Experimental Modal Analysis (EMA) on a vibration cube fixture

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- Variant 3 (shaker armature - sweep)

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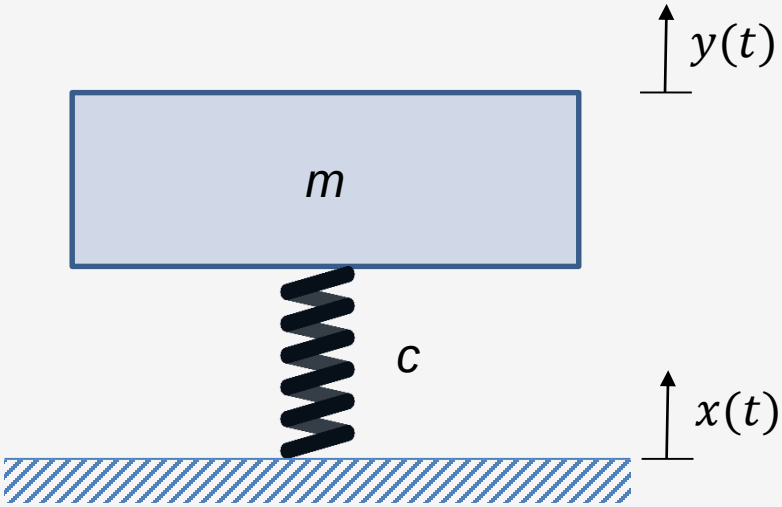
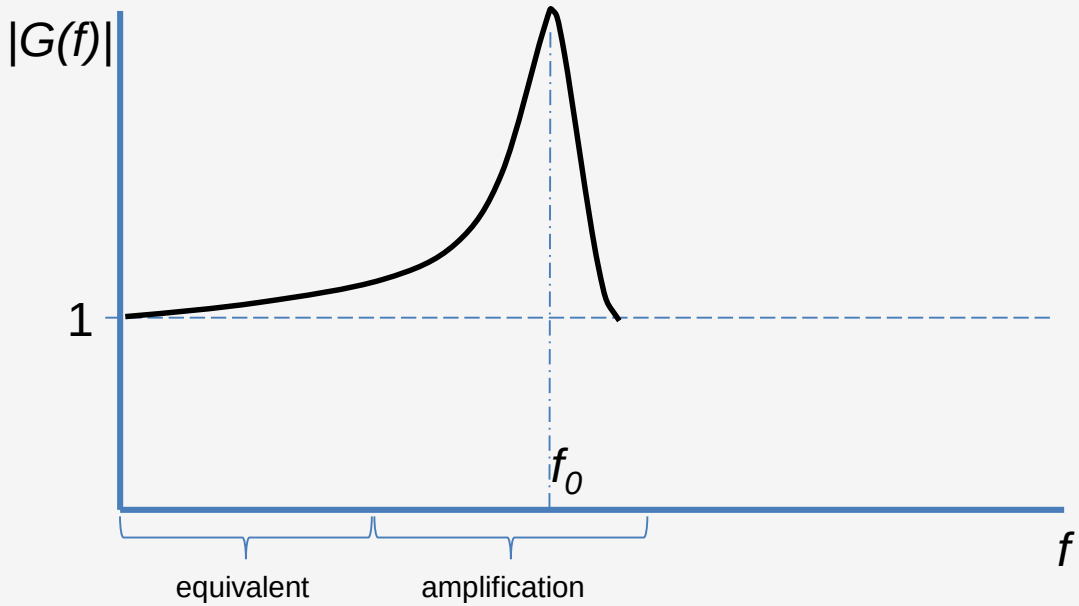
Introduction - Basics

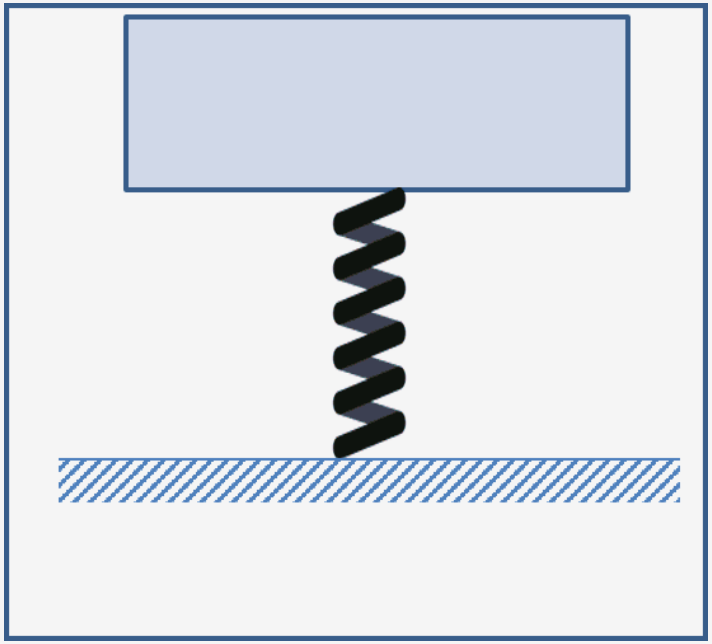
SDOF System



- Idealized systems, e.g.
  - Armature (shaker)
  - Piezo - Accelerometer
- One mass *m* [kg], one spring *c* [N/m]
- Owns one natural frequency (eigenfrequency)
  - $\omega_0 = \sqrt{\frac{c}{m}} \rightarrow f_0 = \frac{\omega_0}{2\pi} = \frac{\sqrt{\frac{c}{m}}}{2\pi}$
- „System prefers to moves at natural frequencies“
- Transmissibility function (amplification function) *G(f)* = $\frac{\text{Response}}{\text{Excitation}} = \frac{\hat{y}\,(f)}{\hat{x}\,(f)}$
  - behavior of the movement regarding to the excitation in frequency domain
    - amplification, isolation (attenuation)

Introduction - Basics





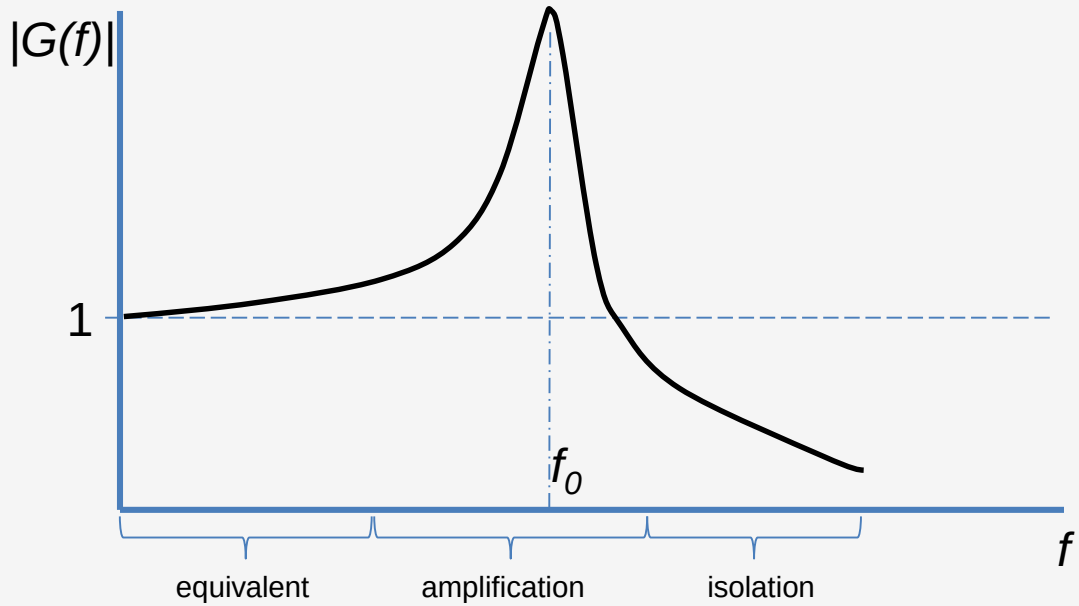
3 areas of transmissibility function

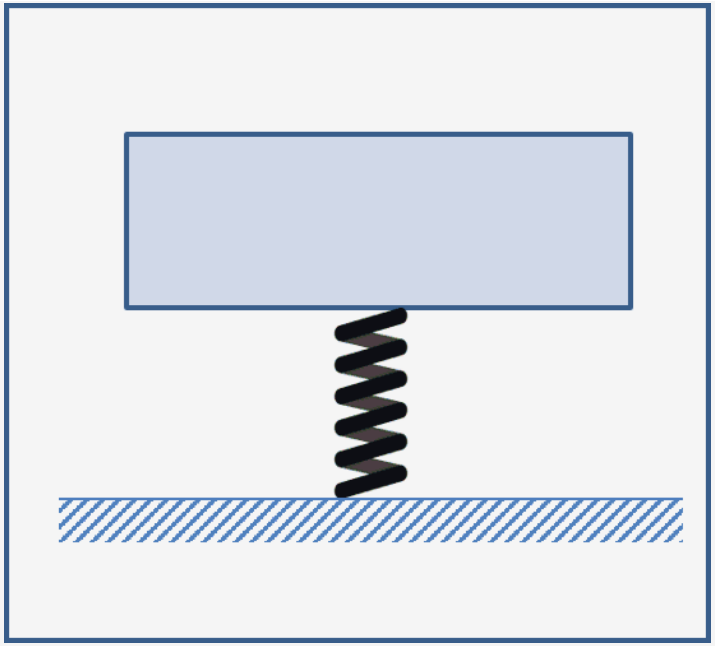
- Equivalent area *G(f)≈1*
- Amplification *G(f)>>1*
- Isolation *G(f)<1*

Resonance

- if $f = f_0$

Introduction - Basics





3 areas of transmissibility function

- Equivalent area *G(f)≈1*
- Amplification *G(f)>>1*
- Isolation *G(f)<1*

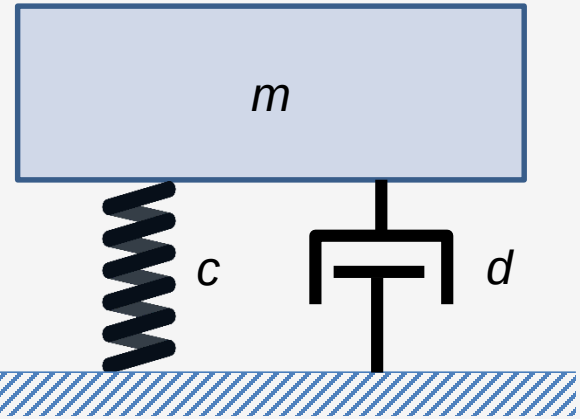
Isolation

- if $f > f_0$

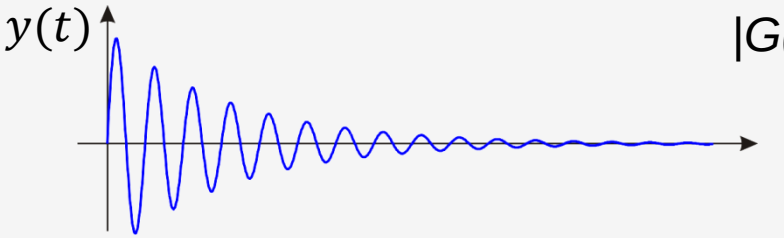
Introduction - Basics

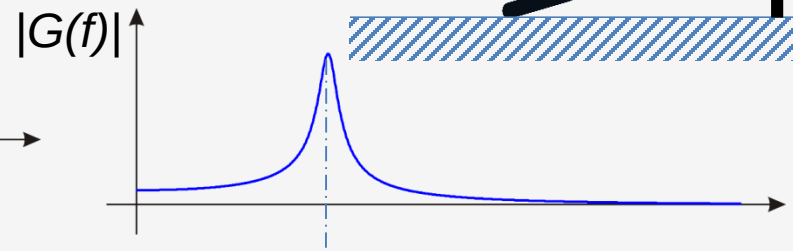
Damping dissipates energy

- Briefer decay time
- Damping coefficient d $[\frac{\mathrm{kg}}{\mathrm{s}}\ \mathrm{resp.}\ \mathrm{N}\frac{\mathrm{s}}{\mathrm{m}}]$

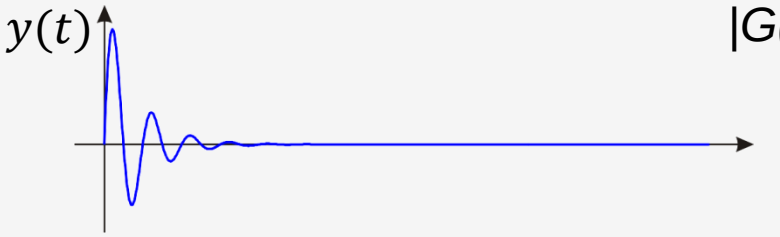


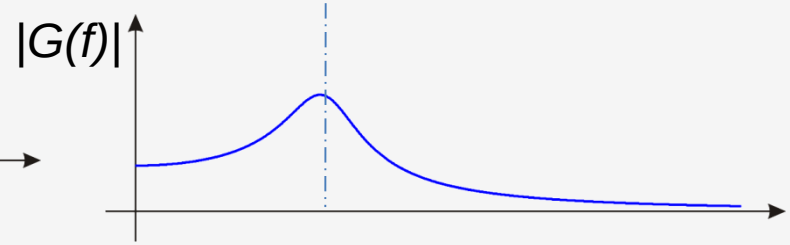
Softly damped system



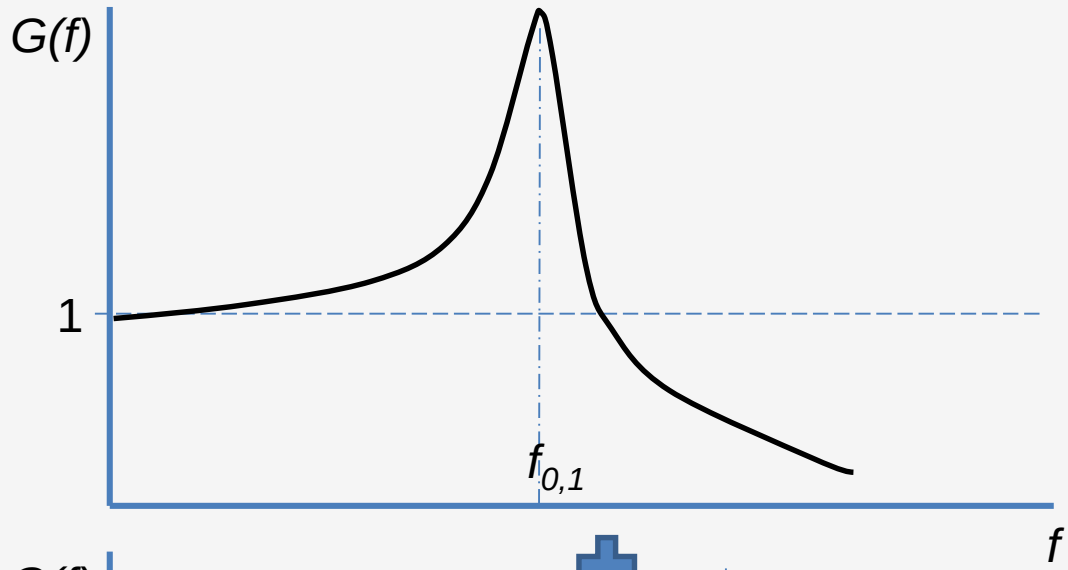


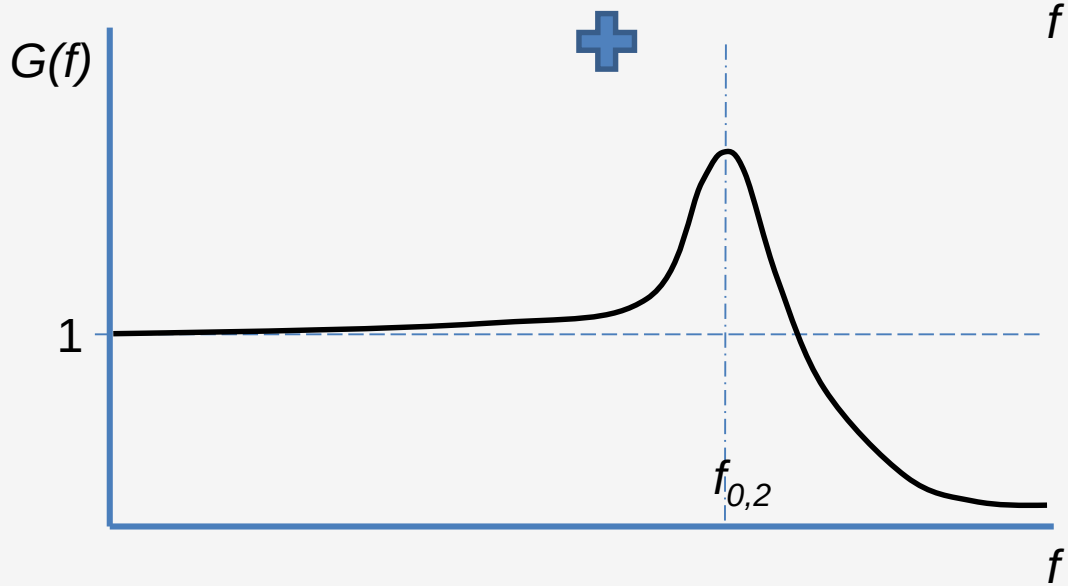
Greatly damped system

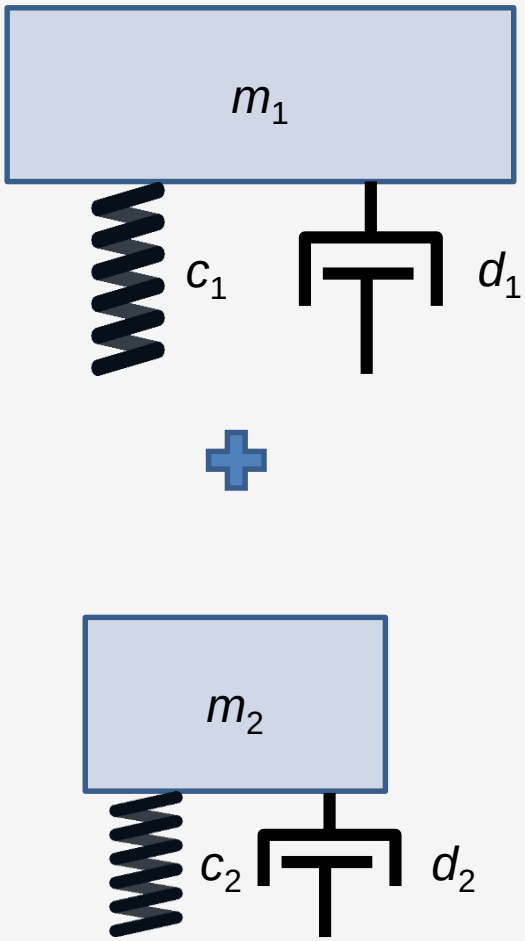




Introduction - Basics



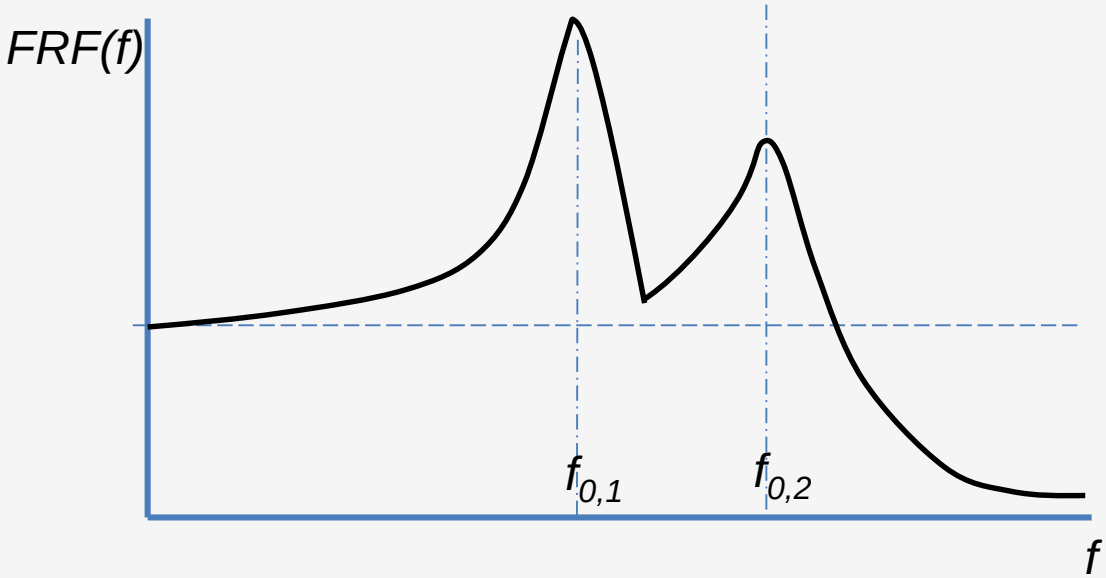


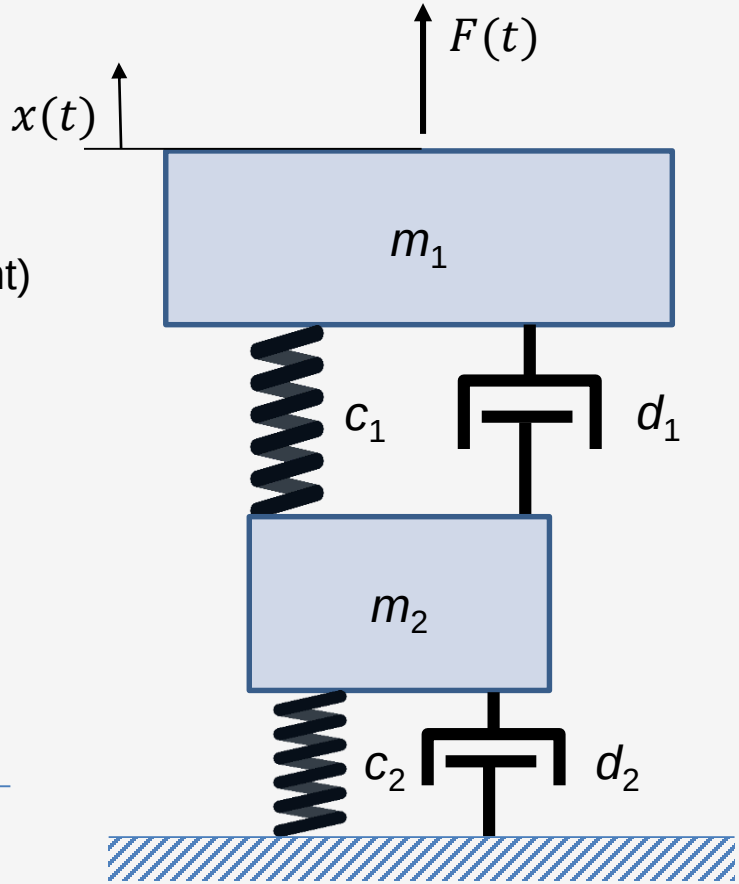


Introduction - Basics

Force excited two-mass spring damper system

- Two natural frequencies
- Two natural modes
- Resonance followed by anti resonance (Drivepoint)
- FRF (Frequency Response Function)
  - Ratio of acceleration, velocity & displacement to force

