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EVALUATION OF STATIC AND DYNAMIC PARASSITIC COMPONENTS ON THE INRIM 1 MN PRIMARY FORCE STANDARD MACHINE BY MEANS THE 500 kN SIX-COMPONENT DYNAMOMETER

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Abstract – A recent improvement on the ancillary instrumentation and on the acquisition software of the 100 kN and 500 kN INRIM six-component dynamometers makes it possible to measure the parasitic components at static conditions and during the weight transition too, in order to weigh up the influence of the dynamic phenomena on the value of axial load.

This paper presents the main results of the evaluation of the parasitic components arising in static and dynamic conditions on the INRIM 1 MN force standard machine by using the INRIM 500 kN six-components dynamometer. It shows that the values of dynamic component can be several time bigger that the values calculated at static conditions, and that they must be measured and monitored in order to avoid any influence on the machine-dynamometer interaction and on the uncertainty of the main axial load.

Keywords: force, deadweight machine, parasitic component

1. INTRODUCTION

Ideally, force standard machines should apply uniaxial loads. In practice, misalignments and deformations of the force standard machines, and interactions with load transducers during measurement result in finite values of the five parasitic components of the force/moment tensor.

The effect of these components on dynamometers output is one of the principal reasons why measured differences between deadweight force standard machines are sometimes greater than expected [1].

In order to improve the accuracy of primary and transfer standards a great progress was made through the measurement of parasitic components: side components F_X and F_Y, bending moments M_Y and M_X, and twisting moment M_Z (Fig. 1).

The measurements were, usually, carried out in functions of various test parameters, in order to bring the sources of error under control, and take, if needed, effective remedial steps.

The inclination correction corresponding to the measured side force components can be easily calculated as in (1):

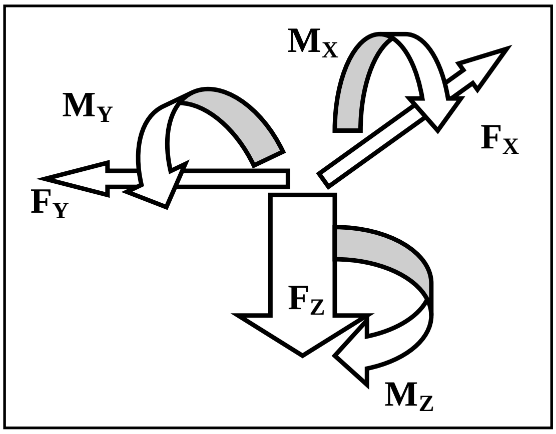


Fig. 1. Sketch of the esa-vector to represent axial force (F_Z) and the parasitic components

$$\frac{\Delta F_Z}{F_Z} = 1 - \cos\beta \cong \frac{\beta^2}{2} \qquad (1)$$

Since $\sin\beta \cong \frac{F_X}{F_Z}$

where β is the angle between the load action line and the vertical axis

$$\frac{\Delta F_Z}{F_Z} = \frac{F_X^2 + F_Y^2}{2F_Z^2}$$

An important role in this field was played by the INRiM (ex CNR-IMGC) with a large activity of evaluation on the main national force standard machines in the world [2].

Since1985 the activity of investigations on the parasitic components were made on seven NMIs in Europe (NPL, TNO, PTB, LNE, RPO, LGAI and INRIM), three in Asia (NIM, NRLM and KRISS) and one in America (CENAM), by using the two INRiM six-component dynamometers.

The results of the measurements and the evaluation of their national force standard machines were published in several papers and reports [3, 4, 5, 6, 7].

A summary of the results of the side components measured on some NMIs force standard machine, are plotted in figure 2.

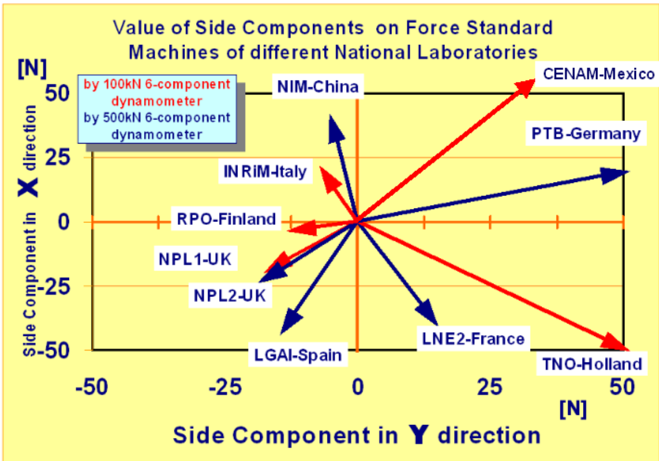


Fig. 2. Graphic representation of the *Fx* and *Fy* side components on several National Force Standard Machines.

