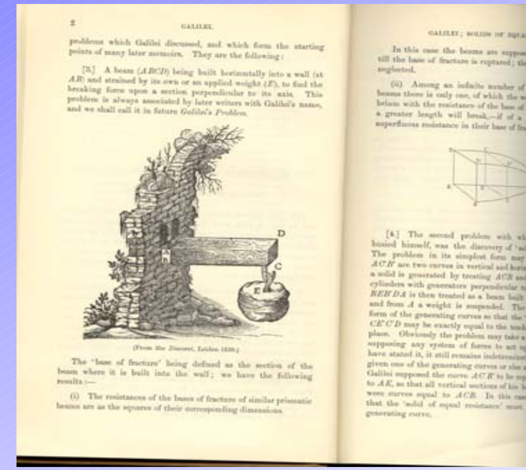
IMEKO 2010 TC3, TC5 and TC22 Conferences

Metrology in Modern Context

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



2 GALILEI.

problems which Galilei discussed, and which form the starting points of many later memoirs. They are the following:

[3.] A beam (ABCD) being built horizontally into a wall (at AB) and strained by its own or an applied weight (E), to find the breaking force upon a section perpendicular to its axis. This problem is always associated by later writers with Galilei's name, and we shall call it in future *Galilei's Problem*.

(From the *Discorsi*, Leiden 1638.)

The 'base of fracture' being defined as the section of the beam where it is built into the wall; we have the following results:—

(i) The resistances of the bases of fracture of similar prismatic beams are as the squares of their corresponding dimensions.

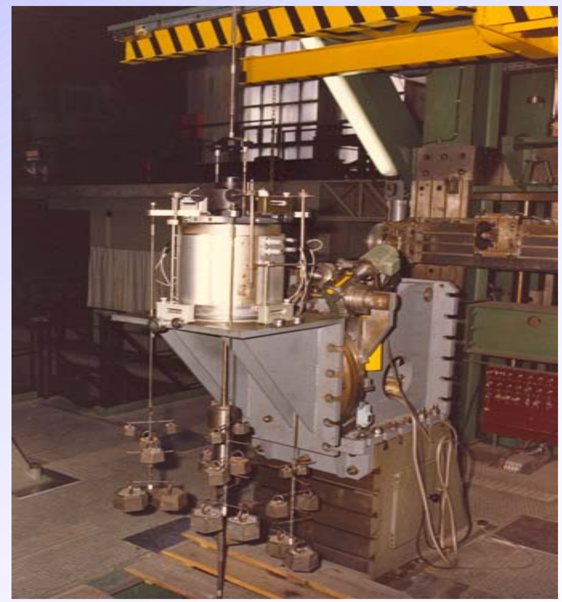
Round table on Multicomponent measurement to improve the traceability in the force chain

Carlo Ferrero

INRiM Consultant

IMEKO TC8 Chairman

EA – Chairman of the "Mechanical Commission"



During the last meting of the TC3 (IMEKO World Congress, Lisbona, September 2009), was decide to organize this Round Table on **Multicomponent measurement to improve the traceability in the force chain**

I am very glad to have this opportunity togheter my colleagues and friend that are the other speakers

Design and analysis of a column type multi-component force / moment sensor

*** J.H. Kim, D.I. Kang , H.H. Shin, Y.K. Park**

Division of Physical Metrology/Mass and Force Group , KRISS ,P.O . Box* 102, *Yusong-Gu* , *Daejeon* , 305- 600, *South Korea

Abstract

A sensing element of column type was devised as a multi-component force /moment sensor by attaching strain gages. The ratio of length over diameter (*L*/*D*) for the sensing element was designed analytically and verified by finite element analysis.

In order to reduce the interference error of each loading component, this paper proposed a decoupling method with the addition and subtraction processes using signals of strain gages. Finally the calibration showed that the interference error of *F* component was less than 7.3% FS, and in case of other components, 5.0% FS.

J.W. Joo, S.Y. Jeoung, G.S. Kim, D.I. Kang, Evaluation of interference error for six-component load cell, in: KSME Annual Fall Conference 96F074 (1996) 441-446. 2.

D.I. Kang, G.S. Kim, S.Y. Jeoung, J.W. Joo, Design and evaluation of binocular type six-component load cell by within 7.6%. The interference error of *F* com- *x* using experimental technique, KSME 21 (11) (1997) 1921–

G.S. Kim, D.I. Kang, S.Y. Jeoung, J.W. Joo, Design of sensing element for 3-component load cell using parallel plate structure, KSME 21 (11) (1997) 1871–1884.

D.I. Kang, Design and application of force measuring system using build-up technique, Ph.D. Dissertation, Dept. of Mech.Engng, KAIST, 1994.

XIX IMEKO World Congress

Fundamental and Applied Metrology

September 6-11, 2009, Lisbon, Portugal

EVALUATION OF MULTI-COMPONENT FORCE TRANSDUCERS HAVING COLUMN TYPE SENSING ELEMENT

Yon-Kyu Park 1, Rolf Kumme2, Dirk Roeske3, Dae-Im Kang4

Fig. 1. Column-type multi-component force transducers.

They were calibrated statically with a force–moment calibration machine in the Physikalisch-Technische Bundesanstalt (PTB), Germany.

We evaluated the dynamic characteristics of the force–moment transducers by using a shaker system and a multi-channel dynamic analyser system.

Table 1. Capacity of the column-type force transducers.

Component	Solid transducer	Hollow transducer
F_x	1.5 kN	2 kN
F_y	1.5 kN	2 kN
F_z	20 kN	20 kN
M_x	40 N·m	60 N·m
M_y	40 N·m	60 N·m
M_z	60 N·m	90 N·m

D. Roeske, “Metrological characterization of a hexapod for a multi-component calibration device,” *XVII IMEKO World Congress*, pp.347-351, Dubrovnik, Croatia, 2003.

Y.K. Park, R. Kumme and D.I. Kang, “Dynamic evaluation of column type multi-component force transducers,” *XVIII IMEKO World Congress*, Rio de Janeiro, Brazil, 2006.

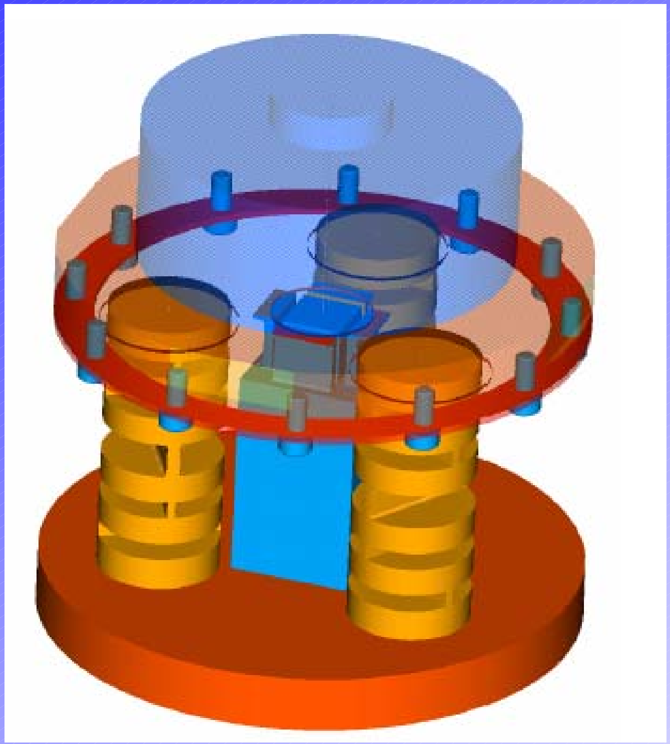
Y.K. Park, R. Kumme and D.I. Kang, “Dynamic investigation of a binocular 6-component force–moment sensor,” *Meas. Sci. Technol.*, vol. 13, pp. 1311-1318, 2002.

XIX IMEKO World Congress

September 6-11, 2009, Lisbon, Portugal

INVESTIGATION AND CALIBRATION OF A FORCE VECTOR SENSOR WITH A CALIBRATION ARTEFACT

Sara Lietz 1, *Falk Tegtmeier* 1, *Dirk Röske* 1, *Rolf Kumme* 1, *Daniel Schwind*



Force vector sensor mounted on the spherical calibration artefact

S. Lietz, F. Tegtmeier, R. Kumme, D. Röske, U. Kolwinski, K. Zöller, *A new six-component force vector sensor – first investigations*, Proc. 20th IMEKO TC3 Conference, Merida, Mexico, Nov 26-30, 2007.

S. Lietz, F. Tegtmeier, R. Kumme, D. Röske, D. Schwind, U. Kolwinski, *Darstellung und Messung von Kräften mittels vektorieller Kraftsensoren*, Proc. Sensoren und Messsysteme 2008, VDI-Berichte 2011, Ludwigsburg, March 11-12, 2008.

IMEKO TC3 Conference, CAIRO, 2005

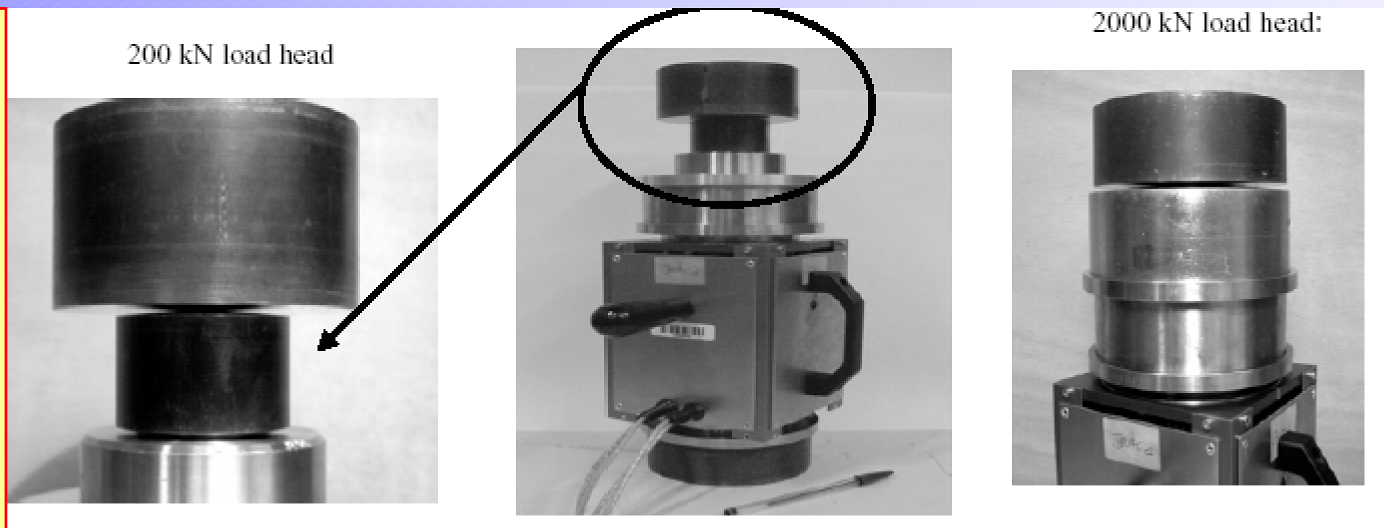
STRAIN CYLINDERS FOR COMPRESSION TESTING MACHINES

Philippe Averlant

ABSTRACT

Measurement results of the compressive strength of concrete specimens depend on the manner of force transfer by the testing machine. This performance is verified according to a standard using strain cylinders. However, the qualification or calibration of strain cylinders is not defined in the standard. This paper presents a new procedure for cylinder calibration. The measurand is defined.

The standard quantity is modelised depending on the specific manner of loading during calibration. Uncertainties are computed using theoretical equations. The results of a first cylinder calibration are given.



Round Table

Coordinator:

Dr. Carlo Ferrero
Istituto Nazionale di Ricerca Metrologica (INRIM)
E-mail: C.Ferrero@inrim.it

Speakers:

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

Dae-Im Kang:
Evaluation of FSM by using build-up system

Rolf Kumme or Dirk Roeske:
Calibration of a force vector sensor with a multicomponent calibration system

Philippe Averlant:
Calibration of strain cylinders

Why 35 years of research in the field of force multicomponents from the beginning of the ’70s ?

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.

Debnam, R.C., Wieringa H., An intercomparison of force standard machines, VDI-Berichte No 212, 1974, pp. 122-132.

