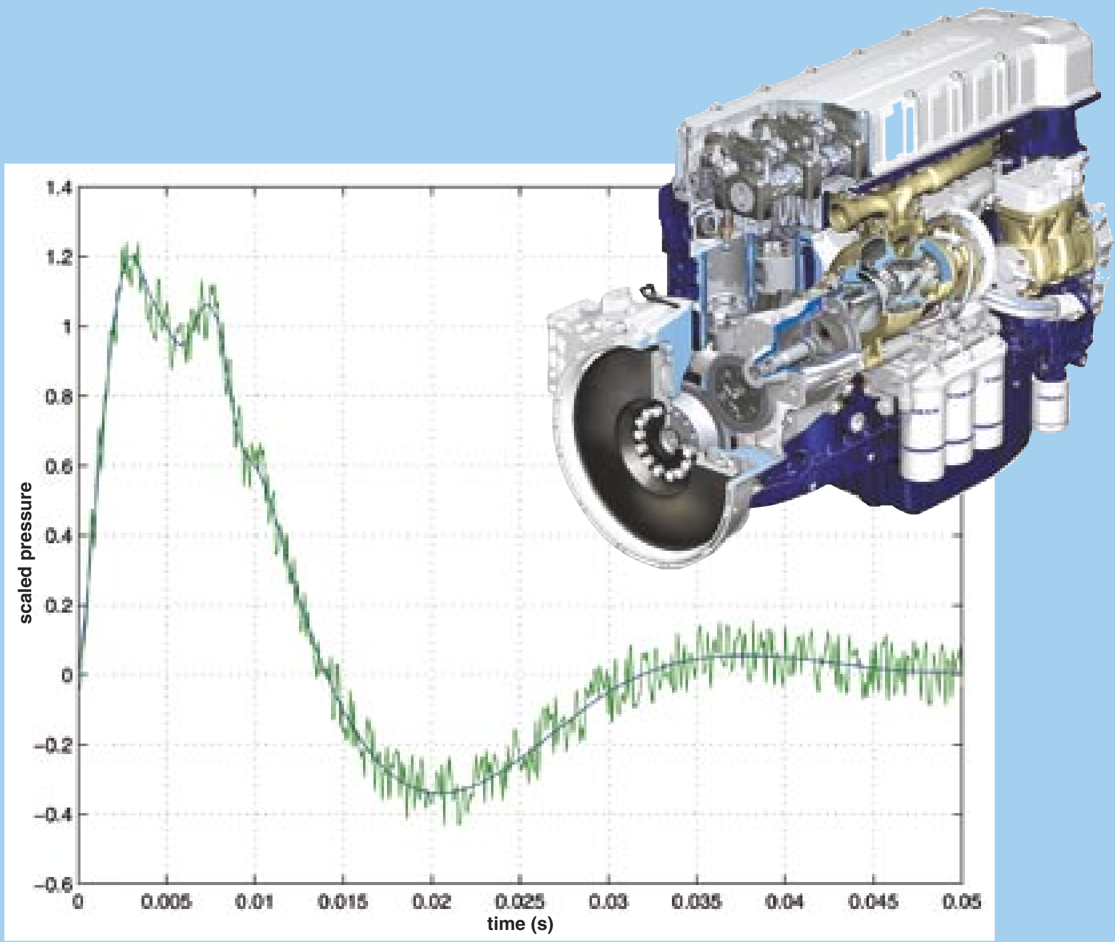
Jan Hjelmgren

Dynamic Measurement of Pressure - A Literature Survey



SP Swedish National Testing and Research Institute
SP Measurement Technology
SP REPORT 2002:34

Abstract

Dynamic pressure is measured in many important fields such as combustion analysis, automotive industry, turbomachinery, aerodynamics, fluid power and control, production processes and within medicine. The encountered amplitudes range from a few Pa to several GPa and frequencies range from below one Hz to about one MHz.

The measurement engineer should not be satisfied with the mere collection of measurement data. Data should also be evaluated and reported with an adjoining statement of measurement traceability and uncertainty. This uncertainty statement is a quantity describing the quality of measurement data obtained by involved operators using stated methods and equipment. Without reliable information about the quality of the measurement data the assessment of the impact of data on product quality is a risky business.

There is a big difference between performing traceability and uncertainty analyses for the cases of static and dynamic pressure measurements. This difference stems from the fact that, in the majority of cases, pressure transducers are traceably calibrated only for static pressures. When pressure transducers are used for dynamic measurements the measurement engineer is faced with a difficult question: how should the difference between the static calibration and the actual dynamic use be handled in the uncertainty budget? If there were methods available for dynamic calibration of pressure transducers it would be much easier to calculate uncertainties for dynamic pressure measurements.

The prime purpose of the present report is to survey the area of dynamic calibration of pressure transducers. To help the reader to understand the importance of and the techniques proposed for dynamic calibrations, introductory chapters are devoted to various application areas, methods of pressure measurements and measurement uncertainty. Finally areas in which further work is needed are pointed out.

Key words: pressure transducer, calibration, dynamic pressure, measurement uncertainty

SP Sveriges Provnings- och Forskningsinstitut
SP Rapport 2002:34
ISBN 91-7848-925-3
ISSN 0284-5172
Borås 2003

SP Swedish National Testing and Research Institute
SP Report 2002:34

Postal address:
Box 857,
SE-501 15 BORÅS, Sweden
Telephone: +46 33 16 50 00
Telefax: +46 33 13 55 02
E-mail: info@sp.se
Internet: www.sp.se

Contents

1 Introduction

Today there is a discrepancy between the relative ease by which dynamic pressure data can be collected and the difficulty encountered in estimating the quality of the dynamic measurement data. In many application areas dynamic pressure measurements are used in a more or less routine manner to improve the performance of a product or a process. Several measurement equipment vendors claim to have products capable of providing measurement data with low measurement uncertainties for dynamic pressures of frequencies extending up to several hundred kHz. The problem for the conscientious measurement engineer is that there exists no sound well-established metrological method to assess the quality of the measurement data. This is due to the lack of traceable dynamic pressure calibration methods.

Traceable calibrations are an essential part of quality assurance as stipulated in modern quality standards such as ISO 9000, ISO/TS16949:2002 (the successor to QS 9000) or ISO 17 025. Of course, a traditional static calibration may fulfil the requirement of being traceable, but when the measurement system is used for dynamic measurements differences between the calibration and the actual measurement situation must be accounted for. This can be done in a number of ways, for instance by use of a validated computational model or by incorporating large uncertainties to be on the safe side or, which is the most popular way, by ignoring the difference between the static calibration and the dynamic use. The more the calibration situation resembles the actual use, the easier it becomes to quantify the quality of the measurement data, or in other words to estimate the measurement uncertainty. This is why dynamic pressure calibration methods should be developed.

The present author does not know the percentage of pressure measurements that are performed with the intention to capture dynamic phenomena. It is quite clear, however, that the lack of traceability for dynamic pressure measurements in industry results in less-than-optimal measurement quality leading to increased costs in terms of reduced quality, increased scrapping and reduced competitiveness.

The present paper is primarily a literature survey concerned with methods for traceable dynamic calibrations of pressure transducers. Before embarking on the main topic, some application areas using dynamic pressure measurements are presented and also some common measurement principles are reviewed. A short introduction to measurement uncertainty and the concept of traceability is given before dynamic calibrations are discussed. The paper concludes with an outline of the work that should be undertaken by the research community to facilitate for the measurement engineer in his strive for lower and accurately quantified measurement uncertainties in conjunction with dynamic pressure measurements.

1.1 What is dynamic pressure?

On a microscopic level, pressure in a fluid (gas or liquid) is the result of the motion and the transfer of momentum from molecules to the object on which pressure is said to act. The magnitude of pressure depends on the number and the momentum of the molecules impacting on the surface on which pressure is measured. On a macroscopic level pressure p, is generally defined as the total force F, perpendicular to a surface of area A,

$$p = \frac{F}{A} \tag{1}$$

The pressure is said to be static when it remains constant for a significant amount of time, generally during the complete measurement. On the other hand, pressure is said to be dynamic when it varies significantly in a short period of time. In this case what is sought for is not a single time-invariant value of pressure, but rather a time-dependent pressure function

$$p = p(t) \tag{2}$$

Another definition of static and dynamic pressure which is not used in the present paper but which is common in flow-related papers, is that static pressure is the pressure in a flow field at the point of zero speed of flow and that dynamic pressure is the impact pressure due to fluid particle motion. The total pressure is the sum of static and dynamic pressures.

1.2 The different modes of pressure measurements

In some cases the absolute value of pressure is the measurand but in many cases it is more interesting (and practical) to determine the pressure relative to some reference pressure. The reference pressure used in most cases, but certainly not all, is the atmospheric pressure. In Figure 1 the three common modes of pressure measurements are defined. They are called the absolute, gauge and differential modes.

As can be seen in Figure 1 there is a relation between the modes saying that the absolute pressure equals the sum of the atmospheric pressure and the gauge pressure.

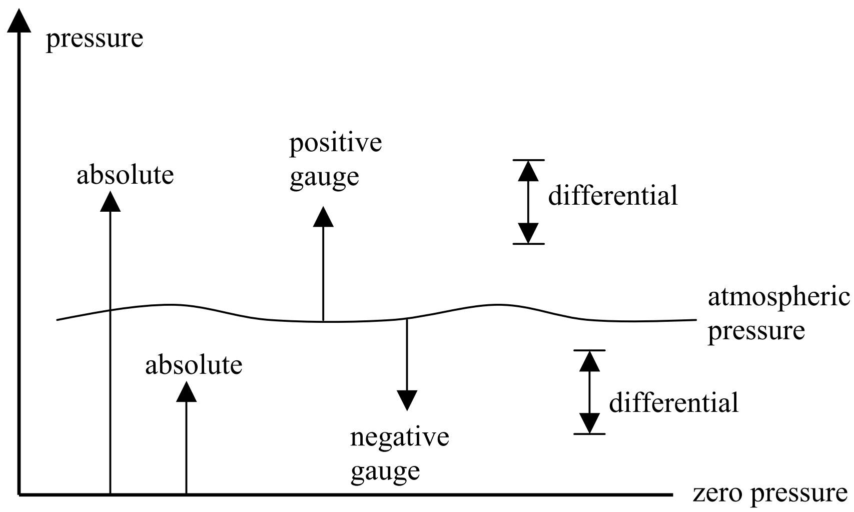


Figure 1. Definition of the three pressure measurement modes

1.3 Pressure units

The history of pressure measurements is long and diverse. This is reflected in the vast number of units in use. Although, the pascal (Pa) has been the prescribed pressure unit of the SI system for a long time there are still a great number of other units being encountered by the modern measurement engineer. Some of them will be discussed in this section.

The pascal is defined as the pressure obtained when a force of one Newton is exerted on the surface area of one square meter. A common unit is bar which equals 10^5 Pa. Some units have a historical origin and are strongly coupled to the way in which pressure is measured. Of these units millimetre of mercury (mmHg) and inches of water (inH_2O) are still, unfortunately, in use. The problem with these units is that they depend on the local gravity as well as the actual density (dependent on for instance temperature and purity) of the liquid column used in measurements. This obviates the need for a standard gravity and standard densities for the complete definition of these so-called manometric units.

The definition of a standard atmosphere (atm) is exactly 101 325 Pa. Another unit sometimes used is the torr defined as exactly 101 325/760 Pa. The definition of torr makes it very close to the so-called conventional mmHg (the pressure generated by a mercury column of unit height and of density 13 595,1 kg/m^3 at 0 °C under standard gravity of 9.806 65 m/s^2). The most common British unit is pound-force per square inch (lbf/in^2 or psi).

It must be emphasized that the correct pressure unit to use is the SI unit pascal. Relations between obsolete units and the pascal are given in Table 1 below.

Table 1. Relations[1] between obsolete pressure units and the pascal

Unit	**Symbol**	**Number of pascals**
pascal	Pa	1
bar	bar	10^5 (exactly)
conventional millimetre of mercury	mmHg	133,322…
conventional inch of mercury	inHg	3 386,39…
inch of water	inH_2O	248,6… to 249,1…
standard atmosphere	atm	101 325 (exactly)
torr	torr	101 325/760 (exactly)
pound-force per square inch	lbf/in^2 or psi	6 894,76…

2 Applications of dynamic pressure measurements

Accurate dynamic pressure measurements are necessary for product development, diagnosis and troubleshooting, control of production processes and product maintenance in several application areas. Some of these application areas are briefly described in this chapter. The list of applications is by no means meant to be exhaustive but should cover the most common applications.

2.1 Combustion engines

Today the main targets when developing combustion engines are to improve the fuel economy and to reduce the amount of hazardous emissions. In order to understand the processes leading to good or bad fuel economy and to low or high levels of emissions it is necessary to look into the cylinders, see Figure 2. This is achieved by measurement of dynamic pressure in the combustion chamber. The amplitudes and frequencies encountered for dynamic cylinder pressures are some tens of MPa and a few kHz.

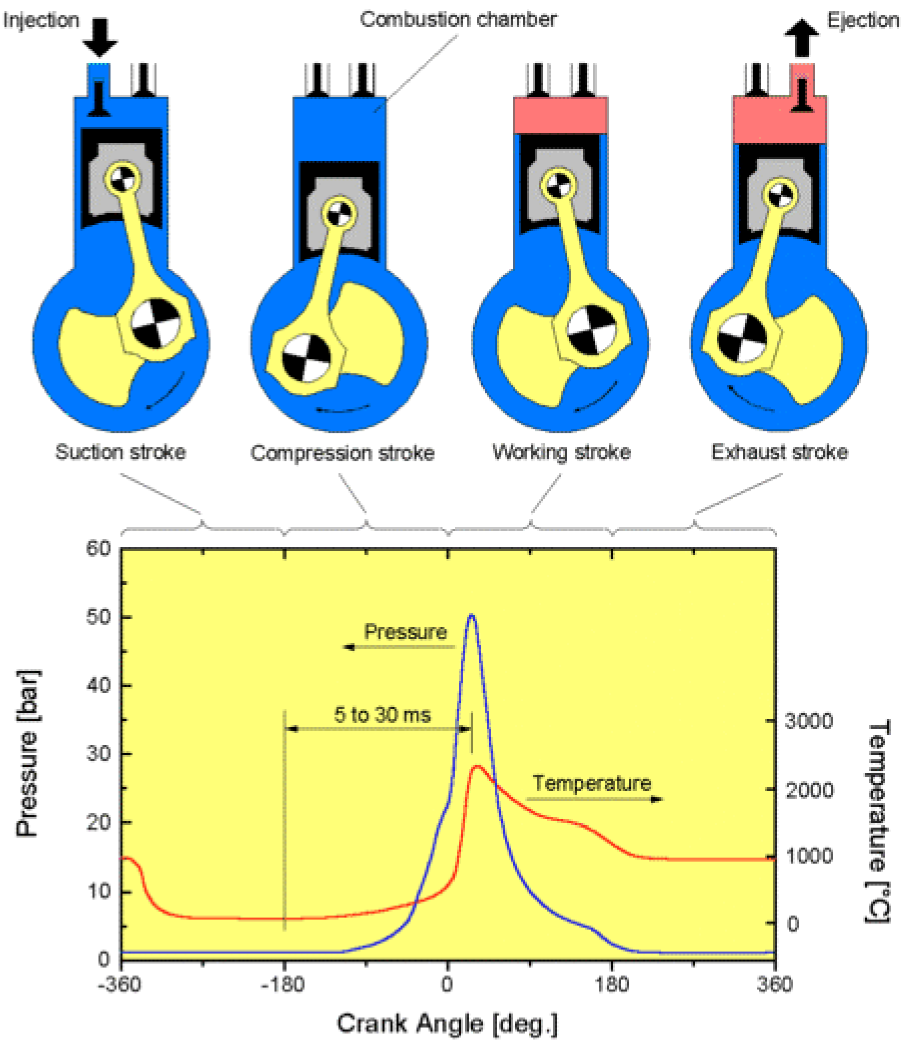


Figure 2. Measurement of cylinder pressure for a four-stroke engine[2]

Detection of engine misfire, or engine knocking, puts higher demands on the measuring system bandwidth since oscillations having frequencies up to 20 kHz, superimposed on the cylinder pressure must be captured.

2.2 Further automotive applications

Apart from the measurement of dynamic cylinder pressure there are several other dynamic pressure applications encountered in the automotive industry. One is the measurement of exhaust system pressure. This pressure is used as a control parameter to determine the amount of fuel to inject in the cylinders to achieve low emissions and a good fuel economy. The amplitudes and frequencies are lower than when measuring cylinder pressure.

Another application is the measurement of fuel injection pressure for diesel engines. The demand for high-efficiency engines has led to injection pressures above 200 MPa. Sought dynamic information is of frequencies less than 1 kHz.

In the development of airbag systems, for an example see Figure 3, it is necessary to measure the time evolution of pressure inside the bag. The (gauge) pressure may reach 700 kPa having an interesting dynamic content up to 1 kHz.

Other applications of dynamic pressure measurements in the automotive industry worth mentioning are measurement of brake pressure, oil pressure in lubricating system and the oil pressure in transmission components.

Figure 3. Development[3] of well-functioning airbags needs accurate measurement of dynamic pressure

2.3 Turbomachinery

A turbomachine is defined as a device in which energy is transferred to or from the device by use of the dynamic interaction between a fluid flow field and mechanical blades. Turbomachines such as compressors, turbines, pumps and fans are important components in steam and gas turbines found in power plants and in jet engines used in aviation.

To find sources of losses and to calculate the efficiency[4] of turbomachines the measurement of dynamic pressure (and velocity) is vital. In the engineering of turbine engines and rocket propulsion systems dynamic pressure measurements are used[5] for feedback sensing, thrust measurement and overpressure indication. These sensors are often removed from the point of measurement by a length of tubing to provide thermal or chemical isolation or because of space constraints. Interesting frequencies range[6] from a few Hz to 30 kHz and with a relatively small amplitude added to a sometimes very high static bias pressure.

Figure 4. Monitoring[7] of a jet engine in a test stand

2.4 Aerodynamics

Aerodynamic forces need to be determined in the engineering of buildings and other constructions as well as for spacecraft, aircraft and other vehicles. The time-dependent pressure field is needed to get a detailed picture of the distribution of aerodynamic forces. During the development of constructions and vehicles, experiments are carried out primarily in wind tunnels. Measurement of dynamic pressure is also sometimes performed for a completed bridge in operation, Figure 5, or for a manoeuvring vehicle, Figure 6.

The typical dynamic pressure amplitudes are quite low (some tens of kPa) and the interesting frequency range[8] is from a few Hz to about one kHz.

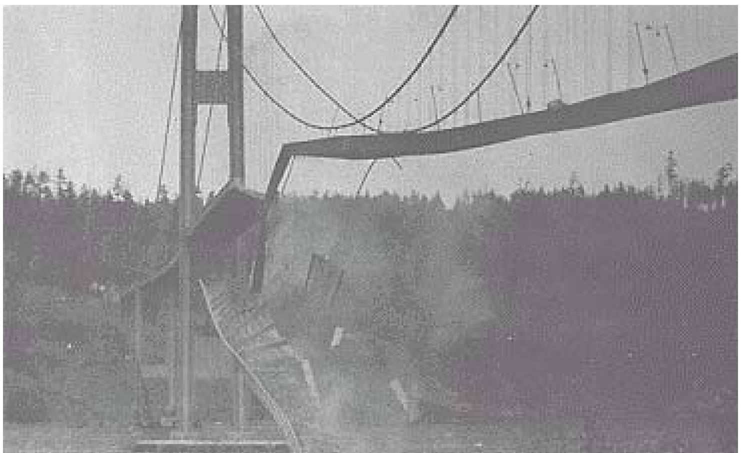


Figure 5. The unsteady pressures[9] acting on the Tacoma Narrows suspension bridge caused instability and failure in 1940

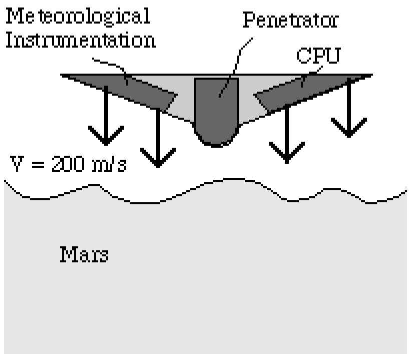


Figure 6. Measurement of the dynamic pressure acting on a microprobe entering the atmosphere of Mars. Micromachined silicon sensors are used[10]

2.5 Acoustics

Acoustic pressure, or sound pressure, are low-amplitude pressure oscillations superimposed on the atmospheric pressure. Sound pressure levels are commonly expressed in decibels (dB) defined by

$$\mathrm{dB} = 20\log\left(p / p_0\right), \quad p_0 = 20\ \mu\mathrm{Pa} \tag{3a,b}$$

in which p is the gauge pressure. This means that what is considered as a high sound pressure, for instance 180 dB, corresponds to an amplitude of only 20 kPa.