2. THE INRIM 0,5 MN SIX-COMPONENT DYNAMOMETER

The 500 kN INRIM 6-component is a six-component device, compression operated, of 500 kN capacity on the main vertical component; it is cylindrical (height 700 mm, diameter 420 mm), and is so designed as to be compatible with most of the standard dead-weight machines.

It is a transfer reference standard to measure vertical force, side forces, bending moments and twisting moment introduced by defects in force transmission and support deformation.

Fig. 3. Thd INRIM 500 kN six-component dynamometer.

This dynamometer is an assembled balance, consisting of six elementary load cells fastened between two circular coaxial plates having a central orifice and was fully describe in previous papers / 8 /

The whole device is made up of:

- three main load cells of 200 kN capacity, placed vertically. They mainly measure the vertical compression force F_z and the two bending moments M_X and M_Y, acting in the two orthogonal planes; they are mounted between two cross flexures, representing a gimbals suspension;
- three secondary load cells, of 2 kN capacity, to measure the two lateral forces F_X and F_Y, and the twisting moment M_Z, connected to the movable loading platform.

On the basis of the overall results obtained with the 500 kN six-component dynamometer during ten years, the main evaluations are: axial load capacity F_Z= 500 kN (relative uncertainty U = 5 ·10^{-5} with k=2); side components F_X and F_Y capacity: 2 kN (U = 1· 10^{-2} with k=2); bending moments M_X and M_Y 0,5 kN m (U= 1.5·10^{-2} with k=2); twisting moment M_Z 0.5 kN m (U= 1.5·10^{-2} with k=2).

The Axial load stability over 3 years <2· and the temperature effect on rated output is 0.002% fs/ K.

3. THE INRIM 1 MN DEAD WEIGHT FORCE STANDARD MACHINE

The 1 MN primary force standard machine was designed by INRIM, constructed by C. Galdabini spa and operating from 1996. The latest constructional criteria internationally adopted were used to meet the following general requirements:

- the weight pieces an the suspension system must act along the symmetry axis;
- the force transmission system must act along the longitudinal axis;
- the loading system must allow loads to be continuously applied without resetting, with the highest number of load levels and the lowest number of weight pieces;
- load application must be carried out smoothly and without giving rise to dynamic components.

The main innovative characteristics introduced in the INRIM standard machines are:

- weight pieces of austenitic stainless steel AISI 304;
- a supporting structure and a loading frame of the three-column type, to ensure high stiffness along the different directions;
- binary weight-piece combination;
- individual suspension and transfer of the weight pieces;
- balancing of the weight of the loading-frame and of the load-transmission system by means of a lever system.

With a binary combination, only few weight pieces are necessary to obtain a high number of load levels, for the INRIM 1 MN machine the sequence is as follows: 10 kN; 10 kN; 20 kN; 40 kN; 80 kN; 4 x 160 kN and 200 kN.

The adoption of the binary combination requires, additionally load to be kept constant on the dynamometer being calibrated during weight-piece substitution, so as to avoid undesirable effects of signal drift.

Load is kept constant, to within 5%, by a feedback system exploiting the deformation elasticity of the loading frame.

Fig. 4. The upper part of the INRIM 1 MN force standard machine.

The great advantage of the two combined methods (binary combination and load maintenance) lies in the self-calibration of the weight pieces, which can be calibrated directly on the machine with uncertainty lower than $5x10^{-6}$, by comparison with a previously calibrated piece.

In this way, calibration can be made far quicker (since the number of weight pieces is small) and self-calibration can be repeated in the course of time, to check the stability of the standard.

A limit to calibration capabilities in deadweight machines is the weight of the loading frame. To overcome this difficulty, in the INRIM machines was adopted the solution of a balancing lever to compensate the loading frame weight. The INRIM machine was asfully describe in previous papers / 9 /

4. BACKGROUND AND NEW IMPROVEMENTS

The very low stiffness of the INRiM six-component dynamometers made it possible, until now, to monitor the variation of the three horizontal signals of the weight pieces oscillation damping during reading time.

