INVESTIGATION AND DEVELOPMENT OF A DYNAMIC PRESSURE MEASUREMENT STANDARD

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ABSTRACT

INVESTIGATION AND DEVELOPMENT OF A DYNAMIC PRESSURE MEASUREMENT STANDARD

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. Along with the development of higher frequency sensors came the need for dynamic pressure calibration. Since dynamic calibrators were not commercially available until relatively recently, many laboratories developed unique calibration devices to suit specific needs. These included a variety of hydraulic and pneumatic shock, pulse, and sine wave pressure generators. The dead weight tester was sometimes used in a pressure release mode to generate a known, negative pressure pulse. This investigation aims to make step change improvements in pressure in for dynamic measurements. To investigate and develop a dynamic pressure measurement standard, a system was designed and manufactured. A drop weight system and impact test machine system were modified and it was automatized. Maksimum acceleration and velocity of dropping mass were masured and thanks to energy conservation laws, pressure value was calculated. A model function was defined. For the pressure transmission media, different oils was investigated in terms of pressure transmission and compressibility. As a pressure range, 500 MPa was tried to exceed at the 1% accuracy.

ÖZET

DİNAMİK BASINÇ ÖLÇÜM STANDARDININ ARAŞTIRILMASI VE GELİŞTİRİLMESİ

Dinamik basınç bir çok önemli alanda yapılan ölçümlerde karşımıza çıkmaktadır. Bu ölçümlerin yapıldığı alanlara örnek olarak; yanma analizi, otomobil endüstirisi, turbo makineler, aerodinamik, akışkan basıncı ve kontrolü, üretim prosesleri ve tıp verilebilir. Karşılaşılan basınç ölçüm aralıkları birkaç Pa'dan başlayıp, birkaç GPa değerlerine kadar değişim göstermekte ve aynı zamanda ölçülen frekans aralıkları da 1 Hz değerinin altından başlayarak 1 MHz değerlerine kadar olan aralıkta değişebilmektedir. Yüksek frekanslı sensörlerin gelişmesiyle birlikte, dinamik basınç kalibrasyonlarına da ihtiyaç duyulmaya başlandı. Dinamik kalibratörlerin yakın zamanlara kadar ticari olarak satışlarının mevcut olmaması sebebiyle, bir çok laboratuvar özel ihtiyaçlarını karşılamak için, bu ihtiyaçlarına cevap verebilecek kendi kalibrasyon cihazlarını geliştirdiler. Bu cihazlar çeşitli hidrolik ve pinomatik şok, darbe ve sinüs dalga basınç jeneratörlerini içeriyordu. Pistonlu basınç standartları da (piston manometresi), zaman zaman basınç tahliye modunda, değeri bilinen negatif basınç üreteçleri olarak kullanıldılar. Bu araştırmanın amacı, dinamik basınç ölçümleri alanında, kaydedilen ilerleme ve gelişmelere katkıda bulunarak bu alanda yapılan araştırmaları bir adım ileri taşımaktır. Bu çalışmada, bir dinamik basınç ölçüm standardı araştırmak ve geliştirmek için bir sistem tasarlandı ve üretildi. Bu amaçla, düşen ağırlık sistemi ve darbe testi makine sistemi modifiye edildi ve otomatik hale getirildi. Düşen kütlenin maksimum ivmesi ve hızı ölçüldü. Enerjinin korunumu yasası yardımıyla basınç değeri hesaplandı. Bir model fonksiyonu tanımlandı. Basınç iletim ortamları için, basıncın iletilebilmesi ve sıkıştırılabilmesi açısından farklı yağlar kullanılarak ölçümler yapıldı. Ölçümler 500 MPa basınca kadar %1 doğruluk hedeflenerek yapıldı.

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LIST OF SYMBOLS / ABBREVIATIONS

ASME	Standard document
GUM	Guide to the expression of uncertainty in measurement
Hz	Hertz
KHz	Kilohertz
MHz	Megahertz
MIKES	Laboratory of the centre for metrology and accreditation
msec	millisecond
NMI	The National Metrology Institute
PTB	Laboratory of Physikalisch-Technische Bundesanstalt
SPG	Sinusoidal pressure generator

1. INTRODUCTION

Pressure sensors are widely used in measurement and process control in many fields such as aerospace, medicine manufacturing, food processing, and electric power plants. There are many kinds of design mechanisms for pressure sensors. Some pressure sensors are appropriate for static pressure measurement and some for dynamic pressure measurement.

In the case of dynamic measurement, the response time of a pressure sensor is a very important parameter, which should be considered when selecting an appropriate pressure sensor for some pressure measurements or for process control. For example, the rise time of a Kistler 609B piezoelectric pressure sensor is about 3μs [1] therefore, it is excellent for use in capturing continuous rapid pressure changes.

Many applications of the measurement of the mechanical quantities force, torque, and pressure are of a dynamic type, i.e. the measurement results show a strong variation over time. The calibration of the respective transducers, however, is still only traceable to purely static procedures at the NMI (The National Metrology Institute) level. This is partly due to the complete lack of documentary standards or commonly accepted guidelines for dynamic calibration of mechanical sensors, which is a consequence of the lack of a joint international research effort in the field.

It is a well-known and accepted fact that mechanical sensors exhibit distinctive dynamic behaviour that shows, with increasing frequency, an increasing deviation from the static sensitivity characteristic. To make things even worse, the deficiencies in the knowledge of the transducers and the lack of dynamic calibration standards carries on to the electrical conditioning part of the measurement chain. The amplifiers used to complete the measurement chain are known to have distinctive frequency dependence in their response, which has to be taken into account in order to achieve a precise and reliable measurement result. But even here, commonly accepted calibration procedures and measurement uncertainty budgets have not been established so far and, in some cases (bridge amplifiers), a reliable dynamic calibration device still has to be developed. This leads to inaccurate measurement results and culminates in an almost complete ignorance of the magnitude of the measurement uncertainty.

The lack of a metrological infrastructure for dynamic mechanical quantities has been recognised for some time, and a number of organisations (both NMIs and commercial entities) have attempted to remedy this. However the solutions offered so far, including those offered as services by some NMIs, have often lacked traceability, or were application-specific, not well-grounded in physical or engineering theory, limited only to aspects of testing rather than calibration, or do not conform with metrological best practice as codified in the guide to the expression of uncertainty in measurement (GUM).

At present traceability exists for static realisations of the mechanical quantities force, torque and pressure. The traceability is established through validated primary calibration devices together with a standardised uncertainty evaluation provided by the *Guide to the expression of uncertainty in measurement* (GUM). The problems that this project addresses arise in dynamic measurements, i.e., those cases in which the frequency-dependent response of a sensor cannot be described by a single parameter (sensitivity) from static calibration. In these cases there will be a need to correct the measurement data for these limitations. This requires that a dynamic model for the system be established through a dynamic calibration.

Various dynamic pressure generation systems developed by NMIs and specialist manufacturers underpin the current state of the art. These systems use a range of pressure generation techniques, including drop weight impacts, fast opening valves, and shock tubes, but they all lack absolute dynamic pressure traceability, instead relying on statically calibrated reference transducers to provide the instantaneous pressure values. The available devices cover ranges up to 800 MPa [2].

The standardised uncertainty treatment in metrology does not account for dynamic measurements. To achieve traceability for dynamic force, torque and pressure, new methods for the evaluation of uncertainties are needed which are consistent with those employed in the static case. This requires development of appropriate mathematical and statistical models for both the calibration and the measurement (or application) stages, much of which will be new to metrology as it is currently practised both at the NMI level and in industrial applications.

NMIs and stakeholders will have access to new systems capable of generating specific pressure waveforms and used to calibrate industrial transducers against the reference transducers characterised in the primary systems. Validated traceability to the SI will be available for the first time, including documented procedures and guidelines for the estimation of measurement uncertainty.

Consequently, completion of these dynamic pressure measurements will help the industry to apply more reliable and reproducible dynamic pressure measurements e.g. for in-cylinder pressure measurement in combustion engines, which is a crucial prerequisite for future fuel efficiency improvements.

Literature search for this thesis research is detailed in following:

V. E. Bean reviewed the properties of dynamic pressure transducers and various methods for determining them [3] in 1993 and studied on development primary standard for dynamic pressure and temperature in 1994 [4]. A brief review of the different methods of determining the transfer function of a transducer and the equipment used for the dynamic calibration of pressure transducers in gaseous media had been researched by J. P. Damion in 1994 [5]. A. V. Shipunov made a study of impulse methods of determining ttle dynamic characteristics of piezoelectric pressure transducers in 1999 [6]. J. L. Scheppe, in 1963 [7], D. W. Rockwell, in 1967 [8], J. S. Hilten, in 1976 [9], B. Granath, in 1994 [10] researched dynamic measurement methods of dynamic pressure sensors. Tokihiko Kobata [11] in 2000, C. Elster, A. Link and T. Bruns, in 2007 [12], S. Eichstadt, A. Link, P. Harris and C. Elster [13, 14] studied evaluation of measurement uncertainty in dynamic measurements and Monte Carlo method, in 2008 and 2011. Additionaly, in 2010, dynamic uncertainty is modeled as compensated second-order systems by S. Eichstadt, A. Link and C. Elster [15]. In 2000, Sang-Mok Chang and Hiroshi Muramatsu made research on principle and applications of piezoelectric crystal sensors [16] and E. Philippot studied on General Survey of Quartz and Quartz-like Materials in [17]. While Jiashi Yang published a book about an introduction to the theory of piezoelectricity in 2005 [18] as Ahmad Safari and E. Koray Akdogan edited a book about piezoelectric and acoustic materials for transducer applications in 2008 [19].

Dynamic pressure sensors have a wide area of usage both in measurement and in controlling process in lots of fields like aerospace, medicine production, food processing and engineering and electric power generating units. It is observed that pressure sensors can be designed in different working mechanisms [1]. Pressure transducers has a mechanical structure. In case using in the measurement of a dynamic parameter effect, transducer will be subjected to some effects. These effects can be make it as deflected, vibrated, resonated, conducted sound signal, experienced stress and strain, and transferred force and motions. Structures of sensors behave in different manner at different spectrum of frequencies at low, medium, and high districts of frequencies [3, 20]. While some pressure transducers are suitable for static pressure measurements some others can be used in dynamic pressure measurements. In dynamic process, one of the most important components of a dynamic pressure transducer is response time of a pressure transducer. Response time parameter should be though about seriously in selection of a convenient pressure transducer during the pressure measurement applications [1]. Pressure sensors with piezoelectric structure generate electric charges, which are proportional to the applied input transient pressure [21]. Generated charges converted into electrical signal values by a connected charge amplifier. A common example design of a piezoelectric pressure transducer is given in Figure 1.1a and Figure 1.1b [22]. An example of a dynamic pressure sensor in quartz structured given in Figure 1.1c.

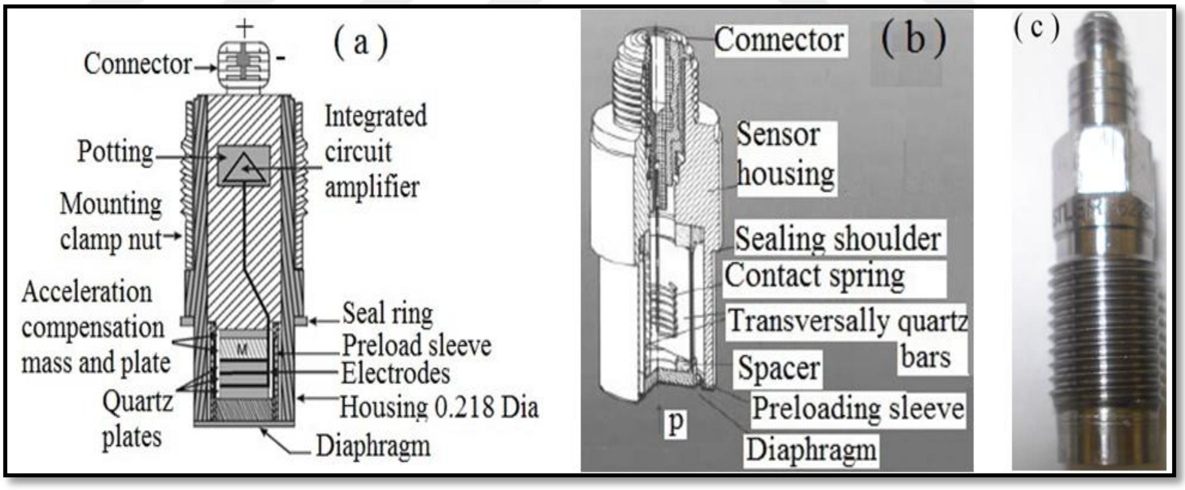


Figure 1.1. Structure of a typical piezoelectric pressure transducer (a) [23], (b) [24], (c) [25]

Some pressure calibration applications show time invariant static characteristics so certain types of transducers can be used to measure such static time invariant value of pressure. If pressure value is changing by time or in other saying if it is time-dependent, it is defined as dynamic because it varies significantly in a short period of time demanding a dynamic calibration. The dynamic pressure effect can be mentioned if the signal value changes in the order of 63.2% of the original size in less than one second of time interval [26, 27]. Many applications of the measurement of the mechanical quantity pressure is of a dynamic type, i.e. the measurand shows a strong variation over time. The calibration of the respective transducers, however, is still only traceable to purely static calibrations. This is partly due to the complete lack of documentary standards or commonly accepted guidelines for dynamic calibration of mechanical sensors [2]. Although lots of instrument are used in dynamic measurement area, today lots of those have been still calibrated across to static references and static calibration procedures, due to the lack of standard calibration procedures, methods for assessment of uncertainty in measurement and metrological traceability in calibrations [26].

Dynamic phenomena research generally caused by necessity for accurate measurements in space activities [24]. The necessities in precise high dynamic pressure measurement have increased in miscellaneous industrial and research applications [12, 28, 29]. For example, including development and monitoring of automotive engines, gas turbine engines, hydraulic systems, and development within the ammunition and firearms, medicine, aviation and spaceflight, defense industries, turbo machinery, aerodynamics, fluid power and control and oil industries [24, 30, 31, 2]. So, it is seen that dynamic pressure is needed to be measured in wide frequency band is appeared [32, 33]. In these outstanding application areas of dynamic pressure, researchers can see wide interval amplitudes and wide interval of frequencies. While amplitudes from a few Pa to some GPa, the frequencies change from below one Hz to about one MHz. While limited study was reported at the 70.s and 80s, at 90s significance information was revealed. Now, a lot of different measurement sensors and auxiliary equipments are available for dynamic measurement applications.

Metrological traceability is property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations [2, 34]. When you report a measurement results, you must assign a uncertainty value for each reported value. It is the measurement uncertainty. Unfortunately, dynamic measurement quantities have lack of traceability for today. Many researches have been done in developing methods and procedures in dynamic measurement field however most measurements realized in industry are made without traceability and without a known measurement uncertainty [24].

For a pressure transducer, sensitivity is defined as ratio of changing in output of the sensor to changing value in input of the sensor for a specific change of pressure. Static structured pressure transducers are characterized by their sensitivity. The sensitivity is practically can be taken a constant value in sensor working range. In dynamic measurements since input quantity value changes by time, rate of changing input value to changing output value isn’t a constant value which is different from the static pressure measurement situation. In case of the dynamic measurement situation transducer can’t be modelled and characterized only with transducer’s sensitivity alone. Reason for dynamic pressure calibration is to determine what is transducer’s transfer function is. These quantities in transfer function are phase and gain information as function of frequency. They define how a sensor behaves in static and dynamic measurement situation [5]. The main purpose of high pressure measurements is evaluating what is dynamic characteristics and performances of pressure sensors at their working pressure value that it is the initial condition to be sure reliable and correct measurement results [35]. The means of a dynamic calibration of a pressure transducer or a measurement system consist of the evaluation of their dynamic treatment with sufficient and suitable accuracy value [36]. Frequency analysing and transient response analysing methods are the conventional methods while determining the dynamic characteristics [32, 37]. In dynamic pressure calibration, a measurement system should be used. This system should generate dynamic pressure which is time varying and reliable and controllable way and whose value is well known. This generated pressure wave is taken as reference pressure value in calibration of transducers. Used pressure generator has an effect both on the calibration procedure and type of test device sensor [36]. Literature shows that the first working reports on dynamic calibration appeared in the 1960s [38]. Later, a guide was published on dynamic calibration of sensors [39] which was reprinted by the Instrumentation, Systems and Automation [40], describing the methods for the calibration of pressure sensors. No standardization of methods and procedures are available for dynamic pressure calibration yet. The estimation of associated uncertainties are seems to be crucial drawback in dynamic pressure calibrations [41]. According to [27], one of the most important challenges for dynamic pressure transducer calibrations is to be able to find the reference pressure value for different frequencies with a high level of confidence in the measurements [26].

Generally, dynamic pressure generators are classified into periodic and aperiodic types. The aperiodic generators mostly generate a signal a like step functions while the periodic generators usually produce sine function signals. Shock tube and quick opening valves are the examples of aperiodic generators [11]. They generate step signal. Signal has short rise time and large amplitude. It has characteristically a few hundred kilo Hertz bandwidth. Bandwidth increases in transient response of step pressure. In several microseconds time interval signal converges toward a steady state [37]. Many of periodic generators generate periodically pneumatic pressure signals which have low amplitude and low frequency. Periodic generators are convenient for surveying the dynamic effect characteristics of a sensor or equipment which is using under periodic phenomena like a relief valve, a pump, and a proportional servo valves [32].

For low pressure sensors and for dynamic microphones' calibration an acoustical shock-generator was developed. For example, at low acoustic frequency and amplitude loudspeaker can be selected for purpose of dynamic pressure generator. For this purpose, measurement set-up suggested by Dibe Lius and Minten [42] using a microphone up to 2 mbar pressure amplitude [24].

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. Using a rotating valve [43] pressure may be switched and supplied to calibration sensor among between two or more calibration values. As a result approximately a rectangular pressure waveform is generated [24].

Weyer and Schod [44] have worked on improved kind of a rotating-valve. This pressure generator is planned to use up to 5 kHz. Hilten et al [45] has another setup to get sine dynamic pressure. He has a liquid-filled tube and tube was mounted on electro dynamic shaker's armature. Del Prete et al [46] demonstrated a vibration shaker and a load cell combination setup. It has the contact area between actuator and sensor to get a basic setup to be used in calibration of dynamic pressure transducers [24].

Shock tube is another method for calibrations of dynamic pressure transducers. It includes a pressure transducer located in the centre of the end-wall. It works by means of a pressurization system based on bottled nitrogen, using either single or double diaphragms up to pressure range of 1.4 MPa. A Plastic shock tube of 0.7 m driver section and 2 m driven section is shown in Figure 1.2a and dynamic transducers connected to shock tube is seen in Figure 1.2b. Burst aluminum diaphragm is given in Figure 1.2c [47].

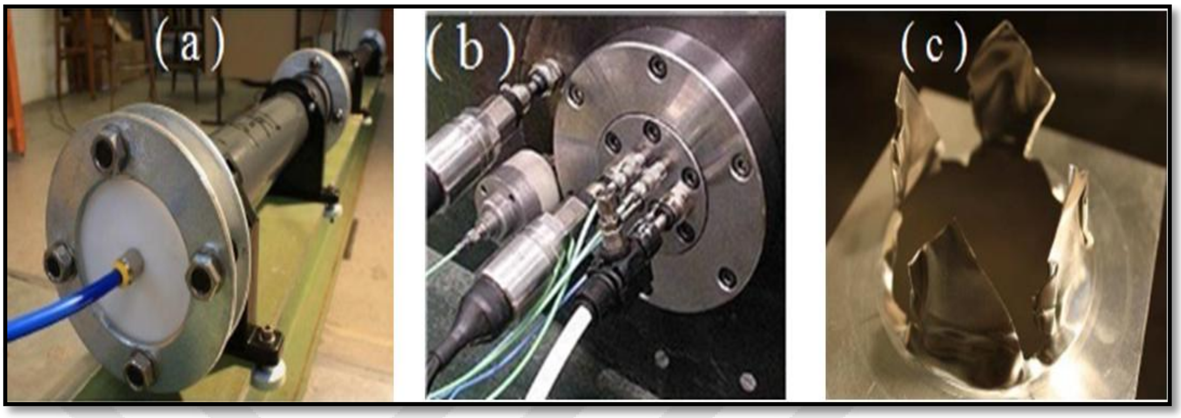


Figure 1.2. Shock tube [47]

The structure of a shock tube composed of a cylindrical plastic tube with uniform cross-section area. The diaphragm separated the tube into two volumes [7, 3, 48, 49]. From one end gas is sent to the first volume. Test sensors are connected into second volume. Increased pressure destroys the diaphragm and shock wave reaches to test sensors which have been connected to another end of the tube. Rise time of the pressure step because of the shock wave is about nanosecond range [7, 3, 39, 50]. Therefore a shock tube is considered as an idealized pressure step including all frequency spectrums above the low-frequency limit.

Another method is negative pressure drop method. In this method, a pressure balance is used as a reference instrument and so reference pressure is calculated based on pressure balance working principle which is pressure equals force per unit area. After system pressurized immediately, pressure line is vented to atmospheric pressure and a simultaneous negative pressure drop is applied on the dynamic pressure sensor.

Quick-opening valve setups are available to produce both negative and positive pressure steps. According to some studies [51, 43] fast opening setups are capable of dynamic calibration up to about 10 kHz. It is suggested [39] that there should be a rate between the produced pressure by the source and reference sensor rise time. It shouldn’t be more than one-fifth. At low frequencies, a gas-operated quick-opening valve instrument can be thinking as to be an extension of the shock tube [52].

Many of scientists are agree that obtain a precise generated pressure is quite difficult. That is why a reference sensor is necessary. When the mass drops directly on to pressure sensor, corresponding response may [43] not be the same like a pressure distribution over whole sensing element. The result pressure pulse like a half-sinus and parabola signal and rise time of it in the order of ms (millisecond) [53].

The dynamic pressure facilities of some set-ups operate according to the “drop mass” principle. The impact on the piston leads to the compression of a small volume of a hydraulic liquid within a pressure cavity that is connected to the test device, thus a shock pressure excitation to the test device is applied [20].

