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Design and Construction of Metrological Equipment for Torque Sensors with a Carbon-based Measuring Arm

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Abstract: The paper presents a comprehensive design of metrological equipment for torque sensor verification and calibration, detailing the process from conception to construction and highlighting the specifics of the structural design to meet metrological requirements. The measuring device's functionality and the individual structural components are described, as is the methodology for creating a complete product. The paper addresses the crucial issue of measurement uncertainty and the required accuracy, achieved through the construction of a special measuring arm made of carbon material. FEM analyses of the carbon arm are presented and compared with the required metrological accuracies. In addition, we discuss the different properties of various carbon structures in Pre-preg materials used in the construction of the measuring arm and present the results of measurements on such carbon materials. This paper provides a comprehensive insight into the design and construction of metrological equipment for torque sensors, with a focus on its compliance with metrological requirements. The proposed device aims to establish the foundations for primary metrology of torque in Slovakia and has potential applications in a wide range of industries.

Keywords: Metrological equipment, torque, design, composite material, FEM.

1. INTRODUCTION

Torque sensors are widely used in various industries and products. Before use, all sensors used in products require calibration. The calibration system is based on another torque sensor (called etalon) that serves as a standard and must be calibrated regularly to ensure its accuracy and intended use. For this purpose, special metrological devices are used, often designed according to basic physical principles with metal components made of special steel or carbon materials [1]-[7].

In this paper, we present a comprehensive design and innovative methods for the construction of metrological equipment for the verification and calibration of torque sensors. Unlike conventional devices that rely on weight changes, our proposed device also incorporates a change in the force arm and the use of carbon composite materials in its construction to create a moment of force. The design of the device considers not only traditional design aspects, but also metrological aspects and measurements of various characters to obtain data for FEM analyses [8], [9].

The goal of this paper is to detail the process from conception to construction, highlighting the specifics of the structural design to meet the metrological requirements. We describe the functionality of the measuring device, its individual structural components, and the methodology used to construct a complete product. We address the crucial issue of measurement uncertainty and the required accuracy, achieved through the construction of a special measuring arm made of carbon material. FEM analyses of the carbon arm are presented and compared with the required metrological accuracies. In addition, we discuss the different properties of various carbon structures in Pre-preg materials used in the construction of the measuring arm and present the results of measurements on such carbon materials.

The paper provides a comprehensive insight into the design and construction of metrological equipment for torque sensors, with a focus on its compliance with metrological requirements. The proposed device aims to establish the foundations for primary metrology of torque in Slovakia and has potential applications in a wide range of industries.

2. SUBJECT & METHODS

A. *Design of a new measuring system*

To create a moment in the + direction, position the arm vertically and a weight with a known mass will generate a zero moment (Fig. 1). Moving the arm in the direction of the

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**Corresponding author:lubos.kucera@fstroj.uniza.sk (Ľ. Kučera)* arrow changes the position of the weight to the IV quadrant, generating a force moment corresponding to the angle of rotation of the arm. The maximum moment is generated when the arm reaches a horizontal position. On the other hand, if the weight is placed on the other side of the arm and the arm is in a vertical position (the weight is in quadrants I and II), the weight generates a zero moment. When the arm passes through quadrant II in the direction of the arrow, a moment of force is generated in the opposite direction (with the value of the moment -) and the maximum moment is reached when the arm with the weight is in a horizontal position on the left side. Fig. 1 shows the change in the angle of the arm with a constant load weight. The required torque can also be derived by keeping the arm in a constant horizontal position and changing the weights from minimum to maximum, which is the standard method. As described, there are three possible methods for deriving the required torque: changing the angle of rotation of the arm, changing the weight of the weights, or a combination of both. However, due to the required measurement accuracy, which must be at least equal to the maximum torque value with an accuracy of 2000 ± 0.04 N.m, this is a complex problem that presents significant challenges to the design of the device as a whole and to the measurement systems used.

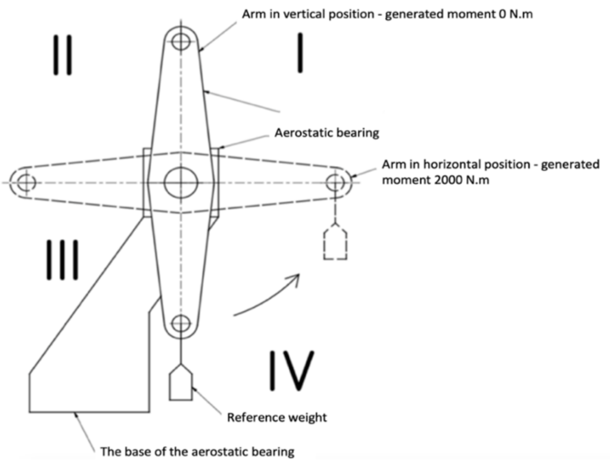

Fig. 1. The principle of torque generation by changing the position of the measuring arm.

