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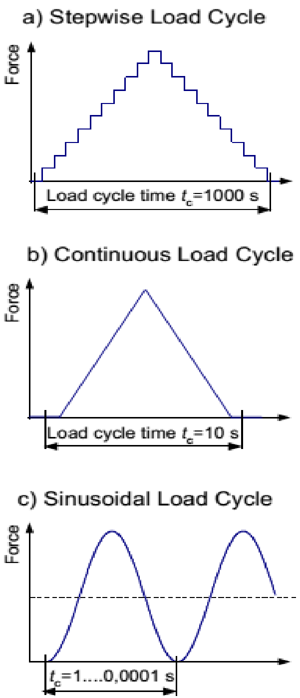
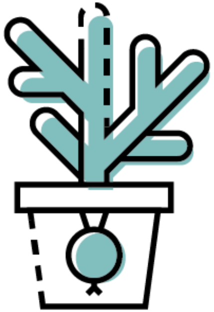
Force measurement uncertainty on an electrodynamic shaker / WP2

Mikolaj Wozniak / ComTraForce Final Workshop / 2023-02-24

Introduction



- RISE will continue to build capability and competence in the area of dynamic force measurement



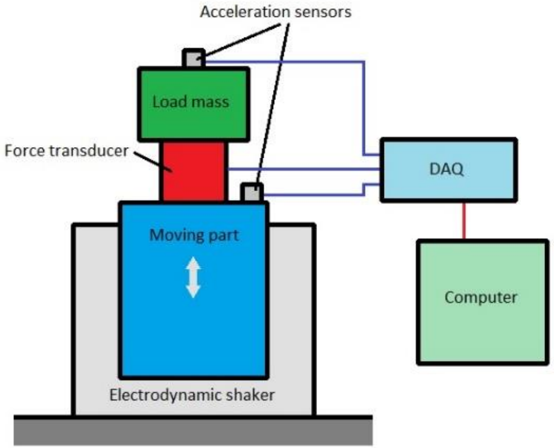
Introduction

- We selected three force transducers + QuantumX amplifier

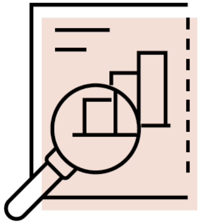
	PCB 208C05 	HBM U10M 	HBM U10M 
Capacity	22.24 kN (C) 2.224 kN (T)	5 kN (T/C)	50 kN (T/C)
Principle	ICP	SG	SG
Static sens.	None / dynamic sens. from PCB: 0.2187 mV/N	$2{,}476 \cdot 10^{-4}$ (mV/V)/N (with QuantumX)	$4{,}116 \cdot 10^{-5}$ (mV/V)/N (with QuantumX)

Introduction

- Dynamic calibration of force transducers (DKD-R 3-10)
- Periodic excitation – sine wave
- Three shaker systems (fixed frequencies and sweep)
- Two different load masses for each transducer
- 3-axial reference accelerometer

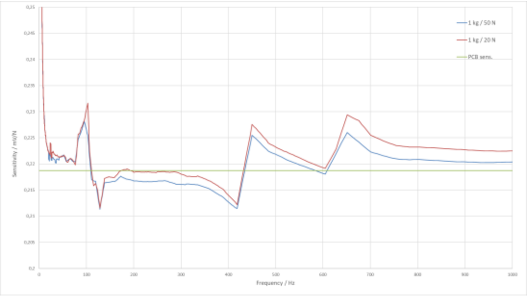


Evaluation of measurement data

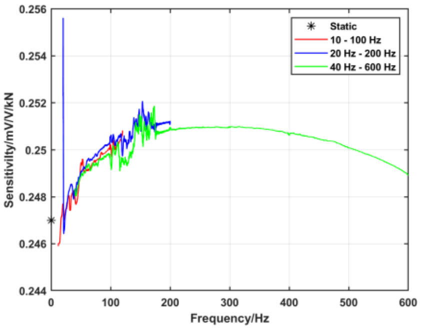


- FFT (Matlab) – converting a time domain signals to frequency domain
- Determination of the head mass from fixed frequency measurements -> transfer function (output force / acceleration) extrapolated to zero frequency
- Determination of the dynamic (force) sensitivity from sweep frequency

