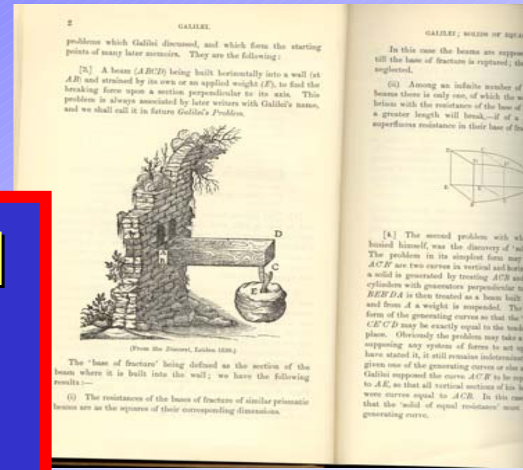
IMEKO 2010 TC3, TC5 and TC22 Conferences

Metrology in Modern Context

November 22–25, 2009, Pattaya, Chonburi, Thailand



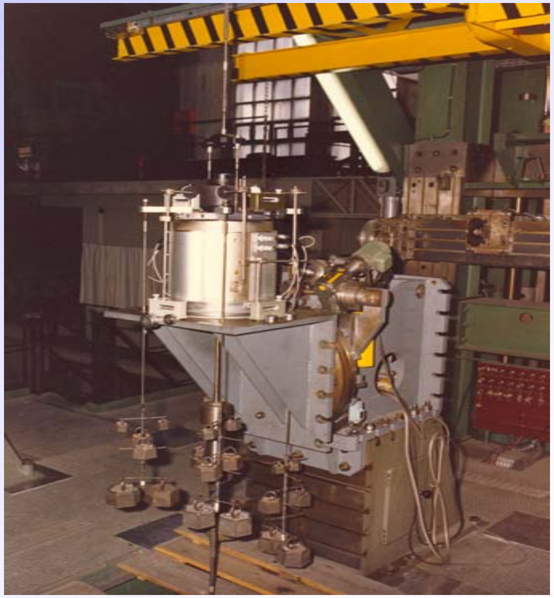
Development and Calibration of the INRiM composite 6-components dynamometers and the results of 20 years of intercomparisons

Carlo Ferrero

INRiM Consultant

IMEKO TC8 Chairman

EA – Chairman of the "Mechanical Commission"



From the Report of Prof. Weiler (PTB) after the 2° IMEKO TC3 (1971)

The 2nd discussion meeting of the Technical Committee Force and Mass" was organized by Dr. H. Wieringa in The Hague, Netherlands, in September 1971.

During the discussion of lectures Prof. A. Bray (IMGC,Torino, Italy) proposed to found an ad hoc committee in order to organize comparison measurements of force standard machines of the different government institutes. The ad hoc committee agreed that Prof. W. Weiler (PTB, Braunschweig, GFR) should start this work by comparing the small dead weight machines for 20 kN and 100 kN where as Mr. Debnam (NPL) and Mr. Wieringa (TNO) should compare the 0.5 MN machines of the Netherlands and of the United Kingdom.

1. **INTRODUCTION**

Several international comparisons of primary force standards demonstrated that the uncertainty of the axial-force value standards is sometimes higher by one order of magnitude than the uncertainty that might be expected on the basis of the relative uncertainties of the values of mass, of the acceleration due to gravity and of Archimede's thrust.

A number of **International comparisons** were carried out with single-component load cells

starting from 1973 up to now.

These comparisons, which evidenced a **rotational effect and overlapping phenomena caused by the interaction of the cells with the machines**, made great improvements possible as regards reduction of the uncertainty in axial load determination (from a few 10-4 to some parts in 10^{-5}) …..**and**……

……**and** showed that a multi component dynamometer (Dubois et al, 1980: Ferrero et al, 1981) is an essential tool in order

•to **improve force standard** deadweight machines,

•to attempt to **explain anomalies**,

•to **optimize testing methods**, and

•to **give manufacturers indications** allowing them to **improve both force machines and load cells**

In order to improve primary force standards as well as to understand anomalies and optimise calibration methods,

it is essential to measure the effect of different parameters on the parasitic components

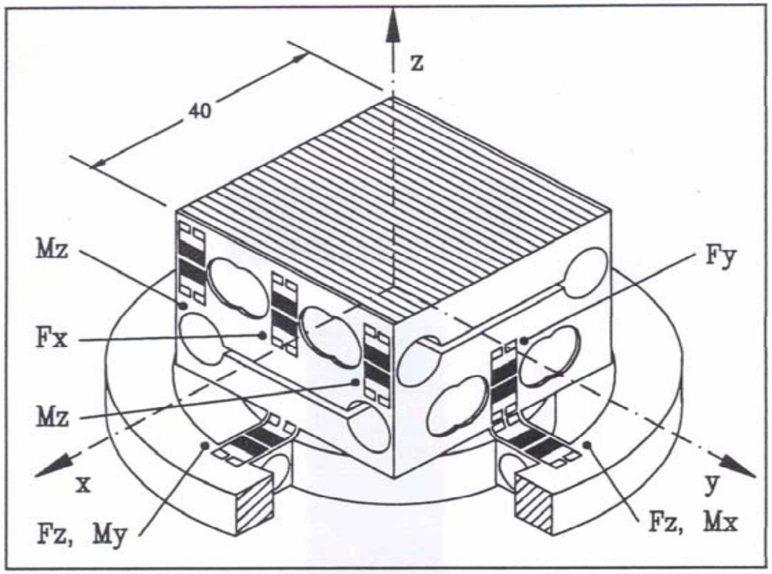
Than to design and to realize six-component dynamometers to measure

parasitic components generate by Force standard machines

Comparison of the Characteristics of Multicomponent Dynamometers

A general evaluation can be given on the differences between the various dynamometers, by comparing the **hyper-volume of the components**, which is the locus of the points of the six-dimensional space representing the maximum value of the components, which can be applied to the dynamometer without altering its metrological characteristics.

$$\frac{\text{secondary component}}{\text{main component}} = \frac{X}{Z} = \frac{Y}{Z} \begin{cases} \text{Transfer Standards} & 10^{-3} \div 10^{-4} \\ \text{wind-tunnels} & \\ \text{machine tools} & 0.1 \div 0.05 \\ \text{robotics} & \sim 1 \end{cases}$$

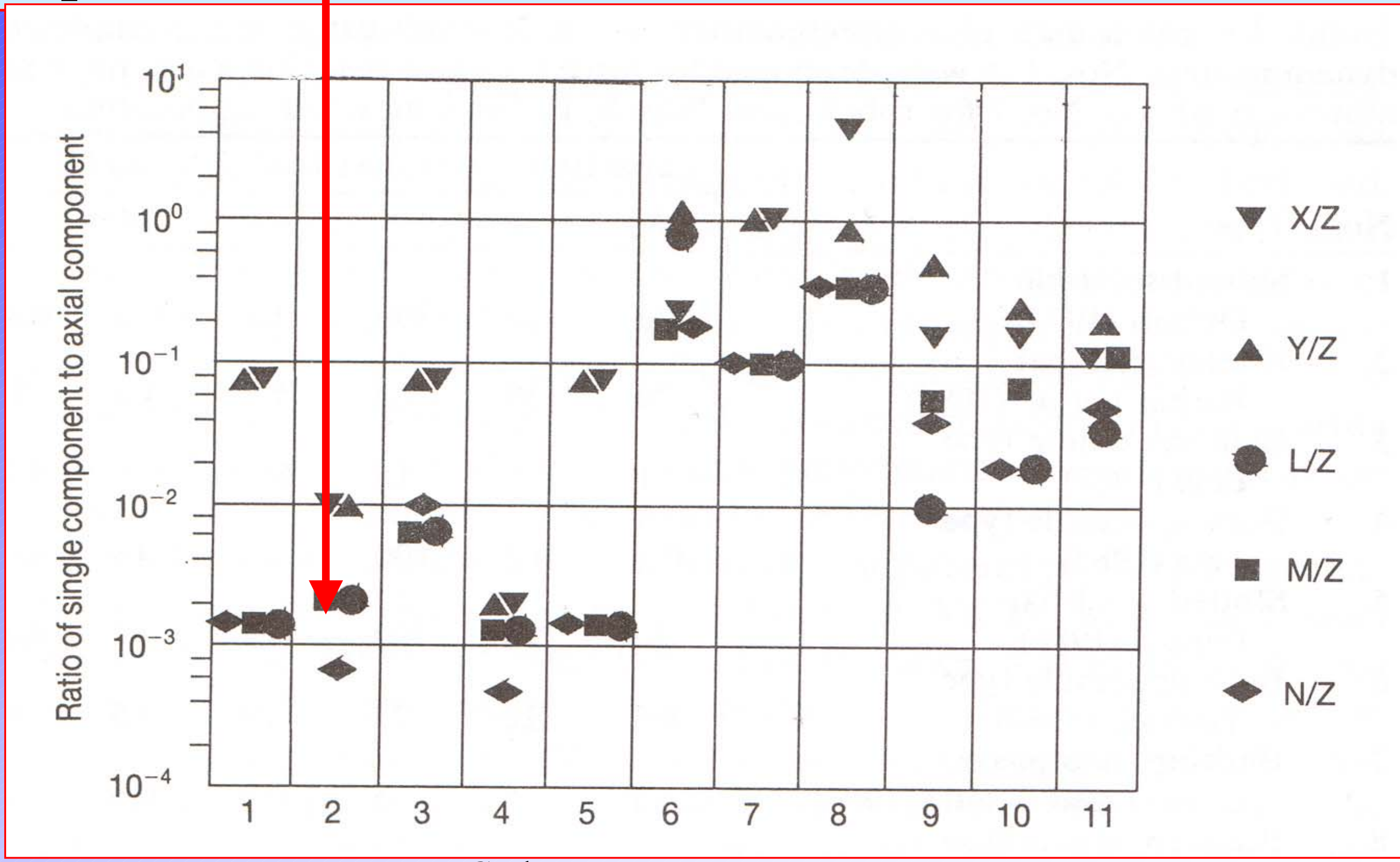


Barbato G, Desogus S, Germak A 1990 Multicomponent force sensors for robotics. ISMCR IMEKO TC-17. IMEKO, Budapest, pp. 11.2.1-2.9

. A single-block dynamometer therefore has certain **intrinsic limitations that prevent cross talk effects** (or interactions) from being reduced, but has the

advantages of less weight, smaller dimensions and high stiffness and in many applications these are the most important requirements (for example in robotics and sting balance)

The **ratio of the secondary components** (the transverse forces and the bending moments) to the main component demonstrates the **peculiarity of the multicomponent dynamometers specifically designed to check force standard machines with respect to those used in other fields:**



General evaluation of multicomponent dynamometers to check force standard machines

The multicomponent dynamometers employed to check force standard machines are essentially of two types, namely,

- **single-block or integral type and**
- **composite (or assembled) dynamometers.**

Single-block dynamometers

Mechanical decoupling cannot be pushed too far for reasons of stiffness and of machining possibility.

A single-block dynamometer has thereferore certain intrinsic limitations that prevent cross-talk effects (or interactions) from being reduced.

THE SIX-COMPONENT DYNAMOMETER, THE

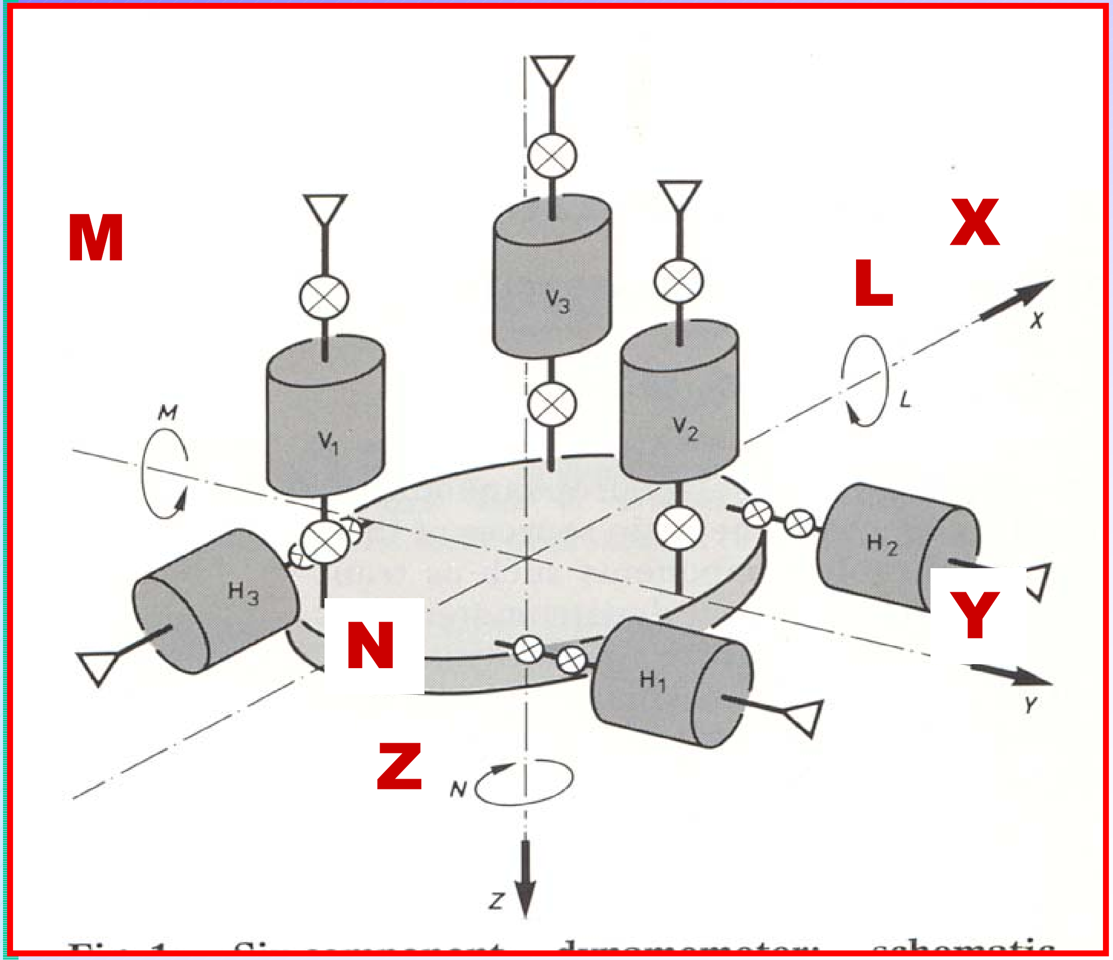
MEASUREMENT SET-UP AND PROCEDURES

The INRiM six-component dynamometers were designed and constructed with the purpose of measuring, in addition to axial load, also the five parasitic components (i.e., transverse forces and moments).

