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# IMPROVEMENT OF METROLOGICAL CHARACTERISTICS OF INTI´S 110 kN FORCE STANDARD MACHINE BY USING THE CENAM'S SIX-COMPONENT DYNAMOMETER FOR STATIC AND DYNAMIC EVALUATION

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**Abstract** − In order to improve the metrological characteristics of the 110 kN INTI primary Force Standard Machine (FSM), an evaluation of the parasitic components that could rise for misalignments and structural deformations, is useful.

The values of the parasitic components in static and dynamic conditions were determined by using the six-component dynamometer property of CENAM.

On the basis of the multi-component analysis and in order to reduce the effect of the parasitic components on the main axial load, a verification of the main frame inclination, of the load eccentricity and of the weight pieces misalignment was carried out.

After some FSM structural correction, tests of repeatability and reproducibility were carried out to verify the parasitic components decreasing.

**Keywords**: Force, force standard machine, multi-component dynamometer.

## 1. INTRODUCTION

The improvements in the quality levels of the industrial measurements emphasized the necessity of improving the uncertainty of the national force standard machines.

INTI´s 110 kN primary FSM was characterized through a bilateral comparison with PTB during 2002-2003. The uncertainty value reached was 0,01%; this high value was strongly conditioned by the high drift in the transfer standards used and the lack of reproducibility in the test carried out in INTI.

Before doing any mechanical upgrading, a 160 kN six-component dynamometer was used to measure the parasitic components.

Dimensional verifications and corrections of several FSM components were done, resulting in a significant reproducibility improvement.

Afterwards, some weights were moved to improve their alignment, and others were supplemented in their supports to improve the parallelism among them.

Finally the six-component dynamometer was used again to determine the resulting parasitic components.

## 2. THE INTI´S 110 kN PRIMARY FORCE STANDARD MACHINE

The INTI´s primary FSM is a GTM K-NME 110 kN, with the following characteristics: 110 kN maximal capacity, 2 kN lowest load, 3 columns loading frame, as shown in Figure 1.

The FSM has a fix sequence with the following load steps: 2 kN, 4 kN, 5 kN, 6 kN, 8 kN, 10 kN, 12 kN, 14 kN, 15 kN, 16 kN, 18 kN, 20 kN, 22 kN, 25 kN, 30 kN, 35 kN, 40 kN, 45 kN, 50 kN, 55 kN, 60 kN, 70 kN, 80 kN, 90 kN, 100 kN, 110 kN. Any weight-piece is connected with the previous and the following one, by three supports at 120 degrees.

The relative uncertainty of the machine is $1.10^{-4}$ ($k$ = 2) over the whole range.

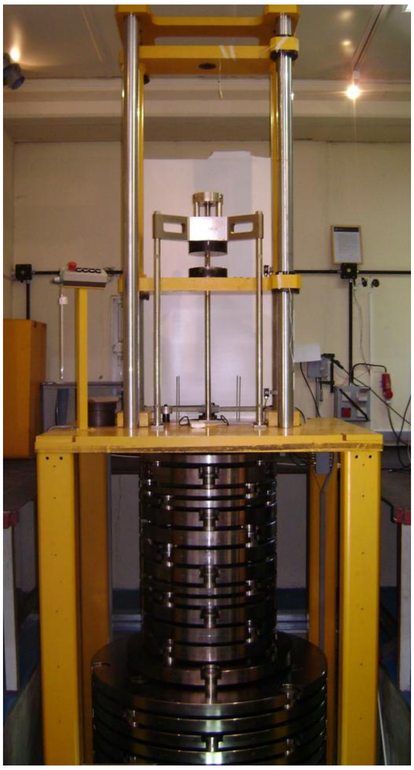

Figure 1. INTI´s 110 kN primary Force Standard Machine.

