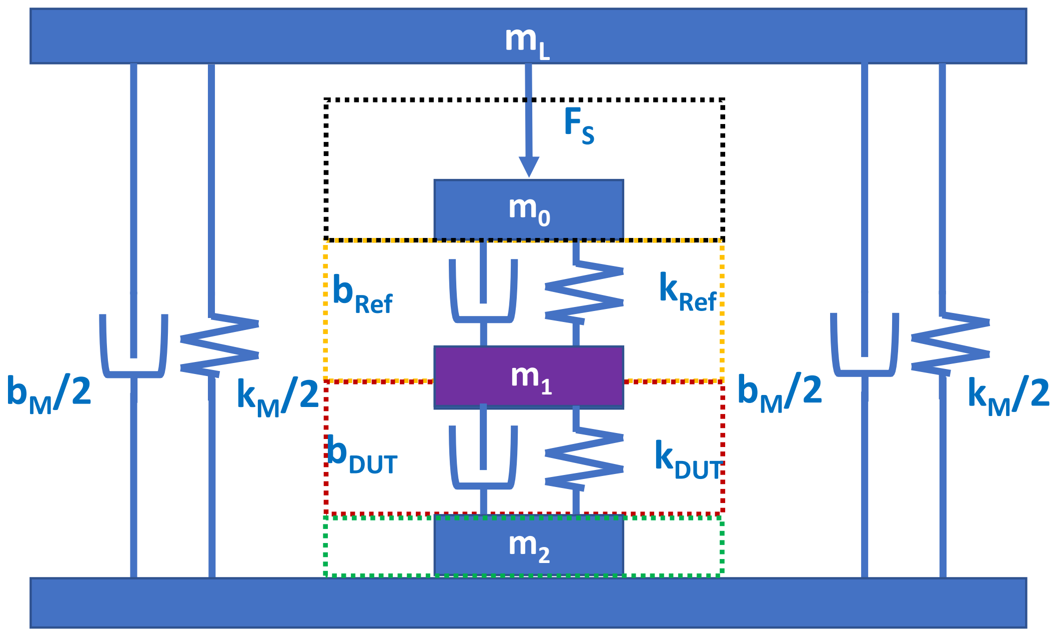
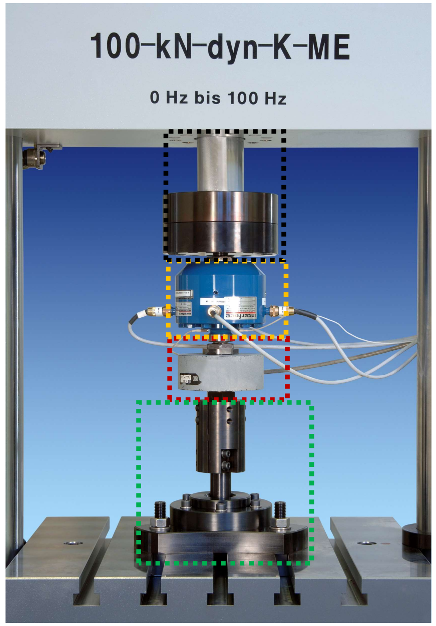
Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin
Nationales Metrologieinstitut

Arbeitsgruppe 1.23
Kraftmesstechnik

State of the Art Model





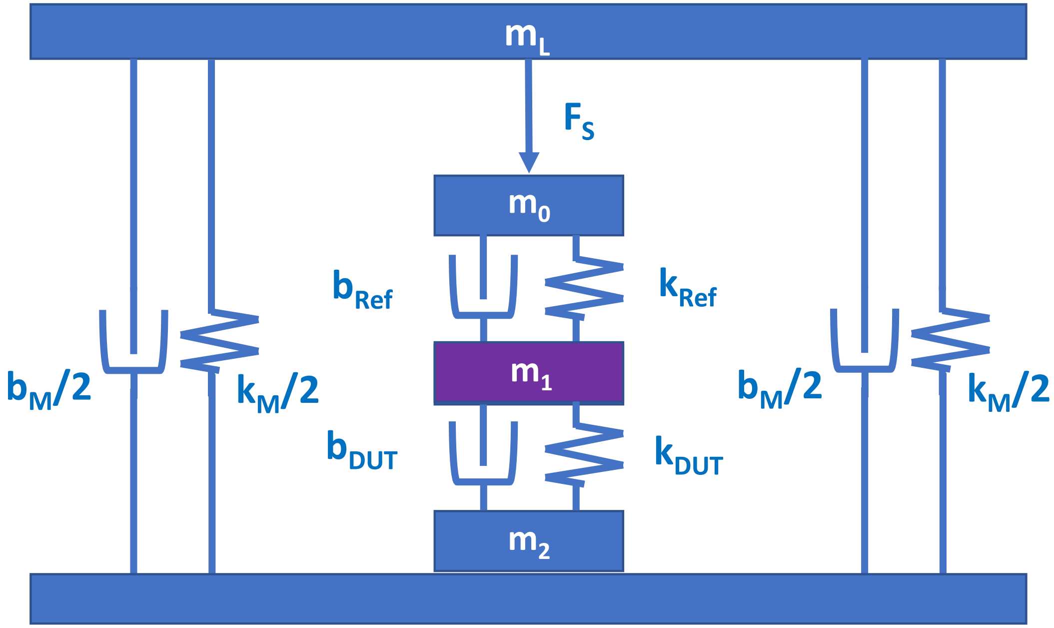
$$m_1 \cdot \ddot{x}_1 = k_{DUT} \cdot (x_2 - x_1) + b_{DUT} \cdot (\dot{x}_2 - \dot{x}_1) - k_{Ref} \cdot (x_1 - x_0) - b_{Ref} \cdot (\dot{x}_1 - \dot{x}_0)$$

