ComTraForce – EMPIR project for continuous and dynamic force measurements

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Project Structure

**WP 1 Review of machines and standards (NPL)**
- Overview of conditions and measurement systems at existing test stands

**WP 3 Traceability chain for static and continuous force (NPL)**
- Development of methods for continuous force measurement and multi-component transducers

**WP 2 Transfer standards – modelling & digital twin (PTB)**
- Development of advanced practical models of force measuring devices
- Development of digital twins

**WP 4 Traceability chain for dynamic force (USStutt)**
- Development of methods for dynamic force measurement

**WP 5 Procedures & recommendations (PTB)**
- Develop calibration procedure for continuous and dynamic loads in testing machines
- Validation of the procedures

**WP 6 Creating impact (PTB)**
- Interaction with stakeholders
- Publications, Workshops
- Input to standardisation

**WP 7 Management & coordination (PTB)**

**ComTraForce**

Sept. 2019

Corona extension

Feb. 2023
Key Objectives

- Review of existing testing machines and standards
- Developing advanced models and digital twins of force measuring devices
- Developing a force traceability chain for metrological services for static, continuous and dynamic forces
- Developing new recommendations and standards for static, continuous and dynamic forces
- Facilitation of the take up of the developed procedures for end users

The **overall aim** of the project was to provide calibration services, in the field of mechanical and material testing, with the methods and guidelines needed for comprehensive traceability of static, continuous and dynamic force measurements.
WP 1 Roadmap

1. General Industry
   - Provide traceable dynamic (continuous, sinusoidal, and shock) force standards incorporating uncertainty for all areas of industry
   - Targets:
     - Improved testing machine verification/calibration (time influence)
     - Calibration infrastructure for piezoelectric force transducers
     - Traceability & uncertainty (< 0.5%) for fatigue machines, including resonance ones
     - Traceability for high-frequency industrial applications e.g., automotive crash testing, acoustics, fatigue testing

2. Materials Testing
   - Provide traceability to the SI for dynamic force and strain to improve accuracy in the area of materials testing
   - Targets:
     - Develop explicit procedures/uncertainty model for low frequency structural testing
     - Clearly defined continuous/dynamic force machine verification procedures
     - Better guidance on machine/specimen alignment
     - Guidance on effects of alignment and temperature on continuous/dynamic machine calibration

Deliverables
- Deliverable 1

WP 2 Selection of the Transfer Standards

Manufacturer information of the force transducer to be examined

<table>
<thead>
<tr>
<th></th>
<th>A_{PK}</th>
<th>B_{DMS}</th>
<th>C_{DMS}</th>
<th>D_{DMS}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal force</td>
<td>F_{nom}</td>
<td>20 kN</td>
<td>20 kN</td>
<td>25 kN</td>
</tr>
<tr>
<td>Measuring range</td>
<td>0.1 - 100 %</td>
<td>10 - 100 %</td>
<td>2 - 100 %</td>
<td>10 - 100 %</td>
</tr>
<tr>
<td>Interpolation error</td>
<td>f_{i}</td>
<td>0.5 % FSO</td>
<td>0.02 %</td>
<td>0.02 % FSO</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>v</td>
<td>0.06 %</td>
<td>0.025 % FSO</td>
<td>0.09 %</td>
</tr>
<tr>
<td>Rotation</td>
<td>b</td>
<td>--</td>
<td>0.045 %</td>
<td>--</td>
</tr>
<tr>
<td>Repeatability</td>
<td>b'</td>
<td>--</td>
<td>0.023 %</td>
<td>0.005 %</td>
</tr>
<tr>
<td>Zero point deviation</td>
<td>f_{0}</td>
<td>--</td>
<td>0.01 %</td>
<td>--</td>
</tr>
<tr>
<td>Creep</td>
<td>--</td>
<td>0.01 %</td>
<td>0.01 % in 20 min</td>
<td>0.01 %</td>
</tr>
<tr>
<td>Temperature error on the characteristic value</td>
<td>T_{K_{i}}</td>
<td>-0.02 %/K</td>
<td>0.001 %/K</td>
<td>0.0005 %/K</td>
</tr>
<tr>
<td>Temperature error on the zero signal</td>
<td>T_{K_{0}}</td>
<td>--</td>
<td>0.001 %/K</td>
<td>0.00025 %/K</td>
</tr>
<tr>
<td>mass</td>
<td>m</td>
<td>0.33 kg</td>
<td>3.1 kg</td>
<td>4.1 kg</td>
</tr>
<tr>
<td>Nominal temperature range</td>
<td>B_{T_{nom}}</td>
<td>--</td>
<td>17 to 27 °C</td>
<td>-40 to 120 °C</td>
</tr>
<tr>
<td>Operating temperature range</td>
<td>B_{T_{G}}</td>
<td>-40 to 120 °C</td>
<td>10 to 35 °C</td>
<td>-55 to 90 °C</td>
</tr>
<tr>
<td>Fundamental frequency</td>
<td>f_{g}</td>
<td>45 kHz</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Rigidity</td>
<td>N/S</td>
<td>1.6 kN/µm</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

