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DIGITAL TWIN CONCEPT FOR FORCE METROLOGY SERVICES

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Abstract – In frameworks of EMPIR project ComTraForce the Digital Twin (DT) concept of force measurement device is developed. The aim of DT is to shade static, continuous as well as dynamic calibration processes, preserving data quality and collecting calibration data for improved decision making. To illustrate the developed DT concept a prototype realisation for static and continuous force calibration processes is developed, involving simulation with ANSYS engineering software. The focus of the current work is placed on the data connection between the physical device and the DT. The DT model is validated using traceable measurements.

Keywords: digital twin, force measurement, finite-element-method, measurement uncertainty, traceability, data transfer

1. INTRODUCTION

In accordance with the Industry 4.0 requirements for automation and data exchange, EMPIR project ComTraForce 18SIB08 [1] was taken to develop prototype of DT of a traceable force transfer standard. The DT is built on the basis of models for static and continuous force transfer standards including measurement uncertainty determination. DT is a management and certification paradigm [2] which allows in real time to predict, optimise and maintain desired functionality of complex systems. Whilst the DT literature has proliferated immensely in recent years, covering various topics such as through-life monitoring and manufacturing, the widely accepted concept of DT was proposed by Grieves [3] and Vickers [4], which identified the following main components: the physical object in real space, the virtual object / model in virtual space and the connections of data and information that ties the virtual and real products together, as shown in Figure 1.

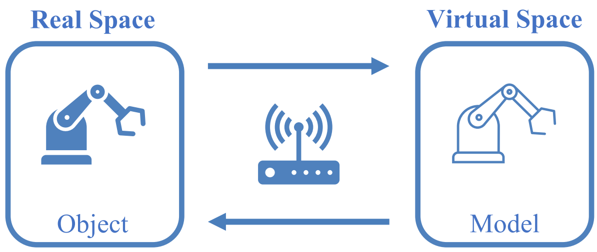

Figure 1 Digital Twin concept of Grieves [3] and Vickers [4]

Other authors have reviewed and refined the DT definition [5] establishing a stronger link to Industry 4.0 and its enabling technologies: "DT is the virtual and computerized counterpart of a physical system that can be used to simulate it for various purposes, exploiting a real-time synchronization of the sensed data coming from the field".

From standardization work perspective, the ISO 23247-1 defines DT as manufacturing fit for purpose digital representation of an observable manufacturing element with synchronization between the element and its digital representation [6]. A digital format for the secure transmission and unambiguous interpretation of measurement data is defined in [7].

All DT definitions lead towards a digital representation, or models, of the physical object, process or service, also called Virtual Twins. The Virtual Twin is able to predict in real time the characteristics of the Real Twin with specified precision, which is established by the needs of each specific application for accuracy and decision speed [8]. The DT models are divided in three main categories:

- Physics based models (FEM, structural health monitoring, computational inverse methods);

- Data driven model (Machine Learning, digital signal processing, statistical inverse methods);
- Surrogate model as a combination of both.

A comprehensive overview on the DT model requirements is given among others in [8]. The DT model must be able to reflect the physical processes, influencing the output parameters. The accuracy of the predicted values should be high enough to be beneficial for the desired application. The speed of computation must be high enough for real time execution of the DT. Whilst FEM is using current knowledge and off-line measurement results to predict the output of the Real Twin, in DT context, the Virtual Twin requires real time sensors information gathered through the entire operational lifetime [8].

The aim of the current work is to develop the prototype of the DT for static and continuous force calibration processes. To achieve this aim, the FEA is chosen for the force measurement device output prediction. However, in order to achieve the required speed of DT execution several simplifications on the geometry, material behaviour, etc. are made. The details on development of the FE-model for the static and continuous calibration test with the focus on applicability for DT are provided. The way to connect the force measurement device information with the developed FE-model in an automatised way is presented. The approach for the physical-to-virtual and virtual-to-physical data communication is discussed.

Current paper is structured as following. In section 2 the overview of the related literature is given; section 3 presents a concept of DT of force measurement device, providing the focus on DT definition as well as listing the Digital Metrological Twin requirements. The creation of FEM model of the force measurement device is presented in section 4. The data communication approach between the FEM model and the real device is discussed in section 5. In section 6 the main conclusions of the work are summarised, providing the outlook on the planed DT developments.

2. RELATED WORK

In [9] a DT based on FEM approach to predict the complex micro-mechanical evolutions of materials during multistage processes on example of sintering is proposed. The focus is placed of the interoperability and robustness of the material data between various FE-steps. Tensile test system, equipped with the optical system to capture full-field geometric images was investigated in [10]. The DT based on FE modelling is used to ensure that the data, collected by the experimental system, can be used quickly and efficiently to proof theoretical models and to determine required material properties. In [11] the FEM is used for characterisation of 5 MN·m torque transducer. The FEM is implied to extend the calibration range up to 5 NM·m level. The method for determination of The Young's modulus is presented, the defined value is used in FE-model. The simulation shows the deviation of the output signal form the measured one to 17.5 %. Another simulation of a 4 kN·m self-built torque transducer in MATLAB Simulink is reported in [12]. The simulation method was developed with the focus on giving the recommendations regarding element type and size. Also different modelling strategies of the strain gauges are proposed. The deviation of the simulated and measured results of 1.3 % was achieved. The best FEM element type for the modelling is the fully-integrated hexahedral element with quadratic formulation was proposed.

