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***Abstract*—Accurate characterization of coil springs, typically in terms of axial and transverse stiffness, is crucial in many applications, in particular in automotive engineering, such as suspensions, vibration reduction, seating, exhaust valves, gear engagement controls, transmission hose, fuel panels, car trunks, and engine hoods. These measurements are usually performed in spring testing machines along the vertical axis in quasi-static conditions. However, when springs are stressed along the main vertical axis, side forces, bending and torsion moments are generated, thus have to be evaluated. For this reason, a hexapod-shaped multicomponent force and moment transducer has been recently devised, realized and integrated into standard spring testing machines capable to measure the displacement along the main and transverse axes. In this way, forces, moments and displacement components generated by the springs can be measured and axial and transverse stiffness derived. In this work, two multicomponent spring testing machines with the hexapod-shaped force and moment transducer are described and measurements on different large coil springs are presented.**

Keywords—multicomponent forces and moments, hexapod-shaped, car suspension, spring testing machine, metrology

I. Introduction

Coil springs are widely used in many fields of engineering. In the particular case of automotive engineering, coil springs are commonly used in vehicle suspension and engines [1]. In the first case, such springs are commonly tension/compression springs which can vary in firmness and quality depending on the application or the vehicle it is utilized on and are assembled with a shock absorber or mounted independently, permitting higher stability of the vehicle when subjected to jolts and loadings. Springs utilized in motors usually work in compression and play a crucial role in closing and opening the valves to inject air or to deplete gasses out of the cylinder head.

In general, coil spring performances, in terms of axial stiffness, are usually measured in uniaxial spring testing machines equipped with a force transducer and displacement sensors along the vertical and horizontal axes in quasi-static conditions with compressive forces. However, when coil springs are stressed with a vertical force, side forces, bending and torsion moments, and transverse displacements are generated by the spring itself [2]. Evaluation of these "spurious" components is fundamental for the accurate characterization of springs and to guarantee correct and safe working conditions. While the axial force and the axial and transverse displacements are usually measured, side forces and moments are usually disregarded. Hence, a transducer capable of measuring such force and moment components is required. To accomplish this task, different multicomponent force transducers (MFTs) have been devised and developed in the last three decades. They are typically composed of different kinds of strain-gauge full Wheatstone bridges each one designated to be sensitive to a particular side or vertical force or to a bending or torsion moment [3]. However, proper calibration protocols or standards for this kind of transducers are still missing therefore the required traceability cannot be guaranteed.

For these reasons, a hexapod-shaped multicomponent force and moment transducer (HS MCFMT) has been recently devised and realized at INRiM to be used in the field of railway spring tests with a capacity of 400 kN [4], but that can be scaled to bigger [5] or lower capacities for different applications [6], like the automotive one. It is composed of six uniaxial force transducers (UFTs) assembled with a six-degree of freedom structure (similar to a Stewart platform [7,8]). In this way, knowing the force output from the six UFTs and the geometrical dimensions of the structure, it is possible to simultaneously evaluate the three forces (side and vertical) and the three moments (bending and torsion). Furthermore, the HS MCFMT can be calibrated according to standard and traceable procedures (e.g. ISO 376 [9]) since all six traditional UFTs are sensitive to the vertical force generated by a force standard machine, therefore the calibration equations of each can be accurately evaluated and traceability guaranteed during first and periodic calibrations. Furthermore, the six UFTs can be easily mounted and dismantled and calibrated according to standard and traceable procedures for further checks.

Once calibrated, the HS MCFMT has been integrated and assembled in two spring testing machines and axial and transverse stiffness measurements are performed on large coil springs. Design, realization and calibration of the HS MCFMT together with coil springs stiffness measurements are presented.

II. The hexapod-shaped multicomponent force and moment transducer (HS MCFMT)

A. *The structure of the hexapod-shaped multicomponent force and moment transducer*

The structure of the HS MCFMT is shown in Fig. 1.