The measurement of sound pressure is performed in a large number of applications ranging from interior noise in buildings and vehicles, exterior noise from vehicles and plants to noise caused by household machinery. Many measurements are coupled to legislative requirements, see Figure 7.

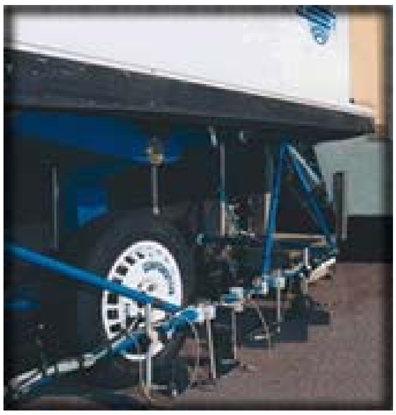


Figure 7. Investigation[11] *of relation between tire noise and road surface texture*

2.6 Production processes

Dynamic pressure measurements are performed in order to optimise production processes. Interesting examples are injection moulding, see Figure 8, and extrusion performed in the plastic industry as well as die-casting. These applications involve high pressure amplitudes but rather low frequencies (probably below 100 Hz).

Figure 8. Injection moulding[12] of high-volume plastic components

2.7 Fluid power and control

Hydraulic and pneumatic components are often used to control the motion of objects. Typical components are engines, pumps, transmissions, actuators and valves. To develop these components, for an example see Figure 9, and to monitor their performance it is necessary to measure the dynamic fluid pressure. In the hydraulic case pressure amplitudes may reach some GPa. During normal operation frequencies are quite low (some tens of Hz), but to capture specific phenomena measurement bandwidth may have to be above 10 kHz. One example of this is when trying to measure the pressure loading produced by cavitation. Cavitation loading consists of high intensity repetitive impacts caused by collapsing cavitation bubbles. The rise time of the pressure loading[13] can be of the order of four microseconds and the amplitude may reach 10 GPa. For pneumatic components requirements on amplitudes and frequencies are lower.

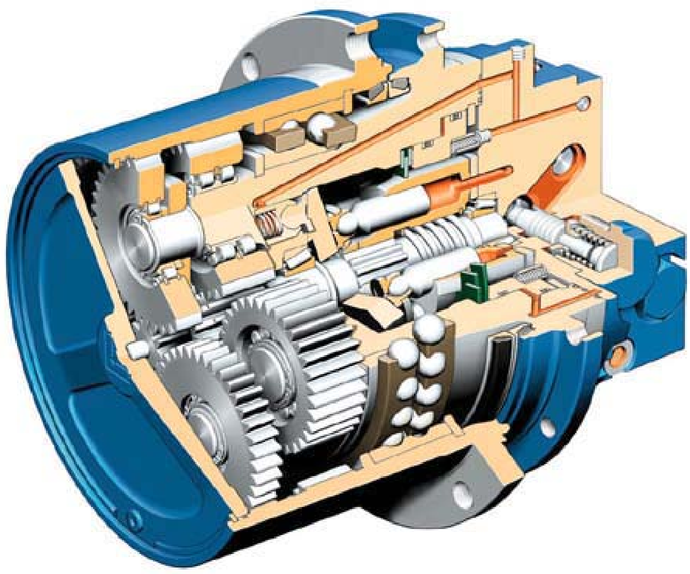


Figure 9. Hydrostatic drive[14] of planetary design used for mini-excavators

2.8 Robotics

In robotics it is very useful to know the distribution of force exerted by a manipulator on the manipulated object, see Figure 10. Pressure map sensors[15] can be used. Encountered frequencies are quite low (a few tens of Hz).

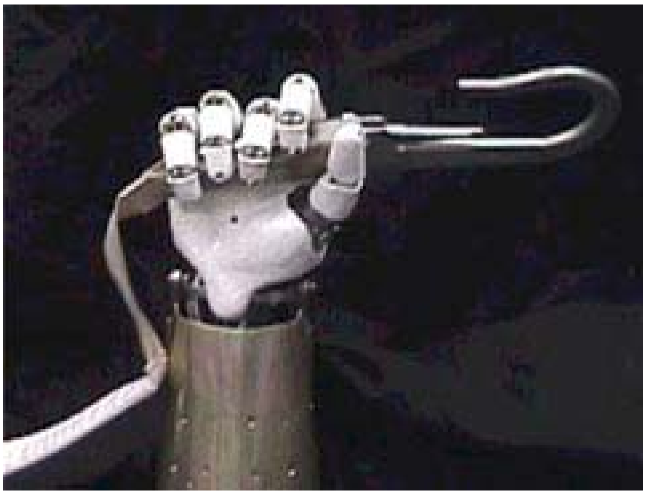


Figure 10. Tactile pressure sensors integrated into a multi-fingered robot hand[16] for real-time autonomous control

2.9 Medicine and ergonomics

There are several emerging applications of dynamic pressure measurements within medicine and ergonomics. In medicine it is known[17] that in blood pressure measurements the dynamic pressure component contains much information in addition to the two common steady state values of systolic and diastolic pressures. Another area is the diagnosis[8] of disease and monitoring of post-operative and post-trauma patients. These areas have given rise to new generations of dedicated “disposable” pressure transducers. The demand on frequency is up to 20 Hz.

In ergonomics there is an interest[15] to measure the pressure distribution as well as the total force between hand and tool during some operation. Measurement of foot pressure during the walk in gait analysis is performed by orthopaedists.

In biomechanics there is an interest to measure dynamic pressures between body parts, or between a body part such as a foot and the ground, during slow processes such as walking or sudden actions such as during an automotive accident. Optimisation and development of orthopaedic implants are facilitated by dynamic pressure measurements, for an example see Figure 11.

2.10 Blast waves

A primary result of the detonation of explosives is the propagation of a pressure pulse known as an air blast wave[18] or an underwater blast wave. The measurement, see Figure 12, of this dynamic pressure is important from two different points of view. Firstly, those developing explosives want to achieve maximal and directed destructive capability and secondly, those developing military and civilian shelters want to achieve constructions which withstand air blast and ground shock loading.

The testing of explosives in free air can produce[8] pressure amplitudes of the order of several hundred MPa and shockwave rise-times are sub-μs events.

Figure 11. A biomechanical knee model[16]

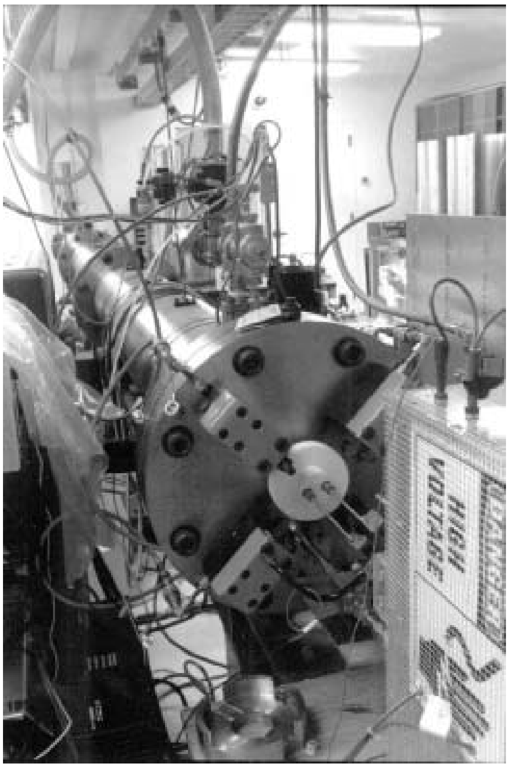


Figure 12. A detonation tube facility[19] used to test explosives

2.11 Ballistics

Dynamic pressure is measured when developing weapon systems such as guns, cannons, missiles, see Figure 13, and ammunition. Some sensor types permit measurement of the direct gun chamber pressure through an unmodified shell case. Possible pressure amplitudes[20] reach 800 MPa with a frequency content of some hundred kHz.

Figure 13. Optimum launch of a missile[21] requires knowledge of internal ballistic dynamic pressure

2.12 A summary of frequency and amplitude ranges

As demonstrated in the sections above, the field of dynamic pressure measurements covers many industrial applications. In some applications interest lies in measuring quite small dynamic amplitudes superimposed on atmospheric pressure and in other applications, amplitudes in the GPa-regime are found. The same large differences are found concerning the frequency content of the dynamic pressure. Low-frequency applications are found close to one Hz and high-frequency applications reach the neighbourhood of 1 MHz. Thus, amplitudes cover eight or nine decades and frequencies cover six orders of magnitude.

Another survey[22] reports the main areas of dynamic pressure measurements to be gauge and differential pressures between 0,1 MPa and 10 MPa, between 0 °C and 50 °C and below 1 kHz.

There are also severe differences concerning the types of environment in which the dynamic pressure measurements are carried out. Some of these differences are

- Temperature range
- Acceleration disturbance
- Fluid medium
- Chemical environment

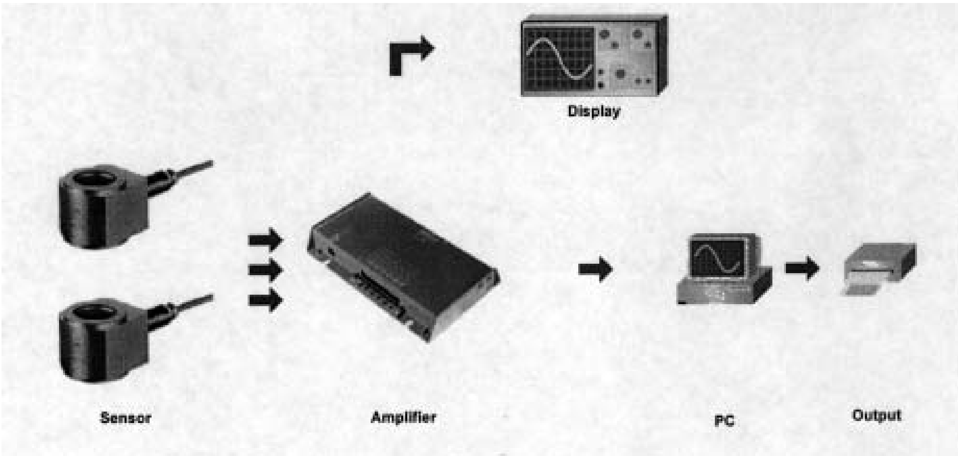
Considering the differences it is natural that there exists a wide range of transducer types and associated instruments. It is also quite obvious that it will not be possible to use one method to achieve traceable dynamic calibrations with required levels of uncertainty for all types of transducers and applications.

3 Measuring instruments for dynamic pressure measurements

There is a wide range of measuring instruments for dynamic pressure measurements available on the market today. In order to perform successful measurements it is important to understand the physical principles of the measurement instruments. This chapter provides a brief introduction to the principles most commonly used when performing dynamic pressure measurements.

3.1 The measurement system

A measurement system for dynamic pressure measurements consists at least of a transducer, an electrical supply system, an amplifier and devices for signal processing and measurement storage and control, see Figure 14. It should be noted that the dynamic characteristics of all components in the measuring chain influence the uncertainty obtained in an actual measurement situation. The following sections are focused on the transducer or sensor.



Figur 14. Measurement system[23] used for monitoring of engine cylinder pressure

3.2 Resistive pressure sensing

Many pressure sensors rely on strain gage technology. The physical principle used in strain gages is that pressure acting on a diaphragm causes the diaphragm to deflect and the change in resistance, due to the mechanical strain, of the bonded strain gages is detected.

Starting from first principles, the stretched conductor in Figure 15 is studied.

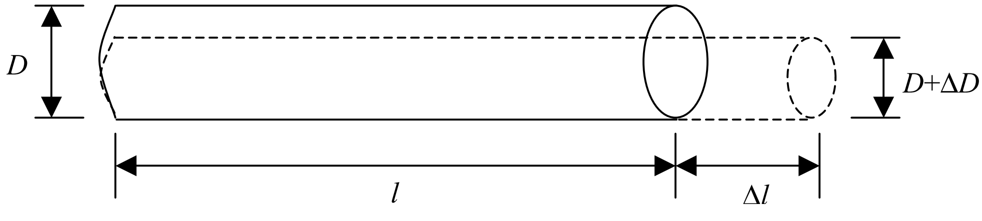


Figure 15. A cylindrical conductor being subjected to axial force is stretched and the resistance is changed

It can be shown that the relative change in resistance is given by

$$k = \frac{r}{\varepsilon} = 1 + 2\nu + \frac{1}{\varepsilon}\frac{\Delta\rho}{\rho} \tag{4}$$

in which k is the gage factor, r is the relative change in resistance, ε is the mechanical strain, ν is Poisson's ratio and ρ is the material resistivity. For traditional strain gages k is between 2 and 4.

By connecting one or several strain gages in a Wheatstone bridge circuit, Figure 16, a voltage output proportional to the change in resistance is obtained. The output from the strain gage is low (typically a few mV/V) so amplification is necessary. The strain gage bridge is supplied either by a DC-system (typically 5-10 VDC) or by a so-called AC carrier frequency system. For static measurements the carrier frequency system can be shown to have some definite advantages, such as higher immunity to thermoelectrical noise. For dynamical measurements, however, the AC-system may be disadvantageous[24] due to inferior high-frequency properties.

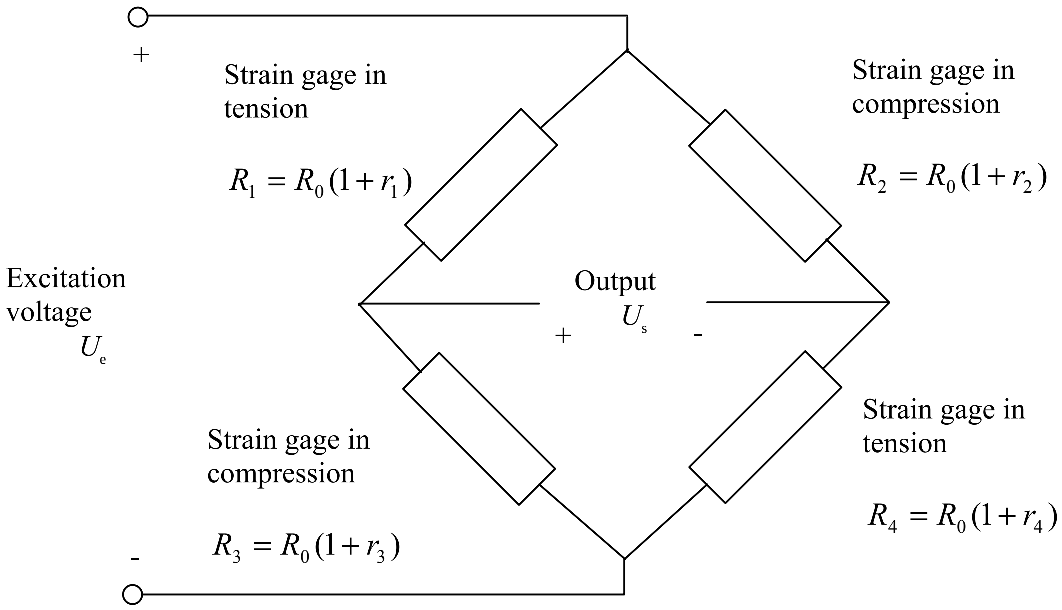


Figure 16. Four strain gages connected in a full-bridge circuit

For a pressure transducer a full-bridge circuit is obtained by positioning, at the diaphragm, two strain gages at positions of tension strain and two gages at positions of compression strain. An example of this is shown in Figure 17.

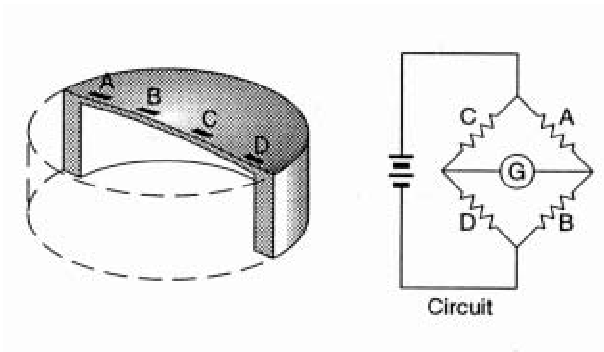


Figure 17. Four strain gages positioned on the diaphragm to obtain a full-bridge circuit[1]

The relatively low gage factor of metallic strain gages means that in order to obtain sufficient signal strength the strain must be relatively high. This means that the diaphragm must be quite flexible leading to relatively low natural frequencies. In dynamic measurements this can be translated to a limited measurement bandwidth. For some semiconductor materials, on the other hand, a gage factor of 80-200 can be obtained. The change of resistance for these materials does not primarily depend on the geometric change when strained, but rather on a strain-related change of material resistivity. For this reason these transducers are called piezoresistive and they are together with piezoelectric transducers, see section 3.3, the most popular ones employed for dynamic pressure measurements.

Monolithic piezoresistive silicon devices are produced using techniques similar to those used to produce integrated circuits. The complete diaphragms are made from silicon, with areas doped with boron to create strain gages, Figure 18. The circuitry needed for amplification, temperature compensation and calibration may[17] also be included on the same IC. Also, the small size means that it has a high frequency response and may be used for dynamic pressure measurements.

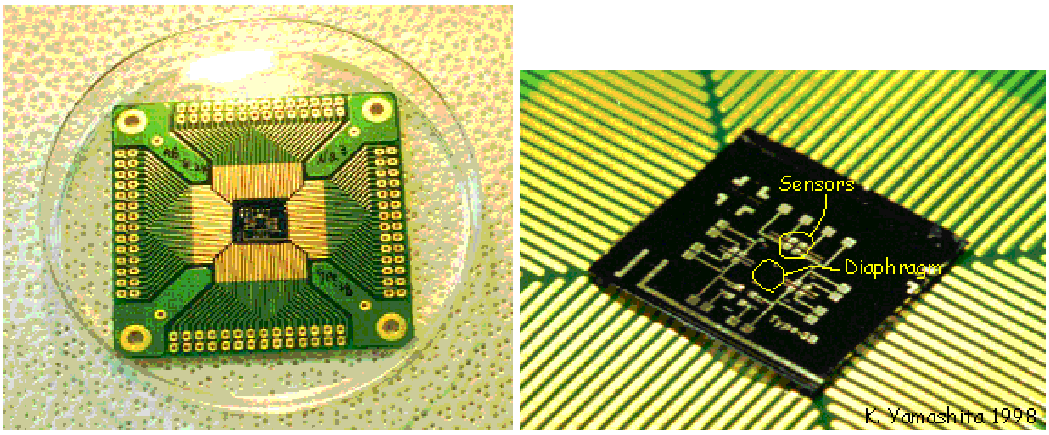


Figure 18. Photograph[25] *of a micromachined silicon pressure sensor. Close-up picture to the right*

Another resistive sensing principle, based on the variation of contact resistance, was demonstrated[15] for generating pressure maps.

3.3 Piezoelectric pressure sensing

Piezoelectric sensors are quite different from sensors based on strain gages. The piezoelectric effect means that certain crystalline materials, e.g. quartz, tourmaline and some ferroelectric ceramics, deposit (Figure 19) an electrical charge on attached metal plates when subjected to changes in applied force. Very small deformations are needed which means that the sensors can be made very stiff resulting in high natural frequencies. This makes them suitable for dynamic measurements.