## 3. THE 160 kN SIX-COMPONENT DYNAMOMETER

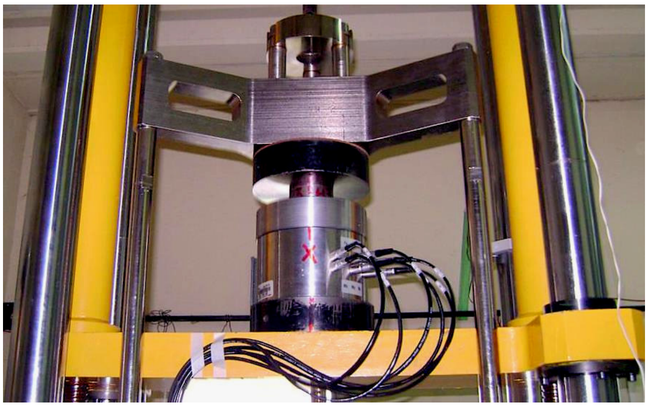

Figure 2. 160 kN six-component dynamometer.

The 160 kN six-component dynamometer is a GTM MKA size III, property of CENAM. It is a rotational-symmetric design, which is able to measure three forces ($F_X$, $F_Y$, $F_Z$) and three moments ($M_X$, $M_Y$, $M_Z$) in X, Y and Z axis, both in static and dynamic applications.

The six-component dynamometer have the following characteristics: 169 mm outside diameter, 82 mm overall height, 0,2 % accuracy class, 0,01 % reproducibility, 0,2 % linearity error, 0,05 % hysteresis, 0,006 5 %/K temperature effect, 0,5 % total error (including hysteresis, linearity and temperature).

The nominal capacity of the dynamometer components and their respective sensitivity are as shown in Table 1.

Table 1. CENAM´s 160 kN six-component dynamometer.

| | Capacity kN | Sensitivity mV/V | | Capacity N·m | Sensitivity mV/V |
|---|---|---|---|---|---|
| Fx | 160 | 2,842 | Mx | 8 000 | 1,270 |
| Fy | 160 | 2,850 | My | 8 000 | 1,256 |
| Fz | 160 | 0,505 | Mz | 8 000 | 1,538 |

The dynamometer is connected to an AC digital indicator (HBM Quantum-X MX840), with a relative uncertainty is better than $1{\cdot}10^{-4}$. It has 8 real-time measurement channels.

## 4. MEASUREMENT PROCEDURE

The test was designed to measure parasitic components when the load of the FSM is applied on the six-component dynamometer and the free system oscillations are presents (static), and during loading transient (dynamic).

Measurements were carried out with the dynamometer at four angular positions (0°, 90°, 180°, 270°), maintaining the laboratory temperature within 20 ± 0,5 °C. At each position, two preloads cycles of three minutes were done.

Measurements were taken at increasing load only. The load steps were maintained during one minute at 0, 20 kN, 40 kN, 60 kN, 80 kN, 100 kN, with one minute of reading time.

The dimensional measurements were performed to confirm the resultant parasitic components and to make the respective corrections.

## 5. EXPERIMENTAL RESULTS AND ANALYSIS

A continuous data recording was used to determine any anomalous outputs during the load application transient.

This FSM does not have a central axis, instead of that, each weight rests in the following one, by means of three supports distributed at each 120 degrees.

An electrical device was connected to check any contact between the weight-pieces and the main frame.

The tests were done using the coordinate reference system as shown in the Figure 3. These were determined using the right hand rule.

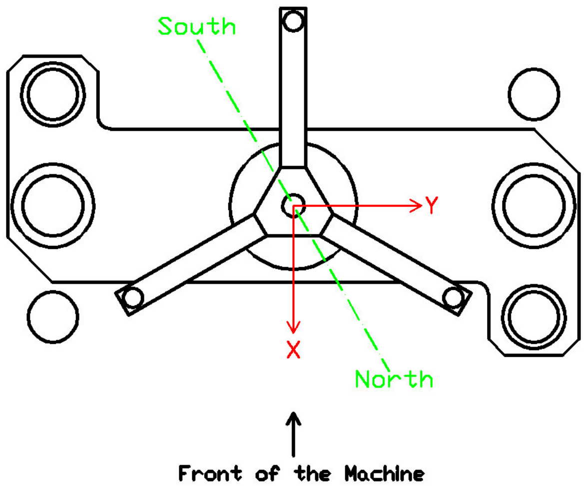


Figure 3. Coordinate reference system used for measurement.

