Le progrès, une passion à partager

Dynamic calibration of pressure sensors

Pressure measurement in non-equilibrium conditions is required in many applications. For example, pressure must be monitored in the cylinders of an engine to study combustion phenomena, in an injection moulding press to study a moulding process, in a Pitot tube to determine the speed of an aircraft, or in a catheter to determine blood pressure. In applications like these the pressure quantity is in dynamic state, i.e. the measurand is constantly changing, including during measurement. In static state a sensor is characterized by its sensitivity for a given measurand, defined as the variation in output quantity divided by the corresponding variation in the measurand. The same calculation performed in dynamic state produces different sensitivity values. Determination of sensitivity as performed in static state is thus not sufficient for dynamic calibration, and a specific method is required. To design this calibration method, the characteristics of the sensor must first be defined. Specific references are then required to perform the calibration. Further studies and calibrations must also be carried out to take into account the specific characteristics of the measurement system (measurement line, recessed chamber, change of fluid, etc.).

1. Principle of dynamic calibration of a sensor at optimum uncertainty level

In the field of static calibration of pressure sensors, establishing traceability to the unit of pressure presents no major problems. In the dynamic state, however, there is no standard of "dynamic pressure" such as a "standard pressure step" or a "standard pressure sine wave" with given frequency and amplitude. Using standard methods, it is not possible to "link" a "dynamic pressure standard" metrologically to "static" fundamental or derived quantities. In this situation, calculation of uncertainty on the input quantity of a sensor cannot be envisaged. For this reason the *Laboratoire de Métrologie Dynamique* (LMD) of *Arts et Métiers ParisTech* has developed a specific method for dynamic calibration of a reference sensor.

The proposed method is based on determination of the transfer function (gain and phase according to frequency), which enables us to describe a pressure sensor in both static and dynamic operation. There are two possible ways to determine the transfer function:

- the harmonic approach
- the transient approach.

The first approach requires periodic pressure generators which supply pressure as a sine-wave signal, the second requires aperiodic pressure generators which deliver pressure as a step or a pulse. LMD opted for the second approach, as fewer generators are needed: periodic generators – pistonphones, diaphragm compression chambers, electro-pneumatic converters, sirens, etc. – cover a limited pressure and frequency range.

In the transient tests performed by LMD, the sensor to be calibrated is subjected to a pressure step and the response delivered by the sensor is recorded. The transfer function $H(f)$ is then calculated point by point and is defined as the ratio of the Fourier transform of the output $S(f)$ to the Fourier transform of the input $E(f)$:

$$H(f)=\frac{S(f)}{E(f)}=\frac{\int_0^{\infty} s(t)\cdot \mathrm{e}^{-\mathrm{j}\omega t}\cdot dt}{\int_0^{\infty} e(t)\cdot \mathrm{e}^{-\mathrm{j}\omega t}\cdot dt}\ .$$

A pressure sensor is chosen among commercially available models for its metrological characteristics. Static and dynamic linearities are essential. The influence of external quantities must be as low as possible, particularly for acceleration and (to a lesser extent) temperature. The specified bandwidth and frequency must be compatible with the envisaged frequency range.

After quasi-static calibration the sensor is subjected to pressure steps of amplitude P_0, using generators whose frequency ranges overlap over a significant area. The output *s(t)* is recorded and used to determine its transfer function *H(f)*. The input *e(t)* is assumed to be a perfect step. Tests are performed several times with the same generator to assess repeatability.

In the case of quasi-static calibration, the input step (voltage or pressure) is measured using calibrated instruments ensuring traceability. For dynamic calibration, as the input is not known "metrologically" the transfer function cannot be calculated.

However, it is possible to estimate a transfer function between an ideal input (perfect step) and the measured output, which is the response to an imperfect step close to the theoretical model. The transfer function thus estimated (figure 1) shows up the variance between the ideal transfer function and the measured function. The more efficient the components in the chain, the smaller the difference between the ideal and measured functions. This transfer function reflects the imperfections of the step generator, the pressure sensor and its associated electronics, and the data acquisition and processing system, but it does not allow us to identify the origin of defects in the sensor response.