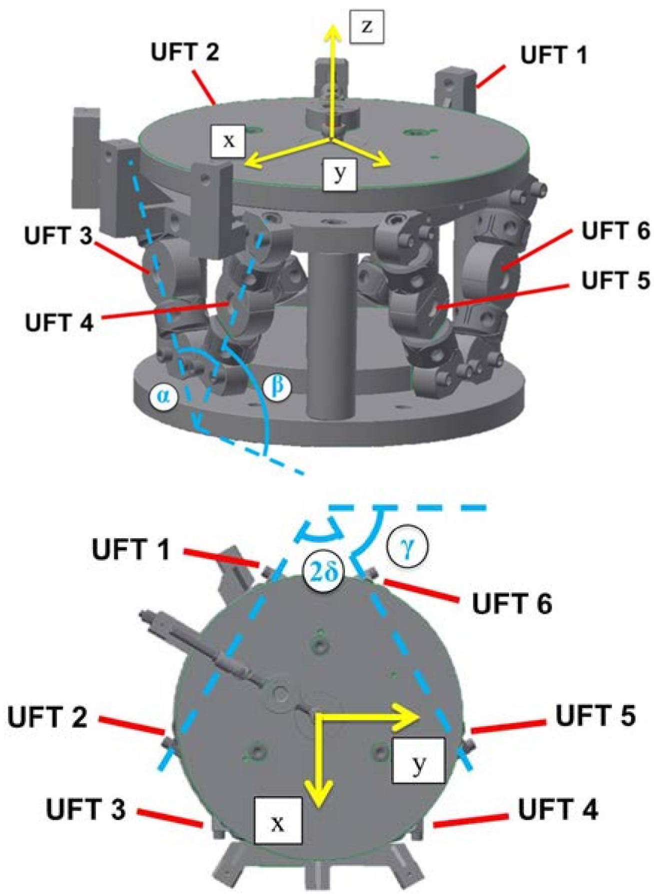

Figure 1. The HS MCFMT (side view and top view).

The HS MCFMT is a cylindrical-shaped transducer with a diameter of 586 mm and a height of 400 mm. All mechanical components are made of hardened and rectified steel. The weight of the whole structure is 400 kg. The transducer is composed of four plates, two at the top and two at the bottom, and six columns, three internal and three externals.

The load is applied on the first upper plate and it is transferred to a lower plate through the three internal columns placed along the circular edge of the two plates at step angles of 120°. Along the lateral surface of the lower plate, three pairs of high precision S-type UFTs (Fig. 2) are mounted at an intermediate position between two internal columns at a distance r of 218 mm from the center of the plate. The six UFTs are tilted by an angle of 27.5° with respect to the vertical axis and are fixed at the top end to a second upper steel plate. This plate is supported by the three external steel columns that lean on another lower steel plate which acts as the base of the whole structure. Each inclined UFT is fixed to the lower and upper plates by means of clamping heads and elastic hinges which allow to compensate for any spurious deformation and keep the geometrical structure stable when loaded. The UFTs of every pair lie on the same plane and are symmetrically mounted. The three ideal planes of the UFTs pairs intersect forming an equilateral triangle. Between the two upper and lower plates there is a space of a few millimeters in order to avoid any contact between them during load. Given such a structure, the six UFTs and the elastic hinges are designed and chosen to work only in tension.

α, β, γ and δ angles are 55°, 62.5°, 60° and 30° respectively. The six UFTs have a capacity of 75 kN. These values entail a vertical force capacity of 400 kN, side force capacities of 100 kN, and moments capacity of 50 kN·m. Maximum deformations of the structure under the highest load are in the order of few millimeters. The six UFTs are connected to an external amplifier, which provides the required supply voltage to the transducers and acquires data.

