The results of comparisons between two different dynamic force measurement systems

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Two traceable dynamic force measurement systems in National Standards Laboratories are described. The systems operate on different physical principles and have been designed for different force and frequency ranges. There is, however, an overlap region and three comparisons between the systems have been carried out in this area. The results are given and the differences discussed.

Keywords: Dynamic force, dynamic calibration, force transducers

List of symbols

$\vec{a}$ Acceleration of the inertia mass m
a Magnitude of the acceleration $\vec{a}$
$\vec{F}$ Dynamic force acting on the force transducer
F Magnitude of dynamic force $\vec{F}$
F_{ref} Force indicated from the reference transducer
F_{ft} Force indicated from the transducer to be calibrated
F_{NPL} Force measured from the NPL
F_{PTB} Force measured from the PTB
m Inertia mass
m_{end} End mass of the force transducer
m_{load} Mass added to the force transducer
U_f Output signal from the force transducer
S_f Dynamic sensitivity of the force transducer

1. Introduction

Recent progress in the field of force measurement has reduced the uncertainties to 10^{-5} for the realisation and transfer of static forces. Force transducers are, however, often then used for dynamic measurements. It is therefore important also to study the dynamic properties of the force transducer and the electronic measurement system as well, because large errors can occur under dynamic conditions. For this reason, two research projects in National Standards laboratories have started to extend the static calibration of force transducers into the dynamic region. One is at the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany, and the other is at the National Physical Laboratory (NPL) in Teddington, England. At the PTB, the determination of dynamic force is based on an absolute method while at the NPL the system is based around a reference force transducer operating on a comparison principle. It was therefore considered valuable to compare periodically the determinations of dynamic force of the two different systems. Three comparisons have been carried out, two at PTB and one at NPL, and have shown good agreement between the two systems.

2. The PTB system

The dynamic calibration of force transducers in the PTB is based on the determination of inertia forces $\vec{F} = m * \vec{a}$. The force transducer to be calibrated is therefore mounted on an electrodynamic shaker and a series of known masses m_{load} mounted above it in turn. A block diagram of the system is shown in Fig 1. As the shaker is operated with sinusoidal vibration, the force $\vec{F}$ experienced by the force transducer may be defined:

$$\vec{F} = (m_{load}+m_{end}) * \vec{a} \quad \ldots (1)$$

where m_{end} is the end mass of the force transducer. This is defined as the part of the transducer mass which contributes to the inertia force.

The sensitivity of the force transducer S_f is defined as the amplitude of the force transducer signal U_f divided

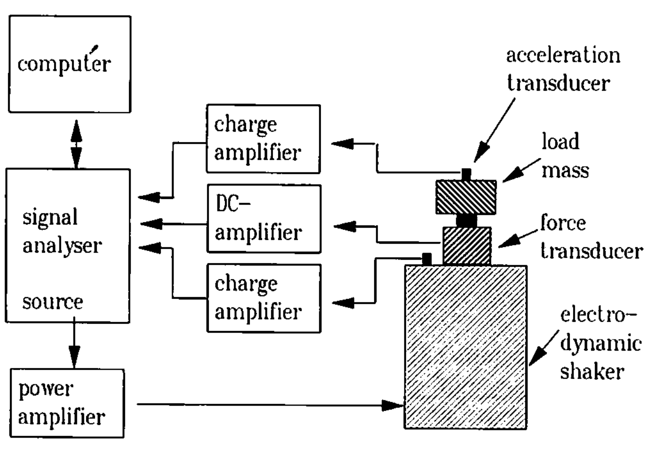

Fig 1 Block diagram of the PTB system

by the amplitude of the acting dynamic force F. Therefore, for each measurement frequency the sensitivity S_f and the end mass m_{end} of the force transducer may be determined by a least-squares-fit according to the equation

$$U_f/a = S_f * (m_{load}+m_{end}). \quad \ldots(2)$$

This procedure is repeated at each frequency point from 20 Hz to 1 kHz in steps of 10 Hz to give the sensitivity as a function of frequency (Kumme *et al*, 1990; Lauer, 1990). For each calibration, the frequency range is swept with 10 masses m_{load} from 1 to 10 kg in increments of 1 kg. This results in a maximum dynamic force acting on the transducer of 1 kN.

The acceleration of the mass is measured by accelerometers calibrated interferometrically at the PTB. The outputs from these and from the force transducer are recorded by a multi-channel signal analyser and the amplitudes measured either by FFT analysis or by a cross-correlation algorithm. The system has been described in more detail elsewhere (Kumme *et al*, 1990).