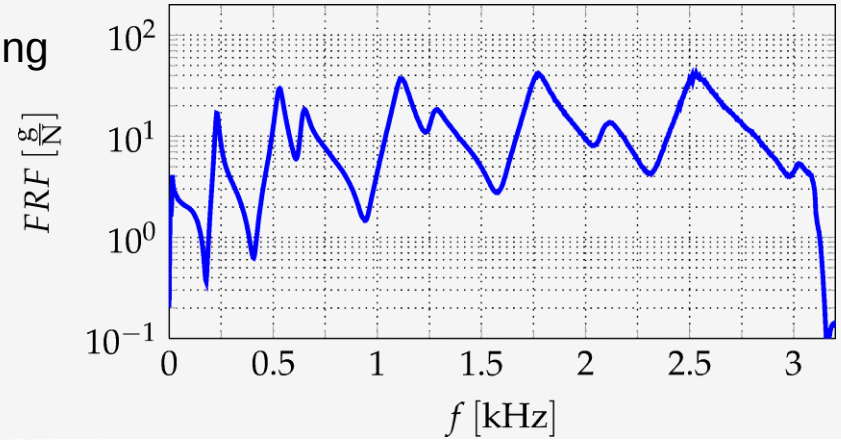


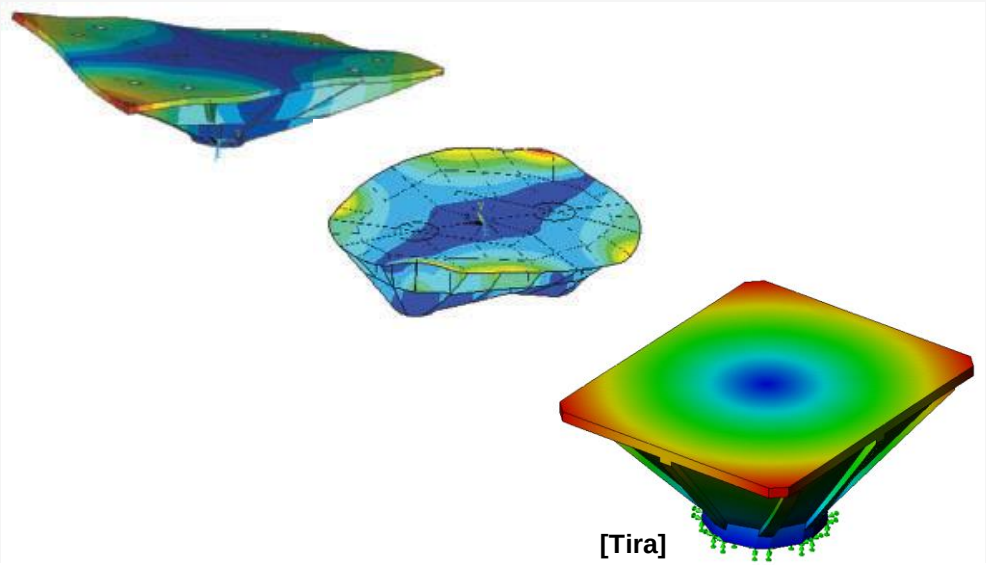


Introduction - Why EMA?

Why modal analysis of fixtures and test sockets?

- Determine natural frequencies/ damping
  - Determine critical frequency range
  - Customizing test definitions
  - Notching / forcelimitation
  - Design features
- Determine natural modes
  - Identification of suitable positions for control sensors, DUT
  - Design features
- FEM validation





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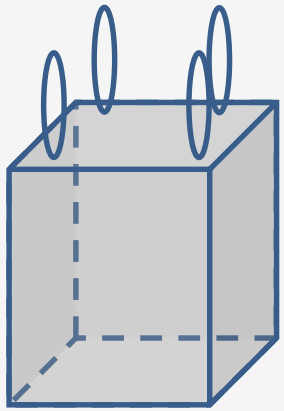
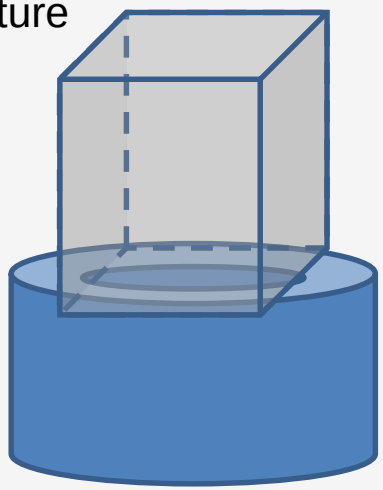
Preparation and execution
- Testing variants

Test object: Cube fixture

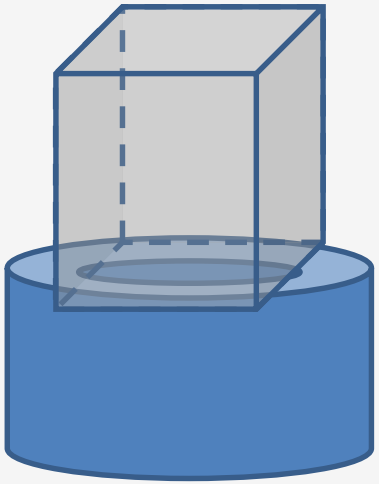
Variant 1:
Elastic suspension
Excitation:
Impulse



Variant 2:
Shaker armature
Excitation:
Impulse



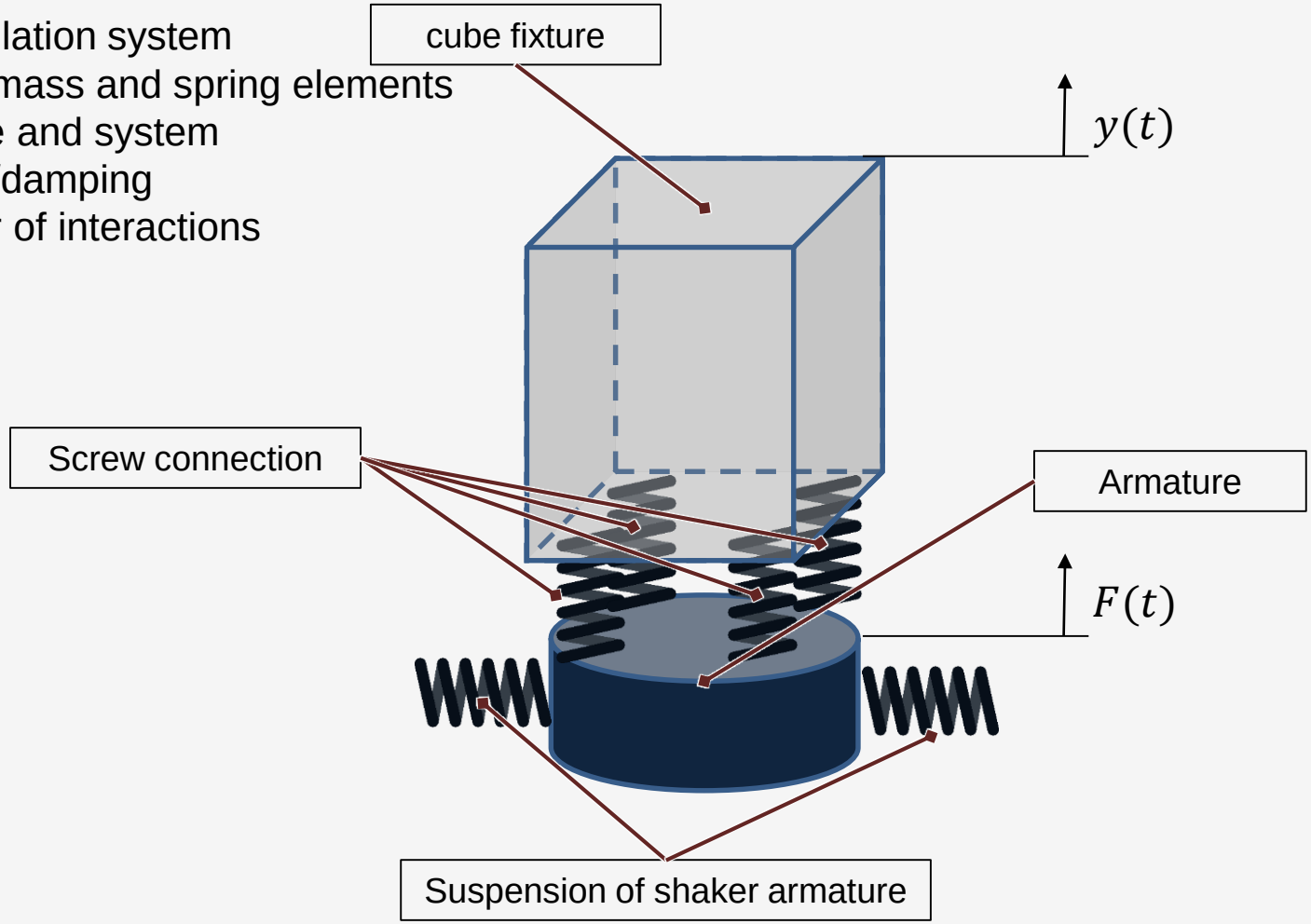
Variant 3:
Shaker armature
Excitation :
Sine sweep
(10 – 2500 Hz)



Preparation and execution
- Testing variants

Approximation system for cube fixture on shaker armature

- Complex oscillation system
  - Several mass and spring elements
  - Structure and system stiffness/damping
- Large number of interactions

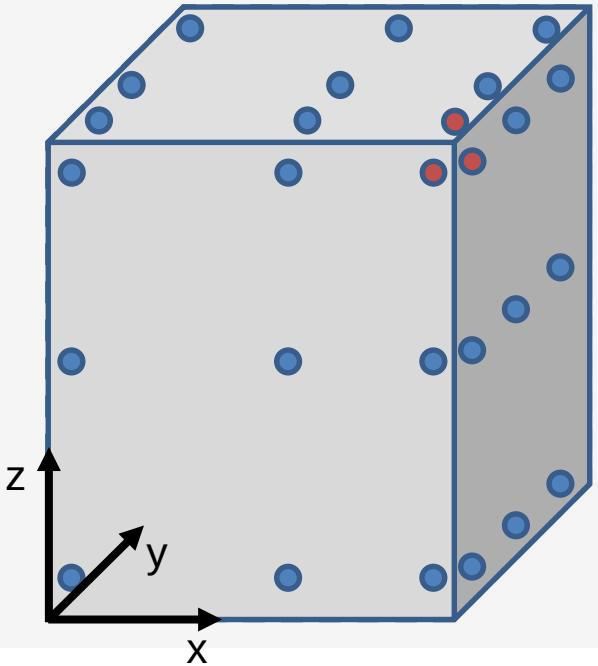


Preparation and execution
- Definition of measuring points/ Geometry creation

Test object:
Cube fixture
- Symmetrical
- Mass approx. 58 kg

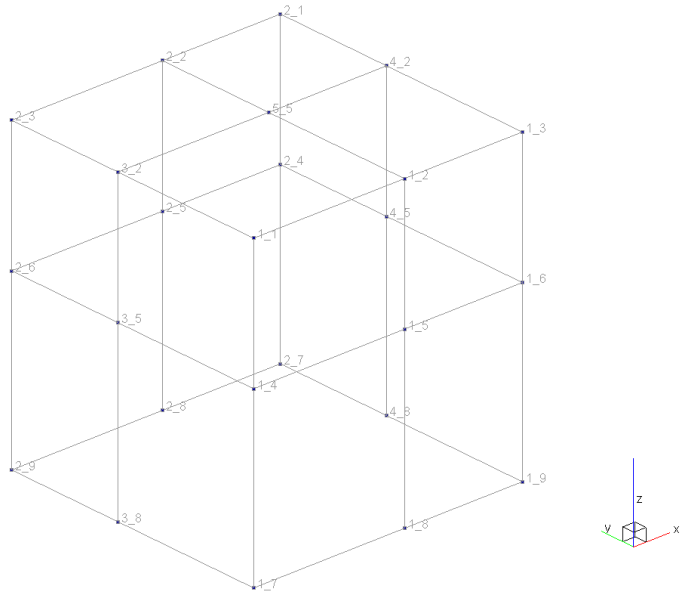
Measuring points:
- 9 Accelerometer per face
  → 45 Measuring points
- Merging of corner points (m+p Analyzer)
  → 3-Dimensionale dynamic

Vorüberlegung bzw. Positionsmessung



Excel Table,
STL-Format

m+p Analyzer Messpunkt-Geometrie



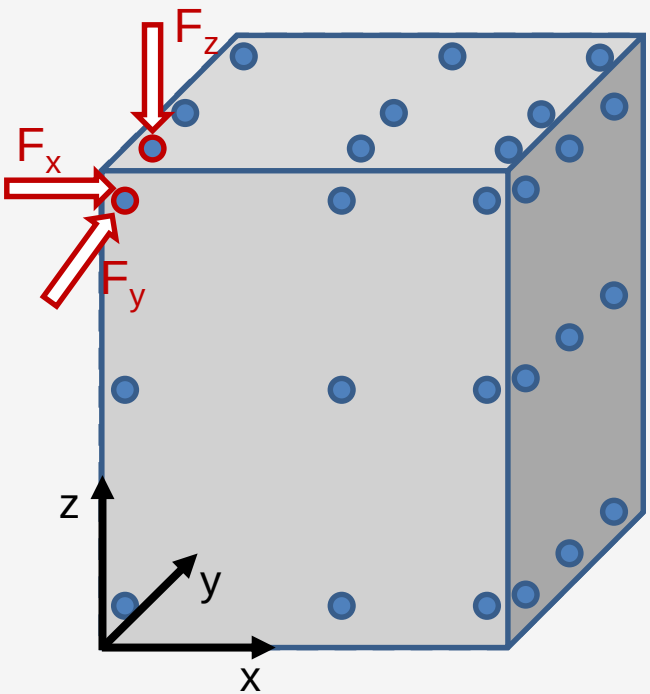
Preparation and execution - Excitation & response

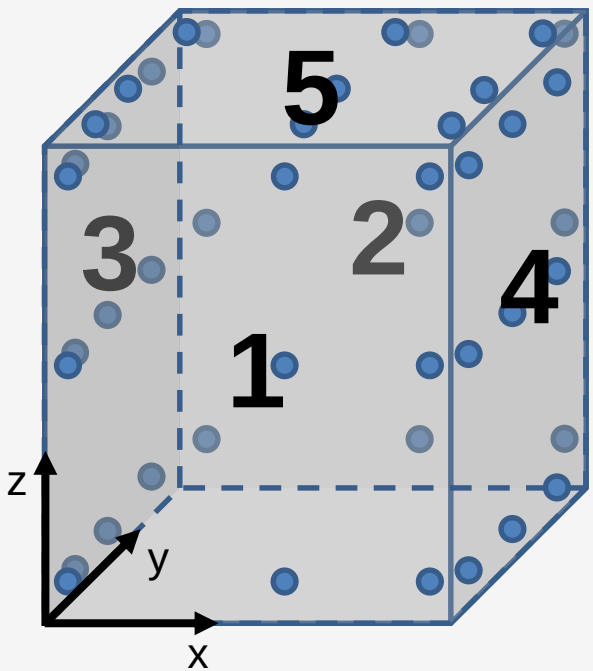
Impulse excitation:

- 3 Drivepoints
- F_x in +x, F_y in +y, F_z in –z
- Impulse hammer with hard plastic tip (0,23 mV/N)
- roving

Impulse response:

- Accelerometer (100 mV/g)
- Measuring direction of points on Surface:
  - **1**: -y , **2**: +y, **3**: -x, **4**: +x, **5**:+z
- fixed

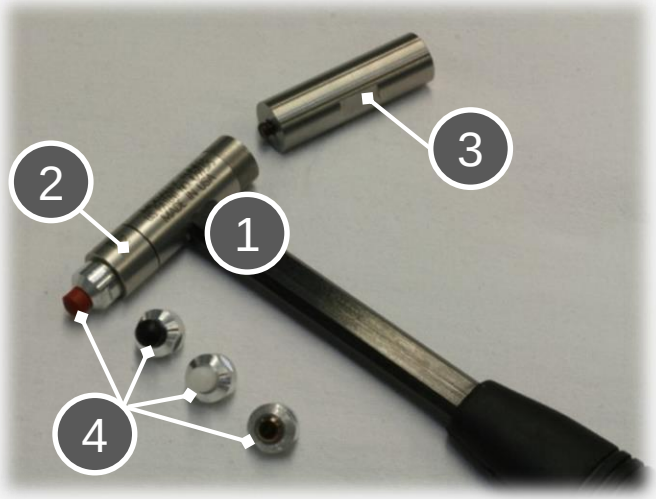




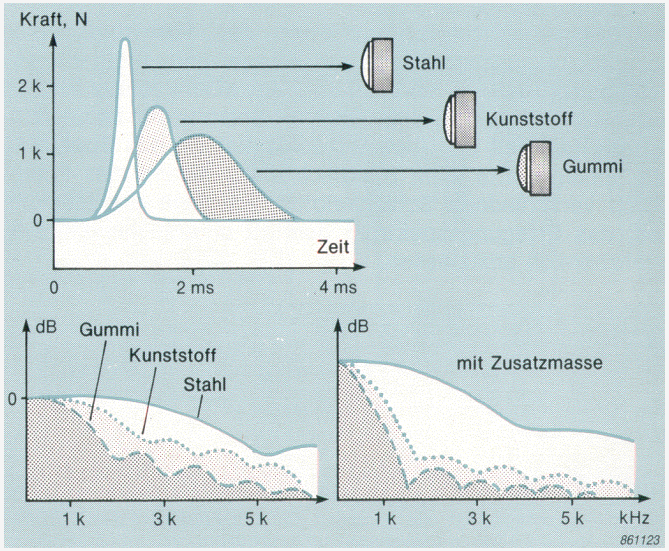
Preparation and execution - Excitation & response

Impulse excitaion:

- Hammer (1)
- Force transducer (2)
- Additional mass (3)
- Hammer tip (4)
- Mass of hammer reaches from a few grams up to several Kilograms
- Excitation frequencies:
  → From 100 Hz
  (Heavy Hammer, soft tip)
  → To more than 50 kHz
  (Light Hammer, hard tip).