In figure 5 is shown, as an example, the variation of the horizontal transducers output during measurement at 200 kN, on the 1200 kN NPL DWM. It is possible to see the freely weight pieces oscillation during the load measurement, and to notice that no interaction effect between dynamometer and force standard machine rises.

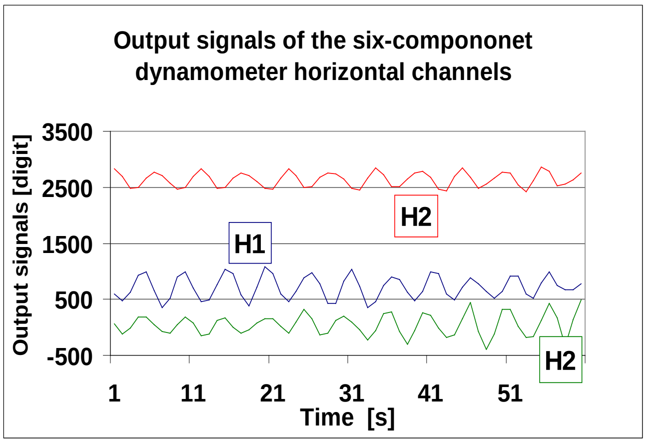


Fig. 5. Free weight pieces oscillation at 200 kN on NPL 1200 kN force standard machine.

Figure 6 illustrates the continuous recording of the horizontal output signals during the load application from 0 up to 500 kN on the 2 MN PTB DWM. As in all the force standard machines evaluated, it is clearly showed the peaks occurring in transient of weight piece application on the carrier, which given rise unknown prominent parasitic components.

By the watching of the peaks was possible to see the influence of the shock due to the change of the masses or to the interactions between loading frame and main frame.

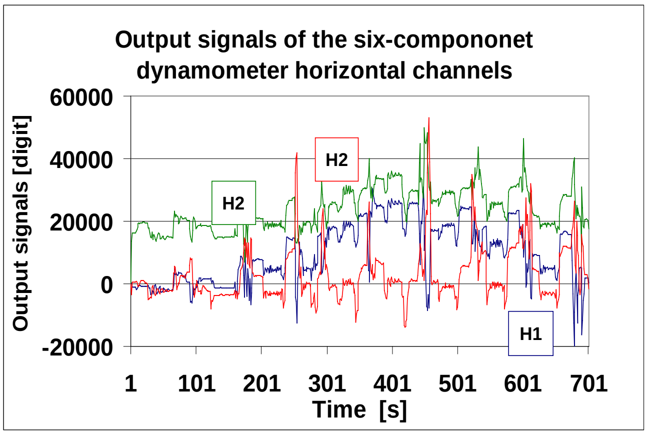


Fig. 6. Variation of the horizontal out signals for increasing and decreasing load on the 2 MN PTB Force standard machine.

Up to 2004 that analysis was possible in static measurement conditions, and only a qualitative evaluation of the dynamic phenomena during the free oscillation of masses or the loading transient was achievable

A new high speed acquisition data logger, and a new version of the communication software make it now possible to read simultaneously all the six outputs of the INRIM multi-component dynamometers in order to calculate side forces, bending and twisting moments when the load is applied, and in transient, during the weights change sequence, too.

5. MEASUREMENT PROCEDURES

The measurements performed on the 1 MN INRIM force standard machine by using the 500 kN six-component dynamometer was focused on:

- Evaluate the 1 MN INRiM force standard machine parasitic components to bring the sources of error under control
- Measure the variation of parasitic components generated by the machine (transverse forces and moments) during the weight pieces oscillation damping.
- Measure the variation of the side components F_X and F_Y, bending moments M_Y and M_X, and twisting moment M_Z, during the application of load and the weights change sequence
- Identify the sources of parasitic components either intrinsic in the machine structure or arising from constructional defects such as: structure flexibility; asymmetric deformation of the loaded machine; non-planarity of the loading crossbeam; non-axiality of the acting force with respect to the main frame; faulty load-cell positioning on the machine; influence of the systems for weight-oscillation damping
- Calculate the maximum value of the parasitic components corresponding to the peak values recorder during the loading procedure, and evaluate if any influence on the interaction machine-dynamometer, or any force contact surface modification and dynamometer hysteresis effect, arise.