The accuracy of the calibration will be reduced if the coupling between the components is poor, as the measured acceleration a is no longer correct for all the components of mass. This normally occurs at higher frequencies and results in an apparent decrease in the sensitivity of the transducer. Additional accelerometers are used to check the mechanical coupling of all mass components.

3. The NPL system

The NPL system consists of a dynamic standard force transducer, coupled to a reference measurement system. Forces are applied by a servo hydraulic actuator in a four-column load frame.

The standard transducer is shown in Fig 2 and consists of a metal element with very low damping on which the elastic strain has been measured by two independent methods. The two indications of strain were calibrated statically and then compared dynamically over the frequency range of interest. The possibility of a systematic error occurring in both methods of strain measurement was minimised by making the two as different from each other as possible. The first method of strain measurement is a strain gauge bridge of eight gauges, four measuring the axial strain and four measuring the transverse strain. The second method of strain measurement is a capacitance transducer consisting of two annular ring electrodes, separated by an air gap. This measures the average strain over the entire length of the transducer and is therefore completely different from the strain gauge bridge which measures strain over eight small areas.

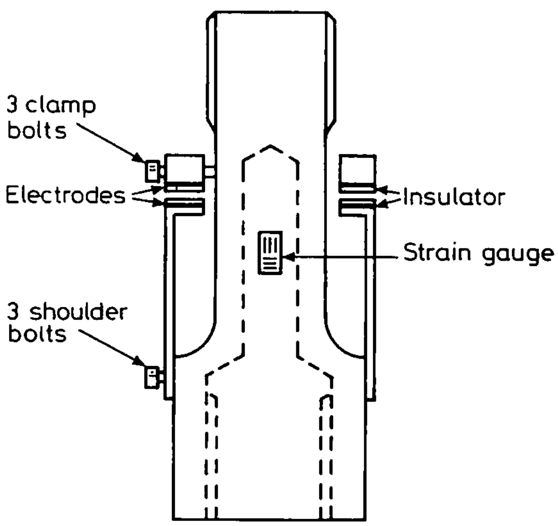

Fig 2 The NPL dynamic standard force transducer

The outputs from the strain gauge bridge and the capacitance bridge are recorded from a calibrated 12-bit digital storage oscilloscope. The data are then transferred from the oscilloscope to a computer and the dynamic amplitudes measured using a cross-correlation algorithm, written at the NPL (Dixon, 1988).

Both methods of strain measurement were calibrated statically in the 50 kN deadweight force standard machine at the NPL. The transducer was then mounted in the servo hydraulic testing machine and the two methods of strain measurement compared from 0.1 to 110 Hz. These measurements were used, with the uncertainty from the instrumentation, to derive an overall uncertainty of dynamic force measurement of ±0.4%. The strain gauge output is now used for absolute measurements of dynamic force, with periodic checks being made against the capacitance gauge. The system is described in more detail elsewhere (Dixon, 1990).

Transducers may be calibrated by mounting them in series with the standard in the load frame and then comparing the two indicated forces over the frequency range. The mass of any adaptor between the two force transducers, combined with the end masses of the two transducers, gives rise to a small inertia error, due to the force required to accelerate this mass m. This may be removed by a second calibration with the combination of transducers inverted in the testing machine. The two sets of results are then averaged. Alternatively, if the end masses of the transducers are known, the acceleration of the adaptor a may be measured with an accelerometer and the inertia force calculated directly.

The relationship between the force output from the reference transducer F_{ref} and the force output from the transducer being calibrated F_{ft} is then given by:

$$F_{ref} = F_{ft}+m * a. \quad \ldots(3)$$

This procedure is well known to manufacturers and users of accelerometers and materials testing machines (Collier *et al*, 1986; Dixon, 1991; Macconnel and Park, 1981; Sawla, 1979) and is usually known as inertia or loadcell compensation.

4. Measurements at PTB

Three sets of measurements were made at PTB. The first, over the frequency range 20–1000 Hz, was used to determine the dynamic sensitivity and end mass of the NPL force transducer. The second, over the frequency range 20–110 Hz, was a set of traceable comparison measurements in the force range over which the two systems overlapped. The third set of measurements was a comparison of the two measurement systems.