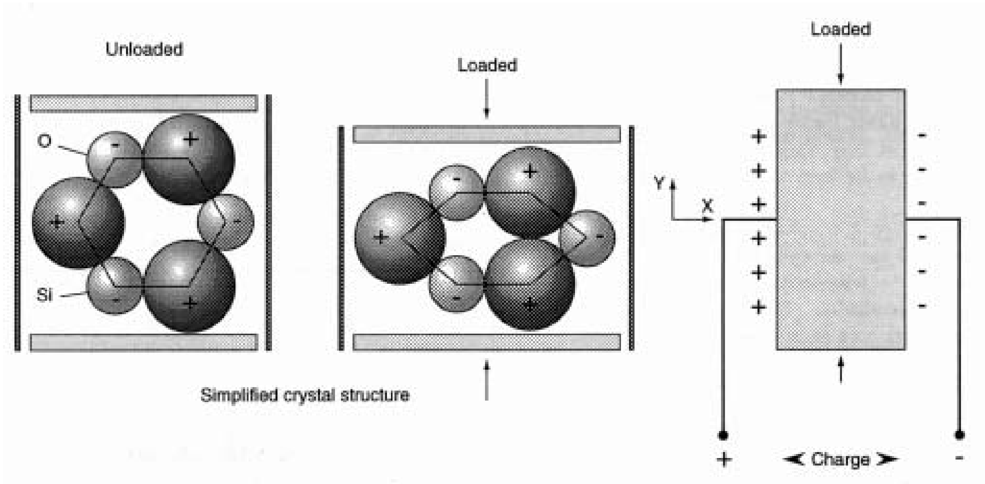


Figure 19. Illustration[1] of the transverse piezoelectric effect

Figure 20 shows a typical[26] design of piezoelectric pressure sensor. The sensor element consists of a bar-shaped transverse-effect quartz element. The sensor element is preloaded with a preloading sleeve. The front part of the sleeve is designed as the pressure transmission component. Pressure applied to the diaphragm is converted to a force which is transmitted to the sensor element. Charges appearing on the lateral surfaces of the quartz bar are collected on vacuum-deposited electrodes. A helical spring connects the charge to the connector.

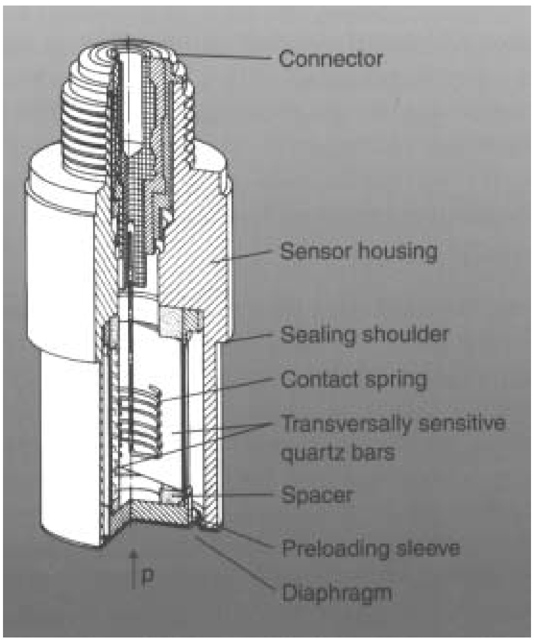


Figure 20. The structure of a typical[26] piezoelectric pressure sensor

Since the charge inevitable leaks out due to finite resistance and capacitance, the sensor is not suited for truly static measurements. The measuring system is characterized by a so-called discharge time[27] that describes the time-rate of charge leakage. Discharge time depends not only on the transducer itself but also on cables and charge amplifiers used, see Figure 21.

The induced charge is not easily measured. Generally, the high-impedance charge signal is converted by a charge amplifier to a low-impedance voltage signal that can be measured (and displayed) with standard instruments. Charge amplification can be performed either by electronics internal to the transducer or by external electronics.

In some applications piezoelectric polymer (PVDF) films are used as the sensing element. These films can be made very thin (0,1 mm) and therefore have high natural frequencies in addition to the advantage of being possible to put on curved surfaces[13].

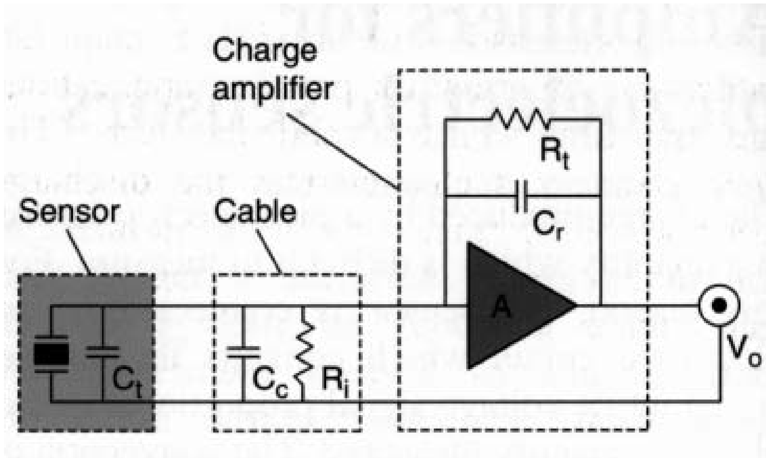


Figure 21. A piezoelectric transducer connected by a cable to a charge amplifier[26]

3.4 Optical pressure sensing

In general, fiber optic sensors have the advantages[28] of small size, low weight, immunity to electromagnetic interference, high sensitivity, elimination of ground loops, very large bandwidth and the capability of combining remote sensing and data transferring. Interferometric sensors and intensity-based sensors are two important sensor categories.

Interferometric sensors measure differential phase changes which are somehow related to pressure. Very high resolution can be achieved with fiber interferometers but the cost of the associated signal processing has been prohibitive to high-volume use. Intensity-based devices measure changes in received optical power. Intensity-based fiber sensors require simple processing techniques but are generally less accurate than interferometric sensors due to sensitivity to the source power drift and fiber attenuation variations.

A low-cost solution utilizes an optical fiber in front of a flexing diaphragm for optical reflection measurement of pressure-induced deflections. This type of sensor was used[29] to detect misfire or knocking in an automotive engine. As a next step a low-cost (not high-accuracy) sensor was developed for dynamic (up to 15 kHz) automotive applications. It consists of an optoelectronic transceiver (fiber optic coupler, a near infrared LED and a PIN photodiode, external power supply, and a minimum of analogue circuitry) coupled to a fiber-optic sensor head, see Figure 22.

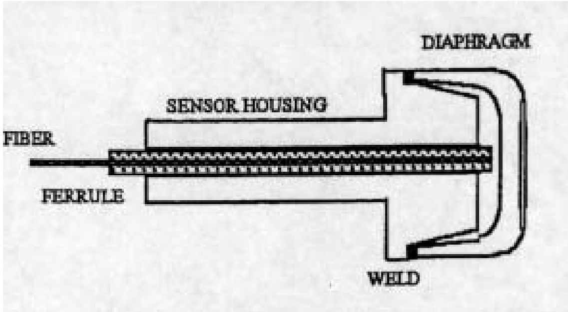


Figure 22. Fiber optic sensor head used in low-cost[29] dynamic pressure sensor

Fürstenau et al described[30] a polarimetric fiber-optic sensor for the measurement of dynamic pressure in which the pressure-induced phase difference between the orthogonal polarization modes in the sensing fiber was detected.

Kobata and Ooiwa[31] developed a pressure measurement technique using a differential interferometer. The sensor principle is based on the change in refractive index of a medium which can be obtained by measuring the optical path difference. For an ideal gas of constant temperature, the change in refractive index is proportional to the change in pressure.

3.5 Capacitive pressure sensing

Capacitive pressure sensors typically use a thin diaphragm as one plate of a capacitor. Applied pressure causes the diaphragm to deflect and the capacitance to change, Figure 23. This change may, or may not, be linear and is typically on the order of several pF out of a total capacitance of 50-100 pF. The change in capacitance may be used to control the frequency of an oscillator or to vary the coupling of an AC signal through a network. The electronics for signal conditioning should[17] be located close to the sensing element to prevent errors due to stray capacitance.

Silicon micro-machining and large-scale integration technologies are being used to produce capacitive sensors that are small, rugged, lightweight and require low power. The size of the sensor may be only a few square millimetres with a thickness of some tens of micrometers yielding a mass[32] of below 0,1 g, Figure 24.

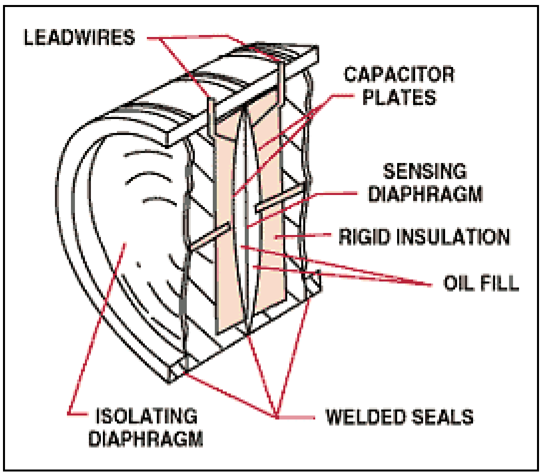


Figure 23. A capacitive differential pressure sensor[17]

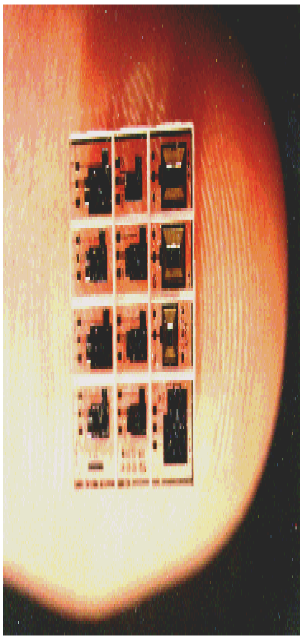


Figure 24. Twelve fabricated micro-machined capacitive pressure sensors on a human finger[19]

3.6 Other physical principles of pressure sensing

Several configurations based on varying inductance or inductive coupling are used in pressure sensors. They all require AC excitation of the coil(s) and, if a DC output is desired, subsequent demodulation and filtering. The linear variable differential transformer (LVDT) types have a fairly low frequency response due to the necessity of driving the moving core of the differential transformer, see Figure 25. The LVDT uses the moving core to vary the inductive coupling between the transformer primary and secondary.

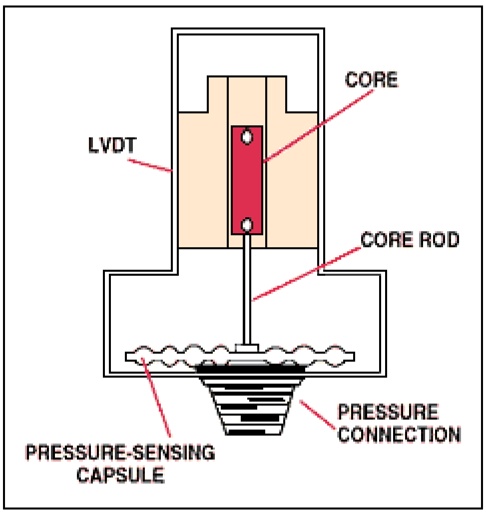


Figure 25. Schematic picture[17] *of a LVDT pressure transducer*

Another variable reluctance pressure transducer is pictured in Figure 26 below. The sensor is composed of a pressure sensing diaphragm and a two-coil inductive half-bridge. The coils are wired in series and are mounted so their axes are normal to the plane of the diaphragm. Clamped tightly between the coil housings, the diaphragm is free to move in response to differential pressure. When a differential pressure is applied to the sensor, the diaphragm deflects away from one coil and towards the opposite. The diaphragm material is magnetically permeable, and its presence nearer the one coil increases the magnetic flux density around the coil. The stronger magnetic field of the coil, in turn, causes its inductance to increase, which increases the impedance of one coil. At the same time, the opposite coil is decreasing its impedance. The change in coil impedances brings the half-bridge out of balance, and a small AC signal appears on the signal line. The output of a variable reluctance circuit at its full scale pressure is 20 mV/V or more. This is about ten times more than the typical output for strain gage transducers.

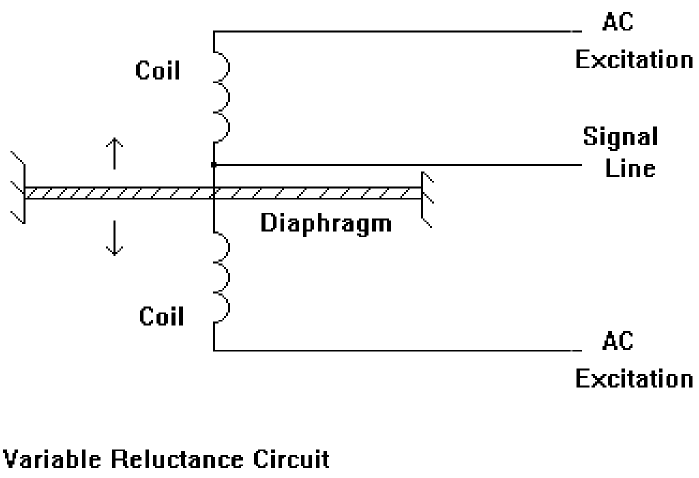


Figure 26. Pressure sensor using the variable reluctance sensing principle[33]

4 The dynamics of the transducer

The dynamics of the complete measurement system will be influenced by the dynamics of all the constituent parts, i.e. transducer, amplifier, A/D-converter and other signal processing and analysing units. A calibration, dynamic or static, should be performed, if possible, with the same equipment being used later for actual measurements. In many cases the dynamics of the transducer or sensor will be the main contributor to the measurement system dynamics. Some simple, but often sufficient, dynamic transducer models will be discussed in this chapter. A deeper understanding of the dynamic effects encountered when measuring dynamic pressures may be obtained by a thorough understanding of the dynamic response of these simple models.

For static measurements a pressure transducer is characterized by its sensitivity which is the ratio of the output to the variation of the input. For a good (linear) transducer the sensitivity is practically constant within the range of the transducer. For dynamic measurements information is needed on the capability to measure time-varying pressures. One way of describing this capability is by use of the so-called transducer transfer function.

A calibration may be thought of as a system identification process. By applying known pressures to a measurement system and by recording the system output a mathematical system model is sought for. This model should then be reported in the calibration certificate together with a statement of traceability and uncertainty. Of prime importance is that the mathematical model should be possible to use in converting the measured electrical signals into pressures. The mathematical model could be either in the time-domain or in the frequency-domain. It is clear[34] that, in order to calibrate a measurement system, the dynamics of it must first be understood.

According to the only available written standard[36] about the dynamic calibration of pressure transducers the following should be determined in a dynamic calibration

- Sensitivity
- Amplitude response
- Phase response
- Resonant frequency
- Ringing frequency
- Damping ratio
- Rise time
- Overshoot

All these transducer characteristics are discussed in the following sections using a simple transducer model.

4.1 A simple linear time-invariant transducer model

Most pressure transducers may be described by a simple linear, time-invariant mathematical model consisting of mass, m, stiffness, k and viscous damping, c. A physical picture of this transducer model is shown in Figure 27.

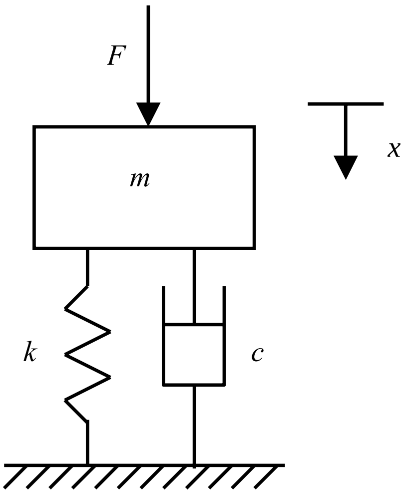


Figure 27. Simple linear time-invariant transducer model

The governing differential equation for this transducer model is

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F(t) \tag{5}$$

in which $F(t)$ is the external load caused by the acting pressure. A common way to rewrite this equation is the following

$$\ddot{x}(t) + 2\zeta\omega_n\dot{x}(t) + \omega_n^2 x(t) = \frac{F(t)}{m} \tag{6}$$

in which the ω_n is the undamped natural frequency and ζ is the relative damping defined by

$$\omega_n = \sqrt{\frac{k}{m}}, \quad \zeta = \frac{c}{2m\omega_n} \tag{7a,b}$$

The general solution to Eq. (6) can be shown[35] to be

$$x(t) = e^{-\zeta\omega_n t}\left(A\sin\omega_d t + B\cos\omega_d t\right) + \frac{1}{m\omega_d}\int_0^t F(t-\tau)e^{-\zeta\omega_n\tau}\sin\omega_d\tau\,d\tau \tag{8}$$

in which the damped natural frequency ω_d is defined by

$$\omega_d = \sqrt{1-\zeta^2}\,\omega_n \tag{9}$$

The first part of the solution given by Eq. (8) is the so-called free response, dependent on the initial conditions, and the part expressed by the integral is the forced response.

4.1.1 Free response of the second-order pressure transducer model

Using Eq. (8) with $F(t) = 0$ and the initial values

$$x(0) = x_0, \quad \dot{x}(0) = 0 \tag{10a,b}$$

the free response is obtained as

$$x(t) = x_0 e^{-\zeta\omega_n t}\left(\frac{\varsigma}{\sqrt{1-\varsigma^2}}\sin\omega_d t + \cos\omega_d t\right) \tag{11}$$

To provide an understanding of the free response, the solution given by Eq. (11) is plotted for some different values of critical damping in Figure 28. It should be noted that for most pressure transducers the value of critical damping is quite low (typically less than 0,05).

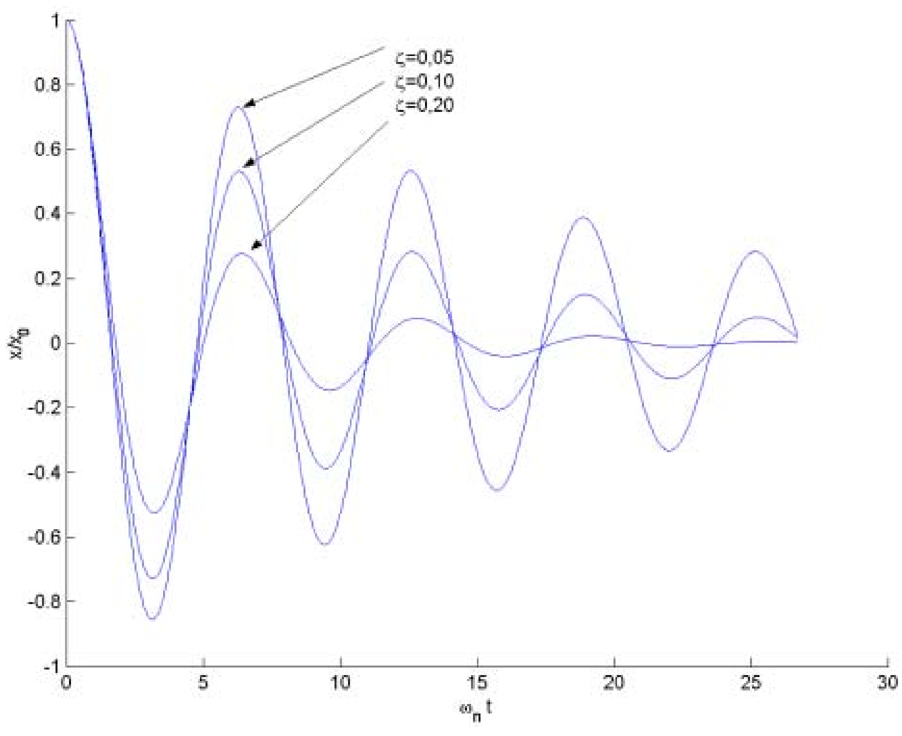


Figure 28. Free response of the linear time-invariant second-order transducer model for some different values of relative damping

4.1.2 Harmonic response of the second-order pressure transducer model

In frequency analysis the forced response of a transducer subjected to harmonic loading of varying frequency is studied. If the external load in Eq. (6) is set to

$$F(t) = F\sin(\omega t) \tag{12}$$

the forced transducer response is given by

$$x(t) = |G(\omega)| F \sin(\omega t - \varphi) \tag{13}$$

in which the transfer function $G(\omega)$ is given by

$$G(\omega) = \frac{1/k}{1 - \left(\frac{\omega}{\omega_n}\right)^2 + i\,2\zeta\left(\frac{\omega}{\omega_n}\right)} \tag{14}$$

From Eqs. (12) and (13) it is seen that the transfer function contains information about the amplitude and phase obtained in the transducer output as compared to the forcing pressure. The amplitude and phase information in $G(\omega)$ are given by the expressions

$$|G(\omega)| = \frac{1/k}{\sqrt{\left(1 - \left(\frac{\omega}{\omega_n}\right)^2\right)^2 + 4\zeta^2\left(\frac{\omega}{\omega_n}\right)^2}}, \quad \varphi = \arctan\left(\frac{2\zeta\frac{\omega}{\omega_n}}{1 - \left(\frac{\omega}{\omega_n}\right)^2}\right) \tag{15a,b}$$

The amplitude and phase expressions of Eqs. (15a,b) are plotted for some values of critical damping in Figures 29 and 30 below. At zero frequency the amplitude of the transfer function is equal to the traditional static sensitivity. It can be seen that already for frequencies of only a fraction of the undamped natural frequency the difference between static and dynamic sensitivities is quite high. This points to the fact that using the sensitivity obtained from a static calibration when performing dynamic measurements may lead to surprisingly large errors. The theoretical relative error for a low-damped transducer is shown in Figure 31. It can be seen that, for instance, when $\omega / \omega_n = 0{,}3$ the theoretical error is close to 10 %.