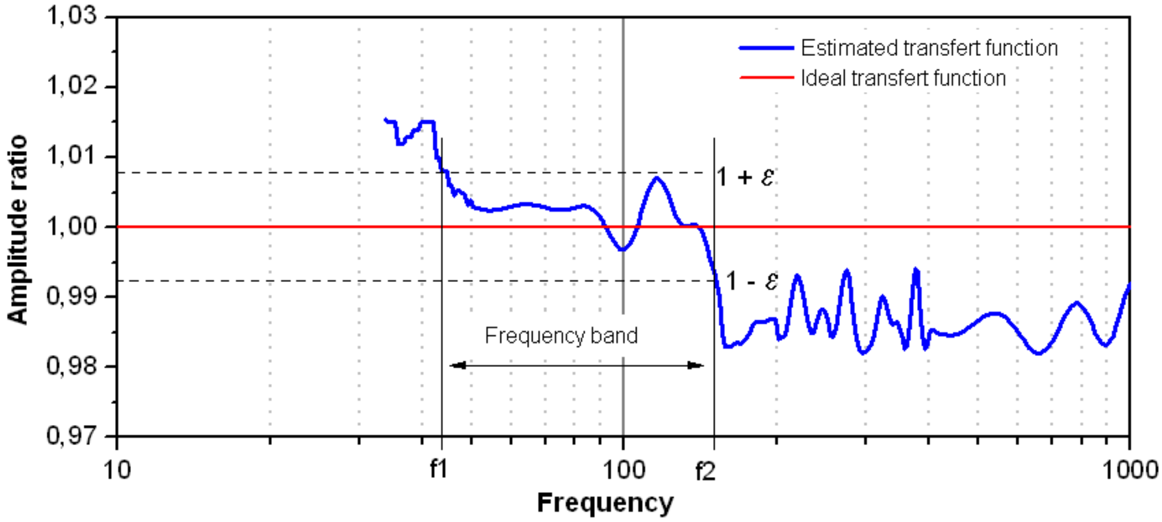

Fig. 1 – Principle of dynamic calibration with a transfer function

In a given frequency band [f_1, f_2], for example, the maximum deviation is ε, which we consider to be the maximum error in the band [f_1, f_2]. This error is caused mainly by the step generator and cannot be corrected. It is taken into account in the form of a standard uncertainty based on a uniform distribution.

In practice, one calibration generator only does not cover a frequency band wide enough to meet our needs. Several calibration generators must therefore be combined to extend the frequency band. They must cover a common amplitude and frequency range so that transfer functions may be compared across the one zone. This comparison enables us to define a common uncertainty for the frequency band.

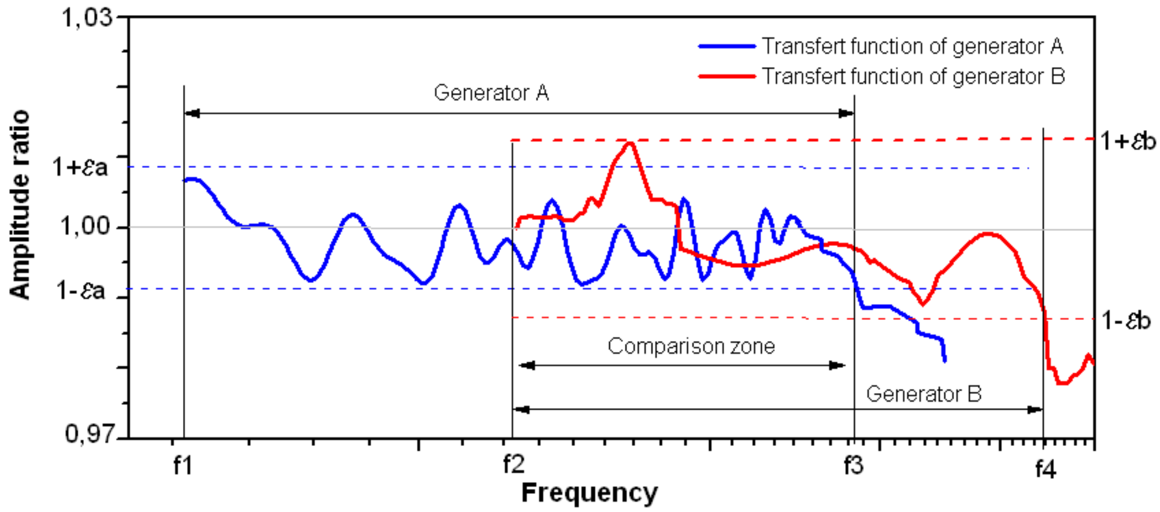

Fig. 2 – Principle of comparison of two calibration methods (A and B)