4.1 Measurement of the sensitivity and end mass of the NPL force transducer

The frequency response of the NPL force transducer was measured from 20–1000 Hz for 10 masses from 1 to 10 kg. The dynamic sensitivity and the end mass of the NPL force transducer were then calculated from Eqn 2. The graph for the sensitivity of the transducer is shown in Fig 3. The sensitivity between 20 and 500 Hz is within 1% of the sensitivity determined by NPL by static and low-frequency (up to 110 Hz) calibrations, based on comparisons between the two different strain measurement methods. Above 500 Hz the apparent sensitivity of the transducer decreases as the coupling between the transducer and the mass becomes worse.

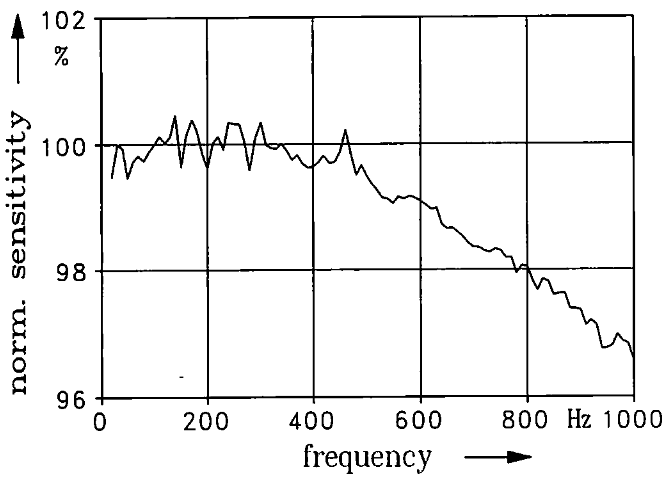

Fig 3 The dynamic sensitivity of the NPL force transducer normalised to the static sensitivity

4.2 Comparison of absolute force measurement

A comparison of absolute dynamic force measurement was then made over the frequency and force ranges where the two systems overlapped. The PTB system operates from 20 Hz to 1 kHz with a maximum force of 1 kN. The NPL standard transducer had been calibrated from 400 N to 20 kN over the frequency range 0.1–110 Hz. Traceable comparisons were therefore made from 20 to 110 Hz, at force increments between 400 N and 1 kN.

The system was operated from 20 to 110 Hz with the 10 kg mass mounted on the NPL transducer and comparisons made at five increments of force. The force from the NPL force transducer was measured by the NPL measurement system and the acceleration from the PTB accelerometer was measured by the PTB measurement system. The end mass value from the previous test was used.

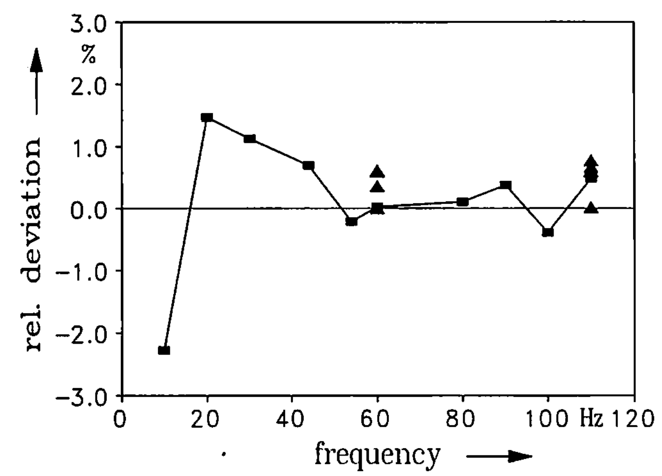

Fig 4 The relative deviation ($F_{PTB}-F_{NPL}$)/F_{NPL} in % for the absolute comparison at PTB, measured with the NPL force transducer: (a) ■ force amplitude 700 N; (b) ▲ force amplitude 150, 300, 450, 600, 800 and 900 N

The results are shown in Fig 4 and show that, at frequencies between 40 and 110 Hz, the overall difference between the two determinations of dynamic force amplitude was less than 1%.

The results at 10, 20 and 30 Hz show differences of up to ±2%. These differences are thought to be caused by the high transverse motion of the shaker combined with the transverse sensitivity of the accelerometers. This was tested by rotating the force transducer on the shaker and measuring at several orientations. The averaged result showed a difference of less than 0.5%.

4.3 Comparison of the two measurement systems

The measurement systems, consisting of analogue to digital convertors and analysis software, were also compared. The difference in amplitude measurement from a standard sinusoidal source was found to be less than 0.2% over the frequency range 10 Hz–1 kHz.

5. Measurements at NPL

A 4 kN strain gauge force transducer of low-profile shear web design was calibrated statically in a force standard machine at PTB. The frequency response was then measured in the PTB dynamic system and the response found to be flat up to 500 Hz. Apparent errors below 50 Hz were neglected as these were known to be caused by transverse motion of the shaker.