INRIM dynamometer **is a composite load cells consisting of six uniaxial load cells arranged to measure the:**

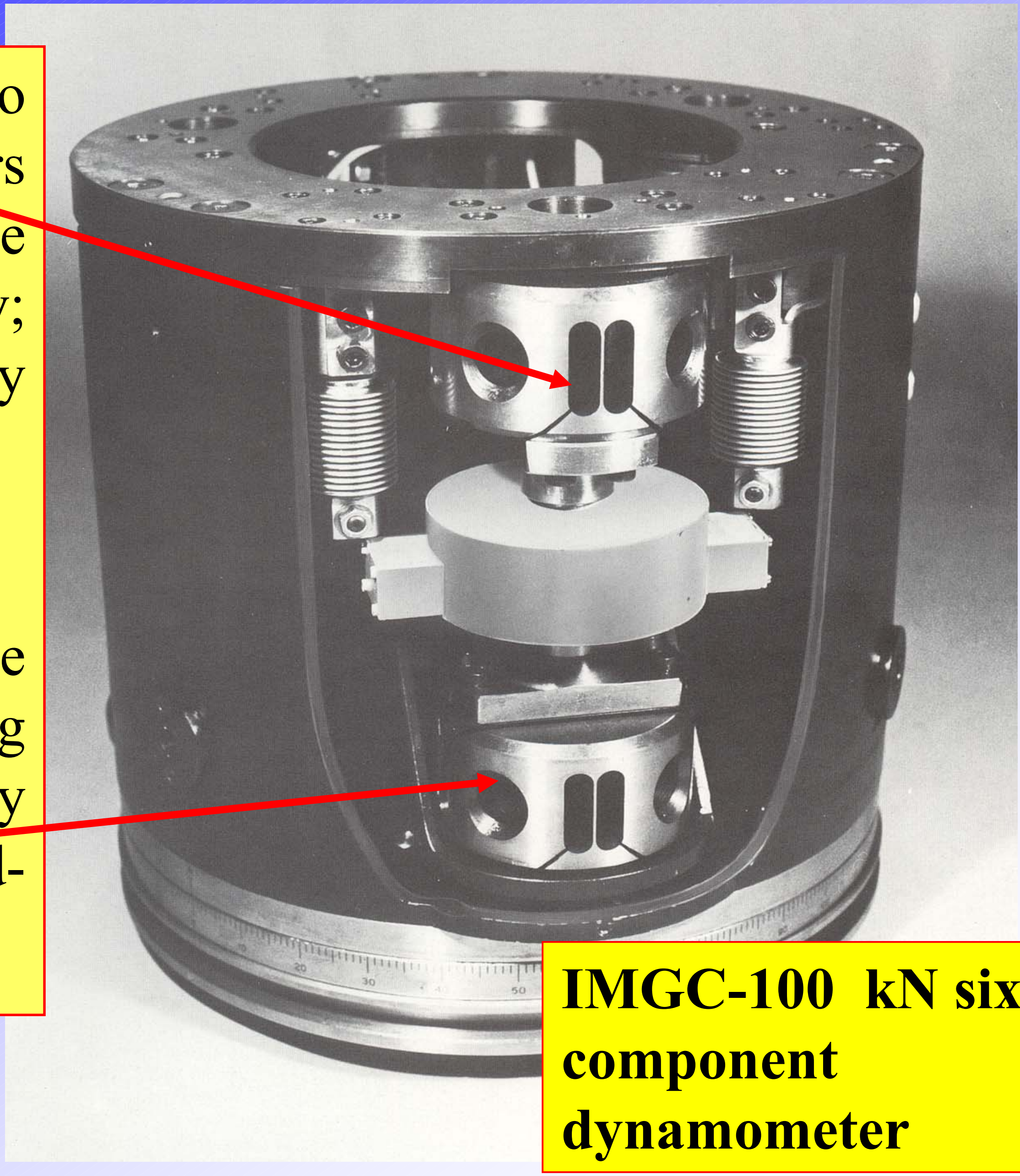
- **Vertical load Z;**
- **Side forces X and Y;**
- **Bending moments L and M;**
- **twisting moments N.**

Decoupling between the load cells is provided **by the use of elastic flexures**



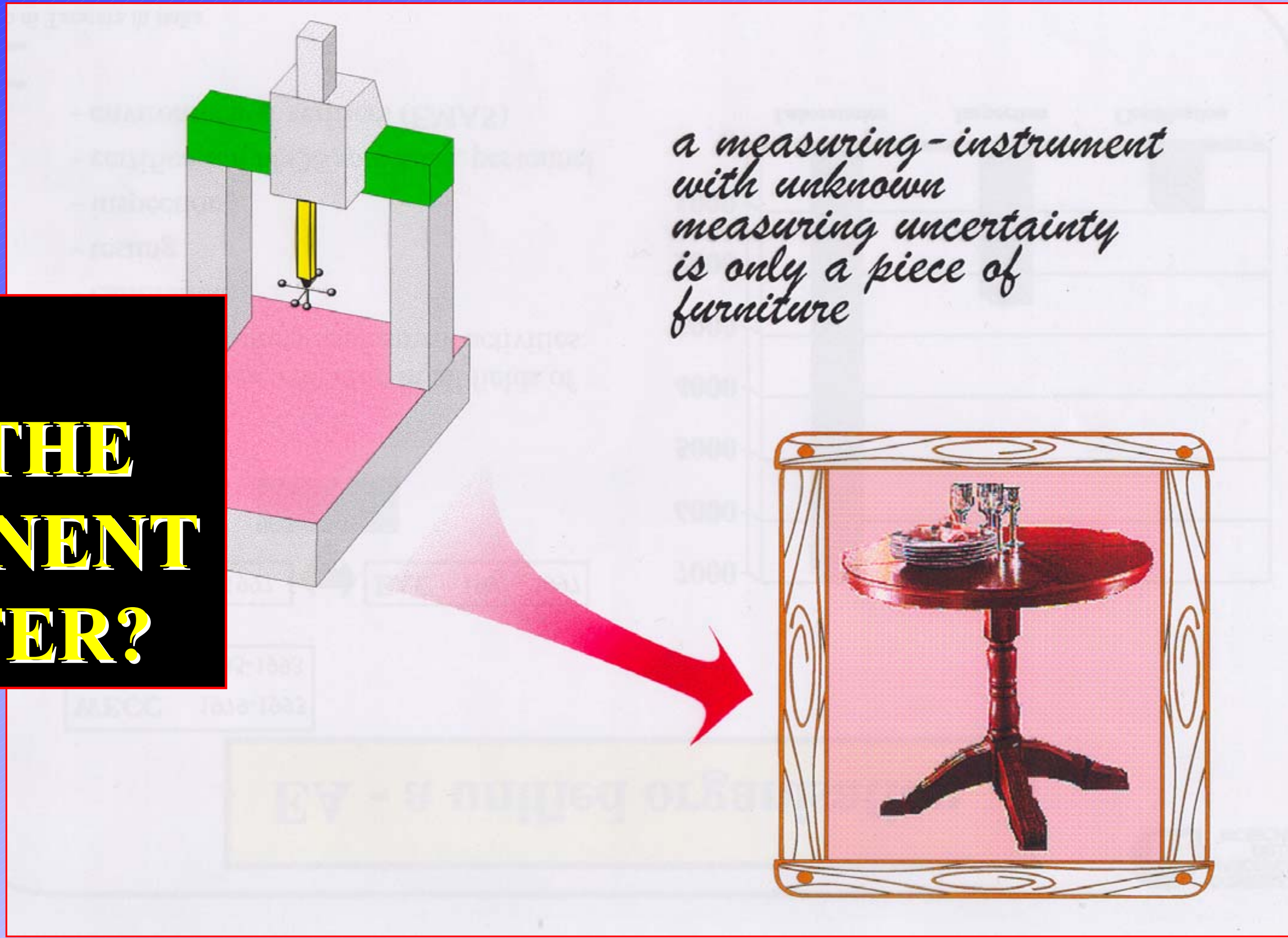
The elastic flexure at the two ends of composite dynamometers allow mechanic decoupling to be made very effectively; interactions are therefore very weak, not to say negligible.

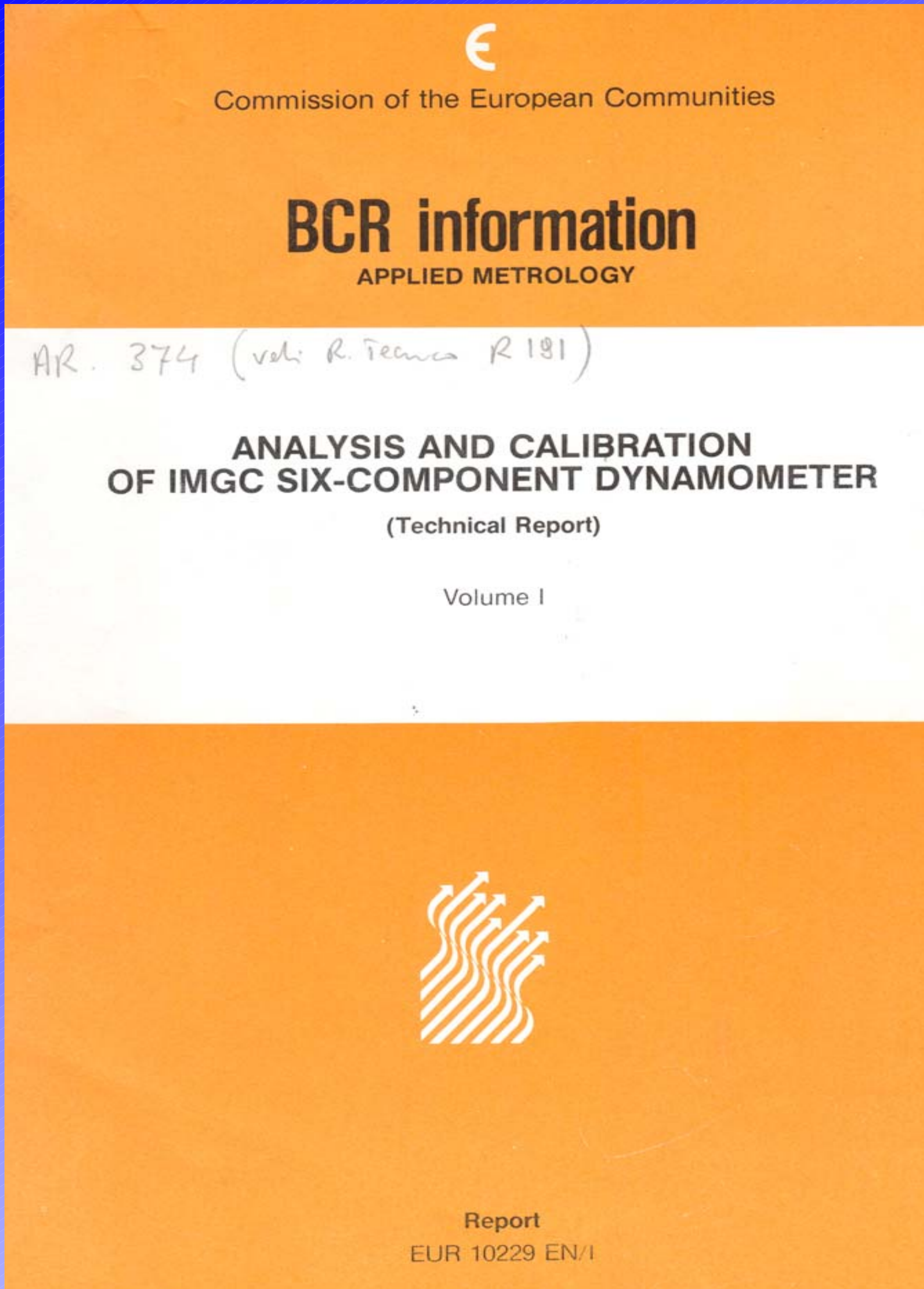
Here the elements measuring the axial component and bending moments work in tension by means of double decoupling end-flexures.



IMGC-100 kN six component dynamometer

HOW TO CALIBRATE THE MULTICOMPONENT DYNAMOMETER?




Commission of the European Communities

BCR information

APPLIED METROLOGY

AR. 374 (vedi R. Tecnica R 191)

ANALYSIS AND CALIBRATION
OF IMGC SIX-COMPONENT DYNAMOMETER

(Technical Report)