### *5.1. Previous measurements using the six-component dynamometer:*

The values of parasitic components measured before any modification of the FSM structure are shown in Figure 4 and Figure 5.

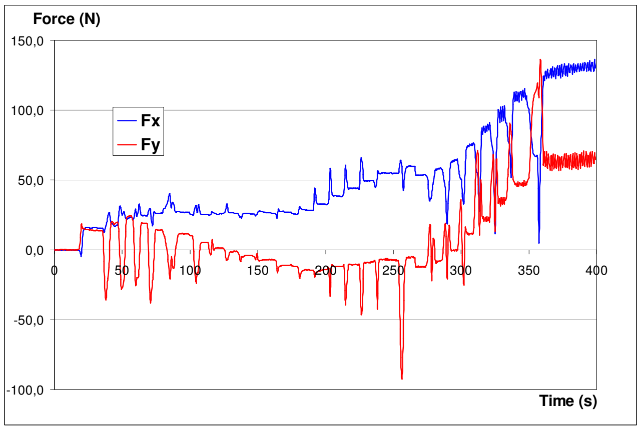


Figure 4. Side components. First measurement.

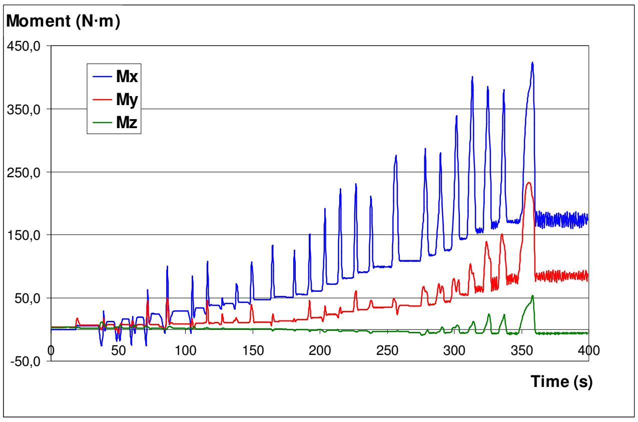


Figure 5. Bending and twisting moments. First measurement.

Their relevant values required to realise mechanical adjustments to the FSM.

### *5.2. Mechanical adjustments carried out:*

The tasks carried out were:

*a) Cross-beam plate horizontality:*

The horizontality of the cross-beam plate for compression was corrected, from 0,25 mm/m to better than 0,05 mm/m.

*b) Loading frame and cross-beam plates parallelism:*

The parallelism between the upper and the lower plate for compression was upgraded by adjustment of their three supports on the loading frame. It was improved from 0,10 mm/m to better than 0,02 mm/m.

*c) Transducer alignment:*

The distance between each column of the loading frame related to the centre of the loading plate was measured. The results showed that it is necessary to displace the transducer under calibration 1 mm along the X-axis (ΔX= -1mm) to achieve a better alignment.

*d) Alignment of the weights:*

The alignment between weight-pairs were measured, both in X and Y direction. The weights which had his axis displaced more than 0,5 mm (related to the upper weight), were moved, by displacing their supports. The following weights were corrected: N° 4, 5, 7, 11, 16, 21 and 22, which correspond to 8 kN, 10 kN, 14 kN, 20 kN, 40 kN, 70kN and 80 kN respectively.

*e) Global dynamic transient:*

The peaks shown in Figure 4 and Figure 5 are due to the lack of horizontality on the lifting cross-beam, which is the main support of the weights. They were reduced by the adjustment of the lifting table supports.

*f) Parallelism of the weights:*

In spite of having corrected the global dynamic transient, there were some significant peaks, it was due to the lack of parallelism between weights.

The gap between each support of each weight was measured, the forward-left support between the loading frame and the first weight was fixed to 0,8 mm.

### *5.3. Final results obtained by using the six-component dynamometer:*

In order to make a better alignment between the centre of the applying load and the centre of the six-component dynamometer, the tests were carried out by using it displaced of 1mm in X-axis (ΔX= -1mm), as in point 5.2.c).