6. EXPERIMENTAL RESULTS AND ANALYSIS

The paper presents the main results of the measurement carried out to evaluate the metrological characteristics of the 500 kN INRiM force standard machine. It analyses the variation of the parasitic components when the masses selected are in place on the loading frame and the free oscillation of weight pieces is on (*static condition*), and during the application of load and the weights change sequence (*dynamic condition*).

6.1 Static condition

The values of F_X and F_Y side components at the different axial load levels are reported in figure 7.

The maximum values of F_Y and F_X are, respectively, 530 N and 150 N.

Their linearity shows that the machine has not undergone noticeable distortions, which would have introduced a quadratic element in side component values vs. axial load.

It is possible to deduce that the side components mainly depend to the initial horizontal setting of the lower plate.

These results are not substantially influenced by test condition such as weight-piece combination and different positions of the loading crossbeam.

The values of the bending moments M_X and M_Y result -250 N·m and -362 N·m, at rated load, and they are plotted in figure 8. The evaluation of the bending moments confirm to be a good tool to check the main frame verticality, for to better alignment of the device above the scale pan's centre of gravity.

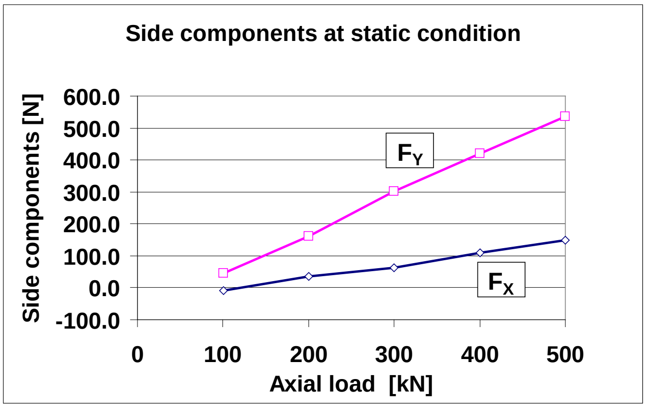


Fig. 7. The side components vs. axial load at static condition.

Its good linearity confirms that there is no effect due to the weight pieces balancing and it is not present any significant interaction between loading frame and main frame.

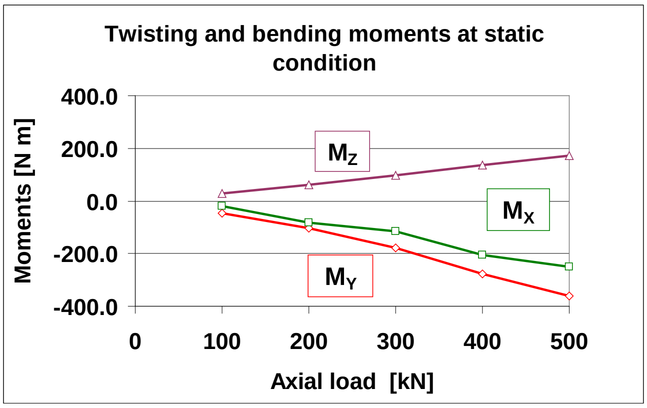


Fig. 8. The bending and twisting moments vs. axial load, at static condition.

6.2 Dynamic condition

The possibility to read the six output signals of the dynamometer with a frequency up to 3.5 Hz, enables to follow their variation during the transient of application load, the procedures of change of weight pieces and all the machine operations before the final measurement.

The continuous recording of the variation of the side components during the weight pieces oscillation damping, at 500 kN of axial force, is reported in figure 10.

The figure shows that the maximum variations of the side components F_X and F_Y are less than ± 1 N, and do not depend to the axial load level or to the side components value.

Any deviation to the sinusoidal shape of the curve is a marker for potential anomalies on the loading procedure.

In figure 11 are reported the oscillation of the twisting moment and the bending moments at 500 kN of axial load.

Also in this case the maximum variation of the three moments is small and always less than ± 1 N·m.

The sinusoidal shape of the curves mean that no influence of the weight pieces oscillation on the parasitic components is detected (average values are quite constant).