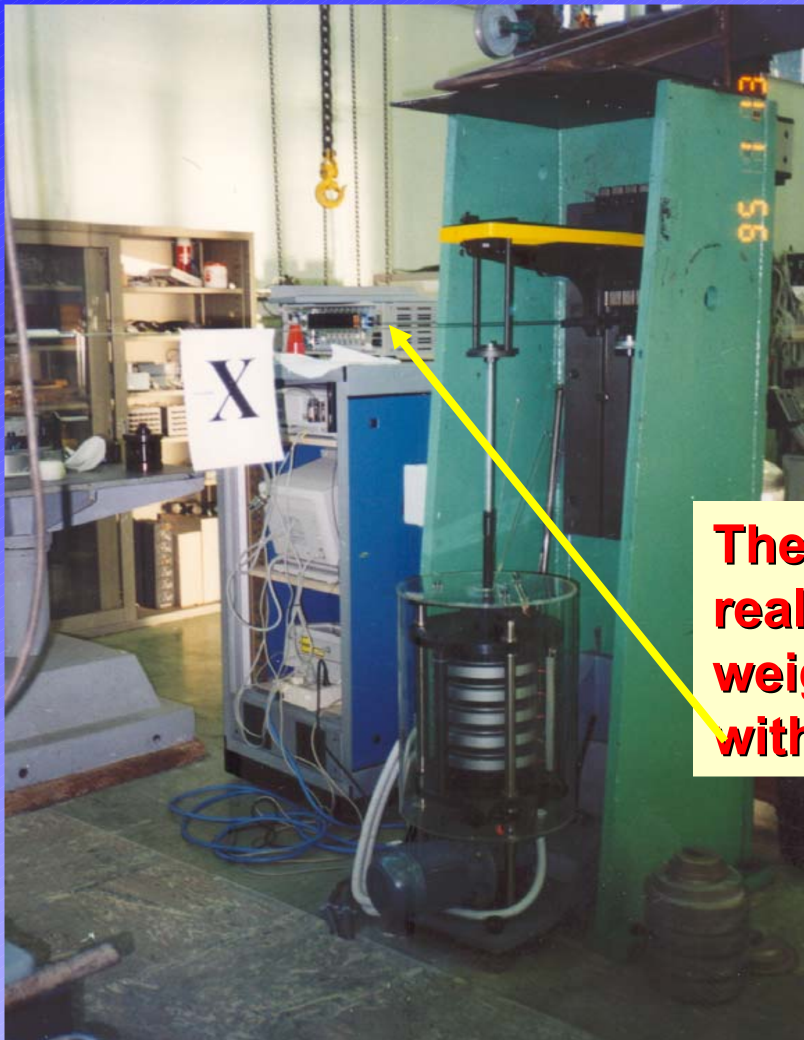
Volume I

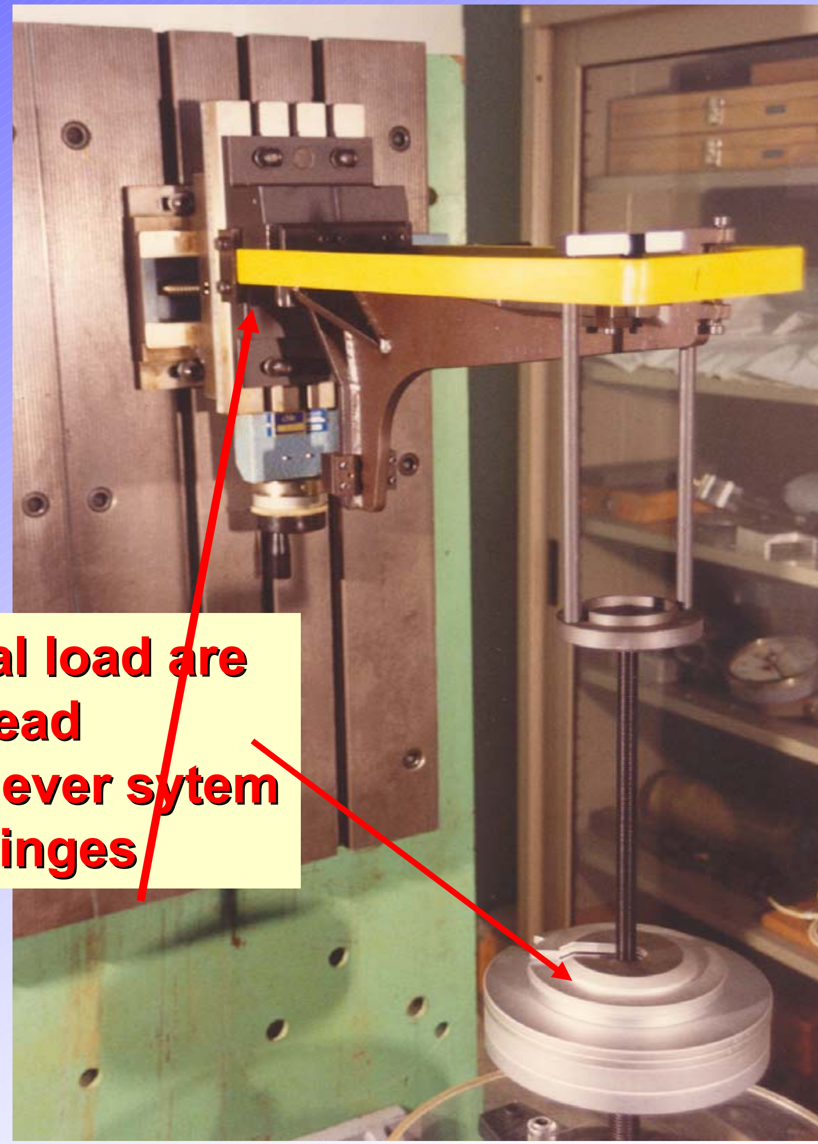
Report
EUR 10229 EN/I

First BCR-IMGC contract for the calibration of the IMGC 100 kN 6-components dynamometer with the ONERA calibration system

INRIM CALIBRATION SYSTEMS

INRIM

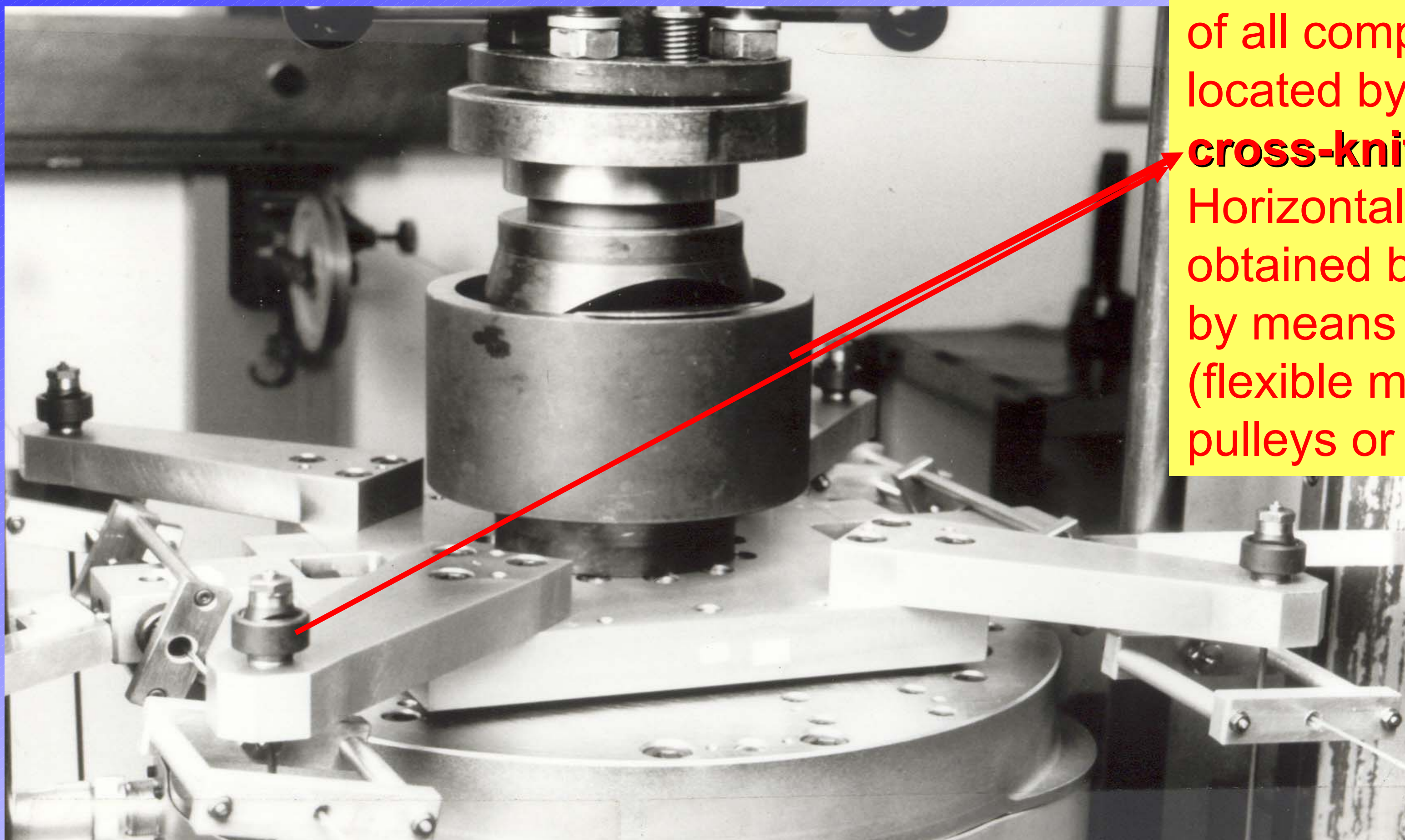




The horizontal load are realised by dead weights and lever sytem with elastic hinges

ISTITUTO NAZIONALE DI RICERCA

The plate was so machined to provide six housings to be used for horizontal loading and five for vertical loading.

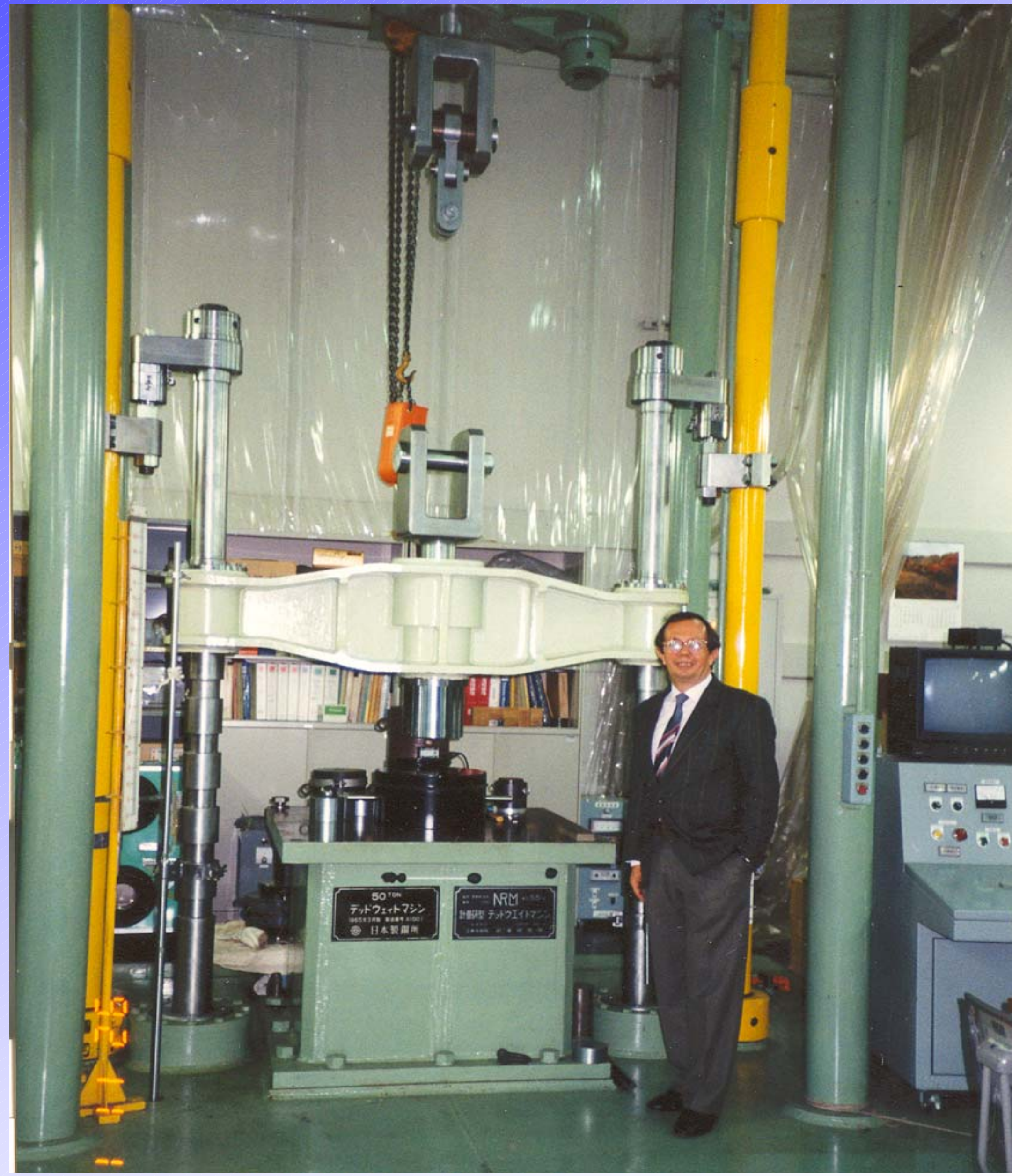


Points for the application of all components are located by means of **cross-knife joints.** Horizontal loading is obtained by deadweights by means of tie rods (flexible metal, cables), pulleys or levers

Many deadweight Force Standard Machines of the main National Institute of Metrology around the world have been evaluated with the **IMRiM six-component Dynamometers**

Institutes	Year
N.P.L (U.K.)	1985 1996
T.N.O. (the Nederland)	1985
L.G.A.I. (Spain)	1994 2003
N.R.L.M. (Japan)	1994
N.I.M. (China)	1986 1998
L.N.E. (France)	1985 1995
K.R.I.S.S. (Korea)	1998
P.T.B. (Germany)	1988 2004
R.P.O. (Finland)	1998

NRLM – 500 kN



Test on NPL 1,2 MN DWM with the 100 kN 6-component dynamometer

Parasitic components

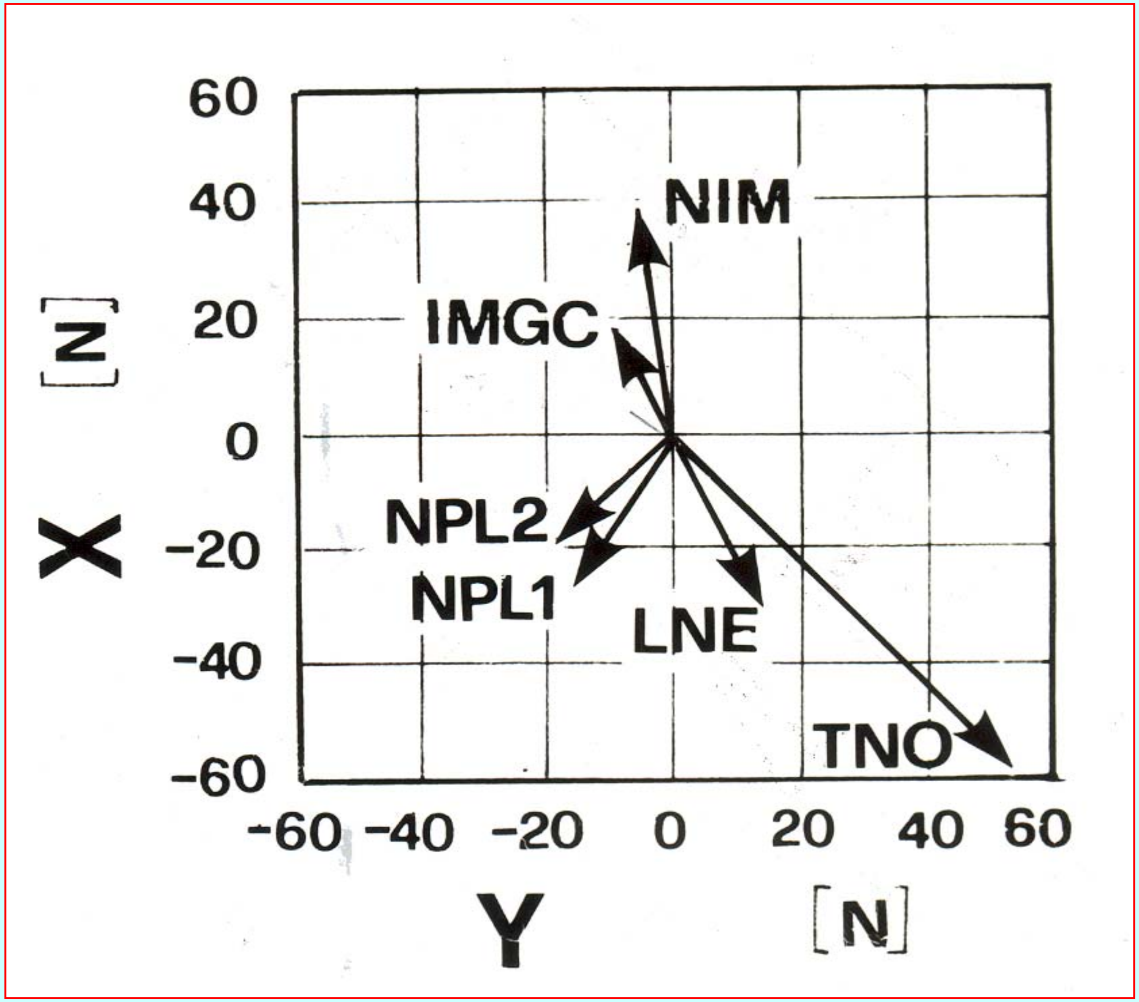
100 kN six-component dynamometer (1983-2001)

Side components (X, Y)

The tested national deadweight machines produce only small side forces (X, Y)

It must be remarked that, although the absolute values of X/Z and of Y/Z are of the same order of magnitude, the vector

(F = Y + iX) representing side forces is situated in different quadrants: in quadrant 2 for the IMGC, PTB and NPL2 machines, in quadrant 3 for the NPL1 machine, and in quadrant 4 for the LNE and TNO machines.