*a) Side components (Fx, Fy)*

Table 2. Side components in X-axis.

| Fz (nominal) | Fx | | | | Fx | |
|---|---|---|---|---|---|---|
| kN | 0° N | 90° N | 180° N | 270° N | *Mean* | *Std dev* |
| **0** | -0,1 | -0,1 | -0,2 | -0,2 | *-0,18* | *0,06* |
| **20** | 1,9 | 4,4 | 1,5 | 4,4 | *3,06* | *1,57* |
| **40** | 18,8 | 17,8 | 15,9 | 22,5 | *18,76* | *2,77* |
| **60** | 36,5 | 32,6 | 40,3 | 33,8 | *35,80* | *3,44* |
| **80** | 50,4 | 57,4 | 55,1 | 46,9 | *52,42* | *4,72* |
| **100** | 65,2 | 71,8 | 64,3 | 60,9 | *65,54* | *4,53* |

Table 3. Side components in Y-axis.

| Fz (nominal) | Fy | | | | Fy | |
|---|---|---|---|---|---|---|
| kN | 0° N | 90° N | 180° N | 270° N | *Mean* | *Std dev* |
| **0** | -0,1 | -0,3 | -0,4 | -0,3 | *-0,29* | *0,11* |
| **20** | -20,1 | -18,9 | -18,4 | -21,3 | *-19,68* | *1,27* |
| **40** | -16,6 | -19,4 | -13,7 | -21,3 | *-17,75* | *3,35* |
| **60** | -4,9 | -3,2 | -11,1 | -14,0 | *-8,31* | *5,09* |
| **80** | 7,5 | 12,8 | 17,2 | 0,9 | *9,60* | *7,03* |
| **100** | 18,7 | 22,4 | 20,2 | 16,6 | *19,46* | *2,46* |

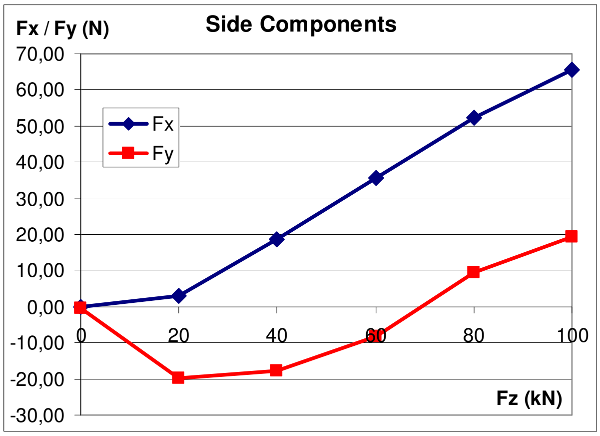


Figure 6. Side components. Resulting mean values.

Table 2 and Table 3 show a good agreement between the values obtained in different angular positions, this is an evidence of the good reproducibility of the FSM.

The side component $F_X$ is proportional to the applied load, it means that mainly depends of the initial setting of the machine.

The $F_Y$ side component has a non-linear behaviour, it points out a structural deformation of FSM under load and the effect of the lack of parallelism between weights.

The correction to be done in the axial force (Fz), is obtain from equation (1).

$$\frac{\Delta Fz}{Fz} = \frac{Fx^2 + Fy^2}{2Fz^2} \qquad (1)$$

The values obtained by means of equation (1) are less than $0{,}5 \cdot 10^{-6}$, for this reason the correction in the axial force can be disregarded for the range from 20 kN to 100 kN.