Figure 2 shows the result of dynamic calibration using two calibration generators. With generator A, in terms of bandwidth, the sensor has a constant transfer function of $1 \pm \varepsilon_a$ in frequency band [f_1, f_3]. With generator B, there is a constant response of $1 \pm \varepsilon_b$ in frequency band [f_2, f_4]. In the comparison zone [f_2, f_3] the sensor response is taken to be $1 \pm \varepsilon_b$, whichever generator is used. By extension, the sensor's amplitude transfer function is constant at $1 \pm \varepsilon_b$ in frequency band [f_2, f_4]. It is thus possible to determine a frequency band where the sensor has a known amplitude response and associated uncertainty, without taking into account the dynamic behaviour of the calibration generators or the sensor.

In order to complete the transfer function with the phase curve, the response of a second sensor is recorded during calibration with the different generators. The dynamic characteristics of the second sensor must be more or less identical to those of the first. The initial time is set arbitrarily shortly before the step transition for the two sensors. The phase difference calculated between the output $s(t)$ (first sensor response) and input $e(t)$ (second sensor response) is then analysed as before, but in terms of bandwidth in phase.

This principle is comparable to the notion of bandwidth and is applicable both to the estimation of the reference sensor's transfer function and to the acquisition and processing chain.

If we apply a voltage step at the input of the acquisition chain, the acquisition transfer function can be determined. The model obtained is shown in figure 3.

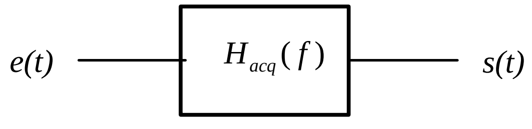

Fig. 3 – Model of acquisition transfer function

If we subject the reference sensor input to a pressure step, we can determine the overall transfer function. The model obtained is shown in figure 4. Note that the transfer function of the acquisition and of the sensor $H_r(f)$ are estimated here, as the component $H_{sensor}(f)$ is not directly measurable.

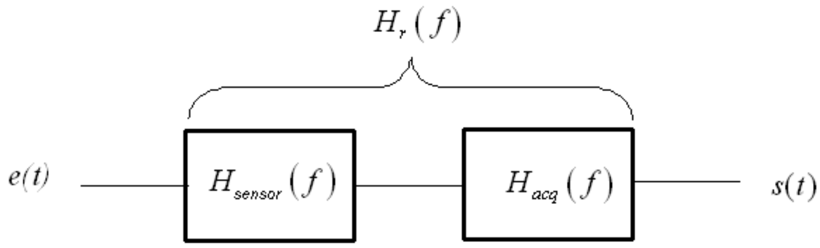

Fig. 4 – Model of reference sensor

In practice, calibration of a reference sensor comprises five stages:

1. quasi-static voltage calibration of the acquisition system
2. quasi-static pressure calibration of the sensor to be calibrated
3. evaluation of the transfer function calculation software
4. dynamic voltage calibration of the acquisition system
5. dynamic pressure calibration of the sensor to be calibrated.

Quasi-static voltage calibration is performed by measuring a signal delivered by a voltage generator. The voltage is measured in parallel by a calibrated multimeter providing traceability. Quasi-static pressure calibration is performed by measuring the pressure delivered by a pressure generator. The pressure is measured in parallel by a calibrated manometer providing traceability. The transfer function calculation software is characterized by injecting the values of a signal corresponding to a reference transfer function. The transfer function calculated by the software is then compared with the reference transfer function to deduce the uncertainty introduced by the software. The transfer functions are then determined, using a voltage step generator for dynamic voltage calibration of the acquisition system and pressure step generators for dynamic pressure calibration of the sensor to be calibrated. Lastly, the overall uncertainty according to frequency is calculated from the different components, as specified in the *Guide to the Expression of Uncertainty in Measurement* (GUM).

2. Aperiodic pressure generators

There are several types of aperiodic generator, generating different types of signal:

- shock tube (step generator)
- fast opening valve device (step generator)
- closed bomb (step or pulse generator)
- pendulum pulse generator
- free-fall pulse generator.