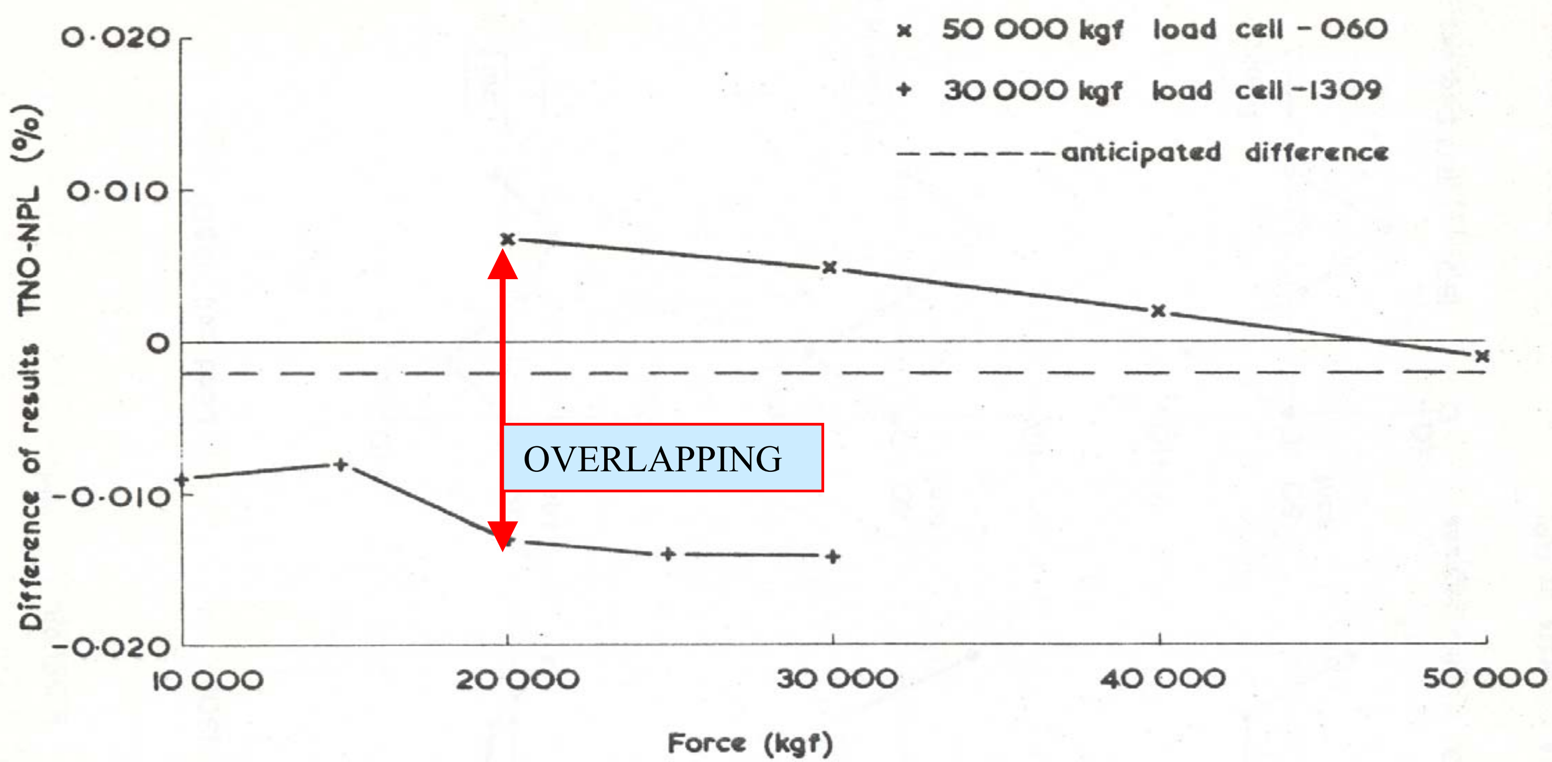
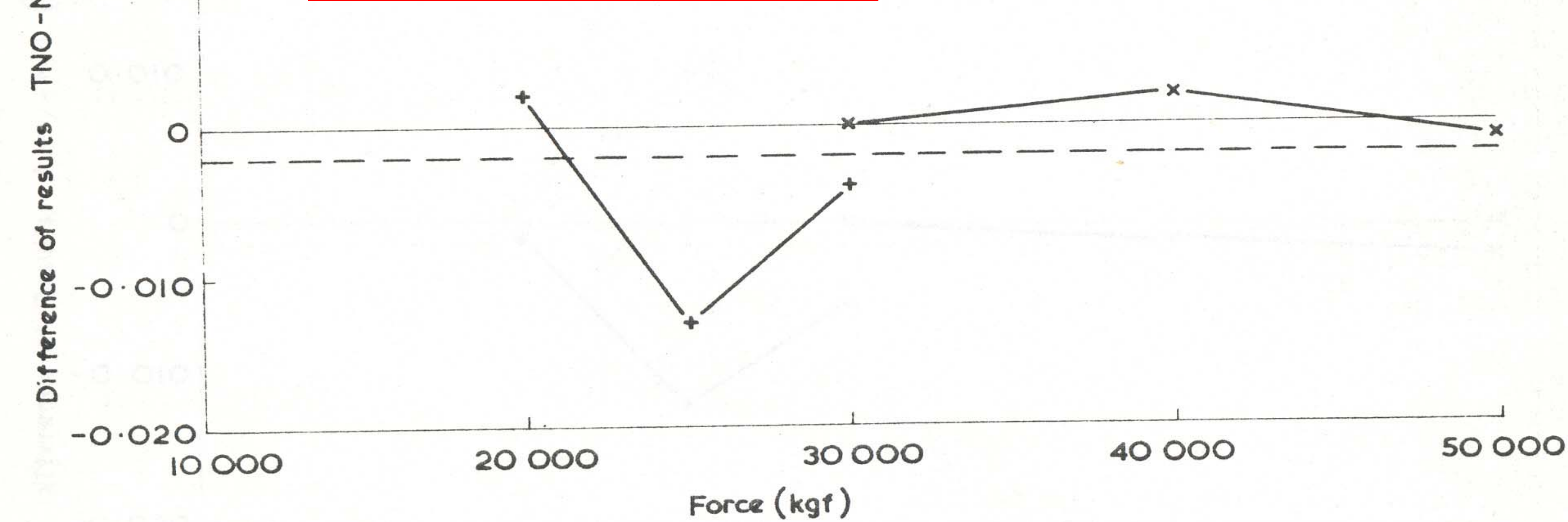


Fig. 3. Results of Intercomparison. April 1973.

Results of the intercomparison made in April 1973

NPL-Machine

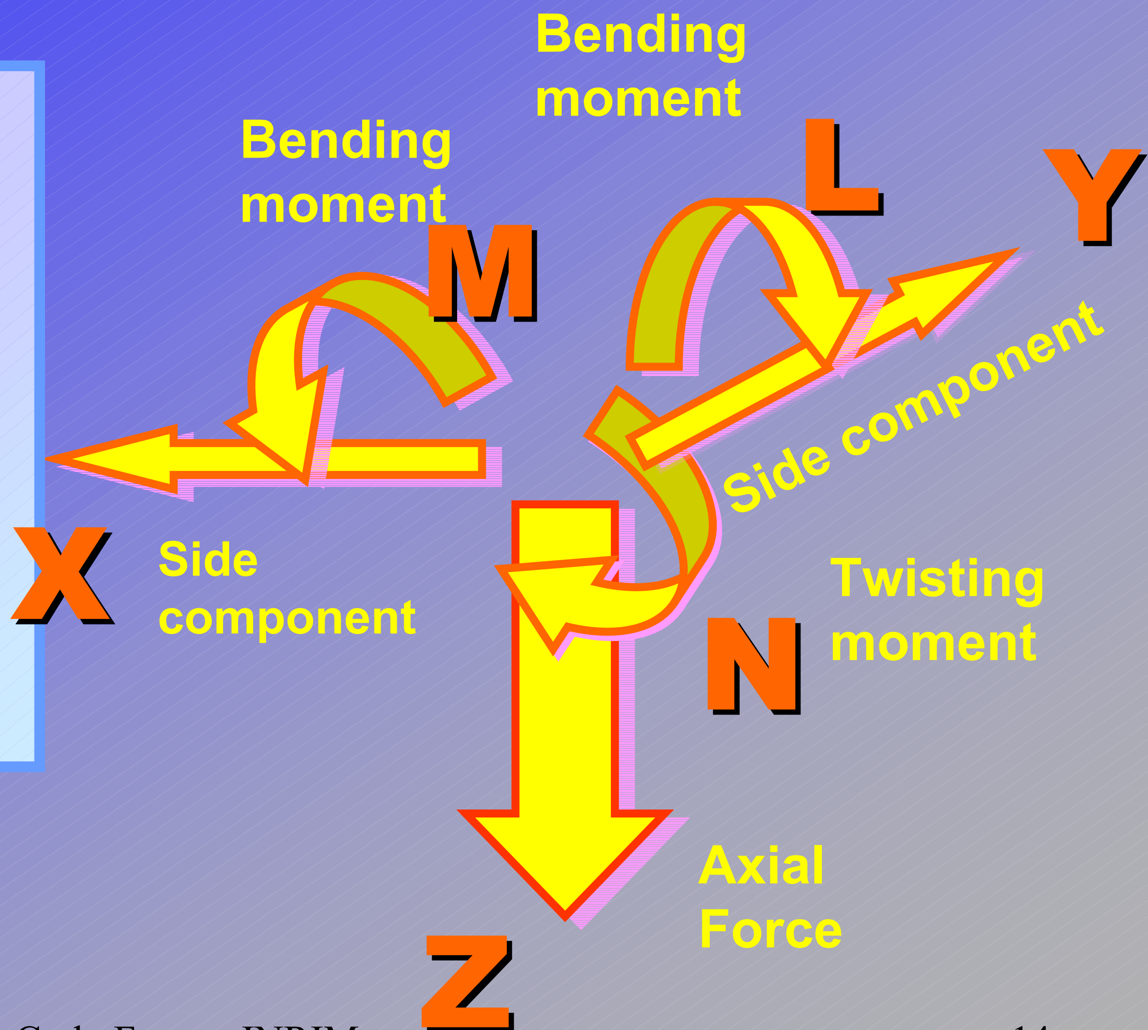
Carlo Ferrero INRIM 15



Result of the intercomparison repeated in May 1975 after to have to check the vertical position of the DWM

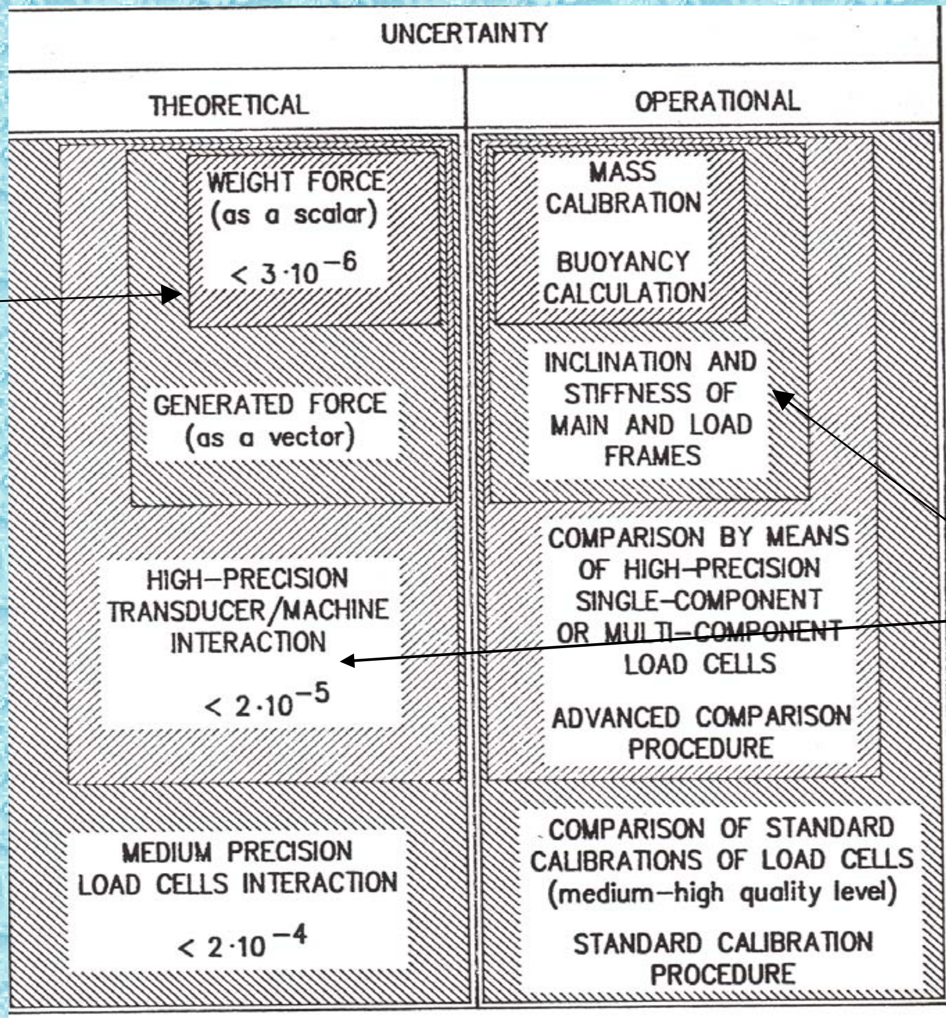
Ideally, force standard machines should apply uniaxial loads only.

In practice, mis-alignments and deformations of the force standard machines result in finite values of **the five parasitic components of the force/moment tensor**.