*b) Bending moments (Mx, My)*

Table 4. Bending moments in X-axis.

| Fz (nominal) kN | Mx 0° N·m | Mx 90° N·m | Mx 180° N·m | Mx 270° N·m | *Mx Mean* | *Mx Std dev* | *Δx mm* |
|---|---|---|---|---|---|---|---|
| **0** | 0,1 | 0,0 | 0,1 | 0,1 | *0,09* | *0,04* | |
| **20** | 5,1 | 4,4 | 5,5 | 5,0 | *5,01* | *0,42* | *0,25* |
| **40** | 0,1 | -0,5 | 0,4 | -0,4 | *-0,11* | *0,41* | *0,00* |
| **60** | -4,0 | -5,7 | -1,4 | -2,9 | *-3,52* | *1,82* | *-0,06* |
| **80** | -6,7 | -12,3 | -7,6 | -4,4 | *-7,73* | *3,33* | *-0,10* |
| **100** | -7,8 | -6,8 | -4,1 | -11,0 | *-7,43* | *2,88* | *-0,07* |

Table 5. Bending moments in Y-axis.

| Fz (nominal) kN | My 0° N·m | My 90° N·m | My 180° N·m | My 270° N·m | *My Mean* | *My Std dev* | *Δy mm* |
|---|---|---|---|---|---|---|---|
| **0** | 0,0 | -0,1 | -0,1 | -0,1 | *-0,08* | *0,05* | |
| **20** | -8,2 | -7,1 | -8,0 | -9,1 | *-8,08* | *0,83* | *-0,40* |
| **40** | -9,2 | -6,4 | -10,3 | -7,8 | *-8,44* | *1,72* | *-0,21* |
| **60** | -9,6 | -8,3 | -5,4 | -12,0 | *-8,82* | *2,74* | *-0,15* |
| **80** | -12,2 | -15,3 | -8,5 | -9,9 | *-11,47* | *3,00* | *-0,14* |
| **100** | -13,6 | -10,3 | -11,5 | -16,0 | *-12,87* | *2,54* | *-0,13* |

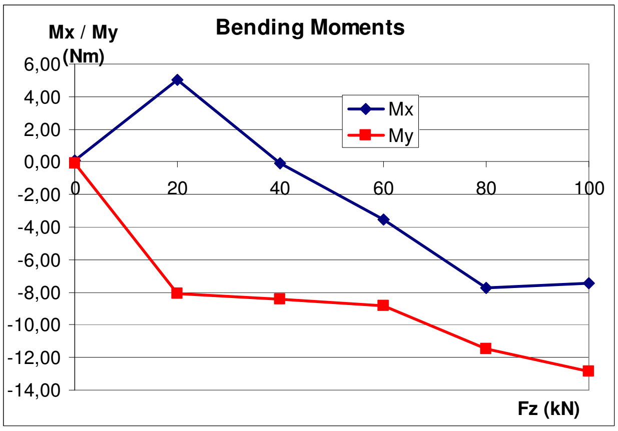


Figure 7. Bending moments. Resulting mean values.

Bending moments $M_Y$ show a quite linear behaviour, in agreement with $F_X$, and confirm that it mainly depends on the initial misalignment.

For bending moments $M_X$ it is possible to hypothesize the same consideration of $F_Y$, in fact its value increases up to 5,1 N·m at 20 kN and decreases to – 7,43 N·m at maximun load.

The last columns on the Table 4 and Table 5 show the calculated non-axiality between the real acting force vector and the vertical vector used to centre the transducer under test, which is calculated using the equation (2).

$$\Delta i = \frac{Mi}{Fz} \tag{2}$$

Where "*i*" can be X or Y axis.

Anyway the bending moments values are low and they have no influence on the correction of vertical load.

*c) Twisting moments (Mz)*

The twisting moments have a linear behaviour, having a maximum value below 8 N·m.

Table 6. Twisting moments in Z-axis.

| Fz (nominal) kN | Mz 0° N·m | Mz 90° N·m | Mz 180° N·m | Mz 270° N·m | *Mz Mean* | *Mz Std dev* |
|---|---|---|---|---|---|---|
| **0** | 0,0 | 0,0 | 0,0 | 0,0 | *0,00* | *0,03* |
| **20** | -2,6 | -2,2 | -1,5 | -3,0 | *-2,34* | *0,64* |
| **40** | -4,5 | -4,0 | -4,3 | -5,0 | *-4,46* | *0,40* |
| **60** | -6,1 | -4,7 | -5,7 | -7,0 | *-5,88* | *0,94* |
| **80** | -7,6 | -5,9 | -7,2 | -8,5 | *-7,29* | *1,09* |
| **100** | -9,0 | -6,2 | -7,6 | -8,7 | *-7,89* | *1,25* |