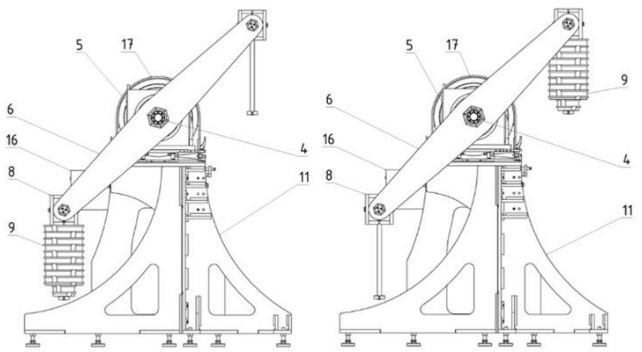

Fig. 2. View of the method of torque generation by changing the position of the measuring arm: left - using quadrant IV, right - using quadrant II.

B. *The principle of the devices and description*

The device (Fig. 3) for calibrating force moment sensors consists of a two-part support frame (11) with an adjustable aerostatic bearing (5) and a control unit (16), a drive (14) on a linear guide (12) with a gearbox (13) and a shaft connected to the calibrated torque sensor (1), a central aerostatic bearing (5) supporting a shaft (4) and a test arm (6) with a test arm pin (10), a secondary bearing (7) with a hinge (8) for hanging weights (9), a mechanical brake (17), and a test arm rotation angle gauge (15) on shafts (3).

The procedure for calibrating force moment sensors is performed by first hanging weights (9) on the test arm (6), stabilizing the vertical position of the test arm (6) with suspended weights (9), and ensuring a zero force moment. Then the force moment sensor (1) is clamped between the connecting accessories (2), and the torque sensor (1) and the test arm tilt angle gauge (3) are reset. The tilt angle of the torque sensor (1) is then changed using the electric drive (14), and the test arm (6) with the weights (9) generates a load on the force moment sensor (1) when the angle is changed.

The value indicated by the force moment sensor (1) is compared with the conventional value of the force moment calculated from the exact length of the test arm (6), the measured value of the angle of rotation (15) and the value of the force caused by the weight of the weights (9). To change the direction of the moment of force, the position of the weights (9) on the arm (6) is changed to either side. To change the magnitude of the moment, the angle of rotation of the arm, the weight of the weights, or both parameters are changed simultaneously.

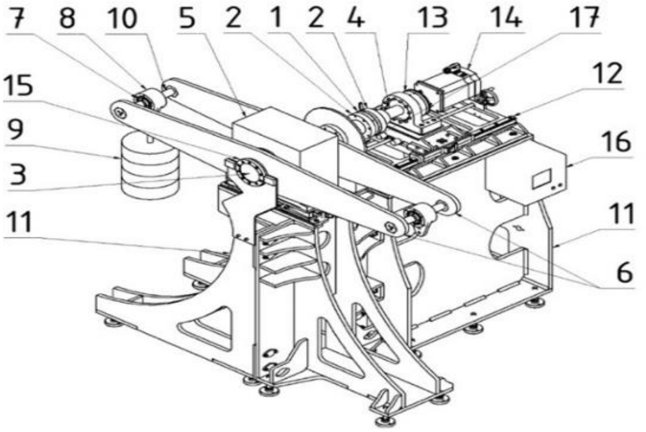

Fig. 3. The basic elements of the equipment: 1 - force sensor; 2 - connecting accessories; 3, 4 - shaft; 5 - aerostatic bearing; 6 - test arm; 7 - secondary bearing; 8 - hinge; 9 - hanging weights; 10 - test arm pin; 11 - supporting two-part frame; 12 - linear guide; 13 - gearbox; 14 - drive; 15 - test arm rotation angle gauge; 16 - control unit; 17 - mechanical brake.