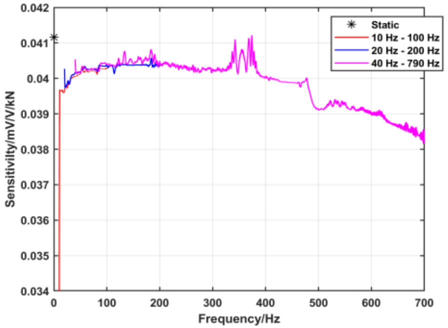
PCB



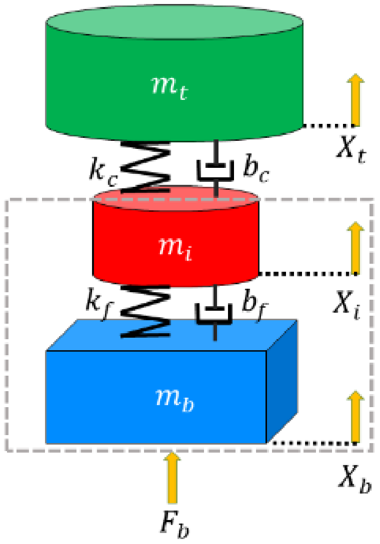
HBM U10M / 5 kN



HBM U10M / 50 kN



Measurement model



- Based on advanced Kelvin-Voigt model
- Assuming high stiffness of the adaptation parts and the spring element of the transducer, the dynamic sensitivity is given by:

$$S_f = \frac{U_f}{a_\mathrm{t}(f) \cdot [m_\mathrm{a} + m_\mathrm{i} + (m_\mathrm{t} \cdot K_0)]}$$