In drop hammer/mass system configuration, test sensor is mounted into close part of a piston and cylinder unit in a closed reservoir or chamber. Piston-cylinder also mounted into a reservoir which is filled with fluid too. Fluid is practically incompressible oil like glycerin. A guided or free falling mass drops on to the piston. Generated pressure pulse reaches to test sensor. After the mass first drop, it is caught by rebound system. Riegeabuer [54] used drop mass method for primary calibration. Lally [55] realized a setup to measure hydraulic pressure pulses from mass drop on a piston-cylinder manifold using with tourmaline piezoelectric sensor. Momma and Lichtarowicz [56] showed a simple calibration technique where steel balls with 4mm to 7 mm in diameter were dropped from different heights from 10 mm to 50 mm on to sensor. Shipunov [6] represented an alternative method. In this method steel balls were dropped directly on to pressure sensor. Kong et al [57] used a accurate force sensor replacing the pressure sensor as a reference.

Especially, pressure transducers in piezoelectric structure are commonly used in dynamic measurements at pressure area as well as force and torque since piezoelectric is convenient by nature. Some examples of piezoelectric structures quartz, natural tourmaline and manmade ferroelectric ceramic materials polarized artificially can be used for dynamic measurements. Piezoelectric structured sensors have been used in a wide linear range. Such sensor has ultrahigh frequency response and rise time as 0.2 µs. They can operate in a wide temperature range. A voltage output is produced as response to corresponding deformation. Quartz sensors can be used in tough environments thanks to their durable solid-state construction [58]. A comparison among the different methods in dynamic pressure calibrations is given in Figure 1.3.

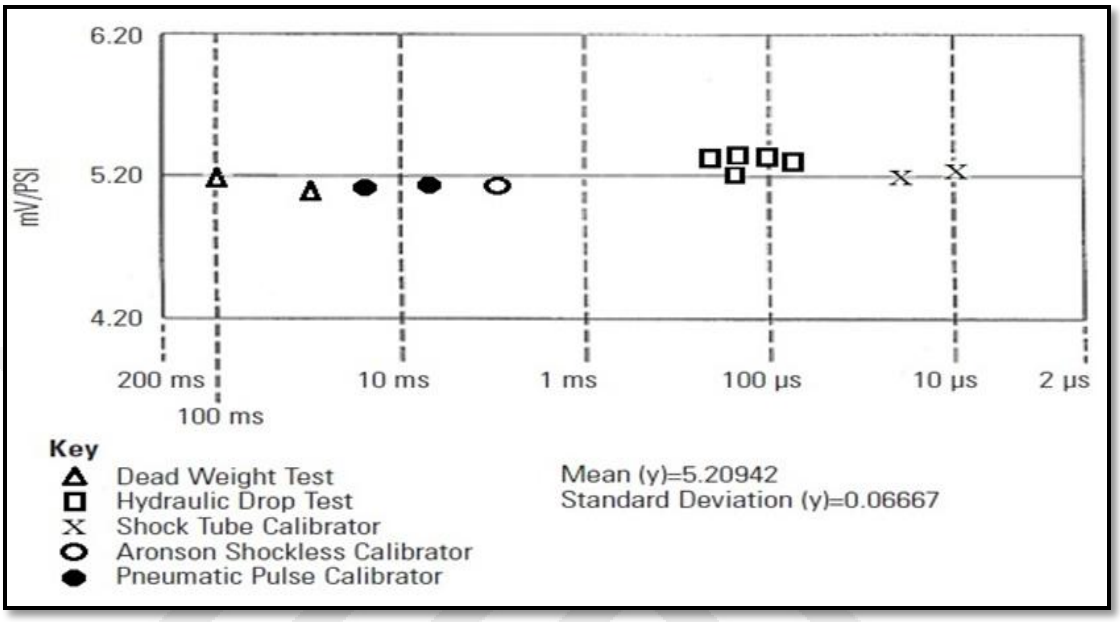


Figure 1.3. Comparison of different methods in dynamic pressure calibrations [58]

On dynamic pressure transducers, there are five testing methods, that may theoretically be used to analyze the dynamic response of a sensor. They are step response, ramp response, impulse response, frequency response, and noise analysis. The selection of a testing method for a pressure sensor depends on the dynamic performance of the tested sensor, the availability and the performance of a reference sensor, and the pressure input signal itself. It is a challenge to dynamically test pressure sensors. For example, an actual pressure change may be treated as a step input for a pressure sensor with slow response but may not be an ideal step input for a pressure sensor with very rapid response. The ramp response method depends on the ramp input, availability of a reference sensor to characterize the ramp input, and the difference between the tested and the reference sensor. Pressure transients, which are used to test the dynamic response of a pressure sensor, can be generated from, e.g., a shock tube that uses a metal diaphragm, a gas tunnel, or a pump. These methods are relatively complicated and expensive in terms of the availability of specific equipment. For example, the metal diaphragm may not fully open, therefore, the actual pressure transient using a metal diaphragm may be unpredictable.

Shockless pressure - step generators are have been developed that generate a rapidly rising pressure step between two pressure levels [7, 8, 59-62]. Most of these units employ a quick-opening valve. However, at least one utilizes a burst diaphragm. The geometry of the generator and the opening time of the valve or burst diaphragm are such as to preclude the formation of shock waves when the device is operated. Shockless step generators have been designed and successfully used to produce both increasing and decreasing pressure steps. Although most of these generators employ gaseous media, a few liquid-medium devices have been developed and used. The shockless pressure-step generator, now commercially available, has the following advantages over other dynamic-pressure calibrators:

i. The magnitude of the pressure step generated by the device is determined by measurements of static pressure on the test transducer before and after the quick-opening valve is opened, thereby permitting high accuracy in its determination.

ii. The duration of constant pressure behind the pressure step can be made as long as desired.

iii. Both the initial pressure on the transducer and the magnitude of the pressure step are controllable over very wide pressure ranges.

iv. In general, it is superior to the shock tube from the standpoint of operational speed and simplicity of technique.

The dynamic characteristics of a shockless pressure-step generator are determined by measurement with a calibrated reference transducer possessing a rise time of no more than one-fifth that of the measurand. The following dynamic characteristics of the generator should be known: rise time, overshoot, undershoot, and the inherent ringing frequencies with their associated damping ratios. Also of interest is the stability of both static-pressure levels P_1 (initial pressure) and P_2 (final pressure).

When the pressure rise time is one-fifth that of the transducer undergoing test or calibration, the error in the measurand value of transducer rise time is less than 1%. If this criterion is not met, the complete rise time must be analyzed carefully for meaningful results.

Acceleration is present during the operation of the shockless pressure-step generator, and this should be minimized by design. In general, the shorter the rise time of the device, the greater is the level of acceleration (ground shock). In those units that utilize poppet valves, it may be necessary to open the poppet valve more slowly when calibrating at very low pressures in order to keep the acceleration level to a minimum.

Associated with the pressure step produced by these generators is a dynamic temperature change in which amplitude is related directly to the pressure change, $P_2 - P_1$, and inversely to the rise time of the measurand. As with shock tubes, the effect of the dynamic temperature pulse on the response of both the test and reference transducers must be determined. When a gas medium is used in the shockless step generator, the rise time of the measurand is inversely related to the speed of sound in the gas. For this reason helium is used when very short rise times are desired.

Pulse generators have been developed to provide single-peaking pulses of reasonably controlled amplitudes. These pulse generators produce a dynamic measurand that is not a step function, but that may resemble a single half cycle of a sine wave. One technique employed to generate such a pulse is to drop a mass onto a piston in contact with the surface of an incompressible fluid contained within a fixed volume [63, 9, 64]. The commercial version of this is referred to as a hydraulic-impulse calibrator. The device consists of a piston/cylinder manifold and a drop tube containing a mass that can be dropped onto the piston from various heights. The amplitude of the pulse is dependent on the fluid incompressibility, the mass, its initial height above the piston, and the piston area. The pulse generator is not an absolute calibration device and requires a comparison pressure transducer of known characteristics to monitor the pulse and provide a peak value measurement for the test transducer. Alternately, commercial versions that operate to 100,000 psi depend on acceleration references on a known mass [65, 10].

The greatest advantage of the pulse generator is the comparative ease with which very high-pressure pulses can be generated. Care must be taken in the selection and location of the reference transducer used since results of the calibration are dependent on this comparison standard. Tourmaline transducers, which are volumetrically sensitive, are commonly used as transfer standards in hydraulic-impulse calibrators [66]. Hydrostatic pressure is applied directly to the crystal. The recommended conditions of operation of 5.2 relative to the comparison transducer apply equally well to these generators. In order to achieve accuracy in calibration using the pulse generator, it is essential that no pockets of gas exist at the diaphragm of either the comparison or test transducers.

Sensitivity of periodic pressure function generators (sinusoidal pressure generators) are used in dynamic calibration of a pressure transducer could ideally be accomplished by sensing known inputs from a periodic pressure generator at known frequencies and amplitudes if such a device existed. The observed response, including the magnitude, waveform, and phase lag could then be compared with the known input at various conditions. In order to calibrate with only one frequency at a time for accuracy and simplicity, a sinusoidal pressure generator (SPG) is required. In practice, there are limitations to this approach. First, the applied average pressure levels and dynamic amplitudes generally are not known by absolute means, and must be measured by another transducer. The SPG generates a pulsating pressure in a small chamber that can be monitored simultaneously both by a reference standard transducer and by the transducer being calibrated [66, 67]. The two transducers must be sufficiently close so that they sense the same pressure, including amplitude, shape, and phase lag. Analysis of the output of the transducer being calibrated is thus entirely dependent on the performance of the reference transducer and what is known about this performance. The reference transducer, if statically calibrated, should also be calibrated by dynamic methods to establish that its sensitivity derived from static and dynamic calibration is the same. Credibility of the dynamic sensitivity of the reference transducer is a basic limitation of SPG utilization to a comparison process. As long as the reference transducer is provided with credible dynamic calibration, it may not be a serious limitation because high-quality reference transducers can be selected that have response characteristics exceeding the pressure, pressure amplitude, and frequency that can be obtained with available SPGs. Otherwise, it may be difficult to present a compelling argument concerning the validity of any calibration that uses a statically calibrated transducer as a reference standard for dynamic calibration.

The governing limitations are associated with the ability of the SPG to provide the desired signal. An SPG device, when used for calibrating a pressure transducer for a specific use, should satisfy the following:

i. The pressure generated is sinusoidal such that frequencies other than the fundamental are negligible.
ii. The frequency range generated covers the frequencies of pressure expected in the intended application.

iii. The operating pressure range covers the transducer rating and/or intended application.

iv. The dynamic pressure amplitude generated is large enough to identify possible nonlinearities in the transducer amplitude response.

v. The SPG is operated with the same medium (gas or liquid) with which the transducer is to be used.

In many cases, these criteria cannot be met, and a less-than-desired match is obtained between the dynamic pressure measurand applied during calibration and that encountered in use of the instrument. Many special devices have been proposed and developed as SPGs, and these are described in considerable detail [68, 7, 69-75]. The SPGs can be categorized as acoustic resonators, variable-volume generators, or variable-mass generators. Little has been done to further develop SPGS, since the 1960s when sinusoidal calibrator research was government funded.

Drop weight machines are also used to get dynamic pressure. Dynamic pressure facilities of MIKES and PTB operate according to the "drop weight" principle. At PTB, a rigid mass ball of about 3 kg is dropped on a piston of a cross sectional diameter of approximately 8 mm [76]. At MIKES, the principle is the same, but the cylindrical mass body is about 14 kg and the piston diameter is of the order of a few centimeters. The following figures show the design of the drop weight system in Figure 1.4 and PTB dynamic pressure system in Figure 1.5 respectively.

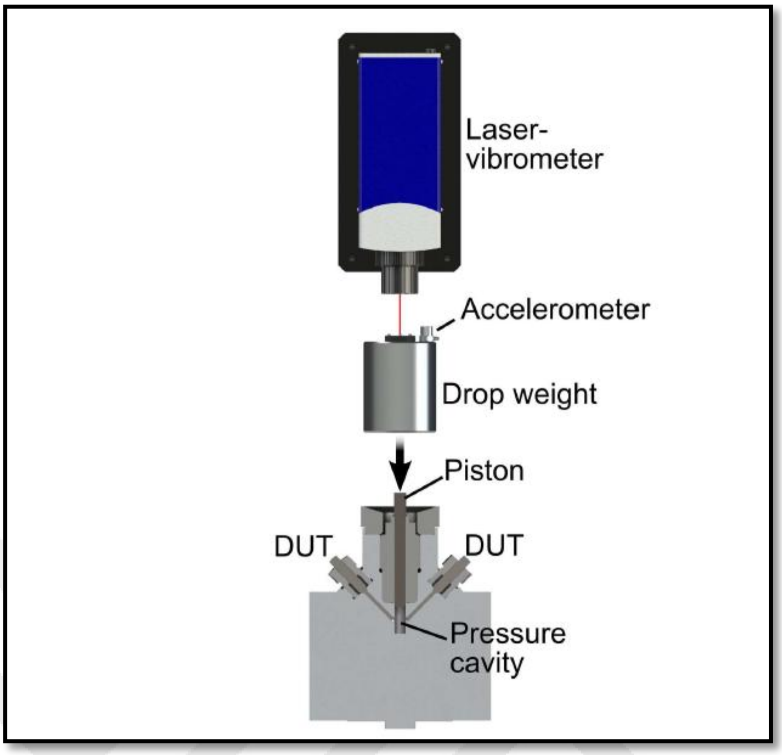


Figure 1.4. Drop weight system [47]

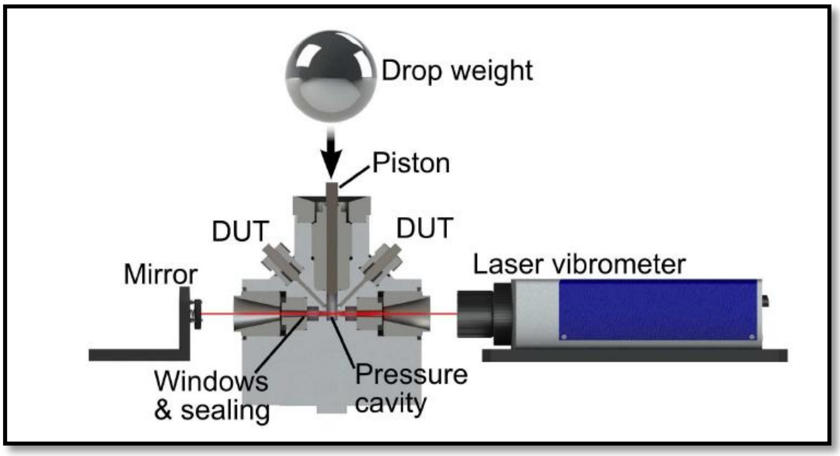
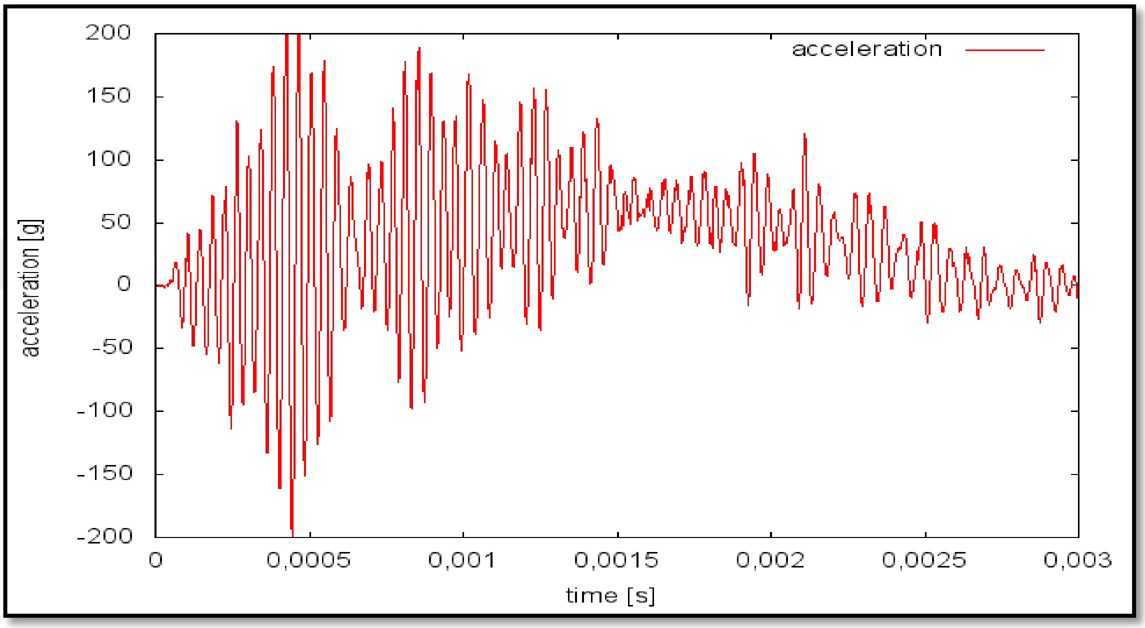


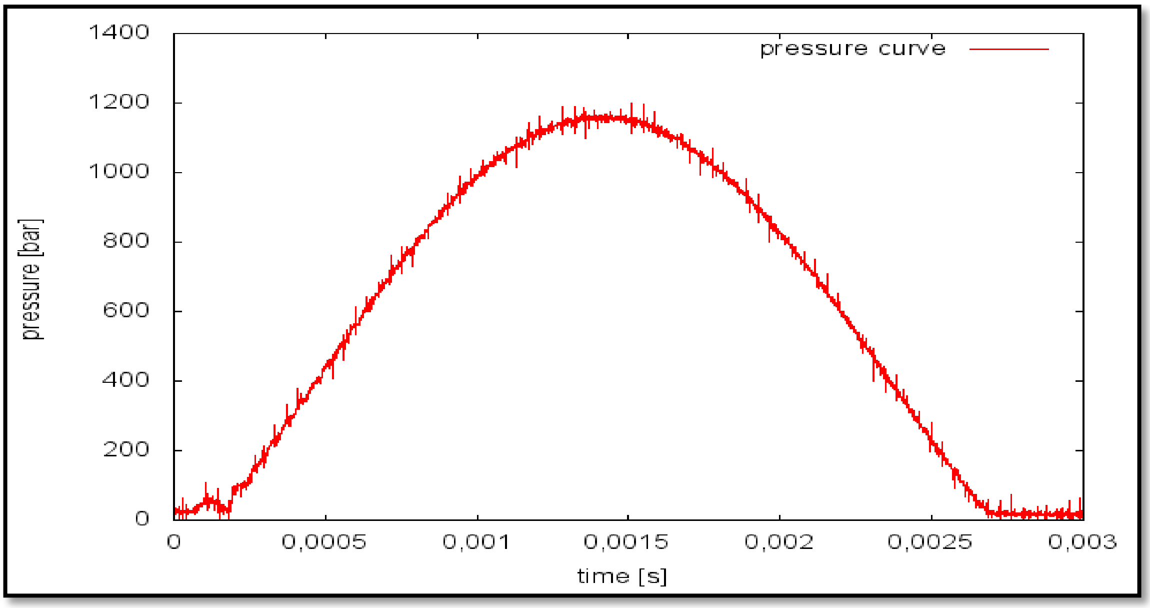
Figure 1.5. Design of the PTB dynamic pressure system [47]

The impact on the piston leads to the compression of a small volume of a hydraulic liquid within a pressure cavity that is connected to the device(s) under test (DUT), thus applying a shock pressure excitation to the DUT. Commonly these devices are used for the comparison of DUT with a reference transducer in a secondary calibration scheme.

However, within the JRP, the laboratories follow two different approaches to obtain a direct pressure measurement without a reference sensor. Figure 1.6 presents a dynamic pressure measurement (unfiltered data) performed at MIKES showing the deceleration of the drop weight and the corresponding pressure pulse of about 2.5 ms pulse length.



(a)



(b)

Figure 1.6. (a) Acceleration and (b) pressure curves [47]

The MIKES device is modified to measure the motion of the piston or the deceleration of the drop-weight during impact to deduce the force transmitted by the piston's crosssection into the hydraulic fluid. Thus via force and crosssection or via displacement and compressibility the actual pressure in the cavity can be determined. The first method gives rough estimations of pressure values, while the latter takes into account cavity and fluid effects, thus providing more information, improved traceability, and smaller uncertainties. The exact determination of the cavity volume, and changes in it due to piston movement, is the key requirement.

The PTB device is under modification to allow for an interferometric measurement of the optical path length through the pressure cavity, i.e., the hydraulic medium. This path length changes as the refractive index of the transmission medium varies as the fluid is compressed. In this approach the actual dynamic pressure can be linked to a static calibration of the optical measurement. The goal is to avoid any effects of inertia in the traceability chain between static and dynamic pressure. Preliminary tests of the measurement scheme are currently being performed in parallel to the modification of the drop weight device.

Shock tube, in its simplest form, consists of two sections of tubing separated by a thin diaphragm. When these two sections are pressurized to different pressure levels, and the diaphragm is suddenly ruptured, the higher-pressure gas will immediately begin to flow and compress the gas at a lower pressure [77, 66, 62] .

It should be noted that most cold-gas, shock-tube-development work occurred in or before the 1960s. However, in 1997, a shock tube was designed and built at a university for a transducer manufacturer. The development report for this new shock tube [65], also updates the literature through the intervening time period.

At a distance of approximately 10 to 15 tube diameters downstream from the diaphragm, a well-formed shock wave is established. This shock wave continues to move through the remainder of the gas in the low-pressure section at approximately a constant velocity. Behind the shock wave, the pressure suddenly rises to a new value, resulting in a positive pressure step. The length of time the pressure remains constant behind the shock wave depends on the dimensions of the shock tube, the position in the low pressure section at which the pressure is being monitored, the degree of smoothness of the inner walls of the low-pressure section, the type and design of the diaphragm, and the type, temperature, and initial pressure of the gas in each section. Air or helium and air in combination are commonly used gases.

When a shock tube is utilized for pressure transducer calibration, several parameters must be measured before the amplitude of the pressure step can be ascertained. These parameters include the shock-wave velocity, V_s, and the initial absolute pressure, P_1, and temperature, T_1, of the gas in the low-pressure section.

The dynamic pressure facilities of NPL operate according to another principle: the shock tube. They have developed a 1.4 MPa plastic shock tube with interchangeable driven sections of 2 m, 4 m, and 6 m lengths. It includes a pressure transducer located in the centre of the end-wall. It works by means of a pressurization system based on bottled nitrogen, using either single or double diaphragms. Future work will include shock wave velocity measurement (via side-wall mounted sensors) and end-wall acceleration measurement. The photographs in Figures 1.7 and Figure 1.8 illustrate the shock tube and a diaphragm after the test respectively.