In this way it is possible to generate the required torque continuously in a certain measurement range. Deriving the required torque can be done in three ways: by changing the angle of rotation of the arm, by changing the weight of the weights, or by a combination of changing the angle and the weight of the weights. This is a complex design task due to the required measurement accuracy, which requires the derivation of torque with an accuracy of at least the maximum torque value of 2000 ± 0.04 N.m. This places high demands on the design of the device and the measurement systems used.

C. Procedure for developing a measurement system

In order to create the device, a procedure was developed that begins with the application of the correct physical principle and ends with the final metrological control of the device. The proposed device was designed using the following structural system.

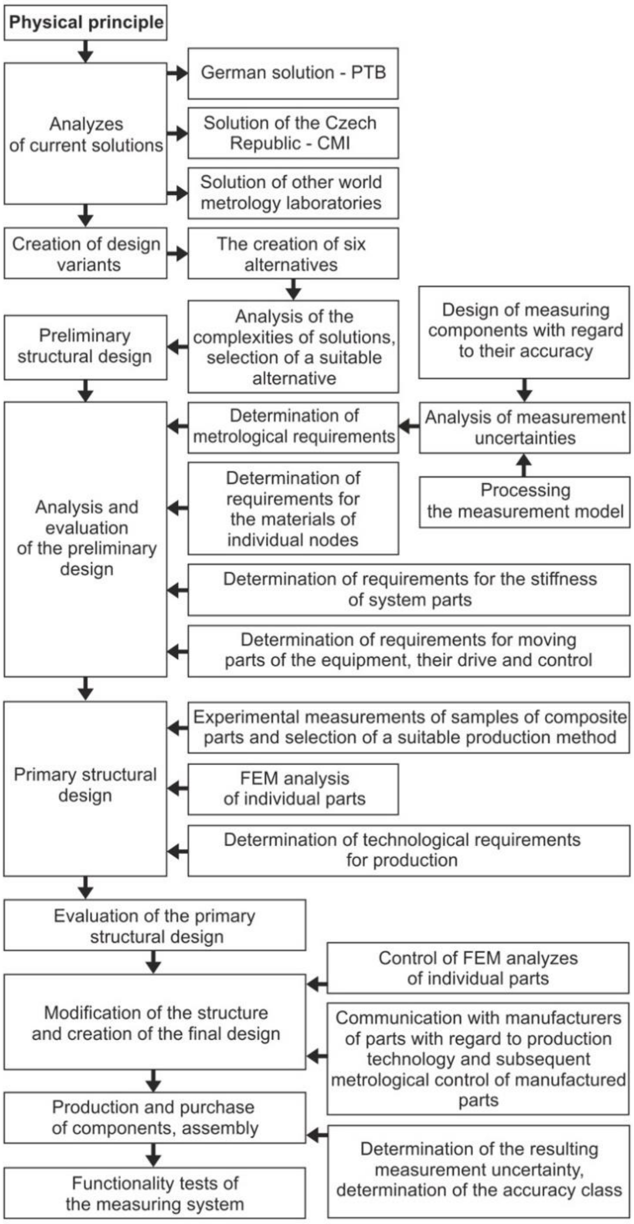

Fig. 4. Development procedure in the creation of new metrological equipment.

D. Influence of metrological requirements on the design of the device

To determine the requirements for stiffness and maximum deformations of each node of the structure before the creation of the primary structural design, metrological requirements are incorporated into the design process. Since the concept of the device is known, all purchased parts are standardized, their accuracy values are known, and we know the required accuracy class of the device, we can create a measurement model. The measurement model is described in [10], and its result is the definition of the requirements for the construction of the measuring arm and other parts of the structure, so that the deformations of the structural nodes have the specified maximum permissible values to meet the condition of the required total measurement uncertainty. Equation 1 describes the proposed model of static force moment generation.

$$M_{E,\alpha}^{(m)} = mg\left(l\cos\alpha + \Delta y_{\alpha}^{(m)}\right) + \Delta m_R\, l_{TR}\, g\cos\alpha + \delta M_{EB} + \delta M_{Emet} \tag{1}$$

where:

- m is the weight of the standard weight in [kg]
- l is the arm length in [m]
- Δm_R is the weight difference (imbalance) in [kg]
- l_{TR} is the coordinate of the center of gravity of the loaded and unloaded part of the arms in [m]
- α is the angle of the arm relative to the horizontal position in [º]
- δM_{EB} is the error of the moment needed to overcome the friction in the bearing in [N.m]
- δM_{Emet} is the error of the force moment caused by the influence of the method in [N.m]