The generators used at LMD are the shock tube and the fast opening valve device.

2.1. Shock tube

A shock tube is a closed cylinder comprising two chambers separated by a diaphragm. In the initial state, the high pressure chamber (HP) contains the driver gas and the low pressure chamber (BP) contains the driven gas. When the diaphragm bursts a pressure wave propagates through the low pressure chamber. The sensor to be calibrated is positioned at the end of the tube or on the wall of the low pressure chamber. The shape of the pressure step depends on the position of the sensor (see figure 5).

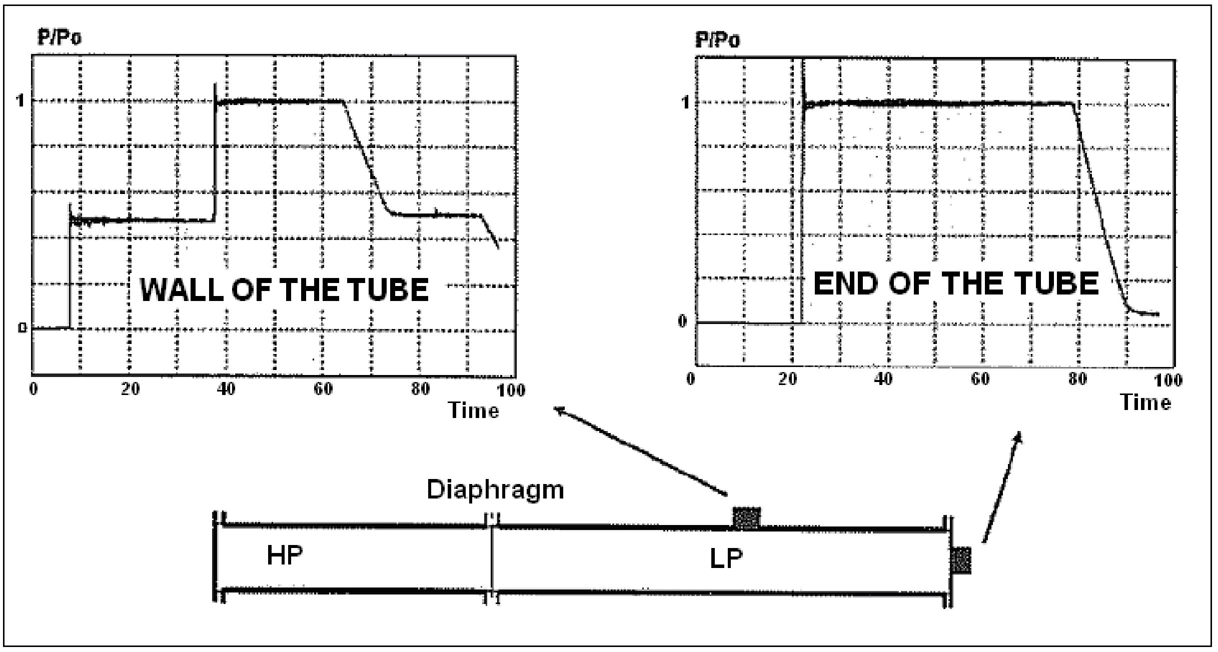

Fig. 5 – Pressure steps observed with a shock tube

As the pressure step rise time is very short, the shock tube is suitable for use with high frequencies (although the diaphragm bursting process limits the range). However, as the pressure step lasts only a short time, this device is limited in the low frequency range. It is suitable for both high and low pressure levels.

2.2. Fast opening valve device

The fast opening valve device is a pressure step generator. It comprises two chambers of very different volumes, called the small chamber and the large chamber, which are separated by an isolation and fast connection system. The sensor to be calibrated is mounted on the small chamber. In the initial state, a different pressure is generated in each chamber. When the two chambers are connected a pressure step is generated. Its relative amplitude is equal to the difference in the two pressure levels (see figure 6).

