Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

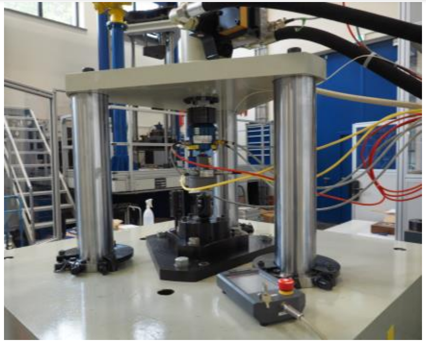
Advanced practical models for describing static and continuous forces

Final Public Workshop 24. February 2023

Jonas Sander
PTB Braunschweig

Agenda

State of the art → ISO 376 static
→ DKD R 3-9 continuous



Aim → A practical description of a force transducer for continuous forces

- Sensitivity
- Time dependent behaviour
- Temperature sensitivity

Introduction
- Force transducers

Sensitivity

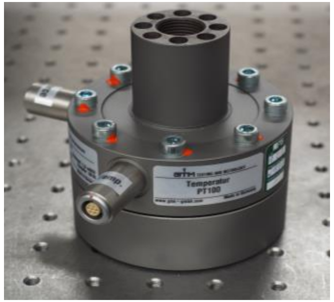
Time dependent behaviour
- Investigation
- Model
- Correction

Rheological Model

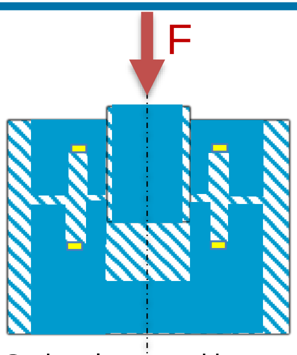
Temperature
- Sensitivity
- Zero signal
- Creep behaviour

Practical model

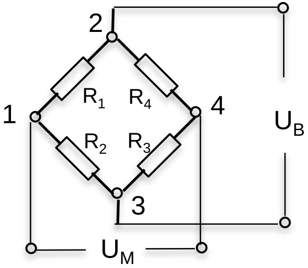
Introduction – Force transducer



Strain gauge force transducer (GTM KTN Z/D)



Springelement with strain gauges

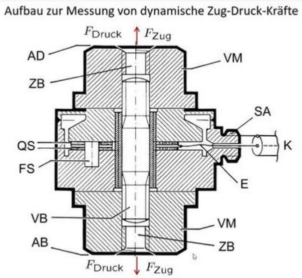


Wheatstone brigde

$$\frac{U_M}{U_B} = \frac{1}{4}\left(\frac{\Delta R1}{R1} - \frac{\Delta R2}{R2} + \frac{\Delta R3}{R3} - \frac{\Delta R4}{R4}\right)$$

in mV/V

Piezoelectric force transducer (Kistler 9331b)



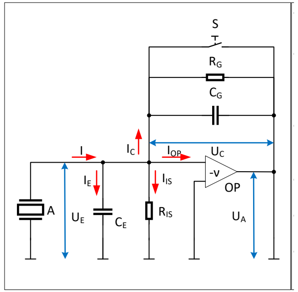
Preloaded Quarz plates

©TU Wien – A. Schirrer

$$Q = q_{11} \cdot n \cdot F$$

in pC

→ Charge amplifier



$$U_A(t) = -\frac{Q}{C_G} + D \cdot t$$

in V

Agenda

Introduction

Sensitivity

Time dependent behaviour

Rheological Model

Temperature

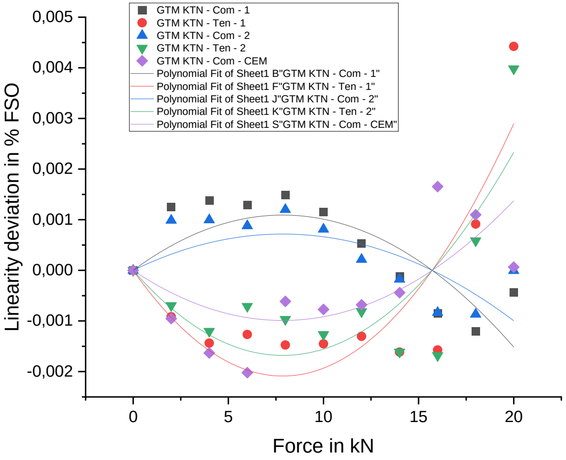
Practical model

Sensitivity

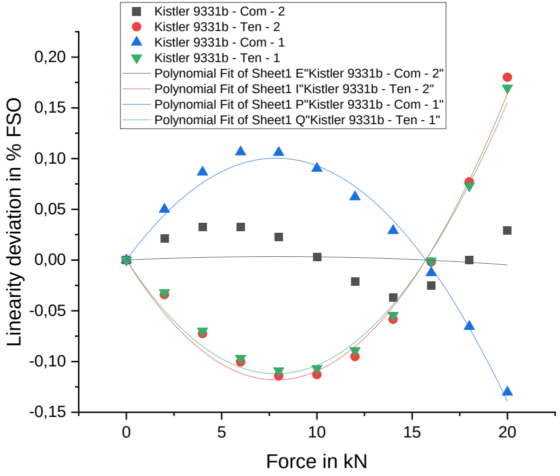
- applications in industry→ single criteria coefficient → Linear sensitivity