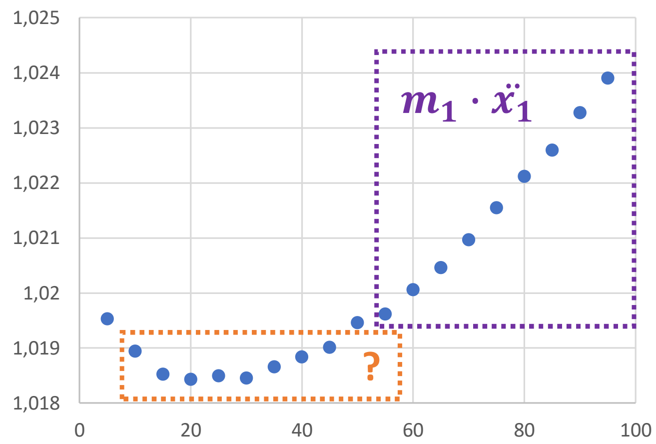
$$G(f) = \frac{F_{DUT}(f)}{F_{Reference}(f) + m_1 \cdot \ddot{x}_1}$$

Neglected dynamic parameter

Bending, Torsion, Side Forces, Side Accelerations, Deformation and movement of the lower adaption, Influcence of the piston damping, mass and acceleration, Machine frame dynamics, modal oscillations, misalignment (Wobbling).

State of the Art Model





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Neglected dynamic parameter

Bending, Torsion, Side Forces, Side Accelerations, Deformation and movement of the lower adaption, Influcence of the piston damping, mass and acceleration, Machine frame dynamics, modal oscillations, misalignment (Wobbling).

Measurement Procedure

Walter & Bai - Controller		
Source	**Parameter**	**Unit**
LVDT	Piston Displacement	mm
Interface	Reference Force - Control Loop	kN
Interface	Bending Moment Mx	Nm
Interface	Bending Moment My	Nm
Controller	Manipulated Variable	%
Controller	Set Point	kN

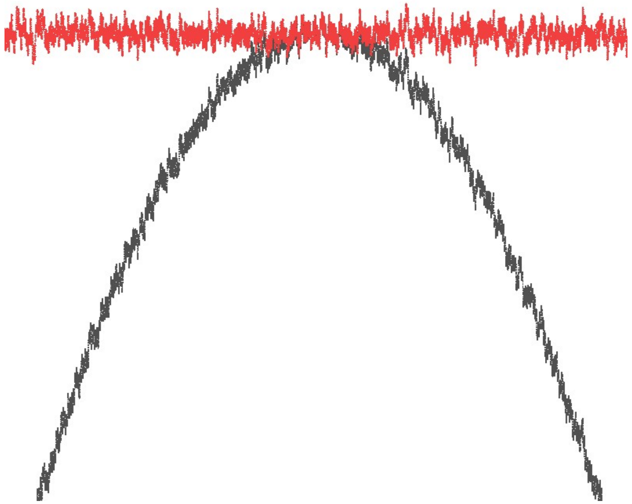
Analog Dewetron Amplifier / Dewesoft DAQ		
Source	**Parameter**	**Unit**
Interface	Reference Force - Separate Measurement	N
PT100 - External	Temperature - Reference Transducer - Interface	°C
PT100 - Internal	Temperature - DUT Transducer - GTM	°C
GTM	DUT Transducer Force	N
GTM	Upper Acceleration - DUT Transducer	m/s²
GTM	Lower Acceleration - DUT Transducer	m/s²
B&K 3D ICP	Various 3D Acceleration Measurements	m/s²

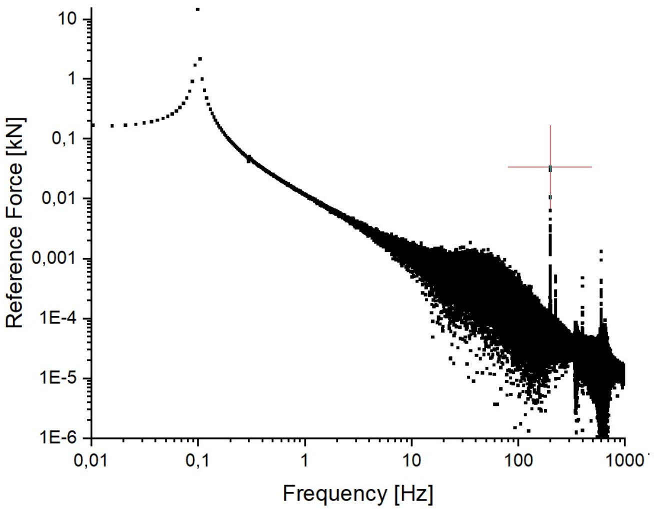
Reference Force Settings		
Offset [kN]	**Amplitude**	**Frequency [Hz]**
-10	5	0.1 , 1 , 2, 5, 10, 20, 30, 40, ……… , 100 Hz
-5	5	0.1 , 1 , 2, 5, 10, 20, 30, 40, ……… , 100 Hz
-5	10	0.1 , 1 , 2, 5, 10, 20, 30, 40, ……… , 100 Hz
0	5	0.1 , 0.5 , 1 , 2, 5, 10, 15, 20, 25, ……… , 100 Hz
0	10	0.1 , 0.5 , 1 , 2, 5, 10, 15, 20, 25, ……… , 100 Hz
0	15	0.1 , 0.5 , 1 , 2, 5, 10, 15, 20, 25, ……… , 100 Hz
5	5	0.1 , 1 , 2, 5, 10, 20, 30, 40, ……… , 100 Hz
5	10	0.1 , 1 , 2, 5, 10, 20, 30, 40, ……… , 100 Hz
10	5	0.1 , 1 , 2, 5, 10, 20, 30, 40, ……… , 100 Hz