A comparison of the different driven sections of the plastic tube, with different burst pressures and diaphragm arrangements, has been carried out. Results indicate that varying the burst pressure has the greatest influence on the characteristics of the end-wall pressure trace.

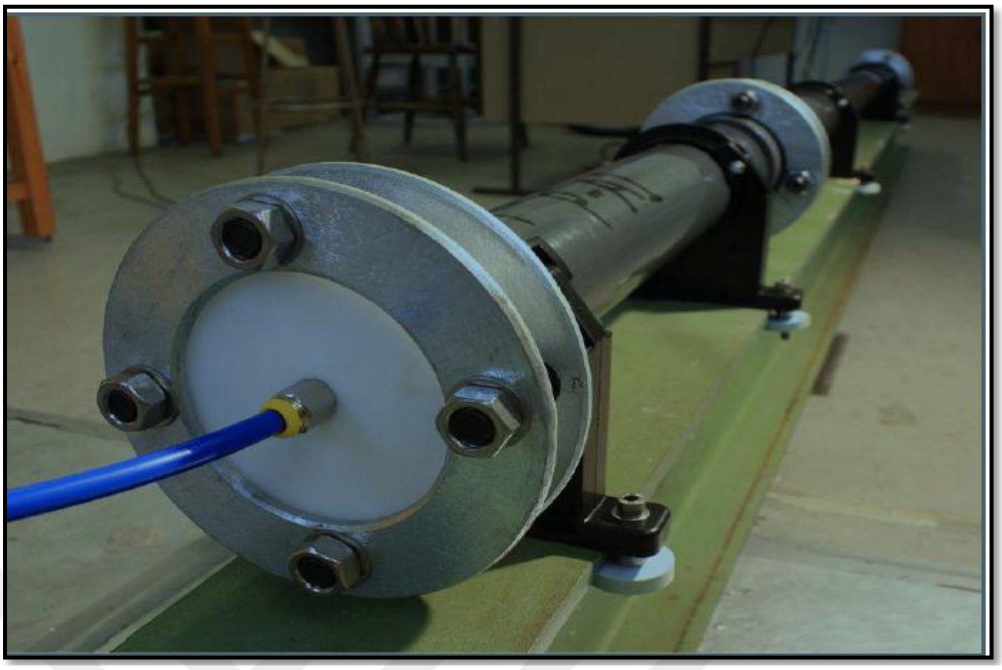


Figure 1.7. Plastic shock tube of 0.7 m driver section and 2 m driven section [47]

Figure 1.8. Burst aluminum diaphragm [47]

In this study investigation and development of a dynamic pressure measurement standard was aimed. Many applications of the measurement of the mechanical quantities force, torque, and pressure are of a dynamic type, i.e. the measurand shows a strong variation over time. The calibration of the respective transducers, however, is still only traceable to purely static procedures. At present traceability exists for static realisations of the mechanical quantity of pressure.

The problems that this investigation addresses arise in dynamic measurements, i.e., those cases in which the frequency-dependent response of a sensor cannot be described by a single parameter (sensitivity) from static calibration. In these cases there will be a need to correct the measurement data for these limitations. This requires that a dynamic model for the system be established through a dynamic calibration.

This study deals with the current lack of traceability for the measurement of dynamic pressure which is one of the dynamic mechanical quantities, including traceability of the response of transducers instrumentation to dynamic stimuli based on drop weight method

2. BACKGROUND

The state of art of dynamic pressure calibration and pressure sensor technology has significantly advanced since 1972 [77]. The ASME standard documents early attempts to develop dynamic pressure calibration methods, some of which never evolved further into successful technology. Most of the calibration devices described were uniquely engineered at individual laboratories to meet their specific measurement needs. However, today, some of these devices have evolved into commercially available products.

The need to measure "nonsteady" dynamic pressure became very important after World War-II during the rapid development of jet aircraft and aerospace technology. Investigations of turbulence associated with launch, shock waves upon re-entry, sonic boom, rocket combustion stability, air blast [68, 78], and the dynamics involved with weapons testing were significant measurement challenges. Investigations in these and other areas have necessitated faithful measurement of pressure variations at frequencies from near zero to the neighborhood of 106 Hertz (Hz). The degree of accuracy with which these measurements must be made varies widely throughout the technical community, as does the use made of information derived from such measurements. Often there are other complicating factors, such as severe environmental effects, which must be considered, if meaningful information is to be obtained. When considering the measurement problem, the investigator must first determine the dynamic characteristics of the pressure transducer. It is toward the satisfaction of this basic requirement that this document is directed.

Dynamic pressure calibration was difficult because of the limitation of dynamic pressure calibration sources available. Dynamic calibrators were simply not commercially available. Since then, substantial improvement has been made in the state-of-the-art of both dynamic pressure calibrators and high-frequency pressure transducers to meet many current measurement requirements for amplitude, frequency, and accuracy. Most of the dynamic calibrators available today incorporating fast-acting valves yield dynamic pressure amplitudes that are independently established. Others use a pressure transducer as a "transfer" standard that the transducer being calibrated is compared against [77, 66].

Although the user’s requirement for information concerning a transducer’s response characteristics has been as varied as the test methods used to obtain the data, current commercial calibrators and digital data acquisition systems have helped to obtain more accurate information. Unfortunately there have been many instances where worthwhile data have gone unused because of the manner in which they were presented.

2.1. DYNAMIC PRESSURE GENERATORS

The dynamic calibration of pressure transducers requires that the measurand produced by a dynamic pressure generator varies in time in both a known and an appropriate manner. With some generators, the pressure-time relationship can be predicted quite accurately. With others, the pressure-time relationship can be established accurately only with the aid of comparison to referenced pressure transducers. While reproducibility is a highly desirable characteristic of the dynamic pressure generator, it is not an essential characteristic. When such a characteristic is lacking in a generator, full dependence on the reference transducer is required [40].

Dynamic-pressure generators fall into two basic classes: aperiodic and periodic. The aperiodic generators are characterized by the pulse shapes they produce, such as the step or the peaking pulse. Quickopening valve devices and pulse generators produce pressure rise times generally in the milli-second range or less. The rise times and the pressure amplitudes generated by these devices vary markedly from one type of aperiodic pressure generator to another. The shock tube, for example, is capable of generating pressure steps having rise times in the nanosecond range. A number of the dynamic calibrators described in this clause are now commercial products [40].

Sinusoidal pressure generators, which require the use of a transfer standard, are the most useful of the various periodic pressure generators available, however, and these devices are limited as to useable range of frequency-dynamic pressure ratio and dynamic amplitude. Nonsinusoidal pressure generators of significant usefulness include the square wave or rectangular wave generators, which may be considered as a special case of the aperiodic or step-function generators. Figures 2.1 and 2.2 present a summary of the capabilities of the dynamic pressure generators [40].

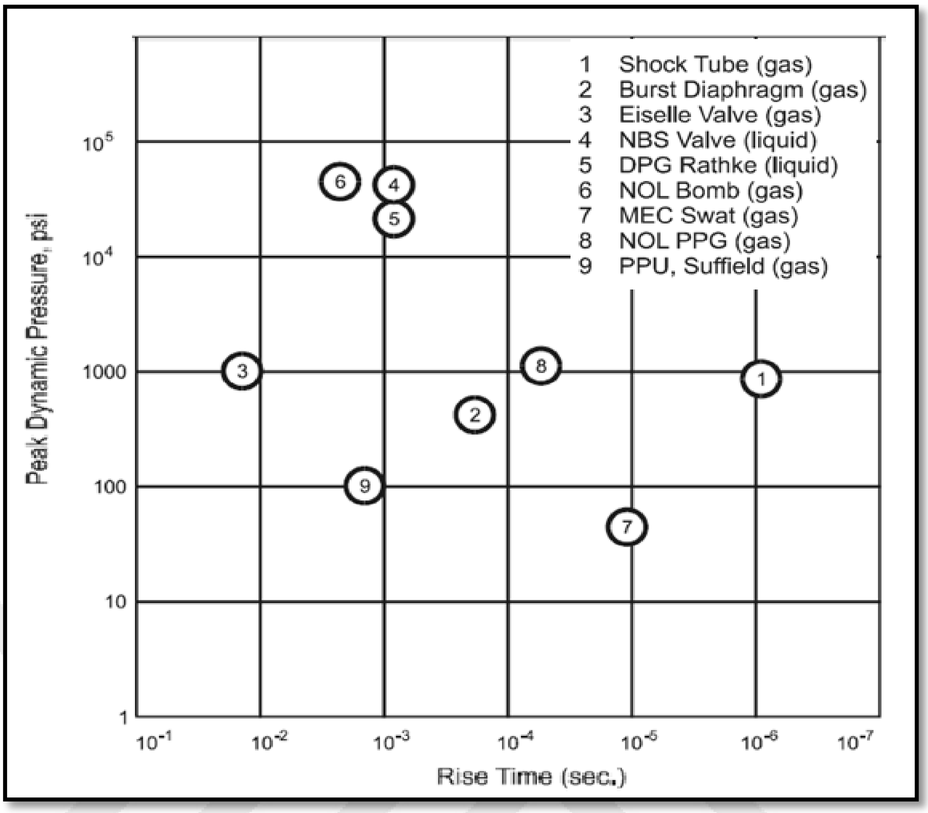


Figure 2.1. Aperiodic generators [40]

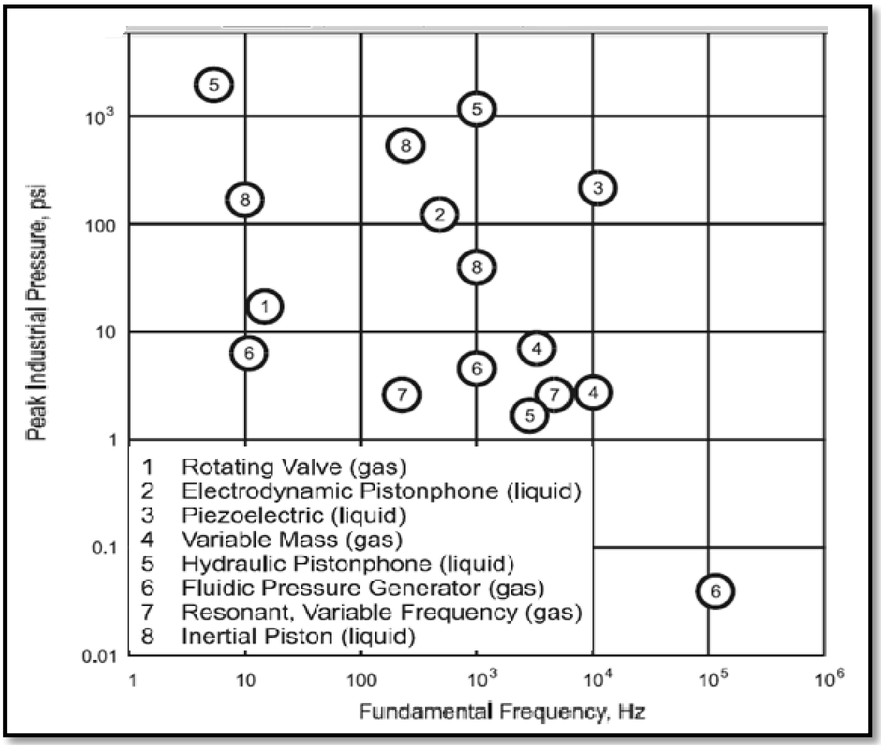


Figure 2.2. Periodic generators [40]

Dynamic pressure is measured by dynamic pressure sensors. They work based on piezoelectric principle. Piezoelectricity is the electric charge that accumulates in certain solid materials in response to applied mechanical stress. The word piezoelectricity means electricity resulting from pressure. For example quartz, deposit as in Figure 2.3 an electrical charge on attached metal plates when subjected to changes in applied force. Very small deformations are needed to produce electrical charge at the terminals. This makes them suitable for dynamic measurements.

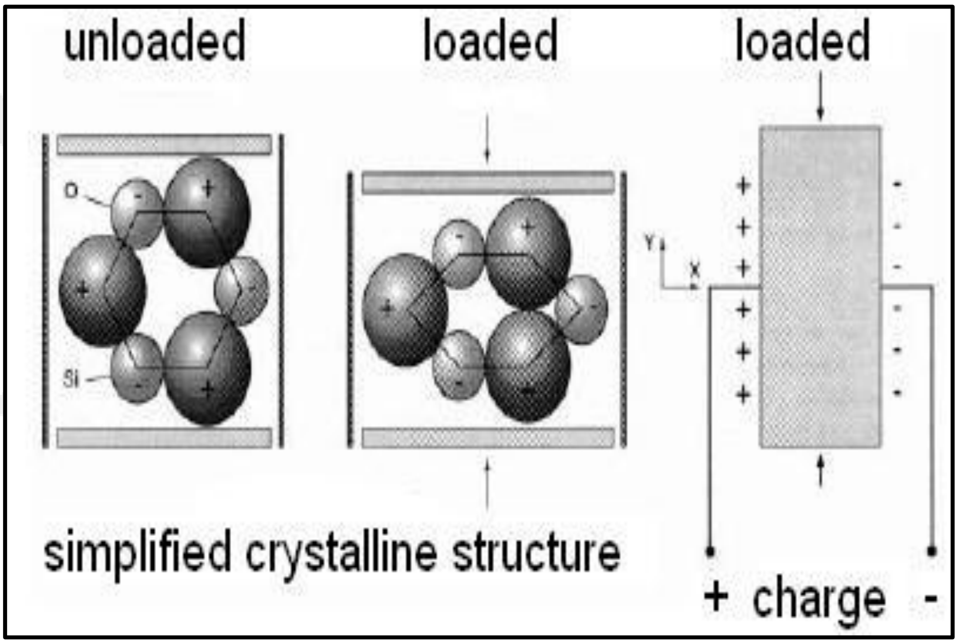


Figure 2.3. Piezoelectric effect [79]

When piezoelectric materials are mechanically deformed, their surfaces get electrically charged. Under mechanical stress the atoms of the tetrahedron get displaced with respect to their former position (indicated by a thin red outline). The positively charged silicon is pushed away from its central position and the whole structure gets electrically polarized is given in Figure 2.4.

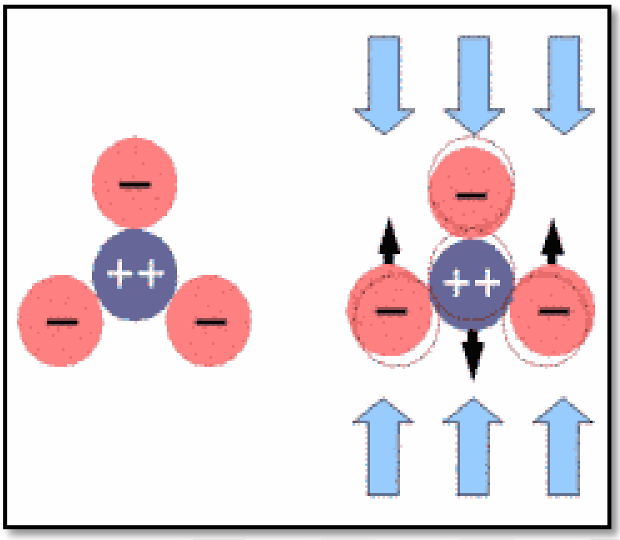


Figure 2.4. Piezoelectric phonemena and effect of deformation on charge distribution [79]

2.2. MEASUREMENT OF TRANSDUCER PROPERTIES

2.2.1. Sensitivity

In a transducer sensitivity measurement, either periodic or aperiodic pressure generators may be used to produce the measurand. It is preferable to use a generator for which the dynamic pressure amplitude can be accurately established without use of a dynamic reference transducer. To a limited extent, the shock tube satisfies this requirement. Today, calibration shock tubes with more precise measurement capability for shock velocity and pressure amplitude are achieving uncertainties approaching 2%. The shockless pressure-step generators (e.g., quick-opening valve devices) expose the transducer being calibrated to a precisely known static pressure in about 50 ms [80]. A fixed-displacement piston-phone, commonly used for calibrating microphones, allows precise sensitivity measurements at low frequencies without a reference transducer, but only at very low-pressure levels. If the transducer responds to static pressures, the typical static-pressure generators (such as hydraulic dead-weight testers) can be readily used to establish the static sensitivity.

When used with a step-pressure source, a transducer with less than critical damping will produce an oscillatory output. In a shock tube, the reflected wave may disturb the transducer output before the transducer oscillations decay. In this case, the average value of the oscillations must be estimated in order to determine the sensitivity. In general, quick-opening valves allow application of an undisturbed pressure long after the oscillations decay.

If the transducer does not respond to static pressures, waiting for the oscillations to decay can contribute to an error in measurement of sensitivity. For example, a transducer with a single RC roll-off at 1 Hz has dropped 5% of its value approximately 8 milliseconds after the application of a pressure step. In this case it requires that the oscillations be averaged in the first few milliseconds for such a transducer. Sinusoidal pressure generators can be used for straightforward determination of sensitivity; however, precise pressures, as measured by a transfer standard transducer, can be generated only at low-pressure levels and relatively low frequencies.

Most of the properties defined for transducers indicate the magnitude of sensitivity variation with these conditions, e.g., variations in response and linearity. It is therefore recommended that measurements to determine the sensitivity be made under user-operating conditions.

2.2.2. Amplitude Response

Amplitude response is one of the most important (but more difficult to obtain) properties of a transducer. Ideally, this measurement is performed with a sinusoidal pressure generator, which is swept over the frequency range, yielding a constant dynamic-pressure amplitude at each frequency. Unfortunately, an SPG, which covers the amplitude and frequency range for most dynamic transducers, does not exist. In general, a flat frequency response (constant amplitude) cannot be guaranteed from the sinusodial pressure generator; therefore, the pressure generated must be monitored by a reference transducer, which should have sensitivity documented through dynamic calibration techniques. The ratio of the response of the transducer under test to that of the reference transducer is recorded. The natural frequency of the reference transducer must be at least five times the measurand frequencies. It is difficult to generate sinusoidal pressures at frequencies as high as the first resonance of most dynamic transducers. Today, dynamic-pressure transducers have frequency response to 500 kHz and some to >1 MHz. This has led to the use of aperiodic generators (such as the shock tube) to measure the transducer's amplitude response [40].

2.2.3. Phase Response

Phase response is determined with a sinusoidal pressure generator by comparing the transducer output voltage waveform with that of the reference sensor, which is simultaneously excited by the periodic measurand. The apparatus is much the same as for amplitude response measurements, except the phase difference between the two waveforms is determined by means of a phase meter, Lissajous patterns, or by accurately measuring the time shift between the two wave forms of a digital recorder; if not dual beam, operate in chop, not alternate, mode. The reference-pressure transducer should have negligible phase shift in the frequency range in which the test transducer is to be measured [40].

The positioning of the transducers in the measurement cavity is more critical for phase measurements than for amplitude measurements. A criterion of placement of l/10 was suggested for amplitude measurements, but this is equivalent to a 36-degree phase shift. Hence the criteria for phase-shift measurements should be increased to l/50 to insure phase differences of no greater than 5 degrees. This is a very stringent requirement and essentially limits phase measurements to low frequencies. A technique for circumventing these criteria is to place the reference and test transducers at "mirror image" locations within the cavity. The use of two reference transducers is required to establish to what extent the locations are mirror images [40].

In general, electronic filters are not recommended for use in phase measurements unless the cut-off frequencies are a decade above the measurement frequencies, or unless the filters used for the reference and test transducers are matched in phase. The use of the insert voltage techniques, to determine the validity of the method, is recommended if filters are used [81]. Phase measurements can also be mathematically derived from shock-tube measurements as a byproduct of the amplitude-response data.

2.2.4. Resonant Frequency

The transducer-resonant frequency is best determined from the transducer's amplitude response, obtained with a reflected shock-tube measurement. Sinusoidal generators do not have high enough frequency to excite the resonant frequency of most dynamic-pressure sensors. It is readily determined by examination as the frequency at which the transducer responds with maximum-output amplitude. Resonant frequency can be measured quickly and accurately using computer-data-processing software [40].

Because the resonant frequency is a function of damping ratio as well as natural frequency, the type of pressure medium is important since the damping effect of a liquid medium can significantly affect the resonant frequency [40].

2.2.5. Ringing Frequency

The response of an underdamped transducer to a step or impulse is a damped oscillatory transient or ringing. The ringing frequency can be determined by applying a pressure-step input, usually from a reflected shock wave to the transducer, recording the output and counting the cycles-per-unit time of the transducer's response. Typically, these data are quickly recorded and analyzed on a high-frequency digital recorder. When a transducer exhibits more than one ringing frequency, the output is a combination of these frequencies, and the measurement is determined with computer software. It can be shown that the frequency response of such a system, below the lowest ringing frequency, is quite similar to that of a single-degree-of-freedom system [40].

2.2.6. Rise Time

Rise time is measured by applying a step input to the transducer and measuring the time required for output to go from 10% to 90% of the final average value. For values of damping ratio of 0.5 or less, the rise time of the step-pressure input must be less than one-fifth that of the transducer for the transducer's rise time to be within 1% of its asymptotic value. So long as the rise time of the step pressure input is less than one-fourth that of the transducer having damping ratio of 0.1 or less, the rise time of the transducer will be within

1% of that obtained with a step-function (zero rise time) input. Care must be exercised that the rise time of the recording system is sufficiently short to introduce negligible error in the measurement [40].

2.2.7. Overshoot

Overshoot is measured by observing the transducer's response to a step input of pressure. The maximum theoretical overshoot that a linear second-order system can have is 100%. This occurs when the damping ratio is zero. Most pressure sensors have damping ratios less than 0.1. Acceleration-compensated pressure transducers have substantially less overshoot than non-compensated transducers. In addition, their overshoot is not linear with step-pressure amplitude. Generally, but not in all cases, their percentage overshoot will increase with larger step-pressure amplitude [40].

2.3. TRANSDUCER INTERFACES

The following four main factors need to be considered when installing dynamic-pressure transducers either for calibration or for performing a measurement:

i. Strain effects
ii. Cavity or passage resonances
iii. Temperature effects
iv. Acceleration effects

Other effects, such as earth-gravity field and those from the earth's magnetic field, which may be significant when dealing with larger, more delicate mechanical instruments, will usually not affect the dynamic behavior of an electrical-pressure transducer but should be checked for in some cases. When calibrating vibration transducers on a shake table, spurious effects induced by the strong variable magnetic field of the table are sometimes encountered. Again, such effects are seldom significant in dynamic calibration of pressure transducers and will not receive consideration in this clause [40].