1. **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.**

SCALAR



Vectorial

FORCE IS A VECTORIAL QUANTITY

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 standard 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


Commission of the European Communities

bcr information

Applied Metrology

THE MEASUREMENTS OF PARASITIC COMPONENTS
IN THE IMGC, NPL, TNO, LNE
AND PTB FORCE STANDARD MACHINES
BY MEANS OF THE IMGC
SIX COMPONENT 100 KN DYNAMOMETER

Report
EUR 12457 EN

Blow-up from microfiche original

Second BCR-IMGC contract for the first European intercomparisons

Five deadweight force standard machines (DWM) belonging to countries of the European Communities (**NPL, TNO, PTB, LNE, IMGC**), were checked by means of the IMGC dynamometer **from 1983 to 1985.**

Dubois, M., Bourateu, J.P., Gosset, A., Priel, M., Intercomparison de trois bancs d'étalonnage dynamométrique de capacité 250-300 kN, Bulletin du BNM, 11, 1980, pp. 17-27

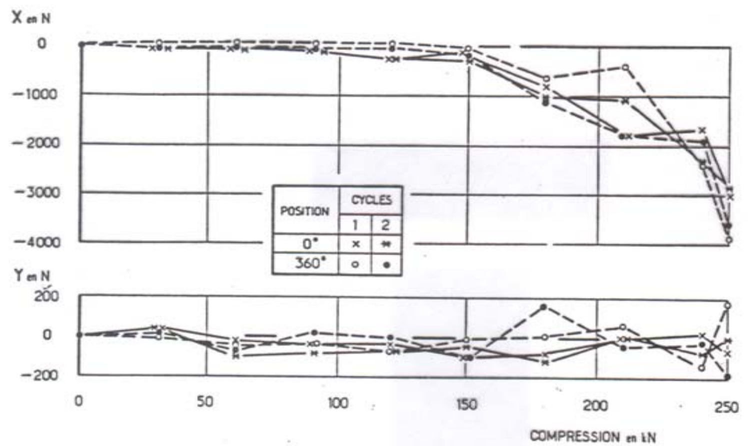


FIG. 14. — Banc ETCA. Forces latérales.

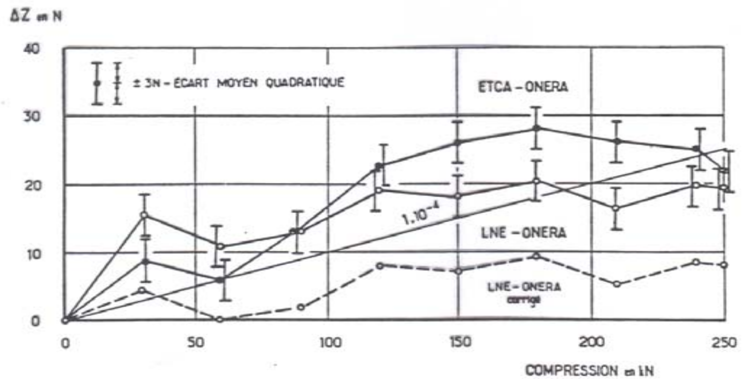


FIG. 15. — Comparaison de la force principale.

Preliminary Results

ONERA 4-component single block dynamometer

Another contract was signed by LNE by using the ONERA 4-components dynamometer.

The standards machines of NPL, TNO, LNE were checked also by means of the **ONERA 4-component dynamometer**, with the aim of:

1. bringing into evidence a **possible influence of the different stiffness of the two dynamometers** on the metrological characteristics of these standard machines, as well as
2. determining the **repeatability and the reproducibility both of primary force standards and transfer standard dynamometers.**


Commission of the European Communities

BCR Information
Applied Metrology

EVALUATION OF
FORCE STANDARD MACHINES
WITH TWO
MULTI-COMPONENT DYNAMOMETERS

Report
EUR 12726 EN

Blow-up from microfiche original

3rd contract BCR-IMGC for the evaluation of the results obtained with the 2 different dynamometers (integral type or composite type) on different DWM

Gosset A, Nossent P 1986 *Mesure de plusieurs machines de force étalons à l'aide d'un dynamomètre multicomposantes de capacité 300 kN en compression*. BCR Technical Report. Laboratoire National d'Essais, Paris

THE SIX-COMPONENT DYNAMOMETER, THE

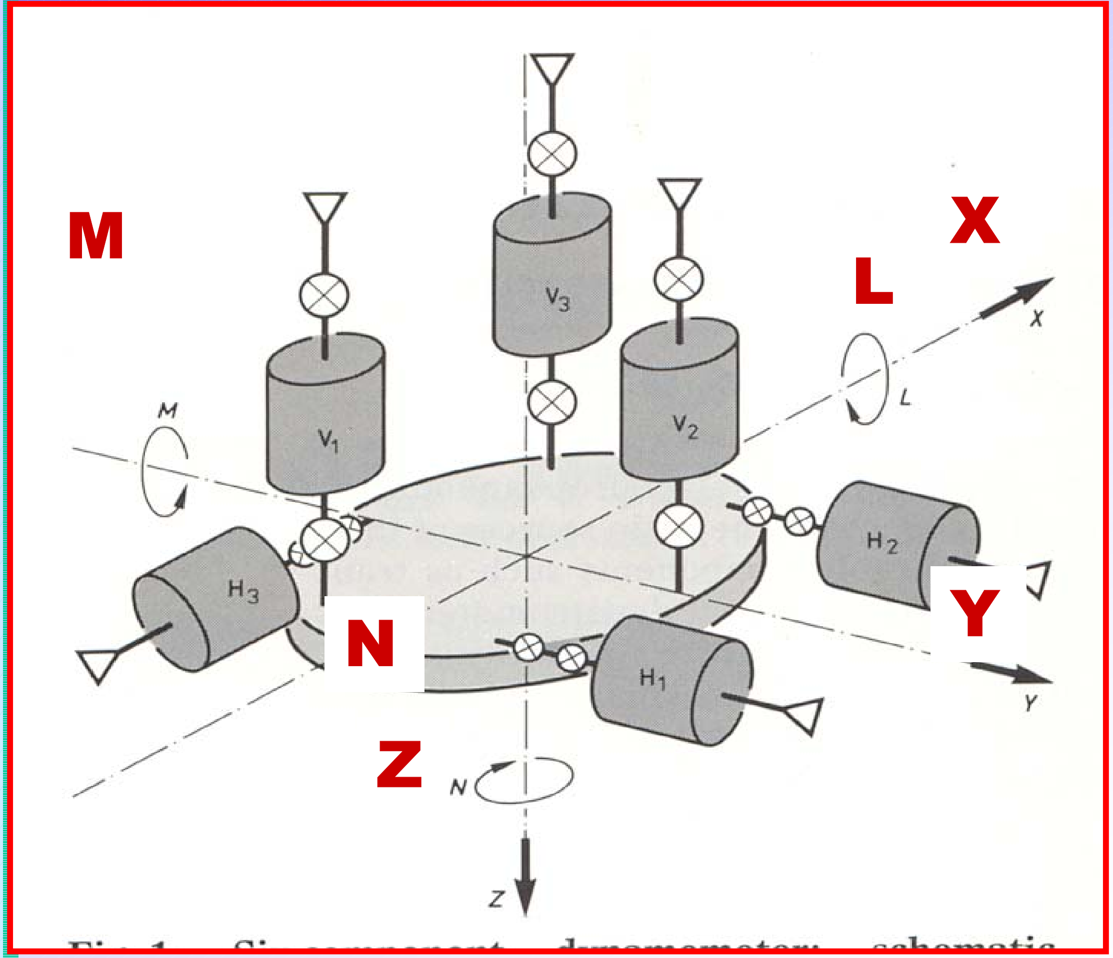
MEASUREMENT SET-UP AND PROCEDURES

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:**

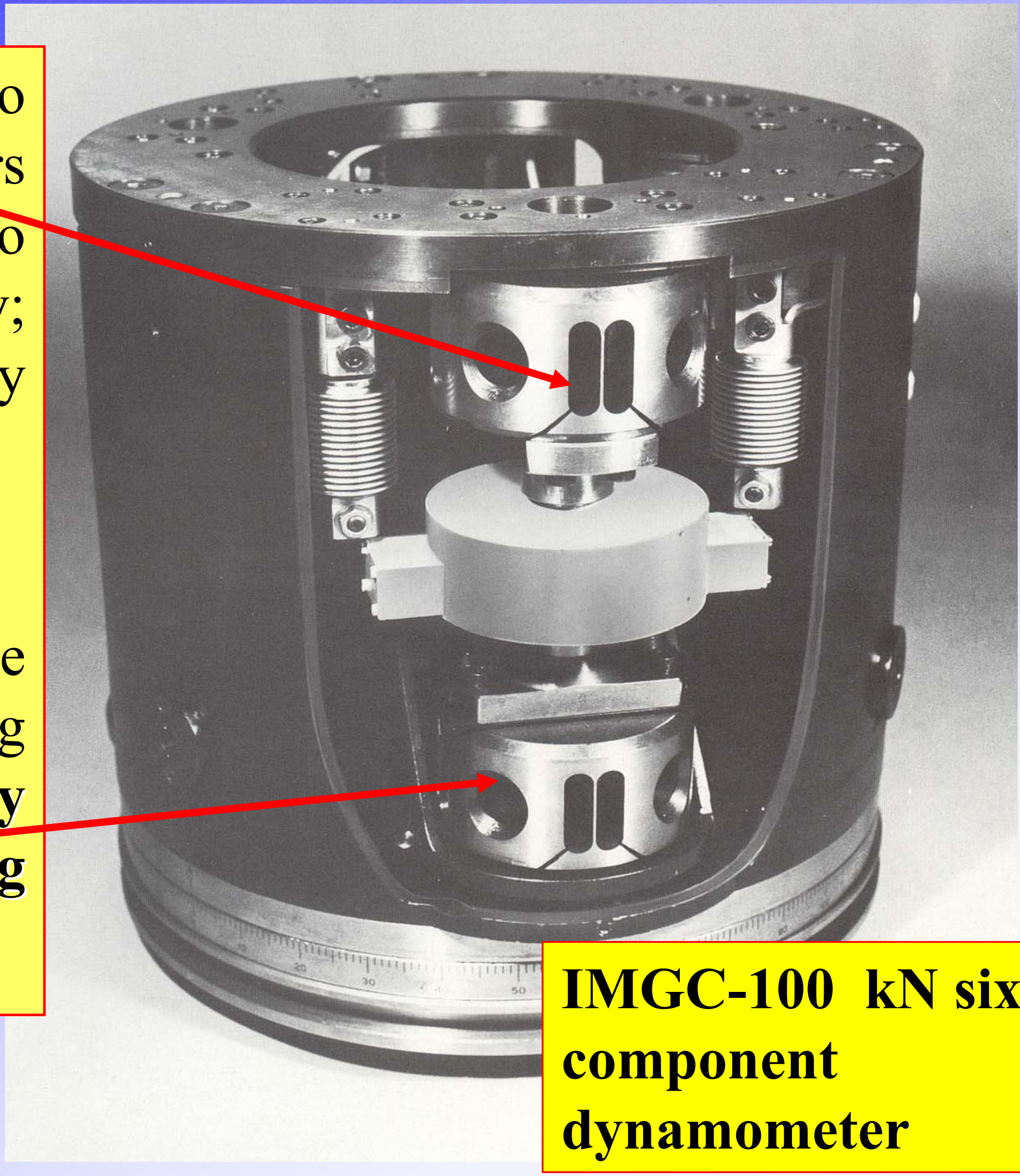
- **Vertical load Z;**
- **Side forces X and Y;**
- **Bending moments L and M;**
- **twisting moments N.**

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.

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

The **composite configuration** has several advantages with respect to other types of multi-component dynamometers:

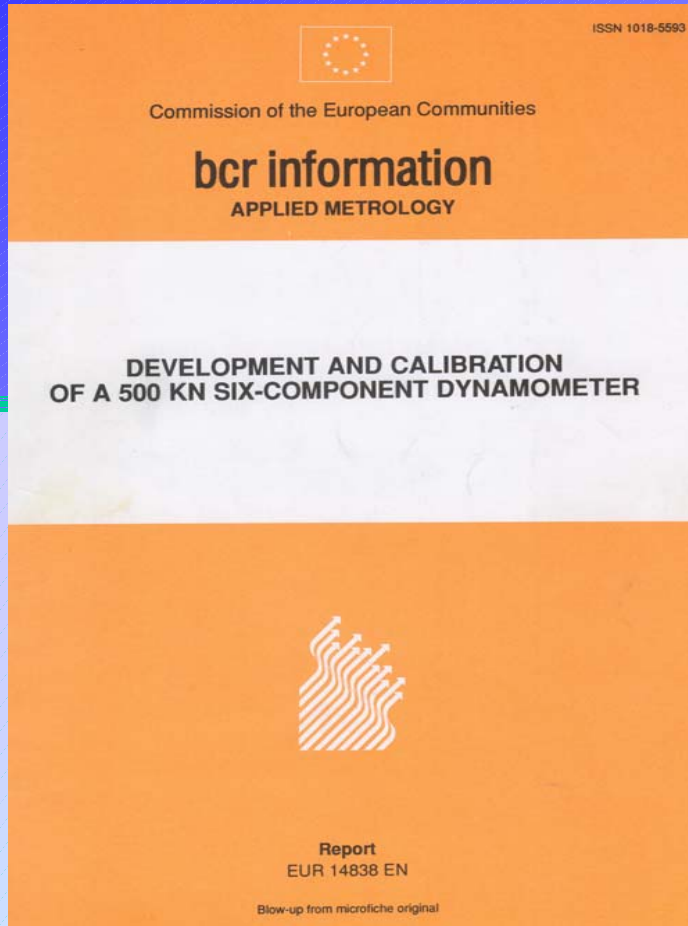
a) **high sensitivity** to transverse components and to twisting moment

b) **low interaction** between the axial component and the transverse components

c) **low dependence** on interface conditions and, consequently, on parasitic components during the load transmission phase