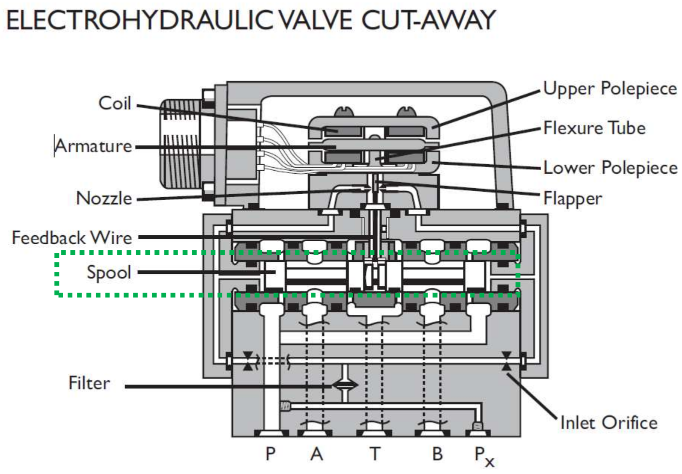
Measurement Methode

- Various pre investigations were applied before every main measurement procedure.
- The measurement procedure were applied to the same measurement set-up but after two different pre-load methods.
- Additional various acceleration measurement, partly 3 dimensional, at different position of the hydraulic machine and the set-up itself were made.
- Measurements for the estimation of the impact of spreading structure-borne noise were also made.

Dithering Signal







Neglected dynamic parameter

- This signal is modulated onto the control signal of the valve.
- It has a fixed amplitude and a fixed frequency of 200 Hz.
- It is supossed to avoid slip- stick effects of the spool.
- It creates a force on its own and interacts with other harmonics.
- As the frequency difference between the dithering and control signal is big enough, the results will be easy to handle.

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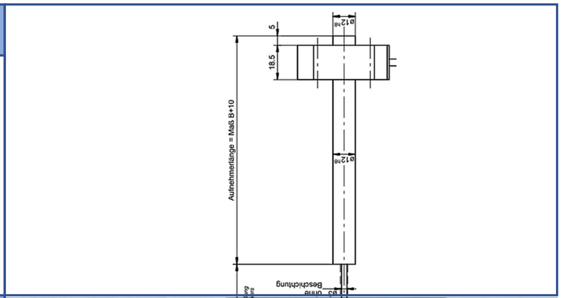
Hydraulic Cylinder Piston

LVDT $Displacement$: X_{Piston}

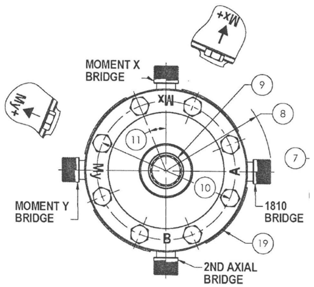
$$F_{Piston} = M_{Piston} \cdot \ddot{X}_{Piston} + b_{Piston} \cdot \dot{X}_{Piston}$$

$\dot{X}_{Piston}$ ~ Valve control current

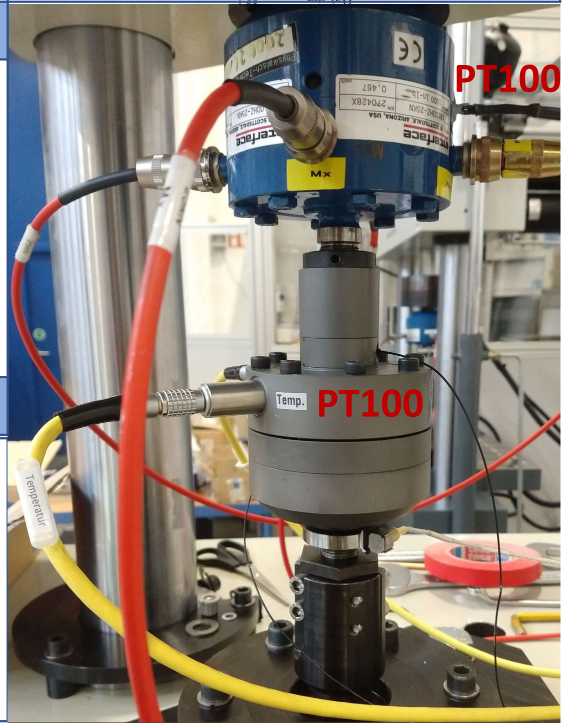
$$F_{Piston} = -M_{Piston} \cdot \hat{X}_{Piston} \cdot \omega^2 \cdot \sin(\omega \cdot t) + b_{Piston} \cdot \hat{X}_{Piston} \cdot \omega \cdot cos(\omega \cdot t)$$



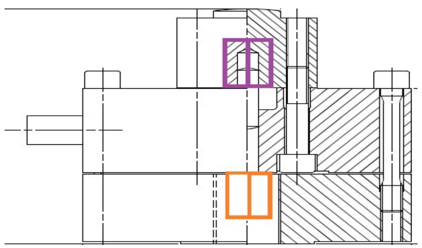
Bending Moments and its derived Parameters



$$Mres = \sqrt{Mx^2 + My^2} \quad \varphi_{res} = \arctan\left(\frac{Mx}{My}\right) \quad M_{Torsion} \sim \ddot{\varphi}_{res}$$