[PCB]



[B&K]

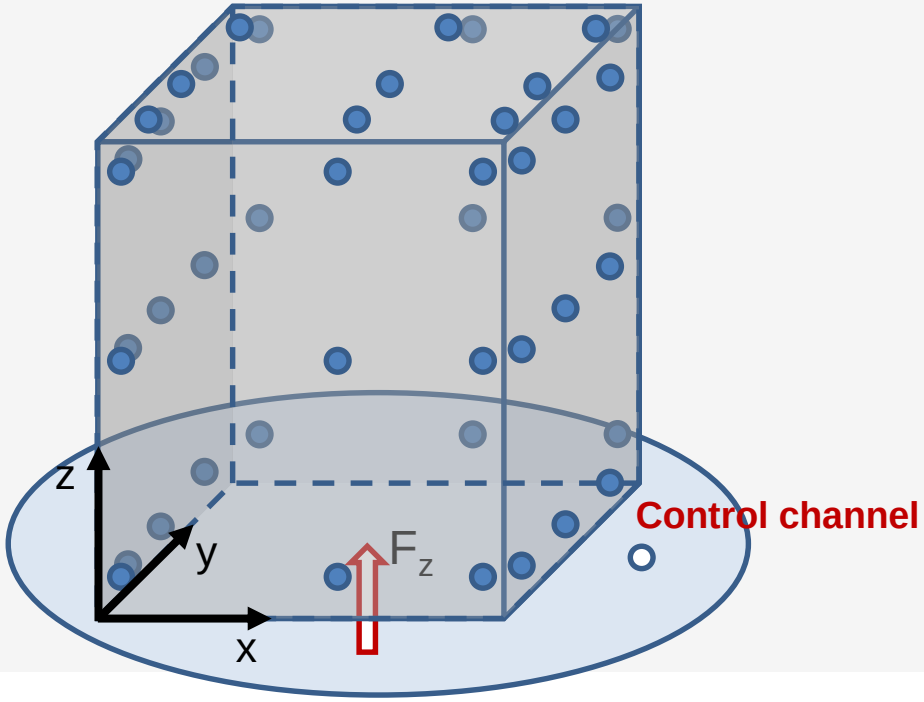
Preparation and execution - Excitation & response

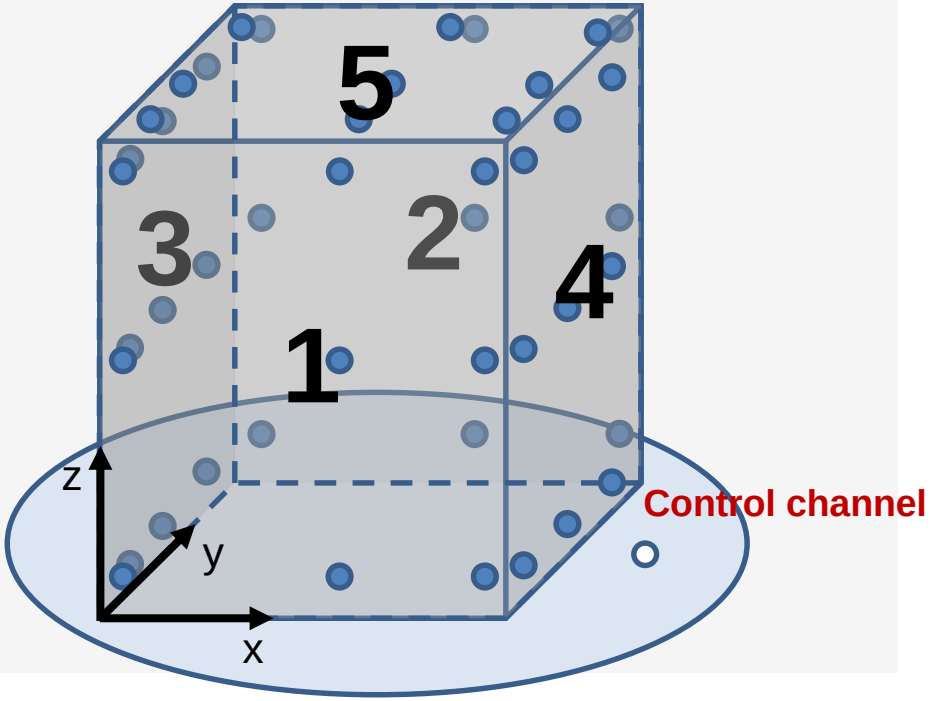
Sine-Sweep-Excitation:

- F_z in +z (Cube on shaker armature)
- Control channel delivers excitation signal
- 10-2500 Hz
- 1g constant
- 1 Octave/min

Impulse response:

- Accelerometers (100 mV/g)
- Measuring direction of points on Surface:
  - **1**: -y , **2**: +y, **3**: -x, **4**: +x, **5**:+z
- fix

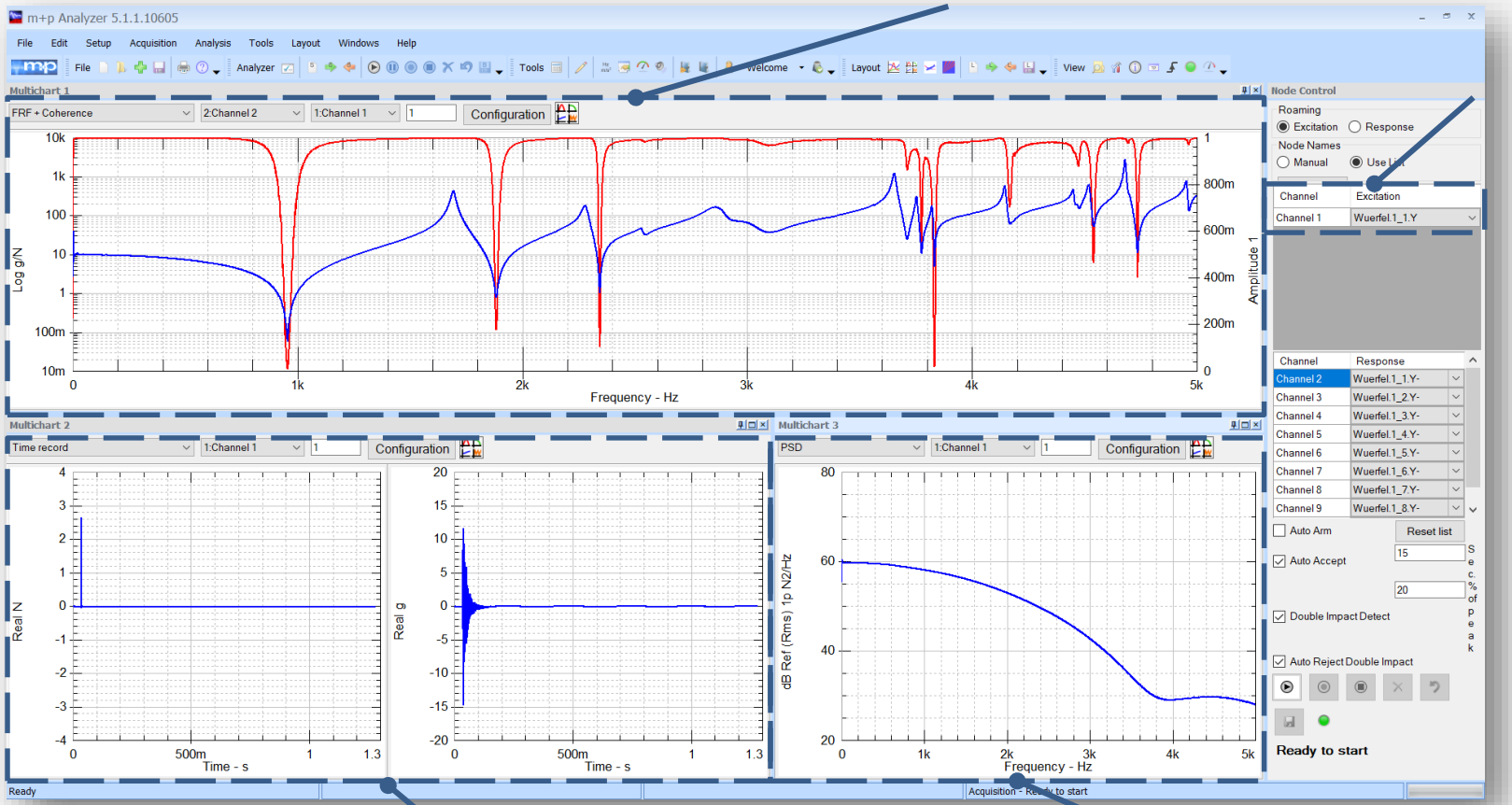




Preparation and execution - Excitation & response

Monitoring during impulse hammer test

FRF (*Frequency Response Function* [g/N]) + Coherence of Drivepoint



Display: Excitation point

Time signal of excitation and response

PSD (Power spectrum density) of hammer impulse

Preparation and execution
- Excitation & response, evaluable frequency range

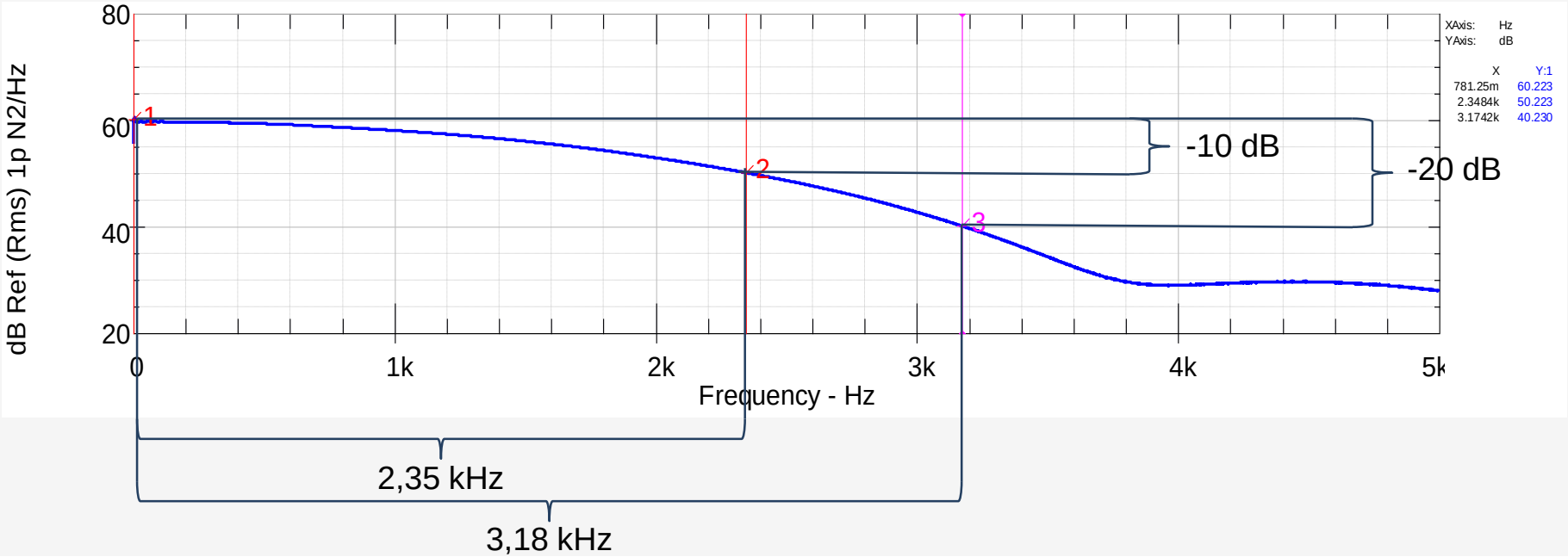
Measured signals:

- Time signals, PSD, FRF, Coherence

Evaluable frequency range for modal parameters:

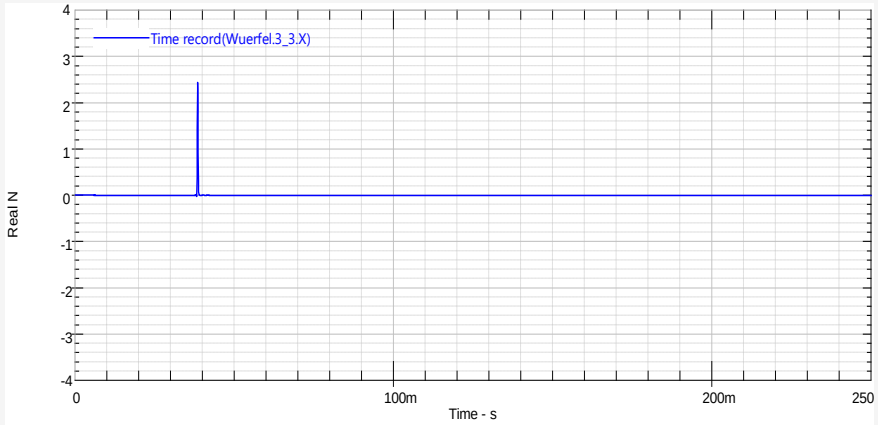
- f_{min} for elastic suspension → 0,8 Hz (longer time window)
- f_{min} for cube on shaker armature → 1,6 Hz (shorter time window)
- f_{max} depends on impulse decrease (10-20 dB difference)
  - Additional considering of coherence

Bsp. PSD of hammer impulse in Y (elastic suspension)

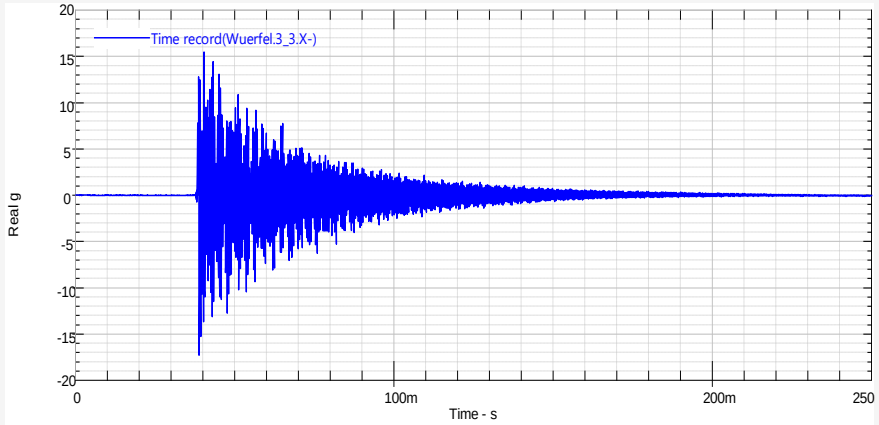


Test results
- Test variant 1 (elast. suspension), Impact in +X

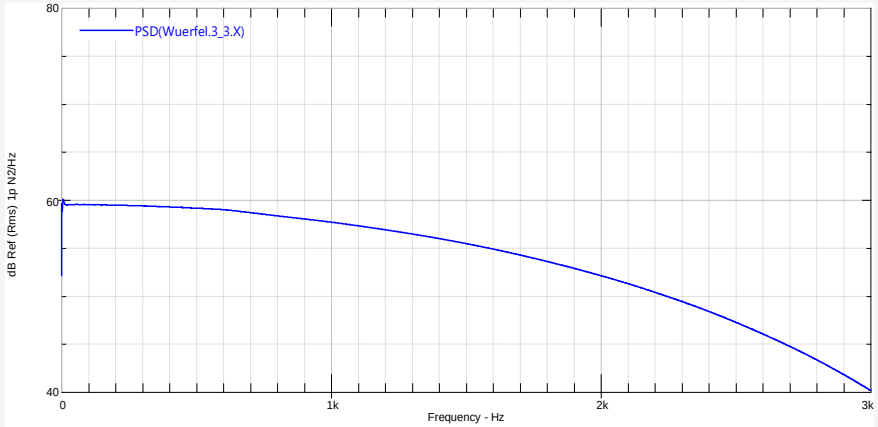
Excitation: Force impulse in time domain



