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PRIMARY CALIBRATION SYSTEMS FOR MULTICOMPONENT FORCE, MOMENT AND VIBRATION TRANSDUCERS

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1. INTRODUCTION

In recent decades, there has been a significant rise in the need for mechanical multicomponent transducers, in particular for the measurement of forces, moments and vibrations. These types of devices are commonly employed in various fields, including industrial automation, civil and aerospace engineering, and machine operations and applications in quality and production engineering. However, a specific traceability chain for these types of transducers is still lacking, internationally, along with standardized calibration methods. For this reason, their traceability is becoming increasingly necessary, as well as a current priority, as indicated in the emerging metrology requirements for the future in the strategy documents of the relevant Consultative Committees of BIPM [1,2]. The main problems related to the calibration of these transducers are the simultaneous generation of different components necessary to represent the typical use of these transducers, the costs in developing ad-hoc calibration machines, the large number of tests to get a suitable experimental plan to reach the lowest required uncertainty level and the lack of suitable calibration and uncertainty assessment procedure. At INRiM, multicomponent transducers, systems and methods for their calibration are under development. Such procedures allow to simultaneously evaluate the main and transverse (or cross-talk) sensitivities, thus providing the required metrological traceability, in static and dynamic domains. These systems involve the use of force or vibration primary reference standards integrated with tilted plates. Preliminary experiments showed consistent results. The feasibility of these systems can be exploited in the future to improve the current standards.

2. PRIMARY STANDARDS INTEGRATED WITH TILTED PLATES

Primary force and vibration standard systems can generate a reference vector along a single direction. In the case of force standard machines, the reference force is generated by a series of weights suspended in the air in the Earth’s gravitational field, whereas in the case of vibrations, the reference dynamic amplitude is usually generated by an electrodynamic shaker equipped with a reference accelerometer. To generate known reference multicomponent forces, moments or vibrations, and find a compromise to all the previously-stated issues, primary uniaxial force and vibration calibration systems are equipped with tilted plates. In this way, the reference vector quantity is decoupled along the three directions through simple trigonometrical laws. The advantage of these methods is that they can be implemented on the current primary standards and machines, thus it is not necessary to devise and develop ad-hoc calibration systems. On the other hand, the main limit is the inability to independently apply the different components, which depend on the input variables of the system, that are, the applied reference uniaxial force or vibration, the angles of tilt and rotation and the misalignments, and consequently higher uncertainties are found. These are, in general terms, in the order of a few parts per cent.

2.1 Generation of reference multicomponent forces and moments

The method employed to generate various force and moment components in the system involves integrating existing force standard machines with a pair of hardened steel plates set at an angle. Figure 1 illustrates how the multicomponent force and moment transducer under calibration is positioned between these plates. By adjusting the angle of tilt, rotating the transducer around its axis, and misaligning it with the machine loading axis, the reference force produced by the force standard machine can be decomposed. This results in the generation of vertical and side forces as well as bending and torsion moments. The equations for these six reference forces and moments acting on the multicomponent force and moment transducers under calibration can be derived easily using basic trigonometric principles. In this setup, the tilted plates and the transducer reference systems are labelled as *xyz* and *x’y’z’*, respectively. Both systems are centered at the center of the transducer. The variables considered are the tilt angle of the plates, the height of the transducer, the anticlockwise rotation angle (from the top) of the transducer, and the misalignments along the *x*- and *y*-axis, respectively. Further details with relevant equations and a comprehensive description of how these factors contribute to the forces and moments applied to the multicomponent transducer during calibration can be found in [3].

According to reference equations, the generated side forces and moments increase as the height of the transducer, tilt angles, and misalignments increase. However, it is crucial to carefully select appropriate geometrical boundary conditions to ensure the overall stability of the structure during loading. This stability is heavily reliant on the friction between the tilted plates and the transducer surfaces. To address this concern, four pairs of hardened steel (34CrNiMo6) tilted plates with angles of 0°, 1°, 2°, and 3° have been designed and fabricated for installation in the deadweight force standard machine at INRiM. Each plate measures 200 × 200 × 70 mm³ and weighs approximately 30 kg. The dimensions and tilt angles of these plates have been meticulously chosen to fit the load platform of the machines and to ensure system stability under high loads, while considering the steel-to-steel friction between the tilted plate and a typical transducer. An example of the 1 MN deadweight force standard machine integrated with tilted plates can be seen in figure 1.