Transfer Function of the DUT Transducer



Upper internal Acceleration Transducer

Lower internal Acceleration Transducer

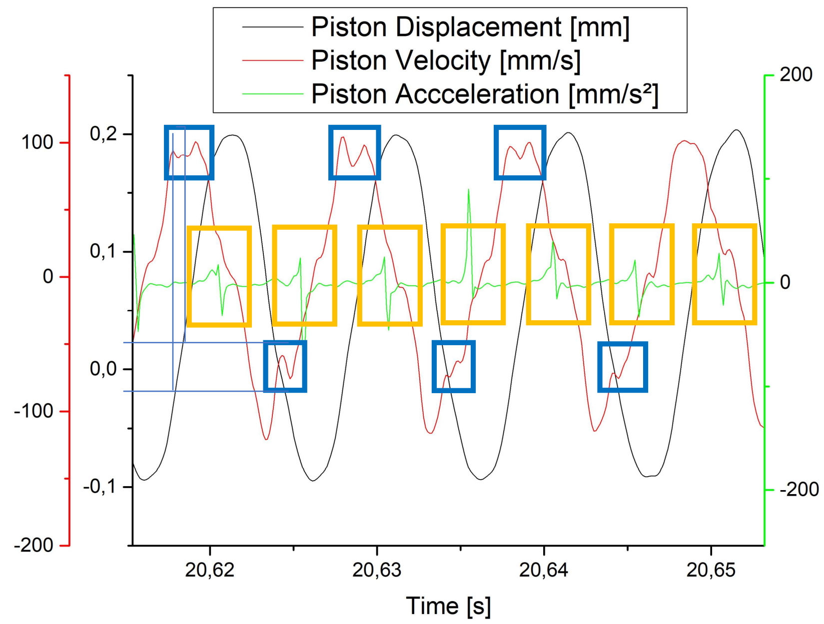
$$G(f) = \frac{a_{Lower}(f)}{a_{Upper}(f)}$$

Hydraulic Cylinder Piston	Control Loop

LVDT $Displacement: X_{Piston}$

$$F_{Piston} = M_{Piston} \cdot \ddot{X}_{Piston} + b_{Piston} \cdot \dot{X}_{Piston}$$

$$F_{Piston} = -M_{Piston} \cdot \hat{X}_{Piston} \cdot \boldsymbol{\omega}^{2} \cdot \sin(\omega \cdot t) + b_{Piston} \cdot \hat{X}_{Piston} \cdot \boldsymbol{\omega} \cdot cos(\omega \cdot t)$$



Valve Dead Zone Effect + Something Else?

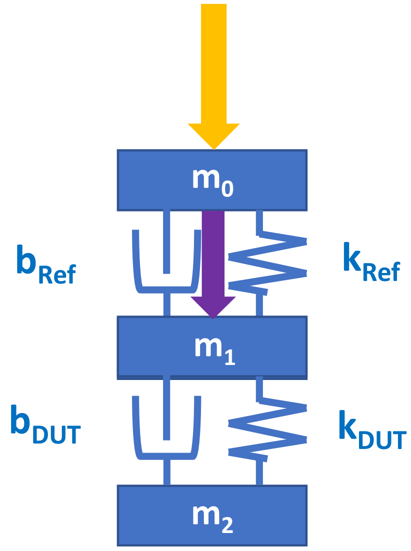
Cyclinder Reverse Jerk?
Or Reverse Cylinder Damping?

Valve Dead Zone Effect

Or is it caused by the load train?

Control Loop

$$F_{Piston} = M_{Piston} \cdot \ddot{X}_{Piston} + b_{Piston} \cdot \dot{X}_{Piston}$$