2.3.1. Mounting and Strain Effects

Both non-precision mounting and over-torquing induce strain into a transducer housing [82] and can be a source of measurement error. Strain introduced into the transducer body may manifest itself either as a change of the sensitivity, an increase in mechanically induced noise, or as a null shift. Strain sensitivity shift is normally noticed when calibration data varies in slope, depending on the mounting torque applied. In order to assess this effect, the transducer should be calibrated first using the recommended mounting torque and then repeated with some specific over-torque and under-torque values, respectively. Calibrating a torque-sensitive transducer satisfactorily is a difficult task since other factors such as concentricity of the mounting hole, tightness of the thread, dirt particles, etc., may affect the sensitivity and thus yield inconsistent results, which are hard to correlate.

The null shift (zero shift) caused by mounting strain represents the component of the transducer signal, which does not depend on the input pressure, but which is a shift in location of the calibration data curve.

No standard technique has been defined yet to accurately determine the magnitude of this effect in pressure transducers. A simple method of detecting significant strain sensitivity is to connect the transducer to its recording equipment and check the change of the output while tightening it to its recommended mounting torque in its mounting hole. This technique is useful only if the system has a good low-frequency response. Manufacturer’s installation drawings should be followed closely and only the mounting parts should be machined according to dimensions provided [40].

2.3.2. Cavities and Passages

The manner in which a transducer is mechanically coupled to the pressure can significantly affect the response of that transducer. Meaningful measurements of pressure fluctuations at frequencies around 10 kHz or higher can only be made with transducers having flush diaphragms. The use of any connecting line or cavity will limit the frequency characteristics of the measurement system itself. There are instances where a connecting line or passage cannot be avoided. In such a case, its length will have to be selected to be consistent with the highest frequency to be measured [40].

If a dynamic measurement or calibration has to be performed through a passage, the highest frequency considered should be less than 1/10 of the resonant frequency of the passage. In air at room temperature and a passage length of 1/4 inch, for instance, frequencies up to 1400 Hz will result in less than one percent dynamic error. This relationship applies only for straight passages. A small passage leading to a cavity in front of the transducer will result in much lower-resonant frequencies [40].

The determination of all mechanical resonances basic to the transducer over the frequency range to be measured is important. The nature of these resonances may be somewhat obscure, and care must be exercised to insure their repetition from one installation to the next if a response analysis is to be valid [40].

Resonances other than the major ringing frequency may sometimes be caused by non-flush diaphragms, discontinuities in the surface near the transducer, and vibration, etc. In short, modulating frequencies above or below the ringing frequency may not be inherent to the transducer at all. The presence of these associated resonances emphasizes the fact that if evaluations of transducer response are to be meaningful, the mounting configuration employed for the calibration must be identical to that used in the actual application [40].

2.3.3. Temperature Effects

Because of the temperature sensitivity of many dynamic-pressure transducers, temperature effects need to be considered in most applications and in calibration as well. When calibrating a temperature-sensitive transducer with compressed air, for instance, the small temperature rise due to adiabatic compression may be sufficient to significantly distort the results. There are two basic effects due to temperature, the temperature-sensitivity shift and the temperature-null shift. Furthermore, unevenly distributed (i.e.,transient) temperatures may cause quite different effects from those obtained with the transducer heated uniformly in a lab oven [83]. Accurate calibration of a dynamic transducer can only be obtained after its temperature sensitivity has been assessed. If that should turn out to be excessive, temperature should be maintained constant at a predetermined value during calibration.

There are at least two methods for evaluating the transient thermal sensitivity of pressure transducers. The easiest method is to make a test measurement with and without ablative coating applied to the transducer diaphragm. This may be practical if the cost factors involved with the test measurement are not significant and the data is repeatable, as might be with periodic compressor measurements. If the periodic measurand is not repeatable, and if practical, two transducers can be used-one with and one without ablative diaphragm coating. One advantage of this evaluation method is that both transducers are exposed to the actual heat flux associated with the measurand [40].

Another method used for evaluating the thermal sensitivity consist of intermittently exposing the transducer diaphragm to a heat source. This test can be accomplished by mounting the transducer on a plate and only exposing the diaphragm to a heat source, which is quickly passed across the transducer’s diaphragm, while observing or recording the output. For comparative evaluation, the test can be performed with and without an ablative diaphragm coating. A variable-speed rotating disk with a slot or square hole in it can be used to better control the heat exposure time and repeatability, This disk is rotated between a heat source and the transducer diaphragm. When the slot or hole in the rotating disk passes in front of the transducer's diaphragm, the diaphragm is exposed to the heat source. A torch or heat lamp can be used to evaluate the effects of various wavelengths from convective or radiant heat sources. If the rotating disk is constructed with multiple slots and driven by a variable speed drive, it may be possible to adjust heat exposure to the transducer's diaphragm in order to approximate the heat exposure of the measurement application. In order, to quantify and control heat flux, a heat-flux transducer can be installed in place of the pressure transducer, and the distance between the heat source and the heat-flux transducer can be adjusted accordingly [40].

Dynamic transducers having large temperature-null shifts can be more precisely calibrated using a liquid medium (water or oil). Care must be taken in order to avoid the creation of an air bubble in front of the diaphragm, since the air bubble will generate some heat when compressed. When calibrations are performed with a gaseous medium, the temperature null shift must be checked by subjecting the diaphragm to a sudden heat input and measuring the signal thus generated.

Three special transducer configurations are used to protect dynamic-pressure transducers from extreme temperatures as encountered in rocket engines, and in internal combustion engines. These are

i. liquid-cooled transducers
ii. gas-bleed transducers
iii. transducers with diaphragm coating

These configurations may affect calibration results and may require special calibration techniques [40].

2.3.4. Acceleration Effects

Dynamic-pressure phenomena are often accompanied by acceleration effects. In a sinusoidal pressure generator, for instance, the pressure variation may cause vibrations of the chamber wall, which in turn may induce acceleration and strain effects in the transducer housing. Transducers are often sensitive to these effects and may generate spurious signals, which are superimposed upon the actual pressure signal. Such errors can sometimes be quite substantial, comprising a large portion of the transducer output signal, especially at low-pressure levels in high-vibration environments. With an acceleration compensated transducer, these effects will be much less severe but may not be completely absent. A transducer that is acceleration-compensated along its most sensitive axis will generally display some acceleration sensitivity along some cross axis [40].

In order to assess the magnitude of the acceleration error, the following procedure is normally used: The transducer is mounted in a blind hole in a similar location and similar fashion as the original mounting. Caution is used caution so that the transducer's diaphragm does not bottom out in the blind hole. Thus, it is presumably exposed to the same vibration (and possible strain) effects, without being subjected to the pressure itself. The size of the error signal can be directly measured. Care needs to be taken to insure proper venting of the volume in front of the transducer. Because of a possible phase shift between the pressure signal and the acceleration signal, determination of the true pressure signal through subtraction of the two signals obtained may not be readily accomplished. When operating transducers in high vibration environments, acceleration-compensated designs will minimize the sensitivity to vibration by an order of magnitude compared to non-compensated designs [40].

In a dynamic calibration with a shock tube, the vibration effects may be especially severe. The large and very abrupt pressure change taking place in the driver end causes compression and expansion waves to travel along the metal walls. These waves may subject the wall and any instrument mounted in this wall to very large accelerations. Modern, miniature, low-mass, acceleration-compensated transducers are much more immune to these effects [84].

2.4. MEASURING AMPLIFIERS

In dynamic measurements two types of measuring amplifiers are commonly used, which are charge amplifiers for piezoelectric transducers and bridge amplifiers for strain gauge or piezoresistive transducers in Wheatstone bridge configuration. In the case of charge amplifiers the calibration is less challenging, since the standard charge signal for calibration can be realized with help of a calibrated AC voltage source and a standard capacitor. For bridge amplifiers the measurement task is more complex, since the measured transducer bridge output voltage U_o is a ratiometric measurand in mV/V and depends on the DC bridge supply voltage U_i, which is provided by the bridge amplifier [47].

Consequently, the dynamic bridge standards need to work in the same ratiometric operation principle to simulate the strain gauge or piezoresistive transducers. Figure 2.5 shows the operation approaches of the NPL dynamic bridge standard as described in [85] and the PTB dynamic bridge standard [86]. Both dynamic bridge standards (DBS) generate the dynamic bridge output voltage with the help of digital-to-analogue converters (DAC). In case of the NPL DBS in Figure 2.5 (a) the AC and DC components of the bridge output voltage are each generated by a separate DAC (V_1 and V_2) that uses the bridge supply voltage V_i as DAC reference voltage and adds up the signals with help of the attenuator resistors (R_5 to R_8) [47].

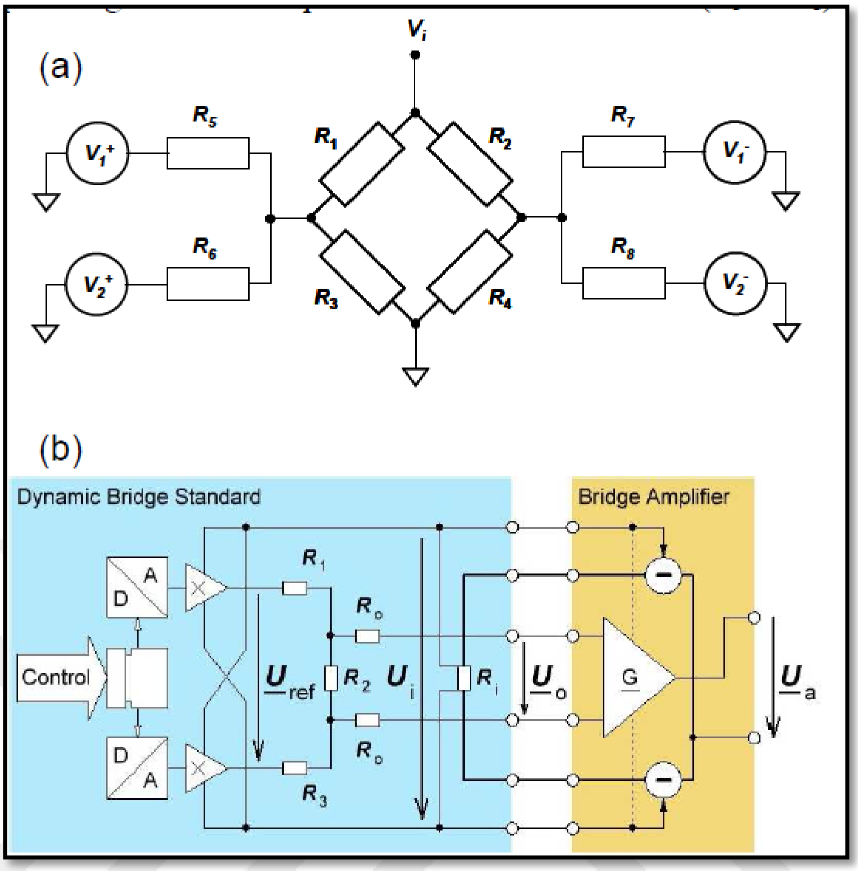


Figure 2.5. Schematic of the strain gauge simulation in the NPL dynamic bridge standard (a) and operation principle of the PTB dynamic bridge standard (b) [47]

The PTB DBS in Figure 2.5 (b) uses multiplying DACs (MDACs) to generate a static or dynamic signal (U_{ref}), which is supplied to a resistive 1/200 voltage divider (resistors R_1 to R_3) with known amplitude and phase behaviour to generate the bridge standard output signal U_o. To match DBS impedances to the typical impedances of strain gauge transducers, the NPL DBS uses the bridge resistors (R_1 to R_4) themselves and the PTB DBS uses the input resistor (R_i) and the two output resistors (R_o) [47].

A preliminary frequency-dependent amplitude and phase characterization of a commercial bridge amplifier was carried out with help of the PTB DBS and is shown in Figure 2.6. The phase information was determined with the help of the MDAC signals, which are used as reference voltage U_{ref}, and the bridge amplifier output voltage amplitude U_a. The measurements were carried out with a single synchronized sampling voltmeter, which is alternately sampling U_{ref} and U_a with the help of a low resistive signal switch [87]. The results for amplitude and phase show characteristics similar to a low-pass filter with decreasing values beyond measurement frequencies of 1 kHz.

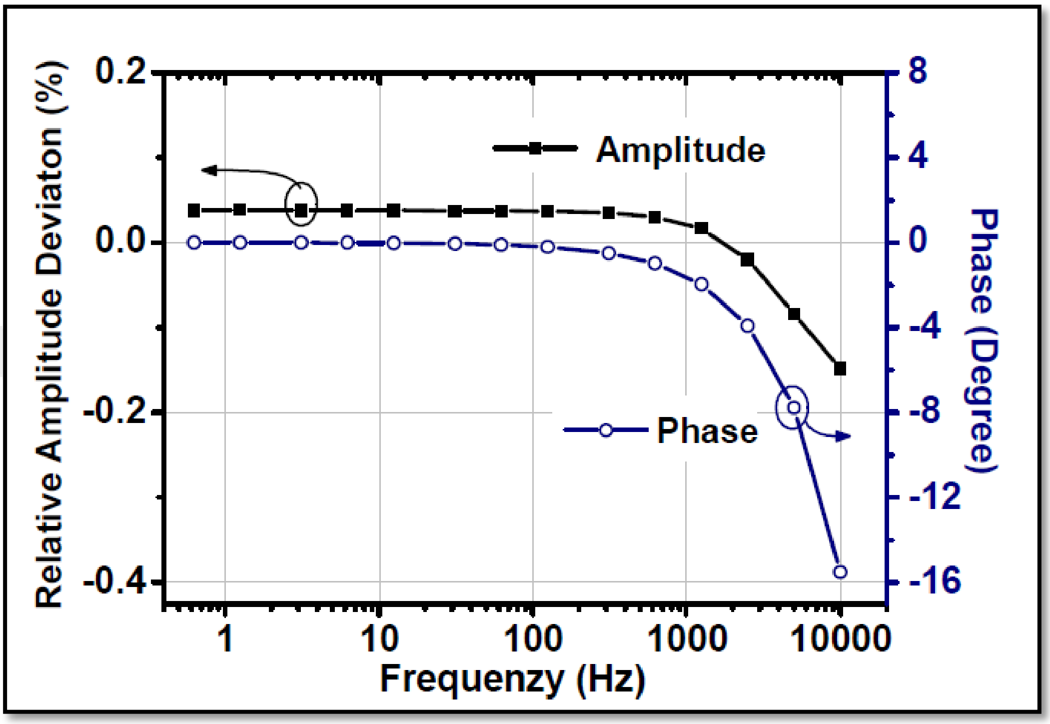


Figure 2.6. Example measurement with the PTB dynamic bridge standard of the frequency dependent relative amplitude deviation and the phase of a typical strain gauge bridge amplifier in the 2 mV/V measurement range [47].

3. MATERIAL & METHOD

At present, no traceable primary standards are exist in the dynamic pressure measurement. There are some secondary systems to produce dynamic pressure but they all have no metrological treacebility. Applications for which these requirements are needed include development and monitoring of automotive engines, gas turbine engines, hydraulic systems, and development within the ammunition and firearms industry.

An approach to generating a fast pressure pulse is using a weight dropped onto a piston cylinder unit, increasing the pressure in the hydraulic medium by up to some hundreds of MPa. Secondary standards generate dynamic pressures of magnitudes and frequencies similar to the conditions in which the industrial transducers are used, and are designed to apply the same dynamic waveform to the industrial transducer as to the reference one, either simultaneously or sequentially. Various such reference transducer-based secondary standard systems already exist, but their performance is not fully characterised and their calibrated sensor lacks metrological traceability.

To investigate and develop a dynamic pressure measurement standard, a system will be designed. For this purpose, a drop weight system and impact test machine system will be modified and it will be automatized. Maksimum acceleration and/or velocity of dropping mass will be masured and thanks to energy conservation laws, pressure value will be calculated. A model function will be defined. For the pressure transmission media, different oils will be investigated in terms of pressure transmission and compressibility. As a pressure range, 500 MPa will be tried to exceed at the 1% accuracy. All design and experimental setup of drop mass system and impact test machine modifications were discussed following. All design and modification parameters were given and presented clearly.

3.1. DESIGN OF DROP MASS SYSTEM

The dynamic pressure facilities of some set-ups operate according to the “drop mass” principle. A drop mass system is given schematically in Figure 3.1. The impact on the piston leads to the compression of a small volume of a hydraulic liquid within a pressure cavity that is connected to the test device(s), thus a shock pressure excitation to the test device is applied [77]. Drop mass system is consists of three main parts. First part is mechanical unit. Second one is control unit and the third part is called data logging and sensor configuration unit. Three dimensional (3D) picture of the drop mass system is given in Figure 3.2.

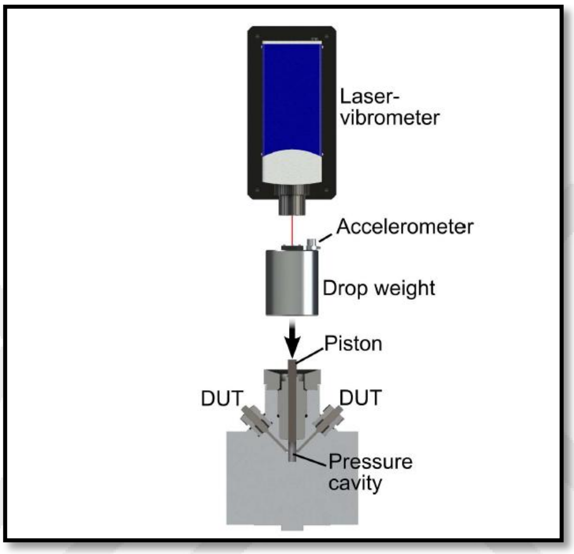


Figure 3.1. Drop weight system [47]

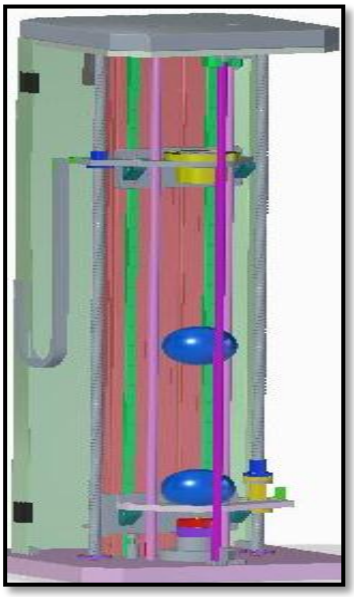


Figure 3.2. Three dimensional (3D) view of the drop mass system

3.1.1. Design of Mechanical Part

Dynamic pressure measurement standard also known as drop mass system. In order to improve a dynamic pressure measurement standard based on drop mass principle, this study was conducted. Three dimensional design of drop mass system is seen in Figure 3.3 and Figure 3.4.

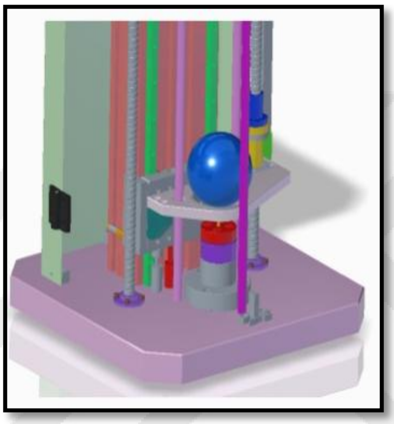


Figure 3.3. Dynamic measurement standard based on drop mass principle system

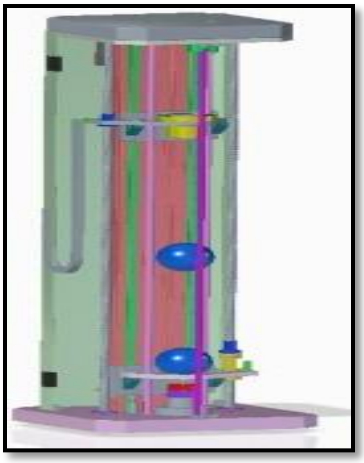


Figure 3.4. 3-dimensional view of the drop mass system

After 3D technical design was completed, all parts of the design for drop mass system were measured by a coordinate measuring machine (CMM). So scales and dimensions for all parts were determined for manufacturing. Figure 3.5 and Figure 3.6 show measuring of connection holes for reference, and also Figure 3.7 shows measuring of piston-cylinder hole.