When comparing the transducer natural frequency (obtained from a specification) with the frequency content of the measured signal care must be taken to ensure that the specified transducer frequency really is the lowest natural frequency for the transducer installed in the system at hand. Additional inertial loading due to fluid and most of all, additional pneumatic cavities may substantially lower the lowest natural frequency of the pressure measurement system.

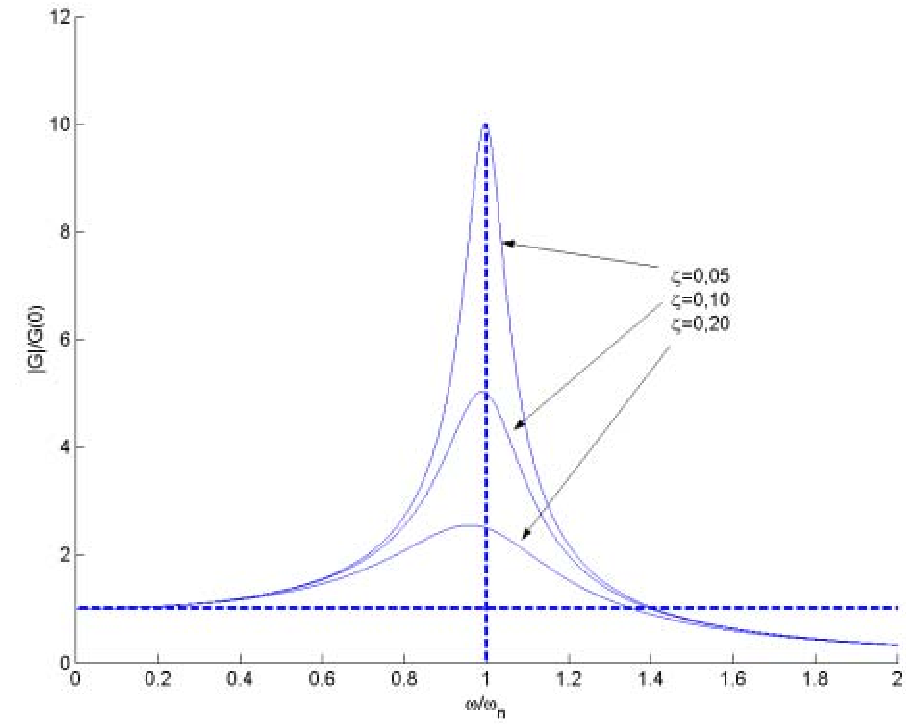


Figure 29. Normalized amplitude of transducer transfer function for some values of relative damping

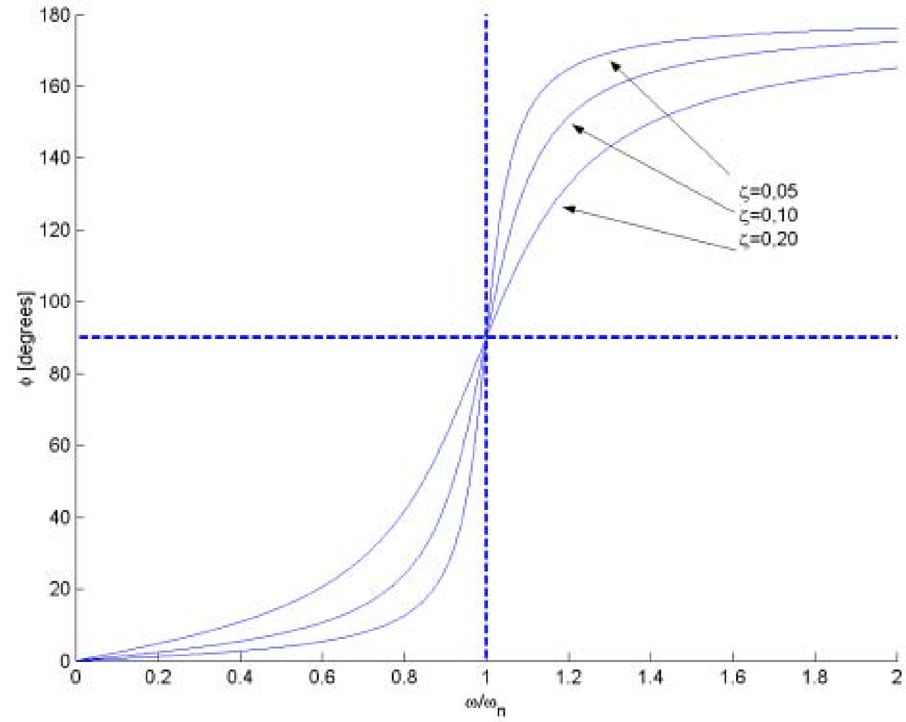


Figure 30. Calculated transducer phase angle for some different values of relative damping

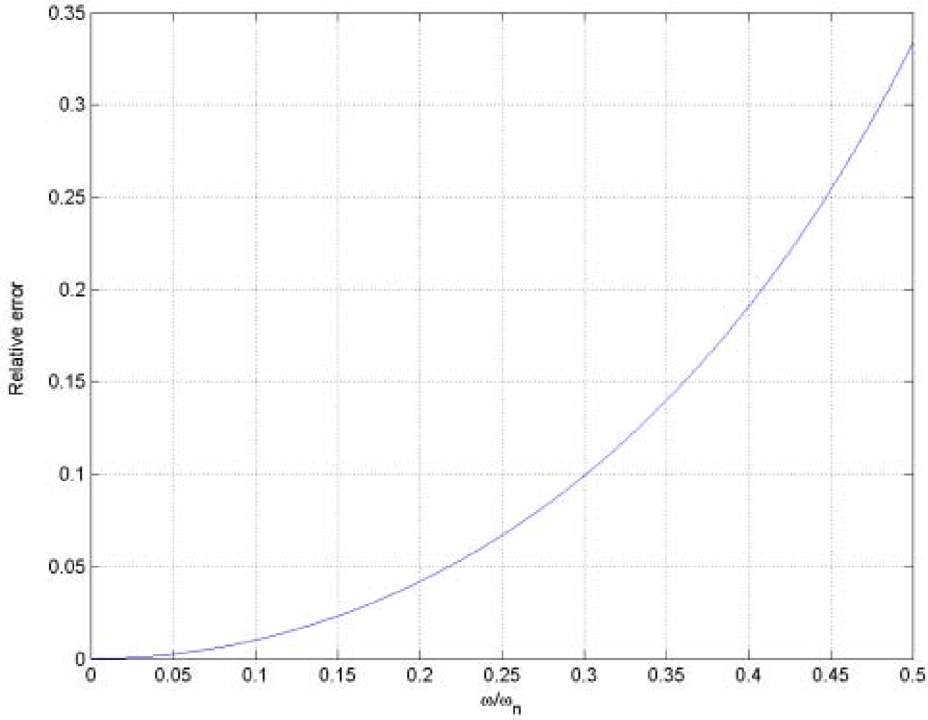


Figure 31. The calculated relative error when using the static sensitivity for harmonic measurements with a low-damped transducer

4.1.3 Transient response of the second-order pressure transducer model

The transducer response to a general transient load is given by Eq. 8 above. Since some calibration methods, i.e. using a shock tube, apply a near step pressure function the theoretical transducer step response is of interest. It can be shown[35] that the unity step response of the linear time-invariant second-order transducer model, with homogenous initial conditions, is given by

$$x(t) = \frac{1}{k}\left(1 - e^{-\zeta\omega_n t}\left(\cos\omega_d t + \frac{\zeta\omega_n}{\omega_d}\sin\omega_d t\right)\right), \quad t > 0 \tag{16}$$

The calculated step response for some values of relative damping is plotted in Figure 32 below. Characteristics of the step response often discussed are delay time, rise time and overshoot. Delay time and rise time are often defined as the times taken for the transducer to reach 10 % and 90 % of the steady state step response value. Overshoot is defined as the relation between maximum value and the steady state step response value. The overshoot, *OS*, can be expressed in closed-form as[36]

$$OS = 1 + e^{-\left(\frac{\pi\zeta}{\sqrt{1-\zeta^2}}\right)} \tag{17}$$

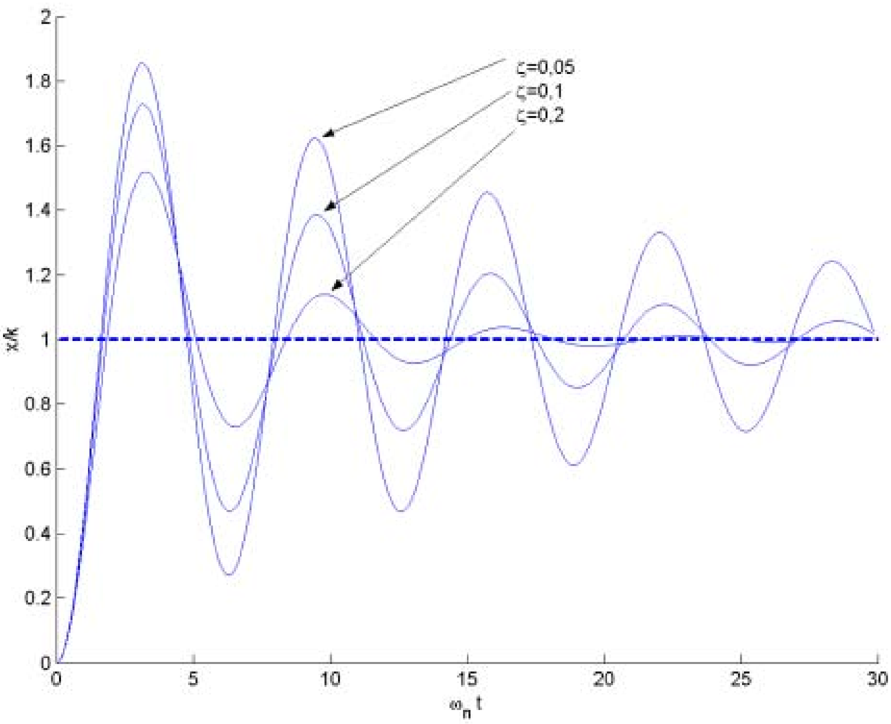


Figure 32. Calculated transducer response to a step function of unity amplitude for some different values of relative damping

For more general transient loads the governing Eq. 8 must be numerically solved. One example of such a solution is shown in Figure 33. In this case the transducer is subjected to an impulsive pressure pulse of half-sine form. A comparison between the theoretical transducer output and the truly applied pressure is shown. It can be seen that although the impulsive loading is not extremely fast as compared to transducer dynamics (ten times slower than the characteristic time of the transducer) the calculated measurement error is above 5% at several times. Also the peak pressure is in error by about 5%. This serves as an illustration of the fact that there is a difference between stationary harmonic and more general loads that has to be accounted for.

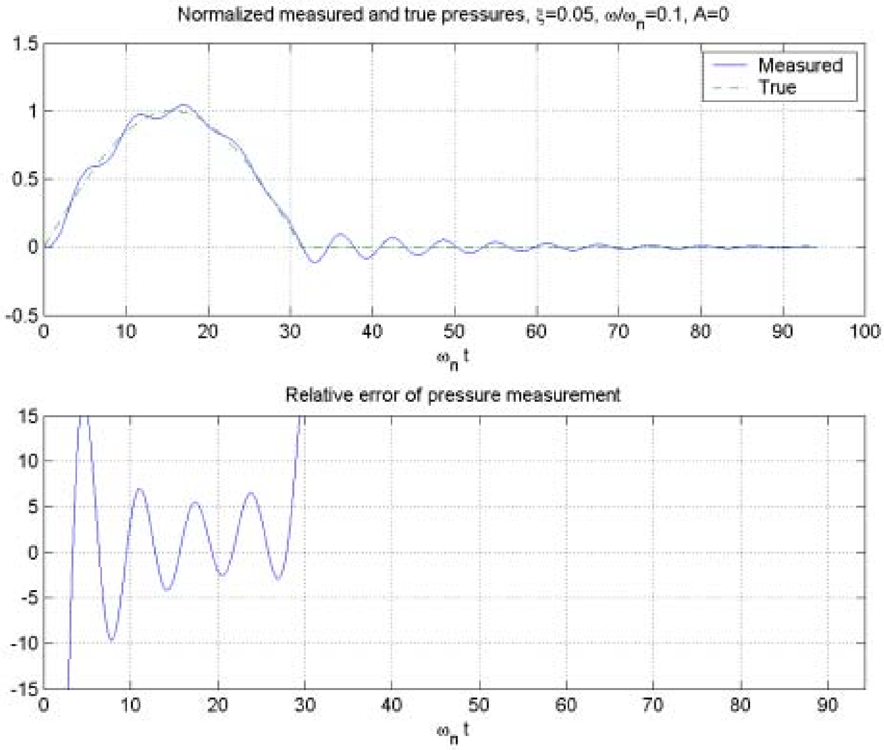


Figure 33. Calculated pressure indicated by the pressure transducer compared to the applied half-sine pressure

4.2 Interaction with another dynamic system

Unfortunately the dynamics of the transducer is not independent of the dynamics of its surroundings. In some cases the natural frequency given in the transducer specification is only the mechanical natural frequency of the diaphragm. This may not be the true natural frequency of the operating pressure transducer considering also the fluid-filled transducer cavity. Even if the specified natural frequency is the correct natural frequency of the complete transducer, problems may occur during some measurement situations. Consider the case shown in Figure 34. The transducer may be dynamically calibrated and it may be known that all transducer natural frequencies are far above the frequency content of the pressure to be measured. The introduction of the pneumatic tubing changes the situation completely by introducing a significant low-frequency dynamic element between the pressure to measure and the well-characterized transducer. This results in a measurement disaster since the transducer signal will not resemble the pressure at the tube port. In fact a tough inverse problem has been created that cannot be resolved without knowledge of the complete system dynamics, obtained by system calibration or by a combination of a transducer calibration and a verified tube model.

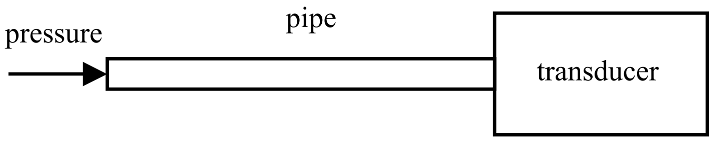


Figure 34. Simple illustration of the interaction between transducer dynamics and the surrounding system dynamics

Ideally, the pressure transducer should be mounted flush on the surface at the point where the pressure is to be measured, but in some cases this is not possible[5,37] due to too much disturbance of the measured flow field or due to a hostile thermal or chemical environment. The dynamics of the tubing can be modelled by the Helmholtz resonator model[38] or the organ pipe model, but to obtain accurate information about the dynamic properties they must[38] be measured. Another complication is that when the bandwidth of interest for a required measurement includes acoustic modes of the measurement system, the transfer function between the measured quantity and the actual quantity is not linear[5].

4.3 Correction of the dynamic measurement data

The result of a dynamic pressure measurement is a time series of pressure values. After the collection of measurement values the measurement engineer must, if deemed necessary, correct the measurement values to obtain a better estimation of the true pressure and, which is always necessary, analyse the measurement uncertainty of the measurement data. In static measurements the correction of measurement data is quite simple since it only involves using the static sensitivities, i.e. it involves only algebraic operations. It is possible to distinguish some different dynamic situations

1. Only a peak pressure value is sought for
2. Stationary harmonic case
3. General transient case

These different situations are briefly described in the following sections.

4.3.1 Correction to find the peak pressure value

If only a peak pressure value is sought for, the simplest correction can be used if the dynamic calibration is performed for a situation that closely resembles the actual measurement situation. The calibration then furnishes the correction value to use in order to obtain the true peak value.

4.3.2 Correction in the stationary harmonic case

In the stationary harmonic case information about the measurement system transfer function is needed to correct measurement values to obtain a closer estimate of the true stationary harmonic pressure values. This approach can be used for any stationary periodic pressure variation since any periodic function can be synthesized using its Fourier components. If the transfer function from measured pressure to real pressure is at hand, probably from a dynamic calibration, the measurement bandwidth may be increased. This is so since, if the transfer function is known, it is no longer necessary to ensure that the measurement system natural frequency is far above the pressure frequency content.

4.3.3 Correction in the general transient case

In the general transient case corrections can be applied if there is knowledge of the measurement system transfer function from true pressure to system output. In this case the approach with Fourier transforms must be used. This implies that the transfer function must be known at all frequencies contained in the system output and not only for discrete frequencies as in the stationary harmonic case. Another approach uses a known time-domain model, obtained through dynamic calibration and least-square fitting, of the dynamics between true pressure and the system output. Using this approach a digital filter carrying out the inverse transformation from measurement system signals to true pressure may be designed[6]. For an illustration of this approach see Figure 35. Parametric methods in the time domain offer some advantages[6] compared to traditional frequency domain methods.

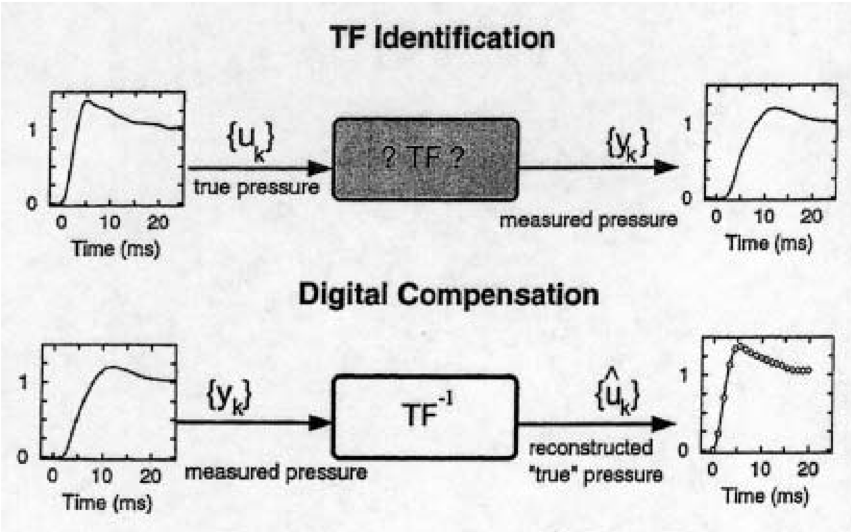


Figure 35. Identification[6] (through calibration) of measurement system transfer function and subsequent digital compensation in order to enhance useable frequency range

4.4 Correction performed internally in the measurement system

Correction may be performed to the measurement data after the measurement is completed but corrections may also be performed internally in the measurement system. This may be performed by internal software, by hardware or both. If the correction is possible to enable/disable or requires parameter settings, it is important that the same settings are used for both calibration and actual measurement use.