The force transducer was then taken to NPL and mounted in the servo hydraulic testing machine in series with the NPL force standard transducer, keeping the adaptor mass between the two force transducers to a minimum. Determinations of dynamic force were made over the frequency range 20–110 Hz. The force transducer combination was then inverted in the testing machine and the experiment repeated. The two sets of

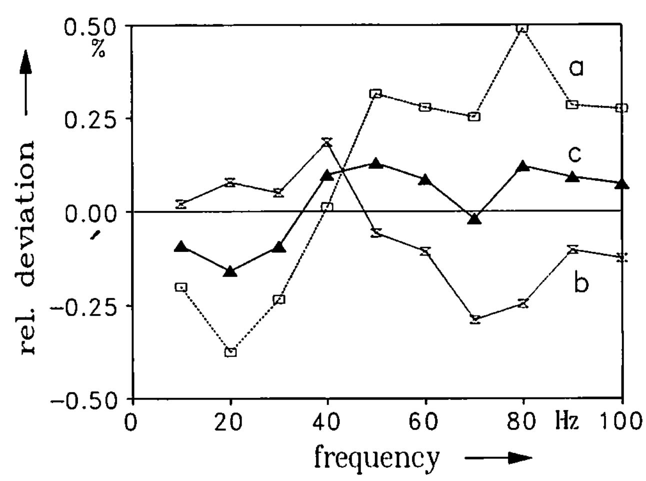

Fig 5 The relative deviation ($F_{PTB}-F_{NPL}$)/F_{NPL} in % for the absolute comparison at NPL: (a) measurements with NPL transducer in base position and PTB transducer in top position; (b) measurements with PTB transducer in base position and NPL transducer in top position; (c) mean values of measurements (a) and (b)

results were then averaged to remove the inertia force from the adaptor and the end masses of the two force transducers. The results are shown in Fig 5.

A comparison between the two transducers was also made from 10 to 500 Hz. For these measurements, an accelerometer was mounted on the adaptor between the two transducers and the acceleration *a* also recorded. As the inertia mass *m*, the sum of the end masses of the two transducers and the adaptor mass, was known from the measurements at PTB, the inertia force was then calculated from Eqn 3 and the comparison measurements corrected. The comparison, before and after compensation, is shown in Fig 6.

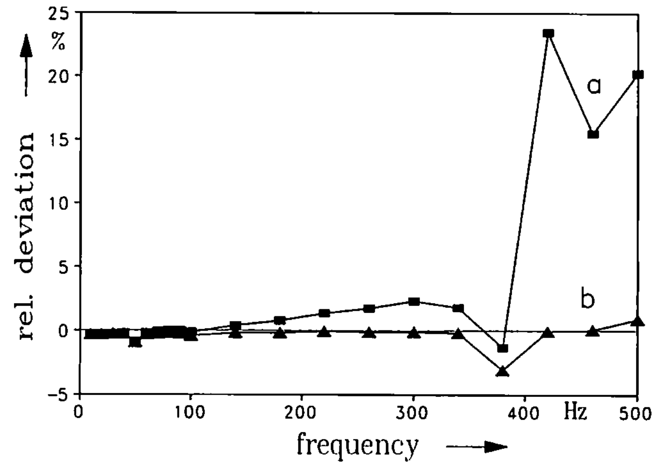

Fig 6 The relative deviation $(F_{PTB}-F_{NPL})/F_{NPL}$ *in % for the measurements at NPL with inertia compensation: (a) ■ without compensation; (b) ▲ inertia compensation*

6. Discussion

The determination of the dynamic sensitivity of the NPL force transducer at PTB has shown that the static calibration is valid up to 500 Hz. For measurements at frequencies up to 1 kHz, the greatest source of systematic error is from the mechanical coupling of the components. A new system of mass attachment to the force transducer adaptor, using collets, has improved the coupling, but it still results in a reduction in apparent sensitivity above 500 Hz.

In the frequency range 40–110 Hz, the difference between the determinations of dynamic force at PTB has, in all cases, been better than 1%. The largest source of systematic uncertainty in this frequency range is in the determination of the end mass of the NPL force transducer by PTB. Below 40 Hz the difference between the determinations has been better than 2%, the disparity being caused by the transverse motion of the shaker.