The result of the solution is the estimation of the measurement uncertainty of the standard combined uncertainty (Fig. 5) and the determination of the maximum possible deflection of the measuring arm in the horizontal direction, i.e., in the direction that affects the calculated length of the arm as a function of the angle of rotation of the arm. The limits of $\Delta yMin$ and $\Delta yMax$, i.e., $\pm\Delta y$, are determined by this calculation, and the actual calculated deviation obtained by the FEM analysis of the designed measuring arm must be within these limits (2).

$$\Delta yMin \leq \Delta y \leq \Delta yMax \tag{2}$$

$$\begin{gathered}\Delta yMin = -\frac{lmg\cos\alpha(r.10^{-k}) - 2u\left(M_{E,\alpha}^{(m)}\right)}{mg}\\ \Delta yMax = \frac{lmg\cos\alpha(r.10^{-k}) + 2u\left(M_{E,\alpha}^{(m)}\right)}{mg}\end{gathered} \tag{3}$$

where m is the weight of the standard weight in [kg], l is the arm length in [m], α is the angle of the arm relative to the horizontal position v [º], r.10-k is for the accuracy class CLASS 005, r = 1 and k = 5, u is the required measurement uncertainty in [%]. Fig. 6 shows the field obtained from the measurement model, which indicates the maximum permissible deviation for the proposed arm structure at different generated torque values. As shown in the figure, when the arm is in the horizontal position and the horizontal direction, the maximum deformation occurs at a generated torque of 2000 N.m and is 0.01 mm, satisfying the criterion of being smaller than the permissible limit. The maximum deformation calculated using the measurement model in this condition is 0.08 mm, which gradually decreases to zero at an arm inclination angle of 80°. The figure also shows the relationship between the deformation of the arm in the horizontal direction and the angle of arm rotation, which varies from 0.01 mm to 0 mm at an inclination angle of 80°.

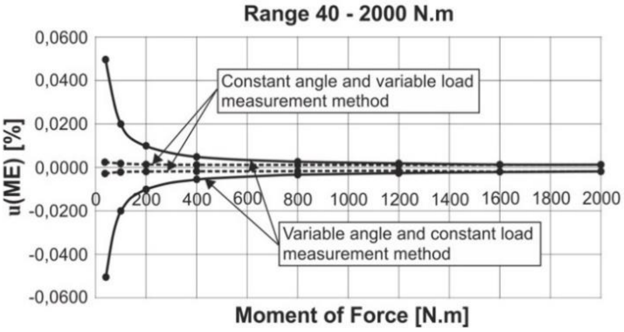

Fig. 5. Measurement uncertainty for two different measurement methods depending on the generated torque.

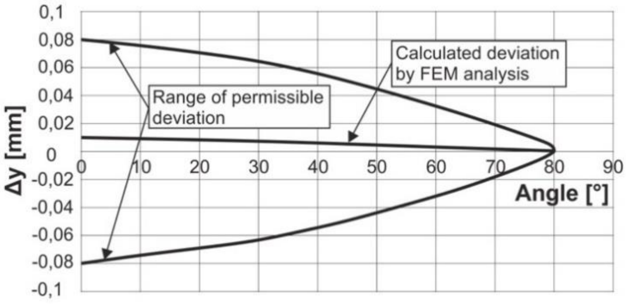

Fig. 6. The course of the permissible deviation and the course of the calculated deviation of the measuring arm made of carbon composite.

E. *Experimental measurement and FEM analysis*

An important part of the device is the measuring arm. The weights are suspended from the measuring arm, and this system generates torque. In deciding on the materials to be used, the research team determined that the measuring arm would consist of two carbon arms. The maximum permissible deformations of the arm in the horizontal state are shown in Fig. 6. This metrological condition must be met with sufficient safety. To fulfill it, it is necessary to choose the material for manufacturing the arms. In order to select such a material, an experiment is required to determine the modulus of elasticity for different types of materials with different carbon fiber orientations and matrices. The next important step is to create a verification FEM model from these materials and only then to create a specific FEM model and FEM analysis based on the results of such structural element analysis. The records of the 3-point bending tests (see Fig. 7) to determine the modulus of elasticity and limit values of contact pressures are shown in the graph (see Fig. 8). The graph shows the results of elastic modulus measurements for different directions of carbon fibers and different types of Pre-preg used with the production technology by gradual hardening in an autoclave. The samples, arranged in sets of 10 pieces with dimensions of 5 x 10 x 100 mm, were loaded with a variable force at a speed of 1000 N/min.

