - Thermal shielding
 - Metrology frame support
 - Static versus transient behavior
 - Minimizing heat generation in manipulation system
 - Thermal compensation
 - Shielding and enclosure (case)

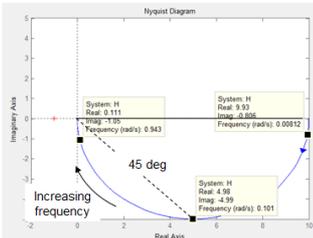
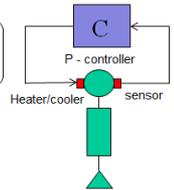


Day 3 (morning): Active Thermal Control

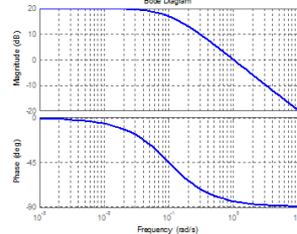
Recap, 1DOF

$$H(s) = \frac{T(s)}{Q(s)} = \frac{1}{cap \cdot s + k}$$

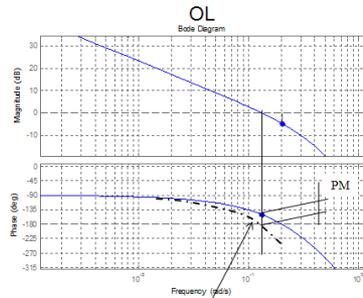
What is maximum achievable BW, can this plant become unstable, with a p-controller?



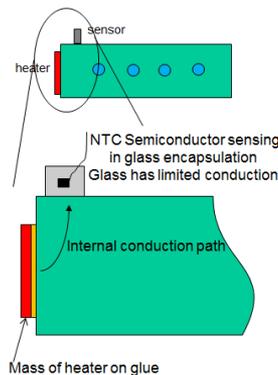
Low-frequent all real



What is important for robustness?



Typical for 'mode 2'+dealy $\tau_2 + \theta$

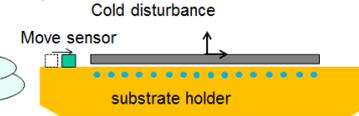


The '**details**' of sensor and heater, and internal conduction i.e. sensor heater distance

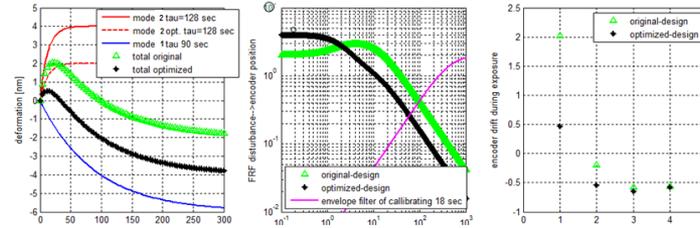
- **Does** effect robustness stability margins
- And does effect performance

3D thermo-mechanical numerical example

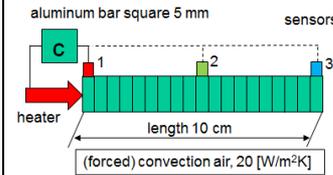
Why frequency thinking aid design thermal systems



performance improved
While steady state deformation increased

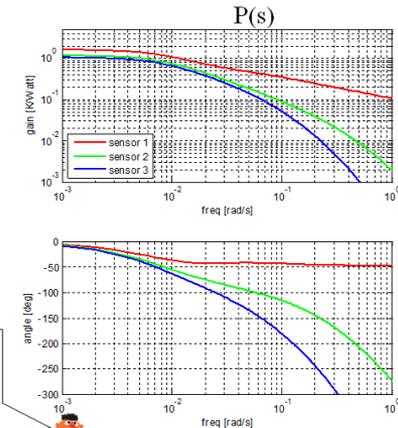


Simple Feedback control design (IMC)



When will $CI(s) \rightarrow \infty$
 $OL(s) \rightarrow -1$

So What is the max achievable BW with a p-controller?
Sensor 1
Sensor 2
Sensor 3

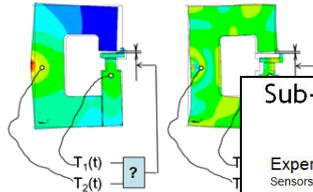


Day 3 (afternoon): Advanced Topics

Thermal –elastic compensation models

Issues w.r.t. compensation model:

- Deformations depends on all temperatures, not only on measured positions
- Can we reduce measurement points by “smart” assumptions about temperature distribution
- From use-case: what distributions or temperature fields are relevant or most likely



Fundamental design/optimisation questions:

- What are the optimal positions and amount of temperature sensors
- How to find the optimal sensitivity matrix S ?