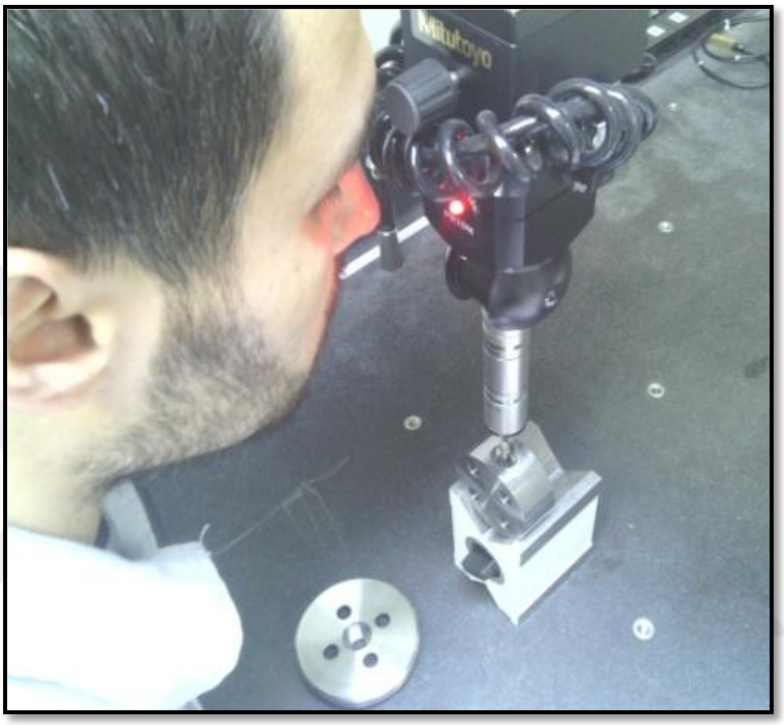


Figure 3.5. Dimensional Measurements of sensor hole-1

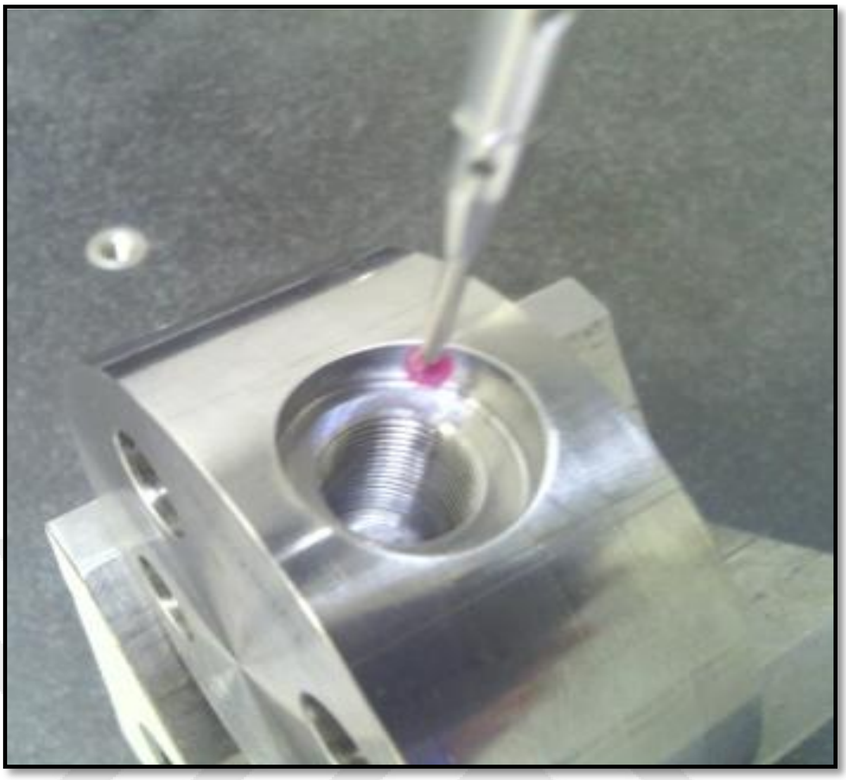


Figure 3.6. Dimensional Measurements of sensor hole-2

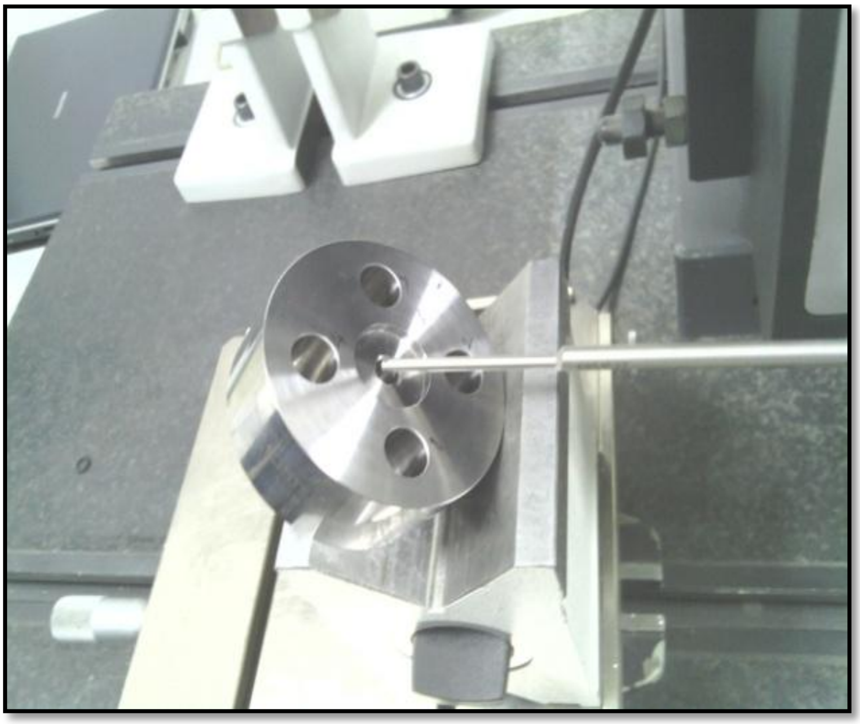


Figure 3.7. Dimensional Measurements of connection part

An electromagnet was designed for keeping the holding sphere ball. Copper wire was rolled around a conducting cylindrical metal. When it is worked at 24 volt direct current (DC), quite powerfull electromagnet will be obtained. The purpose of usage of the electromegnet is to catch the sphere ball and lift it into a certain height for free falling head. The drawing of the electromagnet is shown in Figure 3.8. Manufacturing processes of the electromagnet is seen in Figure 3.9. Electromegnet can be enable or disable by pressing “magnetic start” buton on touch screen as it is shown in Figure 3.10.

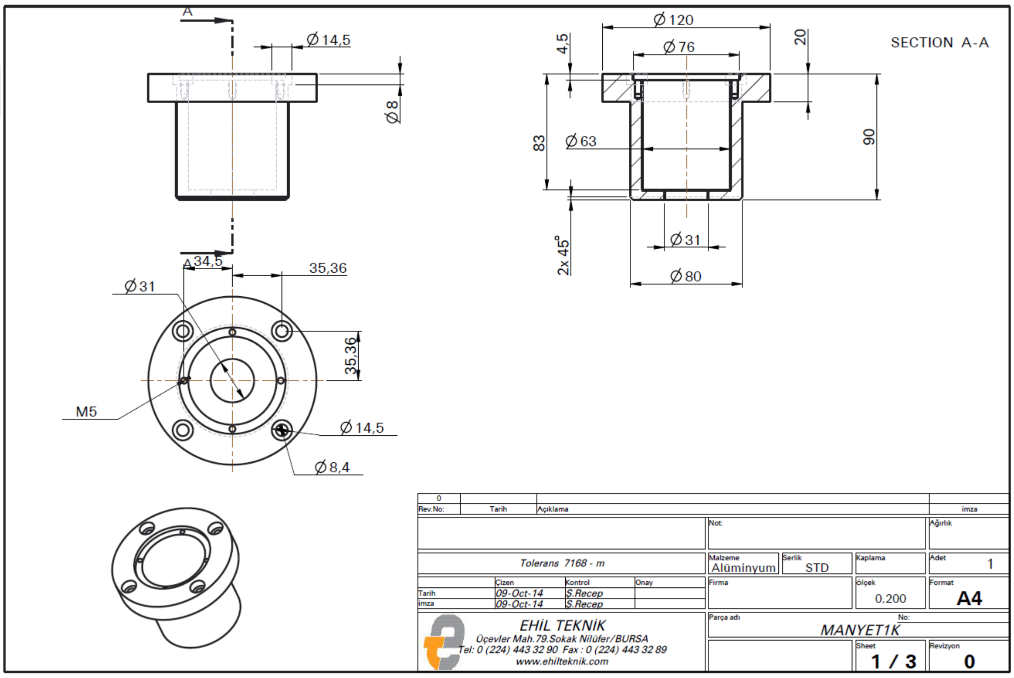


Figure 3.8. Drawing for electromagnet

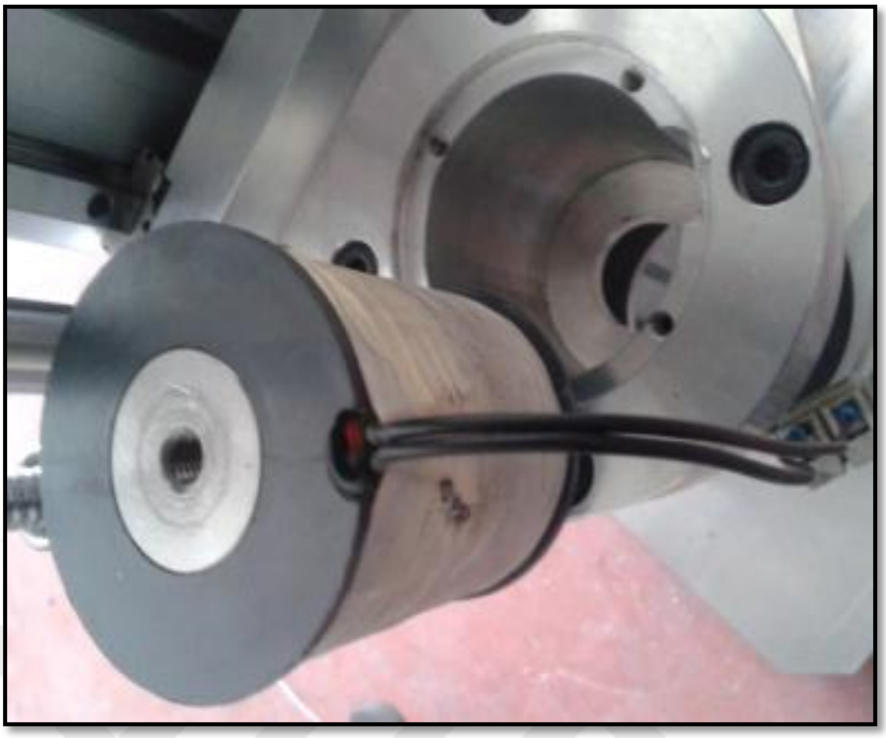
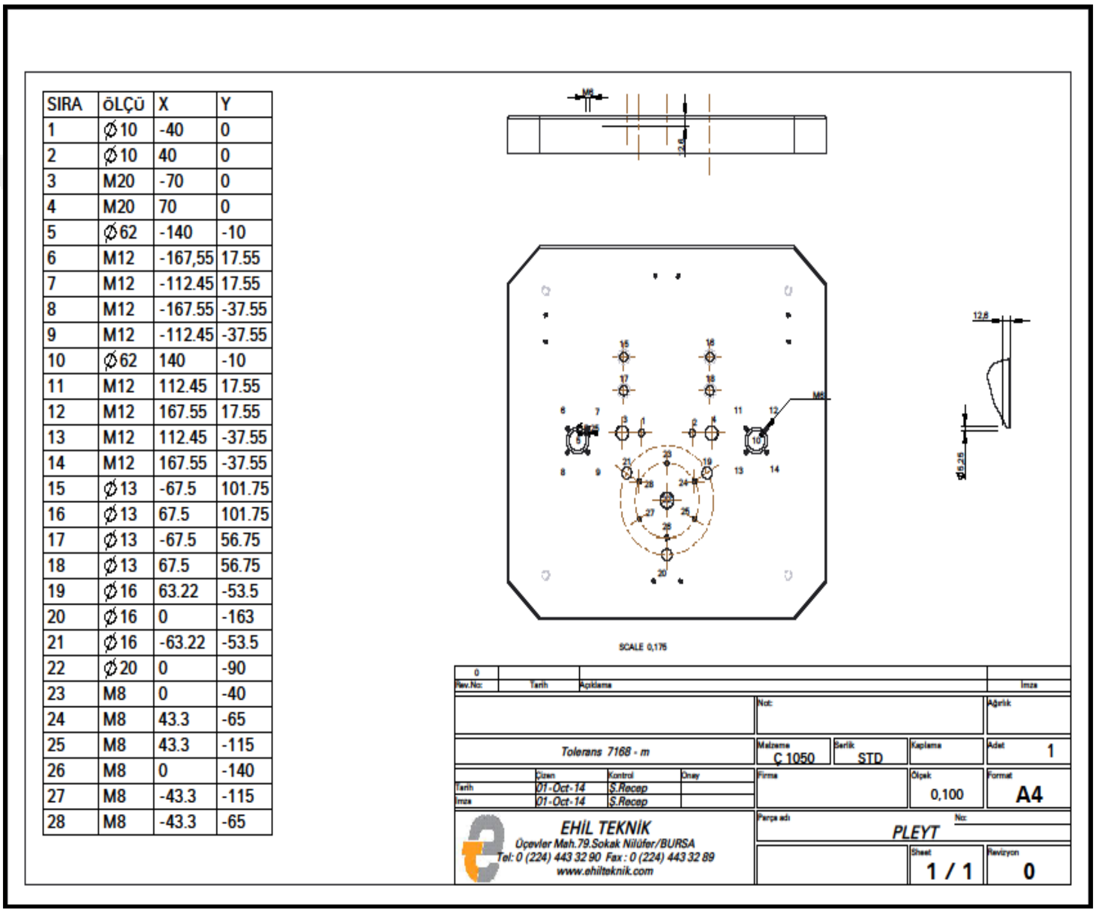


Figure 3.9. Manufacturing of electromagnet

Figure 3.10. PLC and servo engines start display

Basement and roof metal plates were designed. Designs of lower and upper plates were given Figure 3.11 and Figure 3.12, respectively. They are aproximately in square and made of iron. There are some holes both in basement and in roof plates. Holes in the corner of the triangle shape for holding security rods. Security rods start form roof and stand along the drop mass sytem and finish in the basement plate.



SIRA	ÖLÇÜ	X	Y
1	Ø10	-40	0
2	Ø10	40	0
3	M20	-70	0
4	M20	70	0
5	Ø62	-140	-10
6	M12	-167,55	17.55
7	M12	-112.45	17.55
8	M12	-167.55	-37.55
9	M12	-112.45	-37.55
10	Ø62	140	-10
11	M12	112.45	17.55
12	M12	167.55	17.55
13	M12	112.45	-37.55
14	M12	167.55	-37.55
15	Ø13	-67.5	101.75
16	Ø13	67.5	101.75
17	Ø13	-67.5	56.75
18	Ø13	67.5	56.75
19	Ø16	63.22	-53.5
20	Ø16	0	-163
21	Ø16	-63.22	-53.5
22	Ø20	0	-90
23	M8	0	-40
24	M8	43.3	-65
25	M8	43.3	-115
26	M8	0	-140
27	M8	-43.3	-115
28	M8	-43.3	-65

Figure 3.11. The drawing of lower base plate

They do not touch to the sphere ball during the free fall. But if something goes wrong and sphere ball try to goes out of free falling path, security rods stop the sphere ball leaving from the drop mass system. So security rods prevent and accidental situation. Also two infinite screws stand on the plates. They are used for lifting rebound sytem which catches sphere ball after first hit and lifting electromagnet. Basement and roof metal plates were given in Figure 3.13 and Figure 3.14.

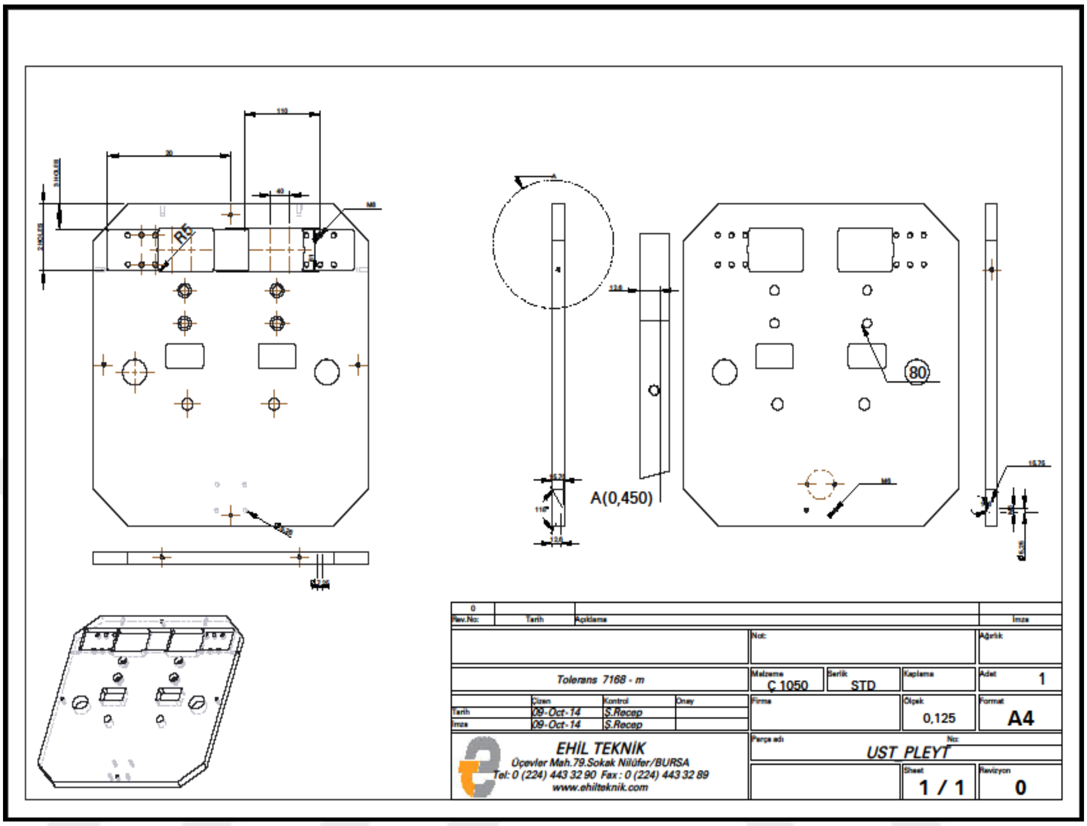


Figure 3.12. The drawing of upper base plate

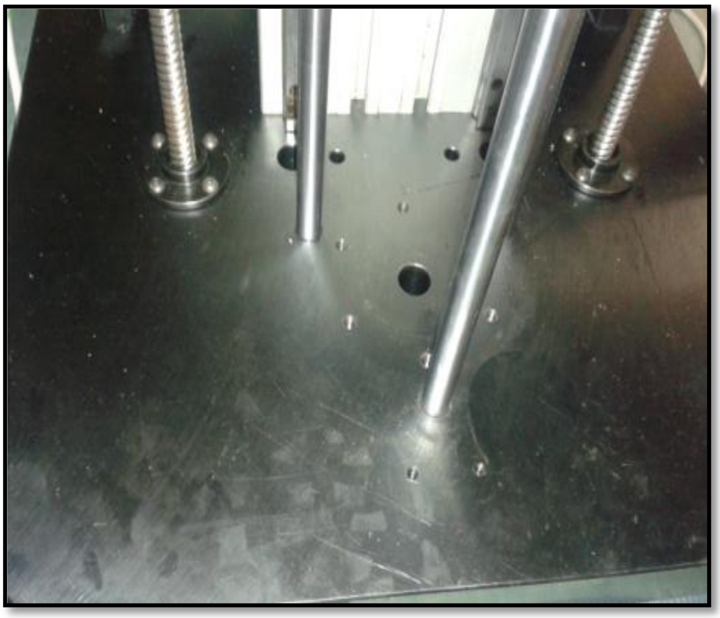


Figure 3.13. Lower base plate

Figure 3.14. Upper base plate

In drop mass standard, pressure pulses are obtained by hitting the free fallen sphere ball on to the piston. If ball is not cathced, it continues to makes some more repetitive hits on to the piston. So some noise signals may appear across the sensors. To prevent repetitive hits of the ball on to the piston, a holder or rebound was designed. It is seen in Figure 3.15.

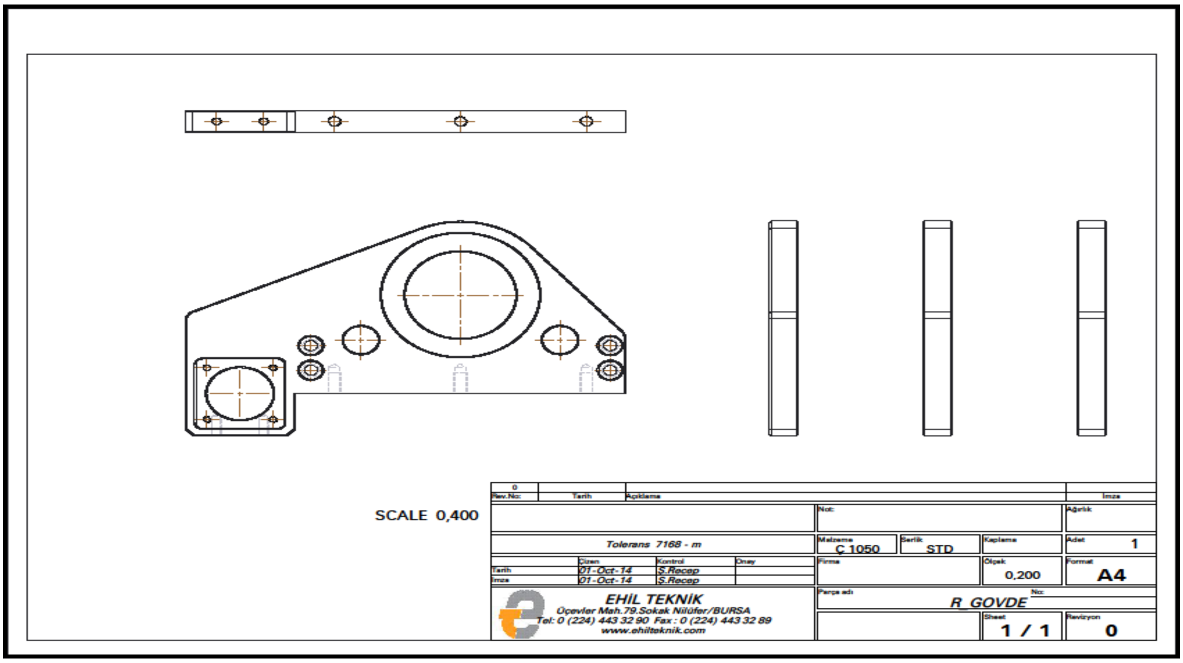


Figure 3.15. The drawing of the holder

Holder or rebound system starts to move upward instantaneously to catch the ball. Rebound system is triggerred by a microphone. Holder or rebound system is given in Figure 3.16 and microphone is given on the right bottom side of Figure 3.16.

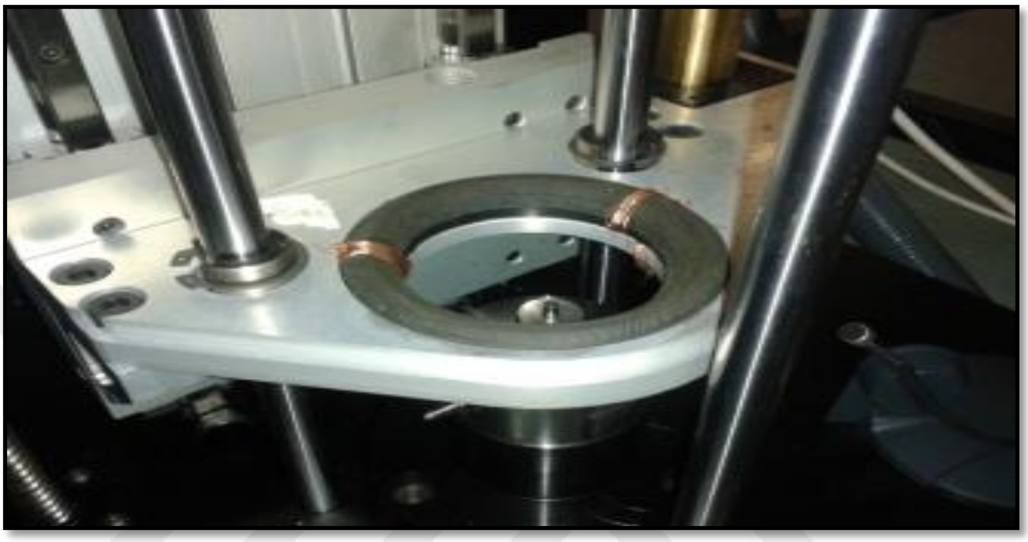


Figure 3.16. The view of holder and microphone

Two infinite screws were ordered. They are located between the lower and roof plates. Both of them are connected to servo engines via gearwheels and belt. So, infinite screw get rotation from servo engines.