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**


ISSN 1018-5593

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APPLIED METROLOGY

DEVELOPMENT AND CALIBRATION OF A 500 KN SIX-COMPONENT DYNAMOMETER

Report

EUR 14838 EN

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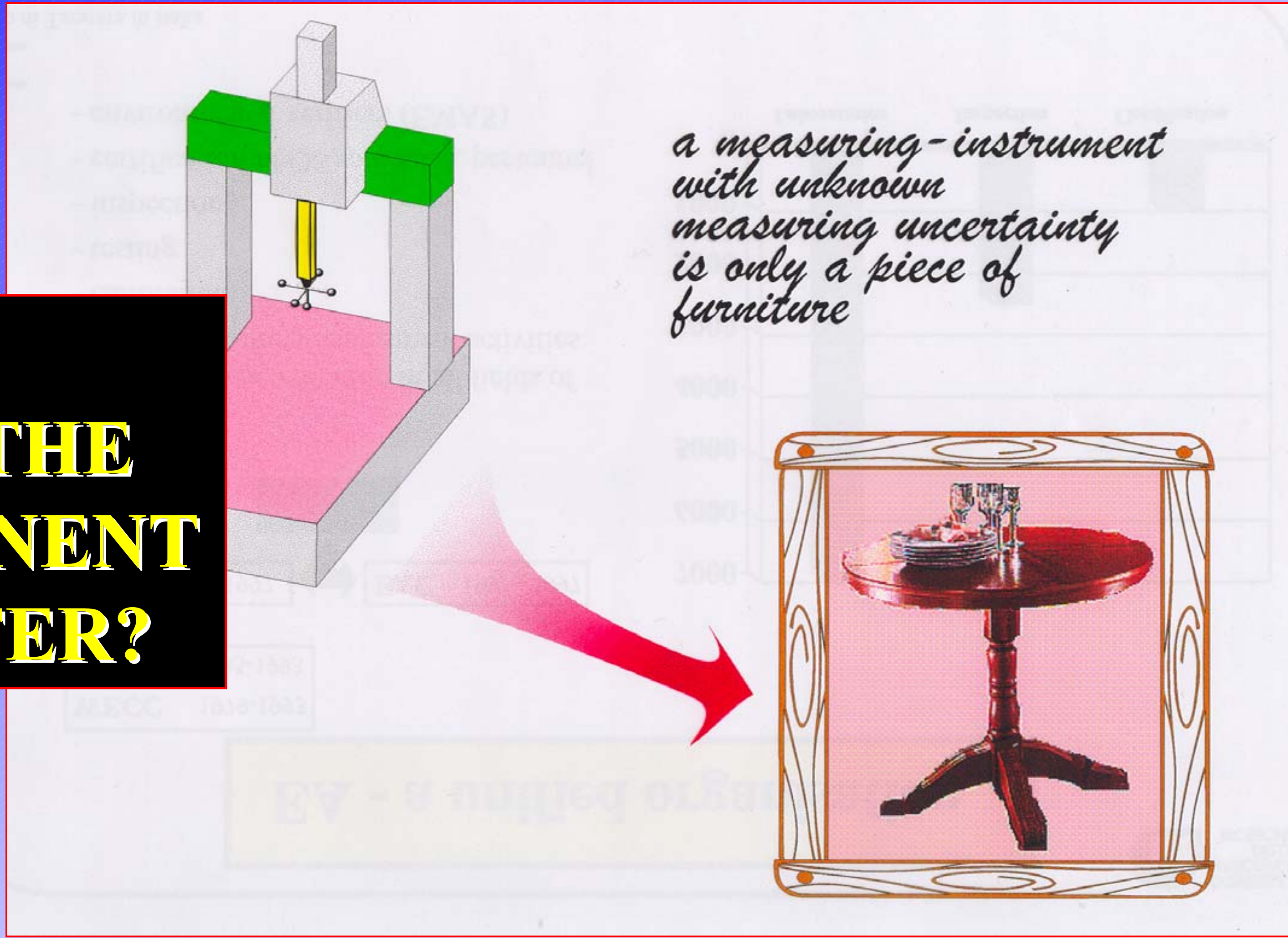
Carlo Ferrero

HOW TO CALIBRATE THE MULTICOMPONENT DYNAMOMETER?

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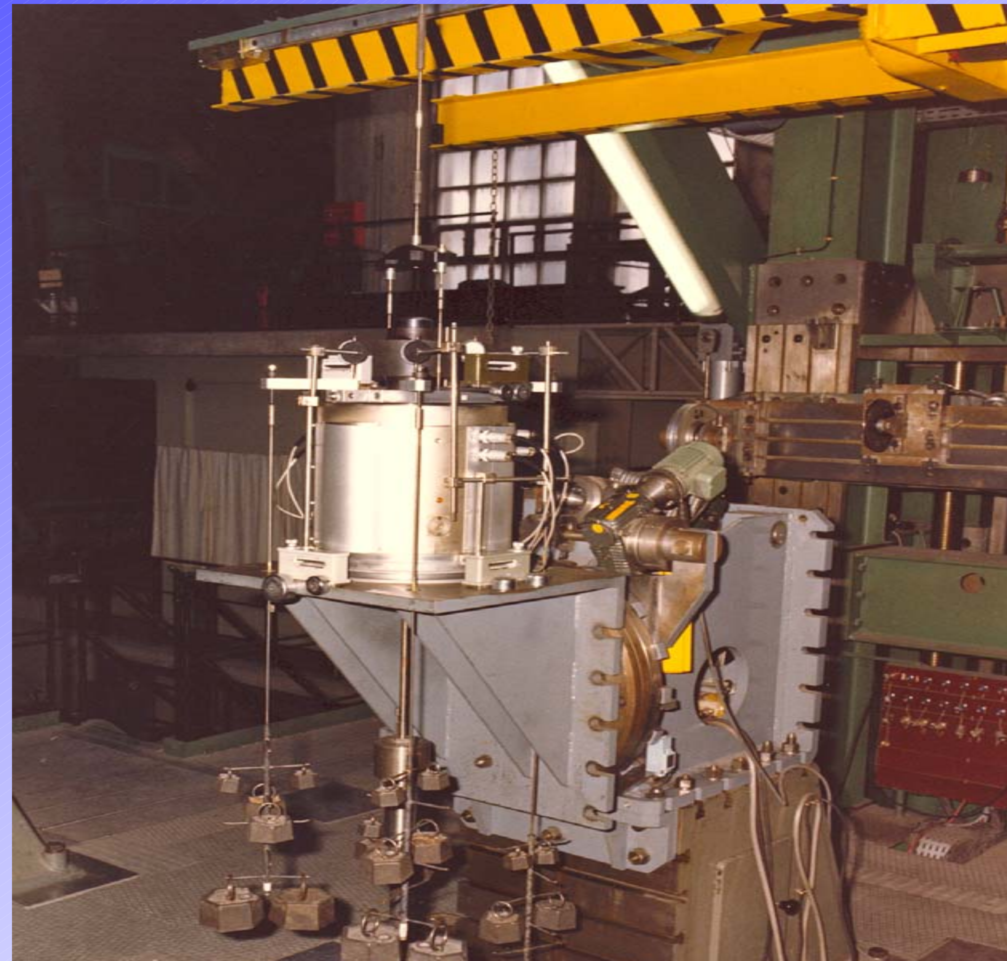
APPLIED METROLOGY

AR. 374 (vedi R. Tecnica R 191)

ANALYSIS AND CALIBRATION
OF IMGC SIX-COMPONENT DYNAMOMETER
(Technical Report)

Volume I

Report
EUR 10229 EN/I

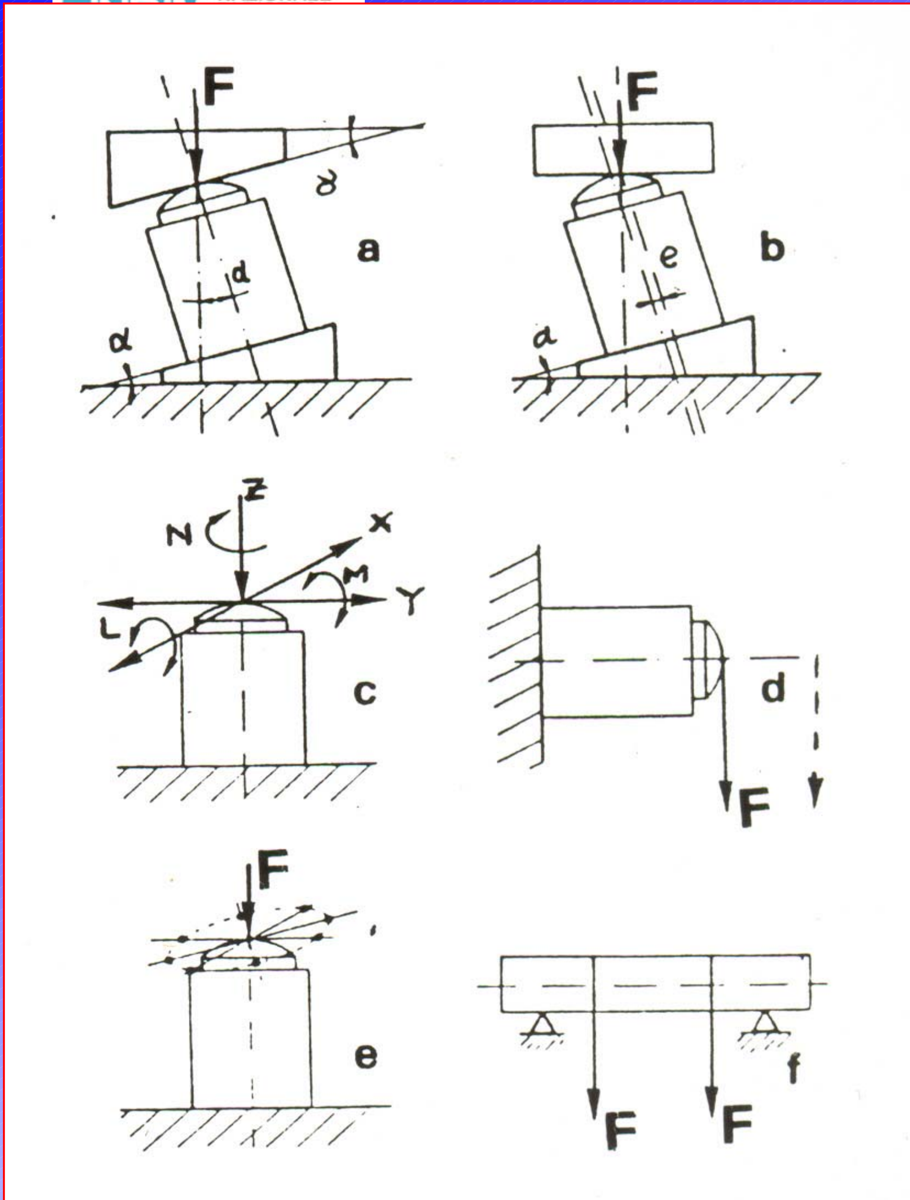


First BCR-IMGC contract for the calibration of the IMGC 100 kN 6-components dynamometer with the ONERA calibration system

SISTEMI DI TARATURA INRIM

CHARACTERIZATION OF LOAD CELLS BY MEANS OF DIFFERENT CALIBRATION SYSTEMS AT IMGC

Different TESTING METHODS AND APPARATUS evaluated by IMGC



The calibration methods can schematically be outlined as follows:

a) **Two-wedge method**: side components (X, Y) are proportional to axial load Z and functions of inclination angle β;

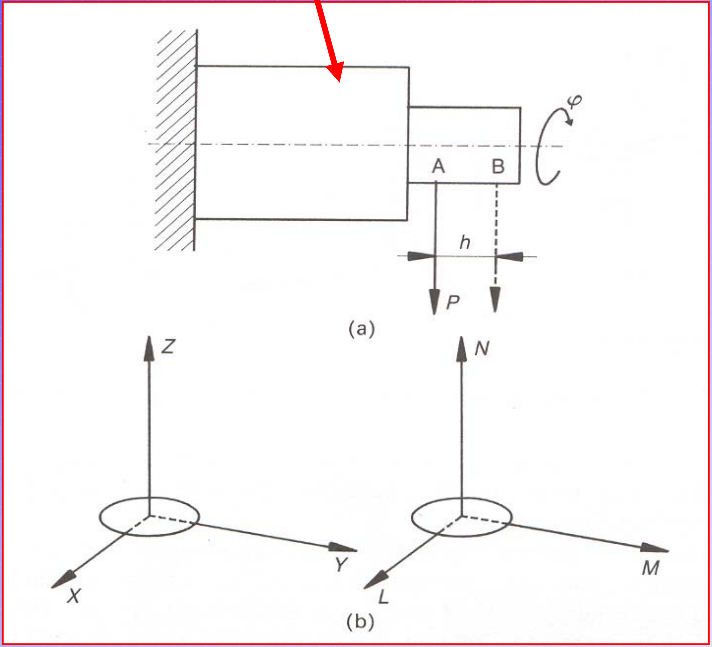
L = M = N = 0

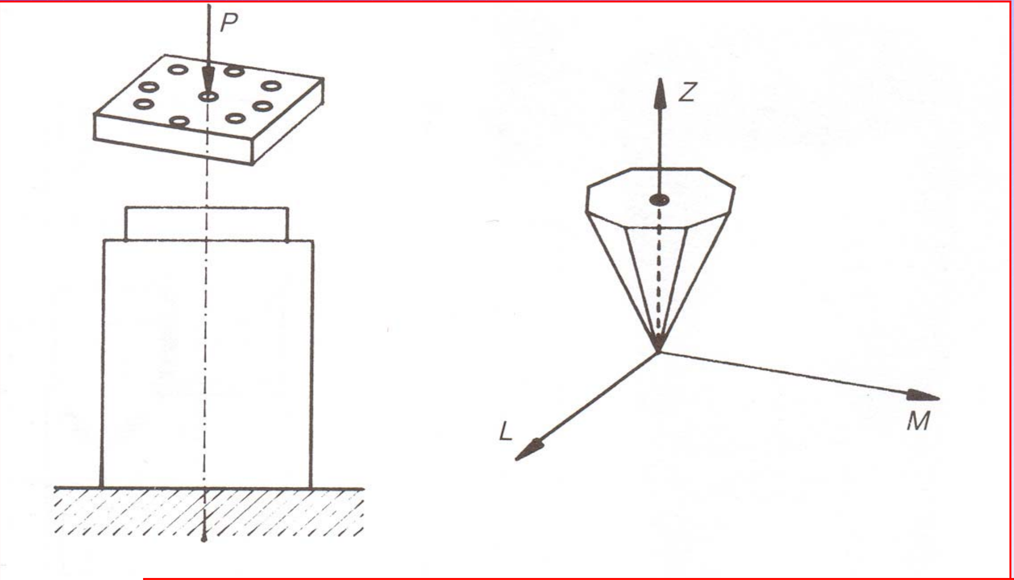
b) **One-wedge method**: transverse components (X, Y) and bending moments L, M are proportional to Z;