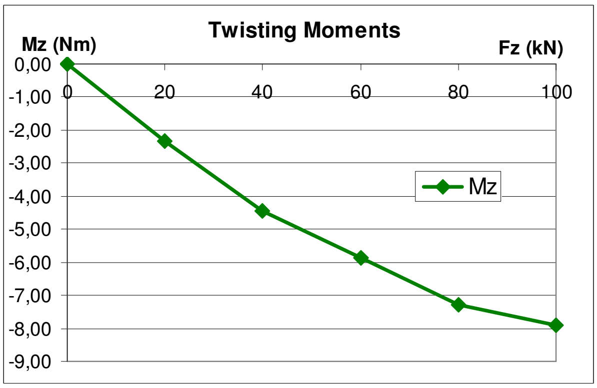


Figure 8. Twisting moments. Resulting mean values.

The twisting moments are mainly due to the low alignment of the different weight-pieces on the vertical plane, and to the different length of the supports to connect each others.

Under the same conditions the twisting moments are repeatable, but they may change considerably in function of the alignment of the transducer under test, as this changes the positioning of the weights.

*d) Static vs. dynamic components (Fx, Fy, Mx, My, Mz)*

The dynamic components are present while the change of load is made. When there is no change in the load the components are considered as static components in spite of being the system in free oscillation.

High values of static components are due to misalignments of the weights, whereas high values of dynamic components are due to misalignments of the weights according to their supports.

Table 7. Static vs. dynamic side components. Mean values.

| Fz (nominal) kN | Fx Dynamic N | Fx Static N | Fy Dynamic N | Fy Static N |
|---|---|---|---|---|
| **0** | | -0,2 | | -0,3 |
| **20** | 48,3 | 3,1 | -25,2 | -19,7 |
| **40** | 10,5 | 18,8 | -51,8 | -17,8 |
| **60** | 4,6 | 35,8 | -36,9 | -8,3 |
| **80** | 52,1 | 52,4 | -66,0 | 9,6 |
| **100** | 63,7 | 65,5 | 20,6 | 19,5 |

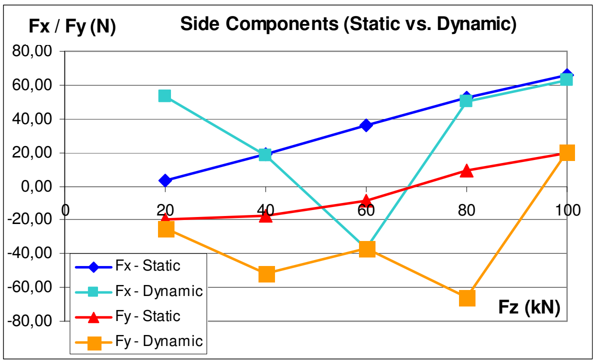


Figure 9. Side components. Static vs. dynamic.

Table 8. Static vs. dynamic bending and twisting moments. Mean values.

| Fz (nominal) | Mx | | My | | Mz | |
|---|---|---|---|---|---|---|
| | Dynamic | Static | Dynamic | Static | Dynamic | Static |
| kN | N·m | N·m | N·m | N·m | N·m | N·m |
| 0 | | 0,1 | | -0,1 | | 0,0 |
| 20 | 4,9 | 5,0 | -9,7 | -8,1 | -3,6 | -2,3 |
| 40 | 3,8 | -0,1 | -14,2 | -8,4 | -5,0 | -4,5 |
| 60 | -3,3 | -3,5 | -21,3 | -8,8 | -8,3 | -5,9 |
| 80 | -9,8 | -7,7 | -22,7 | -11,5 | -11,0 | -7,3 |
| 100 | -8,8 | -7,4 | -20,5 | -12,9 | -11,5 | -7,9 |