- force traceability from National standards → Polynomial function

Strain gauge



Piezoelectric



$$X_a = A \cdot F^3 + B \cdot F^2 + C \cdot F$$

$$F_{CD} = A' \cdot X_a^3 + B' \cdot X_a^2 + C' \cdot X_a$$

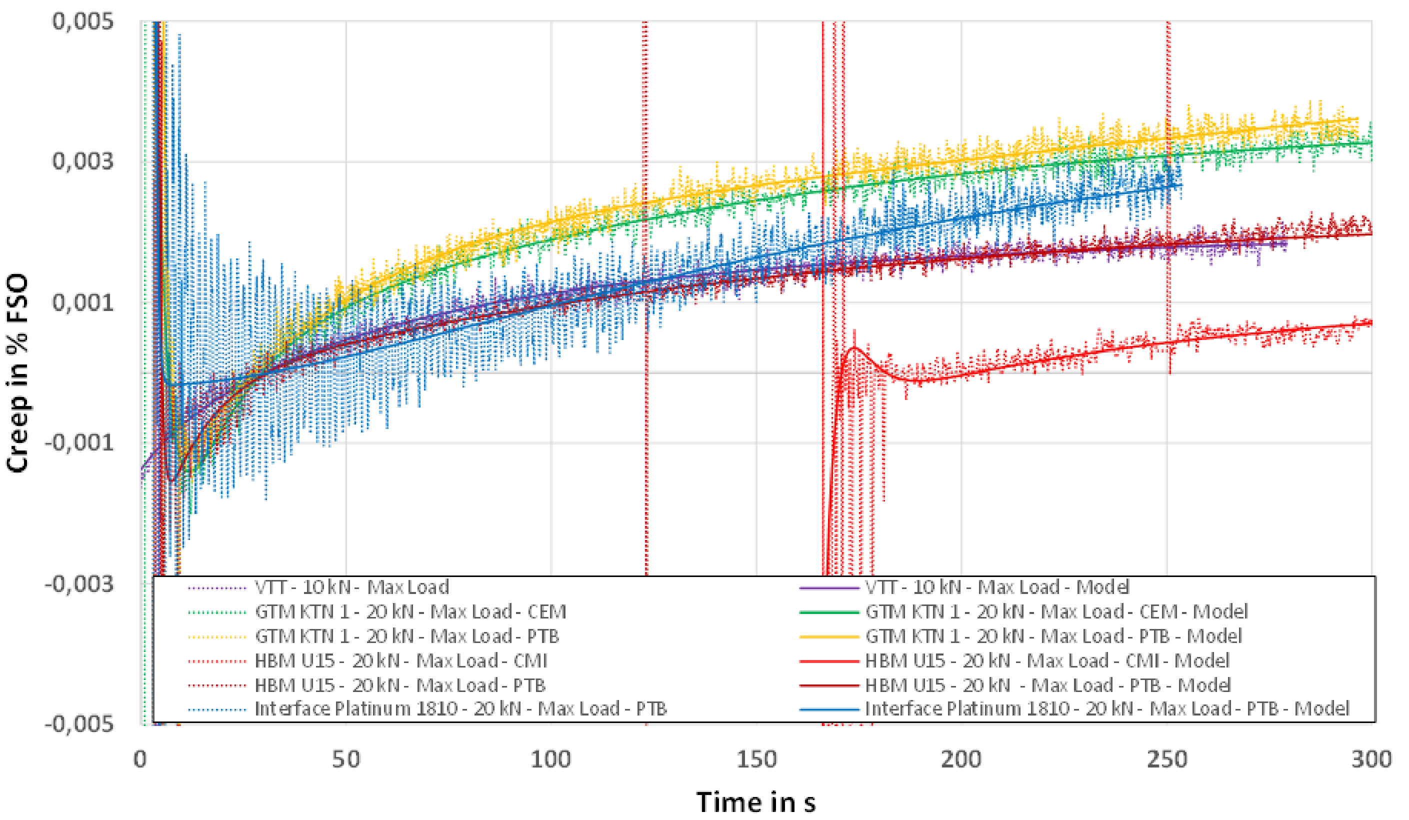
Agenda

- Introduction
- Sensitivity
- **Time dependent behaviour**
- Rheological Model
- Temperature
- Practical model

Time dependent behaviour - Investigation

Creep behaviour of class 00 strain gauge transducers

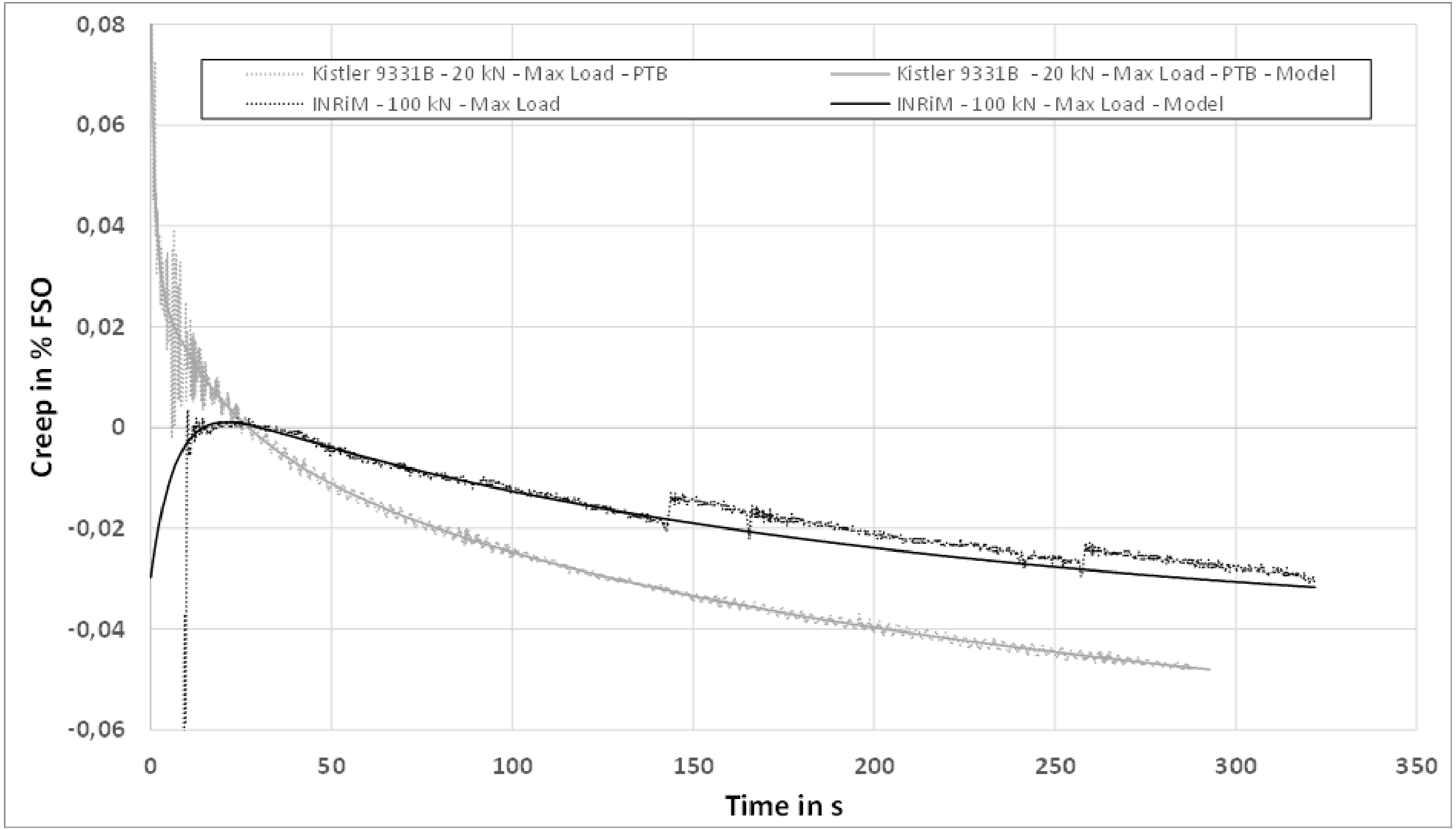
- Relative loading creep from 0 to 300 seconds after loading
- Positive creep behaviours
- Magnitude below 0.005 % !
- Significant differences when loading time is different
- The direction of the creep can change in the first seconds after loading (~15 s)
- Filter of amplifier influences the values directly after application of the load (~1 s)