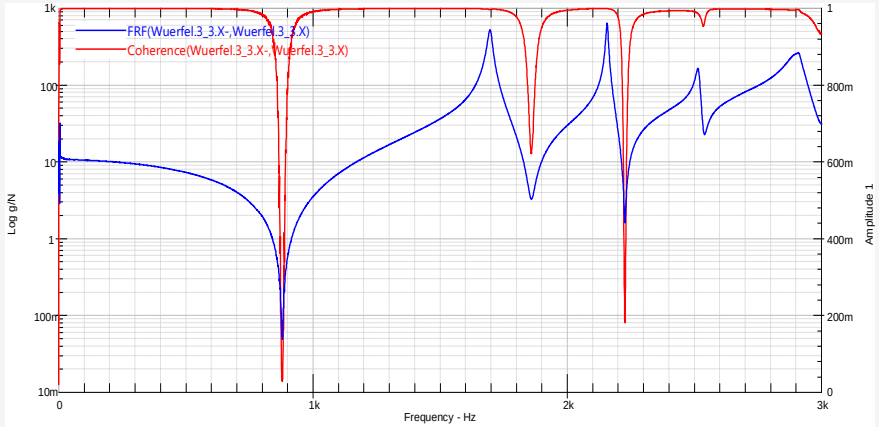
Response: Accel. in time domain



Excitation: Force impulse in frequency domain



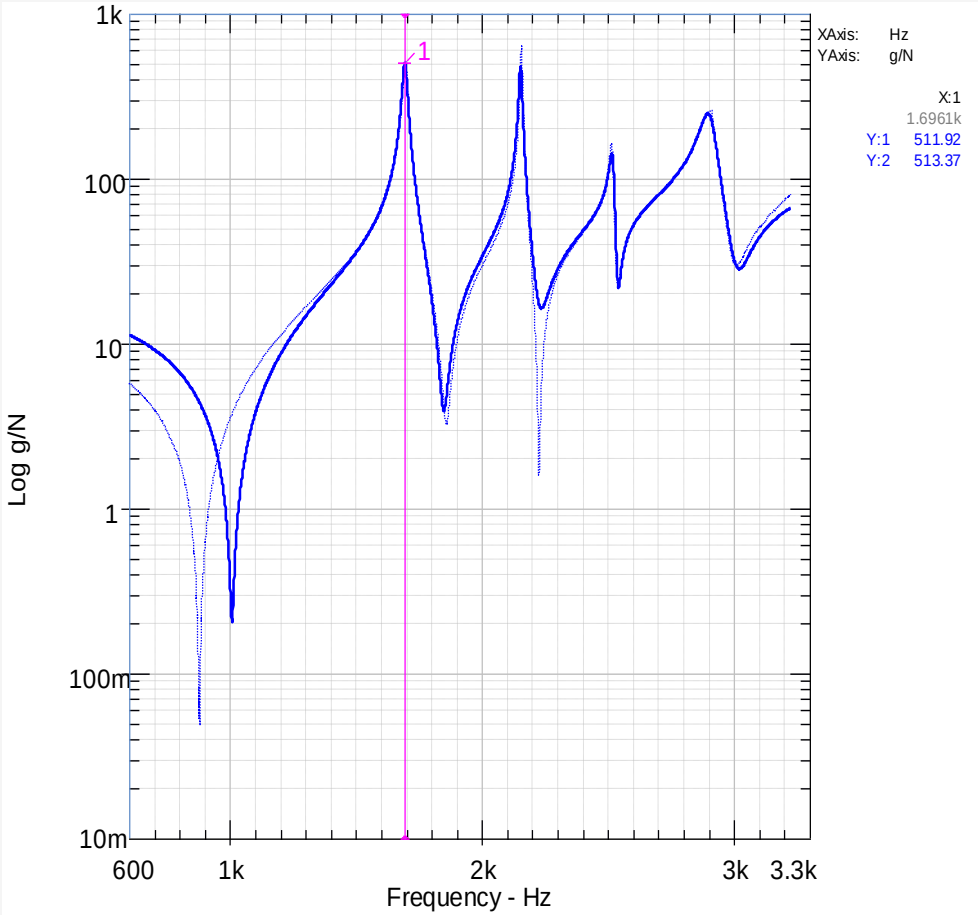
FRF and coherence function

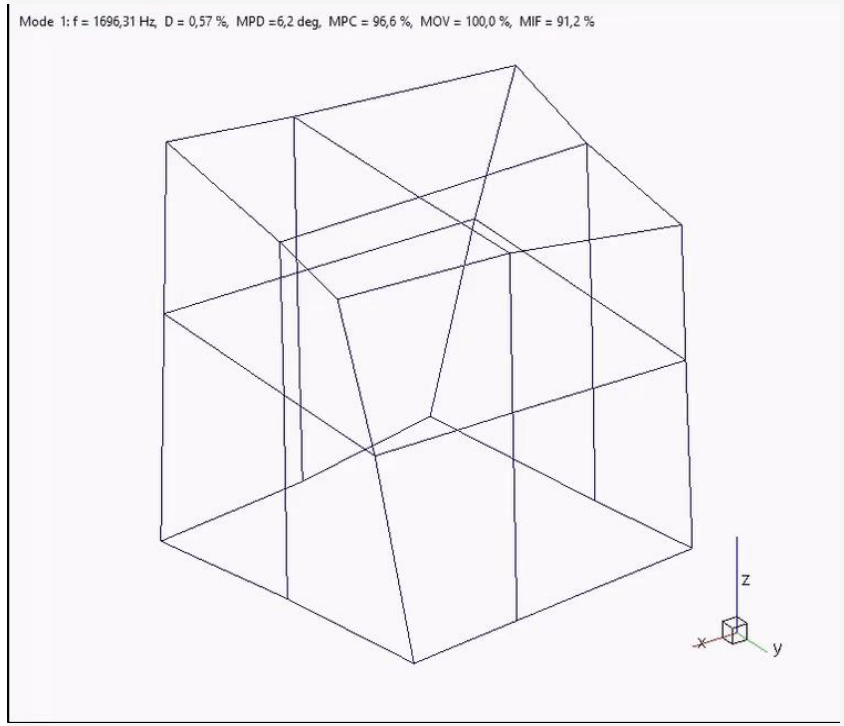


Test results
- Test variant 1 (elast. suspension), Impact in +X

1. Mode: Torsional mode (compare excitation in Y, Z)

Frequency: 1696,3 Hz, Damping: 0,57%; Mode Indicator Function (MIF): ***91,2%***

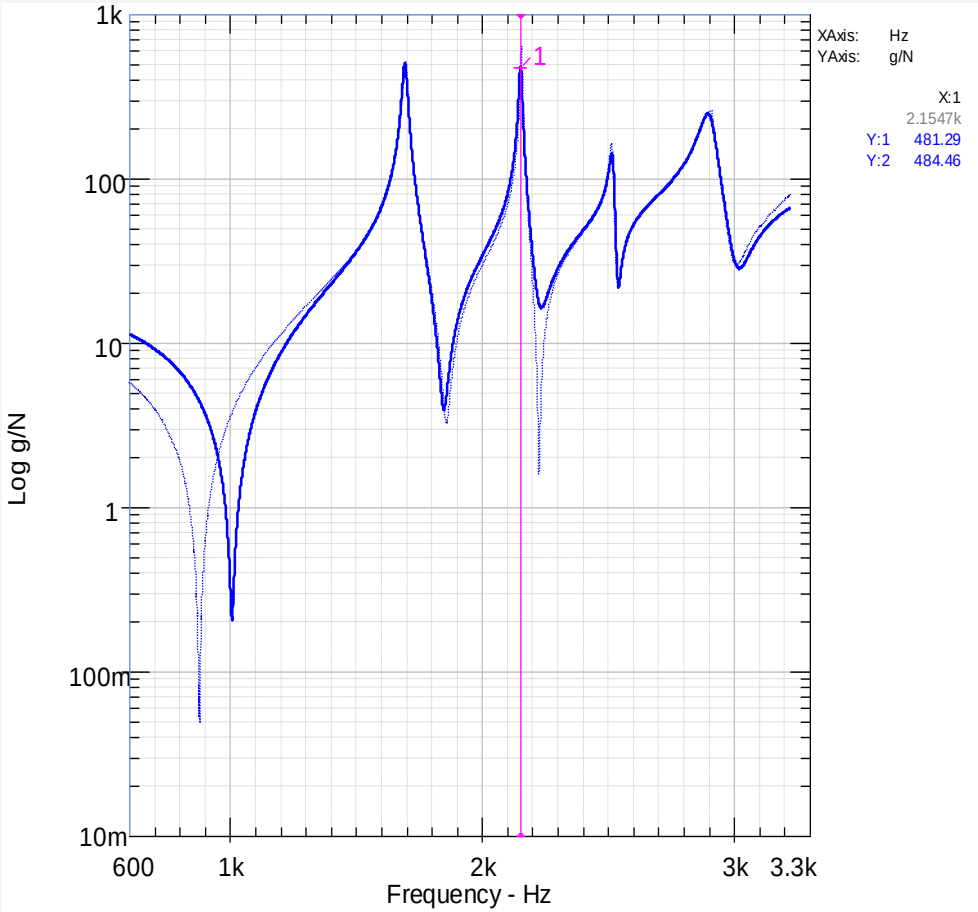


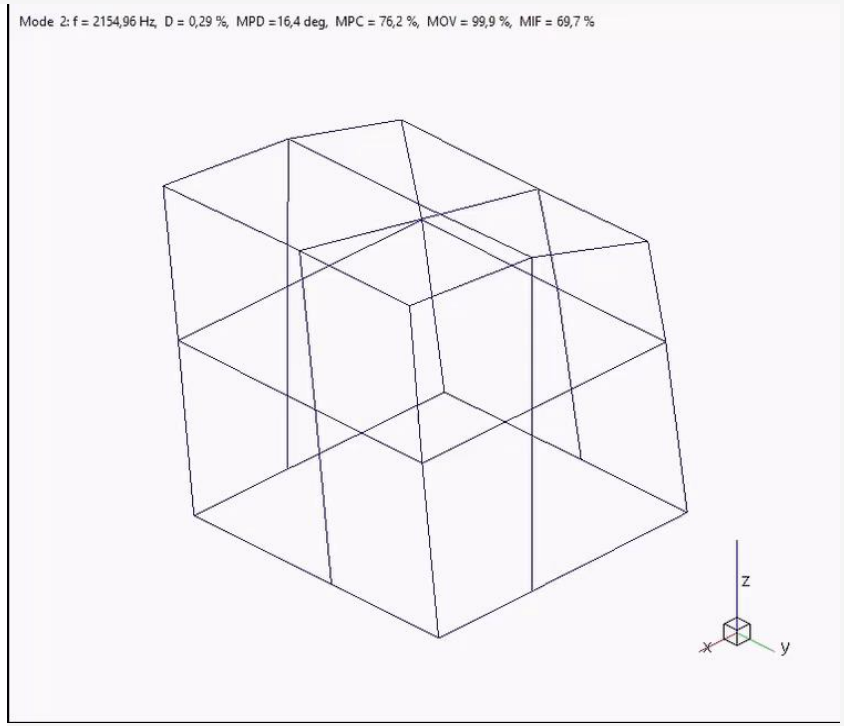


Test results
- Test variant 1 (elast. suspension), Impact in +X

2. Mode: Shear mode (compare excitation in Z)

*Frequency: 2155 Hz, Damping: 0,29%; Mode Indicator Function (MIF): **70%***

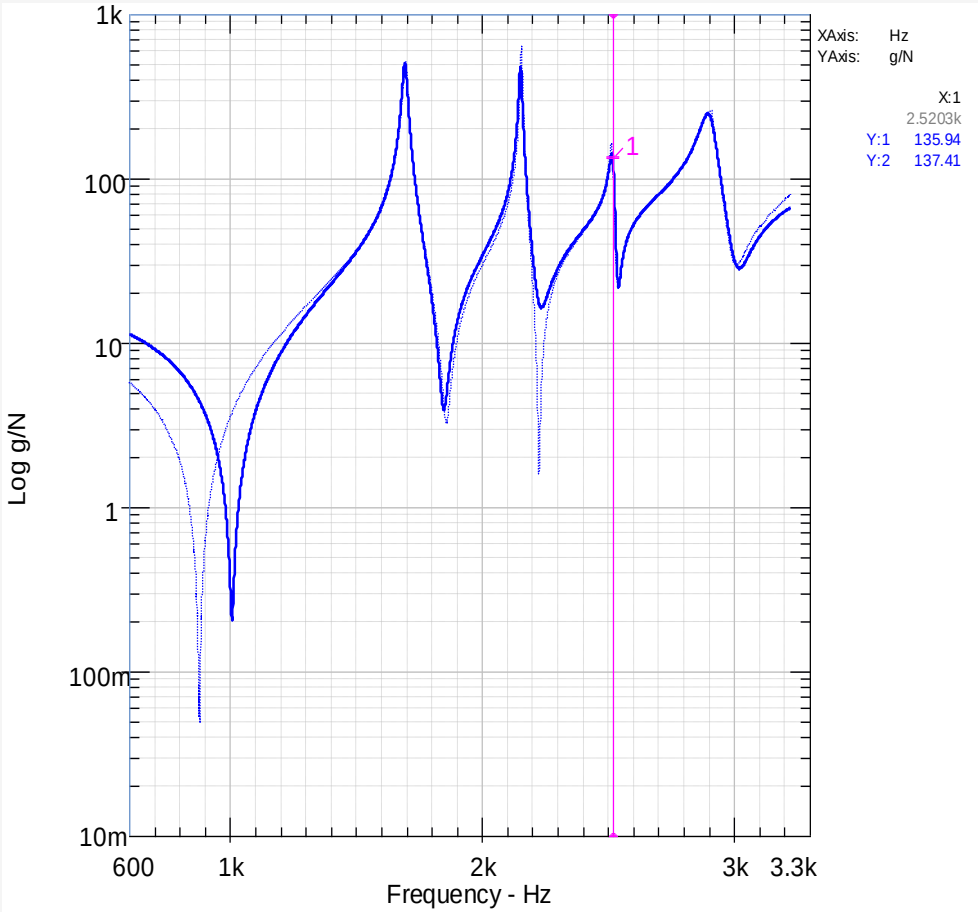


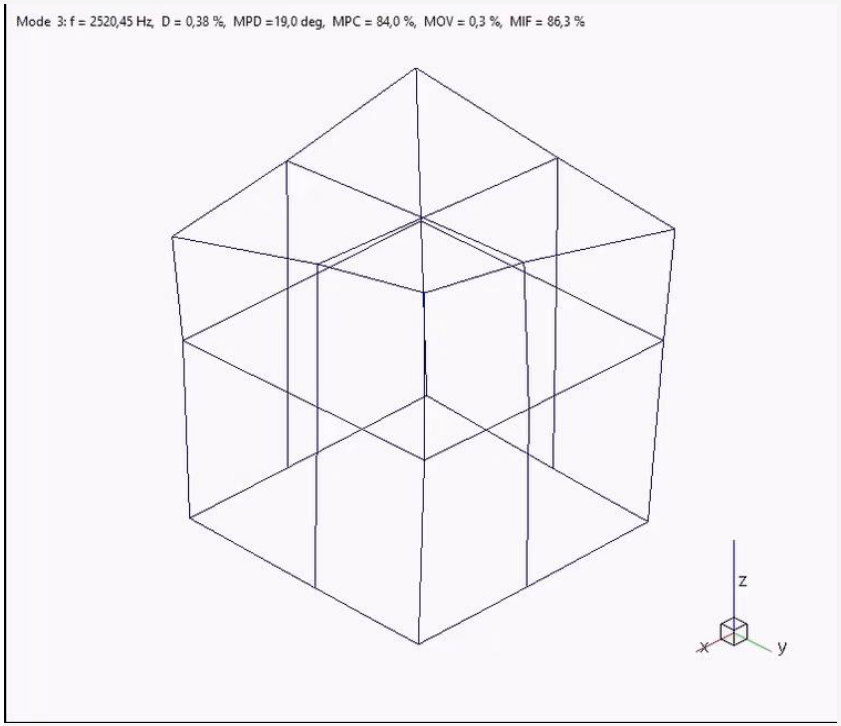


Test results
- Test variant 1 (elast. suspension), Impact in +X

4. Mode (compare excitation in Y,Z)

Frequency: 2520 Hz, Damping: 0,38%; Mode Indicator Function (MIF): ***86,3%***

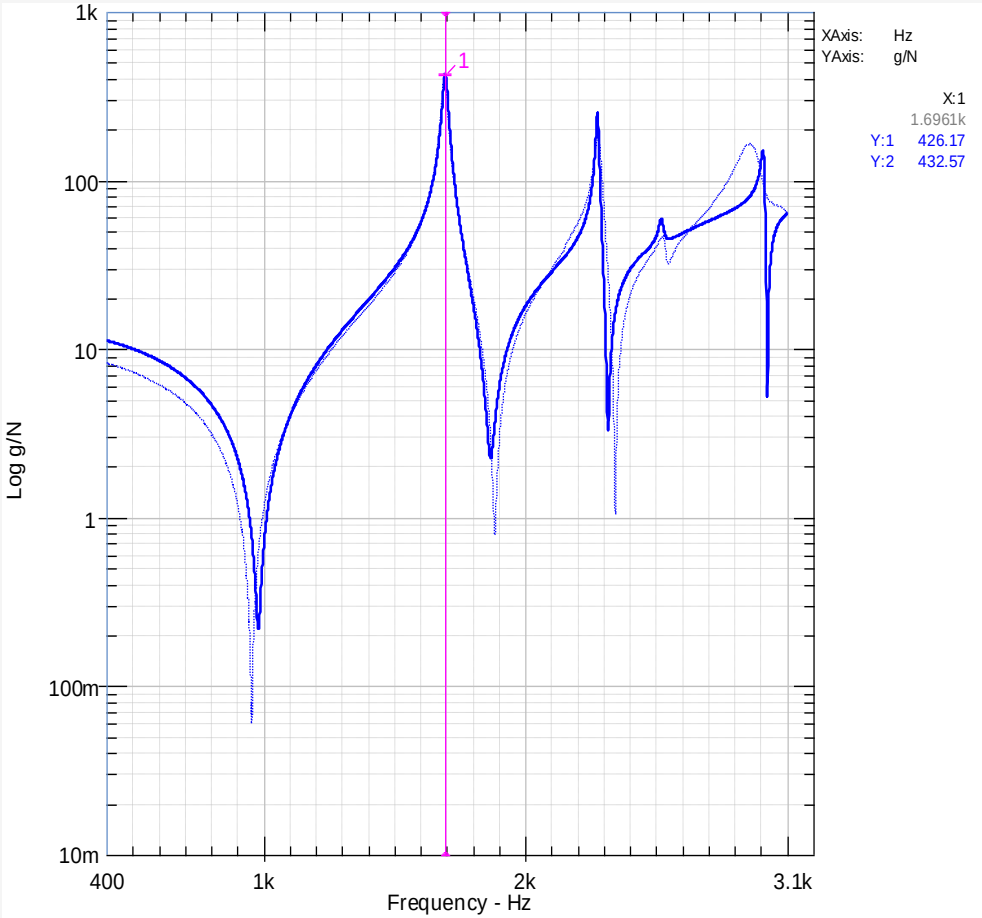


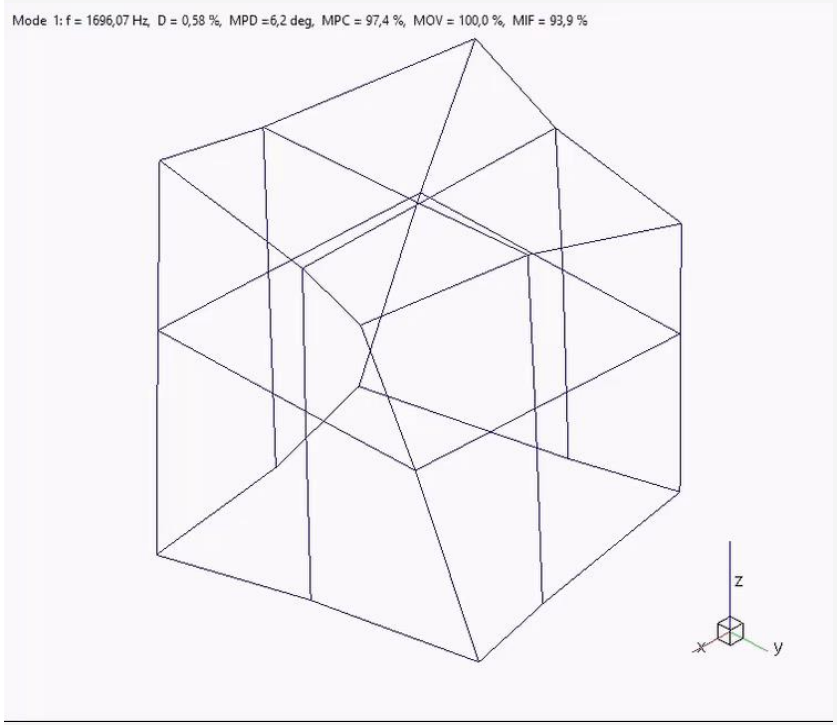


Test results
- Test variant 1 (elast. suspension), Impact in +Y

1. Mode: Torsional mode (compare excitation in X,Z)

Frequency: 1696 Hz, Damping: 0,58%; Mode Indicator Function (MIF): ***93,9%***

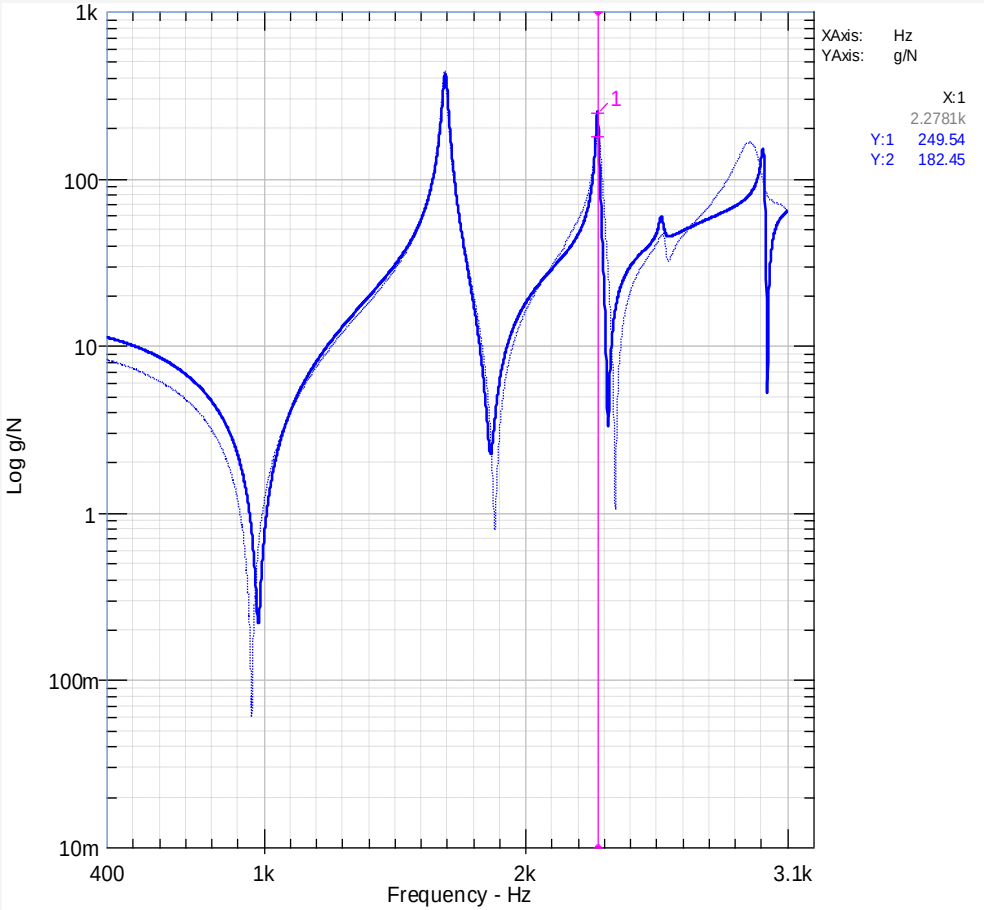


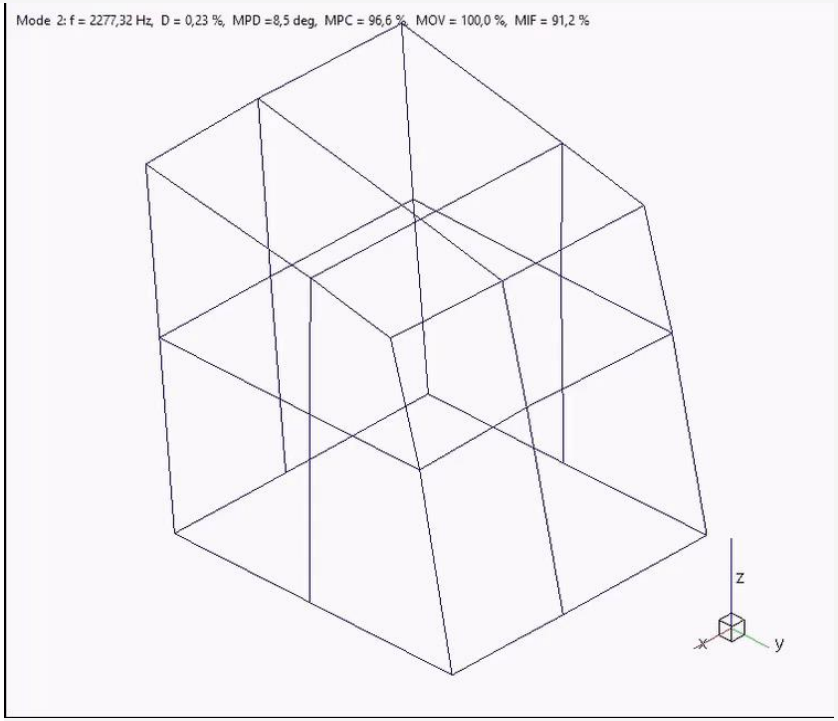


Test results