N = 0.

d) **Transverse-load method**: XM and YL are applied at the same time; **Z = N = 0**

Applied by Prof. Dambacher in the ’70s to evaluate 130 load cells



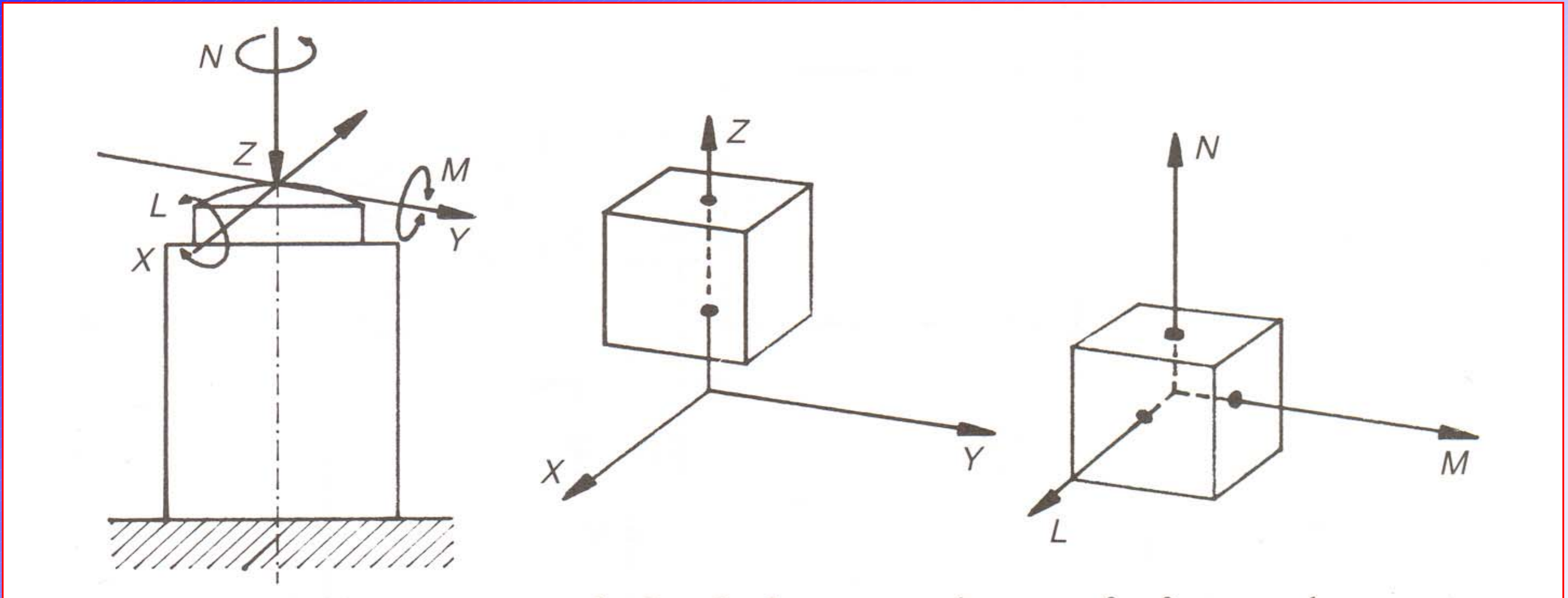


e) **Multi-position method**: bending moments L, M, are proportional to **Z; X = Y = N = 0**

Applied by Prof. Levi

Levi R 1967 Drill press dynamometers. Int. J. Mach. Tool Des. Res. 7, 269-87

c) **multi-component method**: independent or contemporary applications of the six components of the force tensor is possible.



Takada R, Ono K, Ogata K, Kusaki T 1988 An analysis of errors on 6-component force/moment calibration machines. *Proc. 11th IMEKO World Conf. Sensors sector.* IMEKO, Budapest, pp. 121-30

Yoshida T 1984, Six-component force transducer and its applications. *Proc. 10th IMEKO Conf. Measurement of Force and Mass.* IMEKO, Budapest

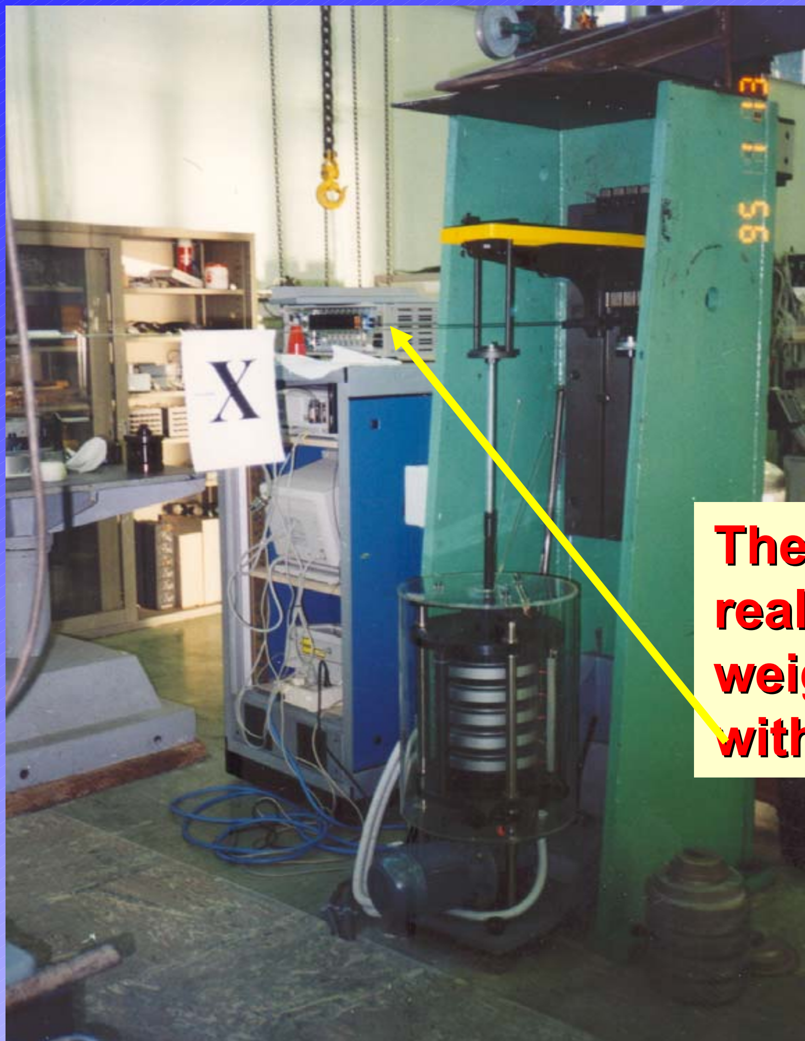
The output signal of a dynamometer as a function of applied components can be adequately approximated in fact by a **second-order polynomial of the type:**

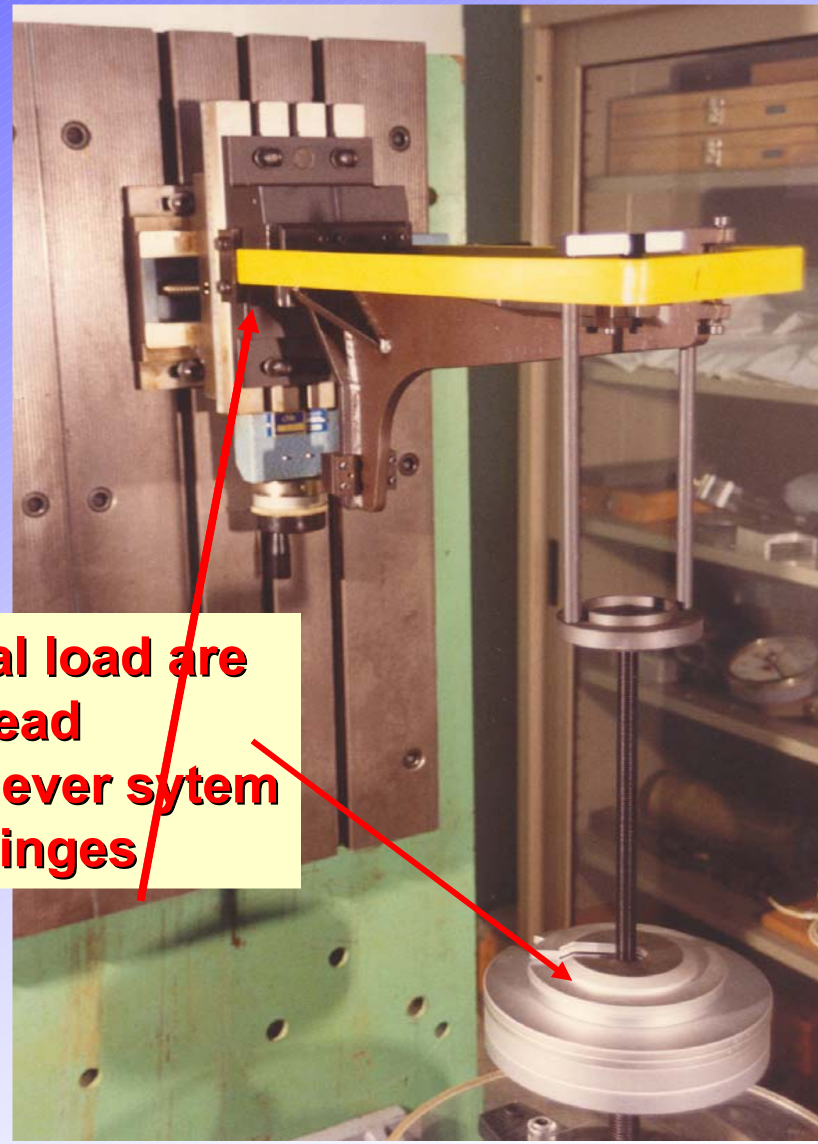
$$y_n = A_o + \sum_{i=1}^{6} A_i x_i + \sum_{i=1}^{6} \sum_{j=1}^{6} A_{ij} x_i x_j$$

Only with a 6-component ~calibration system can all the twenty seven terms in equation be determined

INRIM CALIBRATION SYSTEMS

INRIM





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

LEVER SYSTEM WITH ELASTIC HINGES

CALIBRATION

- K ratio=2
- Sensitivity
- Repeatability
- Reproducibility

INFLUENCE OF SEVERAL PARAMETERS ON K RATIO

- Tilt angle
- Load level
- Errors in vertical and horizontal positions

DETERMINATION OF APPARENT WEIGHT

- Direct methods
- Indirect meth.