$F_{Reference}$

↓

Valve Control Current

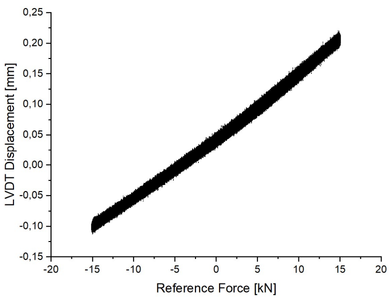
↓

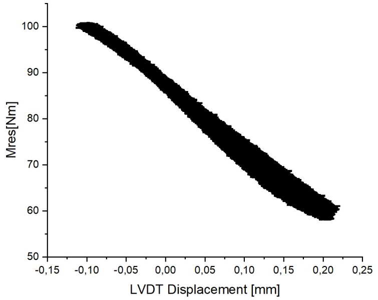
$\dot{X}_{Piston}$

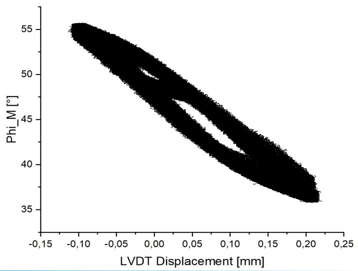
Displacement Matrix

0.1 Hz	45 Hz	100 Hz

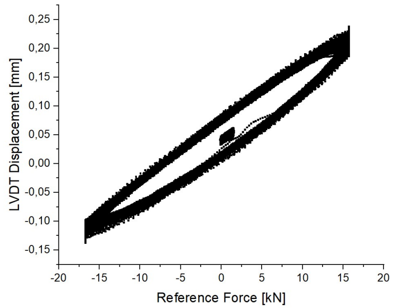
0.1 Hz

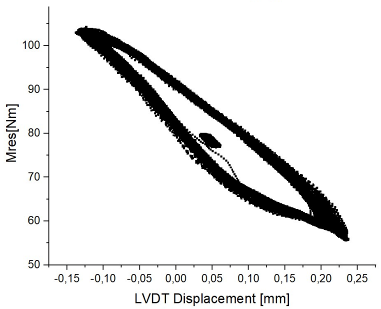


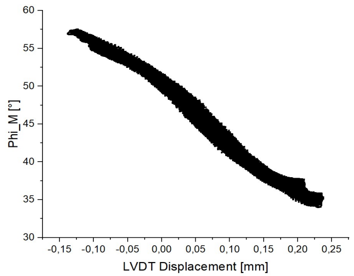




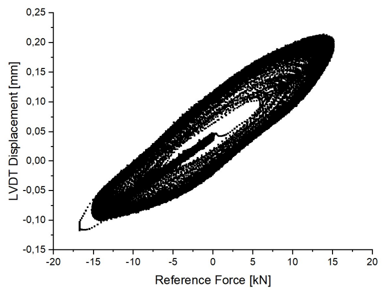
45 Hz

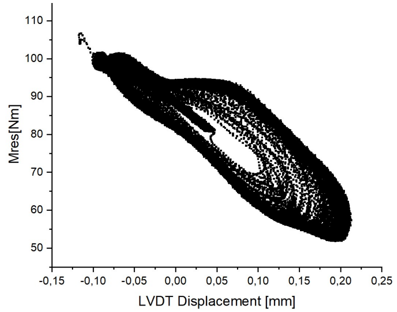


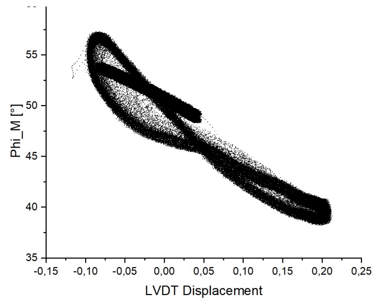




100 Hz



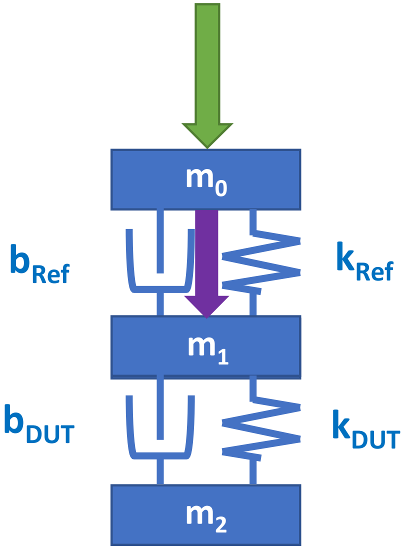




Impact of non linear effects over frequency

Control Loop

$$F_{Piston} = M_{Piston} \cdot \ddot{X}_{Piston} + b_{Piston} \cdot \dot{X}_{Piston}$$



$F_{Reference}$

↓

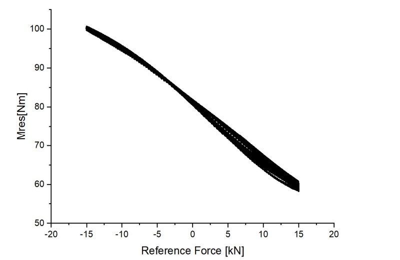
Valve Control Current

↓

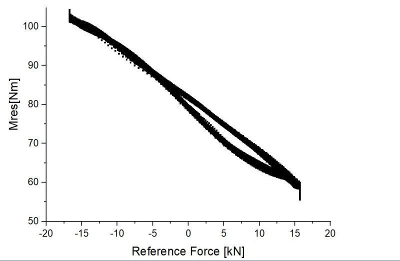
$\dot{X}_{Piston}$

Multidimensional Impact to Reference Force

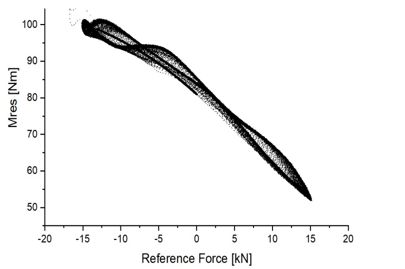
0.1 Hz



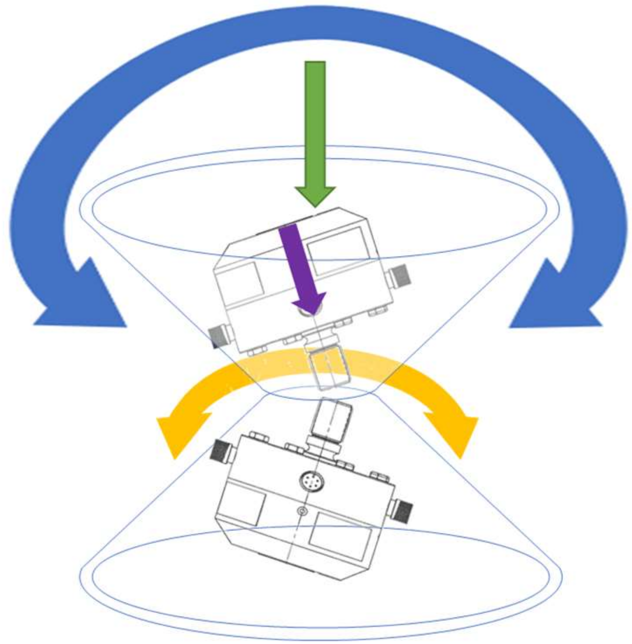
45 Hz



100 Hz



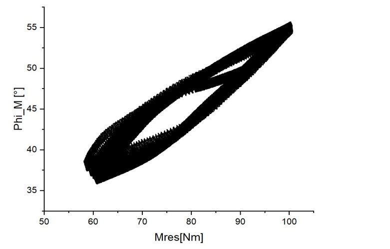
$$Mres = \sqrt{Mx^2 + My^2}$$



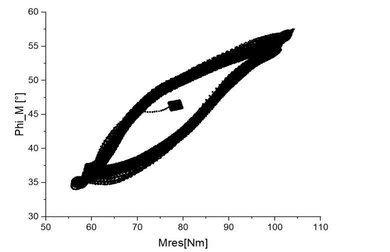
$$\varphi_{res} = \arctan\left(\frac{Mx}{My}\right)$$