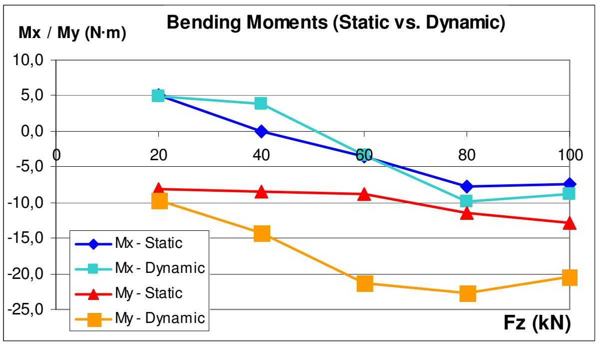


Figure 10. Bending moments. Static vs. dynamic.

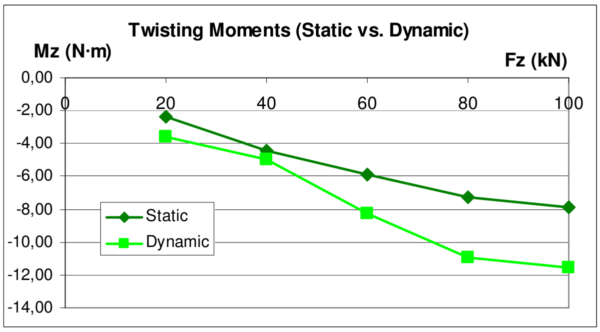


Figure 11. Twisting moments. Static vs. dynamic.

The dynamic components are not very different from the static components, which prove a smooth support while the load level is changing, as shown in Figure 9 to Figure 11.

### *5.4. Comparison between point 5.1 and 5.3 (before and after made the mechanical adjustments)*

The initial measurements were made before doing any mechanical adjustments; these data appear in point 5.1. The final measurements were made after the mechanical adjustments were performed; these data appear in point 5.3.

Table 9. Side components. Initial vs. final measurement.

| Fz (nominal) | Fx | | Fy | |
|---|---|---|---|---|
| | Initial | Final | Initial | Final |
| kN | N | N | N | N |
| 0 | -0,2 | -0,2 | -0,1 | -0,3 |
| 20 | 27,0 | 3,1 | -11,1 | -19,7 |
| 40 | 49,3 | 18,8 | -9,2 | -17,8 |
| 60 | 64,3 | 35,8 | -0,8 | -8,3 |
| 80 | 89,8 | 52,4 | 20,6 | 9,6 |
| 100 | 111,6 | 65,5 | 46,5 | 19,5 |

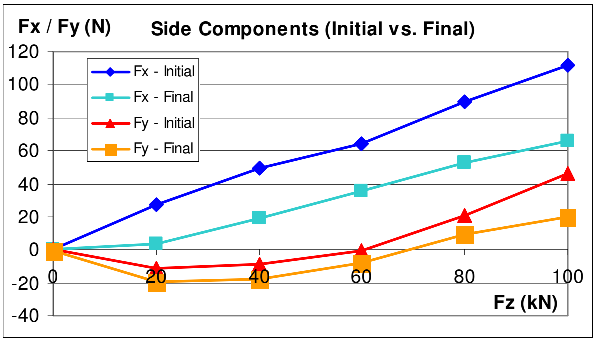


Figure 12. Side components. Initial vs. final mean values.

In the case of $F_X$, the side components were reduced to almost the half of the initial values. $F_Y$ remained to the initial values in the lower range, and was reduced to almost half for the higher range.

Table 10. Bending and twisting moments. Initial vs. final measurement.

| Fz (nominal) | Mx | | My | | Mz | |
|---|---|---|---|---|---|---|
| | Initial | Final | Initial | Final | Initial | Final |
| kN | N·m | N·m | N·m | N·m | N·m | N·m |
| 0 | 0,1 | 0,1 | 0,0 | -0,1 | 0,0 | 0,0 |
| 20 | 51,8 | 5,0 | 9,4 | -8,1 | -2,9 | -2,3 |
| 40 | 91,1 | -0,1 | 27,8 | -8,4 | -5,6 | -4,5 |
| 60 | 125,2 | -3,5 | 39,5 | -8,8 | -8,3 | -5,9 |
| 80 | 153,1 | -7,7 | 56,4 | -11,5 | -9,5 | -7,3 |
| 100 | 169,1 | -7,4 | 74,3 | -12,9 | -10,9 | -7,9 |