Time dependent behaviour - Investigation

Loading creep behaviour of class 05 strain gauge and piezoelectric transducers

- Relative loading creep from 0 to 300 seconds after loading
- Negative creep behaviour
- Piezoelectric shows same kind of time dependent behaviour as strain gauge

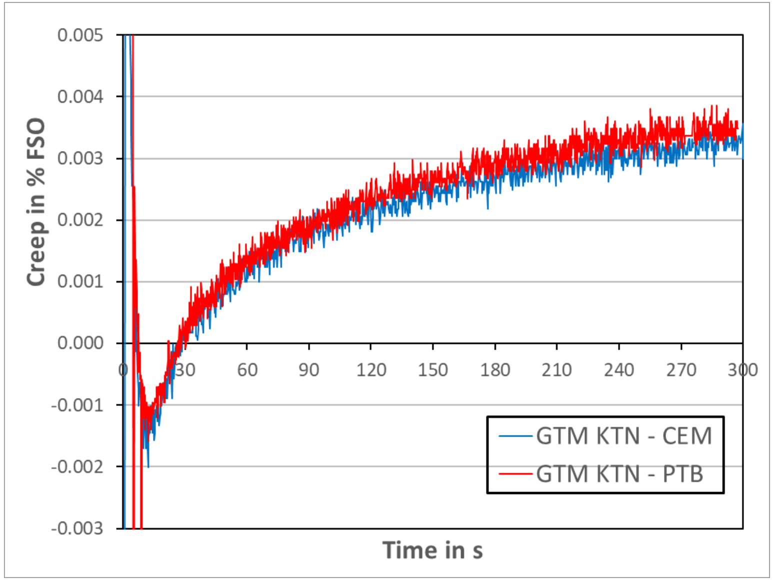


Time dependent behaviour - Model

Strain gauge	• Viscoelastic behaviour of foil and glue • Thermoelastic effect spring element • Material creep (atomic place changing processes)	Creep and relaxation behaviour can be sufficently described with a sum of three exponential functions	$F_{creep,rel}(t) = \sum_{k=1}^{k=3} a_k \cdot (1 - e^{-\frac{t}{\tau_k}})$
Piezo-electric	• Drift of Charge amplifier • Pre-loading of the sensor • Capacities (Sensor, Cable) • Triboelectric effects	Creep and relaxation behaviour can be sufficiently described with a sum of three exponential functions plus a linear term caused by the charge amplifier	$F_{creep,rel}(t) = D \cdot t + \sum_{k=1}^{k=3} a_k \cdot \left(1 - e^{-\frac{t}{\tau_k}}\right)$

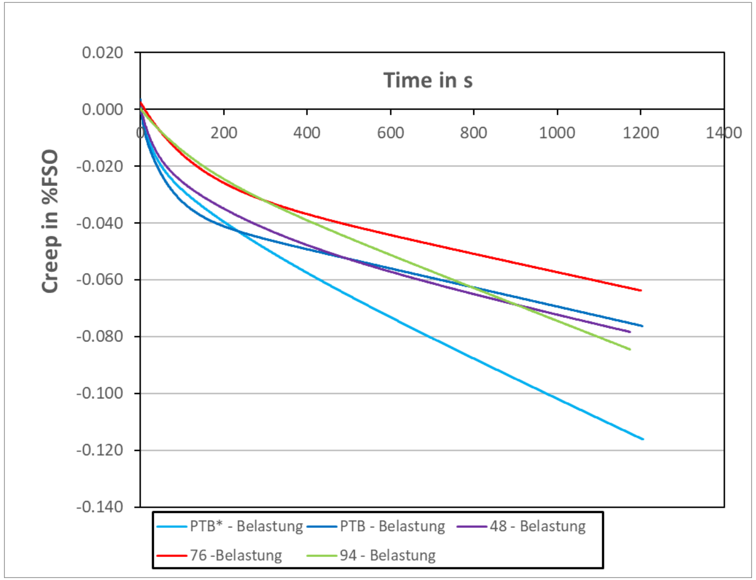
Time dependent behaviour - Correction

Strain gauge



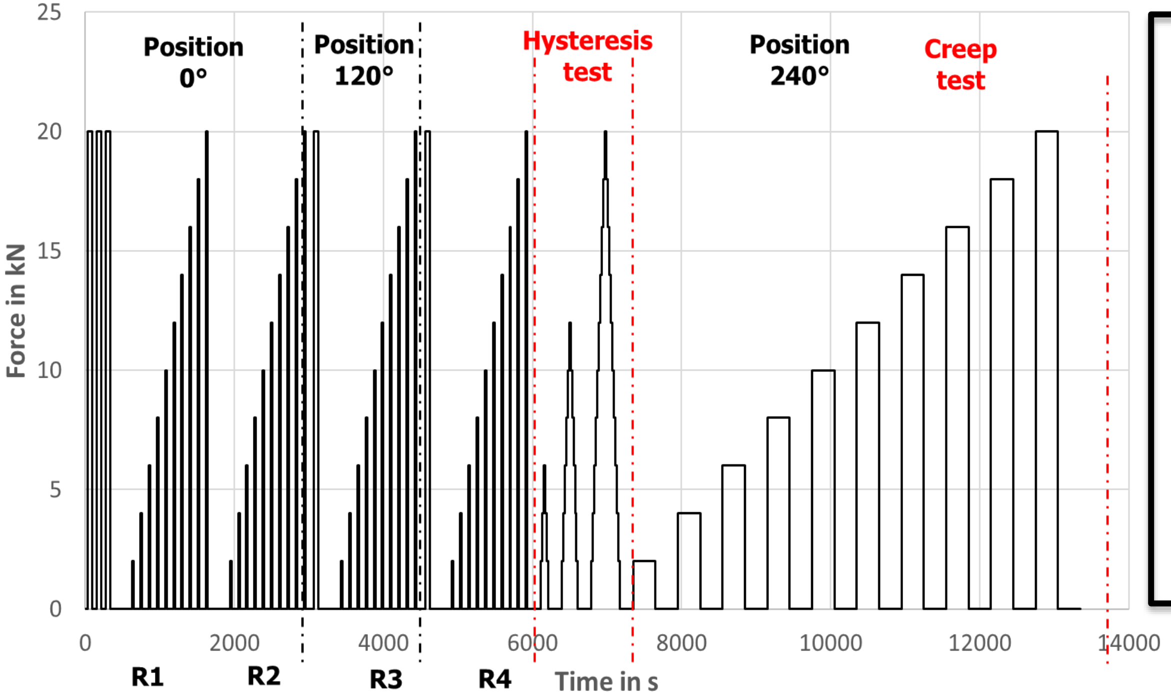
Time dependent behaviour is <u>good</u> reproducable