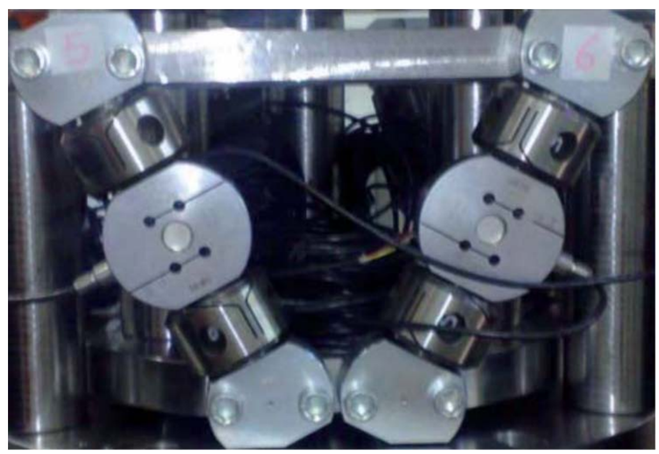

Figure 2. A pair of inclined UFTs with elastic hinges and clamping heads at both ends.

The three forces (F_x, F_y, F_z) and the three moments (M_x, M_y, M_z) are obtained by combining the outputs F_i of each UFT, based on the geometry of the HS MFT (see Fig. 1), according to Eq. 1.

$$\begin{cases} F_x = (F_1 - F_2 - F_5 + F_6) \cdot \cos\beta \cdot \cos\delta \\ F_y = (F_4 - F_3) \cdot \cos\beta + (F_1 - F_2 + F_5 - F_6) \cdot \cos\beta \cdot \cos\gamma \\ F_z = (F_1 + F_2 + F_3 + F_4 + F_5 + F_6) \cdot \cos\frac{\alpha}{2} \\ M_x = (F_1 + F_2 - F_5 - F_6) \cdot r \cdot \cos\frac{\alpha}{2} \cdot \cos\delta \\ M_y = (F_4 + F_3) \cdot r \cdot \cos\frac{\alpha}{2} - (F_1 + F_2 + F_5 + F_6) \cdot r \cdot \cos\frac{\alpha}{2} \cdot \sin\delta \\ M_z = (F_1 - F_2 + F_3 - F_4 + F_5 - F_6) \cdot r \cdot \cos\beta \end{cases} \quad (1)$$

B. *Calibration results*

A first calibration of the HS MCFMT is performed starting from the calibration of the six UFTs according to ISO 376 in the 1 MN primary force standard machine of INRiM, which generates a vertical force F_z. Combining the UFT outputs (in N, through the calibration equations) with the geometrical parameters of the structure, the force and moment components are obtained according to Eq. (1), as previously shown. However, calibration of the single UFTs, not assembled in the HS structure, could entail systematic effects due to the fact that spurious deformations of the HS structure are not taken into account during UFTs calibration. For this reason, it is preferable to calibrate the UFTs once assembled on the HS MCFMT, in order to take into account, in the calibration equations, possible spurious effects and small geometrical defects. In fact, one of the main advantages of such a structure is that by generating a simple vertical force with a force standard machine (FSM), it possible to calibrate the UFTs without dismantling the whole HS MCFMT. This procedure, besides taking into account the above-mentioned possible spurious effects, also avoids generating the reference transverse forces and moments, which, at present, are not traceable since suitable and standard calibration methods are still missing. As reference force acting on every i^{th} UFT ($F_{ref,i}$), it is considered that the known vertical $F_{ref,z}$ generated with the FSM is equally distributed among the six UFTs according to Eq. (2), as done for build-up systems [10].

$$F_{ref,i} = \frac{\frac{F_{ref,z}}{6}}{\cos\frac{\alpha}{2}} \quad (2)$$

The calibration of the HS MCFMT is performed at INRiM with the 1 MN deadweight FSM from 20 kN to 400 kN as shown in Fig 3. The six UFTs outputs are acquired and the second- or third-order calibration equations for each transducer can be obtained according to the standard procedure (ISO 376).