- Test variant 1 (elast. suspension), Impact in +Y

3. Mode: Shear mode (compare excitation in Z)

Frequency: 2277,3 Hz, Damping: 0,23%; Mode Indicator Function (MIF): ***91,2%***

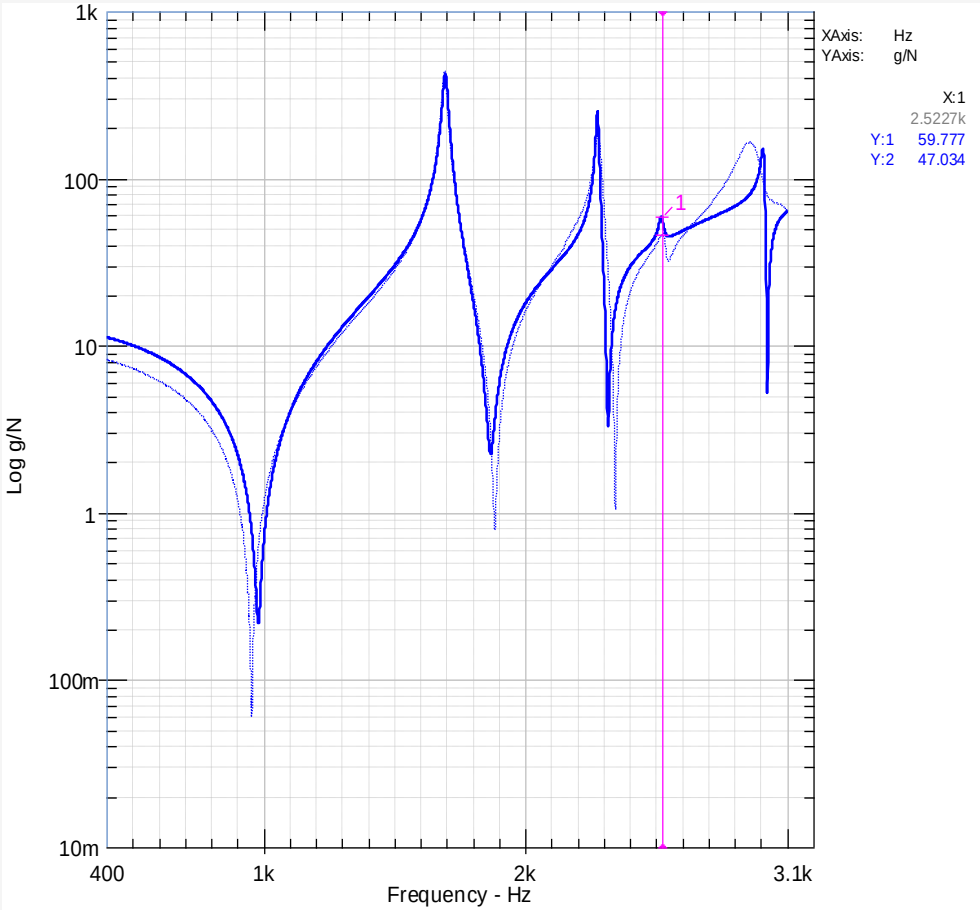


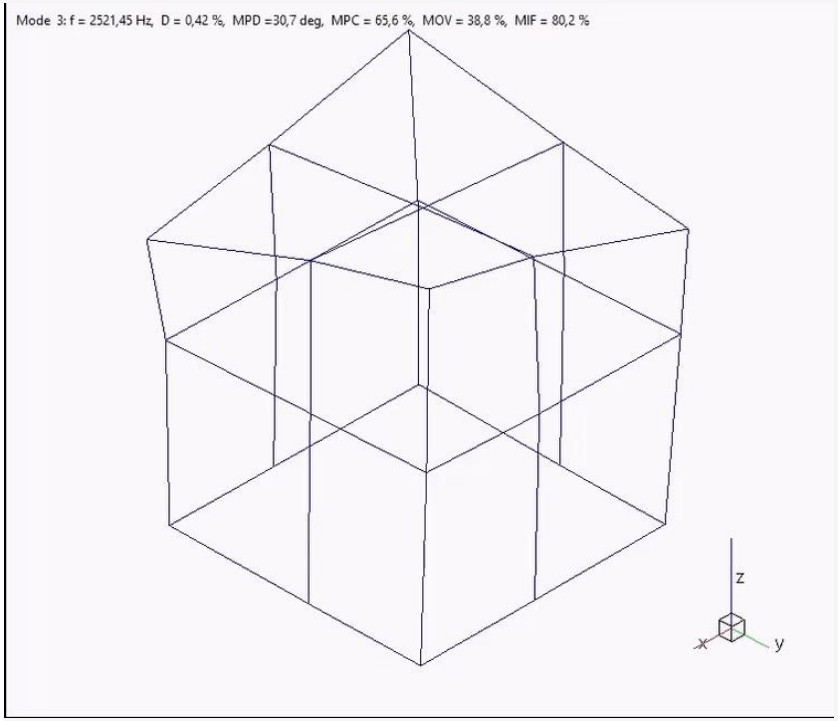


Test results
- Test variant 1 (elast. suspension), Impact in +Y

4. Mode (compare excitation in X,Z)

Frequency: 2521,5 Hz, Damping: 0,42%; Mode Indicator Function (MIF): ***80,2%***

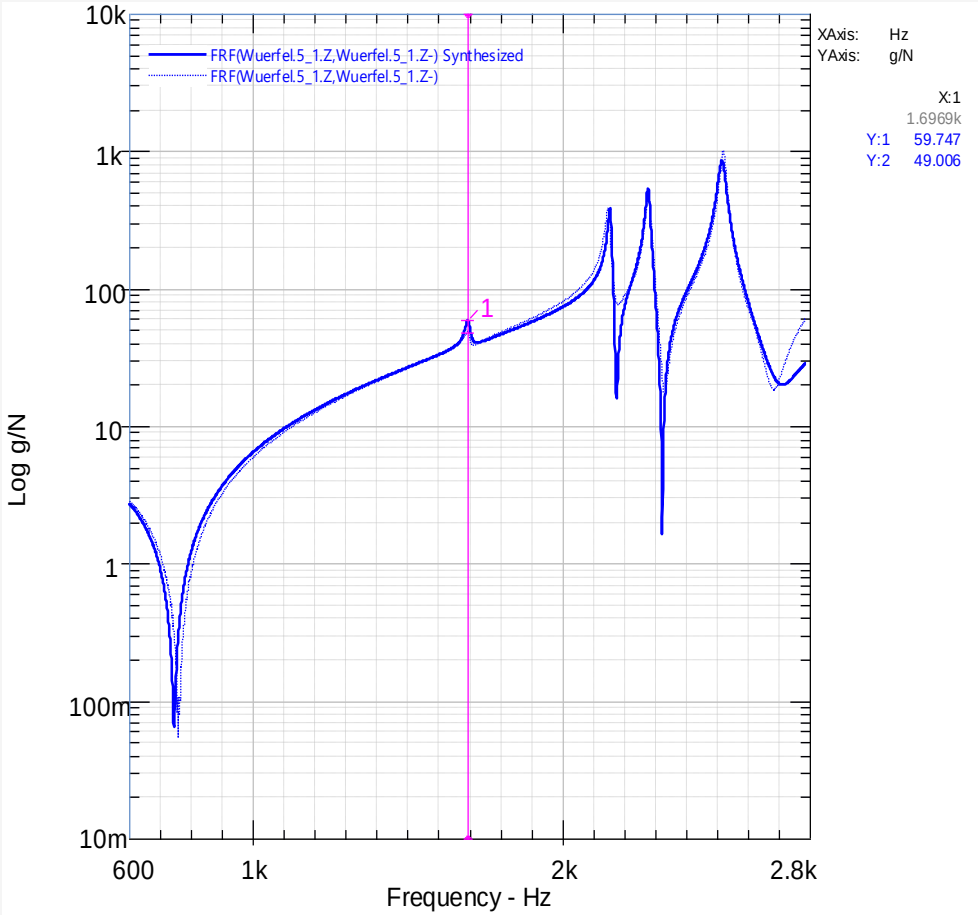


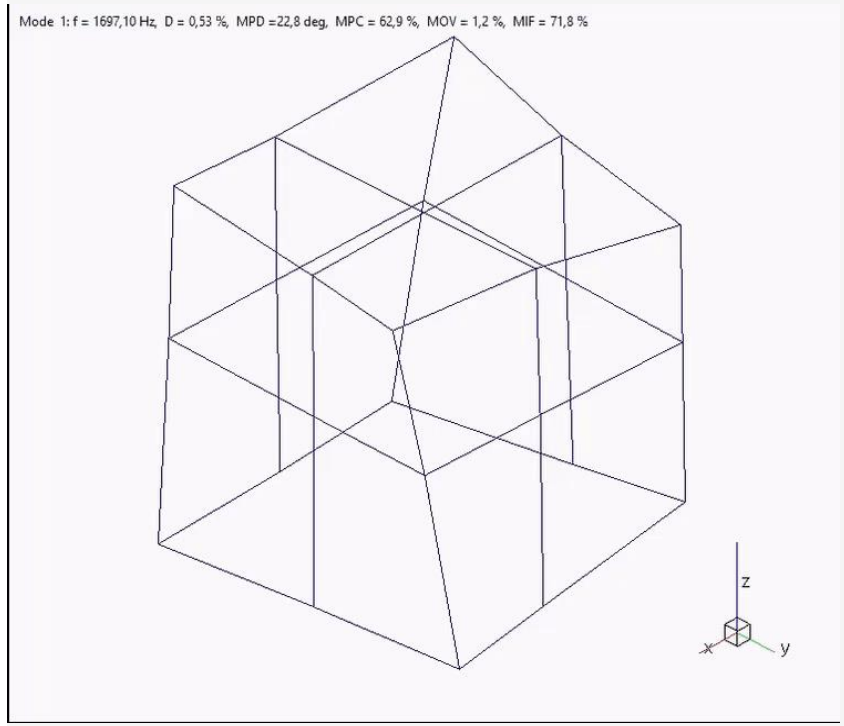


Test results
- Test variant 1 (elast. suspension), Impact in -Z

1. Mode: Torsional mode (compare excitation in X,Y)

*Frequency: 1697,1 Hz, Damping: 0,53%; Mode Indicator Function (MIF): **71,8%***

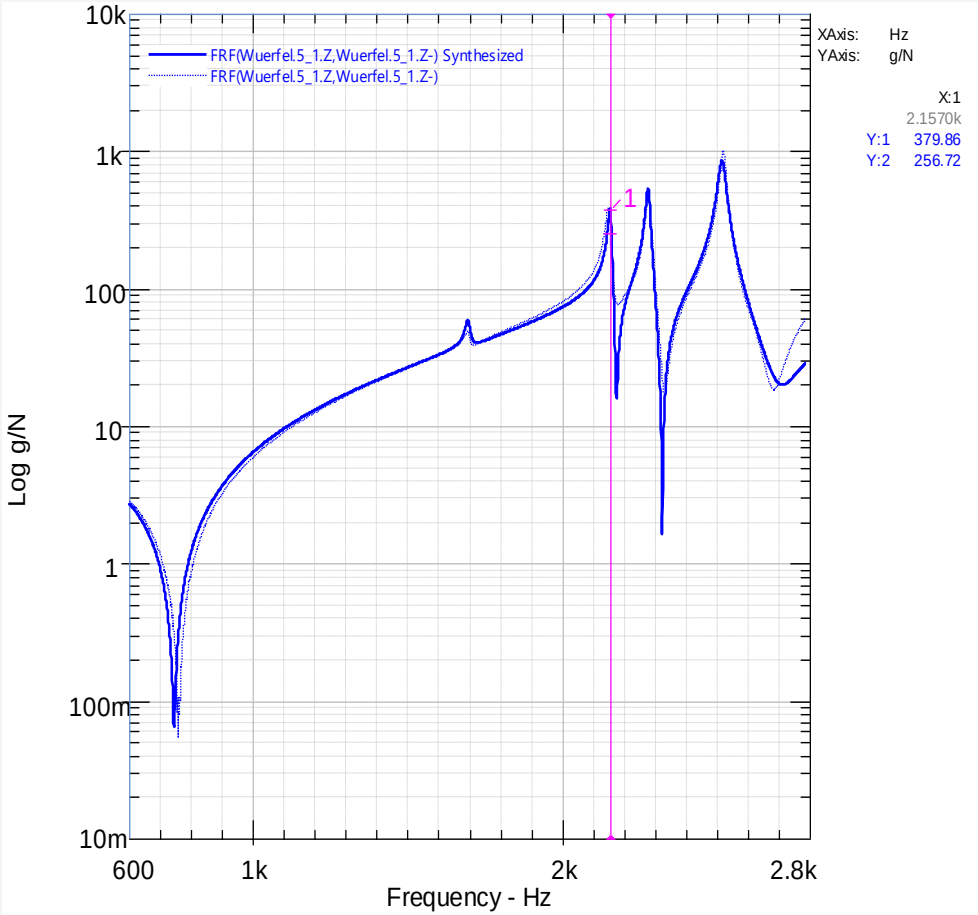


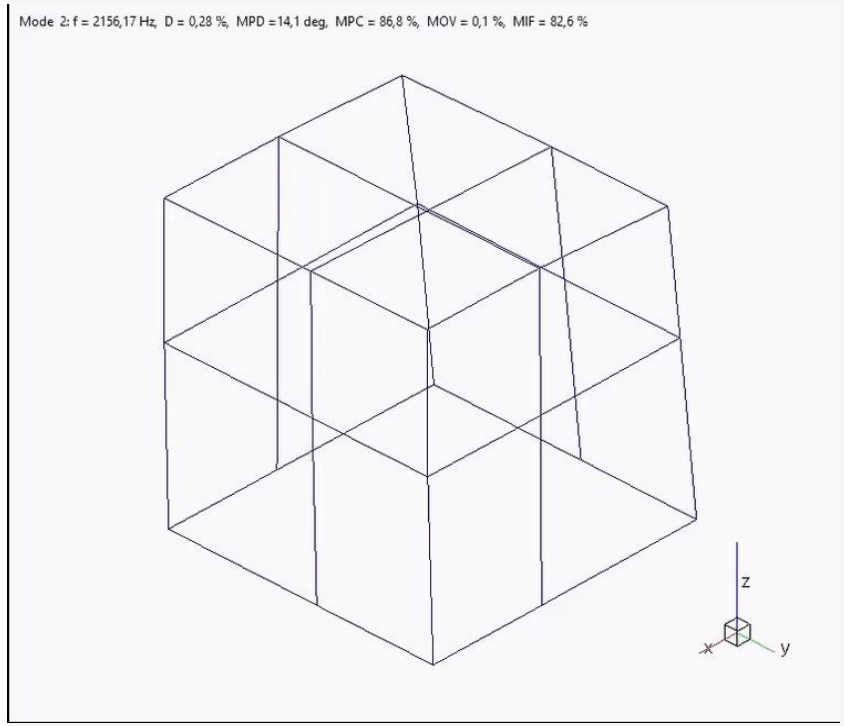


Test results
- Test variant 1 (elast. suspension), Impact in -Z

2. Mode: Shear mode (compare excitation in X,Y)

Frequency: 2156,2 Hz, Damping: 0,28%; Mode Indicator Function (MIF): ***82,6%***

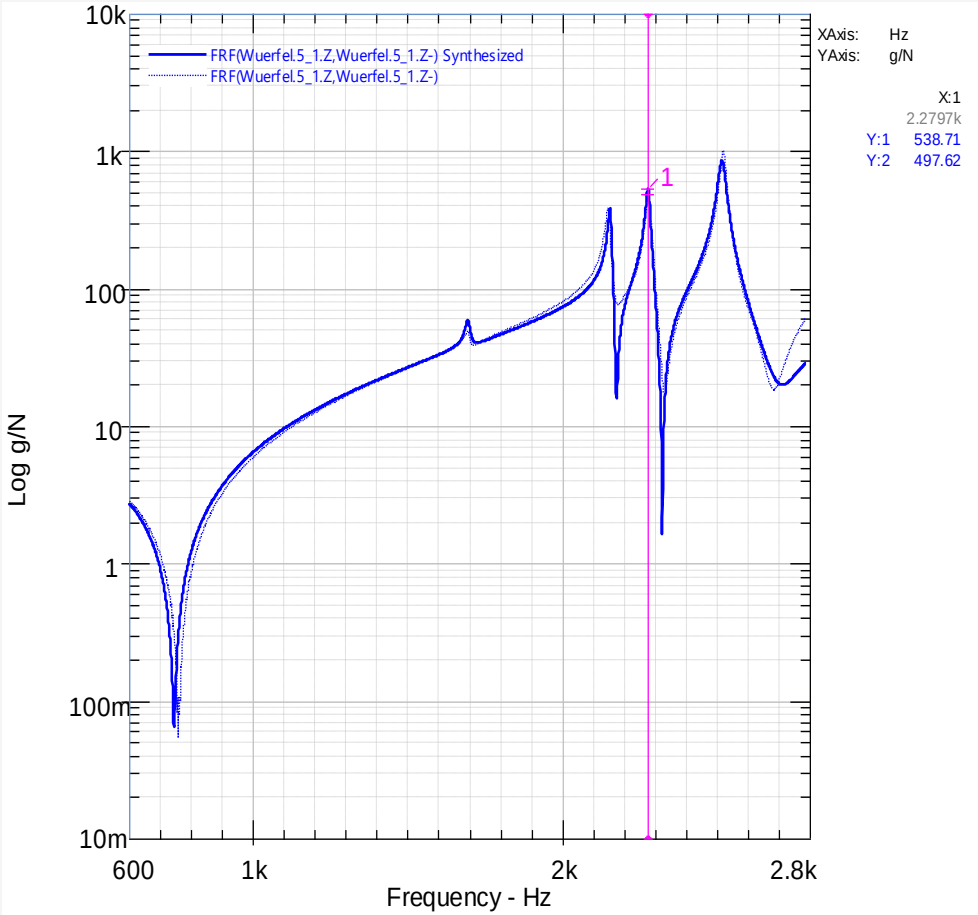


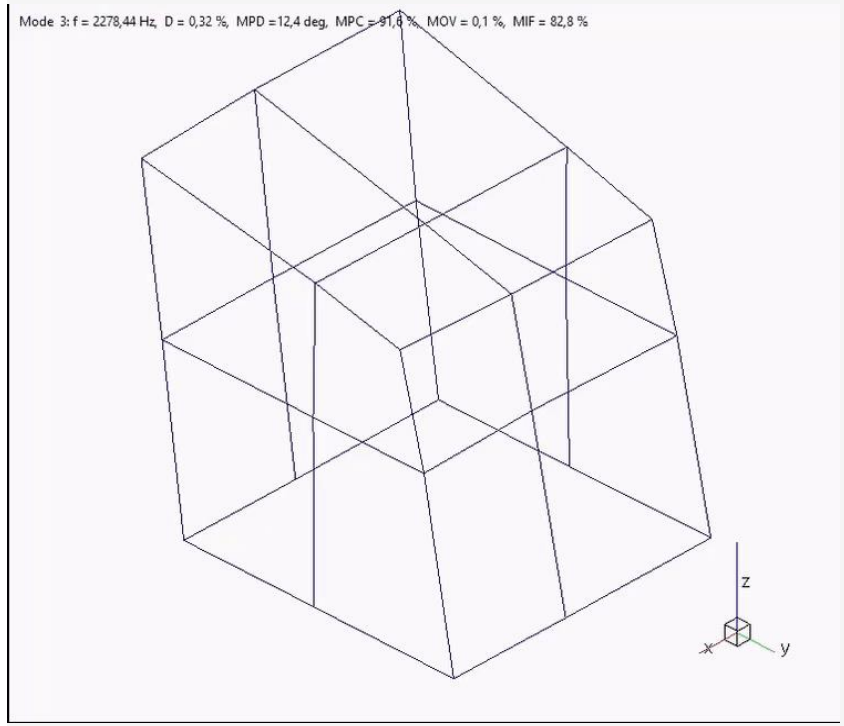


Test results
- Test variant 1 (elast. suspension), Impact in -Z

3. Mode: Shear mode (compare excitation in X,Y)

Frequency: 2278,4 Hz, Damping: 0,32%; Mode Indicator Function (MIF): ***82,8%***





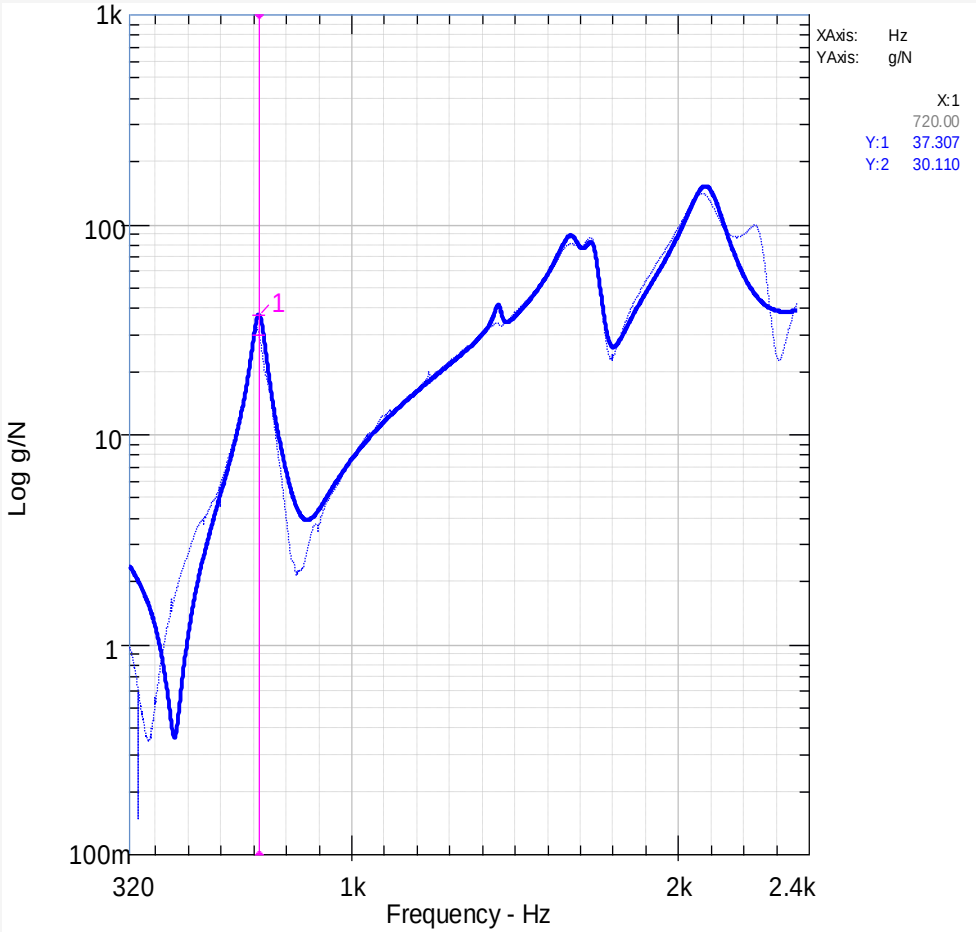
Test results
- Test variant 1 (elast. suspension), Comparision