BALANCE OF APPARENT WEIGHT

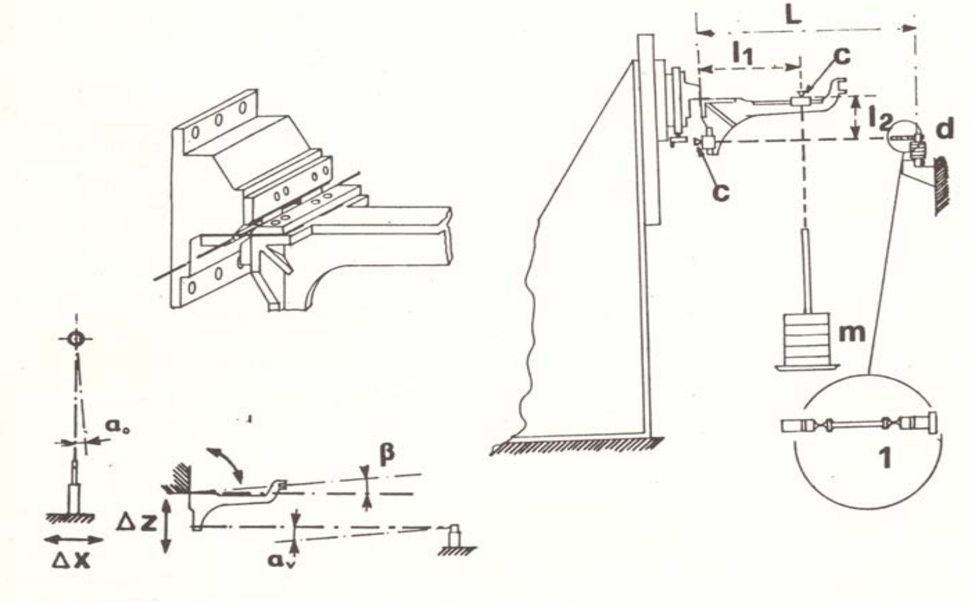


Fig. 2 – Crossed–flexure lever

	LEVER	AIR-BEARING	PULLEY
THRESHOLD	0,5 g/digit	1 g/digit	1 g/digit
REPEATABILITY	$4\ 10^{-5}$	$5\ 10^{-5}$	$6\ 10^{-5}$
VERTICAL DISPLACEMENT EFFECT	$\pm 4\ 10^{-5}$ / mm	$< (\pm 1\ 10^{-5})$ / mm	$< (\pm 1\ 10^{-5})$ / mm
HORIZONTAL DISPLACEMENT EFFECT	$(\pm 1{,}3\ 10^{-5})$ / mm	$(\pm 2\ 10^{-5})$ / mm	$(\pm 2{,}5\ 10^{-5})$ / mm
ROTATION EFFECT	-	$< 3\ 10^{-4}$	$< 3\ 10^{-3}$
LOADING EFFECT	ratio proportional to applied load	pressure proportional to applied load	friction proportional to applied load
REPRODUCIBILITY	$1\ 10^{-4}$	$3\ 10^{-4}$	$5\ 10^{-4}$
OPERATION CONDITIONS	precise adjustment	needs a pressure source	normal
RELATIVE RATIO	3	2	1
ADVANTAGE	highest accuracy	easy installation high accuracy	lowest cost very easy installation
DISADVANTAGE	highest cost precise adjustament	needs a pressure source	bigger rotation effect threshold changes with load

DIFFERENT EXPERIMENTAL CALIBRATION PLANE and RESULTS EVALUATION

Sequential or direct calibration method

5.2 Loading combination in the sequential calibration method.

DATE	TESTS: COMPONENT	TESTS: LOADS	Temp. °C	Atm. pressure (mbar)
28.2	L	−16; −8; 8; 16 kgf m	20.5 (± 0.2)	988.4
2.3	M	−16; −8; 8; 16 kgf m		
3.3	X	−20; −16; −8; 8; 16; 20 kgf		
23.2	Y	−20; −16; −8; 8; 16; 20 kgf		987.9
1.3	N	−4.8; −3.2; −1.6; 1.6; 3.2; 4.8 kgf m		991.3
1.3	ZN	Z = 4000−8000 kgf N = ± (1.6−3.2−4.8) kgf m		
28.2	ZL	Z = 4000−8000 kgf L = ± (8−16) kgf m		988.4
2.3	ZM	Z = 4000−8000 kgf M = ± (8−16) kgf m		992.3
3.3	ZX	Z = 4000−8000 kgf X = 8−16−20 kgf		
25.2	ZY	Z = 4000−8000 kgf Y = ± (8−16−20) kgf		989.1

122 test condition

A complete calibration of a multicomponent dynamometer (namely, a complete determination of all the aj and aij coefficients) by these methods employed at the ONERA and IMGC laboratories (IMGC2) requires separate and independent applications of the six main components, i.e., the three orthogonal forces (X, Y, Z), the three moments (L, M, N), and the 15 cross combinations.

Factorial Methods and ….

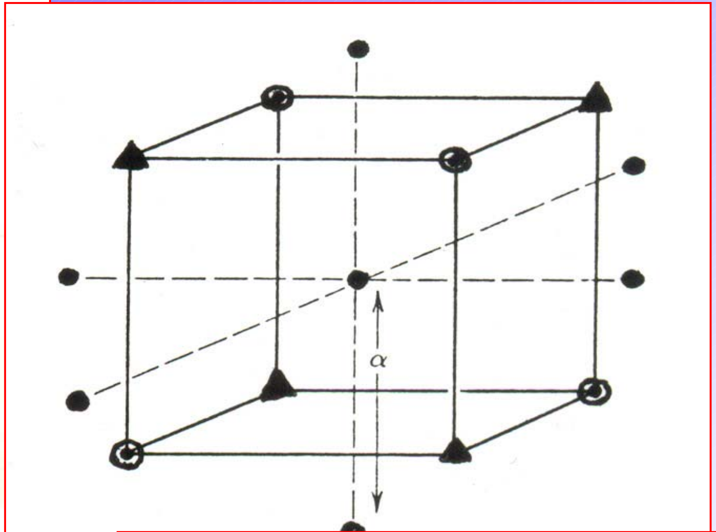
…step-by-step regression analysis

5.4 Combinations for a Central Composite second-order Rotatable design with 6 variables.

x_1	x_2	x_3	x_4	x_5	x_6
−1	−1	−1	−1	−1	−1
1	−1	−1	−1	−1	1
−1	1	−1	−1	−1	1
1	1	−1	−1	−1	−1
−1	−1	1	−1	−1	1
1	−1	1	−1	−1	−1
−1	1	1	−1	−1	−1
1	1	1	−1	−1	1
−1	−1	−1	1	−1	1
1	−1	−1	1	−1	−1
−1	1	−1	1	−1	−1
1	1	−1	1	−1	1
−1	−1	1	1	−1	−1
1	−1	1	1	−1	1
−1	1	1	1	−1	1
1	1	1	1	−1	−1
−1	−1	−1	−1	1	1
1	−1	−1	−1	1	−1
−1	1	−1	−1	1	−1
1	1	−1	−1	1	1
−1	−1	1	−1	1	−1
1	−1	1	[illegible]	[illegible]	[illegible]
−1	1	1	[illegible]	[illegible]	[illegible]
1	1	1	[illegible]	[illegible]	[illegible]
−1	−1	−1	[illegible]	[illegible]	[illegible]
1	−1	−1	[illegible]	[illegible]	[illegible]

x_1	x_2	x_3	x_4	x_5	x_6
−1	1	−1	1	1	1
1	1	−1	1	1	−1
−1	−1	1	1	1	1
1	−1	1	1	1	−1
−1	1	1	1	1	−1
1	1	1	1	1	1
−2.378	0	0	0	0	0
2.378	0	0	0	0	0
0	−2.378	0	0	0	0
0	2.378	0	0	0	0
0	0	−2.378	0	0	0
0	0	2.378	0	0	0
0	0	0	−2.378	0	0
0	0	0	2.378	0	0
0	0	0	0	−2.378	0
0	0	0	0	2.378	0
0	0	0	0	0	−2.378
0	0	0	0	0	2.378
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0

The component values assumed in the STARS was optimized according to the work of Box-Hunter



The spatial distribution of the tests concerning a three component CCRD is schematized in the Figure

Table gives the combinations of one of the designs adopted at IMGC

Table 5.3 Loading combinations with a complete factorial design of the 2^5 type repeated for 3 levels of axial load Z.

Reference	N°	x_2 = L	x_3 = M	x_4 = N	x_5 = X	x_6 = Y	x_1 = Z
I	05	0	0	0	0	0	
(1)	06	-1	-1	-1	-1	-1	
ab	07	1	1	-1	-1	-1	
ace	08	1	-1	1	-1	1	
bce	09	-1	1	1	-1	1	
	10	0	0	0	0	0	-1,0,1
ade	11	1	-1	-1	1	1	
bde	12	-1	1	-1	1	1	
cd	13	-1	-1	1	1	-1	
abcd	14	1	1	1	1	-1	
	15	0	0	0	0	0	
II	20	0	0	0	0	0	
a	21	1	-1	-1	-1	-1	
b	22	-1	1	-1	-1	-1	
ce	23	-1	-1	1	-1	1	
abce	24	1	1	1	-1	1	
	25	0	0	0	0	0	-1,0,1
de	26	-1	-1	-1	1	1	
abde	27	1	1	-1	1	1	
acd	28	1	-1	1	1	-1	
bcd	29	-1	1	1	1	-1	
	30	0	0	0	0	0	
III	35	0	0	0	0	0	
ae	36	1	-1	-1	-1	1	
be	37	-1	1	-1	-1	1	
c	38	-1	-1	1	-1	-1	
abc	39	1	1	1	-1	-1	
	40	0	0	0	0	0	-1,0,1
d	41	-1	-1	-1	1	-1	
abd	42	1	1	-1	1	-1	
acde	43	1	-1	1	1	1	
bcde	44	-1	1	1	1	1	
	45	0	0	0	0	0	
IV	50	0	0	0	0	0	
e	51	-1	-1	-1	-1	1	
abe	52	1	1	-1	-1	1	
ac	53	1	-1	1	-1	-1	
bc	54	-1	1	1	-1	-1	
	55	0	0	0	0	0	-1,0,1
ad	56	1	-1	-1	1	-1	
bd	57	-1	1	-1	1	-1	
cde	58	-1	-1	1	1	1	
abcde	59	1	1	1	1	1	
	60	0	0	0	0	0	
DOUBLE STAR	70	0	0	0	0	0	
	71	-4	0	0	0	0	
	72	-1	0	0	0	0	
	73	1	0	0	0	0	
	74	4	0	0	0	0	
	75	0	0	0	0	0	
	76	0	-4	0	0	0	
	77	0	-1	0	0	0	
	78	0	1	0	0	0	
	79	0	4	0	0	0	
	80	0	0	0	0	0	
	81	0	0	-3	0	0	
	82	0	0	-1	0	0	
	83	0	0	1	0	0	
	84	0	0	3	0	0	-1,0,1
	85	0	0	0	0	0	
	86	0	0	0	-2.5	0	
	87	0	0	0	-1	0	
	88	0	0	0	1	0	
	69	0	0	0	2.5	0	
	90	0	0	0	0	0	
	91	0	0	0	0	-2.5	
	92	0	0	0	0	-1	
	93	0	0	0	0	1	
	94	0	0	0	0	2.5	

By using the STEP BY STEP REGRESSION ANALYSIS (from Efroymson)…

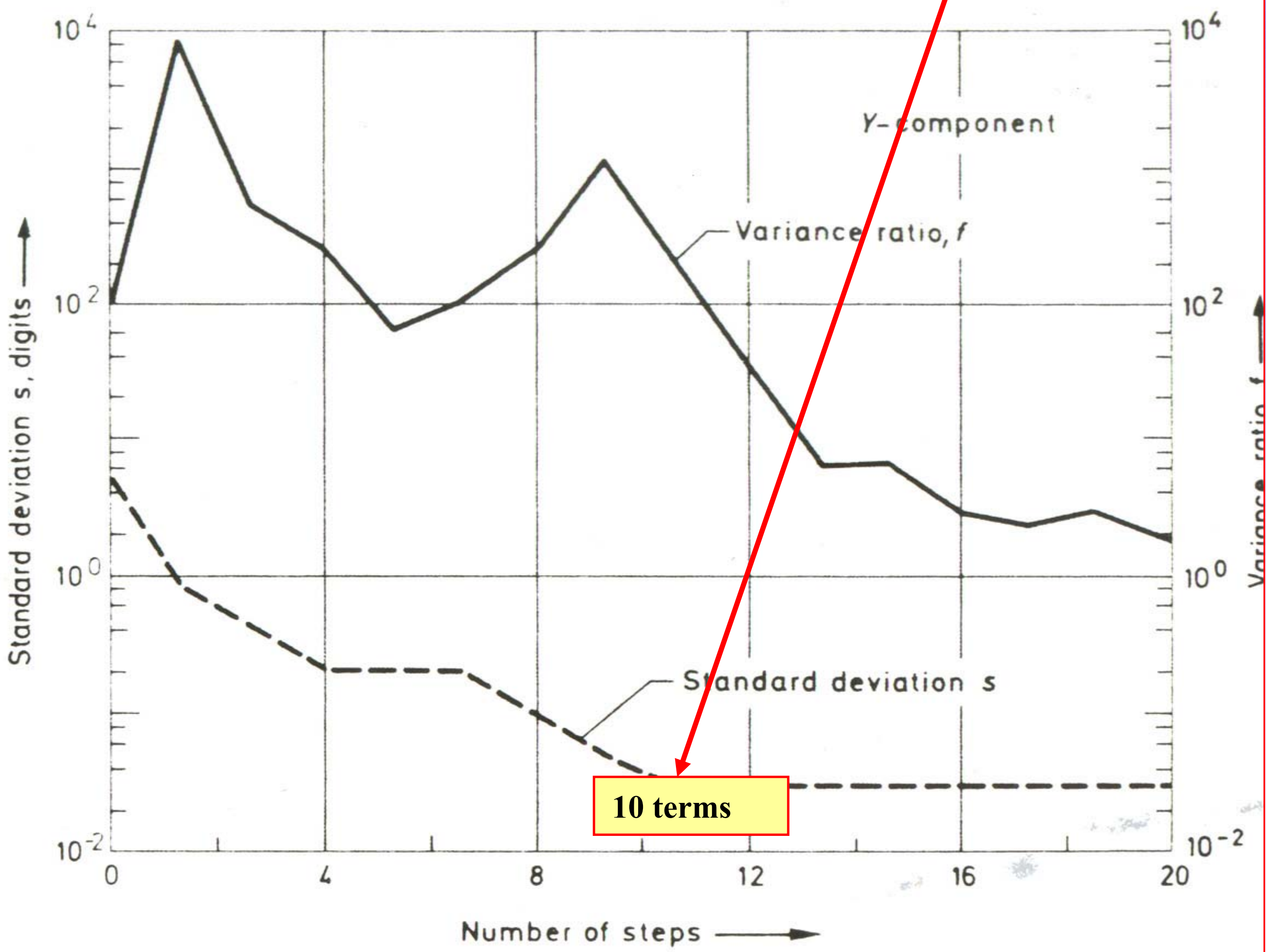
		COEFFICIENT VALUE AT STEP NUMBER								
Variable	Coeff.	1	2	3	4	5	6	7	8	9
O_2	a_6	8.25×10^{-4}	8.13×10^{-4}	6.27×10^{-4}	6.99×10^{-4}	6.99×10^{-4}	7.00×10^{-4}	7.02×10^{-4}	7.02×10^{-4}	7.00×10^{-4}
O_3	a_7		-5.66×10^{-4}	-5.46×10^{-4}	-7.63×10^{-4}	-7.63×10^{-4}	-7.65×10^{-4}	-7.65×10^{-4}	-7.65×10^{-4}	-7.65×10^{-4}
O_1	a_5			-5.10×10^{-4}	-6.97×10^{-4}	-7.01×10^{-4}	-7.01×10^{-4}	-7.01×10^{-4}	-7.01×10^{-4}	-7.02×10^{-4}
$\bar{V}$	a_1				-9.00×10^{-4}	-8.98×10^{-4}	-8.97×10^{-4}	-8.97×10^{-4}	-8.96×10^{-4}	-8.94×10^{-4}
$\bar{V}O_1$	a_{1-5}					4.47×10^{-8}	4.52×10^{-8}	3.43×10^{-8}	3.23×10^{-8}	3.25×10^{-8}
$\bar{V}O_3$	a_{1-7}						3.07×10^{-8}	3.12×10^{-8}	2.89×10^{-8}	2.89×10^{-8}
$\bar{V}O_2$	a_{1-6}							-3.18×10^{-8}	-3.10×10^{-8}	-3.08×10^{-8}
$\bar{V}^2$	a_{1-1}								-1.70×10^{-8}	-1.69×10^{-8}
V_2	a_3									-3.35×10^{-4}
Constant	a_0	9.2×10^{-4}	-2.5×10^{-2}	-4.1×10^{-2}	-3.8×10^{-2}	-2.3×10^{-2}	-1.3×10^{-2}	9.8×10^{-3}	5.7×10^{-4}	5.7×10^{-4}