Piezoelectric



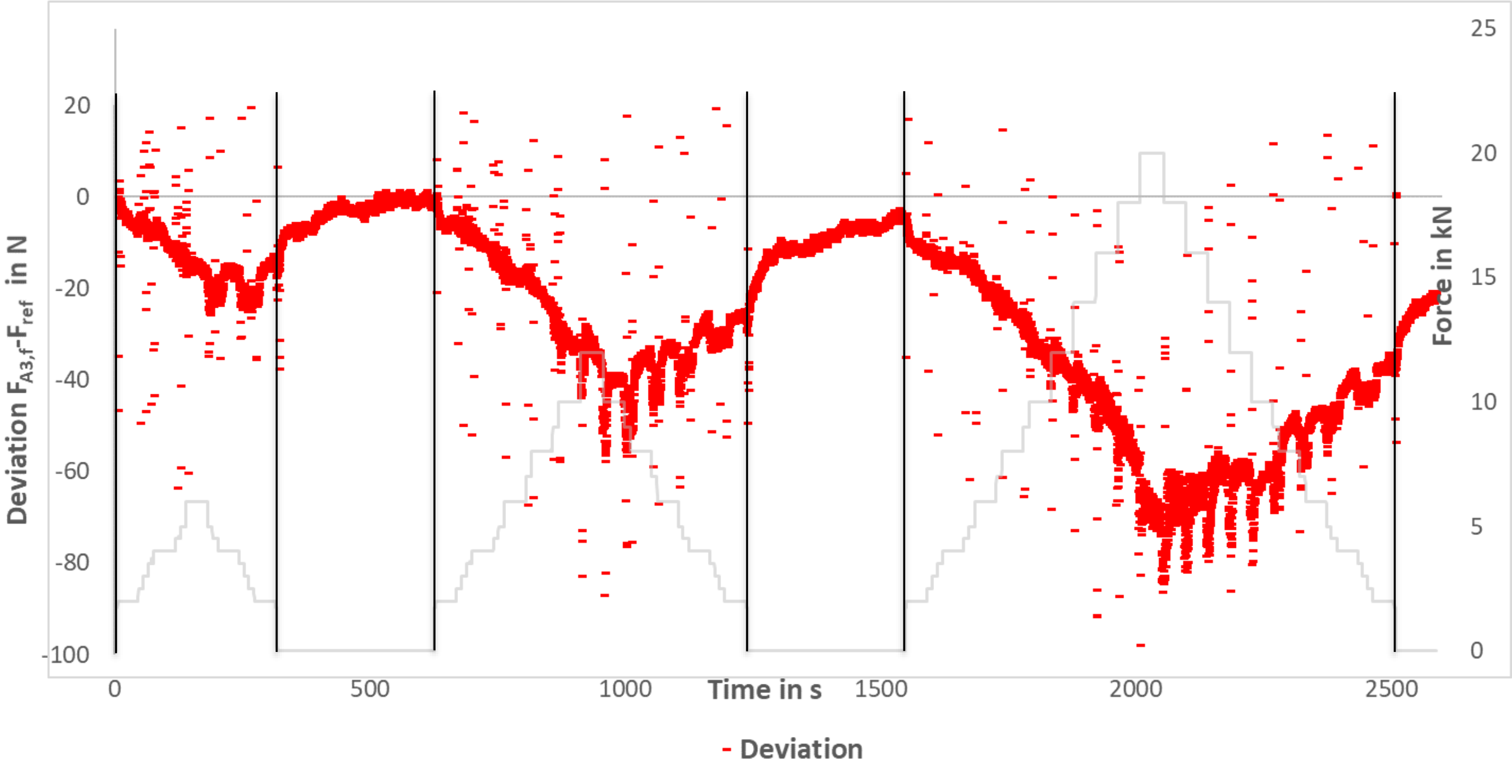
Time dependent behaviour is <u>not</u> reproducable

Time dependent behaviour - Correction



- DC Amplifier – Dewetron DAQP STG
    - Filter: 300 kHz
    - Samplerate: 1 kHz
- Load change time: 2.3 seconds
- Stabilization time: < 0.3 seconds

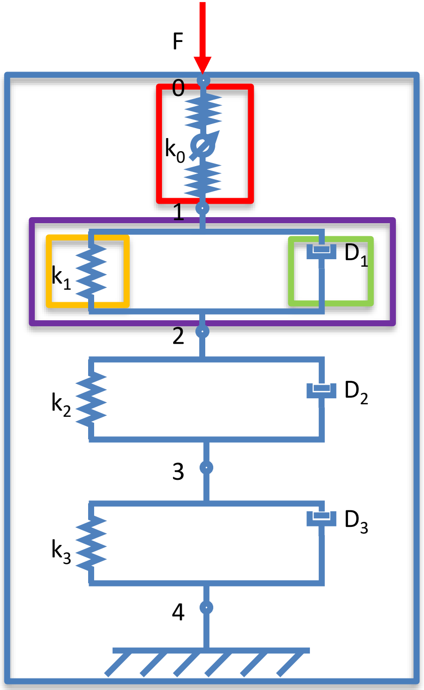
Time dependent behaviour - Correction



Agenda

- Introduction
- Sensitivity
- Time dependent behaviour
- **Rheological Model**
- Temperature
- Practical model