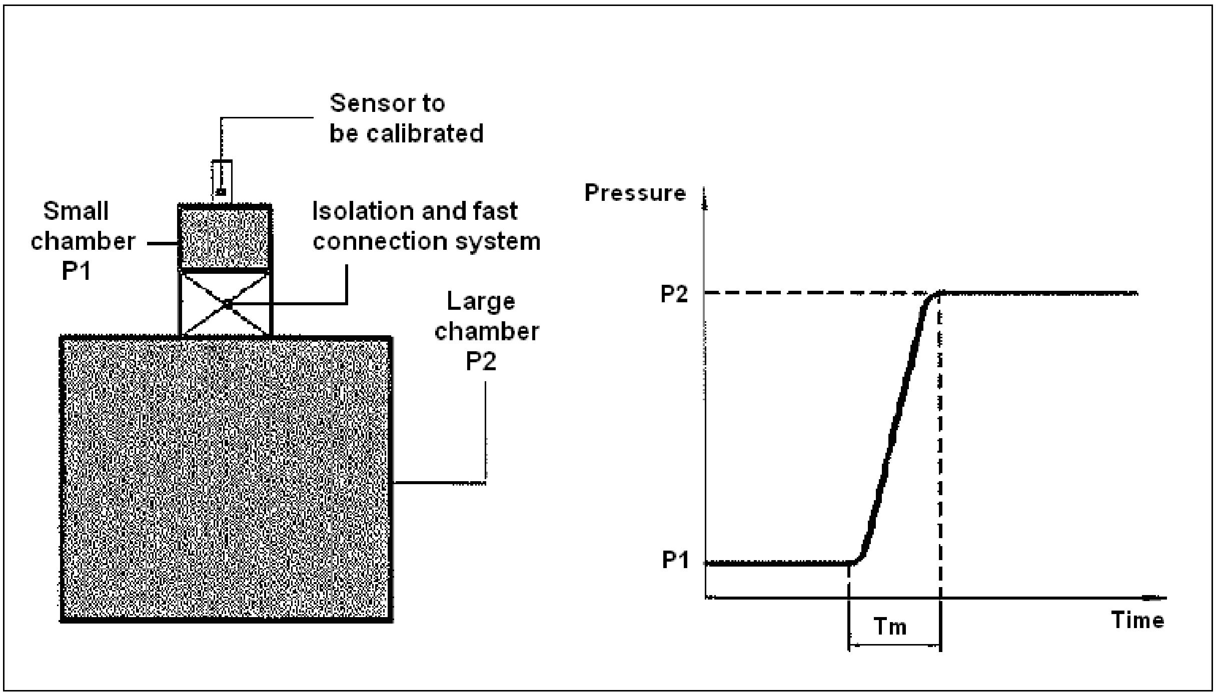

Fig. 6 – Fast opening valve device

As the pressure step lasts an appreciable time, the fast opening valve device is suitable for use with low frequencies. However, the long pressure step rise time limits its use in the high frequency range.

3. Measurement possibilities

LMD has developed a number of shock tubes and fast opening valve devices to cover a range of amplitudes and frequencies corresponding to calibration requirements. These generators are represented in figure 7. A long reference shock tube (TCR) covering low frequencies overlaps the frequencies covered by the shock tubes and the fast opening valve devices.