The correction to the value of axial load on the basis of the value of side components (**inclination correction ΔZ/Z**) was calculated as follows:

$$\Delta Z/Z = 1 - \cos\beta \cong \beta^2/2$$

Since $\sin \beta = X/Z$ (being the angle between the load action line and the dynamometer axis), one obtains

$$\Delta Z/Z = X^2/2Z^2$$

Given these side component values inclination correction ΔZ/Z always results lower than 1×10^{-6} for the four standard machines and, therefore, lower than the sensitivity of the measurement chain.

Side components, even when they do not introduce noticeable variations in axial load Z, may cause - as is well known - **variations in the output signal of the load cell used in intercomparison** exercises (rotational effect).

Care was therefore taken to have the machine properly arranged and settled, with the purpose of reducing such parasitic components.

Twisting moments

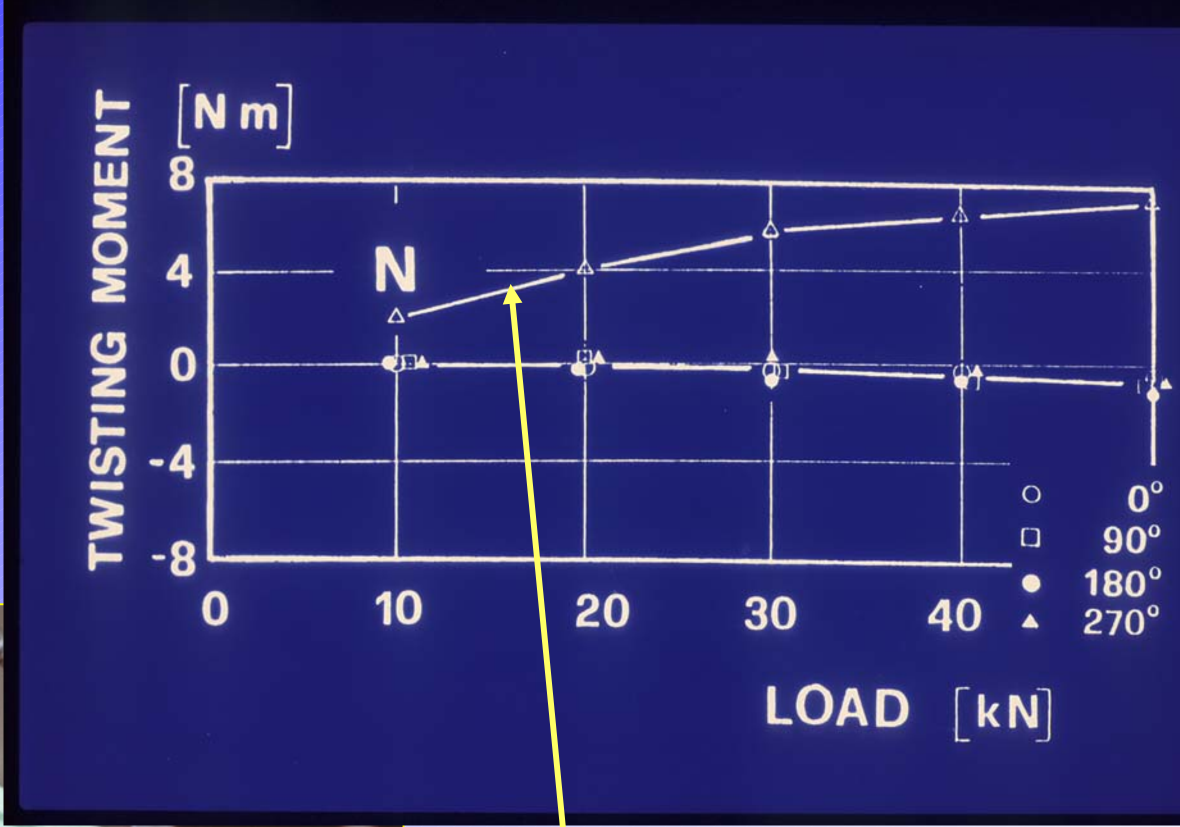
Twisting moment resulted to be lower than 1 N m for IMGC, PTB, NPL and LNE machines at all load levels.

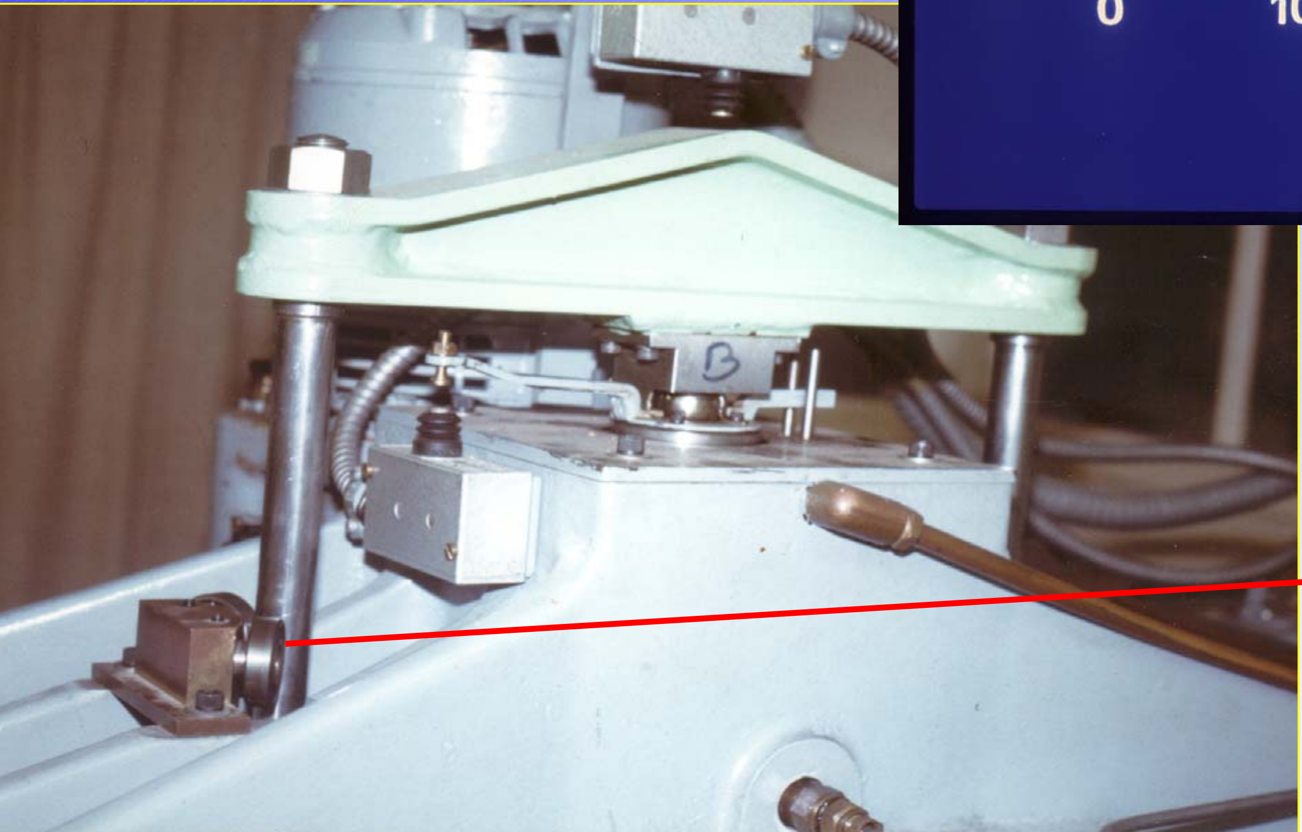
For diagnostic purposes, the twisting moment is the most sensitive tool and a very important component for evidencing possible contact points between the loading and the main frames.

BUT.....WHAT HAPPENS.......????

WHEN.....

NPL-50 kN DWM

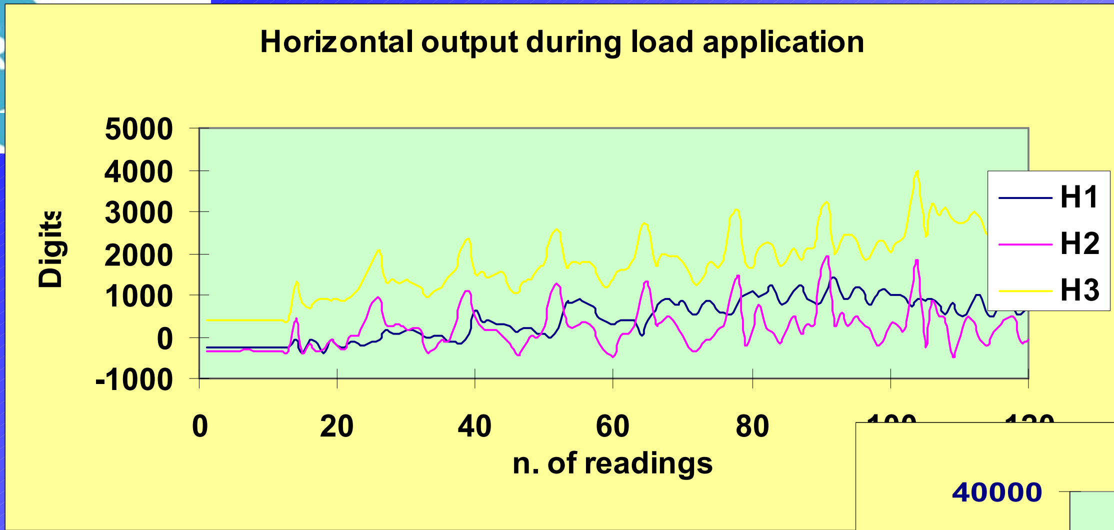


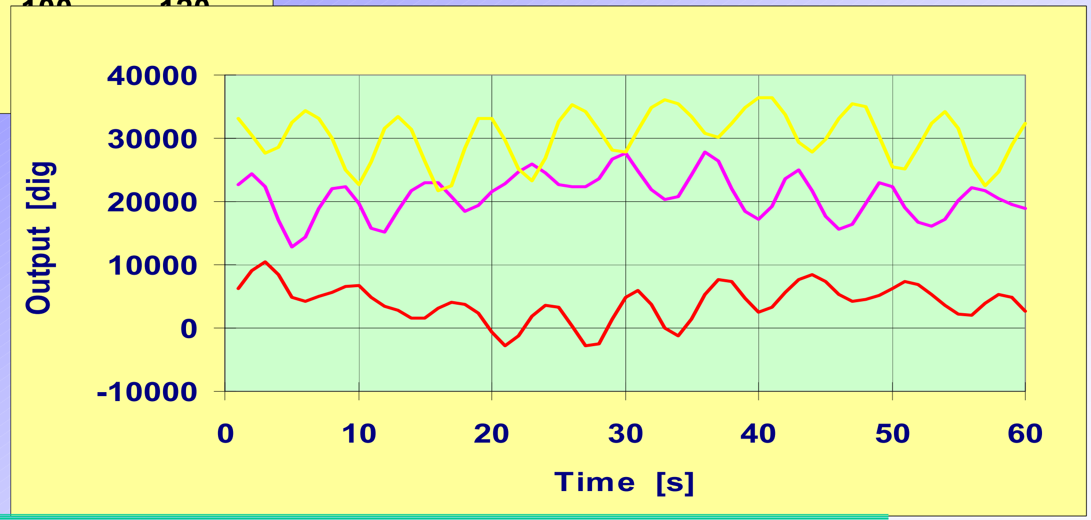


CONTACT OF THE WEEL DURING THE MEASURING PHASE

The versatility characteristics of the dynamometers and the measurement method adopted make it possible to study **dynamic phenomena** of the machine/dynamometer system.

To understand both as **load-application transients** and as **free oscillations** of the system under constant load.





Real-time diagrams of the evolution of the force tensor applied to the dynamometer are a very **useful tool to detect anomalies** that otherwise would be difficult to locate.