Rheological Model



Hooke element

$$\delta = \frac{F}{k}$$

Dashpot

$$\frac{d\delta}{dt} = \frac{F}{D}$$

Kelvin-Voigt element

$$\delta = \frac{F}{k}\left(1 - e^{-\frac{k}{D}t}\right)$$

Extended Hooke element

$$\delta = \left(1 - d(F)\right) \cdot \frac{F}{k}$$

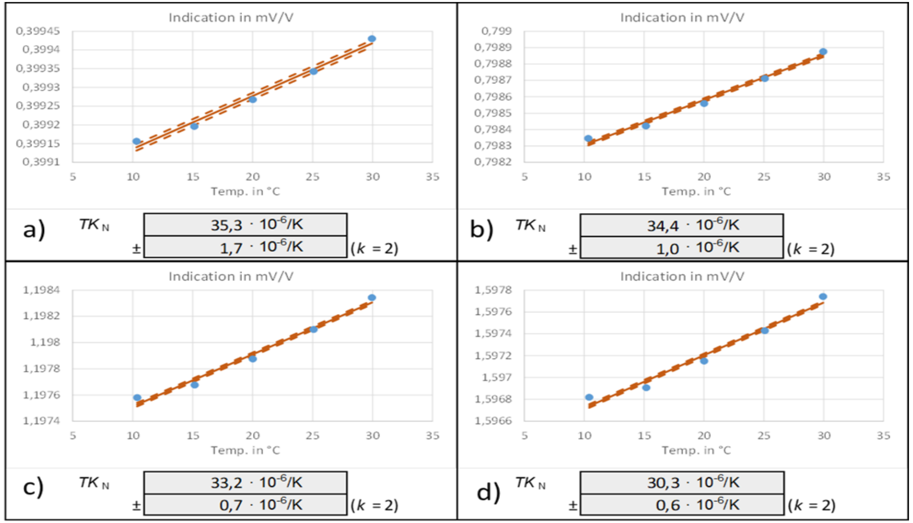
Generalized Kelvin model

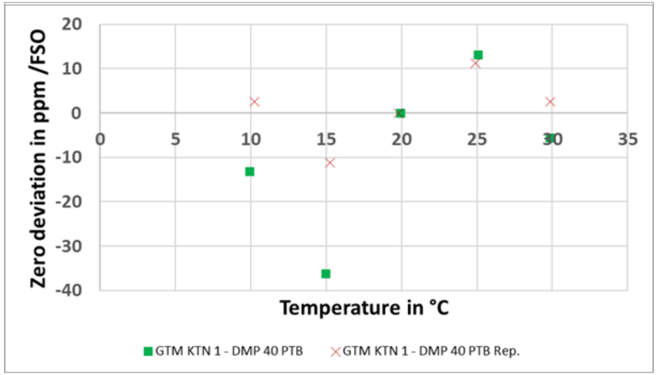
$$\delta = \left(1 - d(F)\right) \cdot \frac{F}{k_0} + F\left[\left(\frac{1}{k_1} - \frac{1}{k_1} e^{-\frac{k_1}{D_1}t}\right) + \left(\frac{1}{k_2} - \frac{1}{k_2} e^{-\frac{k_2}{D_2}t}\right) + \left(\frac{1}{k_3} - \frac{1}{k_3} e^{-\frac{k_3}{D_3}t}\right)\right]$$

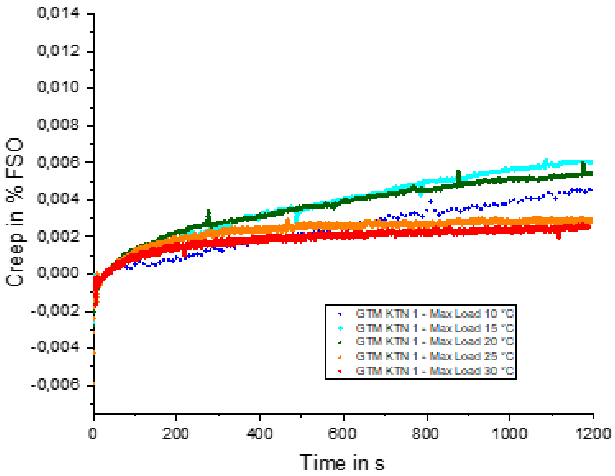
Agenda

- Introduction
- Sensitivity
- Time dependent behaviour
- Rheological Model
- **Temperature**
- Practical model

Temperature







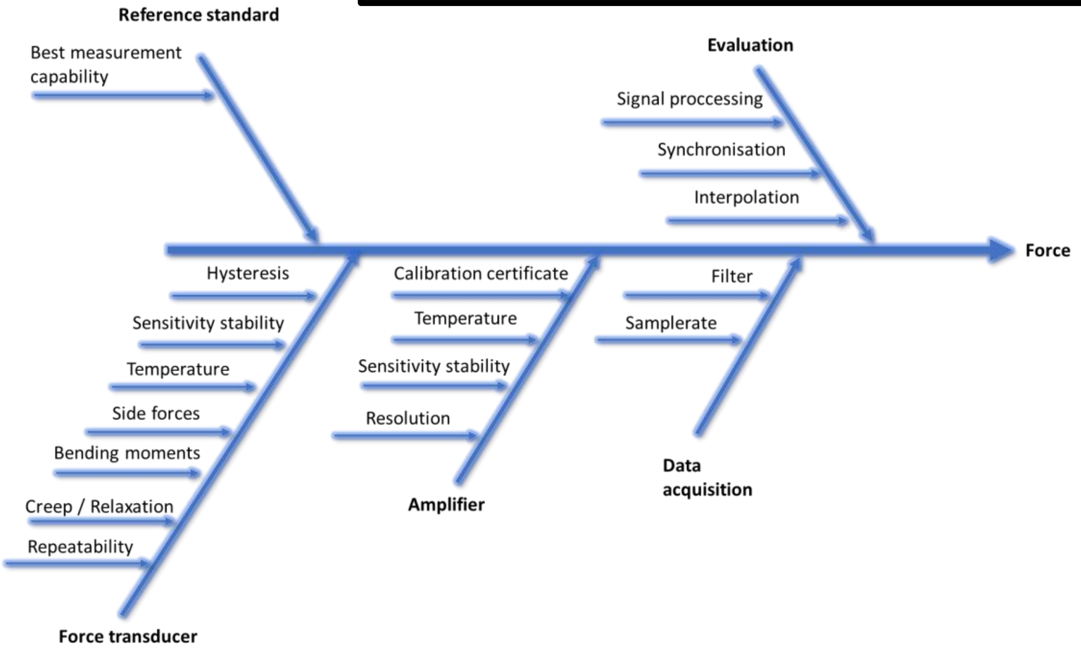
- Linear dependency on sensitivity
- Zero signal compensated
- Creep behaviour subsides earlier with increasing temperature

Agenda

- Introduction
- Sensitivity
- Time dependent behaviour
- Rheological Model
- Temperature
- **Practical model**

Practical model

$$F_{Tra} = R' \cdot X_{instant}^3 + S' \cdot X_{instant}^2 + T' \cdot X_{instant}$$



$$F = F_{Tra} \cdot \prod_{i=1}^{N} K_i$$

$$K_i = \left(1 + \frac{\delta x_i}{|x_i|}\right)$$

18SIB08 ComTraForce is a Joint Research Project within the European Metrology Research Programme EMPIR.