$$M_{Torsion} \sim \ddot{\varphi}_{res}$$

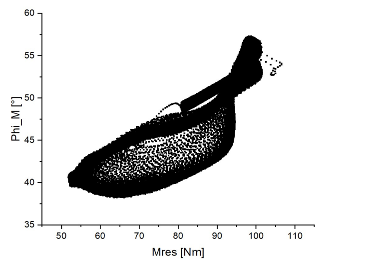
0.1 Hz



45 Hz



100 Hz



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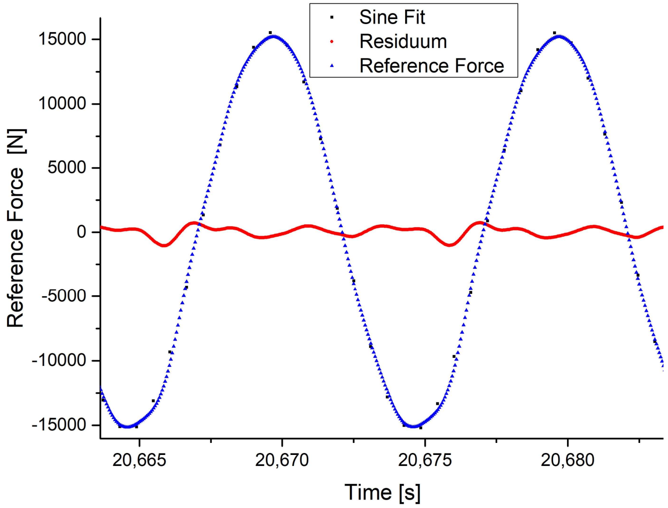
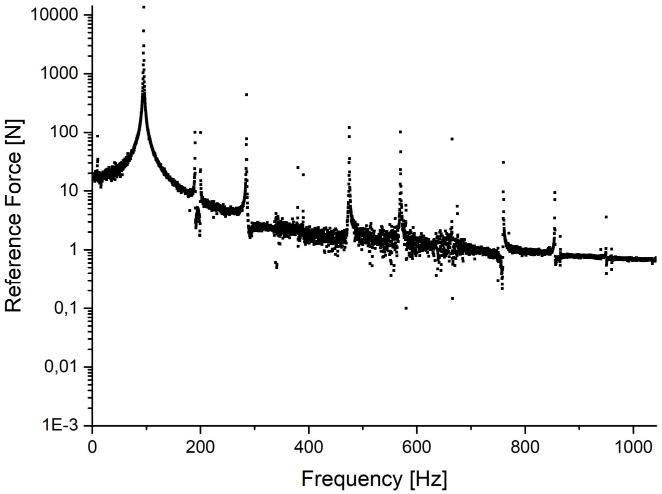
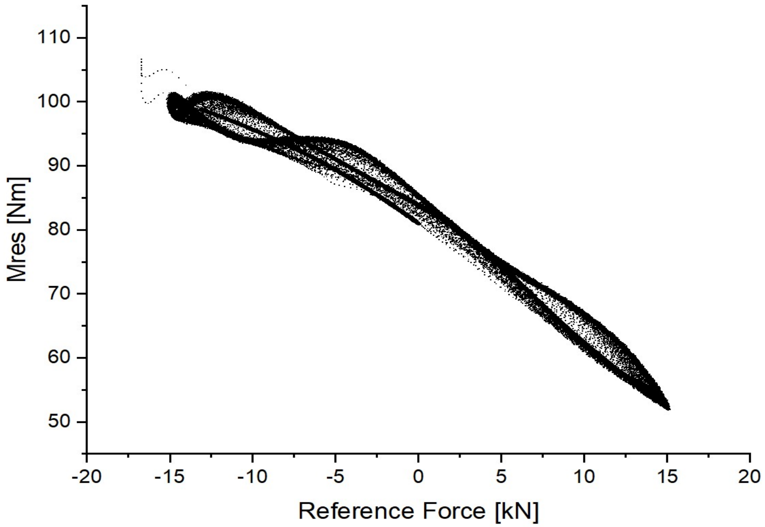
Force Harmonics







Transfer Function vs. Harmonics

- An uncertainty budget would be different for tension and compression.
- The maximum local relative residuum is over 9%.
- This is not caused by moving masses which are considered as the main impact to the transfer function.
- Odd and even harmonics are an indicator for non symmetric non linearities

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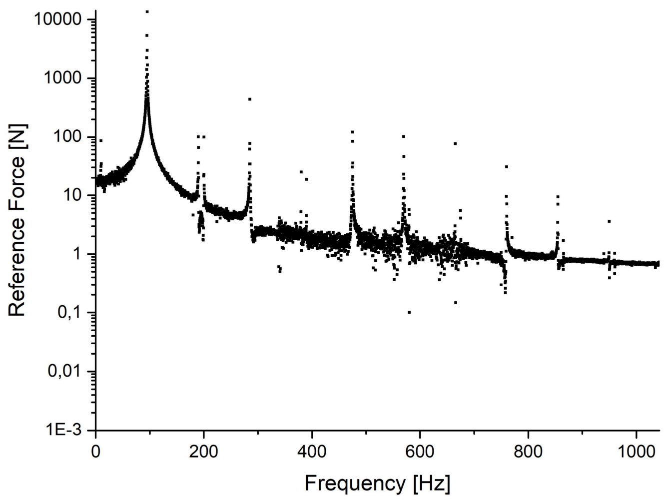
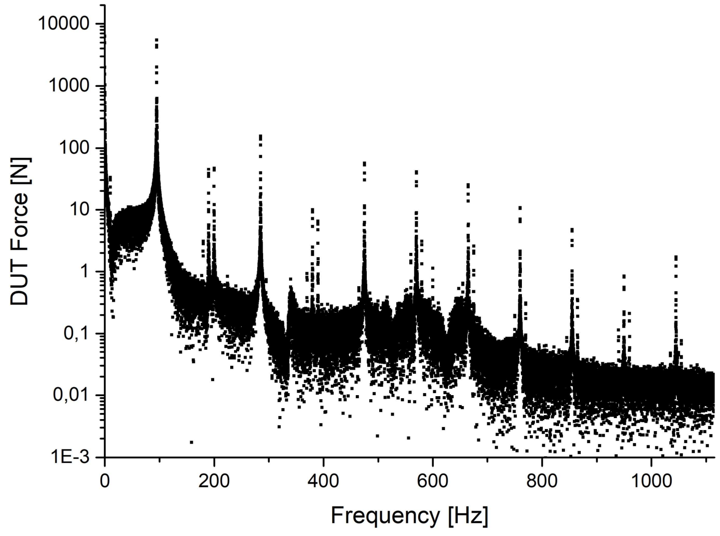
Linear Transfer Functions from non linear Data - Force