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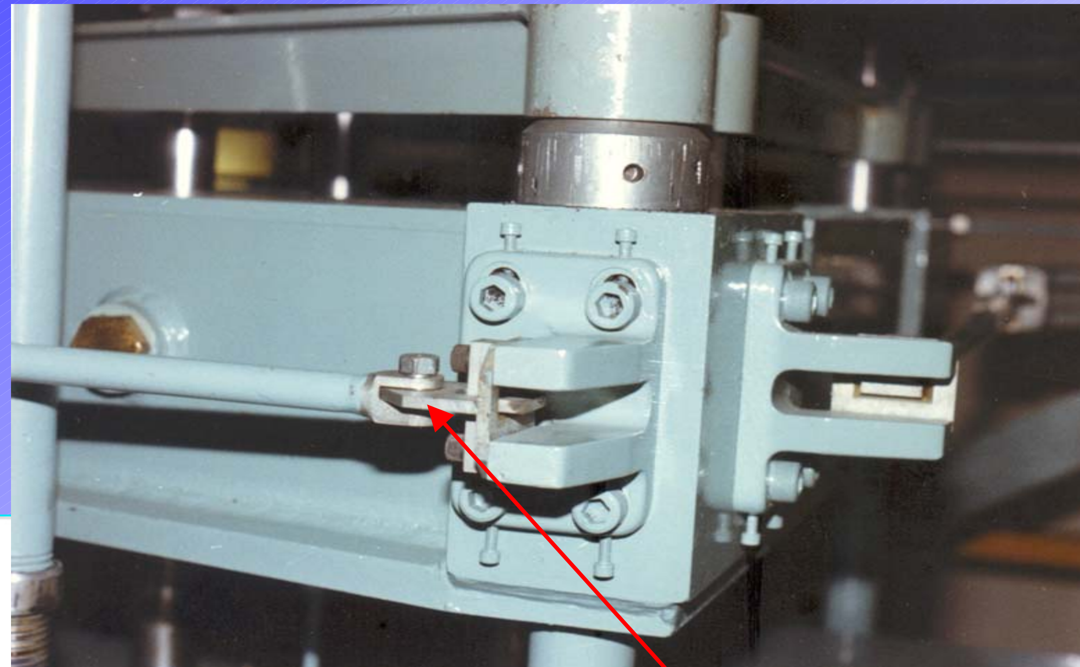
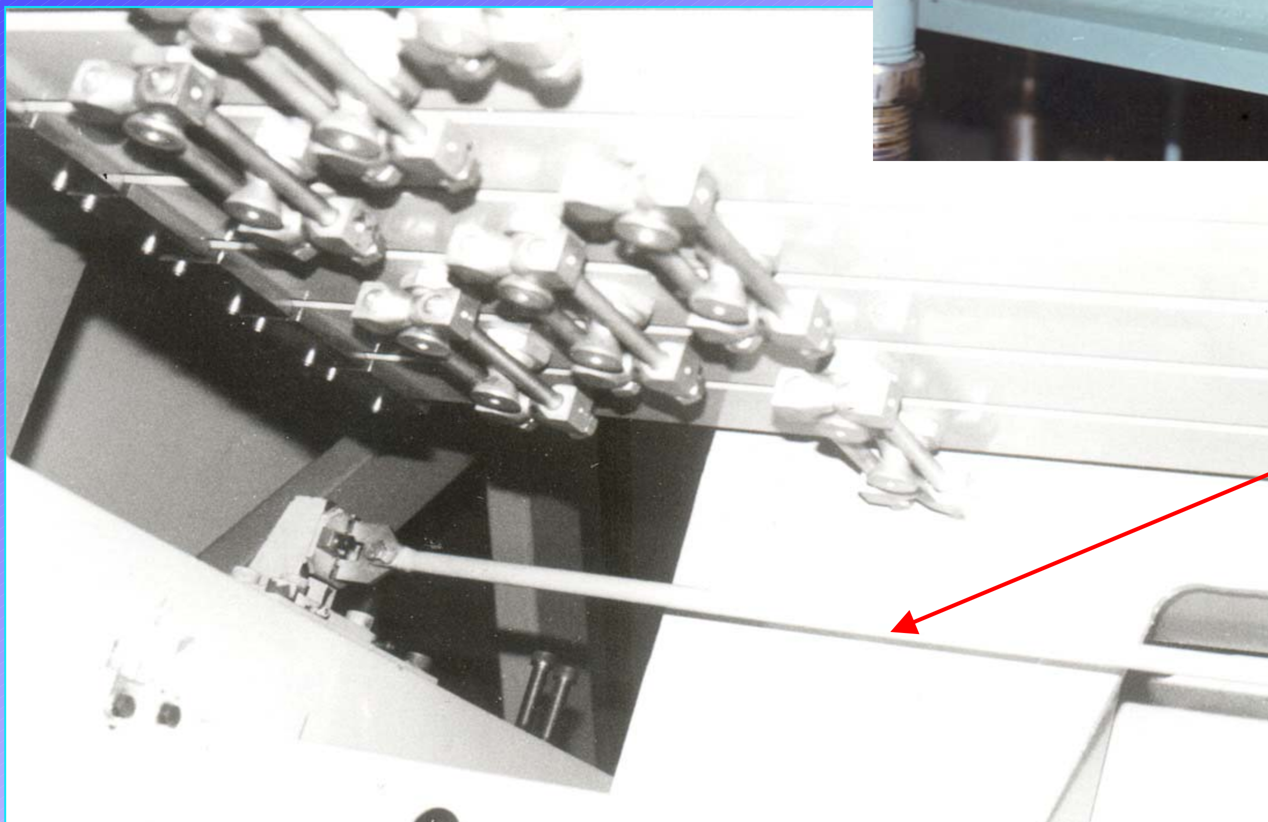
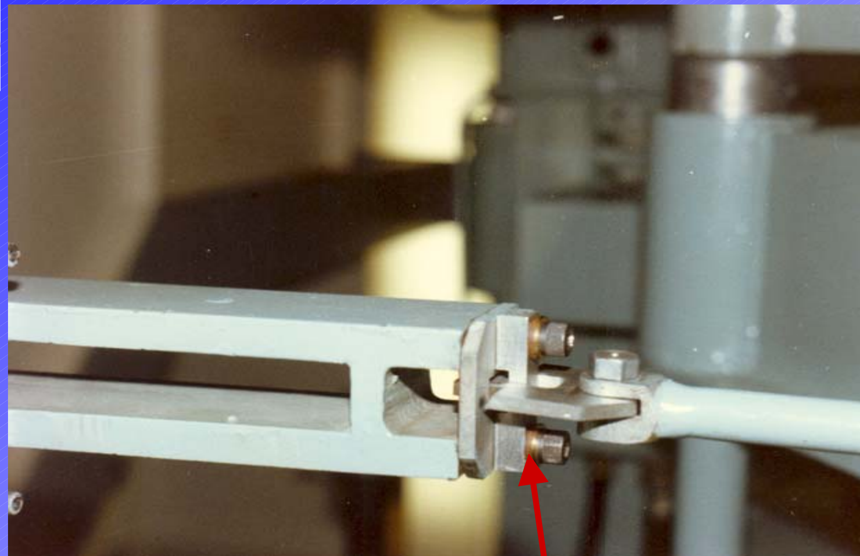
TNO-500 kN

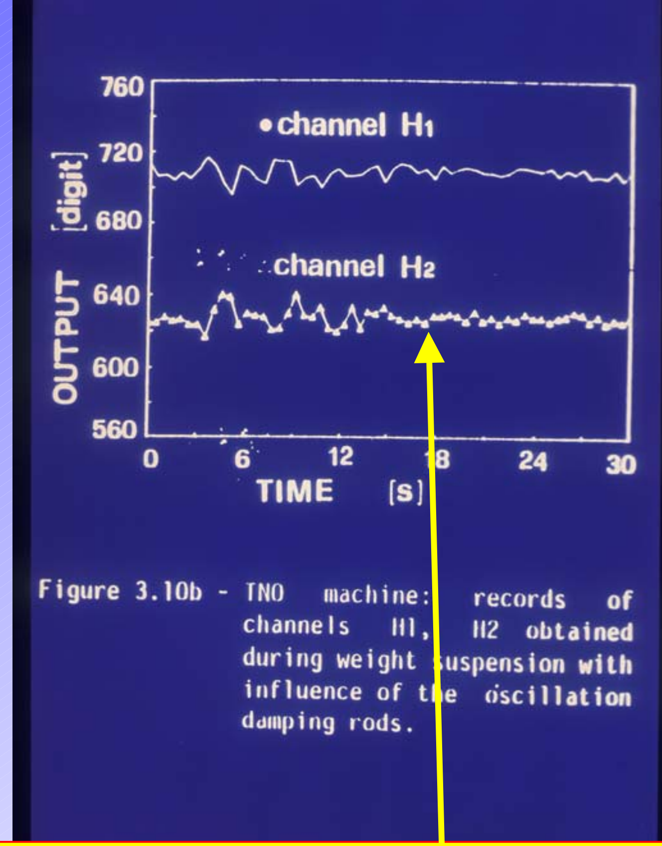




FOR EXAMPLE TNO USED THESE BARS TO REDUCE THE OSCILLATION TIME OF THE MASSES AND THE CALIBRATION TIME.

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

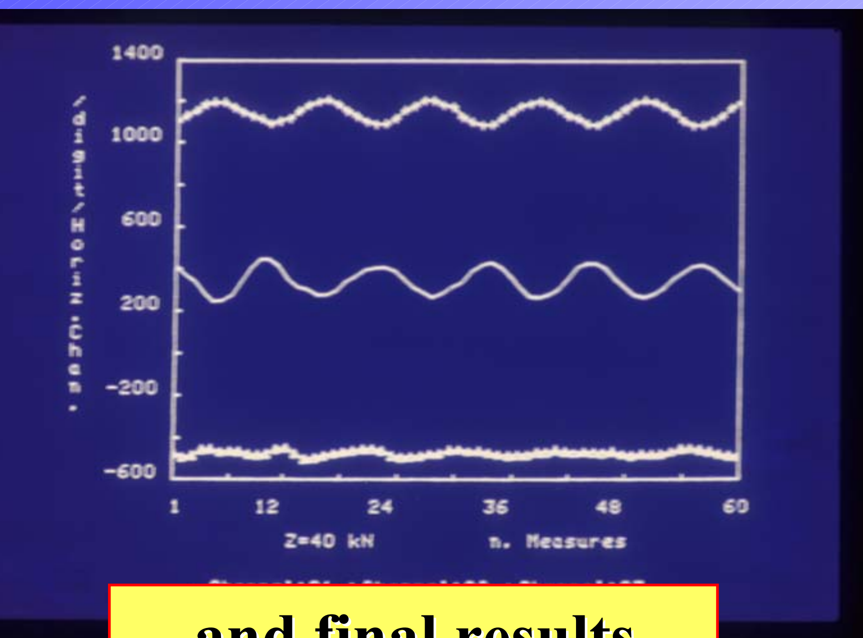




The first indication:

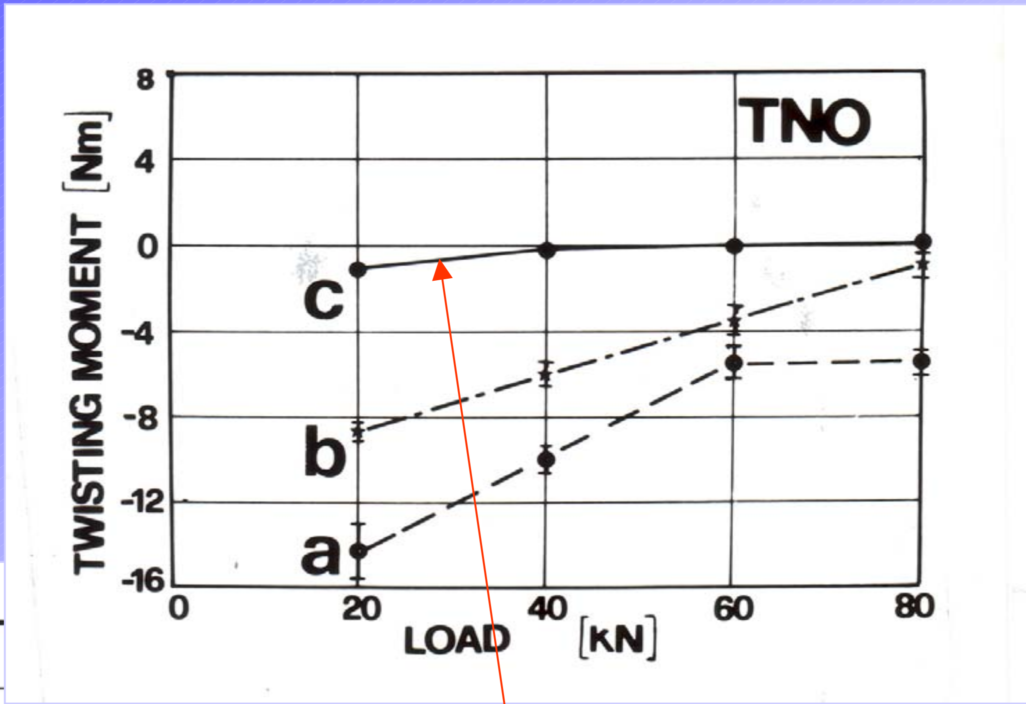
No-oscillation of the masses

The responsible !!

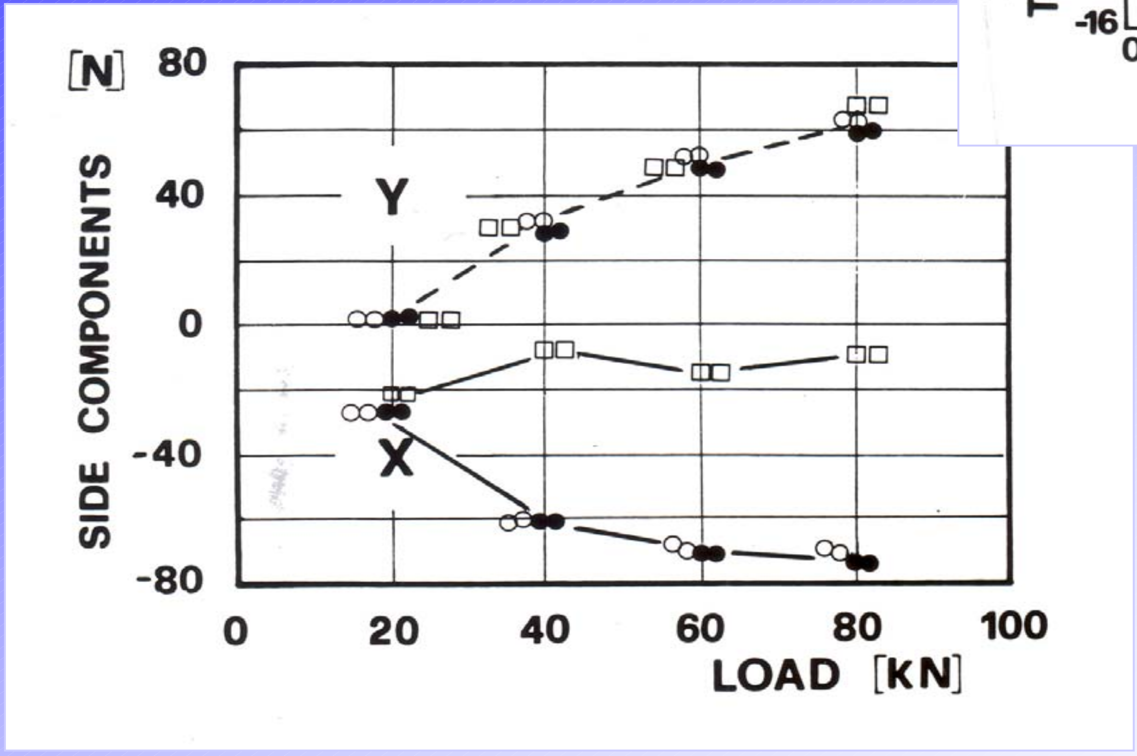


…and final results

Variazione delle componenti dopo vari interventi sulla funzionalità della macchina campione TNO

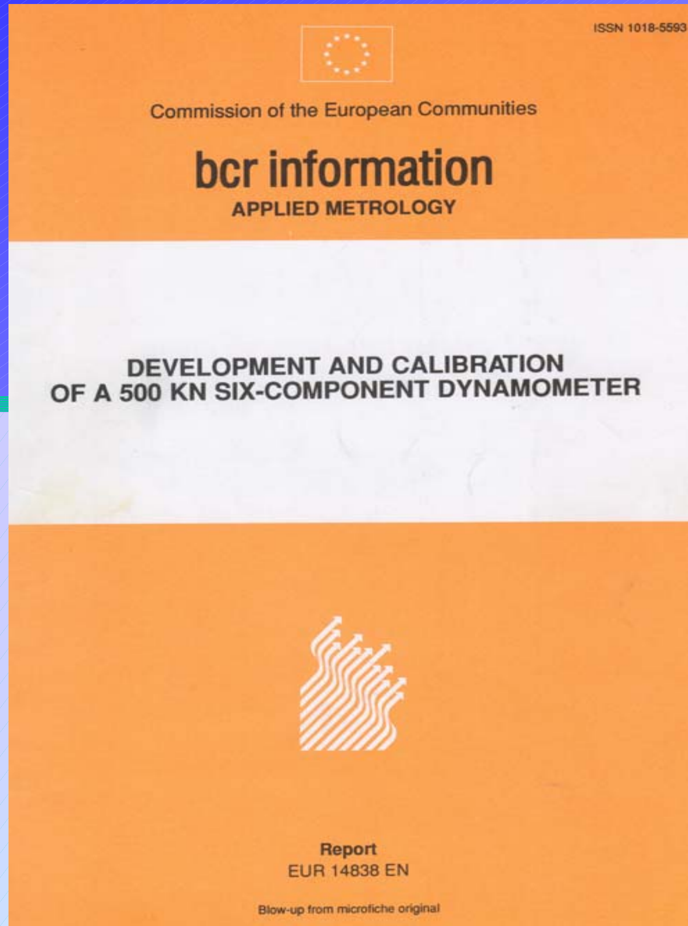


Final results



Quarto contratto BCR-IMGC per la realizzazione del nuovo dinamometro

Following the success of this work, the European Union commissioned IMGC to design and construct a 500 kN six-component dynamometer