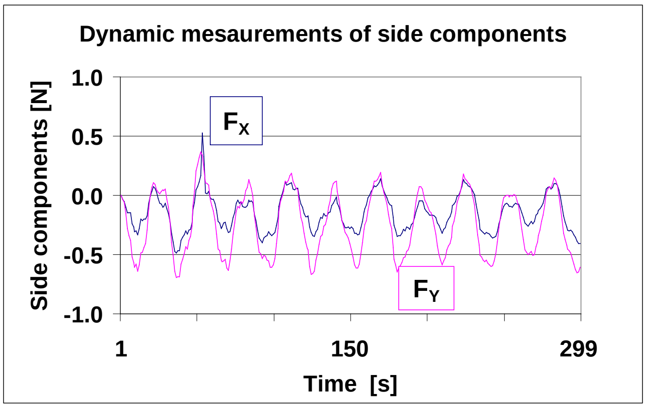


Fig. 10. Variation of the side components during the weight pieces oscillation damping at 500 kN.

In figure 12 the variation of the side components F_X and F_Y during the application of increasing and decreasing load, is reported.

It puts in evidence the large increasing of the parasitic components corresponding to the peak recorded during the loading procedure (clamping of loading frame, change of the weight pieces, and the action of the feedback system for masses selection).

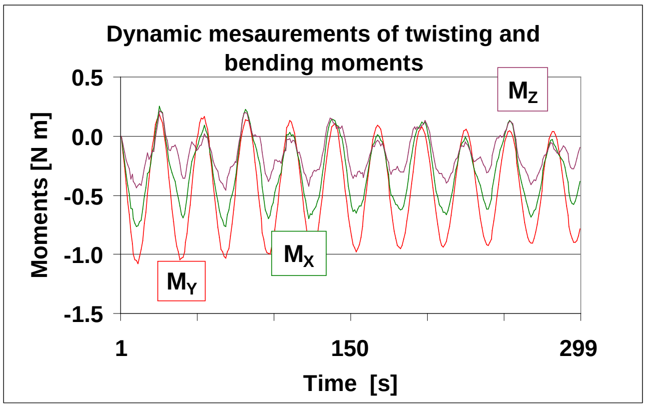


Fig. 11. Variation of the twisting moment and bending moments during the weight pieces oscillation damping at 500 kN.

The maximum variation between static and dynamic component F_Y is included from 68 N (at 100 kN of axial load) up to the 180 N (at 500 kN).

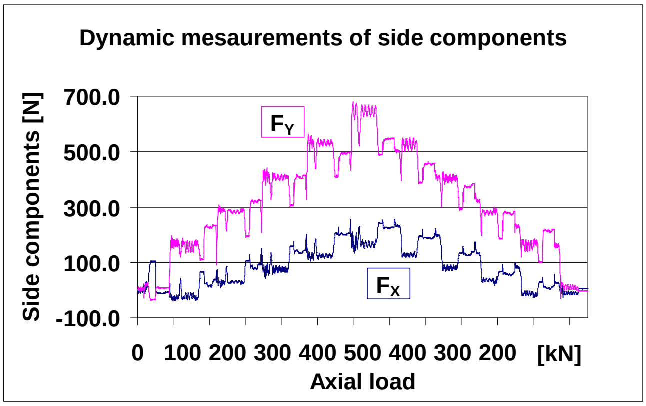
For the side component F_X the variation results -79 N at 100 kN, and -155 N at 500 kN.

These results indicate that the values of the side components, due to the the interaction machine-dynamometer during the application load transient, are significant. It must be monitored in order to avoid any influence on the output of a force transducer with high lateral forces sensitivity.

In figure 11 is possible to analyze, in details, the effects of the single loading sequence on the dynamic components:

a) the points A, B and C indicate the static measurement areas;

b) from zero to A is plotted the variation of the side component F_Y due to the loading frame contact (first step of calibration) and the opening of the clamping system: they make it possible to increase the value of side component from – 22 N up to 100 N;



Fig, 12. Variation of the side components during the application of increasing and decreasing load.

c) from A to B, and from B to C the action of the feedback system for the masses selection and the change of the weight pieces are well represented, and find out a variation between static and dynamic F_Y about 80 N at 100 kN and 100 N at 200 kN.

It is remarkable to underline the anomalous value of the side component F_Y at the point D, with a variation between static and dynamic component about -100 N. It is mainly due to the feedback control delay to exploiting the deformation elasticity of the loading frame to keep constant the axial load on the dynamometer, during the weight pieces substitution.