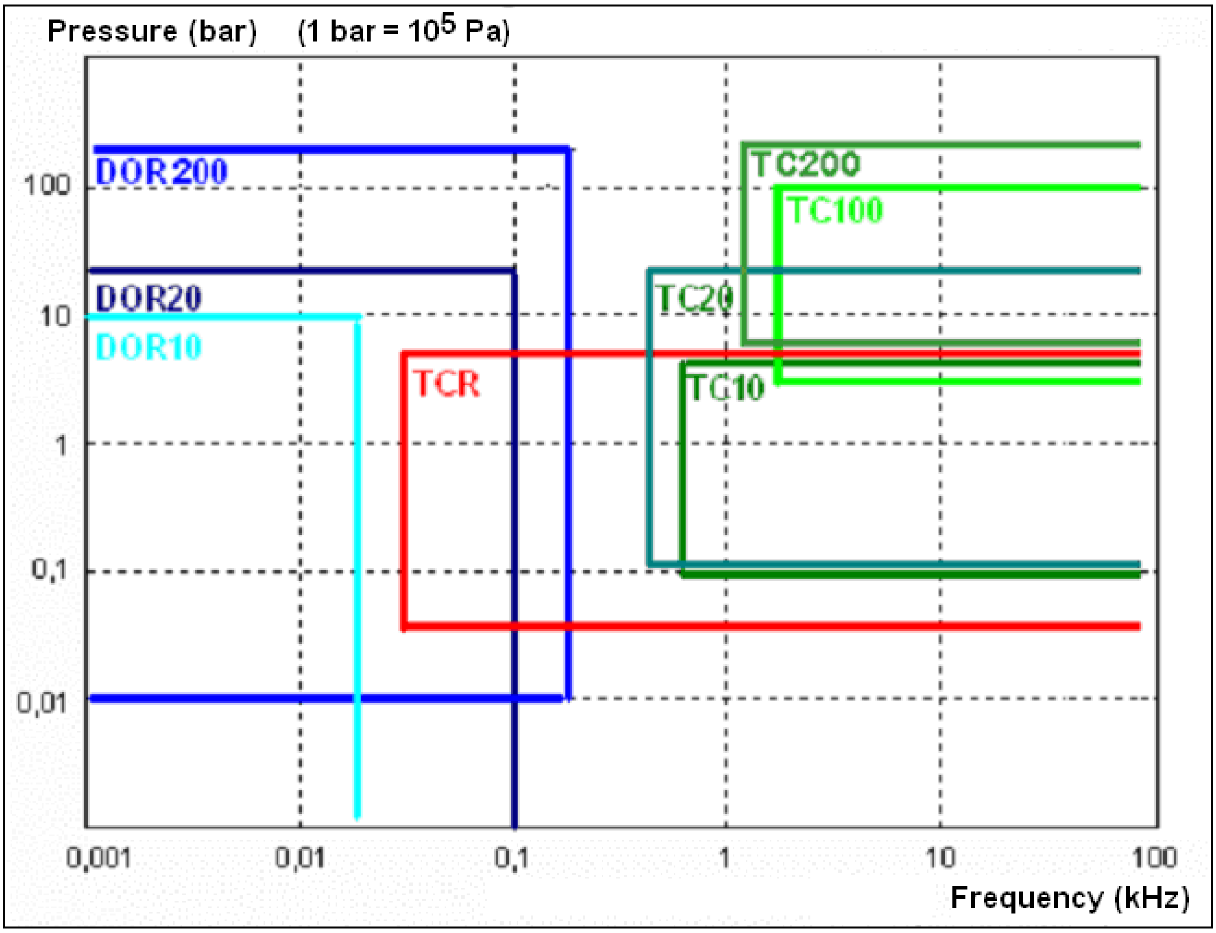

Fig. 7 – Operating range of LMD's step generators
(DORXXX: fast opening valve device, XXX bar;
TCXXX: shock tube, XXX bar)

4. Perspectives

This file presents the methods applied to ensure the traceability of dynamic pressure measurements with a reference sensor. Current research is focused on extending the pressure range to 100 bar (10 MPa), for which LMD is working with the University of Brasilia on the development of a very large shock tube (15 metres in length).

5. Further reading

Website of the *Laboratoire de Métrologie Dynamique* (LMD) of *Arts et Métiers ParisTech*: www.paris.ensam.fr/lmd

J.-P. Damion and A.B.S. Oliveira, « Incertitude de mesure dans la détermination de la sensibilité en quasi-statique d'un capteur de pression », International Metrology Congress, Toulon, France, 20-23 October 2003.

A.B.S. Oliveira and J.-P. Damion, « Détermination de l'incertitude de la fonction de transfert d'un capteur de pression en basse fréquence », International Metrology Congress, Lyon, France, 20-23 June 2005.

M.N. Barcelos Jr., J.N. de Souza Vianna, A.B.S. Oliveira and J.-P. Damion, “Valuation of the influence of gas composition in dynamic calibration in a shock tube”, International Metrology Congress, Saint-Louis, France, 22-25 October 2001.

L.M. Léodido, C. Sarraf and J.-P. Damion, « Caractéristiques dynamiques des capteurs de pression en milieu hydraulique », International Metrology Congress, Paris, France, 22-25 June 2009.

A.C.G.C. Diniz, A.B.S. Oliveira, J.N. de Souza Vianna and F.J.R. Neves, “Dynamic calibration methods for pressure sensors and development of standard devices for dynamic pressure”, XVIII Imeko World Congress, Rio de Janeiro, Brazil, 17-22 September 2006.

J.-P. Damion, « Moyens d’étalonnage dynamique des capteurs de pression », Bulletin du Bureau National de Métrologie, vol. 8, no. 30, 1977.