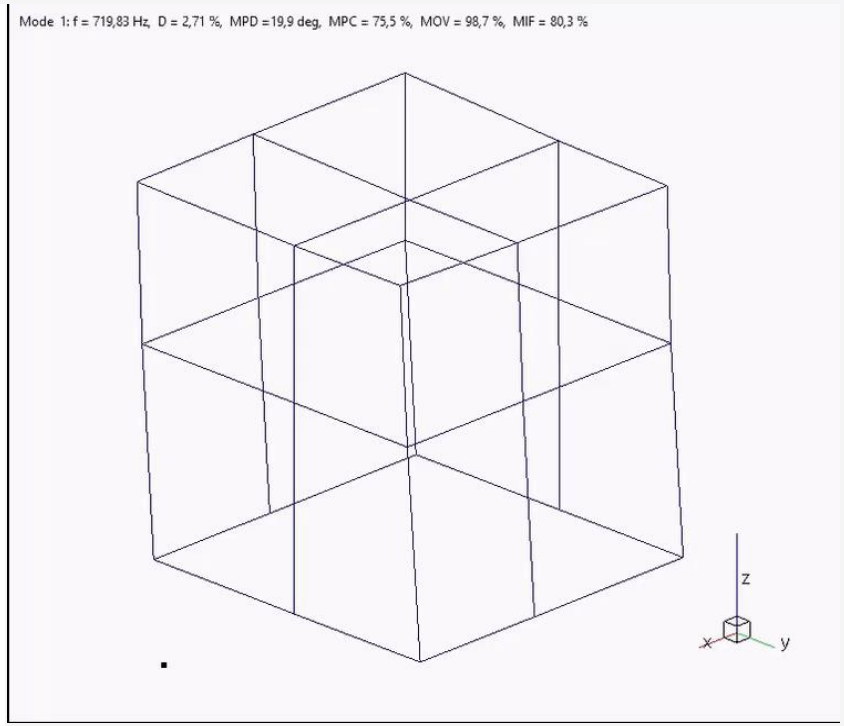
	Excitation +X			Excitation +Y			Excitation -Z		
	Natural freq.	**Damping**	**MFI**	**Natural freq.**	**Damping**	**MFI**	**Natural freq.**	**Damping**	**MFI**
1.Mode	1696,3 Hz	0,57%	**91,2%**	1696 Hz	0,58%	**93,9%**	1697,1 Hz	0,53%	**71,8%**
2.Mode	2155 Hz	0,29%	**70,0%**	---	---	---	2156,2 Hz	0,28%	**82,6%**
3.Mode	---	---	---	2277,3 Hz	0,23%	**91,2%**	2278,4 Hz	0,32%	**82,8%**
4.Mode	2520 Hz	0,38%	**86,3%**	2521,5 Hz	0,42%	**80,2%**	2518,3 Hz	0,47%	**94,3%**
5.Mode	2905 Hz	1,16%	**88,8%**	2912,6 Hz	0,23%	**91,3%**	---	---	---

Test results
- Test variant 2 (shaker armature),Impact in -Z

2. Mode (**not comparable with elastic suspension**):

Frequency: 720 Hz, Damping: 2,71%; Mode Indicator Function (MIF): ***80,3%***

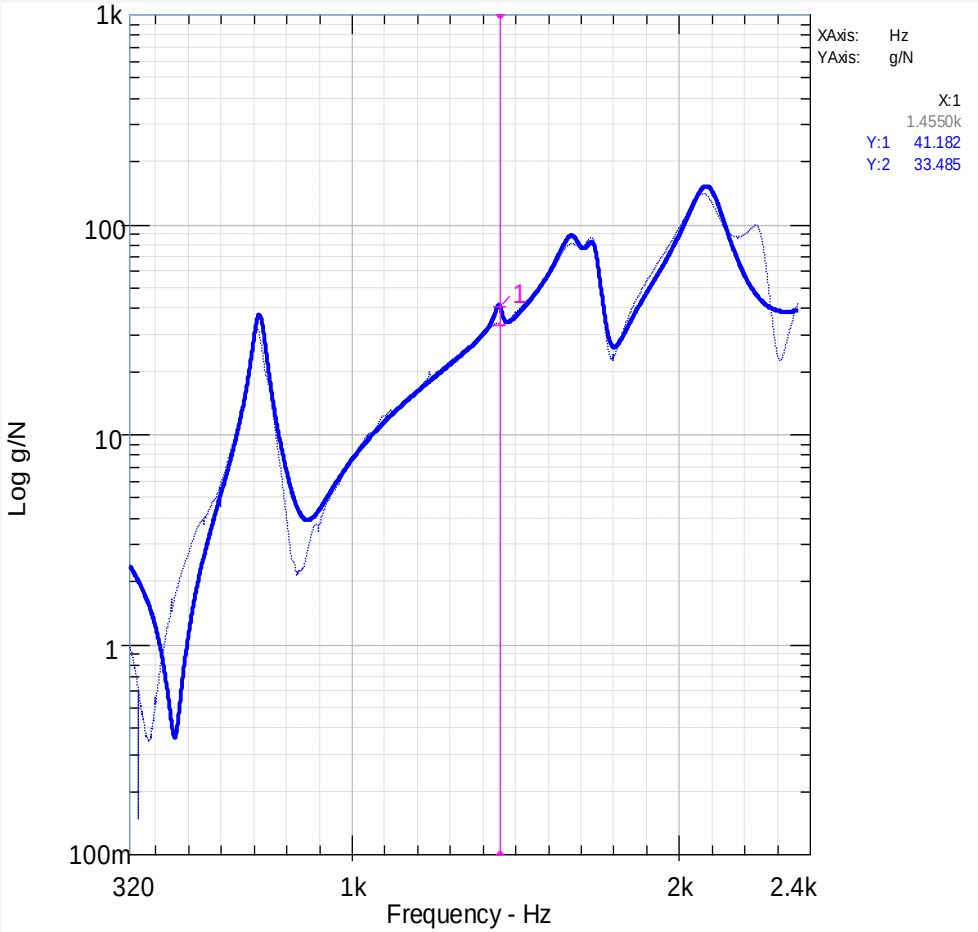


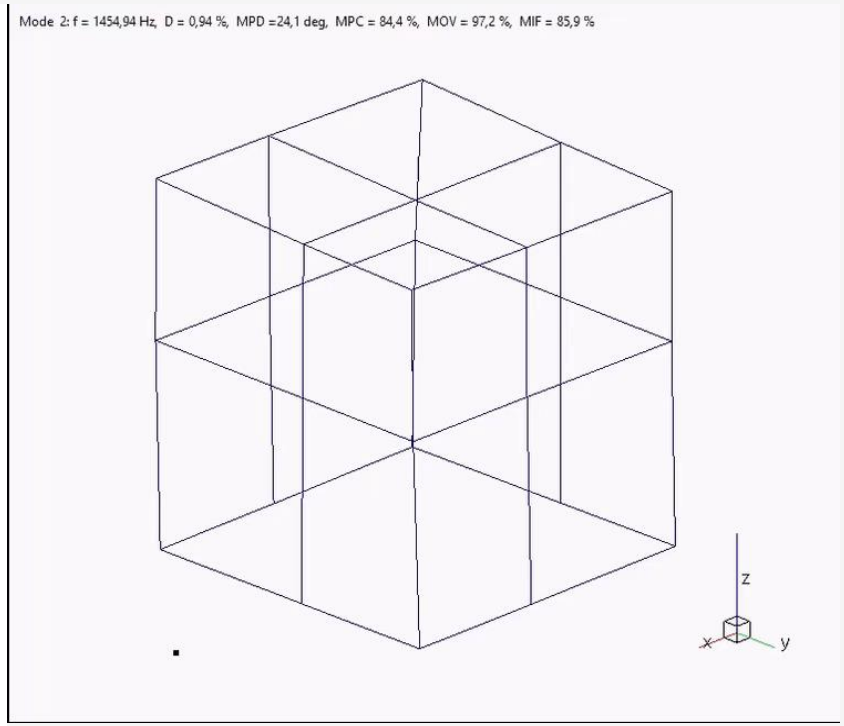


Test results
- Test variant 2 (shaker armature),Impact in -Z

4. Mode: Torsional mode (compare elastic suspension)

Frequency: 1455 Hz, Damping: 0,94%; Mode Indicator Function (MIF): ***85,9%***

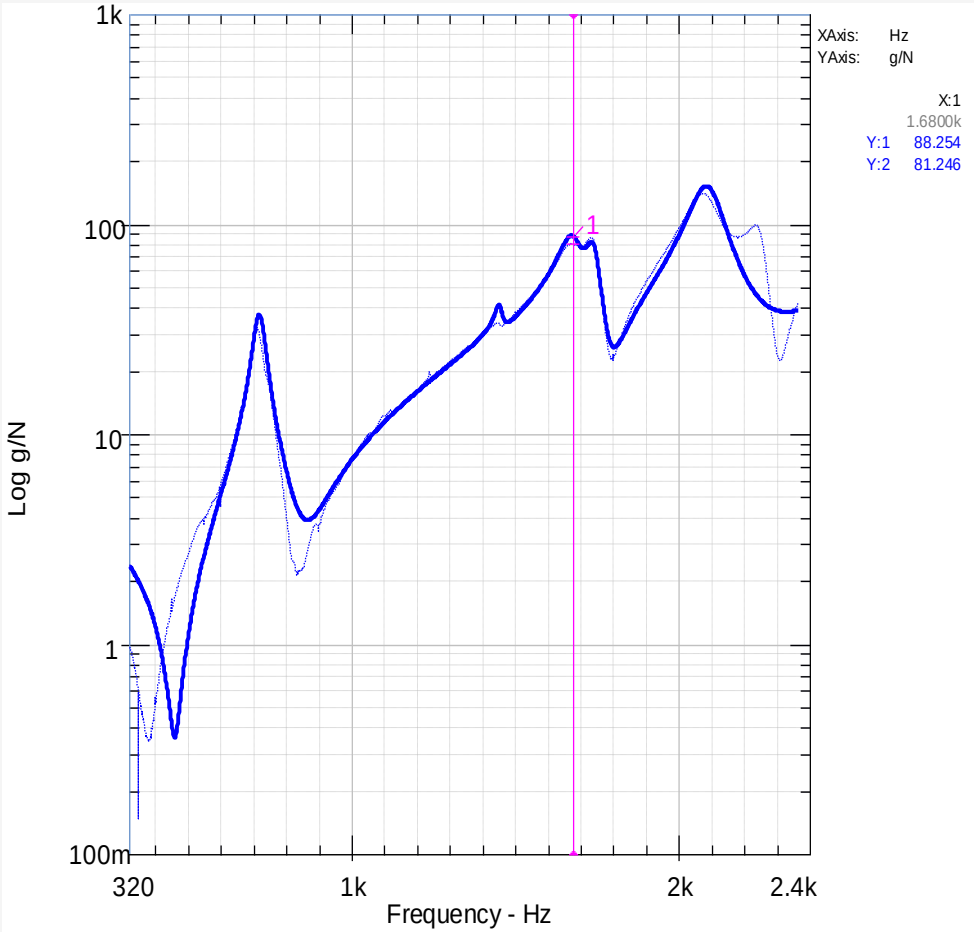


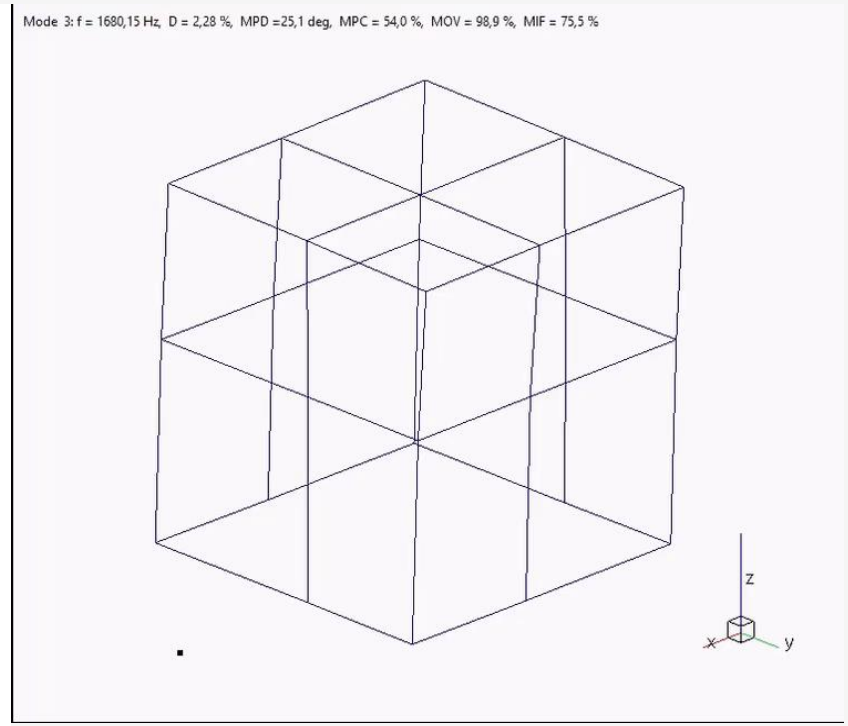


Test results
- Test variant 2 (shaker armature),Impact in -Z

5. Mode:

Frequency: 1680 Hz, Damping: 2,28%; Mode Indicator Function (MIF): ***75,5%***

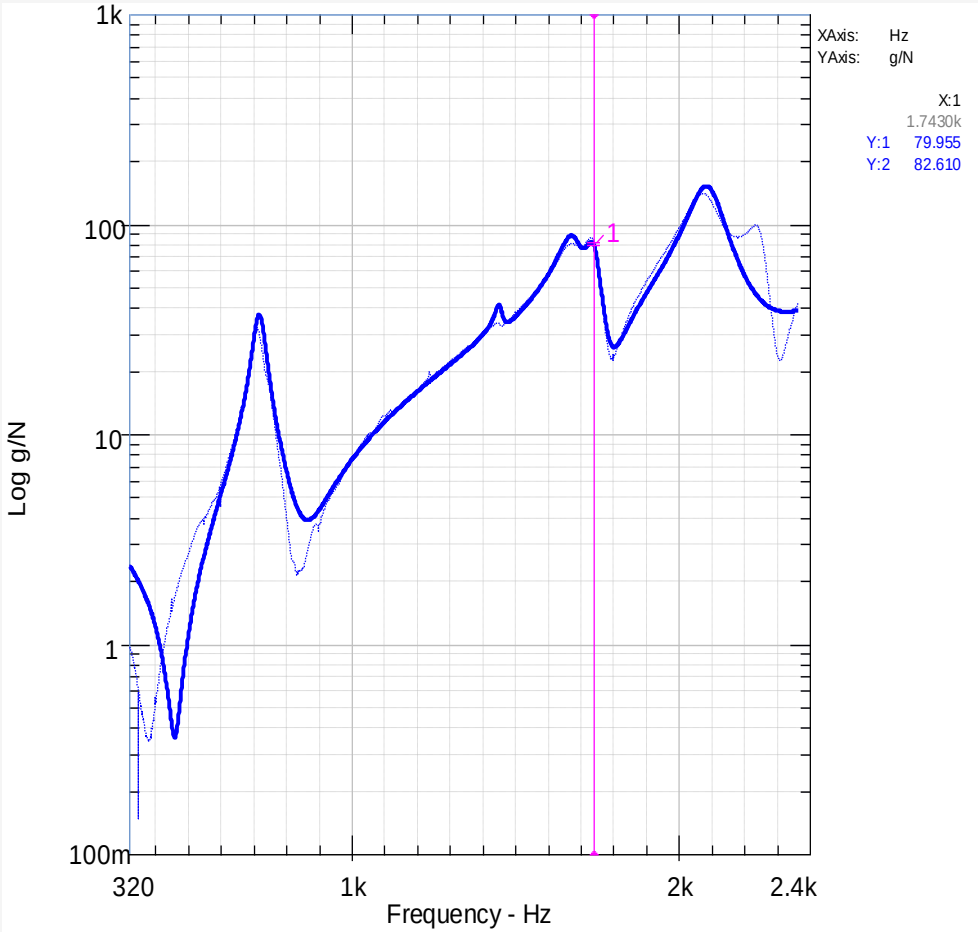


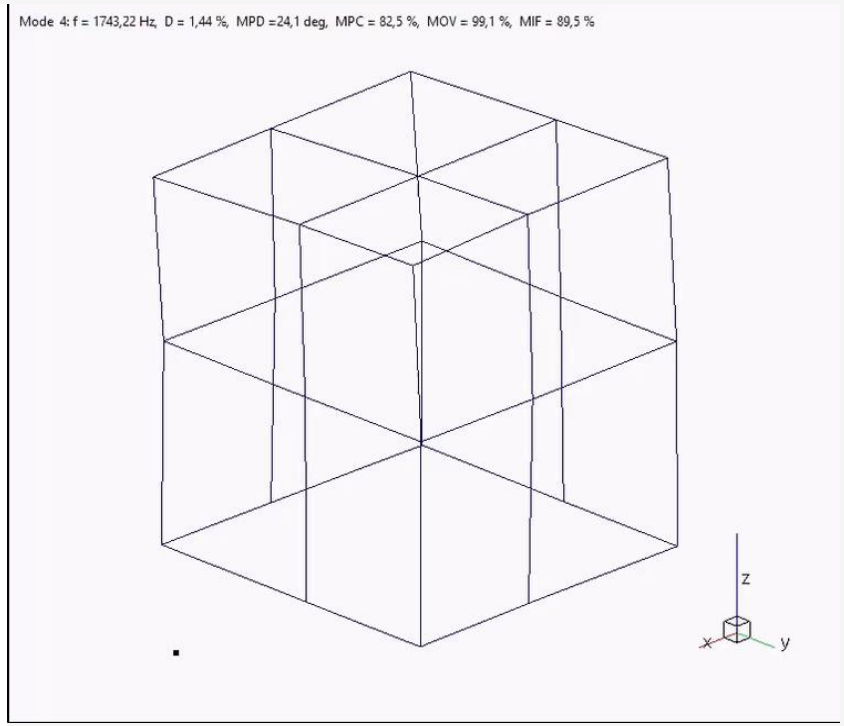


Test results
- Test variant 2 (shaker armature),Impact in -Z

6. Mode:

Frequency: 1745 Hz, Damping: 1,44%; Mode Indicator Function (MIF): ***89,5%***





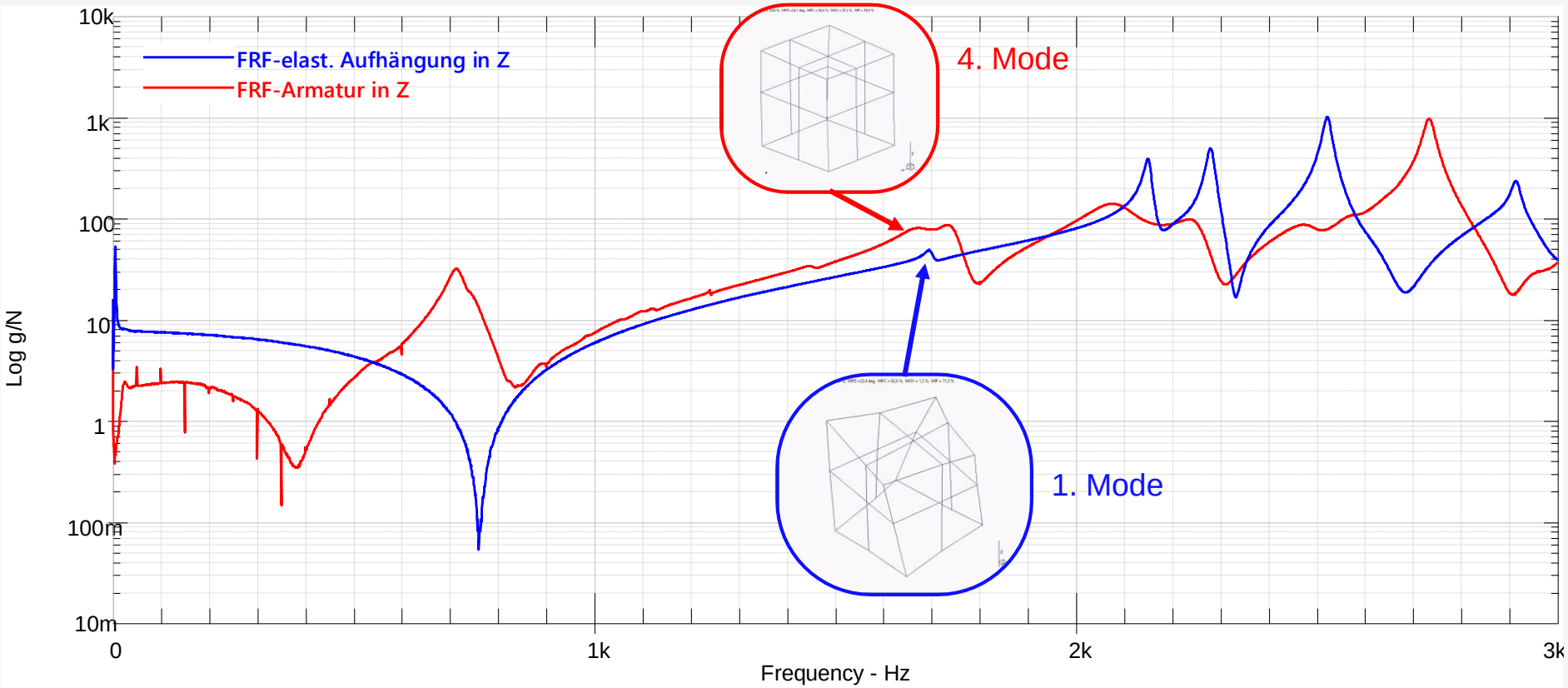
Test results
- FRF Test variant 1 vs. 2, Impact in -Z