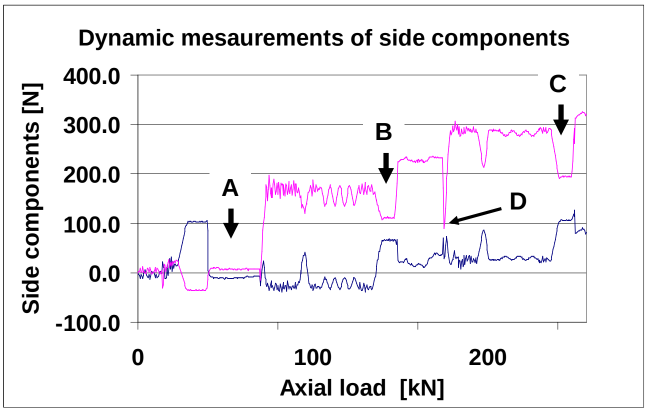


Fig. 13. Variation of the side components during the application of increasing and decreasing load, up to 200 kN.

The variation of the moments in static and dynamic conditions for increasing and decreasing load, up to 500 kN, is pointed up in figure 14.

The twisting moment M_Z varies from 20 N·m at 500 kN to few newton at 100 kN.

For the bending moments M_X and M_Y the variations are respectively -30 N·m and -40 N·m at 500 kN and few newton at 100 kN.

These values authorize to declare that no effects of non-axiality of the acting force or not correct static balancing and misalignments of the weight pieces, are generated.

A similar analysis is carried on for the influence on the dynamic twisting moments (figure 14); noticing that the peak values recorded on the diagram indicate the effect of the weight pieces application on the carrier, and of their not perfect parallelism.

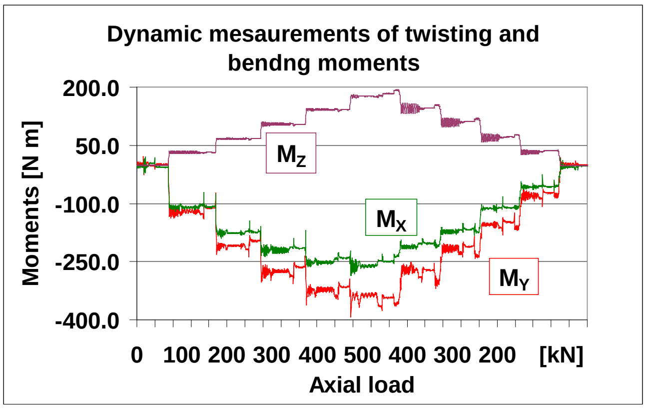


Fig. 14. Variation of the twisting and bending moments during the weights change sequence.

7. CONCLUSIONS

The analysis of the static and dynamic parasitic components during the weight transitions, have allowed to perform a complete evaluation of the INRiM 500 kN force standard machine and to check the influence on the measurements of any anomaly arisen on different test conditions.

The maximum values of F_X and F_Y side components, at the rated load, result respectively 150 N and 530 N. It puts in evidence a noticeable difference between the values of the two side components.

By these results is possible to hypothesize that a relevant F_Y side components mainly depends to the interaction between the balancing lever, to compensate the loading frame weight, and the loading frame itself. This interaction acts just in Y direction.

The values of the bending moments M_X and M_Y result - 250 N·m and -362 N·m . Their evaluation confirm to be a good tool to check the main frame verticality, for to better alignment of the device above the scale pan's centre of gravity. The twisting moment M_Z value results 172 N·m at 500 kN of axial load.

Their linearity shows that the machine has not undergone noticeable distortions, which would have introduced a quadratic element in side component values vs. axial load.

The variation of the side components F_X and F_Y and of the three moments M_X M_Y and M_Z during the weight pieces oscillation damping, is very low and always smaller than ± 1 N. Furthermore it doesn't depend to the axial load level of measurements or to the parasitic components value, but, mainly, to the application load speed.

The measurements of the twisting moment M_Z and bending moments M_X and M_Y, carried out at different axial loads, show that no important structure flexibility, asymmetric deformation, non-planarity of the loading crossbeam, non-axiality of the acting force, or influence of the weight-oscillation damping, are present.

The results discussed in this paper confirm the necessity to measure and to verify the influence of static and dynamic parasitic components on the machine-dynamometer interaction, and to evaluate the influence, if any, of the defects in force transmission, anomalies on the weight change sequence, or on the structural deformations, than can influence the accuracy of a DWM.

The previous results are determinate by a low stiffness six components dynamometer. In the future, it would be advisable to use also a six-component dynamometer with different stiffness, and consequently different machine-dynamometer interaction, to weigh up if any variation of the dynamic components can be recorded.

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