To ensure the precise determination of the point of force application and to prevent the generation of unwanted components, a double-knife joint is placed between the loading frame of the machine and the upper plate. This joint allows for two degrees of freedom along the directions perpendicular to the vertical axis, effectively eliminating and compensating for any spurious components.

The uncertainties linked to the applied reference forces and moments are assessed following the GUM [4]. This involves propagating the individual uncertainty contributions of the input parameters. As reported in [3], the uncertainty associated with the vertical force is significantly lower than that of the other components, which typically range between 4% and 8%. This difference is attributed to the greater number of input parameters involved in the calculations for the other components.

The primary contributors to the combined standard uncertainty are the two misalignments along the two directions, representing the major individual contributions. Following these, the uncertainty contribution due to the rotation angle constitutes the third significant factor. The angle of tilt and the height of the transducer contribute as the fourth and fifth factors, respectively, to the overall uncertainty. The uncertainty contribution arising from the reference force generated by the force standard machine is negligible compared with the other terms.

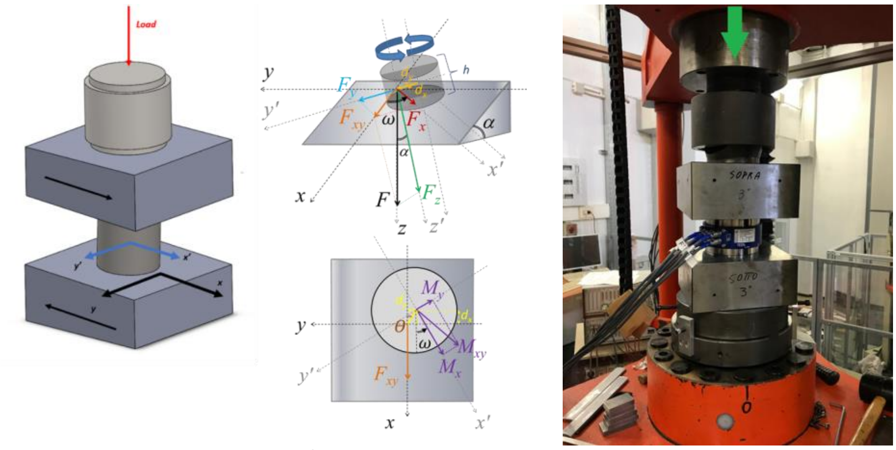

Figure 1. Primary force standard machine integrated with tilted plates

2.2 Generation of reference multicomponent dynamic accelerations

Similarly for three-axis accelerometers, the calibration set-up consists of a single-axis vibrating table on which aluminium inclined planes are screwed, allowing to generate a projection of the reference acceleration along three axes simultaneously. A vertical sinusoidal acceleration acts as the reference acceleration along the vertical *z*'-axis, resulting in proportional accelerations along the three axes on the inclined plane. By applying simple trigonometric laws, the reference accelerations detected by the 3-axis accelerometer along its three sensitive axes can be determined [5].

To perform the calibration, the inclined plane is attached to the vertical vibrating table and the 3-axis accelerometer under calibration is fixed to the inclined plane along the vertical axis of excitation. Figure 2 depicts a configuration of the calibration setup, where the 3-axis accelerometer under test is aligned using an aluminium centring mask screwed to the inclined planes before measurements. Once the MEMS is securely positioned, the centring mask is removed, and the calibration is performed. In dynamic conditions, the overall experimental expanded uncertainties of the primary factors are approximately 2 %. The dominant source of uncertainty is attributed to the rotation angle. To enhance accuracy, future endeavours will focus on enhancing the alignment system, potentially by implementing an automated system instead of a centring mask. This improvement aims to minimize the uncertainty associated with the rotation angle.