One type of internal correction is the correction of acceleration effects. When a pressure sensor is subjected to vibration, this may falsely be indicated as a pressure since internal components in the transducer act as seismic masses imparting inertial loads to the pressure-sensitive element. The unwanted output signal is referred to as the acceleration error of the transducer. To solve this problem, special acceleration-compensated pressure sensors have been developed.

Acceleration-compensated sensors contain an additional system which produce an output signal, due to the acceleration, of (nominally) equal magnitude but of opposite sign as the pressure sensitive part of the sensor. Another, more cost-effective solution has been presented[26] in which an additional seismic mass is introduced to cancel the inertial load on the measuring element. See Figure 36 for an example.

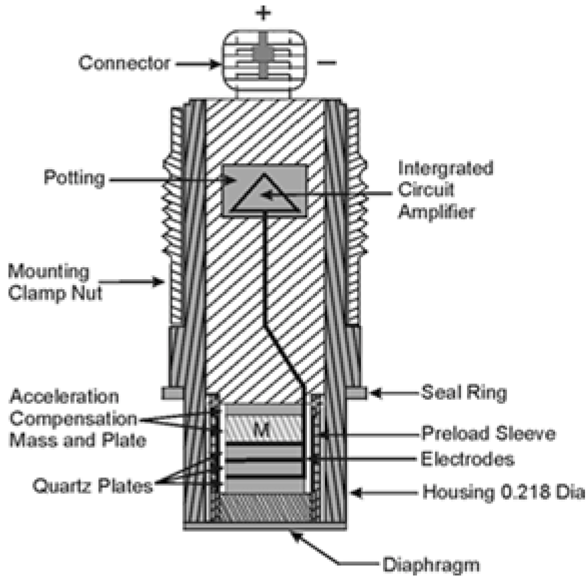


Figure 36. Drawing of a transducer[27] with acceleration-compensation achieved with an additional tuned seismic mass

5 Measurement uncertainty

Assuming that not every reader is familiar with the concept of measurement uncertainty a short summary of the theory is given below. For a more complete treatment the reader should consult the internationally agreed Guide to the expression of Uncertainty in Measurement (GUM)[39].

A formal definition of measurement uncertainty is[40] "a parameter associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand". In simpler terms the measurement uncertainty can be said to be the degree of confidence that is associated with the measurement data obtained by a specific person using stated methods and equipment.

Reporting only the values obtained during a measurement is not sufficient. Since the measurement data in many cases is used to judge the quality of a product, or as a basis for changes being made during a development phase, measurement data must be adjoined by a quality label. This quality label is the so-called measurement uncertainty. A complete report from a measurement of a quantity Y (which in our case is a time series) reads

$$y \pm U \tag{18}$$

in which y is the best estimate (using all available information) of Y and the interval $[y-U, y+U]$ is designed in such a way that it with a given probability (typically 95%) covers the true value of the measured quantity. The quantity U is called the expanded (measurement) uncertainty. The measurement uncertainty represents an indication of the quality (and usefulness) of the measurement. As a simple example, to report that the measurement result is 10,0 ± 0,1 MPa indicates a higher confidence in the measurement than reporting the result 10 ± 5 MPa.

5.1 How to obtain the measurement uncertainty

The general procedure for evaluating uncertainty starts by modelling the measurement (and evaluation) process with a functional relationship f defined by

$$Y = f(X_1, X_2, ..., X_N) \tag{19}$$

in which X_i is a set of input quantities on which the output quantity Y depends. After all measurement data has been collected and used together with information from calibration certificates, experience, data sheets and known literature estimations, the input quantities are calculated. These estimations denoted by x_i are used to obtain an estimate y of the output quantity Y using the equation

$$y = f(x_1, x_2, ..., x_N) \tag{20}$$

It is assumed that all estimations are the most reliable ones, corrected for all significant (known) effects and that this function also describes the errors. If this is not the case, correction factors may be treated as separate input quantities. To obtain a measurement uncertainty for the output quantity, the measurement uncertainty for all input quantities must be obtained. These uncertainties are expressed in terms of standard deviations (standard uncertainty) of the estimated input values and are denoted by $u(x_i)$.

Standard uncertainties are evaluated in two different ways. A type A evaluation of uncertainties is performed by statistical methods on repeated measurement data. Type B uncertainties are evaluated by any other method than statistical analysis of repeated measurements. Typically this involves previous experience, computational models, data sheets and information obtained in the literature. In this case to obtain the standard uncertainty a probability distribution must be assumed (typically rectangular or triangular).

Using the standard uncertainties of the input quantities the combined standard uncertainty of the output quantity can be calculated

$$u^2(y) = \sum_{i=1}^{N} c_i^2 u_i^2(x_i) \tag{21}$$

in which the so-called sensitivity coefficients c_i are given by the partial derivatives

$$c_i = \frac{\partial f}{\partial x_i} = \left. \frac{\partial f}{\partial X_i} \right|_{X_1 = x_1, \ldots, X_N = x_N} \tag{22}$$

This assumes that the first-order terms of the Taylor expansion of the function f are sufficient and that the input quantities are uncorrelated. If the model function f is highly nonlinear and/or the uncertainties are large, higher order terms must be appended and if input quantities are correlated, cross-terms must be used[39].

We now have the standard uncertainty of the estimate y of the measurand Y. It remains to design an interval that with a given probability covers the true value. The expanded uncertainty U serves this purpose. It is given by

$$U = k \cdot u(y) \tag{23}$$

The determination of the coverage factor k can be both simple but also quite involved. In the simplest case when a Normal distribution can be assumed and sufficient information has been collected to estimate its mean, the coverage factor corresponding to a confidence level of 95% will be 1,96 (given by the values of the Normal distribution). If a Normal distribution can be assumed (for instance in the case of any at least three input quantities having standard uncertainties of approximately the same magnitude) but too few measurements (<10) have been collected to reliably estimate the mean, the coverage factor should be taken from the so-called *t*-distribution which means that the coverage factor (for 95% confidence level) will have values normally ranging from 2 to 3. In the third case when a Normal distribution can not be assumed, the actual distribution must be used to calculate the coverage factor which in this case may take on values typically ranging from 1,5 to 3. For further details the reader is referred to the GUM[39].

5.2 Uncertainty in pressure measurements

A simple example is given to illustrate some of the uncertainties that may be encountered in dynamic pressure measurements. It is assumed that one wants to measure the peak cylinder pressure for the engine shown in Figure 37.

Figure 37. Measurement[41] of cylinder combustion pressure

The measured pressures have the general appearance shown in Figure 38.

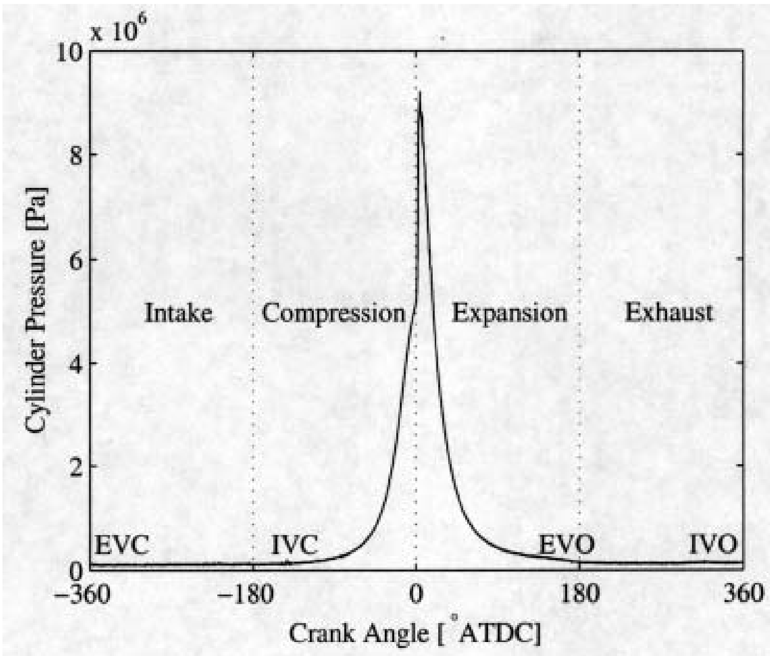


Figure 38. Typical[42] measured engine cylinder pressure

The model function in this case can be written as (observe that additional terms could be added but are left out for the sake of simplicity)

$$p_{\max} = \overline{p}_{\max} + \Delta_{cal} + \Delta_{temp} + \Delta_{acc} + \Delta_{dyn} + \Delta_{drift} + \Delta_{repr} \qquad (24)$$

in which the following notations have been used:

$\overline{p}_{\max}$	measured mean value of maximum pressure
Δ_{cal}	error of pressure transducer and additional instrumentation (from calibration certificates)
Δ_{temp}	error due to difference in temperature compared to calibration event

Δ_{acc} error due to differences in acceleration distribution between actual measurements and calibration

Δ_{dyn} error due to the fact that dynamic measurements are performed while the calibration was performed with static pressures

Δ_{drift} error due to drift of pressure transducer

Δ_{repr} error due to lack of ability to reproduce measurement conditions

Using the available measurements and all other knowledge the maximum value of the dynamic pressure during combustion is reported as (at 95% confidence level)

$$p_{\max} = 9{,}4 \pm 2{,}3 \text{ MPa} \tag{25}$$

Different uncertainties contributed as shown in the uncertainty budget in Table 2, below.

Table 2. Uncertainty budget for the example of Figure 37

Quantity	Estimate (MPa)	Distribution	Standard uncertainty (MPa)	Sensitivity	Contribution to standard uncertainty	Variance (MPa^2)	Degrees of freedom
$\overline{p}_{\max}$	9,38	Normal	0,52	1	0,52	0,27	19
Δ_{cal}	0,00	Normal	0,05	1	0,05	0,0025	∞
Δ_{temp}	0,00	rect.	0,60	1	0,60	0,36	∞
Δ_{acc}	0,00	rect.	0,20	1	0,20	0,04	∞
Δ_{dyn}	0,0	rect.	1,1	1	**1,1**	**1,21**	∞
Δ_{drift}	0,00	triang.	0,06	1	0,06	0,0036	∞
Δ_{repr}	0,0	rect.	0,4	1	0,4	0,16	∞
p_{max}	**9,38**					**2,05**	2781

5.3 Ways to reduce measurement uncertainty

A general approach to reduce uncertainty is to calibrate the used measurement system. There will always be differences between the calibration situation and the situation at which the actual measurements are performed. In the example given above, large uncertainties resulted since there was a considerable difference between calibration and actual use, namely the measurement system was calibrated statically but used dynamically.

The best way of reducing uncertainty in this case is to reduce the differences (not possible to completely eliminate them) between calibration and actual use. Some different approaches seem possible:

1. Dynamic calibration closely matching the actual use
2. Idealised dynamic calibration

The second case means that methods must be available to transfer the results to the actual measurement situation. This will involve testing to obtain information about dynamic properties of the system in which the pressure transducers will be installed as well as computational methods to link this testing to the dynamic idealised calibration. Unfortunately, for the measurement engineer, neither item 1 nor 2 above are commercially available and at present only item 2 is available to a very limited extent at some research labs.

6 Calibration of pressure instruments

The formal definition of calibration is[40] a "set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or a reference material, and the corresponding values realized by standards". In other words this means that in a calibration the output from a pressure measurement system is compared to the pressure realized by a pressure standard.

In the following sections proposed dynamic calibration methods are reviewed.

6.1 The concept of traceability

Modern quality systems all require that calibrations performed should be traceable to national or international standards. In metrology the word traceability means[40] a "property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties".

To have all measurements traceable is necessary to ensure that measurements of the same quantity performed at different times, at different companies, or in different countries can be compared.

In the context of dynamic pressure measurements there is an evident problem when trying to achieve traceable measurements since the only country having national dynamic pressure standards[43], apart from levels associated with sound pressure, is France. The French standards consist of a series of shock tubes and fast-opening devices. NIST in the USA was in the mid 90's planning[44] for national standards but the work seems to have been halted.

One may argue simplistically that pressure measurements are traceable if only a static traceable calibration has been performed. This arguing relies on the definition of traceability that is only concerned with the measured quantity, in this case pressure. A more reasonable arguing points out that the difference between static pressure measurements and dynamic pressure measurements motivates traceability to a dynamic standard instead of a static standard. Some published surveys[22,45] state that the need for traceability to a dynamic standard is recognized and needed in all applications involved in dynamic pressure measurements. This is of course because the need to gain trust in the obtained measurement data, and to quantify the associated measurement uncertainty, are far greater than the wish to satisfy a formal requirement of traceability.

6.2 Primary and secondary standards

In discussing calibration methods and equipment some people prefer to distinguish between primary and secondary methods. The definition of a primary method of calibration is a method that uses primary standards to realize pressure. A primary standard is[40] a "standard that is designated or widely acknowledged as having the highest metrological qualities and whose value is accepted without reference to other standards of the same quantity". On the other hand, a secondary standard is defined[40] as a "standard whose value is assigned by comparison with a primary standard of the same quantity".

It is important to understand that just because a method is primary, the uncertainty obtained in the calibration is not necessarily lower than the uncertainty obtained for the same instrument, when calibrated using a secondary method. In the present report it suffices to understand that when a reference transducer is necessary to determine the realized pressure, the calibration method is a secondary one. Unfortunately, in dynamic pressure calibration no procedure to realize dynamic pressure is sufficiently well understood to serve as a primary method with a low (less than 1%) best measurement capability.

6.3 Static calibration

In contrast to dynamic pressure calibration, the area of static pressure calibration is well developed. A lot of tailor-made calibration methods exist for the different modes of pressure measurement (absolute, gauge and differential) and different pressure amplitude regimes (low vacuum, vacuum, medium pressure, high pressure). In this section only the most common methods are briefly described to furnish a basic understanding.

Pressure balances are used to realize calculable pressures in gas and hydraulic oil in pressure ranges from a few kPa to about 1 GPa. A pressure balance consists of a piston mounted in a cylinder. The internal pressure required to support the weight of the rotating piston and the used masses is

$$p = \frac{mg}{A} \tag{26}$$

in which m is the total mass, g is the local gravitational acceleration and A is the effective area of the piston-cylinder combination. A schematic picture of a complete deadweight tester is shown in Figure 39. The best expanded relative uncertainty obtained using a pressure balance in a calibration is typically on the order of a some tens of ppm.

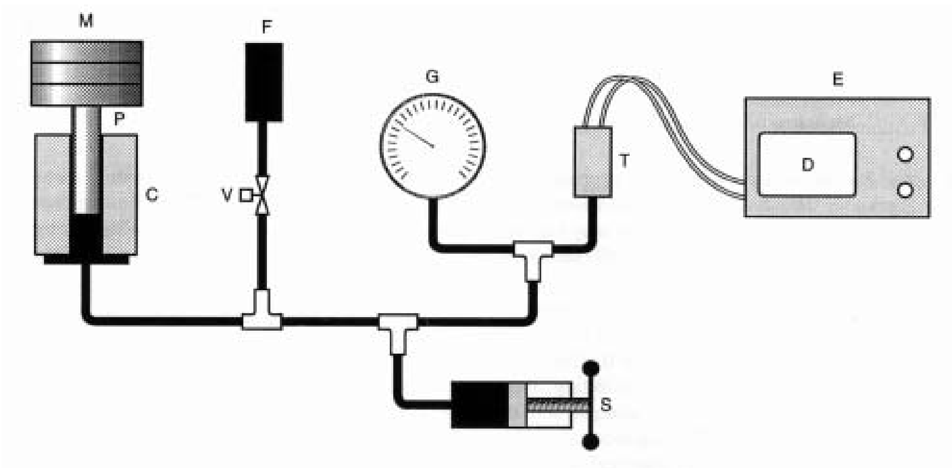


Figure 39. Schematic picture[1] of a deadweight tester used for static calibration of pressure instruments

Other equipment for static calibration of pressure measurement systems are systems based on pressure controllers and so-called portable calibrators. These systems are based on a system for realizing a wanted pressure and a reference transducer to evaluate the actual pressure supplied to the calibration object. These systems are generally less accurate than the pressure balance but the ease of operation and the swiftness by which a calibration can be performed are great advantages. One example of a pressure controller/calibrator is shown in Figure 40.

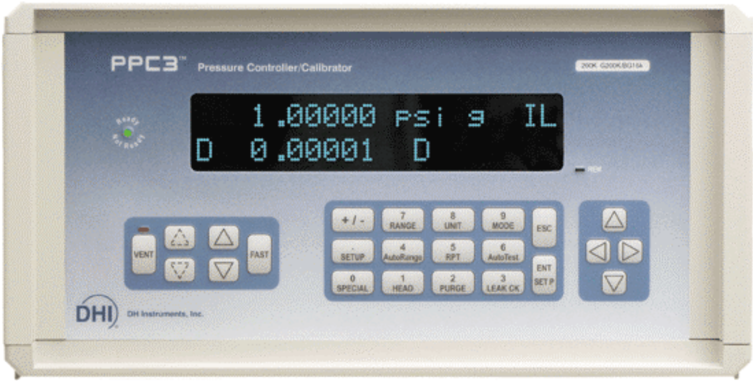


Figure 40. Commercially available[46] pressure controller/calibrator

6.4 Dynamic calibration

A lot of research work on dynamic calibration methods for pressure transducers has been performed during the last forty years. Much of the early work seems to have been driven by the need for accurate pressure measurements within the US space programs. During the 70's and 80's not much work was reported but during the 90's substantial new knowledge was presented. The developed methods and knowledge will be reviewed in the following sections. Considering the number of people involved in the research it must be surprising that even today, there are still no traceable dynamic pressure calibration services, except for sound pressure, on the market.

There is a discrepancy between the need for traceable calibrations expressed by people involved in dynamic pressure measurements and the procedures actually employed. In most cases, used measurement systems are calibrated statically and the conscientious users argue that since the lowest natural frequency of the measurement system by far exceeds the relevant frequency information of the dynamic pressure to be measured, the obtained measurement uncertainty should be quite low. Most people feel that this is not enough[8] and especially so since there are no general guidelines on how to incorporate the uncertainty due to the difference between the static calibration and the dynamic use into the uncertainty budget. In some cases the static calibration is used together with a dynamic checking of the measurement system natural frequency. This puts the dynamic arguing on a somewhat more solid ground.

In a dynamic calibration there must be a way of generating or realizing a dynamic pressure and also some way of determining the dynamic pressure realized. The pressure generator may generate a periodic pressure or an aperiodic pressure. An inherent difficulty is that it is easy to generate a well-known high-amplitude static pressure and also a quite well-known but low-amplitude dynamic pressure at acoustic frequencies but it is hard to generate well-known dynamic pressures of any other kind. This is of course the reason for the availability of commercial pressure calibration services only for static pressure and sound pressure measurements using microphones and other acoustic instruments.

In most cases a reference pressure transducer is used to measure the pressure realized by the pressure generator. Of course, it is important that the dynamic characteristics of used reference transducer are well known. As a simple check it is sometimes recommended[36] that the maximum frequency of generated pressure should not exceed one-fifth of the natural frequency of the reference transducer in order to maintain calibrations accuracy to within four percent, see Figure 31. It is furthermore recommended[36] that calibrations should be performed with the same type of fluid as will be used in the actual application. A liquid is, however, sometimes preferred since this increases the cavity resonances but it should be noted that transducer model parameters may be altered due to increased inertia and changed losses.