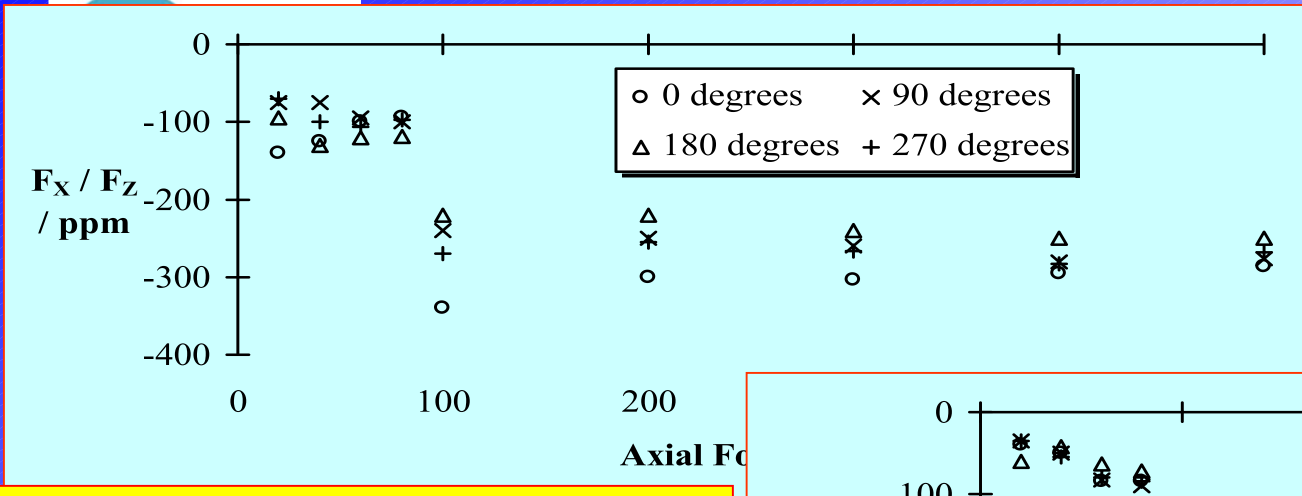


Test on NPL 1,2 MN DWM with the

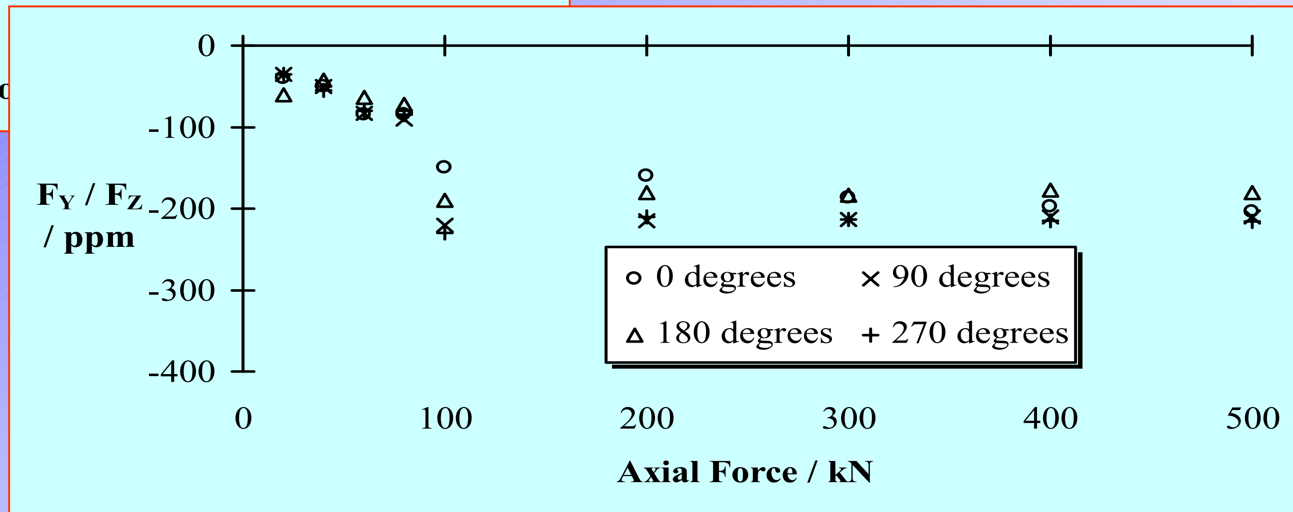
IMGC 500 kN

6-component dynamometer

The NPL 1.2 MN Deadweight Machine



Relative values of the tranversal components



The magnitude of the side force generated by the NPL 1,2 MN DWM is less than 350 ppm of the vertical force

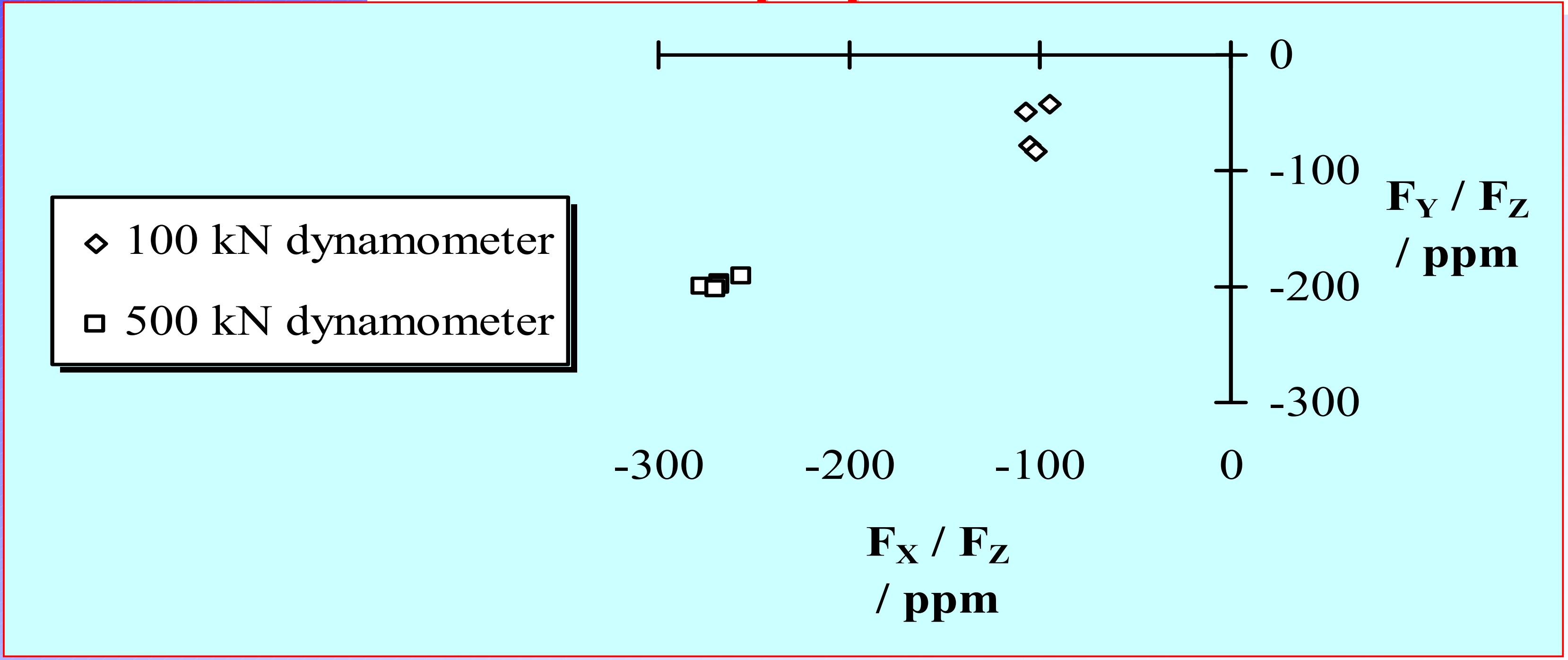
This component depends mainly on the initial level of the lower platen.

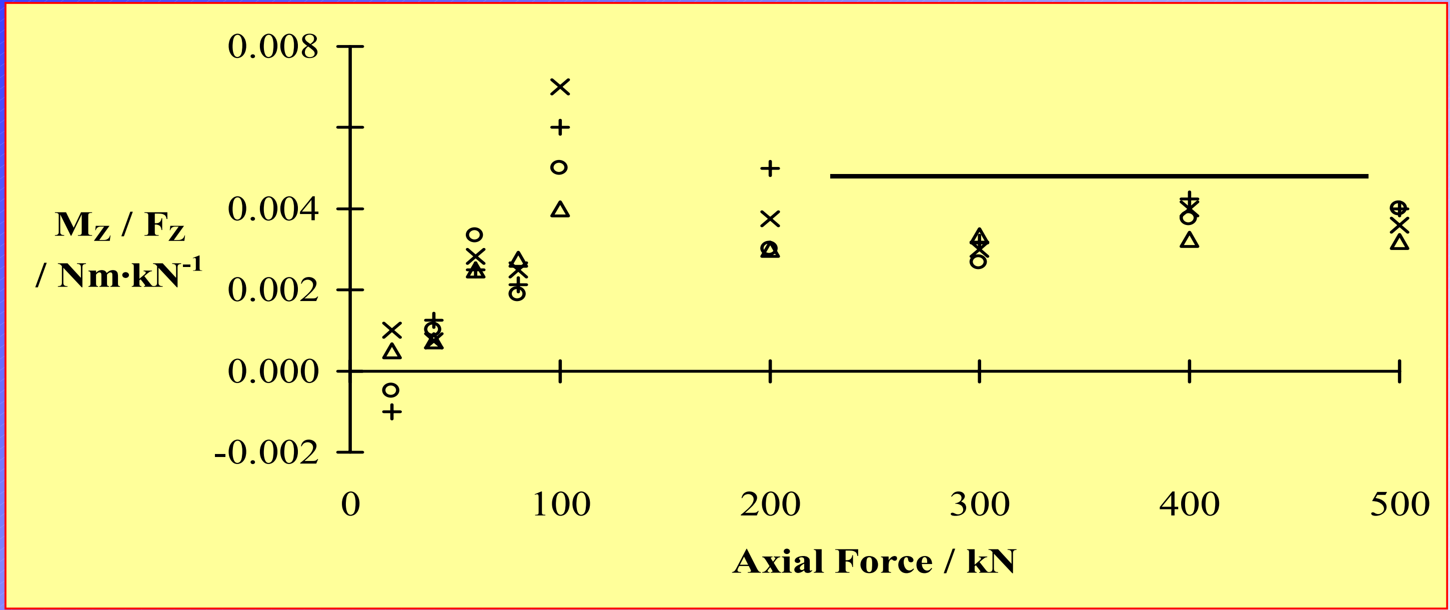
The lack of any second order dependence on load indicates that the platen angle does not vary under load.

The relative values of the two side force components are plotted against each other in figure.

This shows that the direction of the resultant side force is independent of axial load.

For each dynamometer, the side force was observed to be proportional to the axial load.





Relative values of twisting moment, M_Z.

All values are expressed as a ratio of the axial force and the results obtained at each of the four orientations are **always lower than 0,008**

KRISS-500 kN Deadweight Machine

Determination of ***Side components (X, Y)***

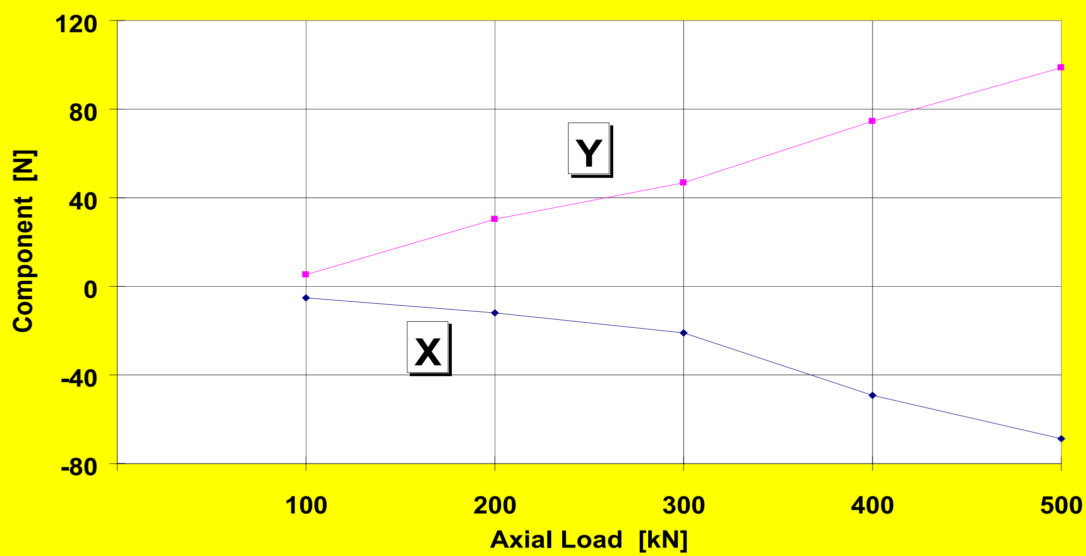
The experimental results indicate that the KRISS 500 kN dead-weight machine produces small side forces (X, Y).