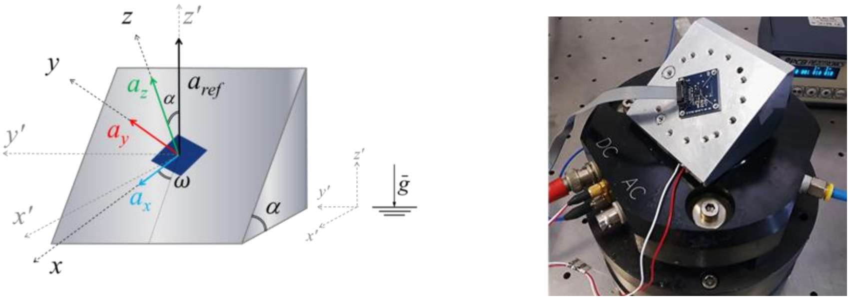

Figure 2. Primary vibration calibration system integrated with tilted plates

3. CALIBRATION OF MULTICOMPONENT TRANSDUCERS

In an ideal multicomponent transducer, every output is only dependent on the relevant component. Nevertheless, in real conditions, this condition is not true, since transducer outputs interact with each other and transverse sensitivities might play a crucial role. In such conditions, each component y_i can be expressed as a linear combination of the n outputs x_j and can be written in general matrix form as **y**=**Ax**, where **y** is a 1×n reference force/moment or dynamic acceleration matrix, **x** is a 1×n matrix of the multicomponent transducer outputs, and **A** is a n×n coefficients matrix, also called exploitation matrix, which is the matrix actually used by end-users to convert transducer outputs into a physical quantity. Diagonal terms correspond to the main sensitivities while out-of-diagonal terms represents cross-talks. Considering the N linearly independent sets of calibration values deriving from the experimental calibration plan, ***y*** and ***x*** become a N×n matrix. With simple calculations, matrix **A** can be evaluated from

$$\boldsymbol{A} = [\boldsymbol{x}^{\boldsymbol{T}}\boldsymbol{x}]^{-1}\boldsymbol{x}^{\boldsymbol{T}}\boldsymbol{y} \tag{1}$$

Also, uncertainties are evaluated according to GUM [4] and reported in matrix form as comprehensively shown in [3,5,6]. The considered uncertainty contributions are the reference applied components (which in turn depend on the reference primary vertical component system, tilt and rotation angles, and misalignment in the case of forces and moments), reproducibility, resolution and zero drift.

From this matrix form mathematics derives Ronald Fisher's seminal work from 1926 [7] which states that the calibration experimental plan has a significant impact on the measured sensitivities and related uncertainties. In fact, when the calibration experimental plan comprises a set of reference components with high correlations between them, it leads to a poorly conditioned matrix. Inverting such a matrix produces poorly defined outcomes with increased uncertainty. Therefore, a suitable experimental strategy, connected to the needed level of accuracy and uncertainty, must be established in calibration operations. If the lowest level of uncertainty is desired, a full factorial experimental plan with a large number of applied reference components should be used, resulting in longer times and higher costs. However, if higher uncertainties are tolerable, fewer measurements can be carried out.

3.1 Calibration of multicomponent forces and moments transducers

As previously mentioned, it is crucial to employ an experimental plan that encompasses all potential combinations of forces and moments to ensure the resulting matrices are not affected by poor conditioning. Additionally, it is important to avoid correlations between variables to satisfy certain assumptions relevant to uncertainty calculation and propagation. Given that a full factorial experimental plan cannot be applied to this calibration system due to the interdependence of its components, an alternative approach is adopted for forces and moments. The first step involves defining values for each independent parameter, allowing for a feasible number of measurements while maximizing the variety of combinations to minimize correlation between applied components [6]. The proposed experimental plan involves placing the transducer in four positions, each determined by different misalignment combinations along *x*- and *y*-axis respectively (0 mm, 0 mm; 8 mm, 0 mm; 0 mm, 16 mm; 16 mm, 8 mm). Additionally, the transducer is positioned at four different tilt angles (0°, 1°, 2°, and 3°) and subjected to seven rotations (0°, 45°, 90°, 135°, 180°, 270°, 360°). Four different load levels (10%, 50%, 80%, and 100% of the maximum applied force) are also utilized. This combination results in a total of 448 measurements (4 positions × 4 tilt angles × 7 rotations × 4 loads). The chosen misalignments and tilt angles are carefully selected to ensure system stability and avoid overloads of the multicomponent transducer outputs. To further evaluate uncertainty and incorporate positive torsion moments in line with ISO 376 standards, an additional 72 calibration conditions are included. These conditions introduce negative misalignments (up to -16 mm). Consequently, a total of 520 measurements are carried out.