One of infinite screws is dedicated to electromagnet. It is responsible for movement of electromagnet both upward and downward slowly. Movement of electromagnet is quite slow comparing to rebound system.

The second infinite screw is connected and assigned for movement of rebound or holder system as shown in Figure 3.17. After sphere ball first hit onto the piston, infinite screw lift the rebound system at a height about 5 centimeters in less than one second.

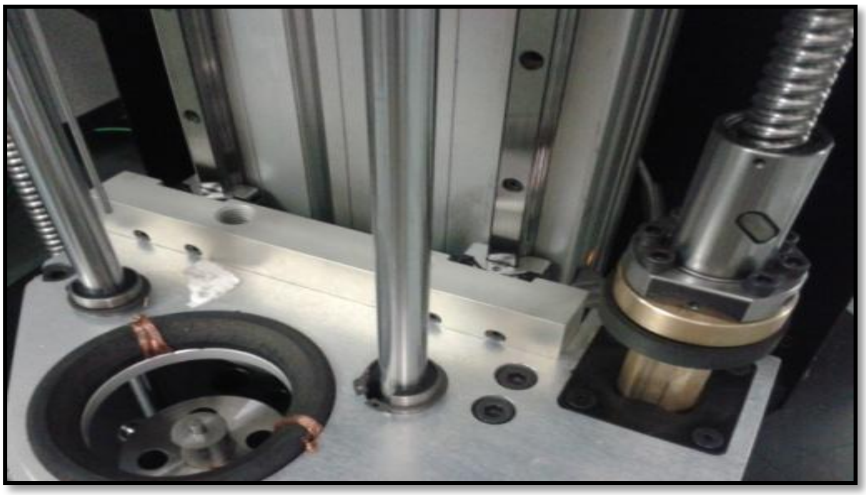


Figure 3.17. Infinite screw for electromagnet

Action of electromagnet and rebound system in upward and in downward direction is provided by two servo engines.Their rotation speed is about 1500 rotation per minute. They are controlled by a programmable logic controller (PLC) via servo engines driving system.

Figure 3.18 shows the belts and gearwheels. These parts tranfer the rotation action from servo engines to two infinite screws.

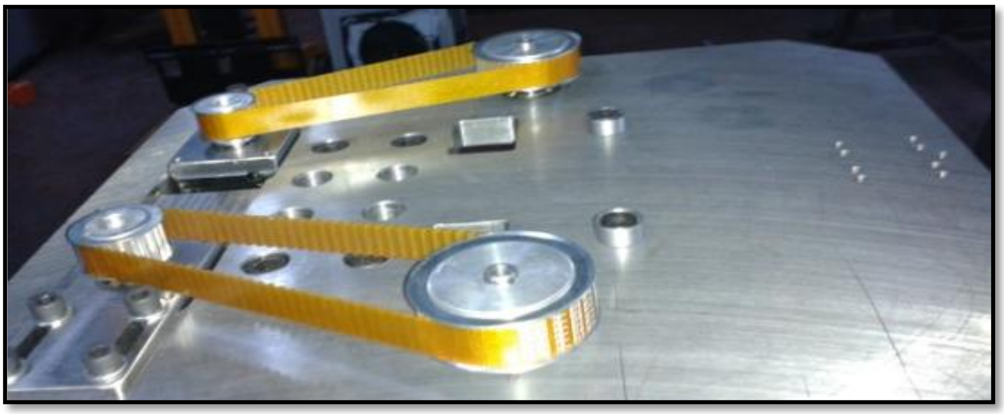


Figure 3.18. Belts of servo engines

Drop mass system is equipped with two posisiton sensors. They are lower reference position sensor for holder as shown in Figure 3.19 and upper reference position sensor for magnet as shown in Figure 3.20. Both of them are inductive based sensors. As soon as they across a metalic surface, an electric signal is sent to PLC to inform of the posisiton. In order to get reference point and position, posisiton sensors use two metal rectangular prism surfaces which were fixed on to the main trunk. While the drop mass system is switched on first, system needs to get and define the reference positons both for rebound system and electromagnet. If system is not get the reference position yet, a black buton is shown in the Figure 3.21 and it reads “reference not get”. If system succesfully get the reference position, black sign button converts to green colour and reads the “reference ok” message as in Figure 3.21.

Figure 3.19. Lower reference position sensor for holder

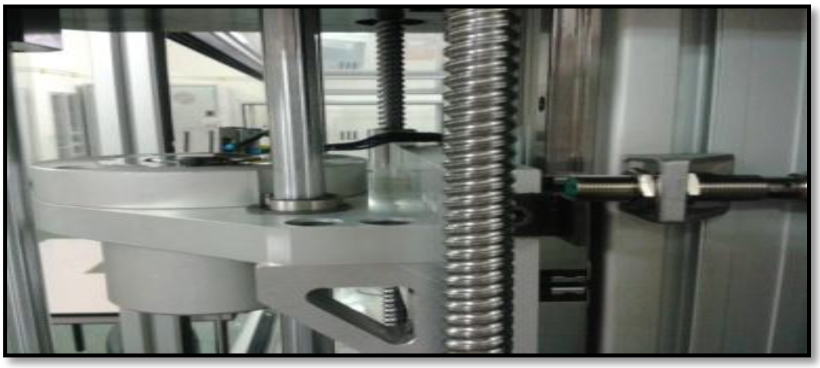


Figure 3.20. Upper reference position sensor for magnet

Figure 3.21. PLC and servo engines data writing and reading display

Principle of this system is based on free falling of a sphere ball. So, it is important to define the height for free falling. Starting point for height is the end of the piston. The responsible servo engine lift the sphere ball via electromagnet at a certain height whose starting point is the end of the piston. Before the measurement, when operator push the “automatic test start button” on touch sceen display in Figure 3.21, electomagnet starts to move downward together with the sphere ball. When the sphere ball just touches onto the top end of the piston a weak electric current flow pass from the piston to sphere ball through the conducting copper wires. So just at this moment, it is recorded as starting point for drop height.

Bottom view of the electromagnet is seen in Figure 3.22. It consists of two cylindrical shape. One is inserted into the other. Copper wires were rolled around the inner small cylinder surface. Also, a hole is drilled so much and the small cylinder and a steel straigh wire is inserted into it. This steel straigh rod is freely moves inside of the inner cylinder both upward and downward direction. Purpose of using this steel rod is to be ensure that central axis of the piston and the central axis of the sphere ball are in the same vertical axis line. If they are concentric, so we can be sure that sphere ball hits centrally to the piston. Then all mechanical energy can be transferred to the sensors via piston and transmitting oil.

Figure 3.22. Concentric method for collision of sphere and piston-1

Top view of the piston and steel rod is seen in Figure 3.23. Before measurements were recorded, electromagnet and steel rod, which were located on the magnet, moves downward and upward to adjust the vertical axises of piston and sphere ball.

Figure 3.23. Concentric method for collision of sphere and piston-2

If operator is sure that both piston and sphere ball is in concentric position as in shown in Figure 3.23, fixing screws are tightened to fix the piston position.

Piston-cylinder unit is the one of the important part of the drop mass system. Cylinder is a cylindrical part with a hole along it to allow the piston insert to inside. It's inner surface of the cylinder should be machined very sensitively as well as piston's surface. Piston and cylinder are shown in Figure 3.24.

Figure 3.24. Piston cylinder unit

Piston-cylinder and reference and test sensors are located on a closed chamber. It has aproximately volume of 0.5 cm^3. During the experiments different transmitting oils were filled into this volume. Closed chamber equipped with piston and sensors are given in Figure 3.25. Together with piston-cylinder unit and transmitting oils, also reference and test pressure sensors are mounted into both sides of the closed chamber. Closed chamber which was equipped with piston-cylinders, transmission oil, sensors and piston top cover is fixed on to piston holder base with three screws.

If operator is sure that both piston and sphere ball is in concentric position as in shown in Figure 3.23, fixing screws are tightened to fix the piston position. Fixing the piston position is done by tightening three hexagonal head screws located on the piston holder base.

Sphere ball hits for each measurement to top of the piston. After some number of measurement are recorded it is possible that some deformation occurs both on the piston and on the sphere ball surfaces. If the hardness of piston and sphere ball is close enough they resist to each other. Piston hardness measurement setup and sphere ball hardness measurement setup are given in Figure 3.26 and in Figure 3.27, respectively.

Figure 3.25. Mounted piston and quartz sensor

Figure 3.26. Piston hardness measurement setup

Figure 3.27. Sphere ball hardness measurement setup

Piston hardness measurement view is given in Figure 3.28 and Figure 3.29. Especially in Figure 3.29, it is possible to observe deformation shape or trace and data. In Figure 3.30, sphere ball hardness measurement trace is seen. Hardness measurements show that while piston has 741 vickers hardness as sphere ball is 825 vickers harness value under the 0.3 Newton force. It is concluded that sphere ball has relatively bigger hardness value than piston.

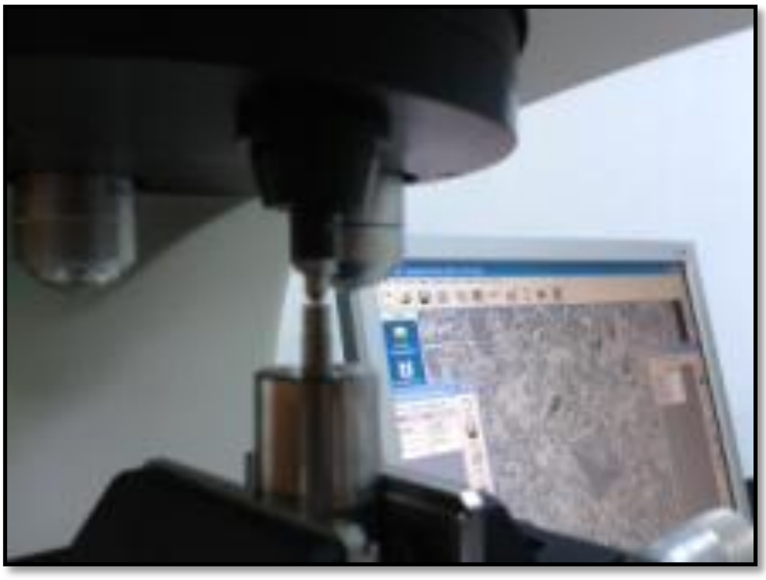


Figure 3.28. Piston hardness measurement

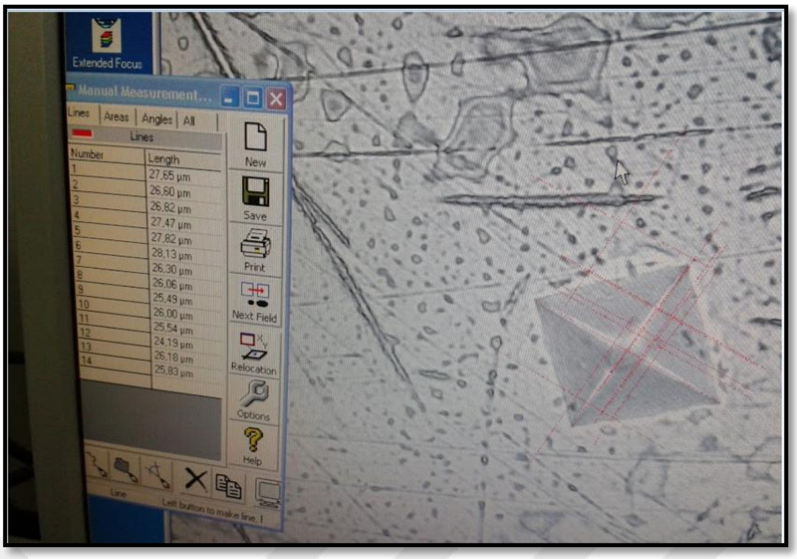


Figure 3.29. Piston hardness measurement (deformation shape and data)

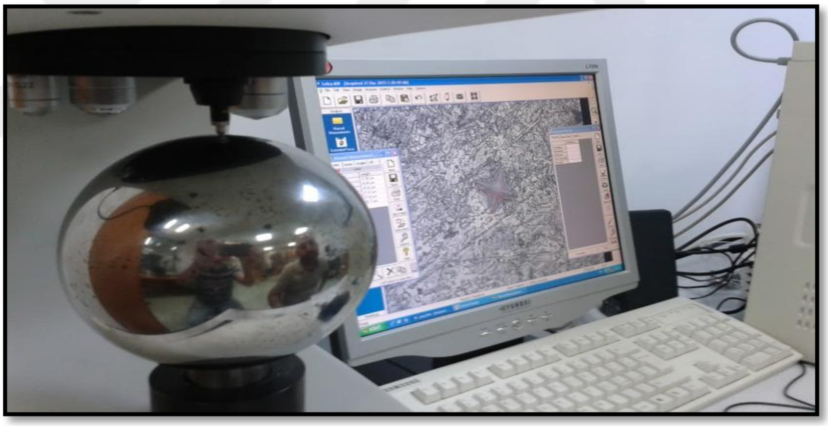


Figure 3.30. Sphere ball hardness measurement and shape

Principle of drop mass standard is obtaining pressure impulse values by free falling the sphere ball on to the piston. While electromagnet lift the ball in upward direction, potential energy on sphere increase. On the other hand potential energy is depends on also mass of sphere as well as drop height. During the free falling potential energy converted into knetic energy and knetic energy has direct proportion with the mass of the sphere. This means obtained pressure impulse value is depend on the mass of the sphere.

During the free fall and hitting period of the sphere ball on to the piston, absolutely sphere rotates. So any part on the surface of the sphere ball can be hit on to top of the piston. If the sphere is really has a good spherical shape, no matter which part of surfaces hit onto the piston. But if sphere is not a good sphere, any energy can not be transferred to piston with respect to the hitting. To be sure from the shape of the sphere, diameter measurement of sphere ball have been done in (-x) – (+x) axis, (-y) – (+y) axis and (-z) – (+z) axis directions. Diameter measurements of sphere are shown in Figure 3.31. Measurement results are axis, (-y) – (+y) axis and (-z) – (+z) Diameter in (-x) – (+x) direction is 119,77673 mm, 119,77437 mm in y direction and 119,77505 mm in z direction. So, there is 19.7 ppm difference between x and y direction results, 14.0 ppm difference between x and z direction and 5.7 ppm in y and z direction measurement results. So it is said that sphere is quite good sphere for drop mass experiments.

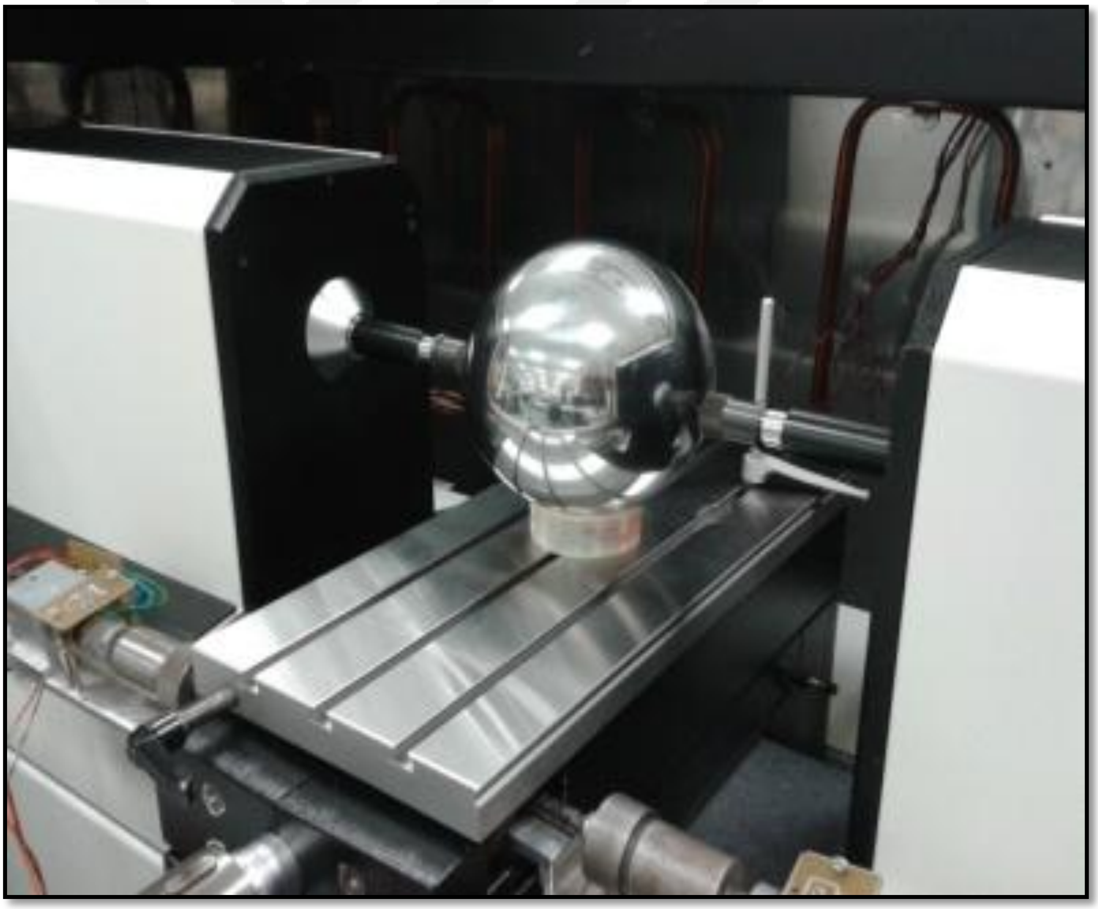


Figure 3.31. Diameter measurement of sphere ball

Figure 3.32 shows the whole drop mass based dynamic measuring standard. Main trunk is located between roof and lower base plates, piston-cylinder and sensors are fixed on to piston holder and on to the lower plate base, sphere ball is on the rebound system and electromagnet is ready to lift the sphere ball.

Figure 3.32. Assemblying of the drop mass system

3.1.2. Control Unit

Dynamic pressure measurement standart is controlled by a programmable logic controller (PLC). Movement of rebound system and electromagnet is done by two servo motors. PLC unit, control touch screen display, servo motor drivers and power unit are located into a rectangular prism box. PLC control program is given in Appendix B.

Control display is located onto cover of the box and PLC, drivers of servo engines and power unit is located inside the box.

Figure 3.33. Inside view of control unit

Inside parts of the control unit is given in Figure 3.33. PLC unit is given in Figure 3.34. It is connected to a computer with a category 6 cable. PLC programmed by a special software installed onto the computer. Logic and conditional behaviours of the components of the drop mass system is programmed and controlled by this programme. For instance, drop height value, dropping timing, operation of electromagnet, sudden lifting of the rebound system which gets trigger from microphone are some of the logic and conditional operations which are done by PLC.

Figure 3.34. PLC unit

Power unit excites the all electrical parts such as PLC, servo engines and their drivers, control display of the drop mass system. Control display program is given in Appendix C.

Servo engines are motioned by servo engines driving system which are controlled by PLC. System has two engine driving system and each one dedicated to one servo engine.

Front view of the PLC and servo engines control display is used to enter some control data to system and PLC as well as reading some output data. It is possible to enter the mass value of the sphere ball mass, gravitational acceleration value, height of the free fall drop, area of the piston and penetration of the bottom end of the piston into the compressed oil. Control display shows the current height of the sphere ball when it is lifting by electromagnet. This distance information is taken from servo engine counter. This display also allows to entering the number of measurement cycle for each pressure measuring point. So, it is possible to repeat the same free fall hit from same height. This specification provides us determination of the repeatability of the measurement at a specific pressure point.

While the drop mass system is switched on first, system needs to get and define the reference positons both for rebound system and electromagnet. Adjusting reference level is done by pressing “get reference” button on the display. If reference is set so, “get reference” button turns into green and reads “reference ok”. Additionally, control display shows whether the system got the reference from the position sensors. There is a “automatic test start” button on this display and measurement starts by pressing this button. Finally, a window displays to operator approximately calculated pressure by PLC based on pre-defined pressure formula which is given as equation (1). Operator can be stop the measurement by pressing the “stop” button located on the right bottom side of the display. Touch scree display shows also date and time, elapsed time for free fall in second as well as speed of mass.

From PLC and servo engines start display window system allows us to enable or disable the electromagnet. It is possbile to move the rebound system and electromagnet as well as sphere ball in vertical direction by manually at a desired speed. Dipslay shows the distance of the rebound and electromagnet posisiton from the reference points. This specification is particulary usefull for concentric adjustment of piston and electromagnet.

3.1.3. Data Logging and Sensor Configuration Part

In dynamic pressure measurement experiments, piezoelectric dynamic pressure sensors were used as reference and test sensors. Reference sensor is given in Figure 3.35 and test sensor is given in Figure 3.36. While the reference dynamic pressure sensor has pressure range up to 800 MPa as test sensor can measure the pressure up to 500 MPa. So measurements were done up to 500 MPa.

Dynamic pressure transducers;

- To measure fast changing pressure saying in other words, dynamic pressure, very fast responsing type of sensors are used.
- Generaly, rise time is about a few micro seconds for these sensors.
- Such sensors are commonly based on piezoelectric effect.

Piezoelectric sensors have proven to be highly successful for the measurement of fast and cyclic processes. Piezoelectric sensors for measuring force, pressure and vibration are used in particular applications in industry, where dynamic processes need to be reliably measured over a long period of time. 800 MPa's data sheet and calibration certificate are given in Appendix D and Appendix E respectively.