Additional mass and coupling create additional constraints

- Increase of oscillating system mass (armature coil)

→ Natural frequencies move downwards

- Additional mode shapes



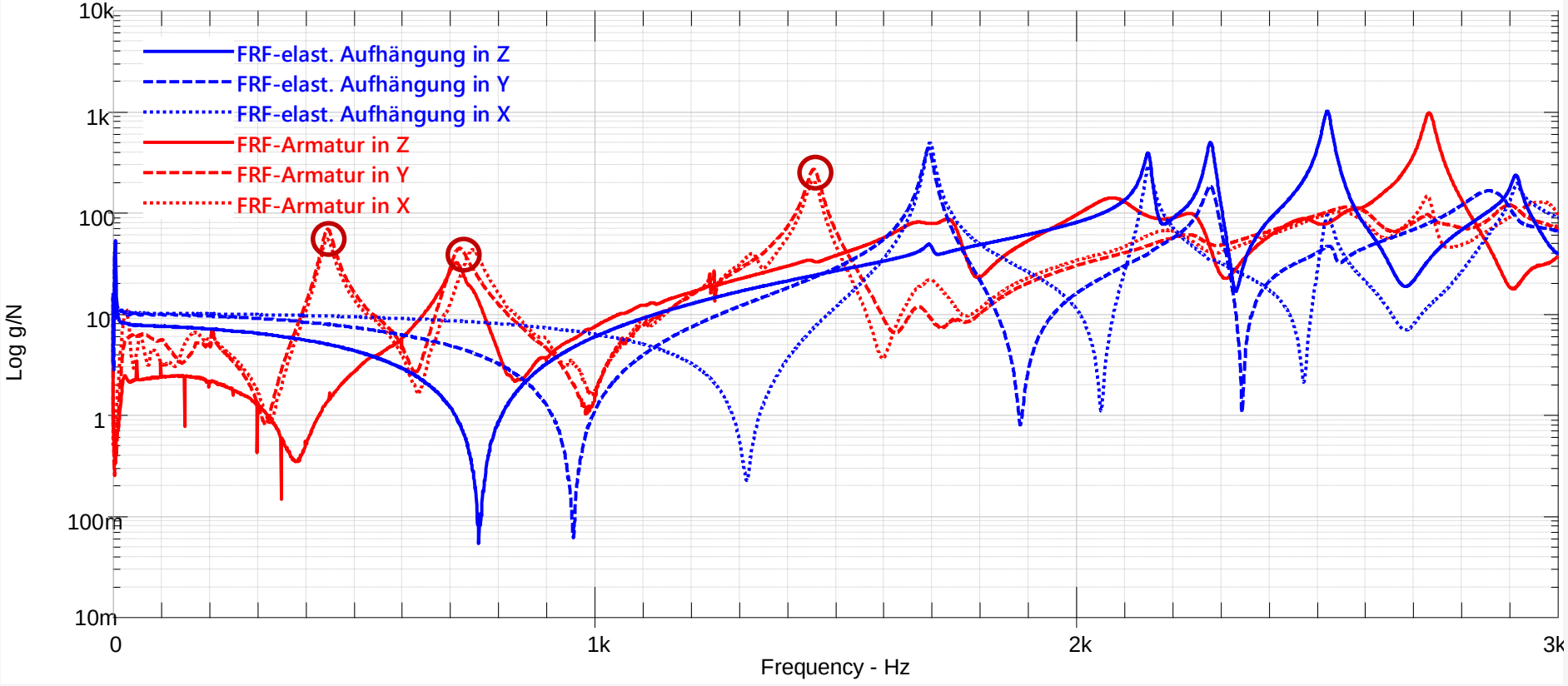
Test results
- FRF Test variant 1 vs. 2

Additional mass and coupling create additional constraints

- Increase of oscillating system mass (armature coil)

→ Natural frequencies move downwards

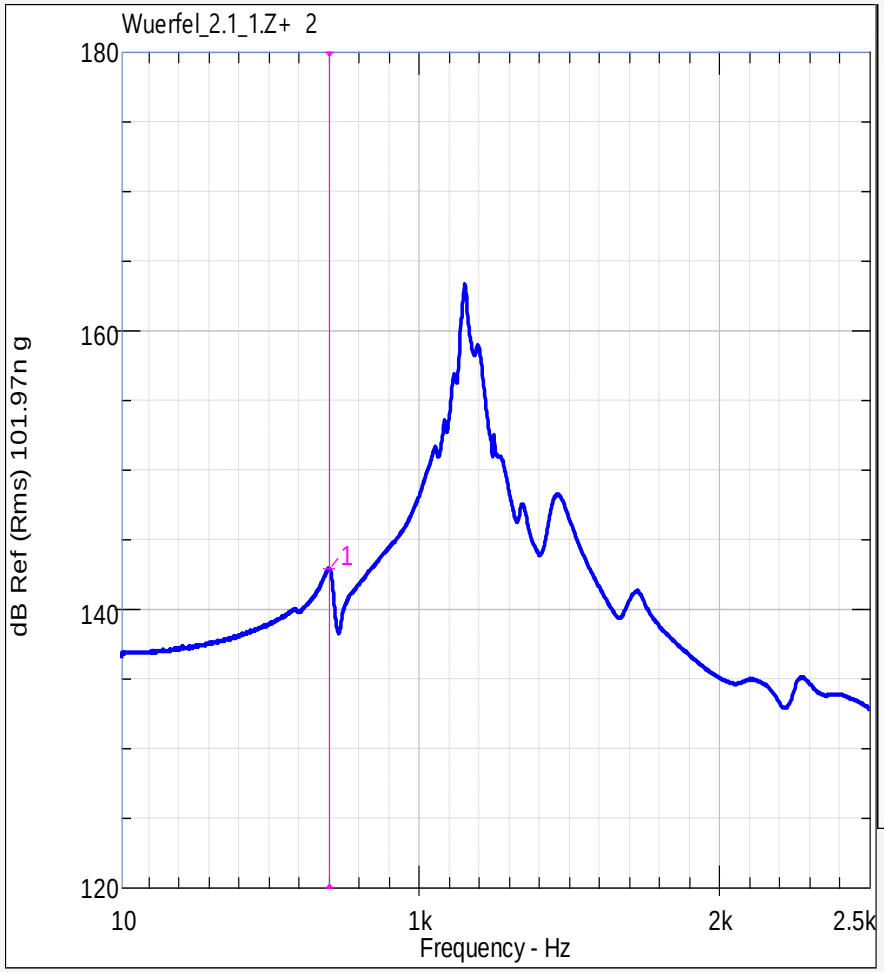
- Additional mode shapes

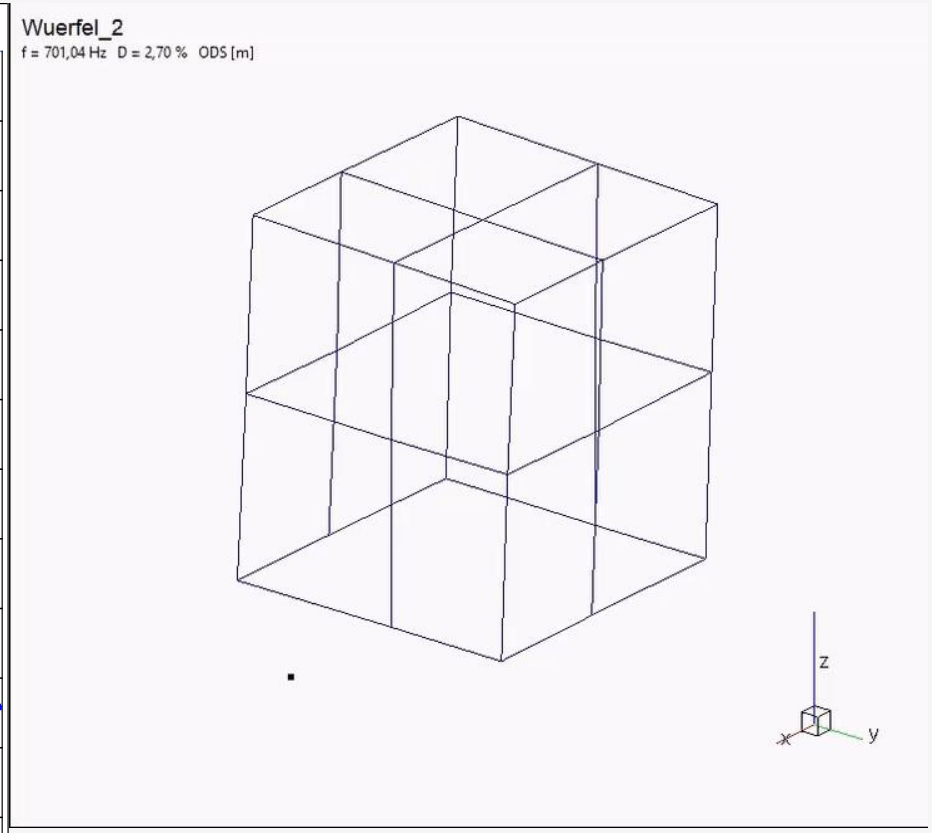


Test results
- Test variant 3 (shaker armature), Sine sweep in +Z

1. Operating deflection shape:

Frequency: 700 Hz, Damping: 2,7%; ODS (Operating Deflecting Shape)

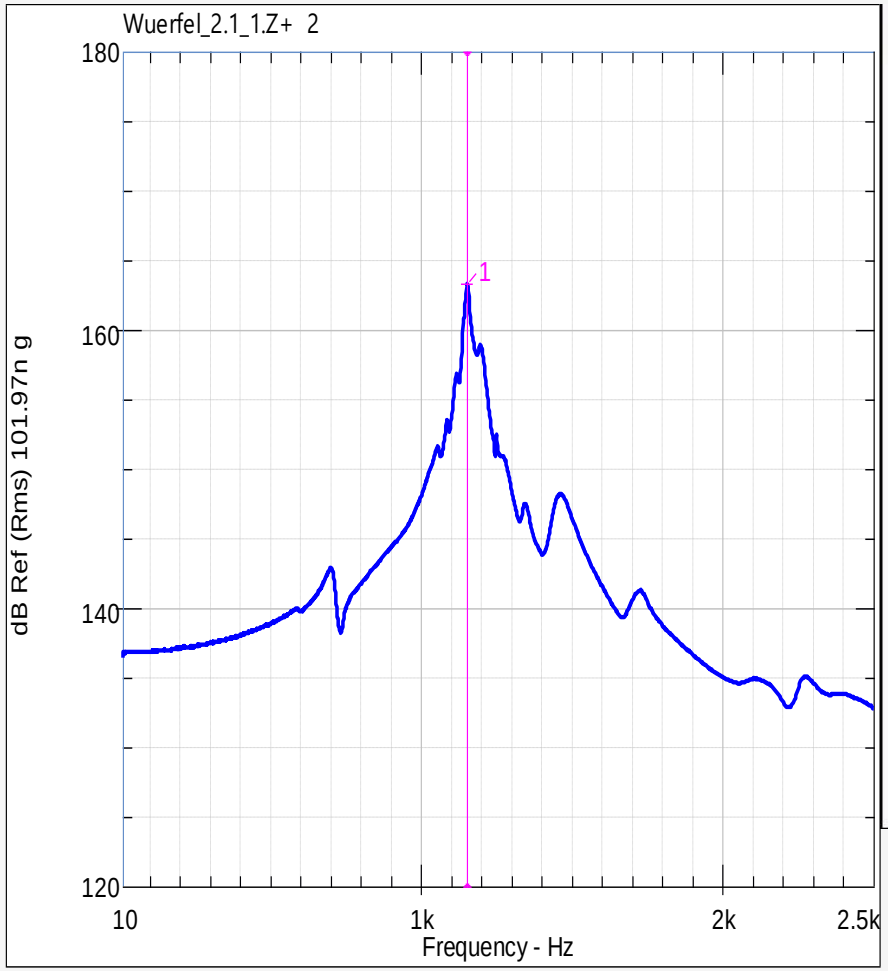


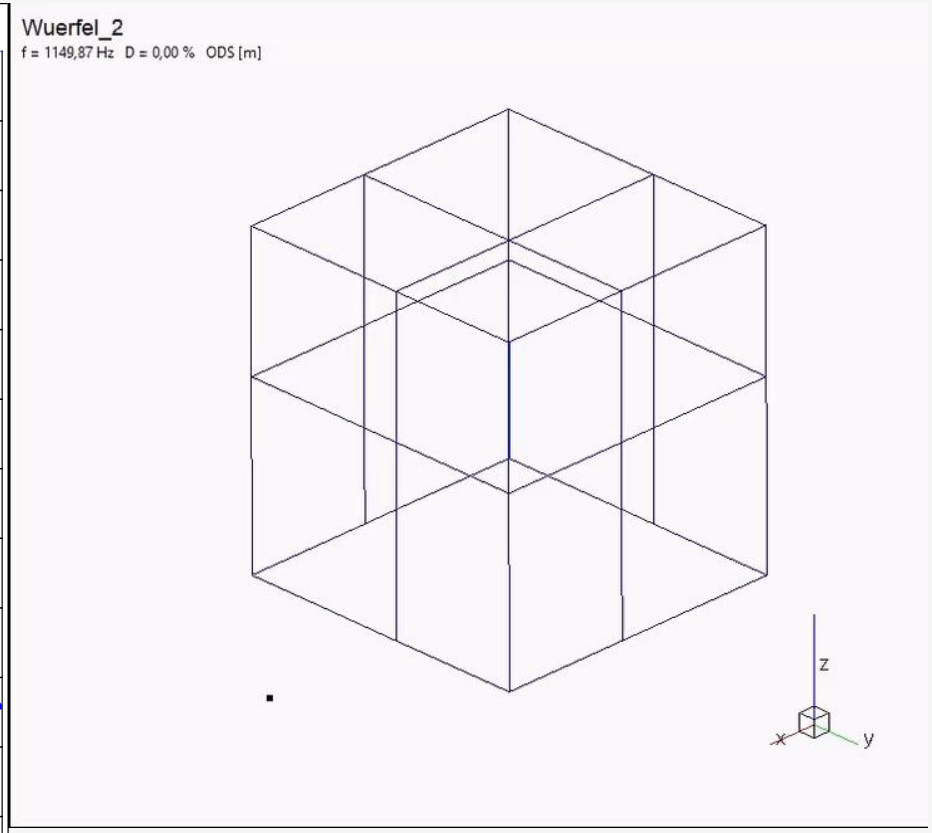


Test results
- Test variant 3 (shaker armature), Sine sweep in +Z

2. Operating deflection shape:

Frequency: 1150 Hz, Damping: 1,2%; ODS (Operating Deflecting Shape)

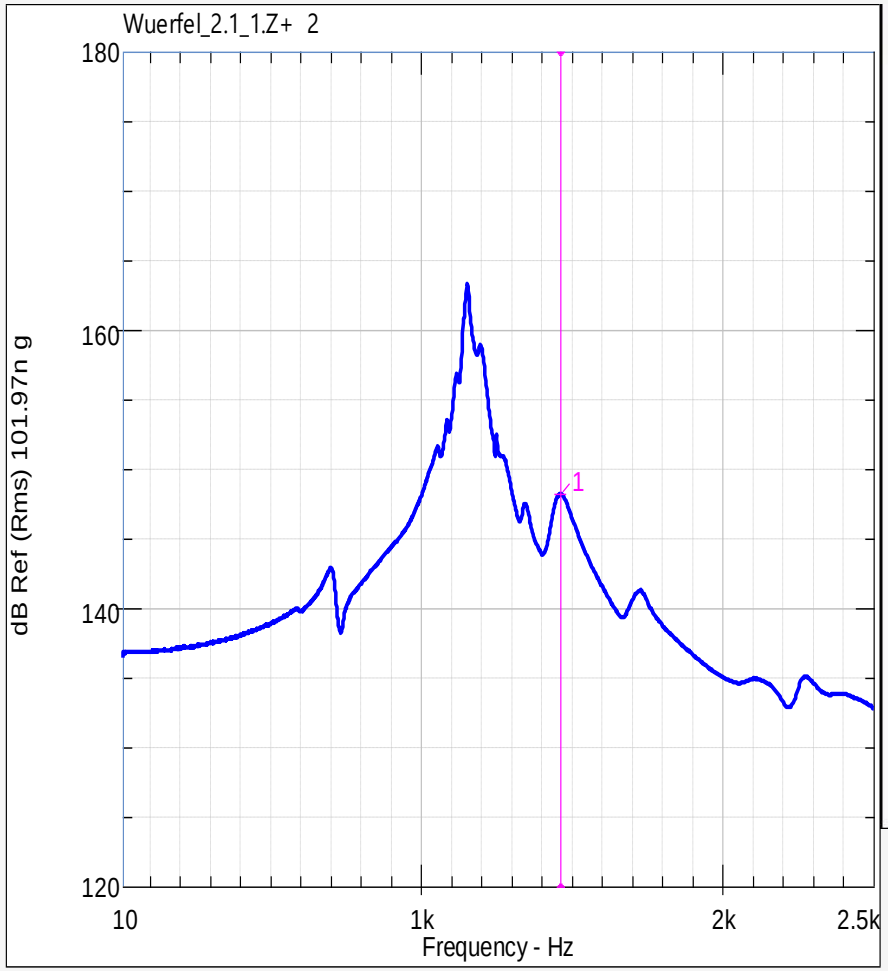


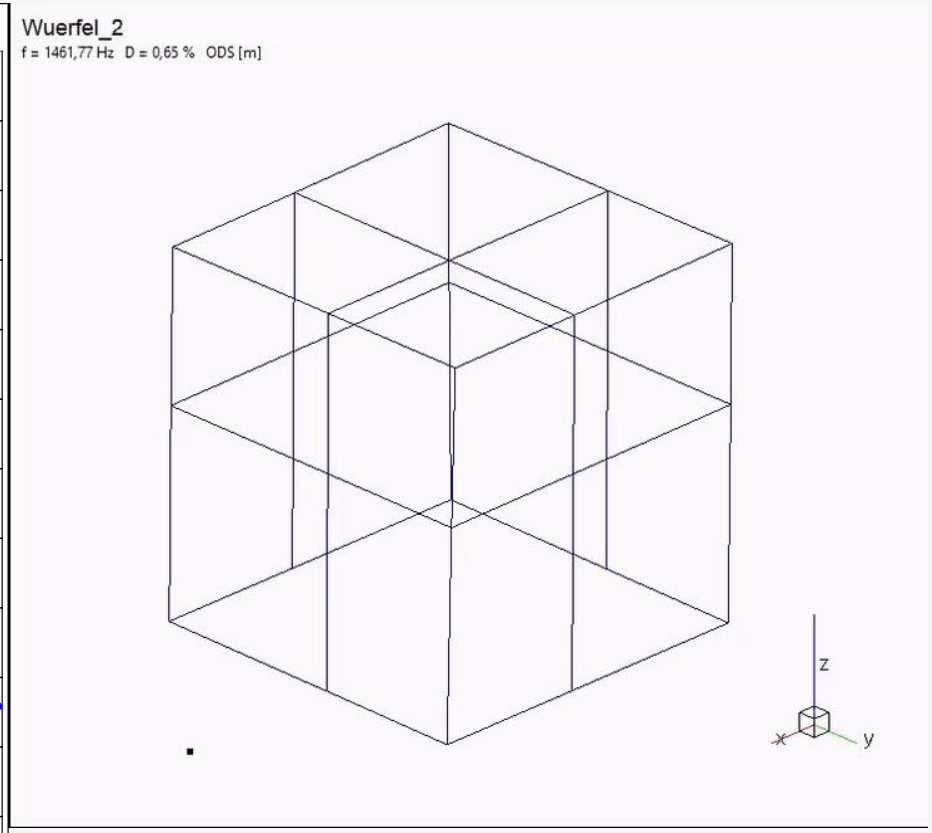


Test results
- Test variant 3 (shaker armature), Sine sweep in +Z

3. Operating deflection shape:

Frequency: 1460 Hz, Damping: 0,65%; ODS (Operating Deflecting Shape)