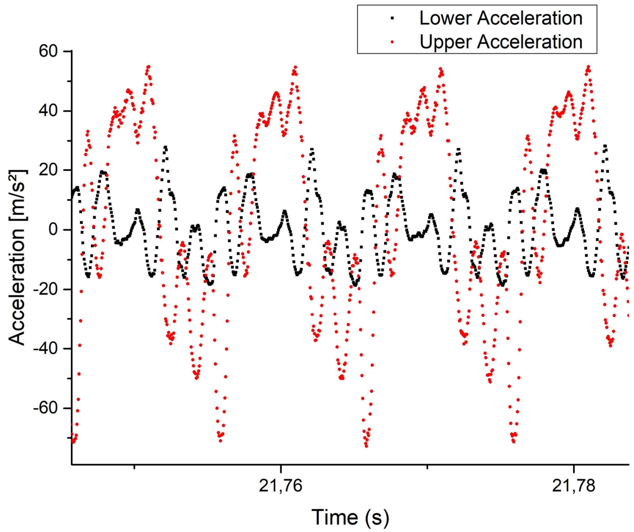


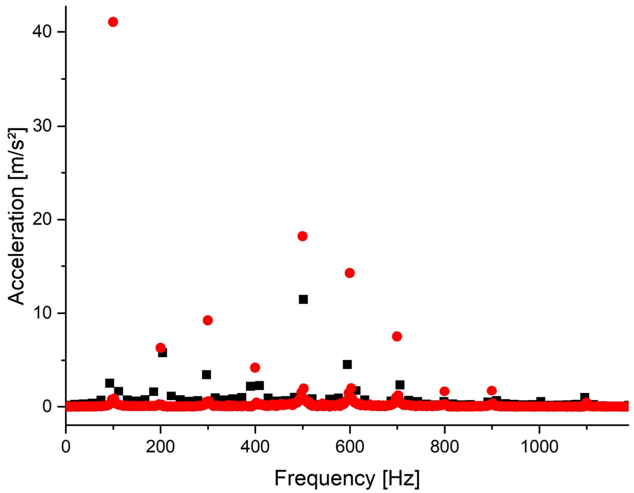
$$G(f) = \frac{F_{DUT}(f)}{F_{Reference}(f)}$$

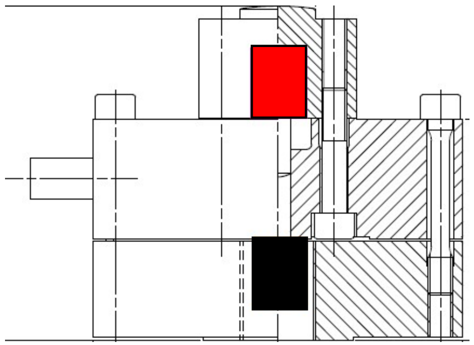
Methods and Preconditions

- The basic harmonic can loss spectral energy to the harmonics as long as it is still the strongest.
- FFT and non-linear fitting methods (Levenberg Marquardt) has to be applied to much steady state cycles as possible.
- A new method created for our data sets, based on the hilbert transformation, works even better. It forces back all of the spectral energy and works even for one cycle. It can also be used as a more reliable peak finder.

Linear Transfer Functions from non linear Data - Acceleration





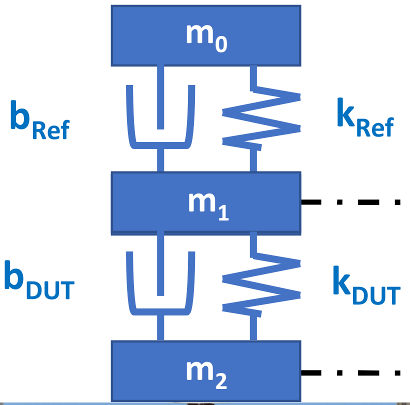


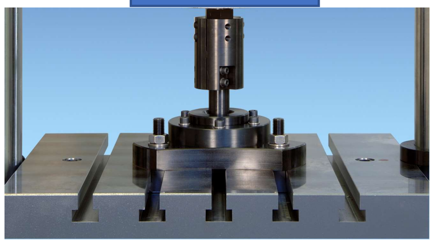
$$G(f) = \frac{a_{Lower}(f)}{a_{Upper}(f)}$$

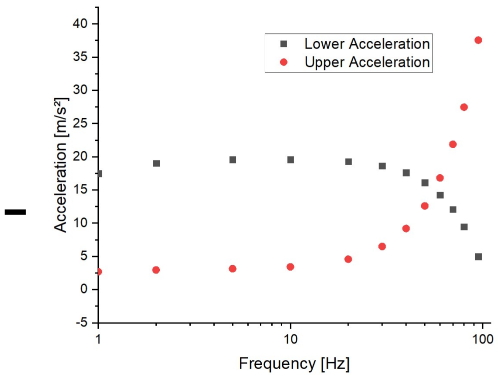
Methods and Preconditions

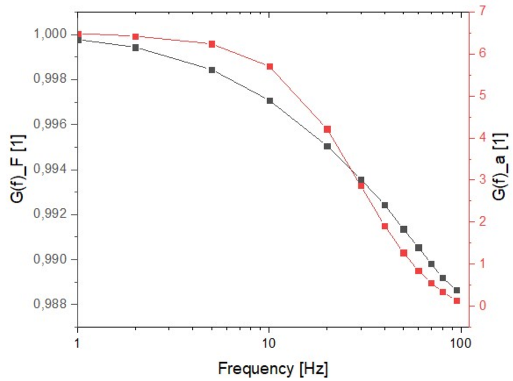
- The basic harmonic can lose spectral energy to the harmonics as long as it is still the strongest.
- Therefore, the spectrum of the lower acceleration at 100 Hz is not suitable. Therefore, the transfer function can only be defined to the next lower frequency at 95 Hz.
- No matter how sophisticated a linearisation method is, it would just “catch” the strongest harmonic at 500 Hz.