Measurements with transverse mounted accelerometers have shown that the transverse motion of the shaker is high at low frequencies. This leads to errors in the determination of dynamic force due to the transverse sensitivity of the axial accelerometer. The effect will be accentuated if the force transducer is sensitive to bending loads. Low-frequency measurements are therefore made in several orientations of the force transducer relative to the shaker, and the results averaged.

At NPL, where the PTB force transducer was assumed to have a flat frequency response at low frequency, the difference between the determinations of dynamic force was less than ±0.2% over the frequency range 10–110 Hz. This is better than the uncertainty of the NPL system (0.4%).

The transverse motion of the NPL system is less because the actuator rod is supported in two hydrostatic bearings approximately 1 m apart and because the load-string is attached at the upper end to the load frame. The shaker bearings in the PTB system are only a few centimetres apart and the system is therefore much less rigid.

Tests at frequencies up to 500 Hz in the NPL servo hydraulic machine demonstrated that the inertia error resulting from the force transducer end mass and adaptor mass could be compensated for by simultaneous measurement of the adaptor acceleration.

7. Conclusion

The NPL and PTB dynamic force measurement systems operate on different physical principles. Three comparisons have shown that the difference in determination of dynamic force is less than 1% over the frequency range 40–110 Hz. Below 40 Hz the PTB system is limited by transverse motion. The NPL system has not been calibrated above 110 Hz due to performance limitations of the actuator.

The PTB system has been developed to determine the frequency response of force transducers with an absolute calibration method at frequencies up to 1 kHz. The calibration method is traceable to the primary physical quantities of mass, length and time. The uncertainty for the determination of the dynamic sensitivity and the end mass is mainly limited by the transverse motion of the shaker.

The NPL system has been developed as a traceable basis for the dynamic force calibration of material testing machines at frequencies up to 100 Hz. The calibration method is based on a comparison calibration with a reference force transducer. The reference transducer relies on comparison between different methods of strain measurement on an elastic element, traceability being achieved via the static force standards. The uncertainty of the calibration can be reduced by compensating for the inertia force between the two transducers. This may be achieved by measuring in two orientations or by accelerometer compensation.

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Coming events

Organised or co-sponsored by IMEKO

Event	Date and venue	Contact
	1992	
8th international symposium on technical diagnostics (TC-10)	23–25 September Dresden, Germany	Conference Secretariat TD 92, WGMA-TD, Clara Zetkin Str 115–117, POB 1315, Berlin 1086, Germany
Temperature '92 – technical temperature measurement (TC-12 co-sponsored)	8–9 October Düsseldorf, Germany	H. Müller, VDI/VDE-GMA, P.O. Box 1139, D–4000 Düsseldorf 1, Germany
Measurements in biology and medicine (TC-13 co-sponsored)	28 October–1 November Paris, France	IMEKO Secretariat
4th workshop: Measurement of surface thermal resistance (TC-12)	3–5 November Budapest, Hungary	IMEKO Secretariat, PO Box 457, 1371 Budapest, Hungary
2nd symposium on measurement and control in robotics (TC-17)	16–18 November Tokyo, Japan	Dr S. Tachi, Mechanical Engineering Dept. 1–2 Namiki, Tsukuba Science City, Ibaraki 305, Japan
AIM 92' – 2nd Australasian instrumentation and measurement conference (TC-1)	24–27 November Auckland, New Zealand	AIM-92, Centre for Continuing Education, University of Auckland, Private Bag, Auckland, New Zealand
	1993	
IFAC symposium on biomedical modelling and control (TC-13 co-sponsored)	April Galveston, USA	IMEKO Secretariat
13th conference on measurement of force and mass (TC-3)	10–14 May Helsinki, Finland	Force and Mass Conference, Finnish Society of Automation, Asemapäällikönkatu 12C, SF-00520 Helsinki, Finland
The nature and scope of measurement science – colloquium (TC-1; TC-7 co-sponsored)	8–10 September London, UK	IMEKO Secretariat
Measurement and control in robotics (TC-17)	September Torino, Italy	IMEKO Secretariat
TEMPMEKO'93-5th symposium on thermal and temperature measurement in industry and science (TC-12)	10–12 November Prague, Czechoslovakia	TEMPMEKO'93 Secretariat, Mr J. Kral, c/o Tech-Market, PO Box 44, CS-160, 17 Praha 6, Czechoslovakia
	1994	
3rd symposium on laser metrology for precision measurement and inspection in industry (TC-14)	March/April Germany	VDI-VDE-GMA, PO Box 10 1139, D-4000 Düsseldorf 1, Germany
13th Imeko World Congress	5–9 September Torino, Italy	IMEKO Secretariat