Several approaches: “nodal modes” / “eigen modes” / “POD

General: thermal mode shapes

In general: Actual temperature field can be described as linear combination of individual (in depended) temperature fields (so-called mode shapes)

$$\mathbf{T}(t) = \vec{\phi}_1 \cdot z_1(t) + \vec{\phi}_2 \cdot z_2(t) + \dots + \vec{\phi}_m \cdot z_m(t)$$

$$\mathbf{T}_{m \times 1}(t) = \Phi_{m \times m} \cdot \mathbf{z}_{m \times 1}(t)$$

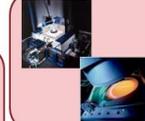
field \rightarrow Thermal States \rightarrow Thermal Mode shapes

Sub-Competences

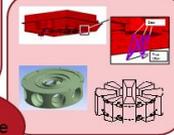
Experimental skills/tools
Sensors, Calibration techniques



Design Principles

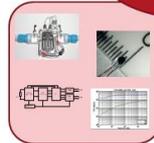


Modeling Techniques
Thermal/Thermal-elastic

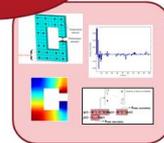


TEMS Competence

Thermal Control
Temperature/heat



Compensation Techniques
Thermal-elastic

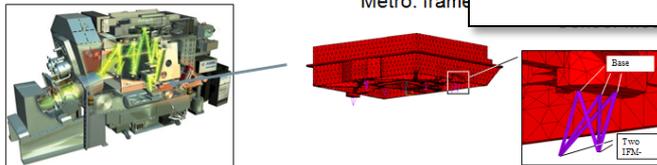


Frequency domain analysis

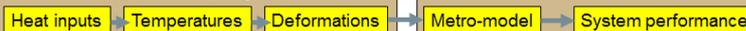
Frequency domain analysis common in structural dynamics

Problems during development of EUV α -tool metrologie frame

Metro. frame



FEM-Software package



Solution, like common in structural dynamics: don't solve transient behavior in FEM on all nodes, but only subtract dynamic model properties from FEM of relevant nodes
 \Rightarrow {eigen-vectors (=mode shapes), eigen-values (=time constants)}

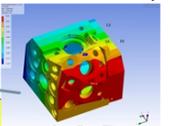
Reduce) data by means of POD

Principal Component Decomposition (POD) or Singular Value Decomposition

Set of temperature fields $T^*_{1..k}$ describing the complete set of data

$$\mathbf{T} = \begin{bmatrix} T_{1,t=1} & \dots & T_{1,t=m} \\ \vdots & & \vdots \\ T_{k,t=1} & \dots & T_{k,t=m} \end{bmatrix} \quad (k < m) \Rightarrow \mathbf{T} = \mathbf{T}^* \Sigma \mathbf{V}$$

Measured T-field at t=t_i



$$\mathbf{T} = \mathbf{T}^* \Sigma \mathbf{V} = \begin{bmatrix} \vec{T}_1^* & \vec{T}_2^* & \dots & \vec{T}_k^* \end{bmatrix}^{k \times k} \begin{bmatrix} \sigma_1 & & & \\ & \sigma_2 & & \\ & & \dots & \\ & & & \sigma_k \end{bmatrix}^{k \times k} \begin{bmatrix} \vec{v}_1 & \vec{v}_2 & \dots & \vec{v}_m \end{bmatrix}^{k \times m}$$

- \mathbf{T}^* : POD shapes (temperature fields/distributions)
- Σ : Singular values (importance of shape)
- \mathbf{V} : Linear combination of shapes over time (transient behaviour)

Sign-up for this training

Via the website of our partner
High Tech Institute