In choosing between periodic and aperiodic pressure generation it is probably wise to choose the pressure generation that most closely resembles the actual measurement situation. If the transducer will be used only for harmonic pressure measurement it seems reasonable to use a harmonic periodic pressure generator for the calibration. If, on the other hand, the transducer will be used for measurement of impulsive pressure pulses it seems reasonable to use an aperiodic pressure generator. Some people prefer[6] aperiodic pressure generators since the associated calibration consists of only one test in which, according to theory, all required frequency information can be determined.

6.4.1 Periodic pressure generators

The pressure generated by a periodic pressure generator is a periodic function such as a harmonic, a square-wave or any other periodic function. In many cases one wishes to generate sinusoidal pressure at discrete frequencies. Unfortunately, sinusoidal pressure oscillations at higher amplitudes and frequencies cannot be generated in a gaseous medium. This is due to the governing physical equations of gas dynamics. Trying to force a gaseous medium to high-frequency sinusoidal motion will result[47] in a saw tooth waveform. In practice there is no[34,43] absolute periodic pressure generator so a reference transducer is needed.

The reference transducer must be located very close to the transducer under test so that the same pressure is seen by both transducers. A rule-of-thumb[36] is that the distance separating the transducers should be less than a tenth wavelength of the pressure wave. The pressure wavelength, λ, is

$$\lambda = \frac{a}{f} \tag{27}$$

in which a is the speed of sound and f is the frequency.

6.4.1.1 Acoustical shock-generator

The acoustical shock-generator was developed for the dynamic calibration of microphones and other low-pressure transducers. Today it is not very often used, due to the development of more efficient methods, but the principle of operation is still interesting. The operation[47] of the device is similar to the sudden bursting of an inflated paper bag. This is achieved by a piston working in a cylinder against a compression spring and then held in this retracted position. The open end is covered by a paper strip and when the piston is released, pressure is increased in the cylinder until the paper bursts at a certain critical pressure. The piston is again retracted and the cycle repeated. The device is motor-driven and controlled by a gear train. Achieved pressure pulses are close to a saw-tooth shape.

6.4.1.2 Loudspeaker

A loudspeaker may be used as a dynamic pressure generator for low amplitudes and acoustic frequencies. For pressure amplitudes up to 2000 Pa, a calibration set-up using a microphone was described by Dibelius and Minten[48]. Two opposing microphones were used by Lokar et al[49] in a prototype dynamic pressure generator for frequencies up to 700 Hz. Sitheeq et al[37] investigated the dynamic characteristics of transducer-tube systems by measuring the frequency response relative to the response of a flush-mounted reference transducer. The goal was to find an optimal tubing. A loudspeaker was used as pressure generator with frequencies below 500 Hz.

Zakrzewski and Wróbel described[38] an approach in which the generator consisted of a loudspeaker placed at one end of a tube with a diameter corresponding to the diameter of the loudspeaker. An electronic generator and a power amplifier drove the loudspeaker. The second end of the tube was closed by a piston moveable along the tube axis, see Figure 41. By proper positioning of the piston, a standing wave was obtained. The frequency range of 280 Hz to 3700 Hz was obtained. The set-up was noisy and no real calibration was performed. The only output was a resonance frequency which can be obtained without the use of a reference transducer.

Common to the references above is the fact that no real calibrations were performed since no discussion about traceability or measurement uncertainty was been presented.

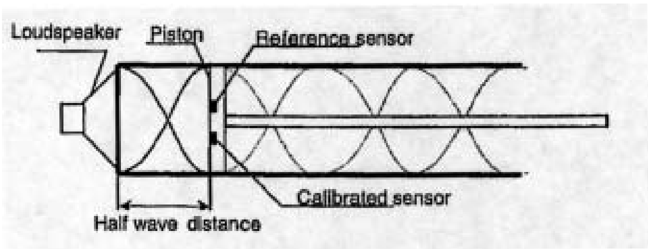


Figure 41. Dynamic characterization[38] of pressure transducer using standing waves obtained by use of loudspeaker and a moveable piston

6.4.1.3 Siren

The siren-tuned-cavity oscillator is a device for generating periodic pressure waves for the calibration of microphones and other low- and medium-pressure transducers. It is a type of variable-mass (as opposed to variable-volume) generator. The device consists of a cylindrical chamber with an axial orifice in one end and a revolving disk or flanged wheel with a number of equally spaced holes arranged around its periphery, see Figure 42. As the wheel rotates, the flow of air from the cylinder is interrupted. The length of the cylinder is adjusted to the rotational speed of the wheel so that a half-wave oscillator is obtained. The critical frequency limitation associated with acoustic dimensions of the chamber applies, and operation is limited to frequencies appreciably below the natural frequency of the chamber which is dependent on the properties of the fluid used and the chamber dimensions. In order to achieve a sinusoidal pressure variation certain conditions relating fluid properties, amplitudes and frequencies can be developed[36]. Operating frequencies up to 10 kHz at pressures of 200 kPa have been reported[34,48]. A reference transducer must be used.

No reference has been found that discusses the traceability and uncertainty aspects of calibrations performed using a siren as dynamic pressure generator.

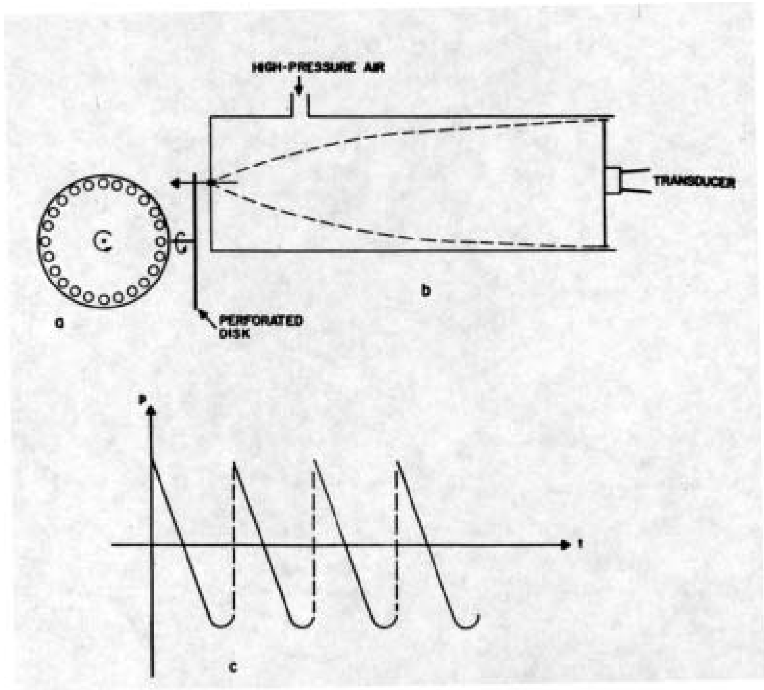


Figure 42. Schematic picture[47] of a siren-tuned-cavity generator with (a) rotating disk, (b) tuned cavity and (c) typical generated non-sinusoidal pressure waveform

6.4.1.4 Rotating valve

A rotating valve[47] may be used to switch the pressure supplied to the calibration object between two (or more) values. In this way an approximately rectangular pressure waveform is generated. In some arrangements of this kind it was found that the pressure steps are distorted by resonance effects which can be attributed to the inertia of the gas column in the valve system. As a consequence, the usefulness of the device is limited to frequencies below where these effects are observed. Older designs are therefore limited to frequencies below a few hundred Hz.

Weyer and Schodl[4] presented an improved type of rotating-valve pressure generator intended for frequencies up to 5 kHz. The measurement results indicated that acoustic resonances were excited at higher revolutions of the valve.

Kobota and Ooiwa[50] recently presented a new rotating valve, see Figure 43, pressure generator for low and medium pressure levels (up to 100 kPa and 1 kHz). An advantage of this rotating valve compared to the older ones is the relatively small acoustic cavity. In its current state the system is used a comparator. Although the acoustic cavity was small, ringing, which was believed to originate from the air column, was observed and to extend the frequency range the valve design must be improved. A reference transducer was used and from the output of the two transducers a comparison[51], using the measurement set-up shown in Figure 44, could be made. No actual calibration was presented. To achieve traceability for the measurement of the generated dynamic pressure Kobota and Ooiwa have suggested[31] the use of an optical interferometric measurement technique based on the pressure dependence of the refractive index of air, see section 3.4.

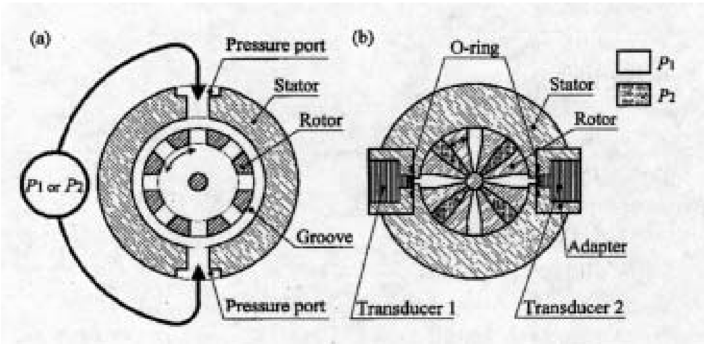


Figure 43. Rotating valve[50] for generating square-wave pressures with pressure input ports (a) and transducer ports (b)

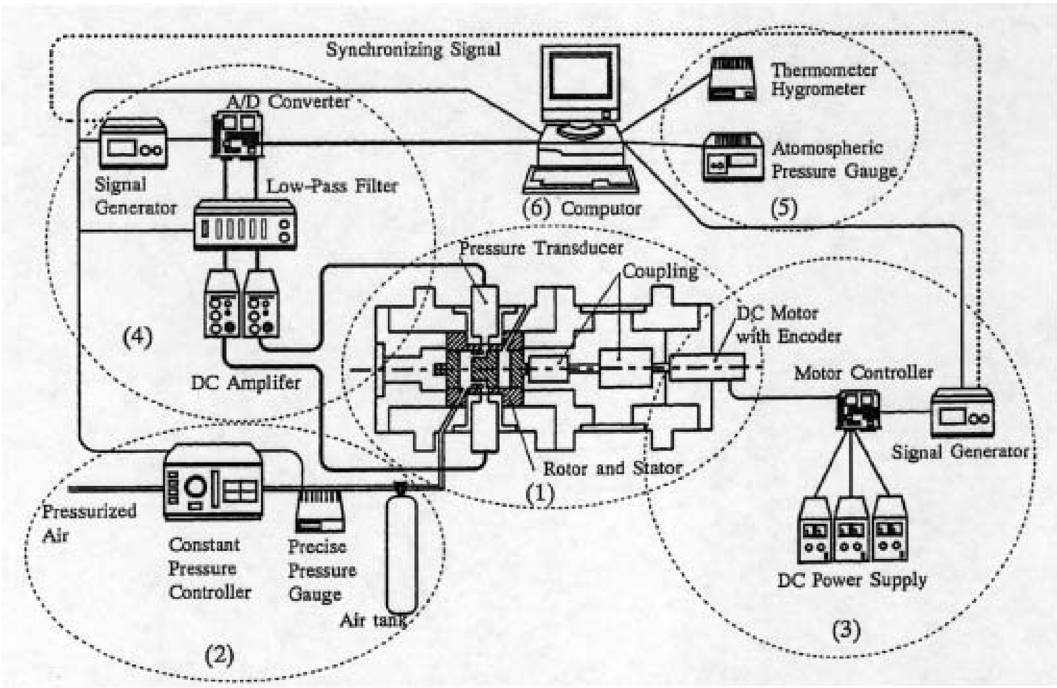


Figure 44. The experimental apparatus used by Kobota and Ooiwa[51] with pressure generator (1), controller for supply pressure (2), valve rotation controller (3), signal processing units (4), device for measuring environmental conditions (5) and computer (6) controlling the units by GPIB.

6.4.1.5 Shaker-based inertial loading systems

Hilten et al[52] used a liquid-filled tube mounted on the armature of an electrodynamic shaker to obtain a sinusoidal dynamic pressure. If the liquid-column is assumed to behave as a rigid body during the forced motion the pressure imparted to the pressure transducer is

$$p = \rho h(g - \ddot{x}) \tag{28}$$

in which $\rho, h, \ddot{x}$ are liquid column density, height and acceleration, respectively. Local gravitational acceleration is denoted by *g*. Dynamic amplitudes of 70 kPa (superimposed on a high bias pressure) with a maximum frequency of 100 Hz were achieved. The method is absolute in the sense that generated pressure is calculable from the measurement of the quantities given in Equation 28. Measurement uncertainty was estimated[52] to be about 5%.

A lower measurement uncertainty should be possible to reach abandoning the absolute nature of the method using a reference transducer instead of measuring acceleration and so on. Lally[53] discussed this method, see Figure 45, without giving any calibration examples. Bean[34] also discussed this method and claimed the upper frequency to be 1 kHz and the maximum pressure to be 7 MPa.

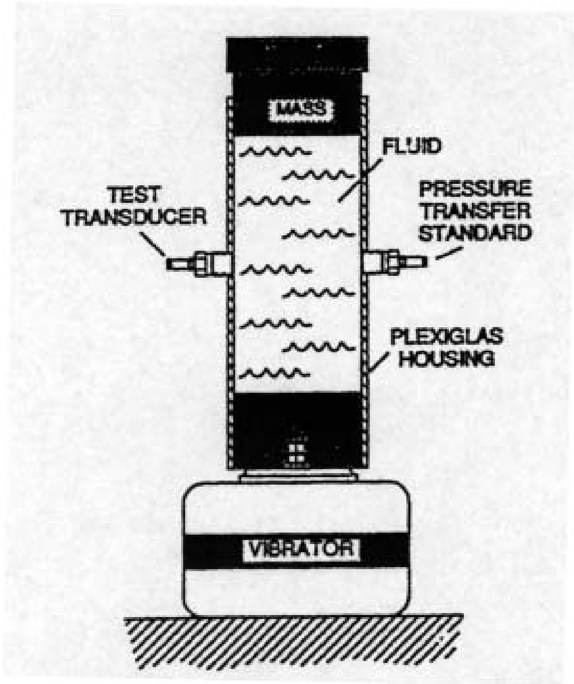


Figure 45. Schematic set-up[53] using a shaker and a liquid column to generate sinusoidal pressure. Note the additional seismic mass on top of the liquid column

6.4.1.6 Shaker-based direct force loading systems

Del Prete et al[15] suggested using a vibrational shaker and a load cell, see Figure 46, in combination with knowledge of the contact area between actuator and sensor to achieve a simple set-up for dynamic calibration of pressure sensors. The uncertainty obtained should be quite high. No results were reported in the paper.

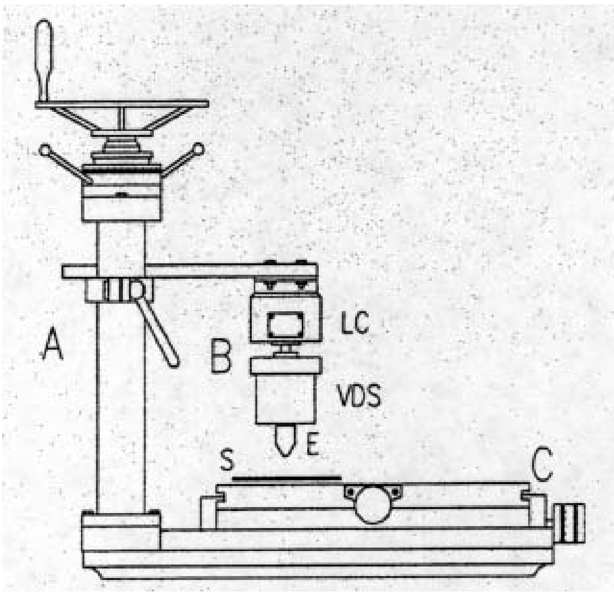


Figure 46. Set-up[15] for static and dynamic testing of pressure map sensors. Letters in the picture denote the frame (A), the operating head (B), the sensor bearing plate (C), the load cell (LC), the voltage driven shaker (VDS), the actuator (E) and the sensor (S).

6.4.1.7 Piston-in-cylinder steady-state generators (Pistonphone)

The obvious way to produce a sinusoidal pressure variation is by means of a piston-in-cylinder device, see Figure 47. Without a reference transducer this approach is limited[52] to low frequencies and amplitudes (even for liquids) due to the inherent nonlinearity of the governing equation. Equations to determine achievable amplitudes and frequencies can be developed[36]. The volume should be minimized to maximize the resonant frequency of the cavity.

The piston-in-cylinder device, or the pistonphone, is most commonly used[53] to act as a precision sound reference source at fixed frequency and amplitude for calibration of low-pressure acoustic sensors. Maly and Kienholz[5] proposed to use an electrodynamic shaker driving the piston to achieve calibration. A reference transducer was used but no discussion about traceability or uncertainty was presented.

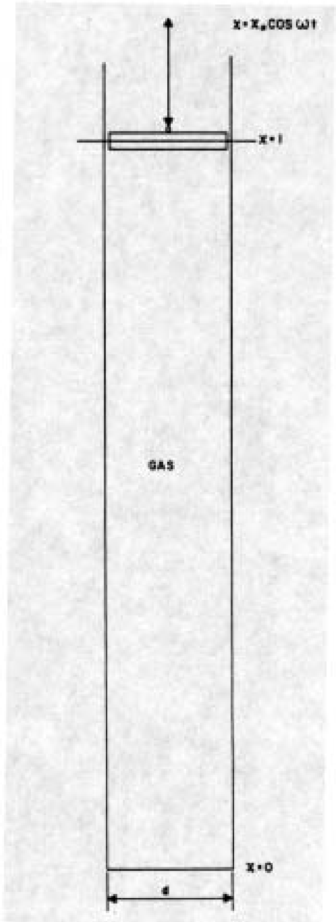


Figure 47. Moveable piston[47] in a cylinder to generate dynamic pressure. Sensor to be calibrated and optional reference transducers are not shown

6.4.2 Aperiodic pressure generators

Aperiodic pressure generators create single-event pressure steps or pressure functions resembling a half-sine wave. Generally frequency-domain techniques are used to find the transducer transfer function. With knowledge of the generated dynamic pressure, its Fourier transform may be determined and from the measurement signal the output Fourier transform can be determined. Using the two transforms the transducer transfer function may be determined by a simple division.

6.4.2.1 Shock tube

The shock tube consists of two elongated chambers, usually of constant cross section, separated by a burst diaphragm, see Figure 48. Initially the gas pressure is higher in one chamber than in the other. When the diaphragm ruptures the expansion of the high-pressure gas into the low-pressure chamber generates a shock wave which travels faster than the expanding gas. The dependence of the pressure in the two parts of the shock tube is shown in Figure 49. The rise time of the pressure is of the order of nanoseconds[44,47] and is considered to be an idealized pressure step generating a high-frequency content.

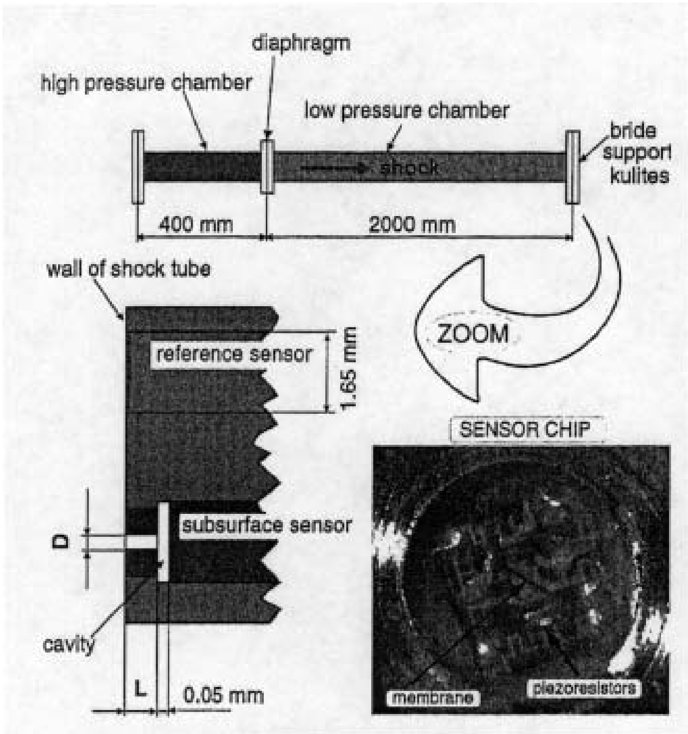


Figure 48. Shock-tube testing[6] with two sensors mounted in the end-wall of the tube

The generated pressure step is calculable from gas dynamics provided that the pressure ratio, temperature, driven gas composition and shock wave velocity are accurately known. The assumptions[47] used are that

1. perfect gas laws apply
2. flow is adiabatic
3. isentropic relation between pressure and speed of sound
4. specific heats are constant
5. diaphragm burst is instantaneous
6. viscous forces are negligible

The first three assumptions are somewhat more realistic[47] than the last three ones. Transducers to be calibrated may be installed either in the side- or end-walls. According to shock tube theory, the pressure step (when air is used in both sections) encountered by a transducer mounted in the side-wall is

$$p_2 - p_1 = \frac{7}{6} p_1 \left(M_1^2 - 1 \right) \tag{29}$$

in which p_1 and p_2 are shown in Figure 49 and M_1 is the shock wave Mach number. M_1 depends on shock wave velocity and temperature.