The measurement campaign lasts around 24 hours (equivalent to 3 days of work), primarily due to the longer alignment procedures compared to the ISO 376 standard one [8]. This comprehensive experimental plan is adopted to minimize associated uncertainties. Although the duration of this measurement campaign is relatively long, it should be contrasted with the time required for six uniaxial calibrations (one for each axis) following ISO 376. Assuming a 2-hour duration for each uniaxial calibration, a total of 12 hours would be needed. However, this approach lacks information about cross-talks, which the proposed method accounts for. Once calibration is performed, data are acquired and analysed according to equation (1) and the exploitation matrix can be derived together with the associated expanded uncertainty matrix.

3.2 Calibration of 3-axis accelerometers

For calibration of 3-axis accelerometers, a reference transducer measures the acceleration along the vertical axis. This reference transducer is calibrated against INRiM primary standard, and data is acquired using an acquisition board NI 4431 (sampling rate of 50 kHz) integrated in the PC, and processed through LabVIEW software to provide the reference value in m/s². The calibration is conducted at 11 frequencies ranging from 5 Hz to 3 kHz and in static conditions, with a reference acceleration of nearly constant amplitude (10 m/s²) generated along the vertical axis for 10 seconds. Measurements are carried out in 48 configurations, obtained by fixing the MEMS accelerometer at the center of the vibrating table with different angles of rotation (with steps of 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°) and inclination angles (with steps of 0°, 15°, 35°, 55°, 75°, and 90°, with respect to horizontal axis). The experimental design ensures no correlation between the independent variables and the constant reference acceleration.

During dynamic conditions, spurious oscillating components along the *x′*-, *y′*-, and *z′*-axis of the reference system must be considered. These components result from the vibrational modes of the inclined aluminium plates and the small horizontal motions of the shaker. To account for these effects, the spurious components along the reference system axes are decomposed and summed to the theoretical reference accelerations along the transducer axes (*x*, *y*, *z*) based on wave interference laws. This correction ensures that the reference theoretical accelerations are adjusted, taking into account the amplitudes and phase differences of the spurious components along *x′*-, *y′*-, and *z′*-axis relative to the reference signal. The average amplitude of the spurious components is approximately 10% of the reference acceleration. The full set of equations is described in [5].

In this way, the calibration process is performed: 3-axis accelerometer data are collected and analyzed using equation (1) from the different boundary conditions, leading to the derivation of the exploitation matrix alongside its corresponding uncertainty matrix.

4. CONCLUSIONS

This study introduces a cost-effective and accessible calibration system along with a suitable calibration procedure for multicomponent force and moment transducers and 3-axis accelerometers, utilizing uniaxial primary standard machines equipped with tilted plates. The calibration method allows for the decoupling of the vertical reference component acting on the transducer under calibration, and enabling the application of bending and torsion moments by misaligning the force and moment transducer placed between the tilted plates. One major advantage of this approach is the elimination of the need to develop specialized calibration systems. However, a limitation arises as the reference components cannot be independently applied and depend on specific input variables. These variables include the applied vertical reference component, tilt and rotation angles, and misalignments in the case of multicomponent forces and moments.

The application of this method at INRiM involves equipping primary force standard machines and vibration calibration systems with tilted plates: the first featuring angles up to 3°, while the second allows for a wide range of angles. Regarding the forces and moments, this limit angle is chosen cautiously to ensure the stability of the entire structure under load, which relies on the steel-to-steel friction between the tilted plates and transducer surfaces. To enhance the value of this angle and subsequently increase the maximum applied side forces and torque (which are linearly dependent on the tilt angle value), it becomes necessary to increase the friction between the contact surfaces of the tilted plate and the transducer.

Uncertainty assessment associated with the applied reference components is conducted according to GUM in matrix form. The relative expanded uncertainties related to side forces and moments are approximately 6 % at maximum capacity, while those related to dynamic acceleration components are in the order of 2 %. By analyzing individual uncertainty contributions, it is observed that the primary contributors to the uncertainties in generating are the rotation and tilt angles, while misalignment plays a significant role in bending and torsion moments. Reducing these uncertainties by an order of magnitude could lower the relative expanded uncertainties to around 0.5 %. This improvement can be achieved by enhancing the alignment processes concerning rotation angles and misalignments.

The calibration systems here described allow issuing calibration certificates within ILAC-P10:07/2020 document [9].

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