- Amplifier for strain gauge: DMP 40 and DMP 41 from HBM
  Dewetron DAQP- STG, Bridge-B
- Amplifier for PK: MGC Plus with ML01B (Voltage measurement)
- Charge amplifier for PK: Typ 5011B from Kistler
WP 2 Advanced Model Static - Strain Gauge

Best measurement capability (bmc)

\[ F_{SG} = F_{ref} \cdot \prod_{i=1}^{11} K_i \]

with

\[ \prod_{i=1}^{11} K_i = K_c \cdot K_T \cdot K_{st} \cdot K_{zero} \cdot K_{rot} \cdot K_{rep} \cdot K_{hys} \cdot K_{inp} \cdot K_{res} \cdot K_{amp} \cdot K_{bmc} \]

and

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

Forces

- c – creep
- t – temperature
- st – sensitivity stability
- zero – zero point deviation
- rot – rotation
- rep – repeatability
- hys – hysteresis
- inp – interpolation deviation
- res – resolution
- amp – amplifier
- bmc – best measurement capability
WP 2  Advanced Model Static - Piezoelectric

Best measurement capability (bmc)

Interpolation deviation
Hysteresis
Repeatability
Rotation
Sensitivity stability
Temperature
Drift

Piezoelectric transducer

Calibration certificate
Temperature
Sensitivity stability

Charge Amplifier

Calibration certificate
Temperature
Sensitivity stability
Resolution

DAQ

Force
WP 2 Advanced Model Continuous

Best measurement capability (bmc)

Interpolation deviation
Hysteresis
Sensitivity stability
Temperature
Tilt
Side forces
Bending moment
Creep / Relaxation

Calibration certificate
Temperature
Sensitivity stability
Resolution
Amplifier

Semplerate
Filter
Synchronicity

Data acquisition

Force transducer

Force
WP 2 Advanced Model Continuous

Best measurement capability (bmc)

Interpolation deviation
Hysteresis
Sensitivity stability
Temperature
Tilt
Side forces
Bending moment

Force transducer

Calibration certificate
Sensitivity stability
Resolution
Amplifier

Creep / Relaxation => Kelvin-Voigts model

WP 2 Dynamic Force Measurement

Frequency dependency of the sensitivity

\[ S_f = S_{f_0} \left(1 - \frac{\mu_{te}}{k_c} \cdot \omega^2\right) \]

Transfer function - Force & Acceleration vs. mass

- 1 kg
- 2 kg
- 3 kg
- 4 kg
- 7 kg

Frequency vs. force and acceleration for different masses.
WP 2 Dynamic Force Measurement

- **Setup**

  - **Electrodynamic shaker**
    - Manufacture: LDS
    - Model: V850T-SPA-K
    - Sine force peak: 17792 N
    - Effective mass of moving element: 14.34 kg
    - Velocity sine peak: 2.0 m/s
    - Acceleration sine peak: 1225.8 m/s²

  - **Laser interferometry**
    - Manufacture: Polytec
    - Laser: He-Ne
    - Wavelength: 633 nm
    - Laser class: 2
WP 2 Dynamic Force Measurement

Different methods of the acceleration measurement
Definition of the stiffness and damping coefficient