The calibration uncertainty resulted in class 00 (ISO 376 classification). The maximum relative expanded calibration uncertainty (at 95% confidence level) of the six UFTs is $6 \cdot 10^{-4}$. By combining these uncertainties with the design tolerances of the geometrical parameters described in Eq. (1) and by propagating them according to GUM [11], it is possible to get the overall uncertainties for the different forces and moments components. It is found that the uncertainties at maximum load for each component are 0.16 kN for transverse forces F_x and F_y, 0.43 kN for vertical force F_z, 0.07 kN·m for M_x, 0.10 kN·m for M_y, and 0.05 kN·m for M_z [4,12].

Figure 3. The HS MCFMT during the first calibration in the 1 MN deadweight FSM at INRiM.

III. THE MULTICOMPONENT SPRING TESTING MACHINES

The HS MCFMT is then integrated into two different types of industrial spring testing machines from the companies *Easydur Italiana* (Arcisate, Italy), and *Officine Meccaniche BBM* (Rossano Veneto, Italy). The two systems are shown in Figs. 4 and 5.

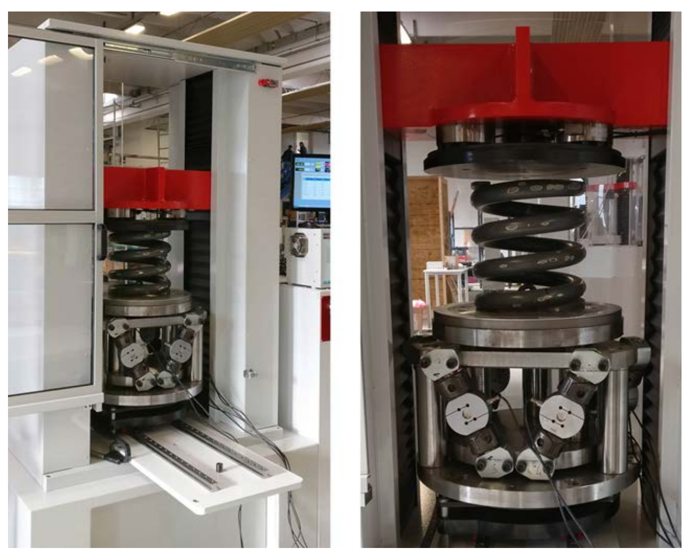

Figure 4. The first multicomponent spring testing machine by *Easydur Italiana* during spring tests.

The multicomponent testing machine has a dimension of a few cubic meters and consists of an electromechanical machine able to perform vertical loads for compression tests. They are equipped with a displacement transducer for the vertical displacement and a lower movable bench aimed to detect the displacement along the transverse axis with a resolution of 0.01 mm. The HS MCFMT is placed upon the lower movable bench. Before starting the test, the springs are manually placed between the loading pad of the movable crossbar and the upper plate of the HS MCFMT, and centered by means of a caliper. The huge friction between the contact surfaces guarantees that no shifts nor slips occur. For the measurement of the side forces (and moments) generated by the spring under load, a hardened steel bar is used in order to fix the HS MCFMT and the lower bench to the base of the spring testing machine. The steel bar is then removed to measure the displacement along the transverse axis.

Figure 5. The second multicomponent spring testing machine by *BBM* during machine verification tests.

IV. Axial and Transverse Stiffness Measurements on Large Coil Springs

Axial and transverse stiffness measurements on large coil springs, mainly used for railway applications, are performed at the companies' laboratories. Six springs are tested in total. One spring is tested at *Easydur Italiana* (spring #1), other five springs (from spring #2 to spring #6) are tested at *Officine Meccaniche BBM*. They have outer diameters (i.e. width) and a free length (i.e. height) of few decimeters. Measurements are performed at a laboratory temperature between 14 °C to 18 °C.

Measurements are performed by rotating the spring four times by steps of 90° to evaluate reproducibility. Measurements are performed in displacement-controlled conditions. The spring is compressed up to an initial vertical position z_i equal to 5% of its free length. After a period of around 30 s, the spring is compressed again up to a final vertical position z_f of 30% of the spring free length. At each position, the three forces (F_x, F_y and F_z) and the positions along *x*- and *y*-axis are measured. To measure the transverse displacements, the lower movable bench is not secured to the ground. Measurement of the three forces (F_x, F_y, F_z) and the three moments (M_x, M_y, M_z) with the HS MFT are performed with the lower bench fixed. The vertical displacement is measured by means of a displacement transducer integrated into the machines.