Figure 3.35. Dynamic pressure sensor up to 800 MPa

Figure 3.36. Dynamic pressure sensor up to 500 MPa

500 MPa's data sheet and calibration certificate are given in Appendix F and Appendix G respectively.

Piezoelectric sensors consist of a piezoelectric material packaged in a suitable housing. The term «piezoelectric» signifies that when loaded with a force, the sensor produces an electric charge Q strictly proportional to the force F with the unit [pC] (1Picocoulomb = 10^{-12} Coulomb). It is therefore an active measuring element. With quartz (silicon dioxide SiO_2) nature has provided an ideal material.

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 (belowed figure) 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. Dynamic pressure transducers which were used in experiments produce electrical load at their output. This electrical load output is sent to amplifier and calibrator via load carrying cable for conditioning and amplifying. Front view of amplifier and calibrator instrument is given in Figure 3.37. It is Portable, microprocessor-controlled calibrator for sensors. The calibrator consists of a 2-channel charge amplifier with analog peak value memories, ADC, microprocessor, LCD and RS-232C and IEEE-488 interface. The operation is completely menu-controlled and can be effected via the front plate as well as the interfaces. The measured values are displayed optionally in bar, psi, N or M.U. (mechanical units) on the LCD.

Figure 3.37. Front view of the amplifier and calibrator

Datasheet of amplifier and calibration certificates of amplifier are gine in Appendix H, Appendix I and Appendix J.

However the measured values are not automatically converted. It has two input channels one is for reference and the other is for test sensors at rear panel. Also it has two analogue output channels for collecting the analogue output data for reference and test sensors. It amplifies the input load signal and convert the amplified load signal to pressure. Operator can both observe the reference and test pressure values and can collect analogue output of the sensors during the experiments. It is said that amplifier behaves like a convertor instrument since it converts the electrical load to analogue output signal. That is why amplifier should be calibrated and it needed to be known if conversion true and what is the error and uncertainty in this conversion. For calibration case, some reference load is applied to amplifier by a reference capacitor and output voltage values are measured by a reference multimeter. Calibration certificate is given in annex 6. Detailed technical information about charge amplifier is given in annex 7.

Output analogue data from the amplifier is collected by a NI-6366 data acquisition box. NI X series multifunction DAQ devices for USB provide a new level of performance with NI-STC3 timing and synchronization technology, NI signal streaming for high performance over USB, a completely redesigned mechanical enclosure, and multicore-optimized driver and application software. It is connected to computer via usb cable. The data acquisition box is programmed by Labview software which has already installed into computer. Additionally, data acquisition board has following technical specifications:

- 8 simultaneous analog inputs at 2 MS/s/ch with 16-bit resolution; 16 MS/s total AI throughput
- Deep onboard memory (32 or 64 MS) to ensure finite acquisitions, even with competing USB traffic
- 2 analog outputs, 3.33 MS/s, 16-bit resolution, ±10 V
- 24 digital I/O lines (8 hardware-timed up to 1 MHz)

Reference and test sensors and amplifier should be configured before the experiment. Configuration software is shown Figure 3.38. Before the measurement, in the configuration stage, measurement ranges and sensitivity values of both sensors is spcified. Output valtage of the sensors are scaled. An example for configuration for measurement is seen in Figure 3.38. For data acquisition and sensor configuration different computers and softwares were used. Complete view for data acquisition and sensor configuration part of the measurement is given in Figure 3.39. Data acquisition program is given in Appendix A.

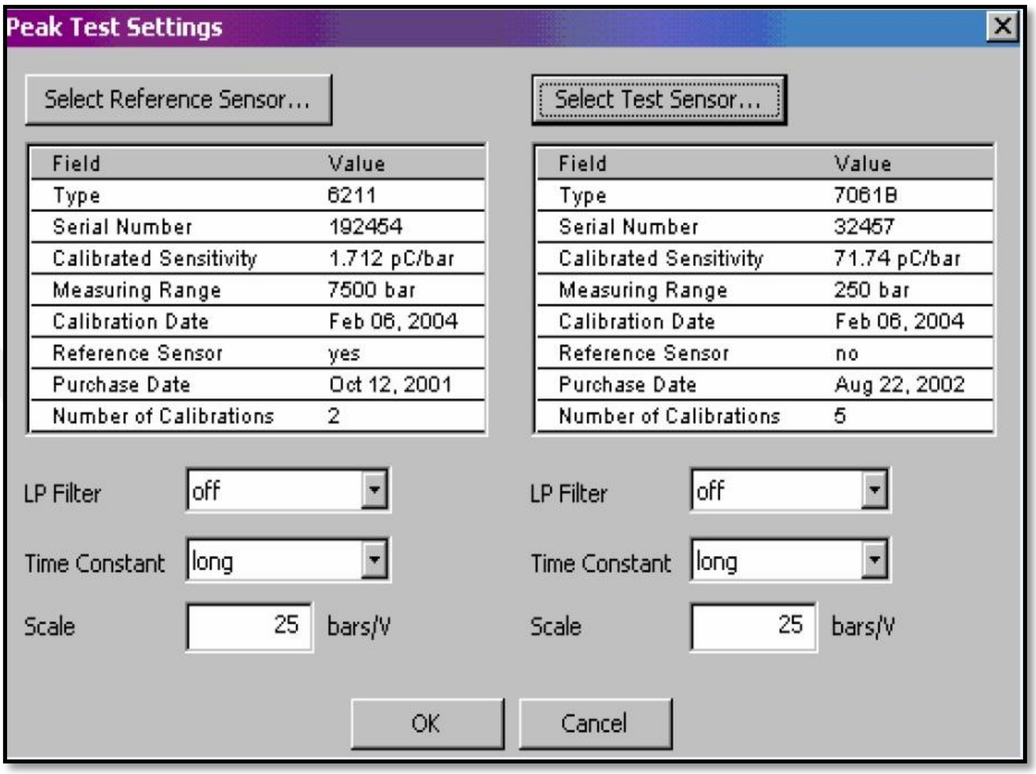


Figure 3.38. An example for configuration for measurement

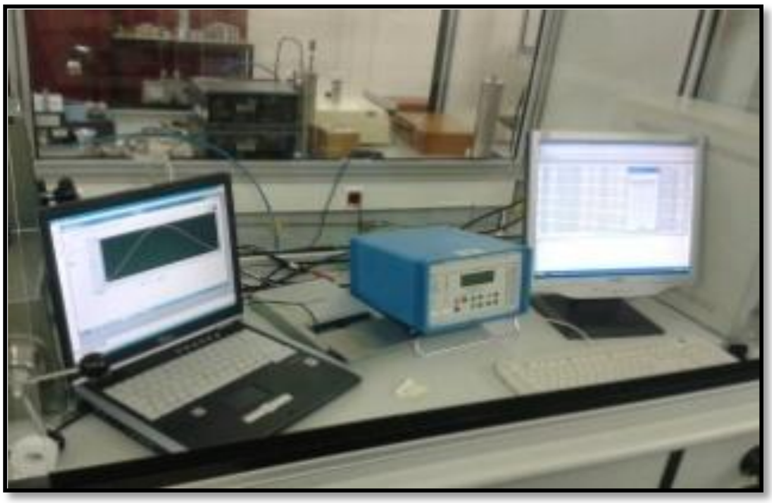


Figure 3.39. Data acquisition and sensor configuration part

Up to now, all experimental setup is completed for dynamic pressure measurements. Before presenting the measurement results let's discuss some definitions: What is static and dynamic pressure? Pressure p, is generally defined as force F, perpendicular to per unit area A,

$$pressure = \frac{force}{area} \tag{3.1}$$

$$p\ (Pascal) = \frac{F\ (Newton)}{A\ (meter^2)} \tag{3.2}$$

In system international (SI) unit system unit for pressure is Pascal [Pa]. Pascal is not a base unit but is is derived from mass,time and lenght. 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.

$$p = p(t) \tag{3.3}$$

Calibration is 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. 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. Figure 3.40 shows the dynamic pressure measurement calibration schedule.

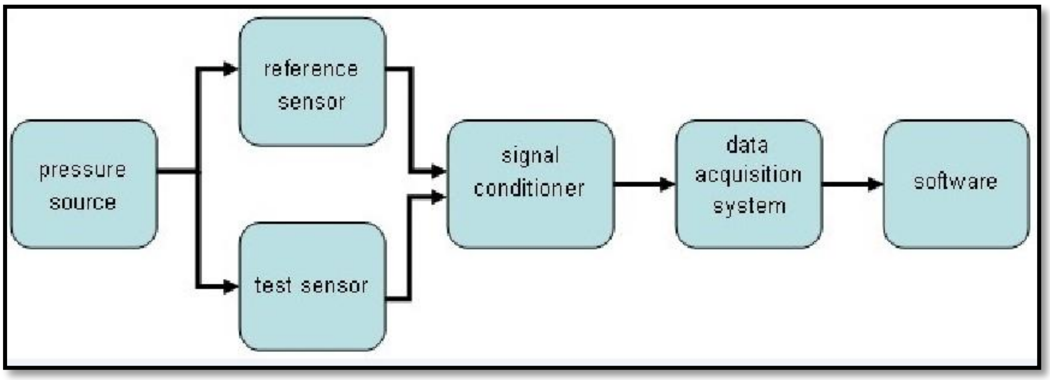


Figure 3.40. Dynamic pressure measurement calibration schedule [72]

The expression of a measurement result is satisfactory only if the results include both the value attributed to measurement quantity and uncertainty of the measurement which is associated with that value. For a traceable dynamic measurement, measurement results should have been expressed with associated uncertainty value A formal definition of measurement uncertainty is 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.

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*

$$y = \pm U \tag{3.4}$$

In metrology the word traceability means 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.

The standardised uncertainty treatment in metrology does not account for dynamic measurements. To achieve traceability for dynamic force, torque and pressure, new methods for the evaluation of uncertainties are needed which are consistent with those employed in the static case. This requires development of appropriate mathematical and statistical models for both the calibration and the measurement (or application) stages, much of which will be new to metrology as it is currently practised both at the NMI level and in industrial applications.

3.2. MODIFICATION OF IMPACT TEST MACHINE

Impact test machines transfer the kinetic energy to tested material using termination probes which can be in different geometries. This energy is produced by free fallen or thrown straight down certain mass. Impact test machine is given in Figure 3.41. Since the impact test machine uses the same principle like drop mass systems, there is a possibility of using obtained impacts in calibration of dynamic pressure sensors as dynamic pressure source. For this purpose, a piston-cylinder system has been placed on the Dynatup 9250HV impact test machine as in Figure 3.42 and Figure 3.43 to make comparison calibration for dynamic pressure transducer. This system provided to us a computer controlled and repeatable dynamic data. For measurements, two dynamic pressure transducers based on piezoelectricity were selected.

Figure 3.41. Impact test machine

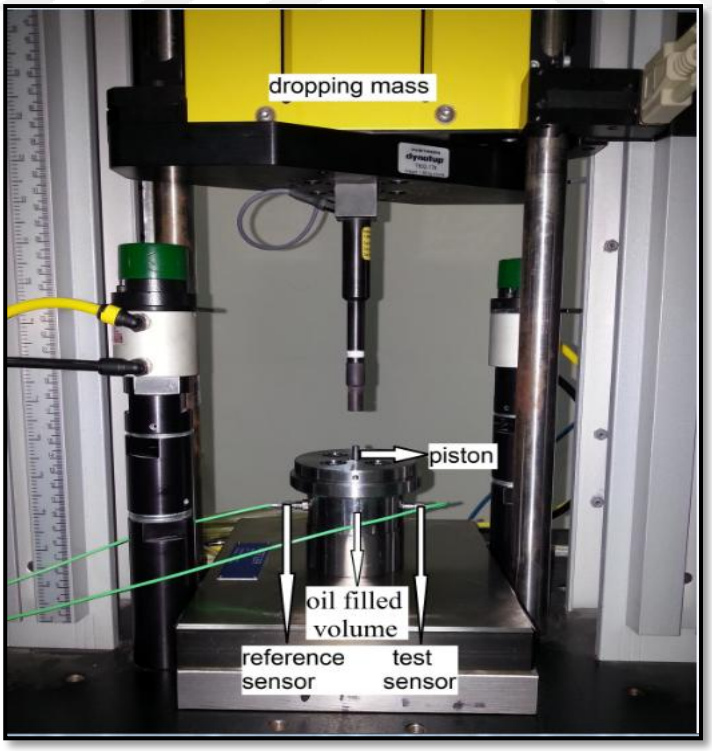


Figure 3.42. Modified part of the impact test machine for dynamic pressure transducer calibration

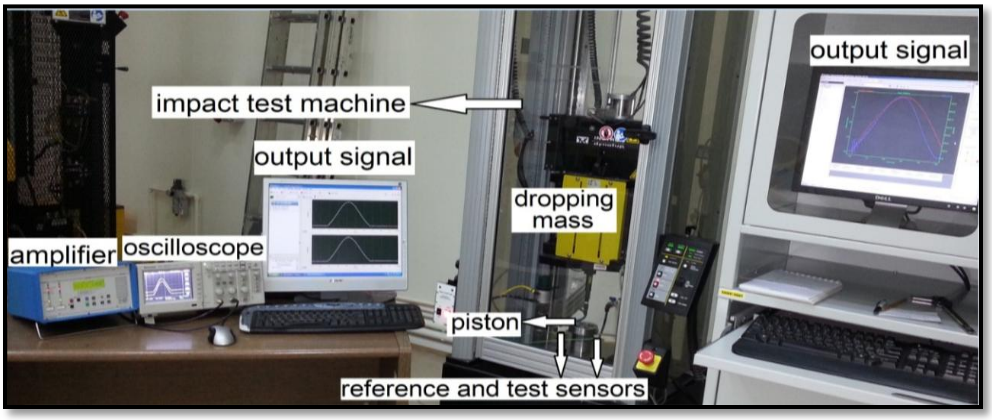


Figure 3.43. Dynamic pressure measurement setup on impact test machine

The transducer Kistler Model 6213BK was used as reference. Oil filled closed chamber equipped with piston-cylinder unit, reference and test sensors, shown in Figure 3.44 is directly located under the vertical axis of probes which is connected to drop mass. This volume was filled by different types of oils such as sebecate, drosera MS5 and Kistler 1053 in measurements as transmitting media. The transducers' outputs were connected to oscilloscope through a conditioning amplifier and then voltage outputs of the measurement chain were transferred to computer in digital form. The maximum mass and force, drop energy, drop velocity, duration etc. data also can be taken by using impact test machine software program.

Figure 3.44. Oil filled closed chamber equipped with piston-cylinder unit, reference and test sensors

3.3. NEGATIVE PRESSURE DROP BY PRESSURE BALANCE

Negative pressure drop system setup by pressure balance for dynamic measurements is given in Figure 3.45. In this method as reference pressure a deadweight tester is used. Reference pressure is calculated using the equation (1). Dynamic pressure sensor is connected to the reference instrument together with the amplifier and multimeter. System is loaded up to a certain static pressure first. In this case dynamic sensor is under stress. Later amplifier and multimeter are zeroed. Immediately system is vented. While pressure goes to zero, dyamic sensor produces an negative output voltage for a specific pressure since it goes to normal situation from a stressed situation.

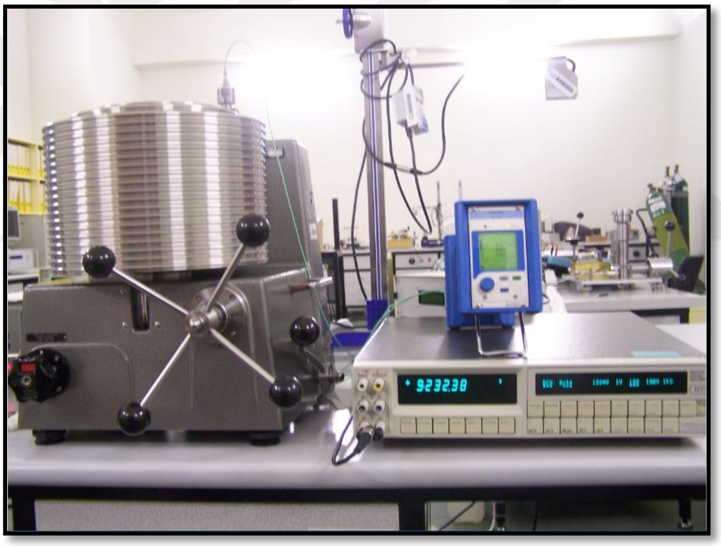


Figure 3.45. Negative pressure drop system by pressure balance

4. RESULTS

4.1. MEASUREMENT METHOD

For each measurement setup an impact mass is released and freely falls onto piston. At the end of the fall the impact mass collides with a piston, much smaller than the mass of the impact mass. The bodies experience an inelastic collision and they continue moving downwards with the same speed. The distance traveled together is relatively small which is about 0.5 mm.

Drop mass system working principle is drawn schematically as in Figure 4.1. Dropping mass creates the impact on the piston leads to the compression of a small volume of a hydraulic liquid within a pressure cavity that is connected to the dynamic pressure sensors.

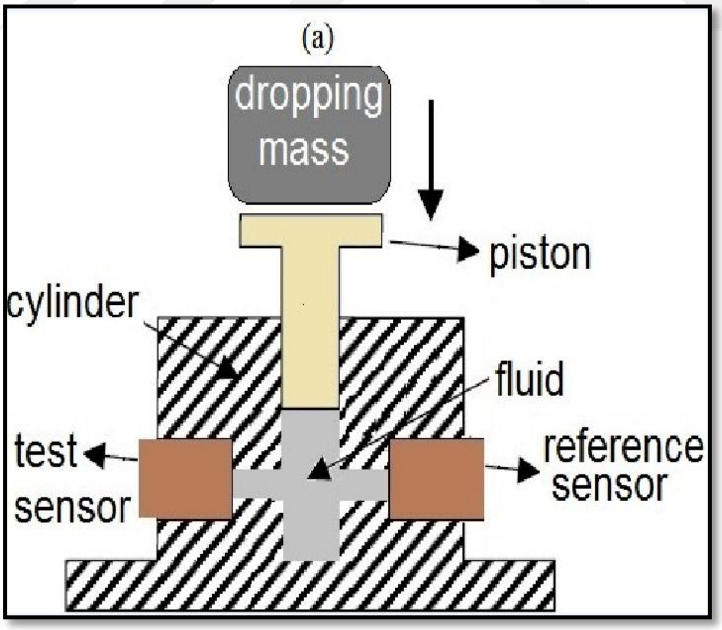


Figure 4.1. Drop mass system working principle

While reference sensor has pressure measurement range up to 800 MPa as test sensor has pressure range up to 500 MPa. Specifications of reference and test sensors are given in Table 4.1.

Table 4.1. Specifications of dynamic pressure sensors used in experiments

Customer	**Model**	**Measurement Range [MPa]**	**Sensitivite [pC/bar]**
Kistler	6229AK	500	-2.400
Kistler	6213BK	800	-1.193

The piston compresses oil causing pressure rise. Eventually the piston-impact mass assembly is stopped nearly all the potential energy of the impact mass has been converted to compression energy of oil. Oil inside the chamber starts expanding as oil starts giving energy back to the assembly. The piston and the falling mass are forced to move upwards. The piston and the impact mass move upwards with the same speed until the initial volume inside the chamber is reached. The piston stops while the impact mass still moves upwards. Duration of a produced pressure peak is about miliseconds.

Approximate equations for pressure calculations:Approximate values can be obtained considering Newton’s second law and solving for pressure. Also, the law of conservation of energy can be used as a starting point. Energy conservation equation assumes that all the potential energy is converted to compression energy and pressure is constant.

$$F = m.a = P.A \tag{4.1}$$

$$P_{max} = m\frac{a_{max}}{A} \tag{4.2}$$

$$E_{potential} = m.g.h = P_{max}.A.\Delta_x \tag{4.3}$$

$$P_{max} = \frac{m.g.h}{A.\Delta_x} \tag{4.4}$$

where,

P_{max} : maximum pressure (Pa)

m : mass of the object (kg)

a_{max} : maximum acceleration of the object (ms^{-2})

A : area of the piston (m^2)

g : gravitational constant (ms^{-2})

h : falling head for object (m)

Δ_x : maximum piston displacement (m)

Oil working like a spring motion can be modeled by using a damped harmonic oscillator equation of motion. Certain parameters can be calculated, e.g. spring constant, damping parameter and the amplitude of the motion.

$$F = m.a = m.\frac{d^2x}{dt^2} = -k.x - C.\frac{dx}{dt} \tag{4.5}$$

$$p(t) = \frac{m.a}{A} = k.e^{\left(\frac{b}{2m}\right).t}.\sin\left(\sqrt{\sqrt{\frac{k}{m}} - \frac{b^2}{4m^2}}\right)t \tag{4.6}$$

where,

m : mass of the piston and impact mass (kg)

a : acceleration of the impact mass (ms^{-2})

x : piston displacement (m)

k : spring constant (Nm^{-1})

C : damping parameter for fluid (kgs^{-1})

Piston-cyclinder unit is seen in Figure 4.2. In order to obtain the pressure, sphere ball is falls on to the piston. So, hardness of the piston and sphere ball is important parameter. Then piston's hardness measurement was done. Hardness of piston is 741 HV0,3 vickers.

Figure 4.2. Piston-cylinder unit

Piston-cylinder unit positioned under the vertical axis of the free fallen sphere ball. At each pressure measurement, sphere ball is leaves to free fallen. So it hits on to the piston. Sphere's hardness is also measured as seen in Figure 3.27. Also to make some calculations such as free fall height mass of the sphere should be known. Mass of the sphere is measured. If the sphere ball is a sphere enough, it is said that a central collision is happens between ball and piston. To be sure that the ball and the piston is concentric, a steel thin rod is used to adjust the centers of the ball and the piston. See the Figure 3.23.

Reference and test sensors are screwed and piston-cylinder unit is inserted into a 0.5 cm^3 closed volume chamber which was filled with pressure transmitting oil. Closed chamber equipped with piston-cylinder unit and reference and test sensors is given in Figure 4.3.

Figure 4.3. Oil filled closed chamber equipped with piston-cylinder unit, reference and test sensors

As pressure transmission fluid, 3 different oils were used in experiments. Each of these fluids are compatible for high pressure measurement but they have different physical and chemical properties. These fluids are sebacate, drosera MS5 and kistler 1053. Their specification are given in Table 4.2.