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
Bundesallee 100
38116 Braunschweig

Jonas Sander
Telefon: 0531 592-1268
E-Mail: jonas.sander@ptb.de
www.ptb.de

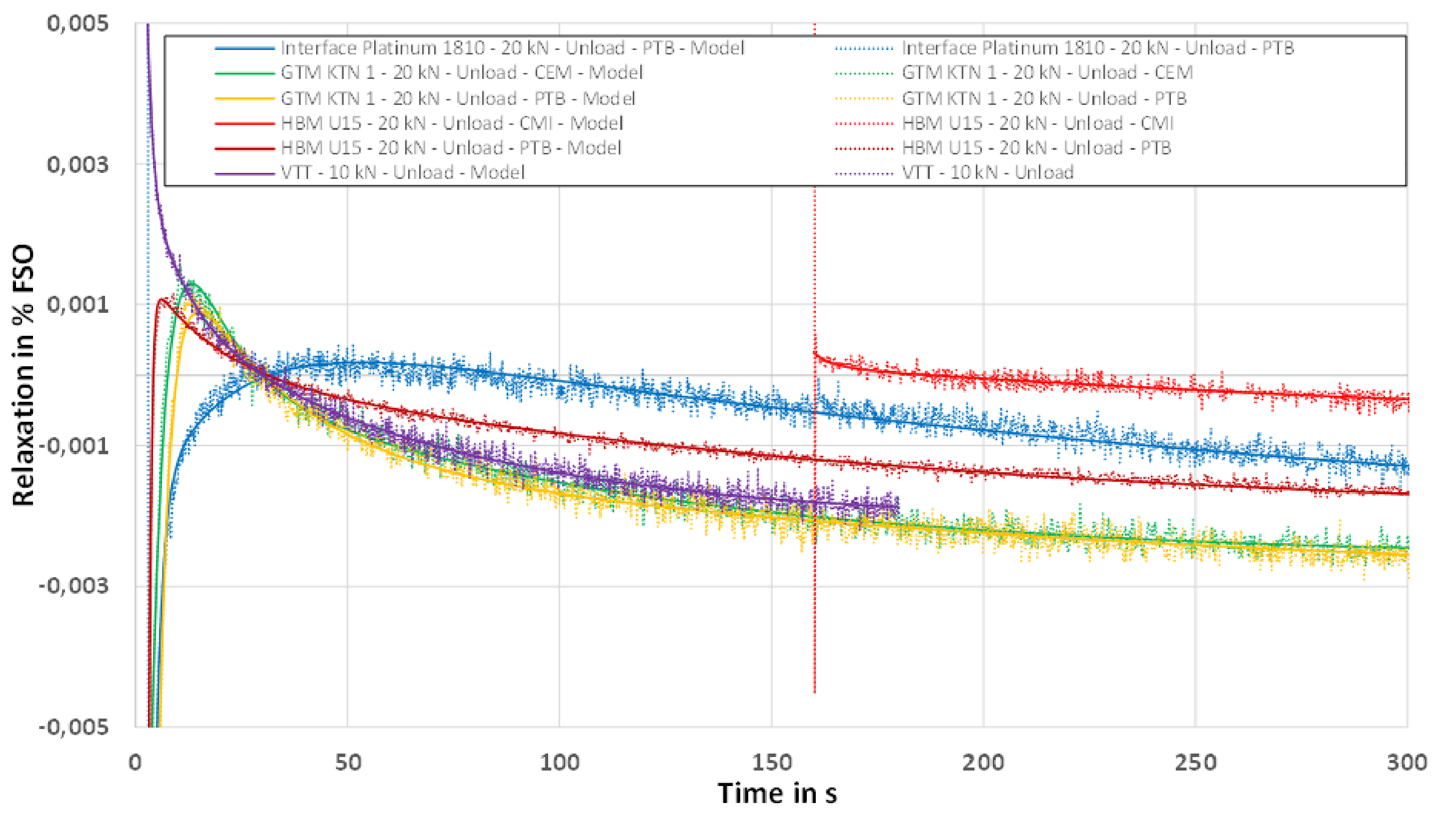
Date: 02/23

BACK UP

Time dependet behaviour - Investigation

Unloading creep behaviour of class 00 strain gauge transducers

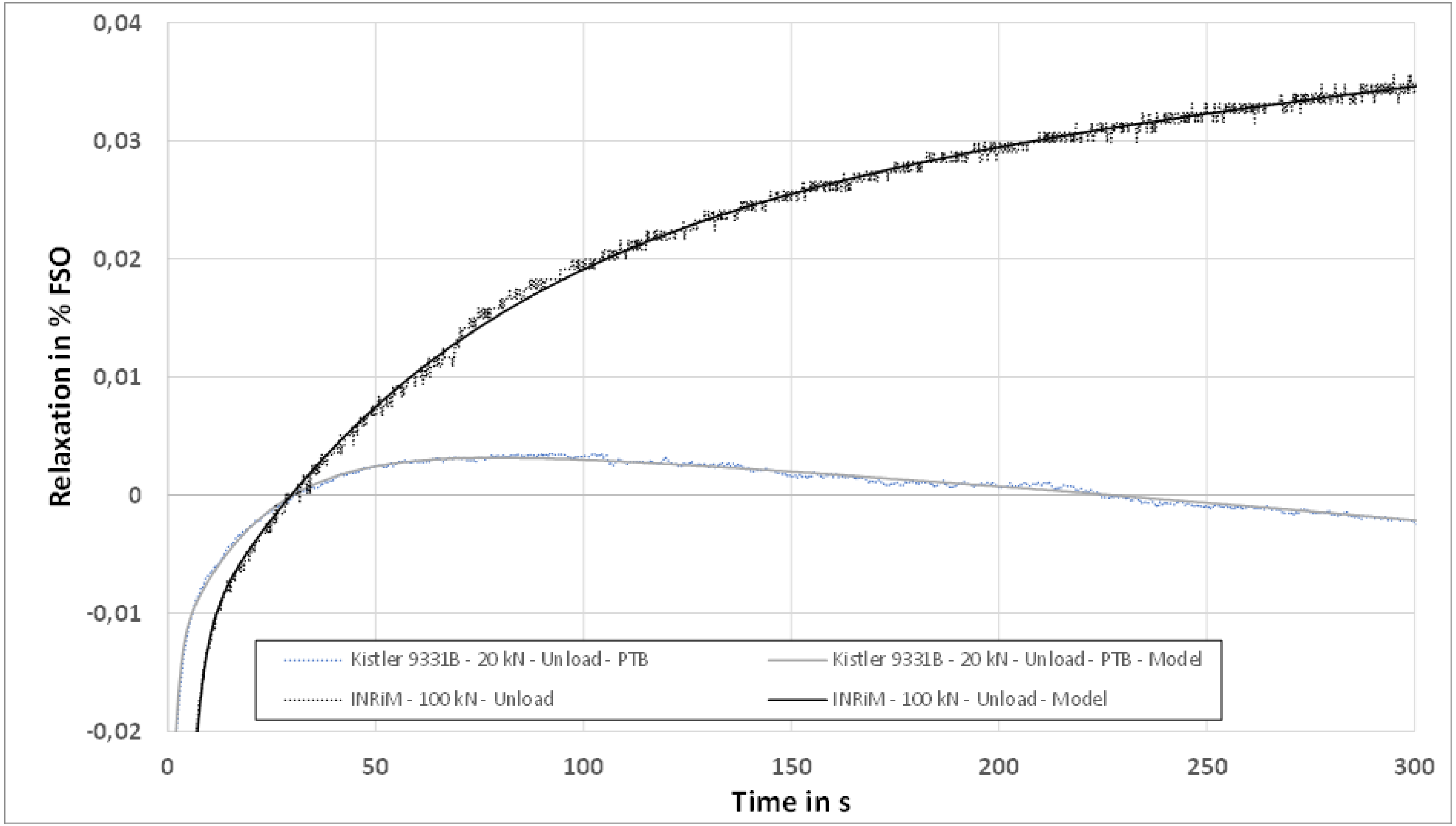
- Relative unloading creep from 0 to 300 seconds after unloading
- Creep behaviour slightly different than loading creep
- Magnitude same as loading creep!
- Filter of amplifier influences the values directly after relieve of the load (~1 s)
- Less disturbance than in the loading creep measurements