When air is used as the working gas, the amplitude of the pressure behind the reflected shock wave encountered by a transducer mounted in the tube end-wall is given by

$$p_5 - p_1 = \frac{7}{3} p_1 \left(M_1^2 - 1 \right) \left(\frac{2 + 4M_1^2}{5 + M_1^2} \right) \tag{30}$$

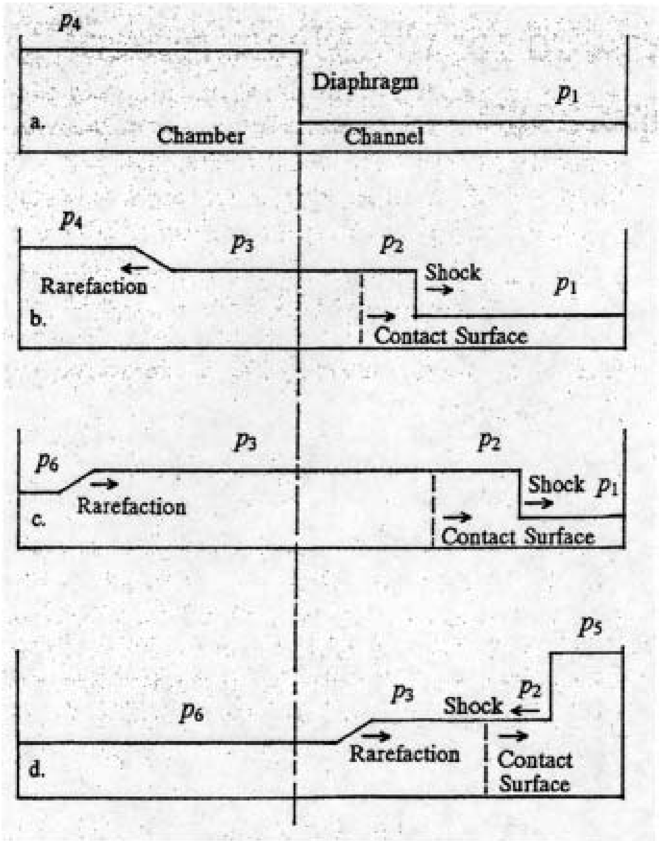


Figure 49. Time sequence plots[44] of pressure as a function of location within a shock tube. On the vertical axis is pressure and on the horizontal the location along the tube. In (a) is the condition before diaphragm rupture, in (b) pressures are given before any wave is reflected, in (c) the rarefaction wave has been reflected at the left end and in (d) also the shock wave has been reflected at the right end

The uncertainties of the pressure amplitudes calculated by Eqs. (29) and (30) are[36,54] of the order of 5%. Reasons for the uncertainty are the limited validity of the shock tube assumptions given above and the transducer sensitivity to the acceleration shock encountered by the transducer through its mounting. This component of uncertainty may be reduced[54] in calibration through a massive design of the shock tube. If the transducer is sensitive to transient temperatures, then the temperature step produced by the shock wave may[36] cause errors in the transducer calibration.

The realized pressure step will be held constant during the so-called dwell time which is a function of the shock tube length. As an example, the dwell time for the NIST[44] shock tube, being 7 metres, is 4 ms when p_5 is 20 MPa. The low frequency limit of the shock tube is the reciprocal of the dwell time, which is a few hundred Hz for the NIST tube. Amplitude limits for most shock tubes are about 20 MPa and the frequency limit is some hundred kHz (above 500 MHz according to Paniagua and Dénos[6]).

The French national standards[43] for dynamic pressure, maintained by ENSAM-Paris, consist of four overlapping shock tubes and some fast opening devices, see Figure 50, covering the range from 10 kPa to 20 MPa.

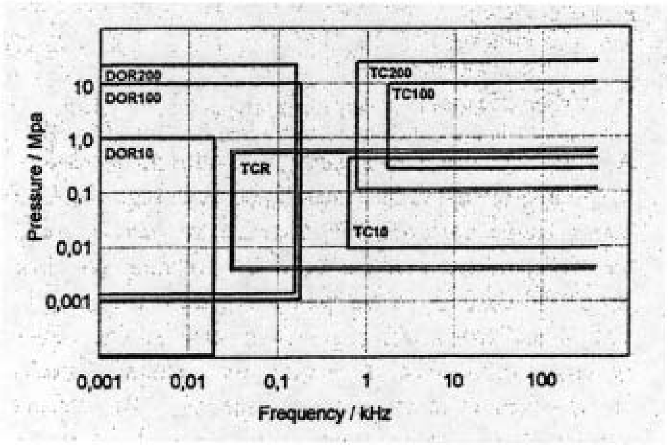


Figure 50. Frequency/pressure domain of the shock tubes and fast opening devices for dynamic pressure calibration[43] at the ENSAM-Paris

Some people prefer to think of the shock tube as a primary standard while others prefer to use a reference transducer to determine the pressure actually realized in the tube. If used as a primary standard, one has to accept the relatively large uncertainties mentioned above. If used with a reference transducer the question of how to calibrate the reference transducer naturally arises. This question is not easily answered since shock tube calibration is the only known practical high-frequency calibration method available. So either traceability is achieved but with a high uncertainty, or a reference transducer is used and it is argued that it must be a lot better than the calibration object. This may very well be so, it may even be extremely probable, but the metrological traceability is lost.

In order to avoid the circular reasoning Rosasco et al[55] at NIST started work to achieve traceability using a new type of reference transducer. The NIST approach is to use the properties of diatomic gas molecules having a fundamental vibration motion whose frequency, measured via laser spectroscopy, is a function of the pressure. When the gas molecule is used as a pressure sensor the common sensor problem of limited frequency response is overcome and the shock tube can be calibrated thereby lowering the uncertainty in realized pressure since idealized shock wave behaviour is no longer a necessary assumption. Preliminary investigations indicate uncertainties of dynamic pressure and temperature below 5% (3 sigma). Unfortunately, no publication about this approach has been found after 1994[44].

Several researchers[56,57] have used the shock tube to compare a transducer to a reference transducer. In almost all cases without bothering about uncertainties and traceability. Walter[57] contributed with a modern approach achieving an easily operated shock tube incorporating software for automized calculation of transfer function characteristics.

According to Lally[53], shock tube calibration has been proven to agree within 3% of other dynamic calibration methods.

Shipunov[58] claims that a shock tube is part of the domestic standard of Russia. No other information about this has been found. The shock tube is used to find the resonance frequency of transducers. The experimentally found resonance frequencies deviate from the specified ones by 5-10% or more. No uncertainties were reported.

De Souza Vianna et al[59] have investigated the influence of the burst diaphragm on the realized pressure pulse in a shock tube.The results show that the characteristics of the diaphragm material and the way in which it bursts influence shock formation, causing variations in the gain of the output signal from the pressure transducer. If the calibration is performed using a reference transducer, the influence of the diaphragm is no longer important. An international comparison between LMD-UnB and ENSAM was presented. The experiments show that the type of diaphragm used in the shock tube is insignificant at low frequencies. At high frequencies, however, the diaphragm may influence the performance of the shock tube. Relative expanded uncertainties of 20% are obtained not much above 5 kHz. A reference transducer is recommended.

Wu et al[60] described a water shock tube for high pressure testing (100 MPa to 1 GPa) making use of detonator as an explosive source. When the detonator explodes a propagating shock wave is produced. A reference transducer must be used and for this purpose a special transducer (with PVDF film as the sensing element) was developed. The natural frequency of this reference transducer is so high that the signals from it are regarded by the authors to be true values. Resonance frequencies for two commercial sensors are measured in the water shock tube. No uncertainties for the experimental values were given.

Paniagua and Dénos[6] investigated transducers not being flush-mounted using a shock tube. In the shock tube a flush-mounted sensor was mounted side by side with a recessed sensor. The flush-mounted was considered to measure the true pressure variation. The dynamic model of the recessed sensor was determined and used to compensate the output so that the behaviour of the recessed sensor approached that of the flush-mounted sensor. The useable frequency range was doubled in the process.

6.4.2.2 Fast opening device

A fast opening device can be regarded as an extension of the shock tube towards lower frequencies. When the opening device is actuated, see Figure 51, the pressure in the small chamber changes from p_1 to p_2. The resulting pressure step is of magnitude $p_2 - p_1$. Because p_2 can be greater or smaller than p_1 the excitation can be a positive or a negative step.

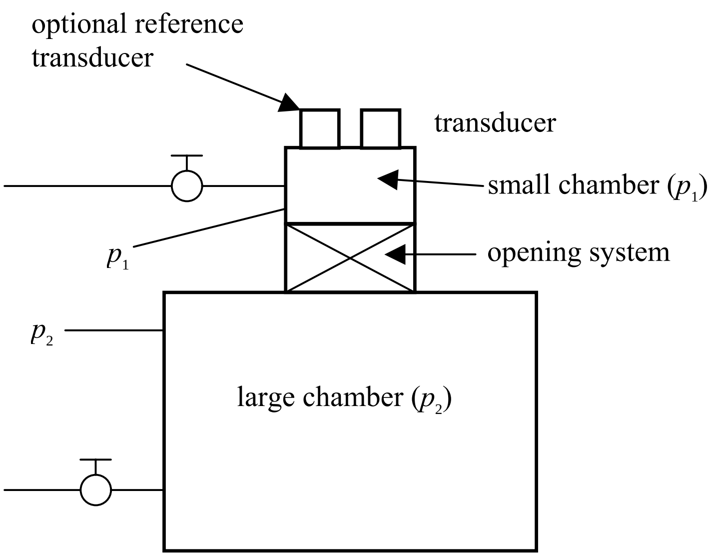


Figure 51. Schematic picture of a fast opening device used for dynamic pressure calibrations

An advantage of the fast opening device, as compared to the shock tube, is that the amplitude of the pressure can be maintained for an arbitrary time. This means that low-frequency (even static) measurements can be performed. The disadvantage is that the rise time is lower than the one obtained in a shock tube. Limits in high frequency depend[43] especially on the opening system and on the small chamber volume. In order to determine the frequency limit it is necessary[34,43] to measure the shape of the transition between pressures with a reference transducer dynamically tested in a shock tube. As an example, the ENSAM fast opening devices (3 pieces) extend to 20 MPa and have[43] rise times from 0,1 ms to 4 ms. Some authors claim[6,47] that fast opening devices can be used for dynamic calibration up to about 10 kHz. It is recommended[36] that the rise time of the pressure generated by the source should be no more than one-fifth of the reference transducer rise time.

Early work on fast opening devices tended to be without reference transducer leading to large uncertainties in generated pressure profiles. Smith[61] used a liquid pressure medium to obtain pressure rise times of about 10 ms. Calibration uncertainty (at an unknown level of confidence) was estimated to between 5 and 7 percent.

Hunziker and Binggeli[62] described an automated computer-controlled set-up for calibrating pressure transducers with a fast opening device incorporating a reference transducer. Pressure amplitudes were from 50 kPa to 3 MPa and pressure rise time was a few ms. Output from the calibration was only a mean sensitivity without any frequency information. Measurement uncertainty was claimed to be 1% but how this was reached with a statically calibrated reference transducer was not discussed.

MacLean and Box[18] calibrated pressure transducers up to the pressure of 700 kPa using the commercial apparatus PCB 903A2. The reference transducer was a Bourdon tube with questionable dynamic characteristics. The used electronics (amplifier and digital storage oscilloscope) were calibrated by use of an AC-standard. The calibration procedure consisted of three pressure steps of at least four pressure levels between zero and the nominal range of the transducer. Mean dynamic sensitivity was obtained. One may say that although the calibration was dynamic the calibration data was not. But of course, it was one step ahead of a traditional static calibration.

6.4.2.3 Aronson shockless pressure step generator

The Aronson shockless pressure step generator, see Figure 52, was developed with the aim[53] of producing pressure steps with rise times approaching those obtained in shock tubes. But the aim was also to develop calibration equipment with greater speed and ease of use as compared to the shock tube.

When calibrating, the pressure in A and E are controlled independently to known values using reference transducers. Pressure steps are achieved by opening the fast-acting poppet valve very swiftly by use of the impact weight. The pressure rise time is determined[53] by

- type of gas used (helium is recommended for fastest rise time)
- diameter of the poppet valve
- initial pressure difference across poppet valve
- design of transducer diaphragm (flush or recess)

According to the supplier[27] it is possible to achieve rise times below 50 µs.

Comparison of static and dynamic calibration of a pressure transducer using the same pressure amplitude in the same device without moving the transducer is possible.

Traceability to NIST is claimed by Lally[53] but this seems of limited value since the reference transducer used is only statically calibrated. No uncertainty budget for a typical calibration was presented.

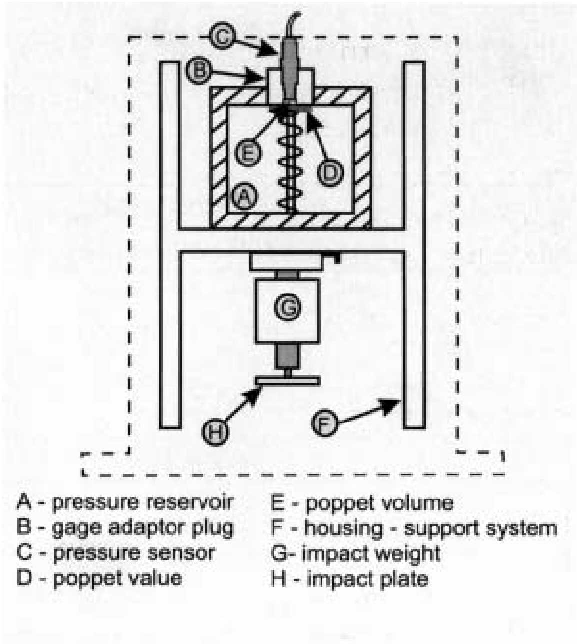


Figure 52. Schematic picture[27] of the Aronson shockless pressure step generator

6.4.2.4 Dropping weight

One of the simplest techniques of achieving an aperiodic loading of a pressure transducer is to let a falling object hit a pressure transducer, either directly or through a piston and a liquid medium, see Figure 53.

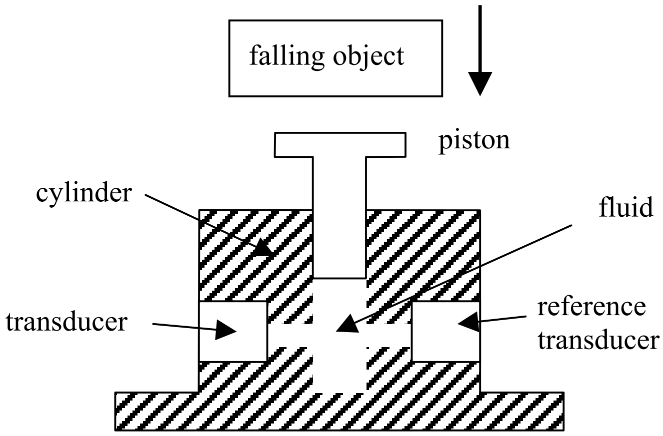


Figure 53. Schematic picture of the method with a dropping weight to dynamically calibrate pressure transducers

Most researchers have recognized that the realized pressure cannot be determined precisely and that a reference transducer is needed. If the weight is dropped directly on the pressure transducer the response may[47] not be the same as to a pressure distributed over the complete diaphragm. The resulting pressure pulse resembles a half-sine with a rise time on the order of milliseconds[34].

Lally[53] used a tourmaline piezoelectric transfer standard to measure the hydraulic pressure pulse from a mass impacting a piston and cylinder manifold. Dynamic pressure amplitudes from 700 kPa to 140 MPa were realized with rise times of about 3 ms and pulse durations of 6 ms.

Riegeabuer[20] tried to achieve a primary calibration using the dropping weight technique. To obtain traceability for a primary calibration in this way certain requirements must be met:

- large mass of foundation without flexibility (no rooms lying underneath)
- concrete foundation connected to solid ground
- accurate knowledge of local gravitational acceleration
- measurement of temperature in the chamber

The rise time obtained was about 1 ms with a pulse width of about 2 ms. No clear picture of the uncertainty possible to reach was given. The complexity of the design and the unclear uncertainty statement make it probable that the device should be considered as a dead end as a primary calibrator. If used with a reference transducer the design could be made much simpler.

Momma and Lichtarowicz[13] presented a simple calibration technique in which small steel balls (4-7 mm in diameter) were dropped from several heights (10-50 mm) onto the transducer. The rebound height was measured. The average force imparted on the transducer can be calculated from (conservation of linear momentum)

$$F_{av} = \frac{m(v_1 + v_2)}{\tau} \tag{31}$$

$$v_i = \sqrt{2gh_i}, \quad i = 1,2 \tag{32}$$

in which m is the mass of the dropping weight, v_i is the velocity before and after impact, τ is the time of contact, g is the local acceleration due to gravity and h_i is the height from which the ball is dropped ($i = 1$) and the rebound height ($i = 2$). The heights as well as the time of contact can be measured implying that the average contact force can be determined. Assuming the force to be equally distributed over the sensitive area of the pressure transducer, a mean sensitivity for the pressure transducer can be calculated. The rise time of the contact force realized was 40-80 µs. The main experimental difficulty was to drop the steel ball onto the small transducer with sufficient accuracy. No uncertainty of the determined mean sensitivity was given.

Shipunov[58] also presented a method in which steel balls were dropped directly onto the pressure transducer. Since he was interested only in obtaining the lowest natural frequency of the transducer he did not have to care about the actual pressure function obtained. If this is the only dynamic characteristic of interest, the frequency analysis of the output signal is all that is needed. Resonance frequencies obtained in a shock tube were compared to those obtained with the dropping-ball technique. The differences did not exceed 6%.

Voitenko and Kuznetsov[63] used a steel ball suspended in a string, thus forming a pendelum. This should make it somewhat simpler (and more repeatable) to hit the transducer with the steel ball. The mean sensitivity of the transducer can be calculated with a stated relative uncertainty (at an unknown coverage probability) of less than 5%.

Kong et al[64] suggested using a force transducer with higher accuracy to replace the pressure transducer as a reference. The falling object was augmented with a specially designed force transducer. Both steel parts and hydraulic columns were assumed to behave as rigid bodies during impact. Neither traceability nor uncertainty was discussed.

6.4.2.5 Negative step with deadweight tester or by other means

Negative step loading means that a transducer is exposed to a sudden change from a well-known static pressure to zero or to atmospheric pressure. This is obviously possible to achieve with the fast opening devices described above but here special methods to obtain the static initial pressure or to release the load are described.

Fürstenau et al[30] used a standard deadweight tester to set the initial static pressure and a valve to vent the pressure chamber to atmospheric conditions. Pressure release times of 60 ms were obtained. The method was used for a qualitative investigation of a new sensor concept. Lally[53] described a similar approach, also without discussing uncertainty associated with the methods.