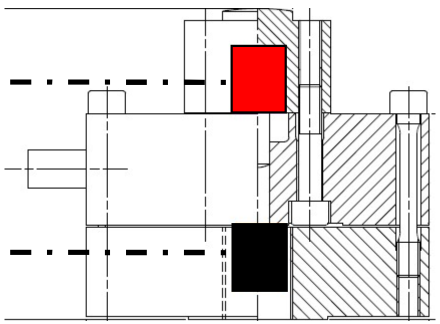
Transfer Functions







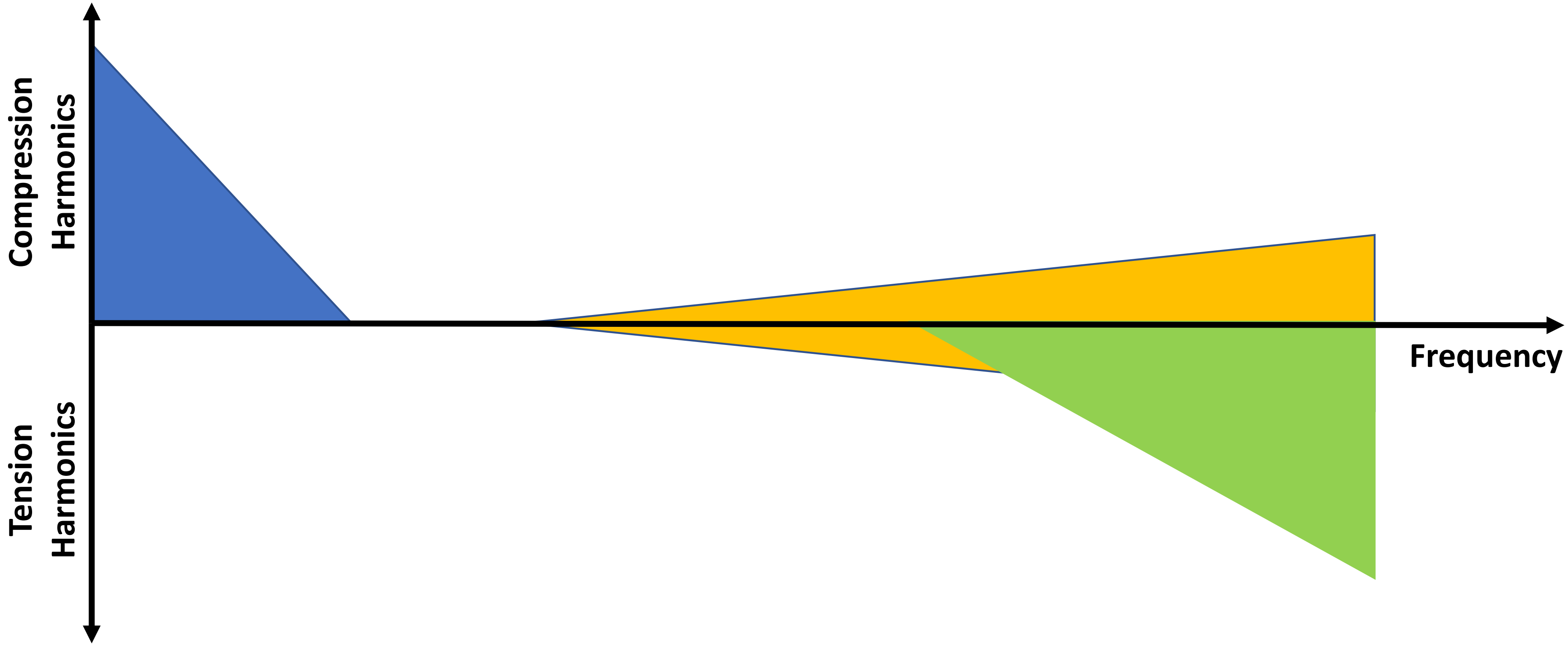




$$G(f) = \frac{F_{DUT}(f)}{F_{Reference}(f)}$$

$$G(f) = \frac{a_{Lower}(f)}{a_{Upper}(f)}$$

Impact of non linear effects over frequency



Principal

- Effects in compression, tension or both can get weaker and disappear while other effects appear and get stronger.

Pre Investigations – Hydraulic Machine and Reference Sensor
- Time series LVDT measurements of the displacement should be done. - Time series measurements of two-dimensional bending moment should be done. - Time series data of reference force, displacement, and the resulting bending moment as also the bending angular should be analysed for non-linearities, non-symmetries and low starting values. - These analyses should take place for at least the lowest, the middle and the highest frequency.
Optimisation– Hydraulic Machine and Reference Sensor
- Reduce the static values for both bending moments as god as possible. - Reduce the starting force value, caused by the pre-load-process, by adjusting the frame height. As possible start at a force and displacement of 0.
Accelerations
- Every position within the set-up which is considered as a stable, not moving position, should be checked by according acceleration measurements. - The piston acceleration should be measured or should be derived by the LVDT displacement data in ideal circumstances. - These analyses should take place for at least the lowest, the middle and the highest frequency.

Q & A

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