**Measurement**: sided
**Position**: on the shaker
**Sensor**: Piezoelectric
**No. of signal**: 1 Top / 1 Bottom

**Measurement**: axial
**Position**: on the shaker
**Sensor**: Piezoelectric
**No. of signal**: 24 Top / 1 Bottom

**Measurement**: sided
**Position**: on the plate
**Sensor**: Laser
**No. of signals**: 24 Top / 16 Bottom
WP 2 Advanced Model Dynamic

WP 2  Digital Twin

Real Space

- force profile
- temperature

DCC

Virtual Space

- measurement uncertainty
- prognosis
- stability

Uncertainty Calculation

PYTHON

FEM (ANSYS)

Database

Deliverable 3

WP 3 Traceability Chain Static / Continuous

Diagram demonstrating force against time profiles for four different steel testpieces
WP 3 Proposed force traceability method

**Step 1**
Develop continuous force calibration reference standard
- Top class force transfer standard, based on static calibration results
- Additional short-term creep test and associated performance criteria

**Step 2**
Calibrate proving instrument against reference standard
- Range of force application rates, determine sensitivity differences
- Proving instrument also to be calibrated statically

**Step 3**
Use proving instrument to calibrate testing machine force display
- Range of force application rates, determine machine errors
- Care needed in data synchronisation
WP 3 Proposed force traceability method

Methodology for continuous calibration of testing machine force indicator has been developed

- Reference standard criteria proposed
- Proving instrument calibration procedure
- Testing machine calibration procedure

Issues identified to have major effect on results

- Data synchronisation – procedure should be as automated as possible
- Instrumentation settings

Traceability Chain for Multicomponent Forces and Moments

MULTI COMPONENT CALIBRATION TRACEABILITY

SI

FSM Force Traceability

Angle and Dimension Traceability

National Level

MCM Multicomponent Calibration Machine

Industrial Level

Multicomponent Application

Source: https://doi.org/10.5281/zenodo.7844513

A multicomponent force and moment transducer (MCFMT) during calibration
WP 4 Traceability Chain Dynamic

Specimen-like elastic element [1]

Bending strains
Force
Temperature
Masses

Dynamometer: Fatigue resistant, 1.6580QT

Accelerometer on additional masses

Stiffness Adapter: Fatigue resistant, EN AW 7075-T6

\[ c = \frac{E \cdot A}{l} \]

140 kN/mm

WP 4 Traceability Chain Dynamic

Introduction
Preliminary Work
Calibration Work
Uncertainty
Appendices

WP 5 Procedures & Recommendations

- Develop calibration procedure for continuous and dynamic loads in testing machines
- Validation of the procedures

State of the art:
- force standard machines for static forces
- force transfer standards & measurement procedures for static forces
- static force calibration of testing machines

Aim of ComTraForce:
- developments for traceable continuous & dynamic forces
- force transfer standards & measurement procedures for continuous & dynamic forces
- continuous & dynamic force calibration of testing machines
WP 5 Procedures & Recommendations

State of the art:
- force standard machines for static forces
- force transfer standards & measurement procedures for static forces
- static force calibration of testing machines

Aim of ComTraForce:
- developments for traceable continuous & dynamic forces
- force transfer standards & measurement procedures for continuous & dynamic forces

National Metrology Institute
Accredited Calibration Laboratory using Transfer Standards
Calibration Laboratory using Reference Standards
Inhouse Calibration Laboratory Using Working Standards
Inspection and Measurement Instruments in Industry
Metrological Infrastructure Industry

• Develop calibration procedure for continuous and dynamic loads in testing machines
• Validation of the procedures

https://www.ptb.de/empir2019/comtraforce/information-communication/deliverables/
Impact by Networking

ComTraForce – EMPIR project for continuous and dynamic force measurements
Summary

- Traceable validated methods for continuous time-dependent forces
- Traceable validated methods for measuring dynamic forces
- Development of advanced force measurement devices with input to industrial market
- Developed methods and techniques enable compensation of dynamic and temperature influences
- Calibration laboratories can extend their accreditation to continuous and dynamic forces
- The project is successful because force traceability is extended from static to continuous and dynamic force through comprehensive traceable force measurement methods
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INRIM, Italy
NPL, UK
RISE, Sweden
VTT, Finland
TUBITAK, Turkey
CU, UK
USTUTT, Germany
ZAG, Slovenia
INMETRO, Brazil

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