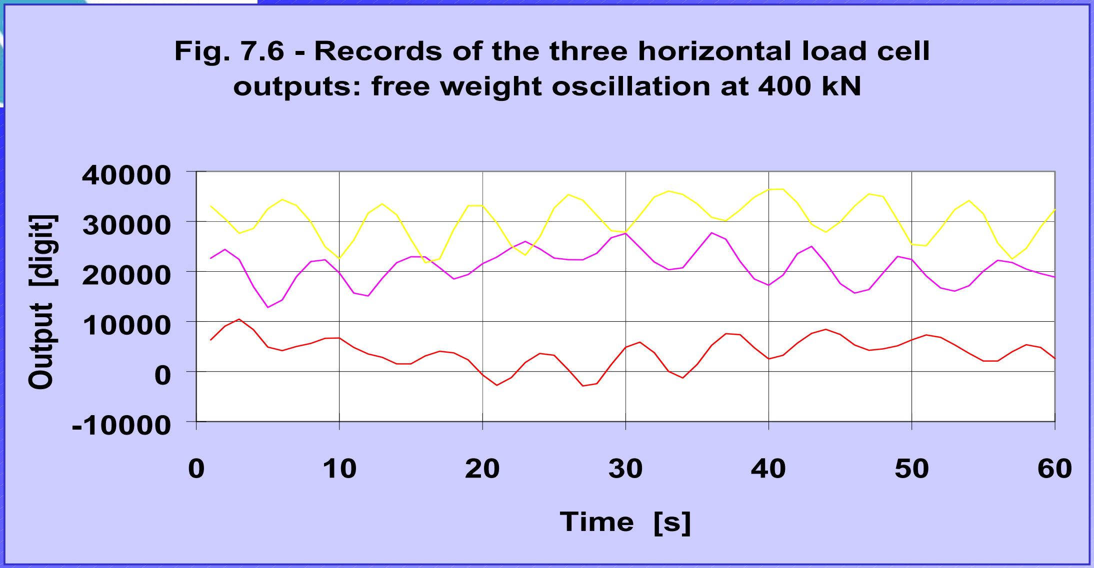
This component depends mainly on the initial level of the lower platen

The **X/Z ratio** is about **(1,4 ± 0,1)10^{-4}**;

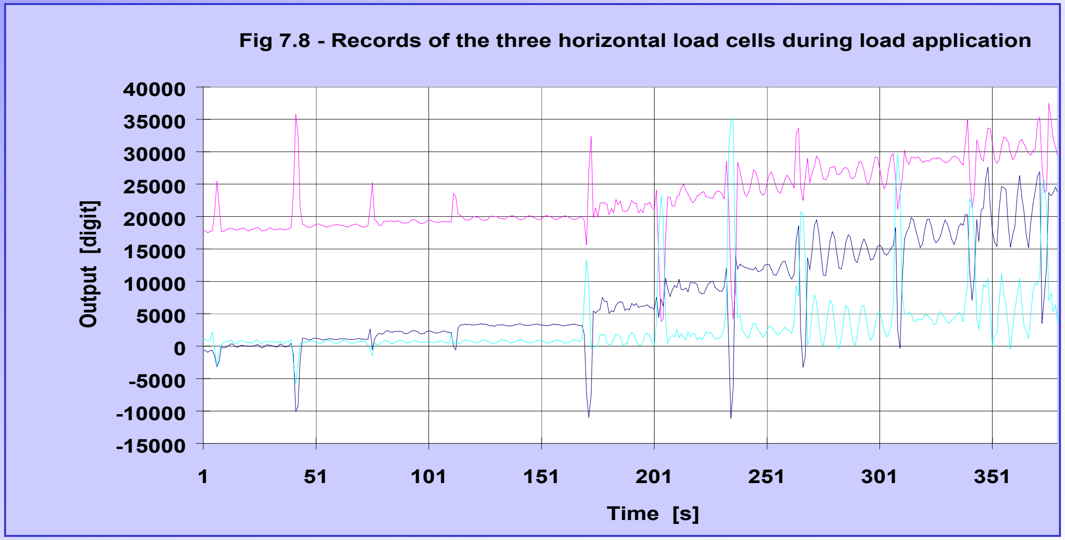
the **Y/Z ratio** is about **(2 ± 0,2)10^{-4}**.

Fig 7.5 - Average values of side components vs axial load at the four angular positions.)

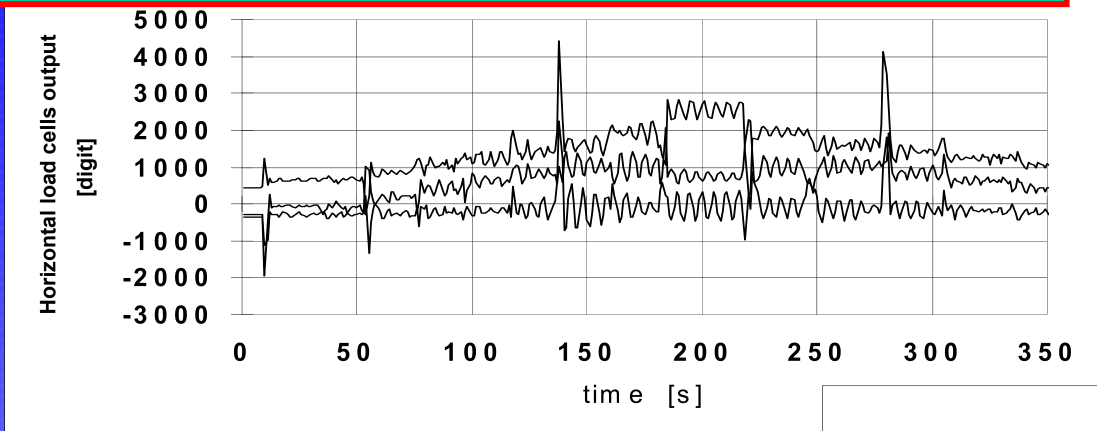




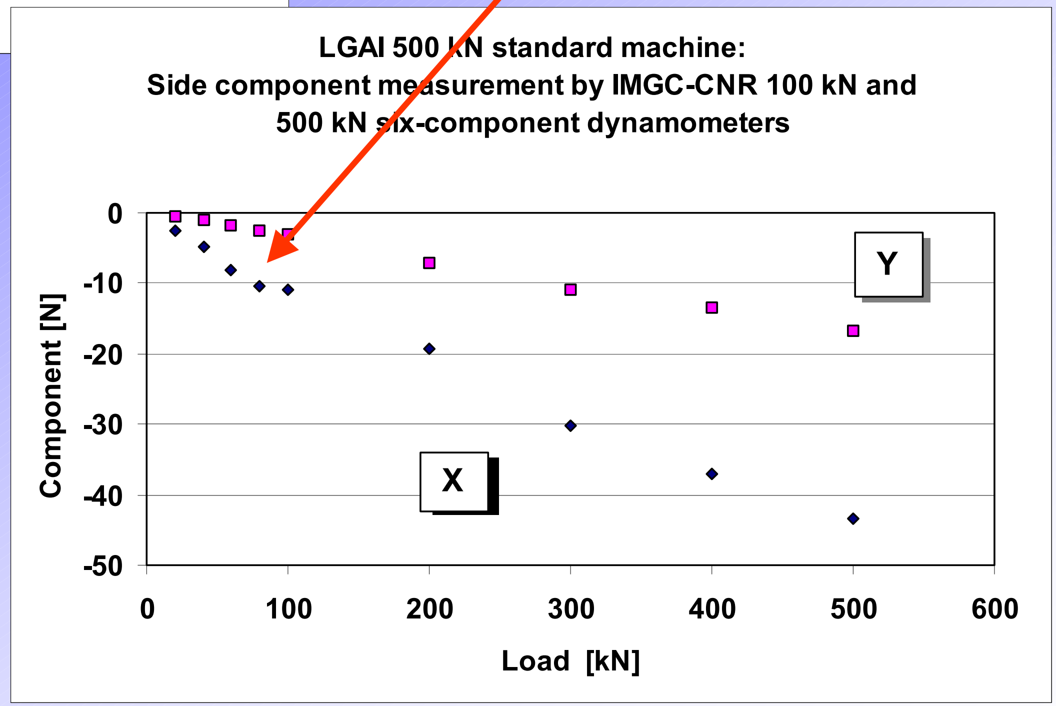
Dynamic Oscillation on 500 kN KRISS DWM



Free oscillation of the masses between the load applications

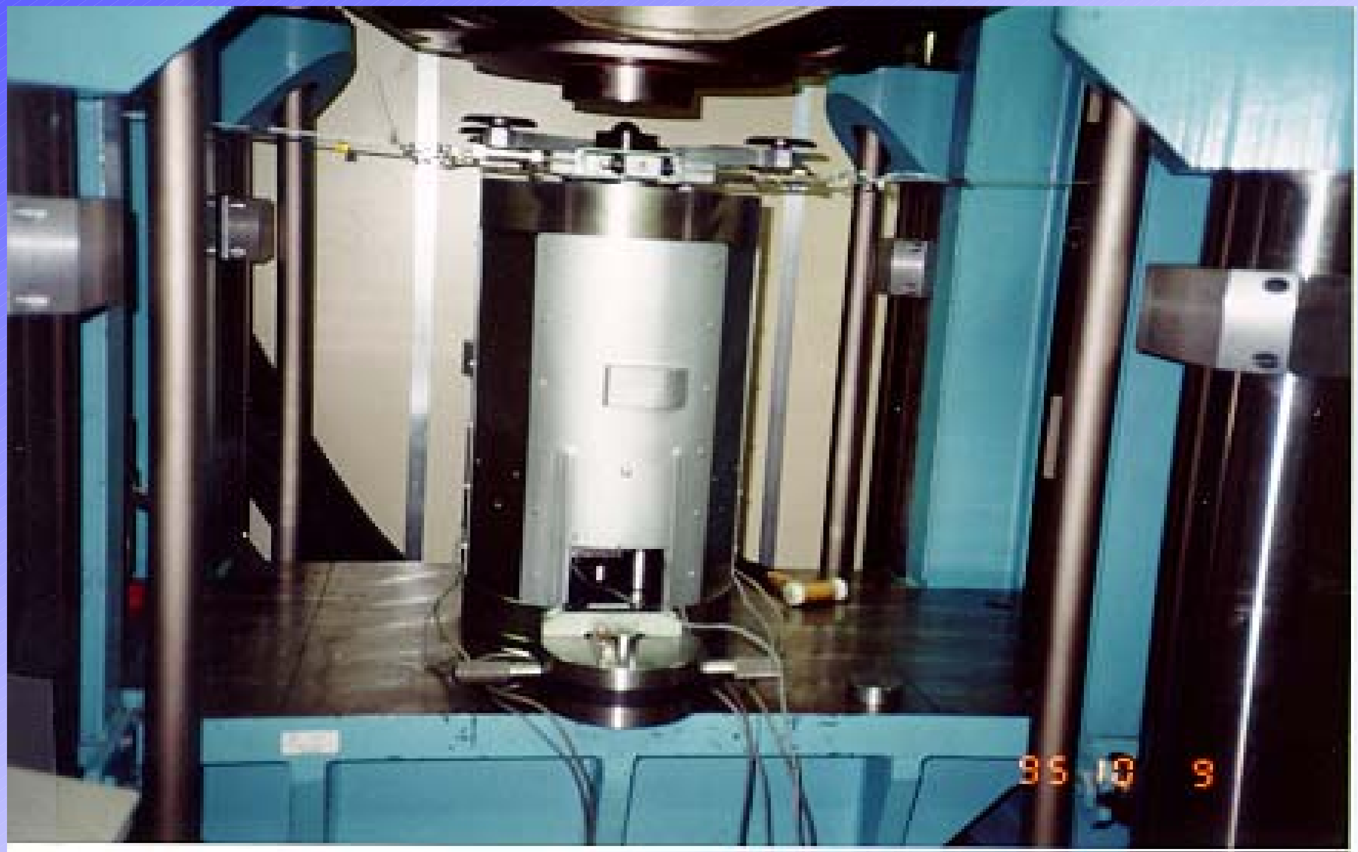


Overlapping of the six-component results obtained with the two dynamometers



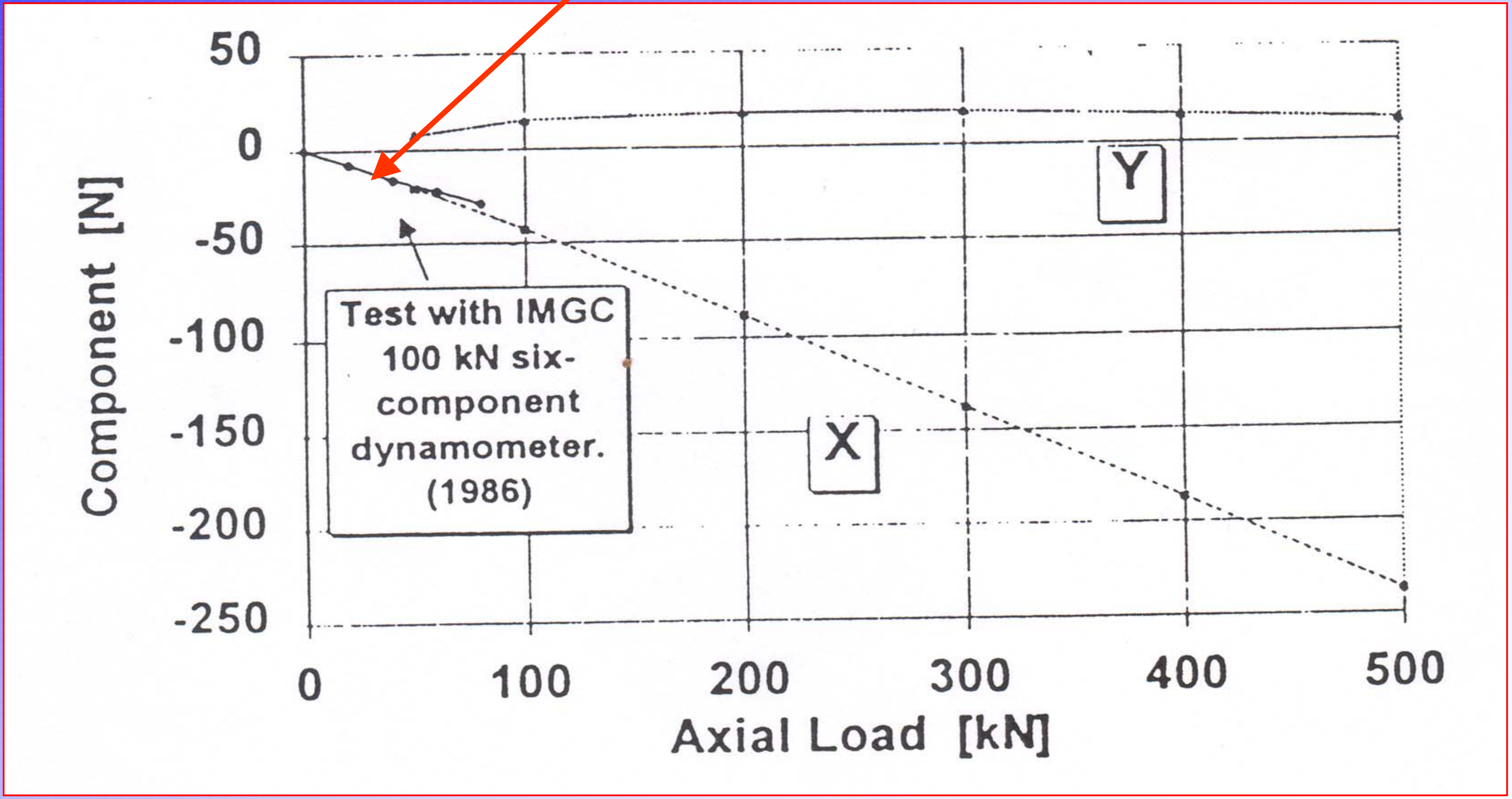
Test at LGAI Lab (june 2003) with the 500 kN dynamometer

Test on LNE 500 kN DWM with the IMGC 500 kN 6-component dynamometer



Comparison of the results obtained after 10 years…..