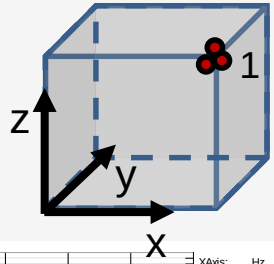


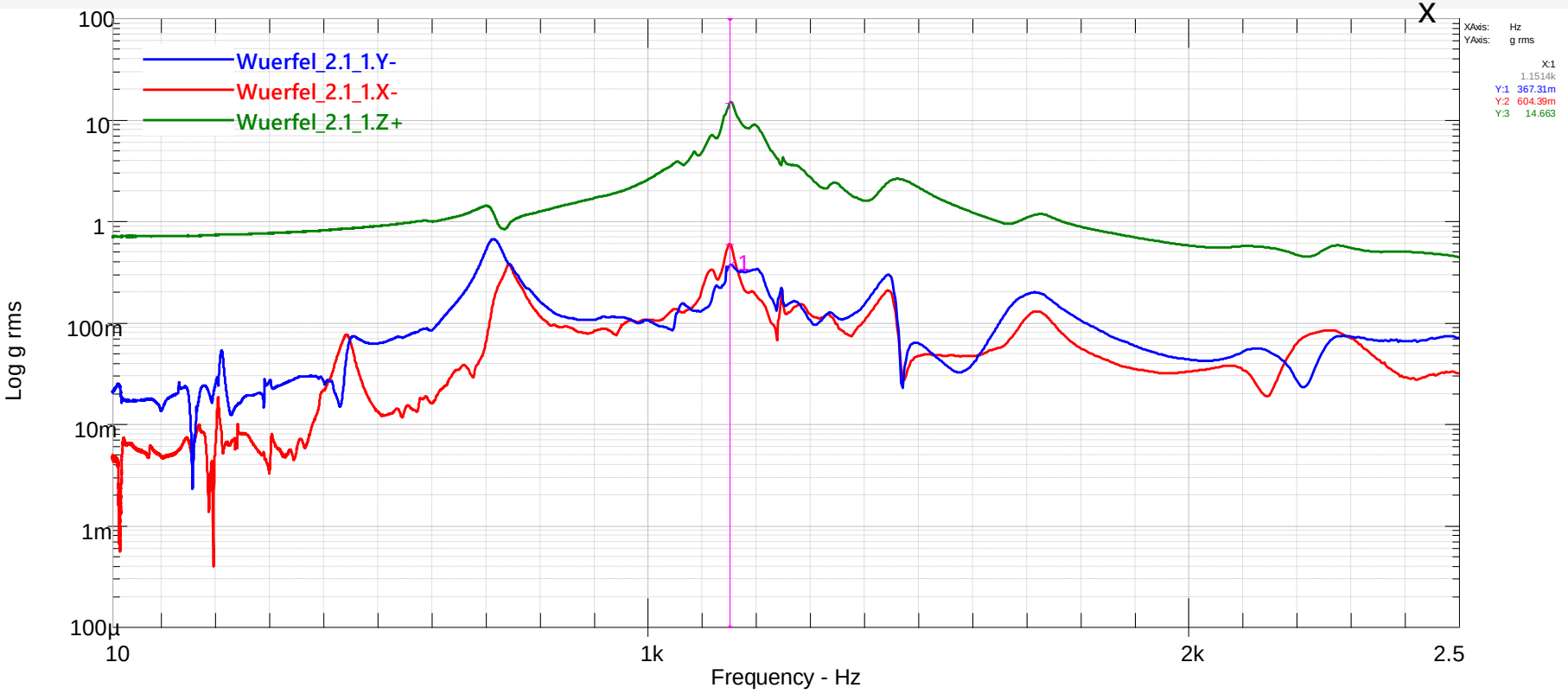


Test results
- Test variant 3 (shaker armature), Sine sweep in +Z

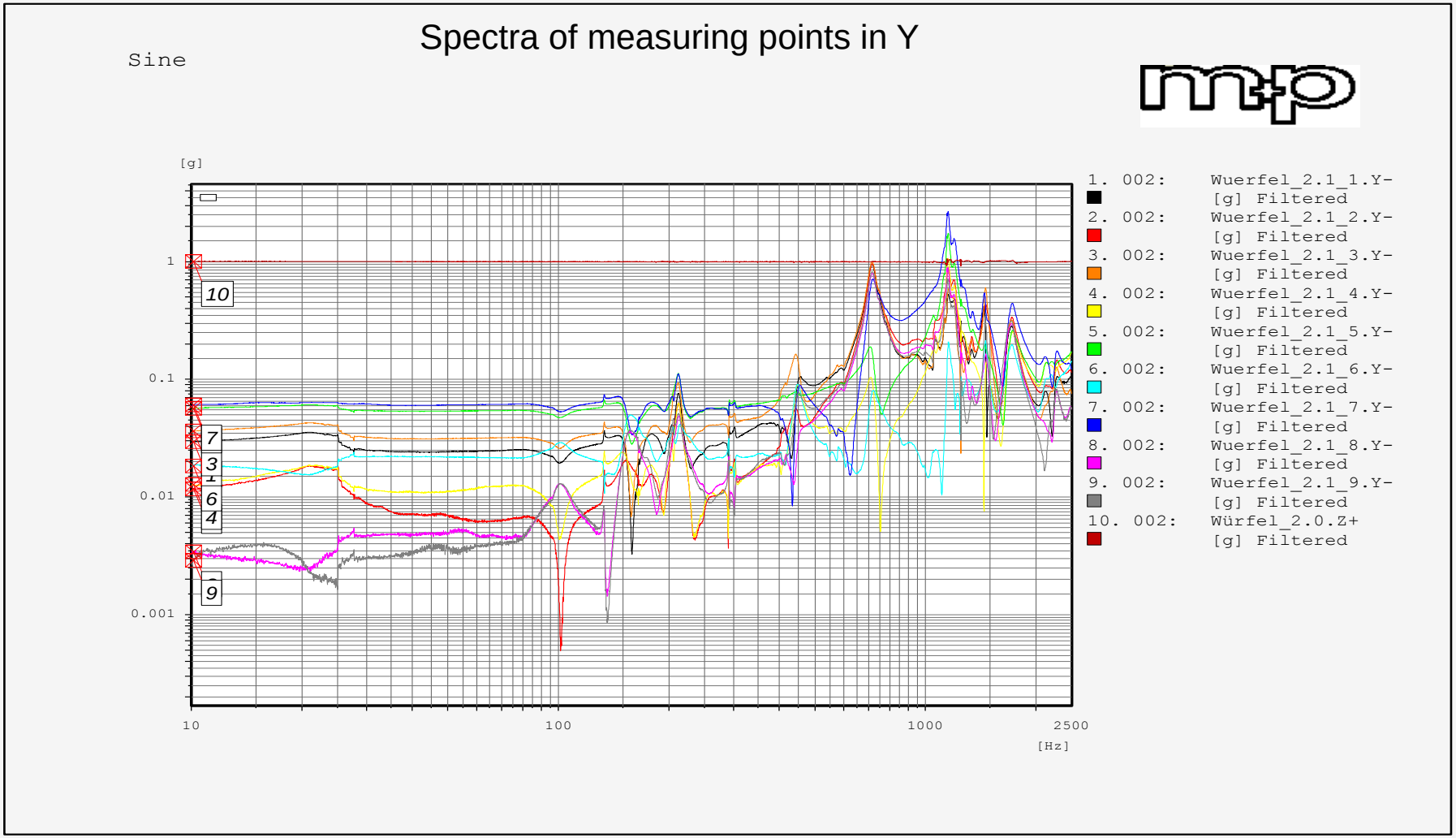
Response spectrum of measuring point 1 (x,y,z)

- Max. lateral acceleration in y: 0,7 g (rms), x: 0,6 g (rms)
- Max. vertical acceleration z: 15 g (rms) at 1155 Hz

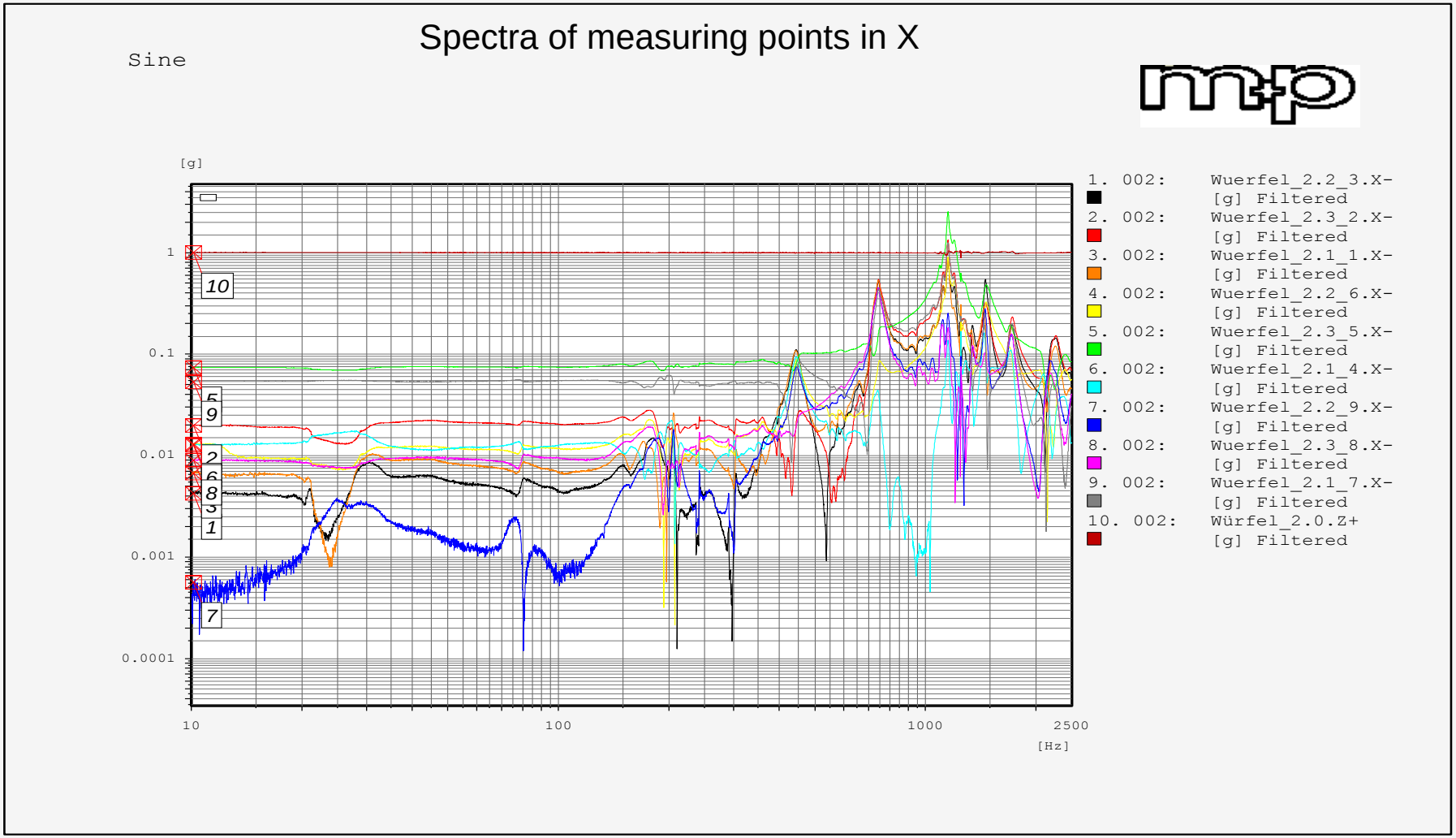




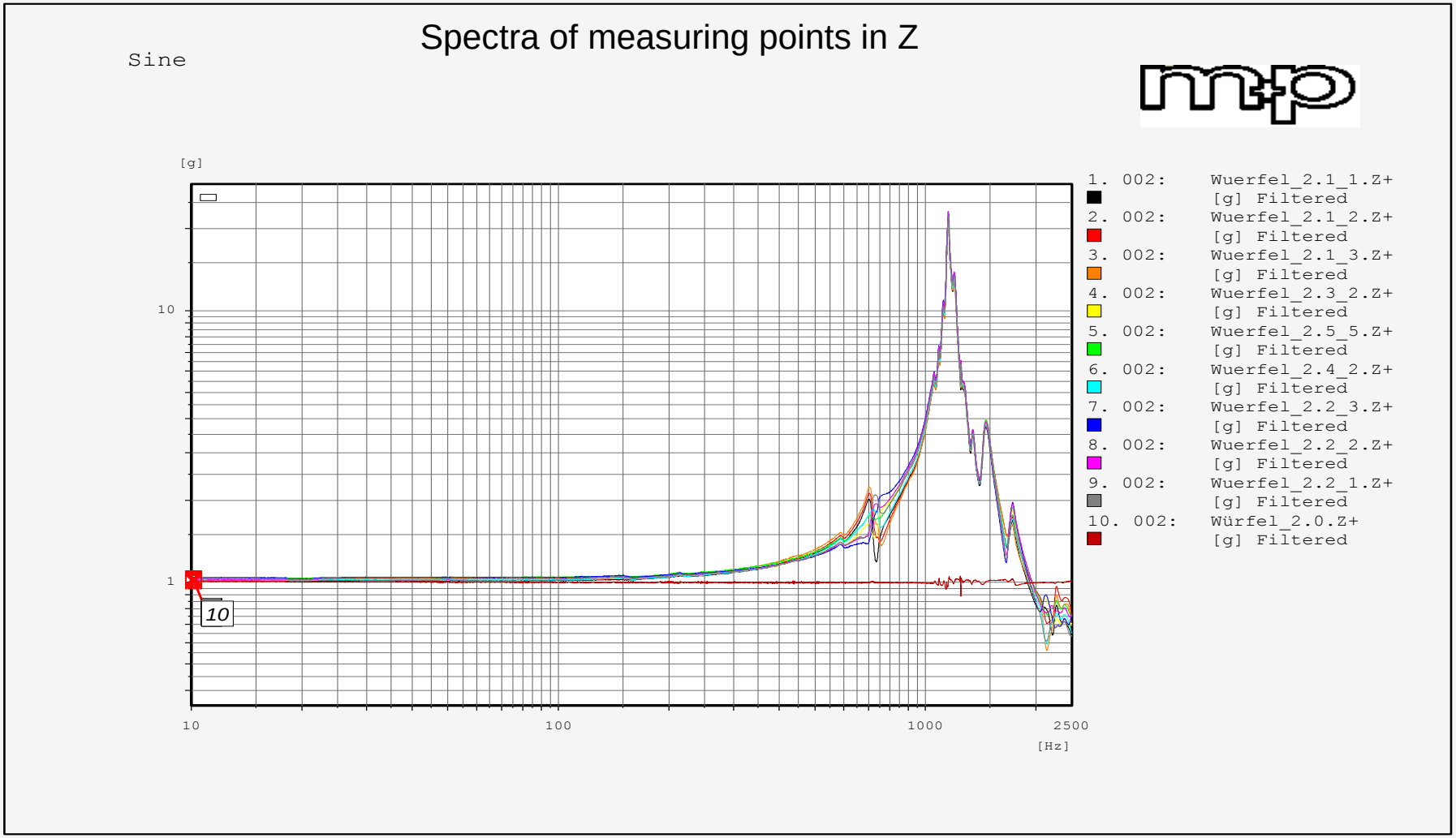
Test results
- Test variant 3 (shaker armature), Sine sweep in +Z



Test results
- Test variant 3 (shaker armature), Sine sweep in +Z

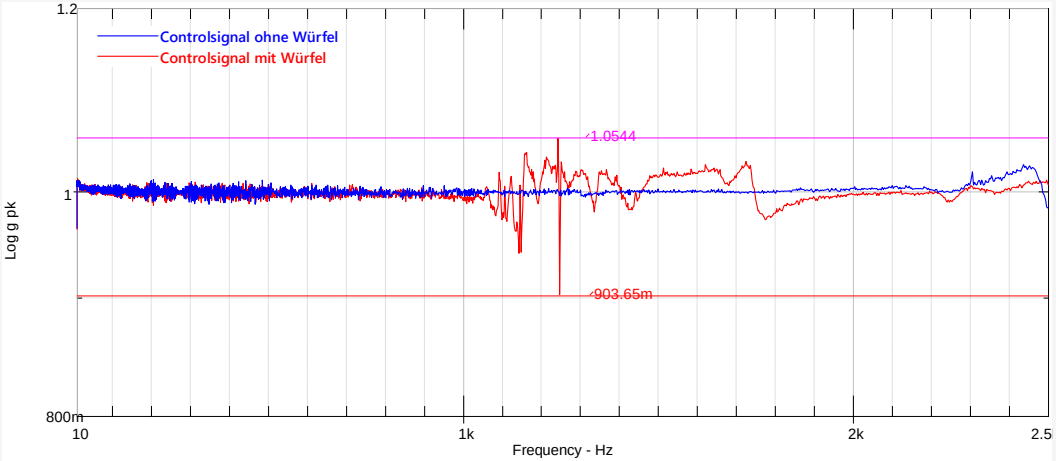


Test results
- Test variant 3 (shaker armature), Sine sweep in +Z

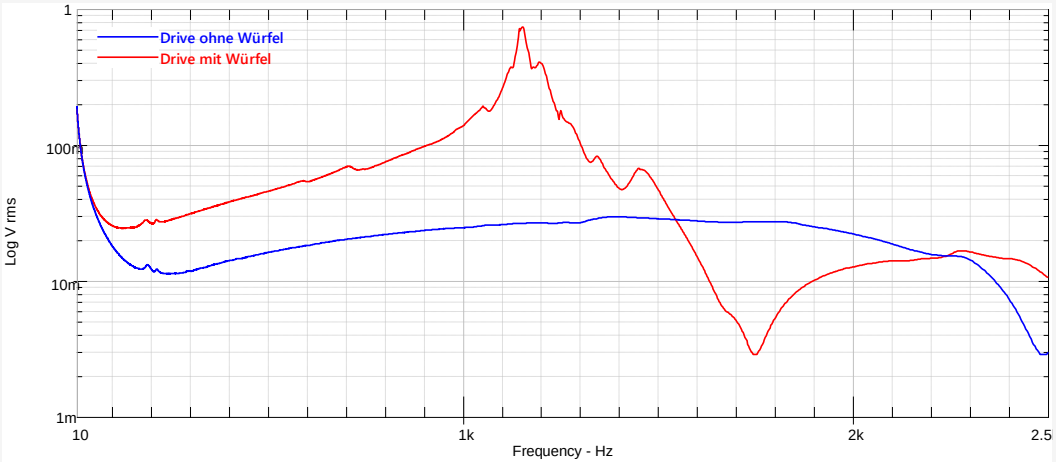


Test results
- Test variant 3 (shaker armature), Sine sweep in +Z

Control-Signal with and without cube



Drive-Signal with and without cube



Summary & conclusion

- **Investigation of the dynamic behavior of the test cube with and without coupling to the shake**
- **Identification of the influences by the coupling to the shaker**
- **Coupling extends the oscillating system (add. masses und stiffnesses)**

  → Change of the modal parameters

- **First natural frequency of the Cube at approx. 1700 Hz**
- **Influence of add. mass of the armature coil**

  → Natural frequencies move downwards

  → Additional mode shapes

- **First natural frequency of the cube + shaker armature at approx. 450 Hz**
- **First point of resonance (excitation in Z) at approx. 700 Hz**
- **Sweep excitation reveals strong resonance at 1150 Hz**

  → Position of control channel on the cube (multi-point control)

Thank you for your attention !