Input quantities

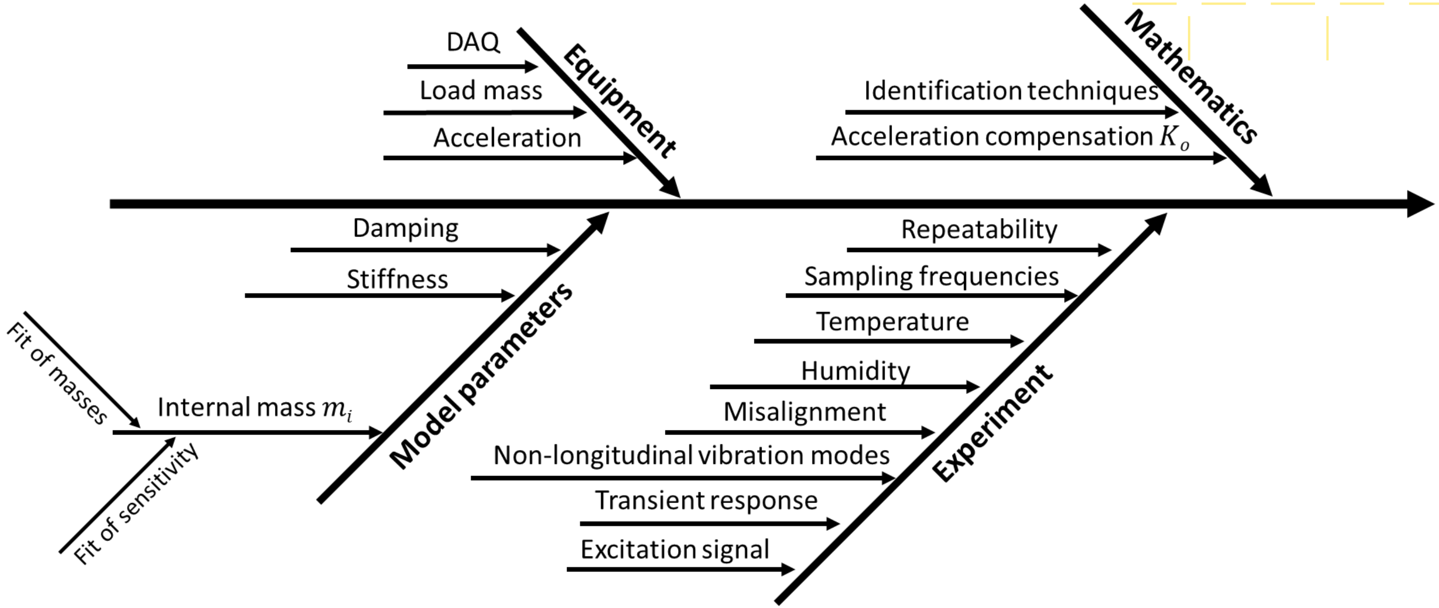


Diagram -> influences on a dynamic calibrated force transducer

Uncertainty analysis

Dynamic sensitivity of the force transducer

$$S_f = \frac{U_f}{a_t(f) \cdot [m_i + m_a + (m_t \cdot K_0)]}$$

Measured transducer's output (U_f)

Uncertainty mainly due to amplifier/ DAQ and misalignment (*frequency dependent*)

$$u_{U_f}^2 = u_{amp}^2 + u_{filt}^2 + u_{misalign}^2$$

- u_{amp}: Uncertainty of the electrical measurement -> mainly from calibration under dynamic conditions (e.g. DKD-R 3-2) and sampling frequencies
- u_{filt}: DAQ filter settings
- $u_{misalign}$: Due to transducer's sensitivity to transverse forces and bending moments

Transducer's internal mass (m_i)

Uncertainty of the mass determination (*assuming strong correlation*)

$$u_{m_i}^2 = \left(c_1 \cdot u_{extrapol} + c_2 \cdot u_{transfer} + c_3 \cdot u_{lin}\right)^2$$

- $u_{extrapol}$: Extrapolation of the transfer function to zero frequency for each load mass
- $u_{transfer}$: Transfer function analysis, if possible to determine
- u_{lin}: Linear fit extrapolated values as function of load mass

Load mass + adaptation parts (m_a, m_t)

Uncertainty due to mass calibration

Uncertainty analysis

Dynamic sensitivity of the force transducer

$$S_f = \frac{U_f}{a_t(f) \cdot [m_i + m_a + (m_t \cdot K_0)]}$$

Load mass correction

Due to internal dynamics of the load mass; uncertainty depends on material properties

Acceleration / displacement

Uncertainty due to measuring device, tilting/rocking motions and vibrations (*frequency dependent*)

$$u_{a_t}^2 = u_{\text{meas}}^2 + u_{\text{tilt}}^2 + u_{\text{vib}}^2$$

Applies mainly to interferometers which are sensitive to vibrations

Mainly accelerometer / interferometer calibration uncertainty

Due to tilting of the calibration assembly, uncertainty derived from complex analysis of parasitic motions (e.g. using DNN)

Other components

Influencing dynamic sensitivity of the force transducer:

- u_{rep} non-repeatability between runs due to various factors, such as noise or different mounting
- u_{temp} due to temperature effects on calibration assembly
- … yet to be identified

Uncertainty model

For the dynamic sensitivity of the force transducer (GUM approach):

$$u_{S_f}^2 = u_{U_f}^2 \left(\frac{\partial S_f}{\partial U_f}\right)^2 + u_{a_\mathrm{t}}^2 \left(\frac{\partial S_f}{\partial a_\mathrm{t}}\right)^2 + u_{m_\mathrm{i}}^2 \left(\frac{\partial S_f}{\partial m_\mathrm{i}}\right)^2 + u_{m_\mathrm{a}}^2 \left(\frac{\partial S_f}{\partial m_\mathrm{a}}\right)^2 + u_{m_\mathrm{t}}^2 \left(\frac{\partial S_f}{\partial m_\mathrm{t}}\right)^2 + u_{K_0}^2 \left(\frac{\partial S_f}{\partial K_0}\right)^2 + u_\mathrm{rep}^2 + u_\mathrm{temp}^2$$

For other parameters, stiffness and damping, uncertainty evaluation according to GUM is proposed.

Conclusions

- In general, not an easy task
- In detail, uncertainty depends on calibration conditions (load mass, frequency, force) and properties of the transducer
- Largest contributions:
  - output signal of the transducer
  - tilting of calibration assembly (shaker/transducer/load mass)
  - acceleration measurement (especially when using acceleration sensors)
- Correlations (tilt in particular)!
- Frequency dependent parameters!

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Thank you for your attention!