LNE standard machine shows very hight stability and repeatability of transversal components over 10 years



PTB-IMGC INTERCOMPARISON

On SIX-COMPONENTS

In June 2004 an intercomparison was realized in order to evaluate the main metrological characteristics of the PTB 2 MN standard deadweight machine by using the 500 kN IMGC six-component dynamometer

CONSIGLIO N

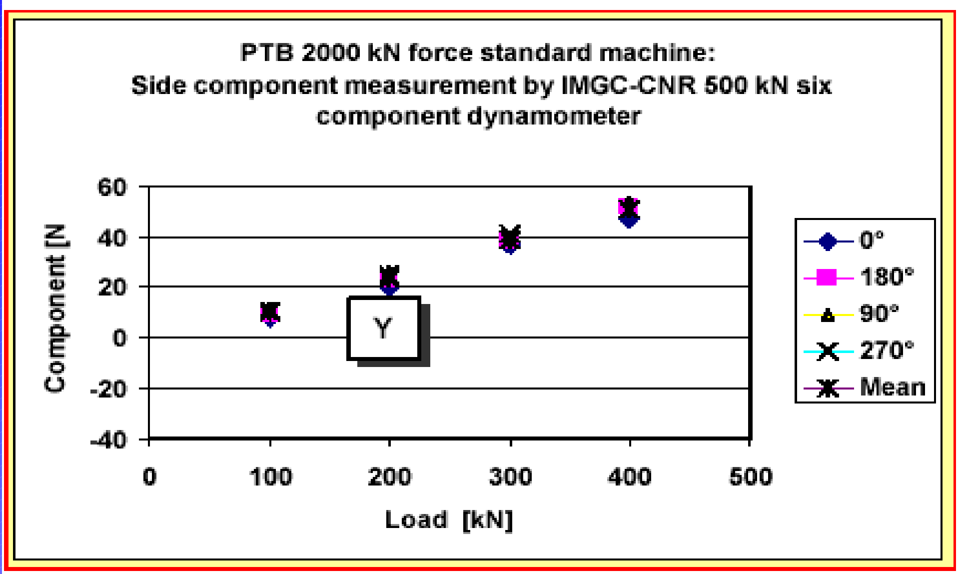
.

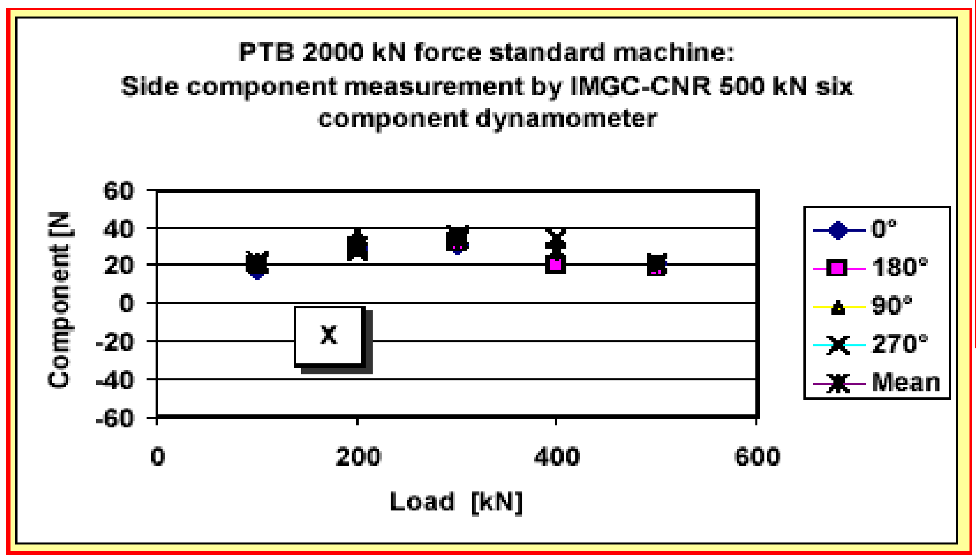
The tests carried out on this machine concerned:

a) determination of parasitic components vs. axial load, with the dynamometer placed at several positions to the machine reference axes, in normal operation conditions;

b) influence of different weight piece combinations on component values;

c) analysis of the dynamic phenomena and of the oscillation of the deadweights.





a) **Side components (X, Y) are repeatable for the standard DWM and correspond to a maximal inclination of the main frame of the order of 10^{-4} rad**

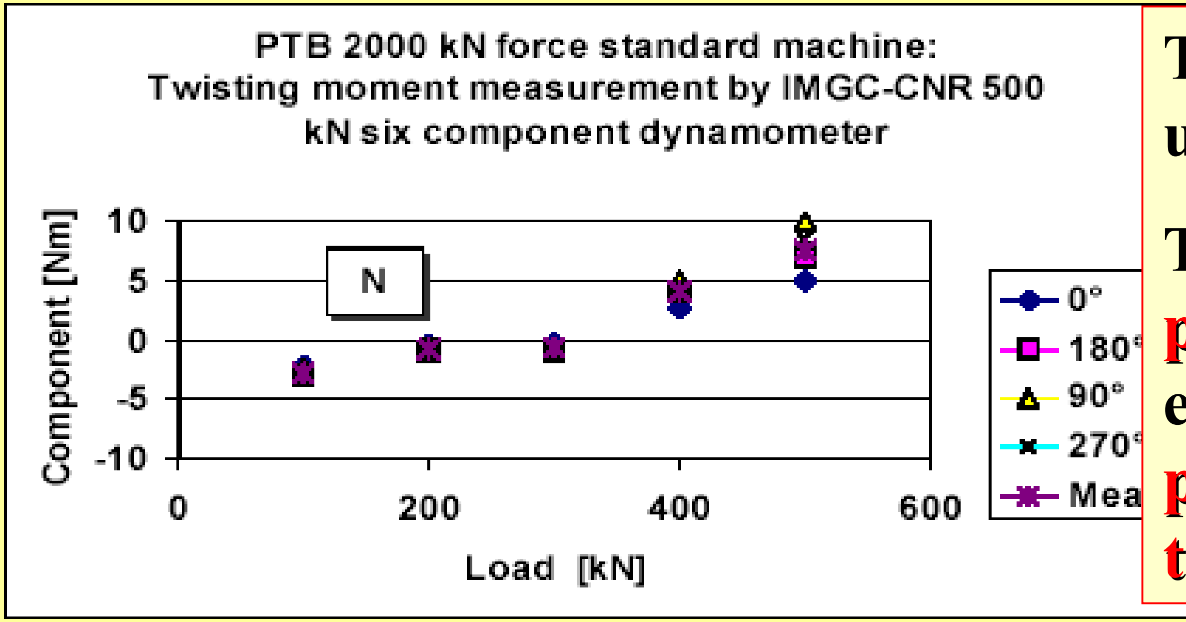
($X_{max} < 35$ N; $Y_{max} < 70$ N).

b) **High repeatability of the values of side components X and Y vs. axial load, for each angular position, is an indication that the standard deadweight machine is highly stable and repeatable .**

This implies:

- **A good reproducibility of the vectorial forces** (axial force and side components) generated by the PTB standard deadweight machine;

- **a very low effect of machine-dynamometer interactions** (rotation effects).

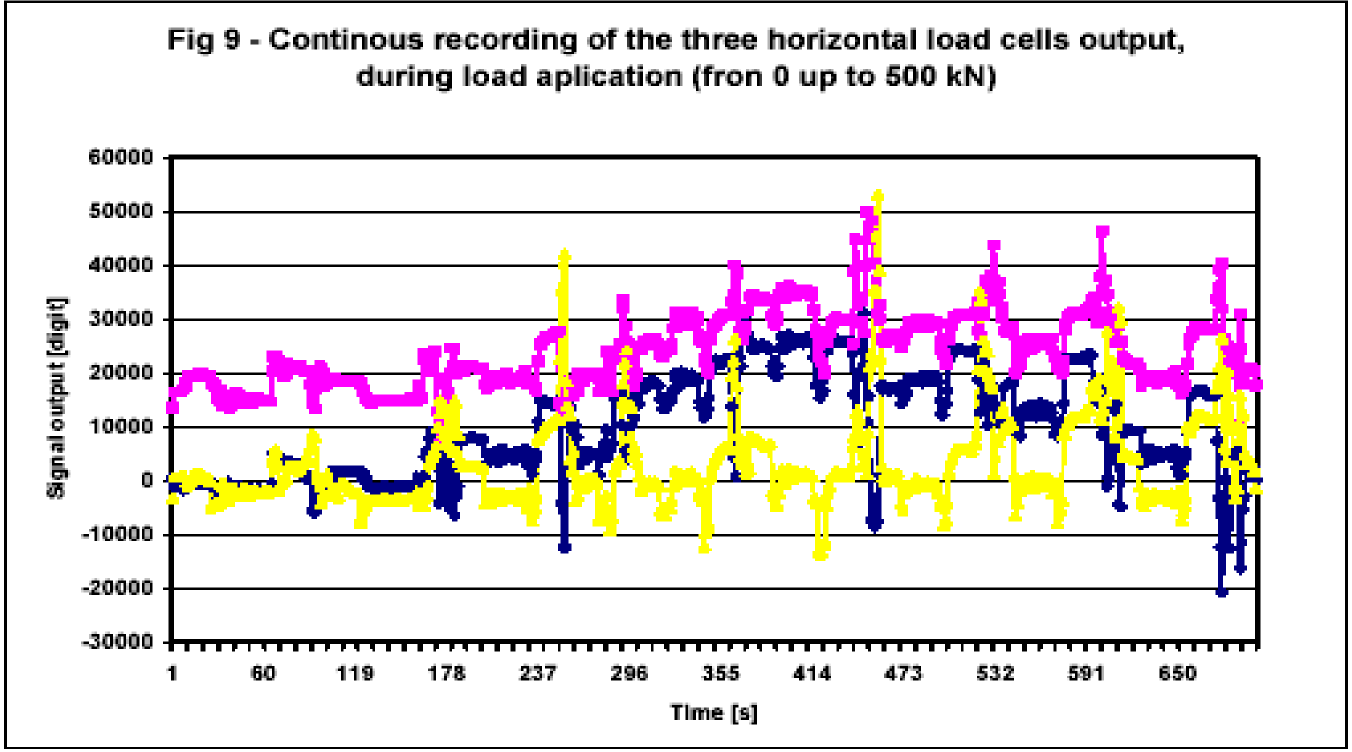


The twisting moment *N* is usually < 10 N·m.

This component is a **powerful diagnostic tool** for evidencing possible **contact points along the load transmission line**

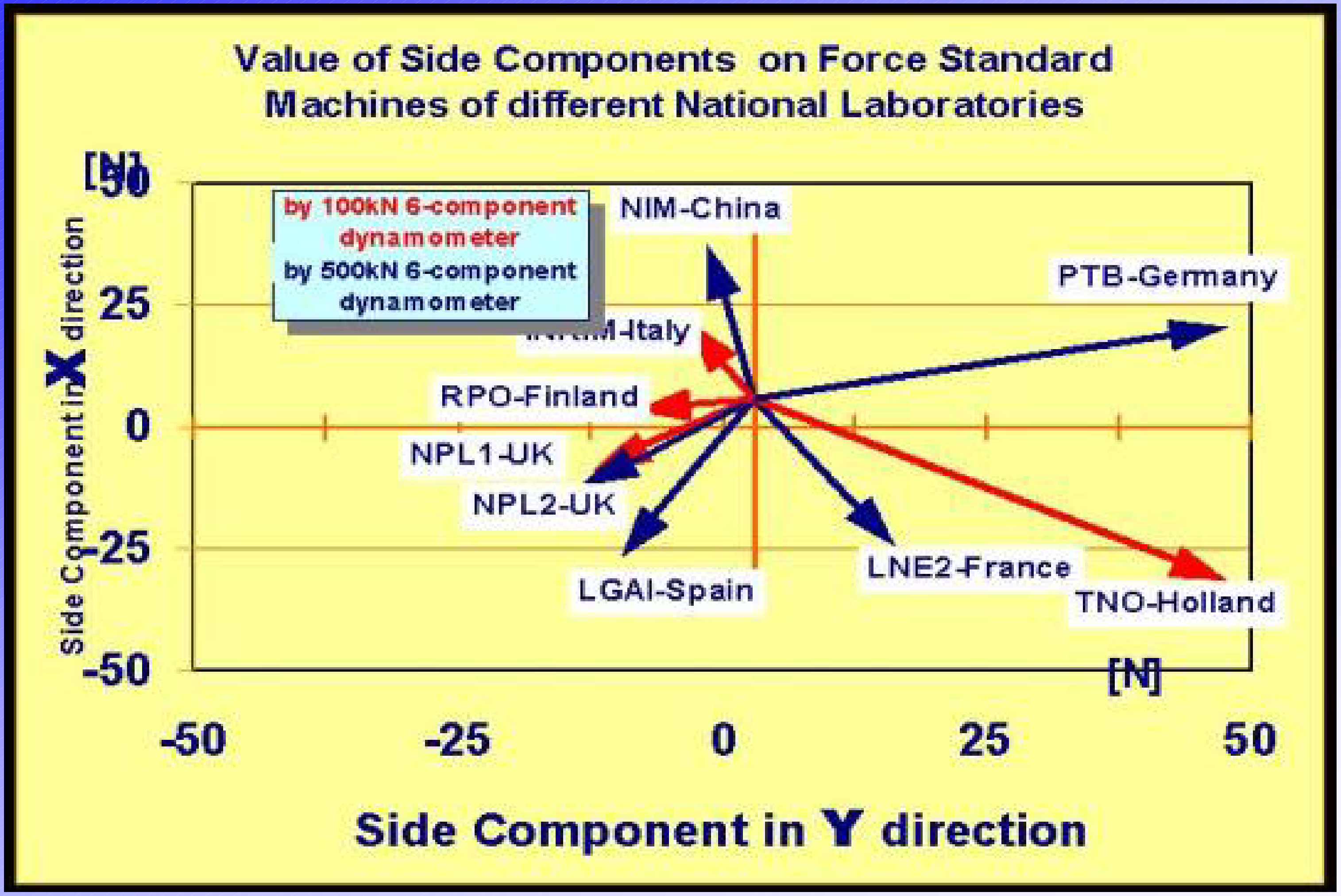
Bending moments values *L*, *M* checked up to rated load confirm that the

eccentricity is lower than 0.2 mm of the load application line to the axis of the dynamometer.



The continuous recording of the signals from the three horizontal load cells (H1, H2, H3) to evaluate if any anomalous load levels born during the load application transient.

Anyway the load application transient do not influences the value of parasitic component at each load level.


Value of Side Components on Force Standard Machines of different National Laboratories
by 100kN 6-component dynamometer
by 500kN 6-component dynamometer
NIM-China
PTB-Germany
INRIM-Italy
RPO-Finland
NPL1-UK
NPL2-UK
LGAI-Spain
LNE2-France
TNO-Holland
[N]
50
25
0
-25
-50
Side Component in X direction
-50
-25
0
25
50
[N]
Side Component in Y direction

CONCLUSIONS

These results indicate that the magnitude of the side forces generated by about all the DWM is less than 500 ppm of the vertical force.

This component depends mainly on the initial level of the lower platen. The lack of any second order dependence on load indicates that the platen angle does not vary under load.

The **inclination correction** corresponding to the measured side force components:

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

Could be considered insignificant (< 0.2 ppm) in comparison to the uncertainty of the vertical force value.

Many Thanks …

for your attention