The FEM analysis was performed using the MARC program. FEM analysis of the arm for the required load of 2000 N.m. Fig. 9 shows the result of stress distribution in the arm at the maximum generated torque.

Fig. 7. The 3-point bending test, composite sample with dimensions 100x10x5 mm using the test equipment LABTEST 1052.

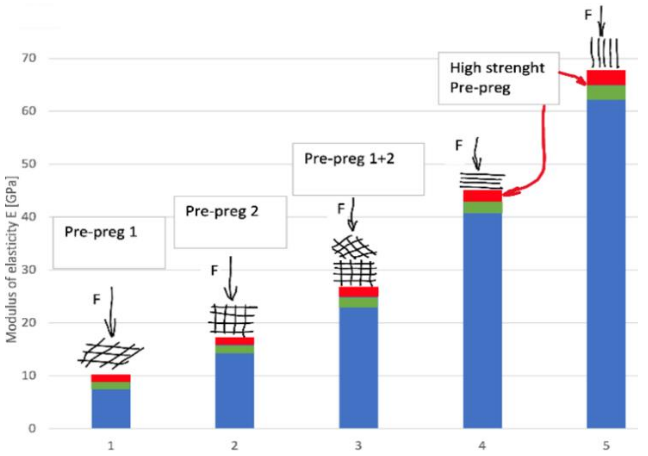

Fig.8. The modulus of elasticity of Pre-preg materials for the FEM analyses.

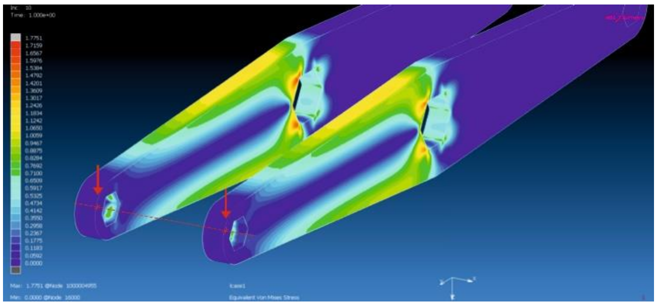

Fig. 9. FEM analysis of the measuring arm with maximum contact pressures 1.77 MPa loaded with a force of 1000N on each arm.

3. CONCLUSIONS

Designing metrology equipment is a very complex task, especially given the level of accuracy required. In order to create a successful design, it is necessary to choose appropriate construction methods already in the initial design stage. Fig. 4 illustrates the design process for solving complex design problems, which involves the analysis of basic physical principles and similar problems to identify several potential solutions. Material requirements and their properties are also considered during development. When designing metrological devices, it is crucial to analyze the measurement uncertainties that depend on the design itself. Fig. 5 shows a comparison of two different design solutions for one physical principle and illustrates the importance of determining the measurement uncertainty to achieve the desired result. During the design process, measures are taken to reduce the measurement uncertainty, designing the entire structural system of the device to meet the criterion of desired measurement uncertainty, rather than being driven by cost considerations. This is a significant difference between the design of conventional manufacturing equipment and metrology equipment. The construction of the measuring arm for this metrology device involves the use of carbon composite material. To meet the minimum deformation condition, extensive measurements were made to determine the modulus of elasticity in different directions and for different internal fiber interlacing structures. The measurement of carbon samples allowed to create a database of properties of different types of carbon materials of the Pre-preg type, which can be used in solving other design tasks related to carbon structures. One of the most important results is the selection of a suitable type of Pre-preg carbon materials, where in Fig. 8, the decisive modulus of elasticity is determined as a function of the method of knitting of the individual fibers. Based on the experimentally determined mechanical properties of carbon materials, the Pre-preg type UD - unidirectional with a thickness of 0.2 mm is determined as a suitable material, while the individual layers are rotated by 45 degrees. In such a case, the orthotropic property of the material is used, where the modulus of elasticity is appropriate in the range from 40 to 63 MPa, depending on the direction of the fibers. Based on the results of the mechanical tests of the test samples, it was possible to perform the FEM analyses of individual structural nodes in order to identify possible deviations and ensure that the required measurement uncertainty is met. In this way it is possible to design a measuring arm that meets the requirements based on the analysis of measurement uncertainties. The final result is the creation of a complex structural design, based on which a new measuring workplace is built. This paper describes the complexity of the structural design of metrological equipment and points out the use of scientific knowledge, especially in the field of metrology and machine design.

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