Time dependent behaviour - Investigation

Unloading creep behaviour of class 05 strain gauge and piezoelectric transducers

- Relative unloading creep from 0 to 300 seconds after unloading
- Creep behaviour slightly different than loading creep (strain gauge)
- Creep behaviour differs strongly from loading creep (piezoelectric)
- Magnitude same as loading creep! (strain gauge)



Time dependent behaviour - Correction

- Creep error is subtracted from the raw signal in each time step
- Creep error is estimated in each time step iteratively, considering the creep history!
- Prerequisite: Before the correction the creep is either at an exactly known value or zero!

$$F_{A_{3,cor}}(t_i) = F_{A_{3,raw}}(t_i) - \delta x_{\mathrm{creep}}(t_i)$$

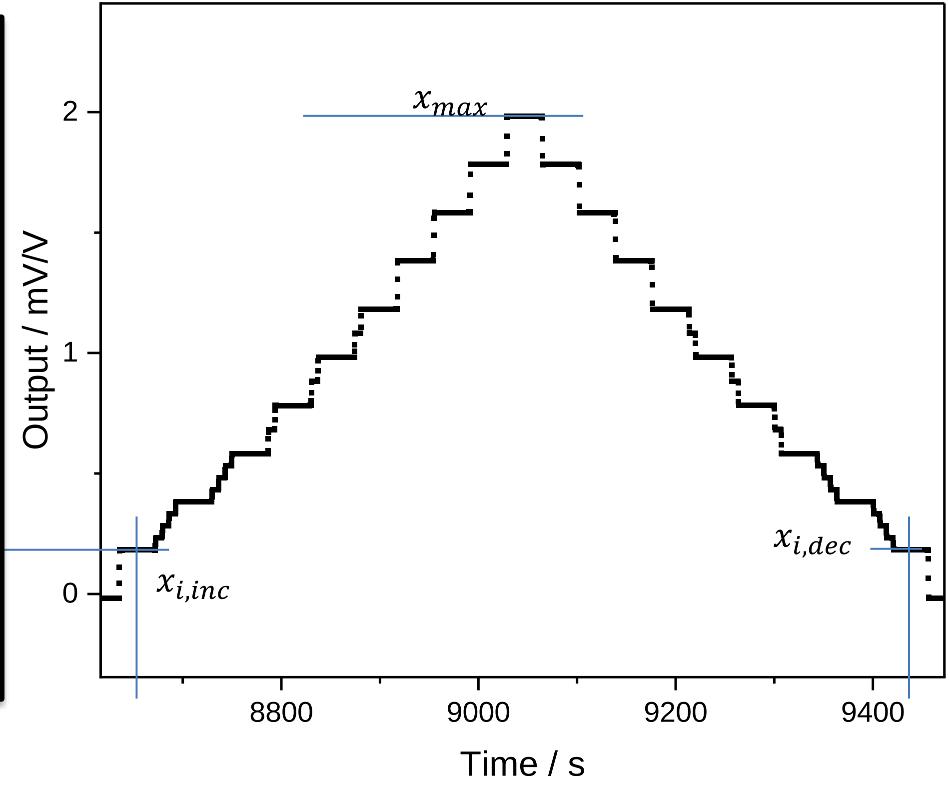
$$\delta x_{\mathrm{creep}}(t_i) = \sum_{k=1}^{k=3} a_k \left[F_{\mathrm{A}_{3,\mathrm{cor}}}(t_{i-1}) - e^{-\frac{t_i}{\tau_k}} \sum_{j=0}^{i-1} \left(F_{\mathrm{A}_{3,\mathrm{cor}}}(t_j) - F_{\mathrm{A}_{3,\mathrm{cor}}}(t_{j-1}) \right) e^{\frac{t_j}{\tau_k}} \right]$$