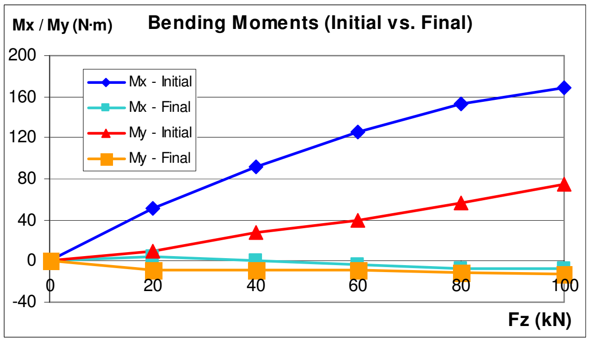


Figure 13. Bending moments. Initial vs. final mean values.

The bending moments were reduced considerably in both X-axis and Y-axis.

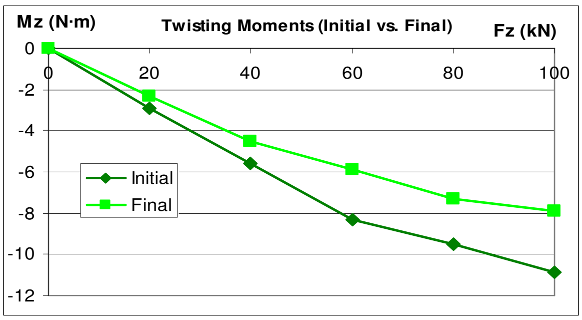


Figure 14. Twisting moments. Initial vs. final mean values.

Twisting moments were reduced in a small amount. Further investigations have to be done in order to reduce them further more.

## 6. CONCLUSIONS

The results of the measurements on the INTI´s 110 kN primary force standard machine, regarding the improvements on it of the metrological characteristics, allow the following main conclusions:

a) Side components (*Fx, Fy*) are repeatable, correspond to a maximal inclination of the main frame of about $10^{-3}$ rad ($Fx \leq 66$ N, $-20$ N $\leq Fy \leq 20$ N). The resultant correction of the axial load is less than $0{,}5.10^{-6}$.
b) The reproducibility of the side components indicates that the machine is stable and the interaction of machine-dynamometer is very low.
c) Bending moments are low, and in the case of Y-axis, could be improved by centring the transducer under load displaced –0,15mm in the Y-axis.
d) Twisting moments are higher than the desired level. In the case of transducers with high sensitivity to parasitic components, it is advisable to perform two warming loading cycles. This is to improve the positioning of the weights according to the transducer under test centre.
e) The value of twisting moments are about 0,08 N·m per kilonewton from 20 kN up to 100 kN, with a linear behaviour. It advises a further investigation to check if any contact is active between loading frame and main frame of the machine.
f) The linear behaviour of side component $F_X$ and bending moments $M_Y$, indicates that they depend essentially on the initial setup of the FSM.
g) The no-linearity for the side component $F_X$ and for the bending moments $M_Y$ is an indication that the machine has same mechanical deformations on the plane YZ.
h) Bending moments checked from 20 kN to 100 kN, confirm that the mean eccentricity is lower than 0,25 mm.
i) The dynamic components are appropriately measured by the multi-component dynamometer. They clearly put in evidence the influence of the changing weights, of the structural deformation, of the misalignments and of the possible contacts between main frame and loading frame, on the parasitic components rising during the application of load.
j) The main values obtained by this project are enough to improve the machine uncertainties. A good characterization can be achieved by a new inter-comparison.
k) The parasitic components could be considerably reduced by centring each weight using a non-friction joint in compression. To reduce the dynamic components and the twisting moments the same inclination level in each weight before and after being loaded must be used. This can be achieved by having the same gap in the three supports of each weight.

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