……..the evolution of the coefficients of the regression equation is determined at each step.

The relevant ratios of the **regression equation coefficients** *to* the **standard deviations** at the corresponding steps **are determined** as well

Variable	Coeff.	RATIO VALUE AT STEP NUMBER 1	2	3	4	5	6	7	8	9
O_2	a_6	1.28×10^1	1.56×10^1	1.46×10^1	1.77×10^2	2.49×10^2	3.35×10^2	7.83×10^2	9.59×10^2	1.00×10^3
O_3	a_7		-1.07×10^1	-1.34×10^1	-1.92×10^2	-2.70×10^2	-3.62×10^2	-8.49×10^2	-1.04×10^3	-1.15×10^3
O_1	a_5			-1.19×10^1	-1.71×10^2	-2.40×10^2	-3.23×10^2	-7.54×10^2	-9.24×10^2	-9.76×10^2
$\bar{V}$	a_1				-1.56×10^2	-2.19×10^2	-2.93×10^2	-6.87×10^2	-8.37×10^2	-8.88×10^2
$\bar{V}O_1$	a_{1-5}					1.41×10^1	1.91×10^1	3.20×10^1	3.60×10^1	4.02×10^1
$\bar{V}O_3$	a_{1-7}						1.27×10^1	$+3.03 \times 10^1$	3.32×10^1	3.67×10^1
$\bar{V}O_2$	a_{1-6}							-3.01×10^1	-3.58×10^1	-3.93×10^1
$\bar{V}^2$	a_{1-1}								1.01×10^1	-1.11×10^1
V_2	a_3									-6.81×10^1

Cut criteria are better defined in the diagram of fig, which gives the behavior of experimental values of **variance ratio F and standard deviation Sy for component Y.**

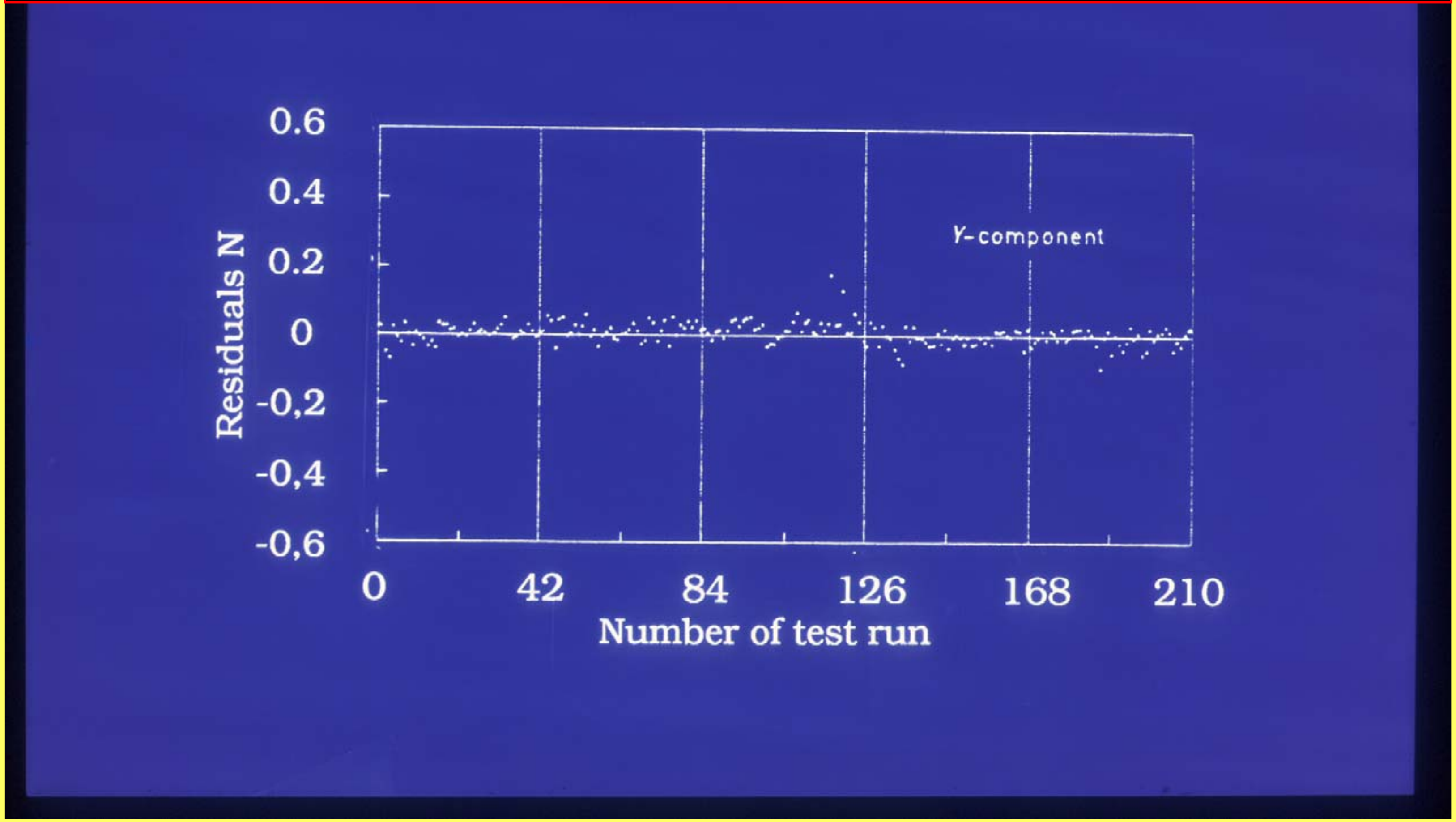


For purpose of economy; only the terms giving **meaningful contributions are maintained in the equations.**

Forces	Terms
$X = a_0 + a_1\overline{\mathbf{V}} + a_2\mathbf{V}_1 + a_4\mathbf{V}_3 + a_5\mathbf{H}_1 + a_6\mathbf{H}_2 + a_7\mathbf{H}_3$	linear
$+ a_{1,1}\overline{\mathbf{V}}^2 +$	square
$+ a_{1,3}\overline{\mathbf{V}}\mathbf{V}_2 + a_{1,4}\overline{\mathbf{V}}\mathbf{V}_3 + a_{1,5}\overline{\mathbf{V}}\mathbf{H}_1 + a_{1,6}\overline{\mathbf{V}}\mathbf{H}_2 + a_{1,7}\overline{\mathbf{V}}\mathbf{H}_3$	crossed
$Y = a_0 + a_1\overline{\mathbf{V}} + a_2\mathbf{V}_1 + a_3\mathbf{V}_2 + a_5\mathbf{H}_1 + a_6\mathbf{H}_2 + a_7\mathbf{H}_3$	linear
$+ a_{1,1}\overline{\mathbf{V}}^2$	square
$+ a_{1,3}\overline{\mathbf{V}}\mathbf{V}_2 + a_{1,5}\overline{\mathbf{V}}\mathbf{H}_1 + a_{1,6}\overline{\mathbf{V}}\mathbf{H}_2$ **10 terms**	crossed
Moments	
$L = a_0 + a_1\overline{\mathbf{V}} + a_2\mathbf{V}_1 + a_4\mathbf{V}_3 + a_5\mathbf{H}_1 + a_6\mathbf{H}_2 + a_7\mathbf{H}_3$	linear
$+ a_{1,1}\overline{\mathbf{V}}^2$	square
$a_{1,2}\overline{\mathbf{V}}\mathbf{V}_1 + a_{1,3}\overline{\mathbf{V}}\mathbf{V}_2 + a_{1,5}\overline{\mathbf{V}}\mathbf{H}_1 + a_{1,6}\overline{\mathbf{V}}\mathbf{H}_2$	crossed
$M = a_0 + a_1\overline{\mathbf{V}} + a_2\mathbf{V}_1 + a_4\mathbf{V}_3 + a_5\mathbf{H}_1 + a_6\mathbf{H}_2 + a_7\mathbf{H}_3$	linear
$a_{1,1}\overline{\mathbf{V}}^2$	square
$+ a_{1,3}\overline{\mathbf{V}}\mathbf{V}_2 + a_{1,4}\overline{\mathbf{V}}\mathbf{V}_3 + a_{1,5}\overline{\mathbf{V}}\mathbf{H}_1 + a_{1,6}\overline{\mathbf{V}}\mathbf{H}_2 + a_{1,7}\overline{\mathbf{V}}\mathbf{H}_3$	crossed
$N = a_0 + a_1\overline{\mathbf{V}} + a_3\mathbf{V}_2 + a_5\mathbf{H}_1 + a_6\mathbf{H}_2 + a_7\mathbf{H}_3$	linear
$+ a_{1,1}\overline{\mathbf{V}}^2$	square
$+ a_{1,5}\overline{\mathbf{V}}\mathbf{H}_1 + a_{1,6}\overline{\mathbf{V}}\mathbf{H}_2 + a_{1,7}\overline{\mathbf{V}}\mathbf{H}_3$	crossed

With the IMGC dynamometer only from 9 to 12 coefficients are retained in the equations.

Finally, **residuals** (differences between calculated and actual values) for 210 testing conditions obtained with different load combinations are quoted in figure which illustrates the behavior of component Y (Y = 200 N)



Sensitivity Coefficients Matrix

COMPONENTS			Channel V1	Channel V2	Channel V3	Channel H1	Channel H2	Channel H3
LINEAR TERMS	Force	Z	-32.5526	-32.9338	-32.5518	0.5095	0.1634	-0.903
		X	321.1	-158.5	-162.7	-432	171.6	881.4
		Y	6.02	-282.75	276.5	-344.3	-61	411.4
	Moments	L	1	-441.25	441.87	6.25	2	10.03
		M	513.75	-260.6	-254.35	0.4	10.09	-0.6
		N	0	0	0	1098	1093.7	1088
SECOND ORDER TERMS	Square terms 1OE-06	Z^2	3.44	-8.2	6.08	8.05	-9.96	-[illegible]
		X^2	0	0	0	0	0	[illegible]
		Y^2	0	0	0	0	0	[illegible]
		L^2	0	0	0	0	0	[illegible]
		M^2	0	0	0	0	0	[illegible]
		N^2	0	0	0	0	0	[illegible]
	Rectang. terms 1OE-03	ZX	2.17	1.25	1.1	1.975	3.62	[illegible]
		ZY	0	-0.635	-0.5	-0.715	-0.45	[illegible]
		ZL	0.1	-1.2	-1.562	-0.156	0.1	[illegible]
		ZM	2.02	0.94	1.09	2.69	1.25	[illegible]
		ZN	0	0	0	2.75	3.125	3[illegible]

It is interesting to show that the SUM of the VERTICAL CHANNEL (Vi) is not interacting with the other components

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

GENERAL EVALUATION

Intercomparison tests of DWM exhibited sometimes lack of agreement inconsistent with the accuracy of the machines and the estimated uncertainty of measurement.