3. DIGITAL TWIN OF FORCE MEASUREMENT DEVICE

DT in metrology requires specific definitions, clearly stating obligatory requirements for measurement traceability. German National Metrology Institute PTB developed the following definition of the Digital Metrological Twin (DMT) [13]: a Digital Metrological Twin is a numerical (prediction) model that depicts a specific measurement process and indicates an associated measurement uncertainty for a specific measurement value, which is traceable to the units of the international system of units. Moreover, it complies with the requirements that:

- the measurement uncertainty is calculated according to recognized standards [14];
- all input parameters are traceably determined and stated with the corresponding measurement uncertainty [14];
- and it is validated by traceable measurements.

The following definition provides the requirements, by fulfilment of which, the generated DT output can be utilised for metrological services.

DMT is the enhanced way to generate, process and store data on calibration device with the time stamp. Beyond the concept of a digital calibration certificate (DCC) [15], where calibration data is collected, DMT will allow to correlate the force transducer output with the physical processes occurring in the transducer and allows its seamless connection with the factory of the future. All relevant data in such database is traceable and represented with SI units, if applicable. This data can be used by the end user in the further life-cycle of the calibrated device. Furthermore, the use of DMT will allow calibration system to learn from itself and improve the measurements uncertainty for future calibration processes with the same device as well as deliver data to derive correlations between calibration conditions, mounting, etc. as well as output values for devices of the similar class.

The concept of force measurement device DMT covers three main functions, see Figure *2*. The first function allows for a prompt reading of selected device information, e. g. sensors reading (temperature, strain sensors). Here the key role plays the speed of communication as well as preservation of data quality. The physical-to-virtual communication is realised by reading of relevant device information from a DCC for force measurement. The second function of DT is the data processing by means of one of three models, mentioned above. The main outcome of data processing is the prediction of force measurements device output as well as measurement uncertainty.

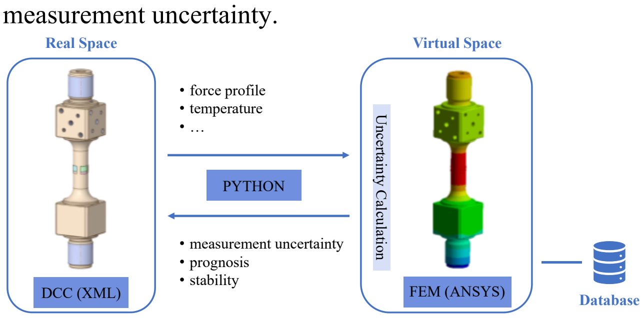

Figure 2 Concept of DMT of force measurement device

For the DMT it is crucial that the input / output parameters are traceable and are stated with the corresponding measurement uncertainty. Additionally, the validation of the static, continuous and dynamic models within DT must be performed using traceable measurements. The third function enables saving of the modelled output which can be used to recalculated uncertainty in future calibration procedures.

As the first prototype of the DMT of force measurement device, the FEM model of the transducer is developed. At the first attempt the models of static and continuous calibration processes are developed in FE simulation software ANSYS, see section 3. The synchronization between the force measurement device and its DT is performed after each calibration process in form of reading and subsequent update of the DCC by means of Python programming. The calculated with DT device output as well as measurement uncertainty are saved after each calibration in a database. The corresponding database of DT represents the device history, allowing the DT to recall any state of the device history.

4. FEM ANALYSIS

4.1 Numerical model set up

The development of the transducer design is discussed in details in [16]. More details on the creation of digital construction of the transducer are provided in [17]. The transducer is mounted on the 20 kN calibration machine available at PTB. The machine is working according to the principle of the direct loading. The weight forces generated by the mass bodies are introduced to the transducer via a load hanger. The load bodies are arranged in such a way that transducers with nominal forces of 2 kN can be calibrated in 12.5 % steps and with nominal forces of 5 kN, 10 kN and 20 kN in 10% steps according to DIN EN ISO 376.

The geometrical model was simplified to the transducer itself and strain gauges in order to enable fast run of the simulation, see Figure 3. The material of the transducer is quenched alloyed steel 1.6580 QT. The strain gauge is simulated as a polyimide substrate and a grid made of constantan. The contribution of the glue layer is neglected. The transducer is partially meshed with the tetragonal TET10 elements with the size of 2 mm size. The strain gauges as well as the transducer region, close to strain gauges placement are meshed with hexagonal Hex20 elements to insure better mesh consistency. The element size of 0.6 mm was set for HEX20 elements. Further element size refinement below 0.6 mm led to no significant improvement of the simulated output signal.