From these measurements, axial and transverse stiffness can be obtained according to Eq. (3) [2],

$$\begin{cases} K_z = \dfrac{F_{z,f} - F_{z,i}}{z_f - z_i} = \dfrac{\Delta F_z}{\Delta z} \\ K_r = \dfrac{1}{2}\left(\dfrac{F_{x,f} - F_{x,i}}{x_f - x_i} + \dfrac{F_{y,f} - F_{y,i}}{y_f - y_i}\right) = \dfrac{1}{2}\left(\dfrac{\Delta F_x}{\Delta x} + \dfrac{\Delta F_y}{\Delta y}\right) \end{cases} \quad (3)$$

where K_z is the axial stiffness, K_r is the transverse stiffness, and ΔF_z, Δz, ΔF_x, Δx and ΔF_y, Δy are the differential forces and displacements occurring along the vertical and the transverse axes during the compression of the spring.

It is worth noting that bending and torsion moments are measured by the HS MCFMT but they are useless for the determination of axial and transverse stiffness.

Experimental axial (K_z) and transverse (K_r) stiffness (mean values of the four rotations) are reported in Table I.

TABLE I. Experimental Axial and Transverse Stiffness

	K_z / kN/mm	K_r / kN/mm
Spring #1	0.72±0.01	0.57±0.10
Spring #2	0.91±0.02	1.39±0.21
Spring #3	0.96±0.02	1.44±0.20
Spring #5	0.95±0.02	1.42±0.23
Spring #6	0.99±0.02	1.45±0.22

Uncertainties are evaluated by taking into account the reproducibility of stiffness values, obtained from the four rotations of the spring, and the instrumentation uncertainty due to forces and displacements measurements performed with the HS MCFMT and the displacement transducers, respectively. As expected, it is found that the major uncertainty contribution is due to the reproducibility of stiffness measurements. Expanded uncertainties (at a confidence level of 95%) are in the order of 2% for axial stiffness and around 15% for transverse stiffness. By way of example, the uncertainty assessment for K_r of spring #1 is reported in Table II. $u^2(x_j)$ represents the variance of the individual uncertainty contributions (x_j), c_j is the sensitivity coefficient, $u_j^2(K_r)$ is the variance of the dependent variable (K_r in this example) due to the individual uncertainty contributions, and $U(K_r)$ is the expanded uncertainty.

TABLE II. Example of Uncertainty Assessment for K_R of Spring #1

Type	$u^2(x_j)$	c_j	$u_j^2(K_r)$
Instrum.	6.28E-04	1	6.28E-04
Reprod.	1.78E-03	1	1.78E-03
		$u^2(K_r)$	2.41E-03
		$U(K_r)$	9.81E-02

V. Conclusions

The accurate evaluation of coil springs stiffness is fundamental in many engineering applications and in particular in automotive. In this work the performances of multicomponent spring testing machines composed of displacement transducers and integrated with a hexapod-shaped multicomponent force and moment transducer, recently devised and realized at INRiM, are evaluated. Uncertainties related to the measurement of the vertical forces and bending and torsion moments, starting from calibration uncertainties, are in the order of 0.1%-0.3%, whereas for side forces they are in the order of 1%. Measurements of axial and transverse stiffness of six large coil springs are then performed with two different spring testing machines integrated with the HS MCFMT at two companies' laboratories. It is found that the uncertainties are in the order of 2% for axial stiffness and around 15%.

Acknowledgment

The authors thank Renato Affri, Stefano Piazza and Luca Candia from *Easydur Italiana*, Arturo Barbieri, Giacomo Bigolin, Carlo Bin from *Officine Meccaniche BBM* for the use of their spring testing machines and for their assistance and support during experimental measurements.

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