Such errors, are originated mainly

- **by the presence of unwanted, transversal force (and moment) components, applied by the deadweight machine**
- **the non-zero sensitivity to these components exhibited by the load cell.**

Quantitative evaluation of parasitic load components applied by the machine, and of their single and combined effects on load cell output, are to be obtained in order to reduce uncertainty in force measurement.

However,

1) **Transversal load components applied by deadweight machines must be measured**, **and effective steps taken to limit their magnitude,**

2) **Measurement of load cell sensitivity to transversal loads is also to be performed systematically**.

In other words it will be necessary in future activities of the Force Working Group

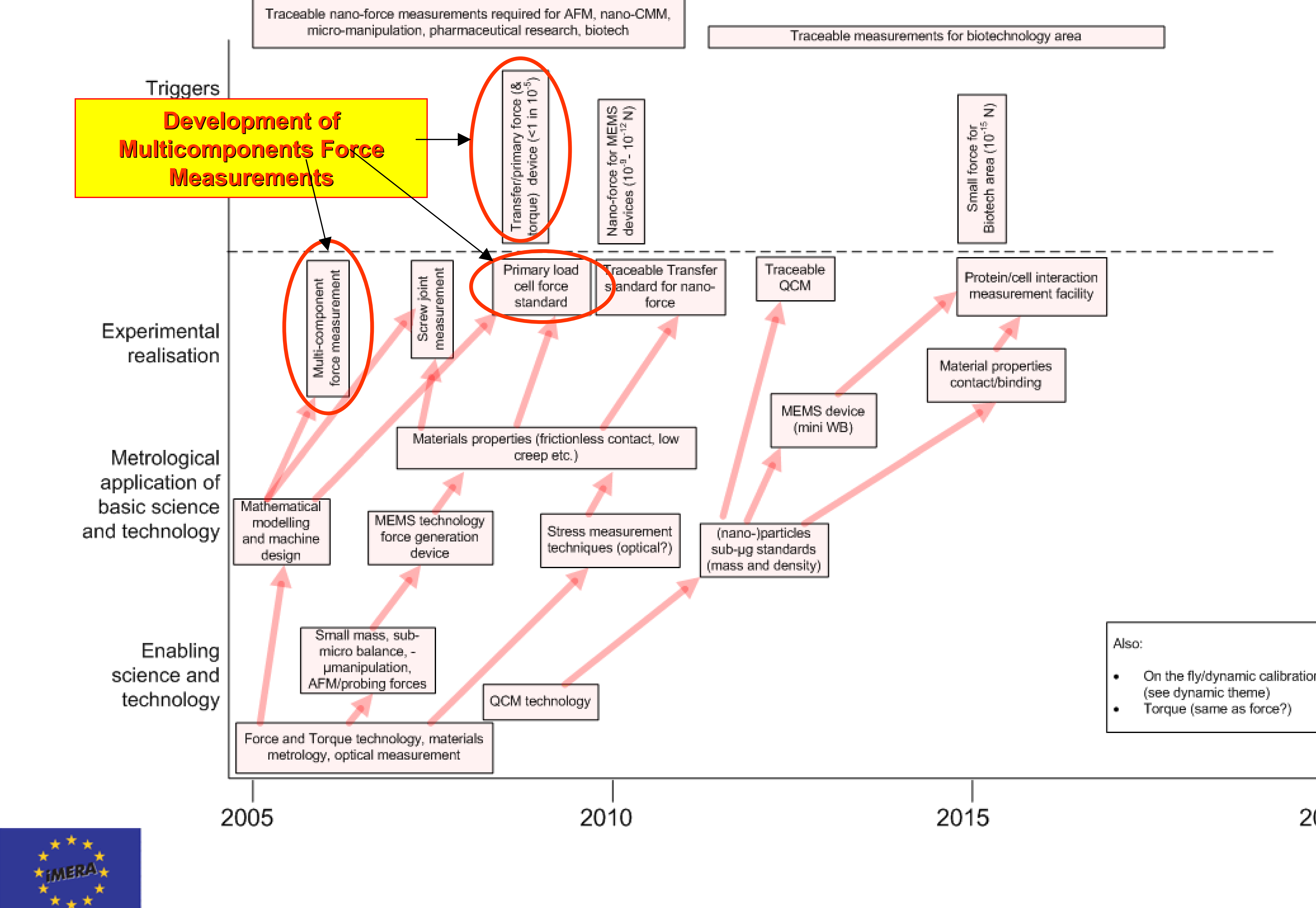
a) to prescribe **methods and means** wich ensure **uncertainty estimation of parasitic components** in force measurements;

b) to define an accepted **theoretical volume of the parasitic components for the primary standards**;

c) to **determine (and limit) the sensitivities** to transversal loads and bending moments **for the transfer standards to be used in force comparisons**.

What was disseminate in the last 30 years by INRiM?

What the future in the multicomponent force activities: research and intercomparison?



Traceable nano-force measurements required for AFM, nano-CMM, micro-manipulation, pharmaceutical research, biotech
Traceable measurements for biotechnology area
Triggers
Development of Multicomponents Force Measurements
Transfer/primary force (& torque) device (<1 in 10^-5)
Nano-force for MEMS devices (10^-9 - 10^-12 N)
Small force for Biotech area (10^-15 N)
Experimental realisation
Multi-component force measurement
Screw joint measurement
Primary load cell force standard
Traceable Transfer standard for nano-force
Traceable QCM
Protein/cell interaction measurement facility
Material properties contact/binding
MEMS device (mini WB)
Metrological application of basic science and technology
Materials properties (frictionless contact, low creep etc.)
Mathematical modelling and machine design
MEMS technology force generation device
Stress measurement techniques (optical?)
(nano-)particles sub-µg standards (mass and density)
Enabling science and technology
Small mass, sub-micro balance, -µmanipulation, AFM/probing forces
QCM technology
Force and Torque technology, materials metrology, optical measurement
Also:
On the fly/dynamic calibration (see dynamic theme)
Torque (same as force?)
2005
2010
2015
iMERA

KRISS- Corea

Application mainly in ROBOTIC

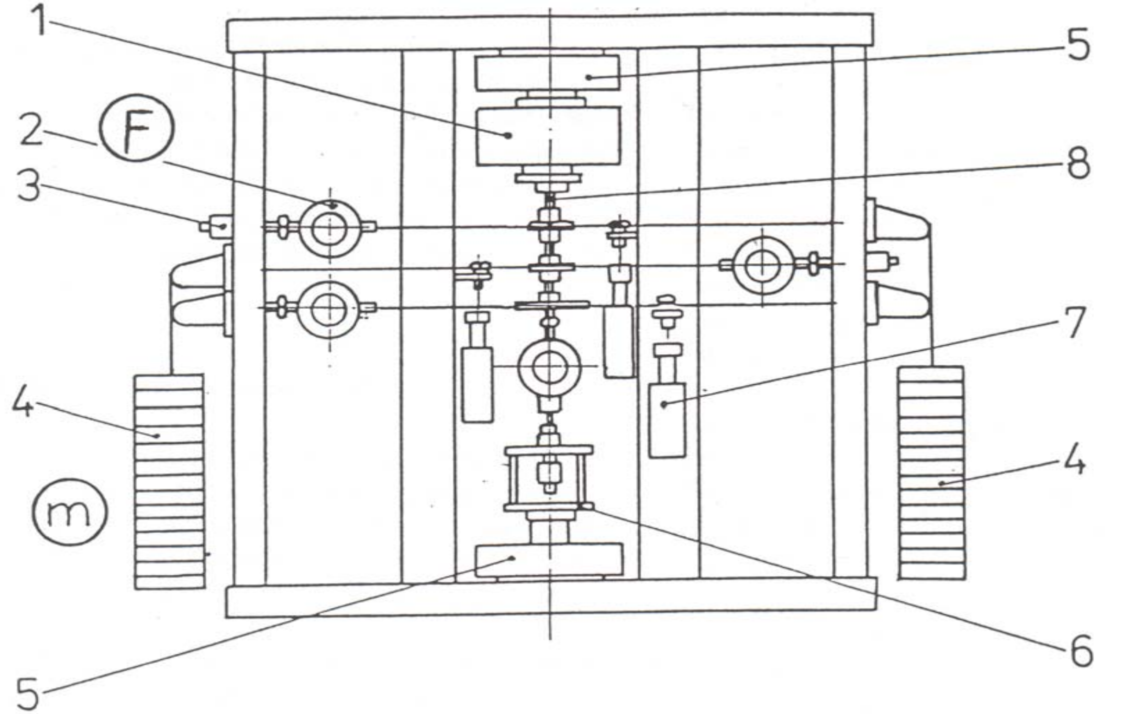


Fig. 1 Force and mass versions for calibration stand

An interesting method was developed by

Dae-Im Kang and his collaborators

by using **build-up** system for the evaluation of FSM

Cooperation Ferrero-Dae Im Kang (1996)

NIM CALIBRATION SYSTEM - CHINA

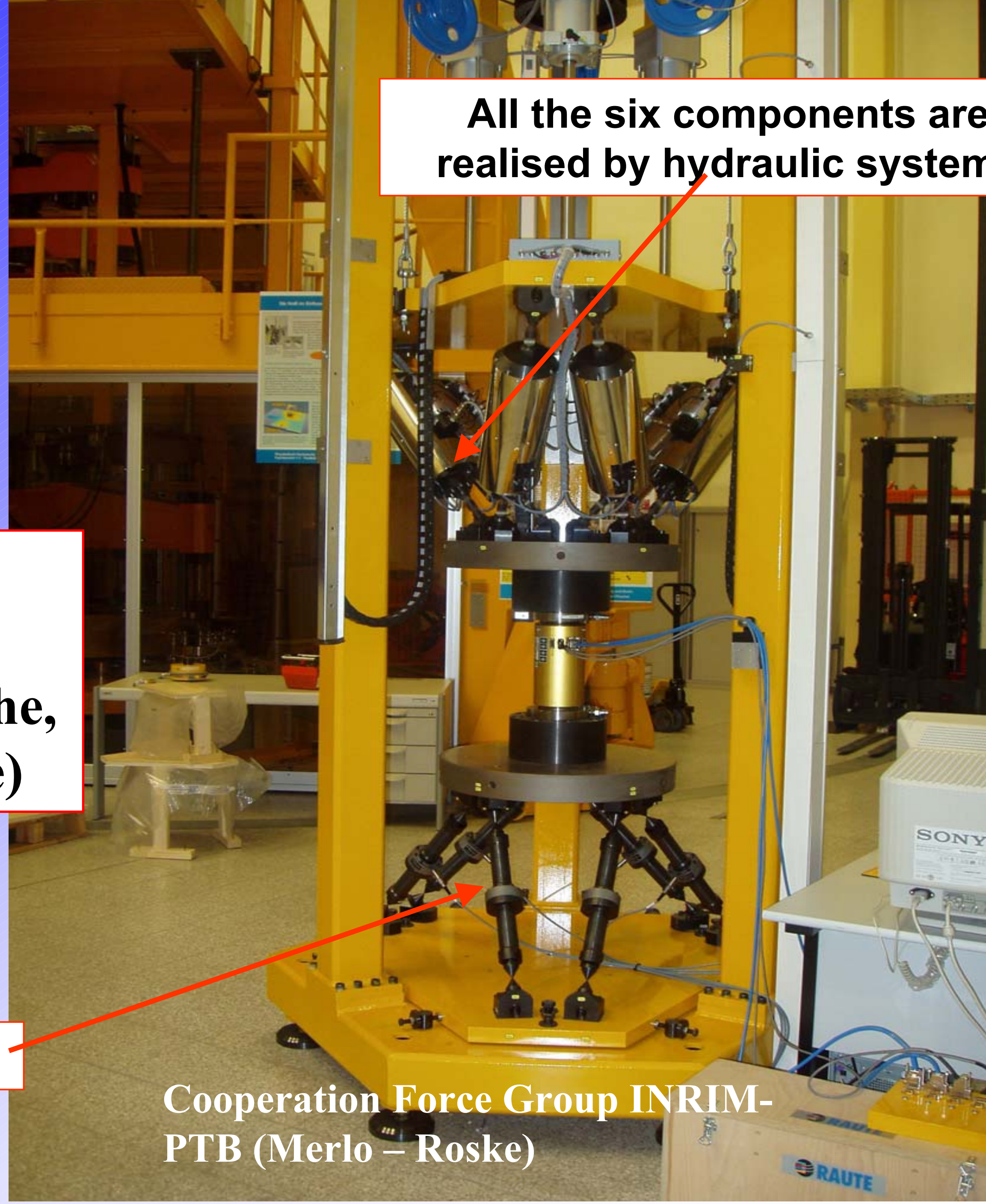
System developed in China to be used in the aero-space field (**very hight force and moment components)**

Cooperation Bray-Ferrero-Li QingZhong-Marinari

(dal 1983 al 1995)

PTB SYSTEM FOR HIGH FORCES

Controllo delle componenti nel tempo in strutture in cemento armato (ponti, dighe, costruzioni in zone sismiche)



Cooperation Force Group INRIM-PTB (Merlo – Roske)

Many Thanks …
for your attention