$$with\colon F_{A_{3,cor}}(t_0) = F_{A_{3,raw}}(t_0)$$

Agenda

Hysteresis

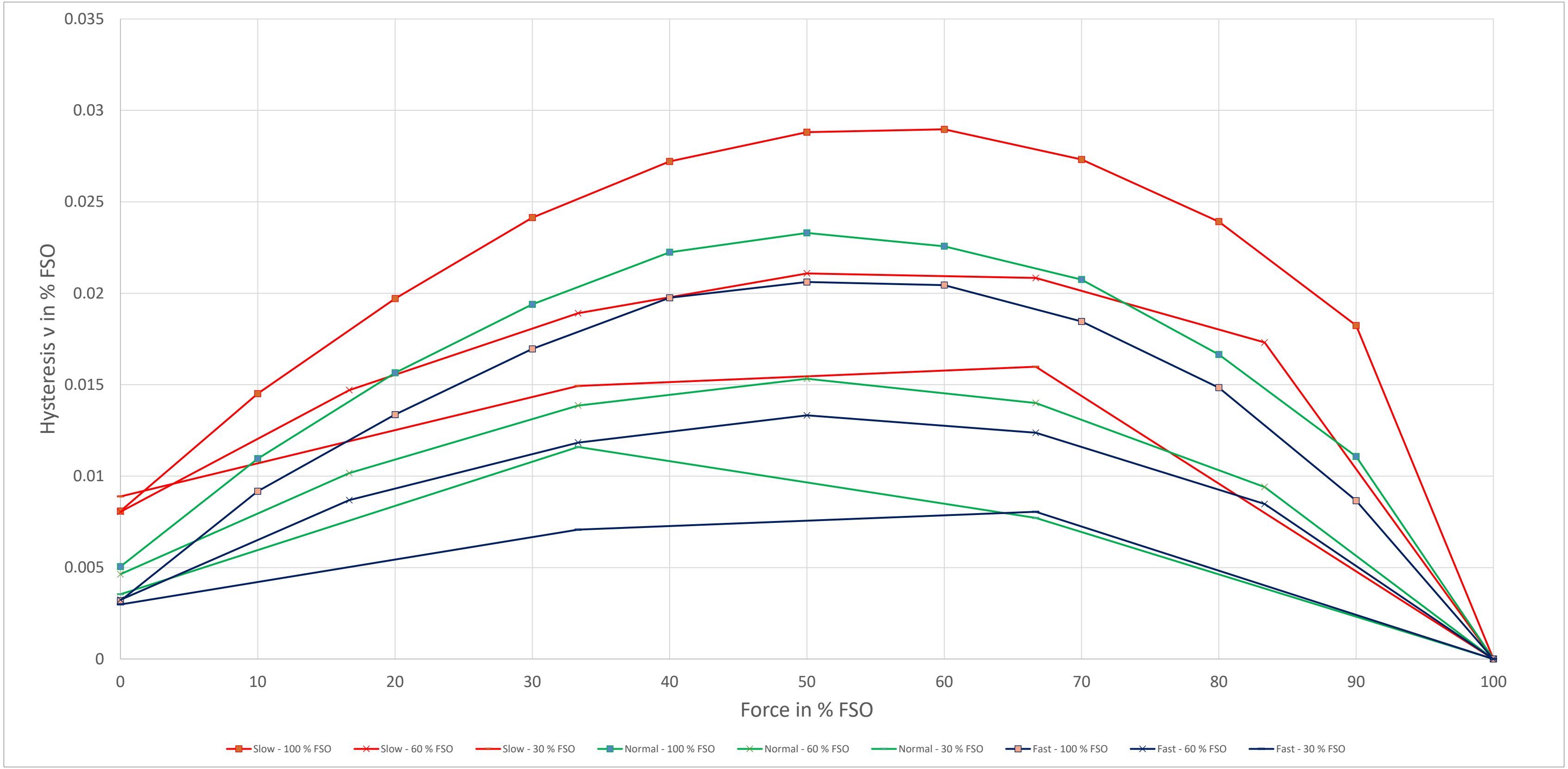
- Three different force time profiles
  - 1 second dwell
  - 30 second dwell
  - 600 second dwell at max Force
- with three different maximum forces
  - 30 % max Force
  - 60 % max Force
  - 100 % max Force



$$\nu = x_{i,inc} - x_{i,dec}$$

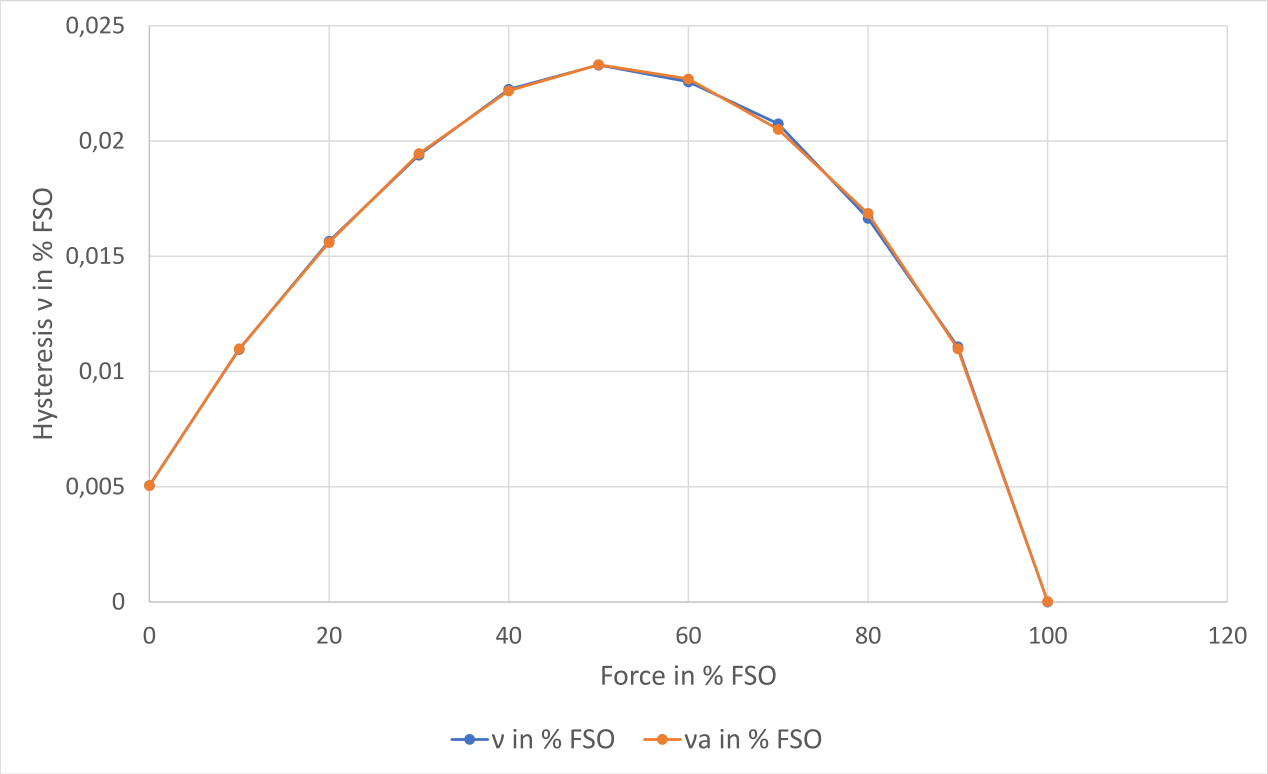
$$\nu_{FSO} = \frac{x_{i,inc} - x_{i,dec}}{x_{max}} \cdot 100\ \%$$

Hysteresis



0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Hysteresis v in % FSO
0
10
20
30
40
50
60
70
80
90
100
Force in % FSO
Slow - 100 % FSO
Slow - 60 % FSO
Slow - 30 % FSO
Normal - 100 % FSO
Normal - 60 % FSO
Normal - 30 % FSO
Fast - 100 % FSO
Fast - 60 % FSO
Fast - 30 % FSO

Hysteresis



Hysteresis error may be fitted with a 6th degree polynomial

$$\nu_a = A \cdot F^6 + B \cdot F^5 + C \cdot F^4 + D \cdot F^3 + E \cdot F^2 + G \cdot F + H$$

Time dependent behaviour - Correction

- Designed for dynamic calibration of dynamic test stands
- Nominal capacity of 20 kN
- Full brigde for force measurement