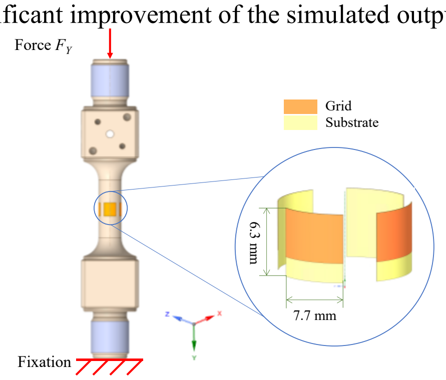

Figure 3 Simulation model of force transducer and strain gauges

4.2 Static force model

To investigate influence of the static forces on the measured signal of transducer the static mechanical analysis of ANSYS was set. The concentrated force F_Y was applied stepwise in axial direction to reproduce the loading during calibration experiments, until the nominal values of 20 kN was achieved. Fixation boundary conditions ($U_X = U_Y = U_Z = UR_X = UR_Y = UR_Z = 0$) were applied on the opposite side of the transducer, simulating transducer mounting in the loading train. Elastic material properties of 1.6580 steel [18], polyimide [19] and constantan [20] were defined.

4.3 Continuous force model

During continuous calibration test, output signal variation with time under application of the constant load is observed. In force measurement industry this phenomenon is defined as creep [21]. One of the physical mechanisms, leading to the output signal variation is the superposition of the thermoelastic strains in the load cell itself as well as materials of the strain gauge. To simulate this effect the transient coupled field analysis in ANSYS was performed. Key role of the model plays the definition of the thermal material properties, such as heat expansion coefficient, specific heat and thermal conductivity, [18], [19] and [20]. Simulated compression load was applied in axial direction for 20 seconds up to maximal nominal value of 20 kN and subsequently held for 600 second. The full unloading was simulated for 20 seconds as well and the final strain was measured after 600 seconds, capturing unloading creep.

4.4 Simulation Results

To validate developed FEM model the static as well as creep calibration experiments according to ISO 376:2011-09 with the nominal force of 20 kN were performed. Comparison of the simulated output of the strain gauge bridge after static loading profile with the experimental measurements and analytical solution [17] is presented in Figure 4.

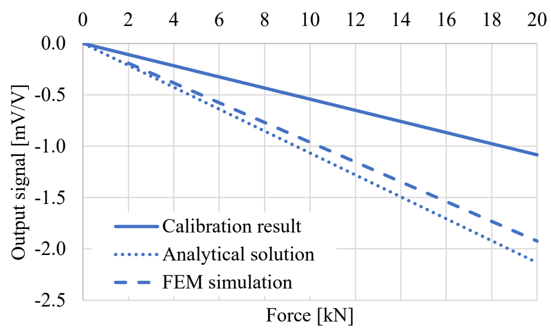

Figure 4 Simulated and experimentally measured output signal

The discrepancy between the simulated result and analytical solution lies by around 9.8 %. For the reliable DT functionality, the precision must be improved, for example through the consideration of the glue layer contribution. Measured creep results showed output signal deviations due to creep of 0.214 % and 0.211 % after loading and unloading correspondingly. The simulated results reported 0.45 and 0.47 % output signal deviations for loading and unloading. Thus, both static as well as continuous simulations show almost double signal in comparison to the measured values.

5. DATA COMMUNICATION

5.1 Data Input

The physical-to-virtual communication is realised by reading of relevant device information from a DCC in XML format. The benefit of direct use of data from DCC is that the results data is provided in SI format. The data transfer from DCC ensures that the input parameters of DT are traceable and stated with the given measurement uncertainty, as required by the definition of DMT. The reading is realised with the Python programming. Use of Python enables automation of the data reading, simulation, and data post-processing in ANSYS environment [22]. The collected data is transferred as loading and boundary conditions of FE-simulation in form of the Python command.

5.2 Data output and storage

The calculated with the DT force transducer data is used to calculate measurement uncertainty considering effects from mechanical system, surrounding the force measurement device. In future developments, the collection of the selected information to a database will be realised. Each dataset will be completed with the metadata stating the calibration time. In this way the continuous calibration history of the force measurement device will be created.

6. CONCLUSIONS AND OUTLOOK

Digital replica of the force measurement device based on FEM model is created in this work. The first results of force transducer output for static and continuous calibration processes are obtained. The static results show good agreement with the analytical solution. Almost double discrepancy from the experimental results points out on the necessity of checking the bridge wiring, which can affect results interpretation. In future works it is planned to extend DT model with the dynamic calibration process models. The developed concept of the DT will be applied to estimate the effect of not proper mounting, material properties as well as parasitic force components on the measurement uncertainty. By combining the obtained simulation data with the experimental one and analysing both with the Machine Learning algorithm, the surrogate model will be created.

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