Momma and Lichtarowicz[13] reported an easy-to-use dynamic calibration method to achieve a closer resemblance to cavitation loading. It is generally easier to release a load quickly, e.g. by breaking a weak link holding the load, than to apply it quickly. A calibration method using a pencil lead as the weak link was presented. The release time of the load was 7-8 μs. Output from the calibrations were mean sensitivities reported without uncertainties.

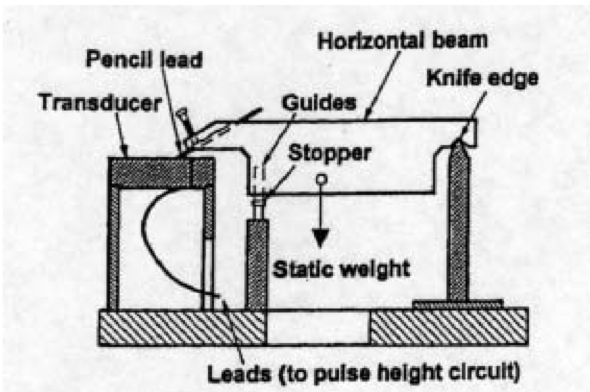


Figure 54. Negative step loading[13] by use of the static weight of a water volume and a breaking pencil lead

6.4.2.6 Explosions

As mentioned above it should be advantageous to calibrate transducers in a way that resembles the way in which they will subsequently be used. This simplifies, and reduces the number of components in, the uncertainty budget for a practical measurement situation. Some researchers have therefore suggested using controlled explosions as pressure generators for the calibration of pressure sensors used for measurement of impulsive loads that may, or may not, originate from explosions. Obviously, these kind of pressure generators are not easily calculable so a reference transducer is needed to keep track of the actually generated pressure.

Schweppe et al[47] described some early experiments on explosions in closed compartments for calibration purposes. Pressure amplitude was controlled by changing the chamber volume. Rise times of 300 µs were reported.

Bean[34] also recognizes that variations in the pressure generated by explosives make it necessary to use a reference transducer. He concludes that the approach seems more likely to be used in military laboratory than in a metrology institute.

Zakrzewski and Wróbel[38] used a punctured balloon to generate dynamic pressure up to 20 kPa. They mounted the transducer to a long tube, see Figure 55, to avoid disturbances. Due to the dynamics of the acoustic cavity of the tube it may very well be that the obtained response will be dominated by tube dynamics. They were only interested in natural frequencies which means that a reference transducer is not necessary. No uncertainty analysis was reported.

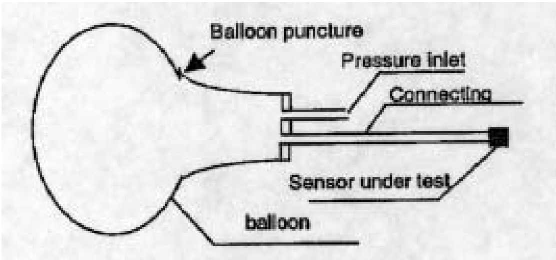


Figure 55. One possible set-up[38] using a punctured balloon to obtain a negative pressure step

Paniagua and Dénos[6] used a pressure line to pressurize a standard plastic balloon to a pressure ranging from 70 to 300 mbar above the atmospheric pressure. When the balloon was exploded, using a needle, the pressure within the balloon evolved as a falling pressure step to atmospheric conditions in about 700 µs. A fast-response pressure sensor was placed adjacent to the tested pneumatic probe, see Figure 56. The fast-response reference sensor had a rated natural frequency of around 250 kHz and was considered to measure the true pressure variation. Repeated tests showed variations from test to test below 1%. Identified parametric models were used to compensate the output from slow pressure probes thereby extending the useable frequency range.

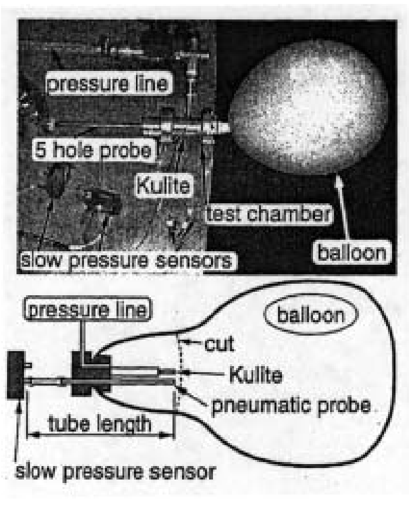


Figure 56. Dynamic calibration[6] of pressure probes using a burst-balloon device and a fast-response reference transducer

7 The need for further work

Having come this far in the report it is quite obvious that although research work on dynamic calibration of pressure transducers have been ongoing during the last forty years, quite a lot of research work remains to be done. The aim must be that any user involved in dynamic pressure measurements knows:

- how to determine if a dynamic calibration is necessary
- that an efficient dynamic calibration service suited to his needs (pressure amplitude, pressure frequency and uncertainty) is available
- how to incorporate, and, if needed to compensate the output from the dynamic calibration into his uncertainty budget for the actual measurement situation

Some of the steps needed to take in order to reach this situation are discussed in the following.

7.1 Static or dynamic calibration?

One thing that seems to have been overlooked is that there must be a method of determining whether a dynamic calibration is needed or not. Since no traceable commercial dynamic calibration methods are available, the question may at the present time be of academic interest. Factors influencing the need for a dynamic calibration are:

- the relation between measurement system and pressure signal bandwidths
- the uncertainty needed in the actual measurements

In many cases this reasoning is partly made when choosing transducers with a bandwidth much higher than the pressure signals intended to be measured. What is missing is that there is no clear-cut approach to incorporating the uncertainty due to the fact that a static calibration is used for a measurement system used for dynamic measurements. One should work further with the results of Figures 31 and 33 to obtain general guidelines on uncertainty components.

7.2 Dynamic calibration methods

As described above the only area resting on a firm (traceable) foundation is the calibration of low-pressure and quite low-frequency acoustic transducers. The opinion of the present author is that efforts on periodic pressure sources for higher frequencies and amplitudes are probably less valuable than work on aperiodic sources. One reason for this is that the actual users are not prepared to pay for lengthy and complicated calibration procedures. The wish is rather to achieve cheaper and simpler calibrations than today. In this respect aperiodic sources are more promising.

A problem common to all dynamic calibration methods is that in order to achieve traceable calibrations with uncertainties below about 5% a missing link must be found. Pressure generation is neatly generated with shock tubes, fast opening devices and dropped weights. But neither of the sources is calculable if low uncertainty is wanted. In order to achieve low uncertainties a new kind of reference transducer is needed. A link to fundamental constants, as suggested by Rosasco et al[55], is the holy grail of most metrology. The problem with this fundamental reference transducer is that it will probably take a lot of resources to develop and therefore, it should be internationally cooperated on. In parallel to the development of the fundamental reference transducer the methods of dynamic calibrations using shock tubes, fast opening devices and dropping weights must continue as if the fundamental reference transducer was available. Detailed uncertainty budgets must be developed showing the influence of various terms.

Aperiodic pressure calibrations must be made more efficient by the use of modern control and software techniques.

More effort must also be devoted to the influence of acceleration and temperature on the behaviour of pressure transducers.

7.3 Computational methods

To put the present experiments using non-ideal reference transducers on a more solid ground computational methods to predict their behaviour should be exploited. A combination of static calibration, dynamic characterization and dynamic computational models should be able to lower the uncertainty of the reference transducer as well as the production transducer used for industrial measurements.

Simple computational models to incorporate the dynamic influence of cavities not present in the calibration should also be of value to many users.

The similarities between dynamic calibration and system identification should be explored. It is the present author's belief that the standard toolbox of linear system identification can be used to advance the field of dynamic pressure calibration.

7.4 Handling dynamic calibration data

Today many users have problems understanding and using the results obtained from a static calibration. These problems may be even bigger for dynamic calibration results. Dynamic calibration results may be given in various ways:

- as mean sensitivities obtained for some special loading
- as a frequency limit below which the static sensitivity is valid with some stated uncertainty
- as a complex frequency response function having a stated uncertainty
- as a linear or nonlinear identified transducer model having a stated uncertainty when used within some range of pressure and time

All these variants must be presented to the user in such a way that it is obvious how the results should be used. The user must understand what happens, in terms of uncertainty, if the information is not used to correct the measurement results. No references have been found discussing how the dynamic calibration data should be presented in order to be of maximum use for a calibration customer.

8 Conclusions

Many important engineering fields employ dynamic pressure measurement in everyday work. Measurement equipment suited for dynamic measurements is available in abundance on today's market. Although much work has been performed on developing methods of dynamic pressure calibrations, most measurements carried out in industry are carried out without traceability and without a known measurement uncertainty.

The approach employed in most cases, and felt to be unsatisfactory by most people, is to choose a measurement system with a bandwidth many times that of the pressure signal to be measured. In addition to this, the measurement system is normally calibrated statically. Of course, it would be much more satisfying if traceable dynamic calibration services would be developed and publicly made available.

Work should be directed in the following directions:

- develop methods to determine whether a dynamic calibration is necessary and how to incorporate the static calibration data in the uncertainty budget of a dynamic measurement
- develop fundamental reference transducers for aperiodic pressure sources
- develop detailed uncertainty budgets for shock tubes, fast opening devices and dropping weights
- increase productivity by use of modern control and software techniques for the above-mentioned methods
- develop computational models of non-ideal reference transducers to lower the uncertainty
- explore the similarities between dynamic calibration and system identification
- tailor the output of a dynamic calibration to maximum use for the end-user

References

[1] "Guide to the Measurement of Pressure and Vacuum", The Institute of Measurement and Control, ISBN 0-904457-29, 1998
[2] www-mat.ee.tu-berlin.de
[3] www.autoliv.com
[4] Weyer, H. and Schodl, R., "Development and Testing of Techniques for Oscillating Pressure Measurements Especially Suitable for Experimental Work in Turbomachinery", ASME Journal of Basic Engineering, December 1971, pp. 603-609
[5] Maly, J. R. and Kienholz, D. A., "Development of a Dynamic Pressure Response Calibrator", ISA Instrument Society of America, ISA paper No. 93-083, 1993, pp. 185-201
[6] Paniagua, G. and Dénos, R., "Digital compensation of pressure sensors in the time domain", Experiments in Fluids", Vol. 32, 2002, pp. 417-424
[7] www.sensotec.com
[8] Clark, C., "The Practice of Dynamic Pressure Measurement", Measurement and Control, Vol. 22, December/January 1989/1990, pp. 298-301
[9] www.vibrationdata.com
[10] micromachine.stanford.edu
[11] www.bksv.com
[12] www.raytec-diecastingandplastics.com
[13] Momma, T. and Lichtarowicz, A., "A new calibration method for dynamically loaded transducers", Proceedings of the 1994 ASME Fluids Engineering Division Summer Meeting, Lake Tahoe, Nevada, USA, June 19th-23rd, 1994, pp. 103-107
[14] www.rexroth.com
[15] Del Prete, Z., Monteleone, L and Steindler, R., "A novel array sensor based on contact resistance variation: Metrological properties", Review of Scientific Instruments, Vol. 72, No. 2, February 2001, pp. 1548-1553
[16] www.pressureprofile.com
[17] Cook, J., "Fundamentals of Sensor Technology: Pressure", Proceedings of the Sensor Expo, Baltimore, Maryland, USA, May 4th-9th, 1999, pp. 401-415
[18] McLean, A. and Box, P., "Calibrating Air Blast Transducers with the PCB Dynamic Pressure Pulse Calibrator", Australian Department of Defence DSTO, DSTO-TN-0278, May 2000, pp. 1-10
[19] www.galcit.caltech.edu
[20] Riegebauer, J.,"Dynamic Pressure Calibrator", Proc. Workshop on the Measurement of Transient Pressure and Temperature, NISTIR 4828, Gaitersburg, Maryland, USA, 1992, pp. 151-182
[21] www.fmv.se
[22] Barbera, B. and Molinar, G. F., "A survey of pressure measurements under dynamic conditions in Italy", Proceedings EUROMET seminar on Dynamic Pressure, ENSAM-Paris, France, June 3rd, 1991, pp. 1-7
[23] www.kistler.ch
[24] Kumme, R., "Influence of measuring amplifiers on dynamic force measurements", Proceedings of the 13th International Conference on Force and Mass Measurements, Helsinki, Finland, May 10th-14th, 1993, pp. 25-31
[25] http://toshi.fujita3.iis.u-tokyo.ac.jp/research_project/pressuresensor.html
[26] Bill, B., "Measuring with Crystals – Principles and applications of the piezoelectric measuring technique", Verlag Moderne Industrie, 2002
[27] www.pcb.com
[28] Wang, J., Xiao, H., Deng, J, May, R. and Wang, A., "Self-calibrated Interferometric/Intensity-Based (SCIIB) Optical Fiber Pressure Sensor", Proceedings drom the SPIE Conference on Harsh Environment Sensors, Boston, Massachusetts, USA, November 1998, pp. 21-27
[29] Poorman, T. J., Kalashnikov, S. and Wlodarczyk, M. T., "New Generation of High-Temperature Fiber-Optic Pressure Sensors", Proceedings of the Sensor Expo, Boston, Massachusetts, USA, May 16th-18th, 1995, pp. 291-297
[30] Fürstenau, N., Schmidt, M., Bock, W. J. and Urbanczyk, W., "Dynamic pressure sensing with a fiber-optic polarimetric pressure transducer with two-wavelength passive quadrature readout", Applied Optics, Vol. 37, No. 4, February 1998, pp. 663-671

[31] Kobota, T. and Ooiwa, A., “Pressure Measurement using Laser Interferometer for Evaluating Dynamic Pressure Generator”, Proceedings of the IMEKO-XV World Congress, Osaka, Japan, June 13th-18th, 1999, pp. 231-236
[32] http://www.microsystems.metu.edu.tr/capacitiveps/capacitiveps.html
[33] www.validyne.com
[34] Bean, V. E., ”Dynamic Pressure Metrology”, Metrologia, Vol. 30, 1993/94, pp. 737-741
[35] Meirovitch, L., “Elements of Vibration Analysis”, McGraw-Hill Inc., ISBN 0-07-041342-8, 1986
[36] “A Guide for the Dynamic Calibration of Pressure Transducers”, ANSI B88.1-1972, The American Society of Mechanical Engineers, New York, USA, 1972
[37] Sitheeq, M. M., Farell, C. and Iyengar, A. K. S., “Experimental and Theoretical Analysis of Dynamic Response Characteristics of Pressure Transducer-Tube Systems”, The Instrument Society of America, 1997, pp. 11-20
[38] Zakrzewski, J. and Wróbel, K., “Dynamic Calibration of Low Range Silicon Pressure Sensors”, IEEE Instrumentation and Measurement Technology Conference, Budapest, Hungary, May 21st-23rd, 2001, pp. 493-496
[39] BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML, ”Guide to the expression of Uncertainty in Measurement”, ISO, ISBN 92-67-10188-99, 1993
[40] BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML, “International vocabulary of basic and general terms in metrology”, ISO, ISBN 92-67-01075-1, 1993
[41] www.ricardo.com
[42] Tunestål, P. A., ”The Use of Cylinder Pressure for Estimation of the In-Cylinder Air/Fuel Ratio of an Internal Combustion Engine”, PhD Dissertation, University of California at Berkeley, 2000
[43] Damion, J. P., ”Means of Dynamic Calibration for Pressure Transducers”, Metrologia, Vol. 30, 1993/94, pp. 743-746
[44] Bean, V. E., Bowers Jr, W. J., Hurst, W. S. and Rosasco, G. J., “Development of a Primary Standard for the Measurement of Dynamic Pressure and Temperature”, Metrologia, Vol. 30, 1993/94, pp. 747-750
[45] Hunt, A, ”Standards for the measurement of dynamic force, torque and pressure”, Andrew Hunt Consultants Ltd, November 1998
[46] www.dhinstruments.com
[47] Schweppe, J. L., Eichberger, L. C., Muster, D. F., Michaels, E. L. and Paskusz, G. F., ”Methods for the Dynamic Calibration of Pressure Transducers“, National Bureau of Standards Monograph 67, 1963
[48] Dibelius, G. and Minten, G., “Measurement of Unsteady Pressure Fluctuations Using Capillary Tubes”, Proceedings of the 7th symposium on measuring techniques for transonic and supersonic flow in cascades and turbomachines, Aachen, Germany, 1983, pp. 17.1-17.19
[49] Lokar, T., Smrecnik, A. and Bajsic, I., ”Generating Dynamic Pressure with Loudspeakers”, IMEKO, 2000, pp. 509-515
[50] Kobota, T. and Ooiwa, A., “Square-wave pressure generator using a novel rotating valve”, Metrologia, Vol. 36, 1999, pp. 637-640
[51] Kobota, T. and Ooiwa, A., “Method of evaluating frequency characteristics of pressure transducers using a newly developed dynamic pressure generator”, Sensors and Actuators, Vol. 79, 2000, pp. 97-101
[52] Hilten, J. S., Lederer, P. S., Vezzetti, C. F. and Mayo-Wells, J. F., “Development of Dynamic Calibration Methods for Pogo Pressure Transducers”, National Bureau of Standards Technical Note 927, USA, 1976
[53] Lally, J. F., “Dynamic Step-Pressure Calibration”, Proceedings from the NIST Workshop on the Measurement of Transient Pressure and Temperature”, Gaithersburg, Maryland, USA, April 23rd-24th, 1991, pp. 104-119
[54] Favour, J. and Stewart, R., “Primary calibration of pressure transducers to 10 000 Hz”, Proceedings of the 15th Aerospace Instrumentation Symposium, Instrument Society of America, USA, May 1969, pp. 89-96
[55] Rosasco, G. J., Bean, V. E. and Hurst, W. S., “A Proposed Dynamic Pressure and Temperature Primary Standard”, Journal of Research of the National Institute of Standards and Technology”, Vol. 95, No. 33, 1990, pp. 33-47
[56] Liu, H., Miller, D. W., and Talnagi, J. W., ”An experimental method to dynamically test pressure sensors using a rupture disk”, Review of Scientific Instruments, Vol. 73, No. 2, February 2002, pp. 459-463

[57] Walter, P. L., ”Dynamic Characterization of Pressure Transducers – An Industry/University Approach with Today´s Technology”, Proccedings of the 1998 44th International Instrumentation Symposium, Reno, Nevada, USA, pp. 513-521
[58] Shipunov, A. V., “Determination of the dynamic characteristics of piezoelectric pressure transducers and a comparative analysis of methods”, Measurement Techniques, Vol. 42, No. 10, 1999, pp. 959-961
[59] de Souza Vianna, J. N., de Sousa Oliveira, A. B. and Damion, J. P., ”Influence of the diaphragm on the metrological characteristics of a shock tube”, Metrologia, Vol. 36, 1999, pp. 599-603
[60] Wu, Z. M. and Jian, W. X., “Water Shock tube for High Pressure Dynamic Calibration”, IEEE WEP 1-8, 1994, 3 pages
[61] Smith, R. O., ”A Liquid-Medium Step-Function Pressure Calibrator”, Journal of Basic Engineering, December 1964, pp. 723-728
[62] Hunziker P. and Binggeli, E., “Calibration of piezoelectric pressure and acceleration transducers”, Proceedings of the 1998 5th International Conference on Structures Under Shock and Impact, Thessaloniki, Greece, 1998, pp. 263-271
[63] Voitenko, V. A. and Kuznetsov, L. I., ”A Pendulum Method for Calibrating Piezoelectric Gages”, Instruments and Experimental Techniques, Vol. 35, No. 4, Part 1, July-August, 1992, pp. 709-711
[64] Kong, D., Zhu, M., Li, Y. and Sun, H., “A New Force-testing Method for Direct Calibration of Dynamic Pressure”, Proceedings of the ISTM/99 3rd International Symposium on Test and Measurement, Xi’an, China, June 2nd-4th, 1999, pp. 1006-1009

SP Swedish National Testing and Research Institute
Box 857, SE-501 15 BORÅS, Sweden
Telephone: + 46 33 16 50 00, Telefax: + 46 33 13 55 02
E-mail: info@sp.se, Internet: www.sp.se

SP REPORT 2002:34
ISBN 91-7848-925-3
ISSN 0284-5172