Table 4.2. Physical and chemical properties of sebacate, drosera MS5 and kistler 1053 [88-90]

property / quantity			**candidate oils**		
engl.	***symbol***	***unit***	**Sebacate**	**Drosera MS5**	**Kistler 1053**
Name			**Di-2-ethylhexyl sebacate**	**Distillates (petroleum), hydrotreated middle**	**1053 Kistler special high pressure oil containing glycol ether**
chemical Formula			$C_{26}H_{50}O_4$		
CAS No.			122-62-3	64742-46-7	
chemical compound or mixture			chemical compound		mixture
vapour pressure	p_{vap}	Pa	$2.4 \cdot 10^{-5}$ @ room temperature (02a,f)		
Density	ρ	kg/m³	0.914 g/cm³ at 20 °C (02a)	About 821 kg/m³ at 15°C	About 980 kg/m³ at 20°C
compressibility	κ	1/Pa	$7.5 \cdot 10^{-7}$ (01b)		
thermal expansion coefficient	γ	1/K	-0.00078 (01c)		
density variability with gas content			DEHS' density decreased by (46±5) ppm after 2 h of nitrogen gas exposure at 101 kPa (01a)		
surface tension	σ	mN/m	31 (01b)		
dynamic viscosity	η	mPa·s	22 (01e)	Kinematic viscosity at 40°C: about 5 mm²/s	
transparency			colourless(01f)	colorless to light yellow	Yellowish
purity of the compound or mixture *i* as mass fraction, molar fraction, volume fraction,…	w_i, x_i, ϕ_i,...	%	≥ 98 % (GC)Merck		
Physical state			liquid	Liquid	liquid
data sources			(01a) J. H. Hendricks, J. R. Ricker, J. H. Chow and D. A. Olson; Measure, Vol. 4 No. 2, June 2009, 52-59 (01b) G. F. Molinar, R. Maghenzani, P. C. Cresto and L. Bianchi; Metrologia 1992 (29) 425-440 (01c) Temperaturkoeffizient ist aus dem Programm von Dr. Klingenberg übernommen		

Dynamic pressure measurements based on drop mass system have been done on the drop mass system setup which is given in Figure 4.4.

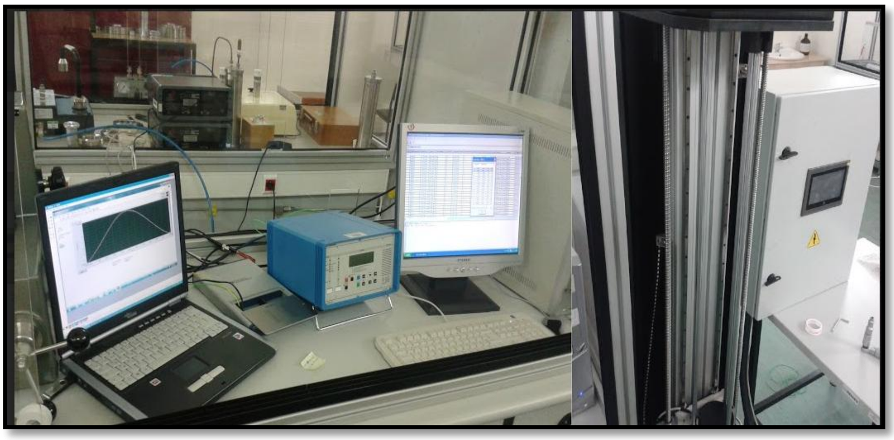


Figure 4.4. Data acquisition and sensor configuration part

4.2. MEASUREMENT RESULTS ON DROP MASS SYSTEM

Drop mass standard system provides us a computer controlled and repeatable dynamic data. Dynamic pressure constituted in closed cavity is sensed and measured by means of two piezoelectric pressure transducers, named reference and test transducers. Piston, test and reference transducers are mounted on to a closed volume as seen in Figure 4.3. Oil filled closed chamber equipped with piston-cylinder unit, reference and test sensors. This volume was filled by different types of oils as pressure transmitting media. These oils are Kistler type 1063, sebecate and drosera MS5 type oils. The piston is directly located in line the vertical axis of free dropped spherical. Load outputs coming from dynamic sensors through the load carrying cable are connected into amplifier channel 1 and 2. Analogue output signals which are corresponding input load signals are taken out from channel 1 and channel 2 of the signal conditioner Kistler Type 6907B as as seen in Figure 3.37. Outputs of signal conditioner are then connected to the data acquisition box (NI DAQ 6366) as channel 0 and channel 1. The transducer Kistler Model 6213BK was used as reference. Because the reference transducer has pressure range up to 800 MPa and test transducer can measure the pressure up to 500 MPa, measurements were performed up to 500 MPa starting from 100 MPa with step of 100 MPa. Data sampling rate was 200 kHz and 300 K sample was taken for each mass drop. The drops were repeated five times for each height and outputs of signal conditioner measured by means of computer controlled NI DAQ board. And also corresponding pressure values indicated on the monitor of the signal conditioner were recorded. Drop height of a seven kilogram spherical ball freely dropping and corresponding pressure values are given in Table 4.3, Table 4.4 and Table 4.5. Also summary is given in Table 4.6. The deviations for test values from the reference pressure for each different oil media are also illustrated in Figure 4.5, Figure 4.6 and Figure 4.7.

Table 4.3. Reference and test sensor measurement results in Kistler 1053

Reference Pressure, oil type: Kistler 1053								Analogue output scale:500 Bar/V			
	Nominal value Bar	cycle 1	cycle 2	cycle 3	cycle 4	cycle 5	average value Bar	deviation %	repeatability %	drop height mm	average value MPa
Reference sensor	1000	1048	1138	1135	1138	1138	1119,4	11.9	1.60	19	111.94
	2000	2195	2215	2210	2215	2210	2209.0	10.5	0.17	60	220.9
	3000	3290	3270	3280	3270	3275	3277.0	9.2	0.11	115	327.7
	4000	4230	4335	4290	4320	4320	4299.0	7.5	0.44	180	429.9
	5000	5020	5010	5040	5035	5055	5032.0	0.6	0.16	235	503.2
Test sensor	1000	1013	1100	1095	1100	1098	1081.2	8.1	1.58	19	108.12
	2000	2135	2115	2130	2135	2130	2129.0	6.5	0.17	60	212.9
	3000	3205	3190	3190	3185	3185	3191.0	6.4	0.12	115	319.1
	4000	4150	4245	4210	4240	4240	4217.0	5.4	0.42	180	421.7
	5000	4945	4945	4965	4950	4975	4956.0	-0.9	0.12	235	495.6

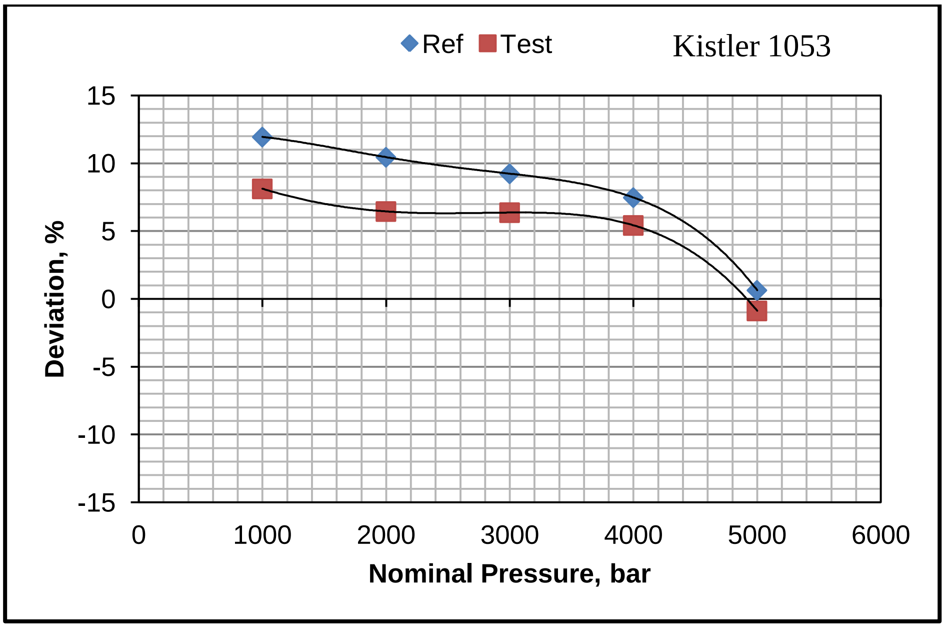


Figure 4.5. Deviation for reference and test sensors versus pressure in Kistler 1053

Table 4.4. Reference and test sensor measurement results in Drosera MS5

Reference Pressure, oil type : Drosera MS5								Analogue output scale: 500 Bar / V			
	Nominal Value Bar	**cycle 1**	**cycle 2**	**cycle 3**	**cycle 4**	**cycle 5**	**average value Bar**	**deviation %**	**repeatability %**	**drop height mm**	**average value MPa**
Reference sensor	1000	1023	1020	1025	1018	1018	1020.8	2.1	0.14	19	102.08
	2000	2015	2020	2020	2025	2025	2021.0	1.1	0.09	60	202.1
	3000	3030	3030	3030	3030	3020	3028.0	0.9	0.07	115	302.8
	4000	4020	3975	3965	3960	4010	3986.0	-0.4	0.31	180	398.6
	5000	4830	4875	4930	4775	4800	4842.0	-3.2	0.57	235	484.2
Test sensor	1000	993	993	990	990	990	991.2	-0.9	0.07	19	99.12
	2000	1973	1960	1958	1960	1958	1961.8	-1.9	0.14	60	196.18
	3000	2975	2965	2970	2965	2955	2966.0	-1.1	0.11	115	296.6
	4000	3965	3925	3910	3910	3910	3924.0	-1.9	0.27	180	392.4
	5000	4870	4830	4895	4725	4750	4814.0	-3.7	0.69	235	481.4

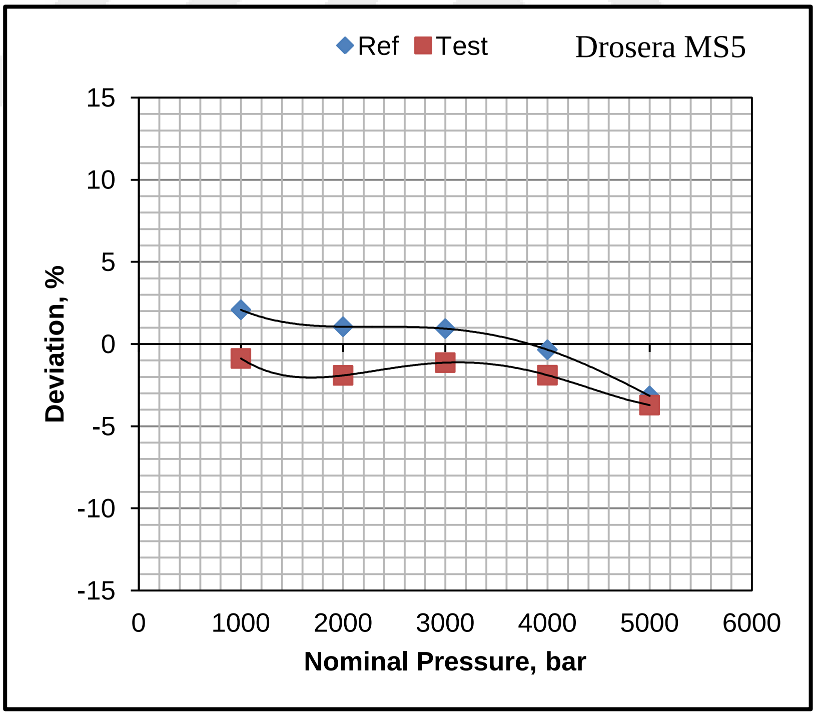


Figure 4.6. Deviation for reference and test sensors versus pressure in Drosera MS5

Table 4.5. Reference and test sensor measurement results in Sebacate

Reference Pressure, oil type : Sebacate								Analogue output scale:500 Bar/V			
	Nominal Value Bar	cycle 1	cycle 2	cycle 3	cycle 4	cycle 5	average value Bar	deviation %	repeatability %	drop height mm	average value MPa
Reference sensor	1000	1005	1005	988	988	993	995.8	-0.4	0.39	19	99.58
	2000	2020	1998	1985	1990	1975	1993.6	-0.3	0.38	60	199.36
	3000	3050	2995	2975	3005	2995	3004.0	0.1	0.42	115	300.4
	4000	3910	3959	3945	3930	3955	3939.8	-1.5	0.23	180	393.98
	5000	4855	4945	5060	4990	4965	4963.0	-0.7	0.67	235	496.3
Test sensor	1000	1008	1008	1005	1005	1005	1006.2	0.6	0.07	19	100.62
	2000	1995	2000	1998	2000	2000	1998.6	-0.1	0.05	60	199.86
	3000	3010	3010	3010	3025	3015	3014.0	0.5	0.10	115	301.4
	4000	4005	4035	4035	4005	4030	4022.0	0.6	0.17	180	402.2
	5000	5035	5120	5120	5120	5120	5103.0	2.1	0.33	235	510.3

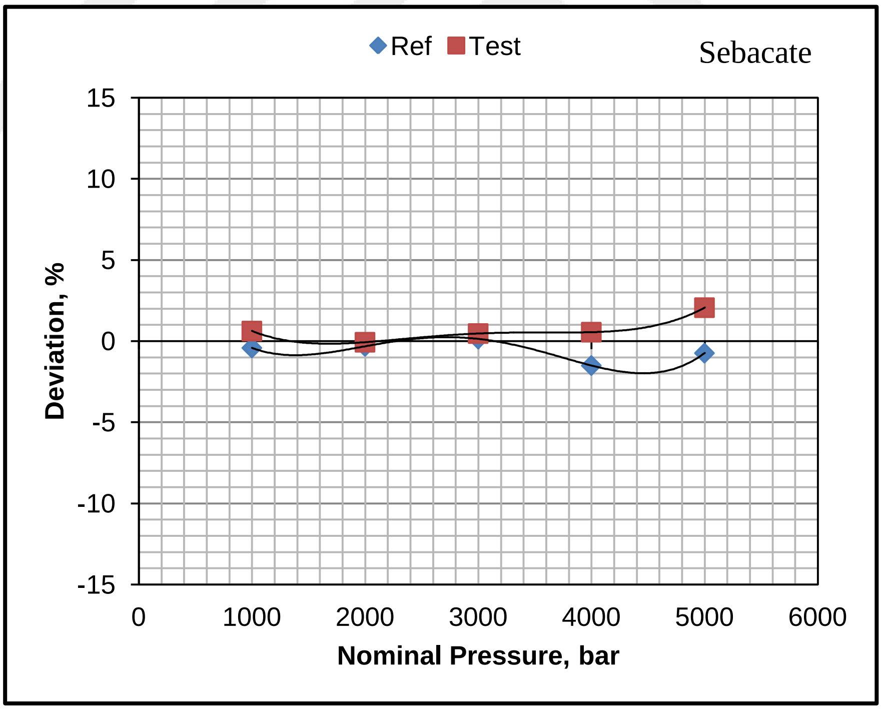


Figure 4.7. Deviation for reference and test sensors versus pressure in sebacate

Table 4.6. Summary of measurement results for the reference sensor range from 100 MPa to 500 MPa

Type of Oil Used							
Drop Height [mm]	Nominal Pressure [MPa]	KISTLER 1053		DROSERA MS5		SEBECATE	
		Measured Pressure [MPa]	Deviation from Nominal [%]	Measured Pressure [MPa]	Deviation from Nominal [%]	Measured Pressure [MPa]	Deviation from Nominal [%]
19	100	111.94	11.9	102.08	2.1	99.58	-0.4
60	200	220.90	10.5	202.10	1.1	199.36	-0.3
115	300	327.70	9.2	302.80	0.9	300.40	0.1
180	400	429.90	7.5	398.60	-0.4	393.98	-1.5
235	500	503.20	0.6	484.20	-3.2	496.30	-0.7

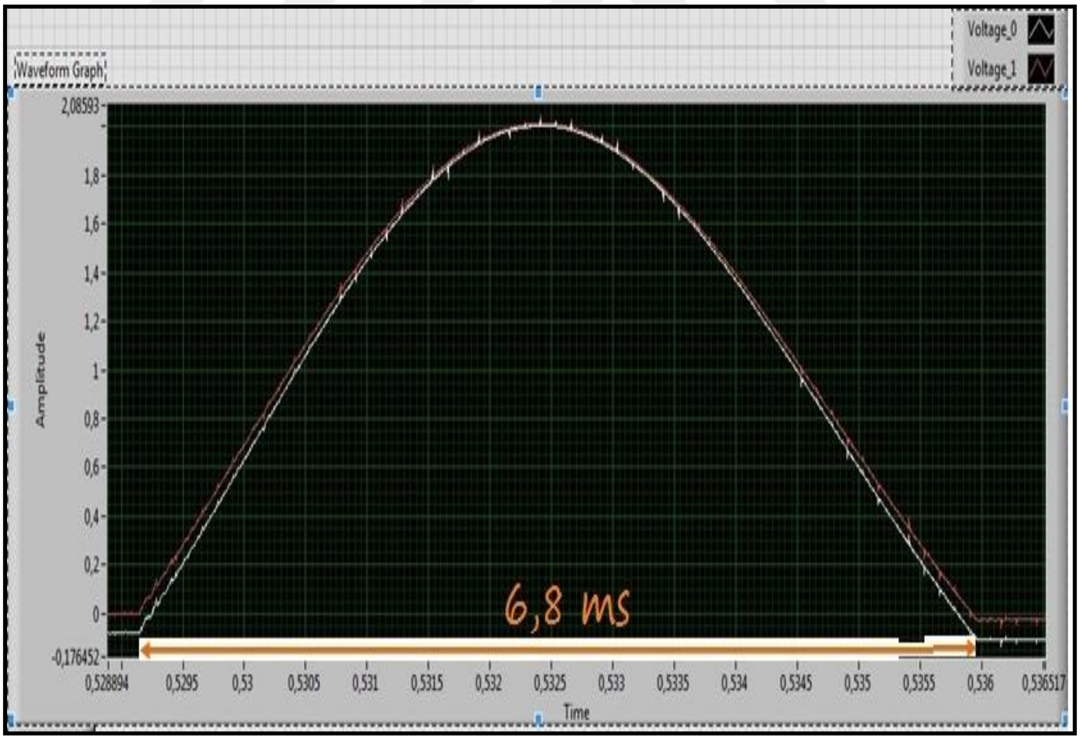


Figure 4.8. Electrical outputs of reference and test channel, white and red line respectively for sebacate type oil at 100 MPa

Typical graphical representation of electrical output of the pressure measurement system for sebacate oil at 100 MPa pressure range is given in Figure 4.8, for the oil Drosera graph is given in Figure 4.9 and for the oil Kistler 1053 graph is given in Figure 4.10.

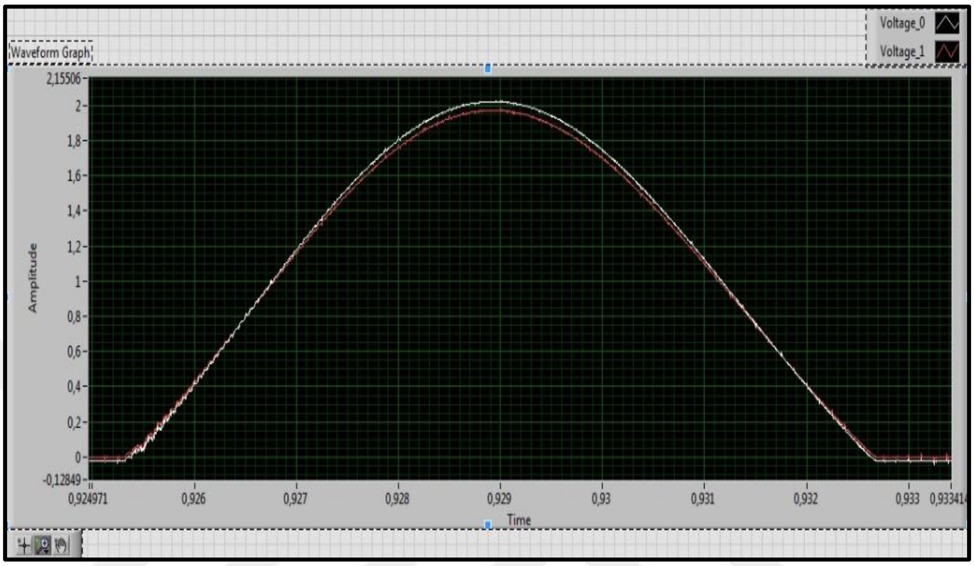


Figure 4.9. Electrical outputs of reference and test channel, white and red line respectively for Drosera MS5 type oil at 100 MPa

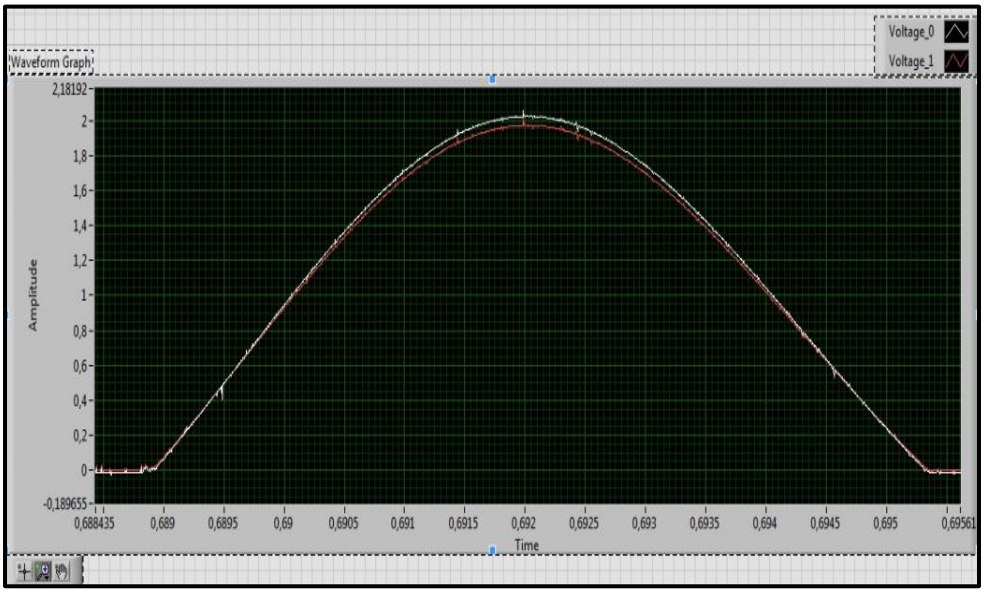


Figure 4.10. Electrical outputs of reference and test channel, white and red line respectively for Kistler 1053 type oil at 100 MPa

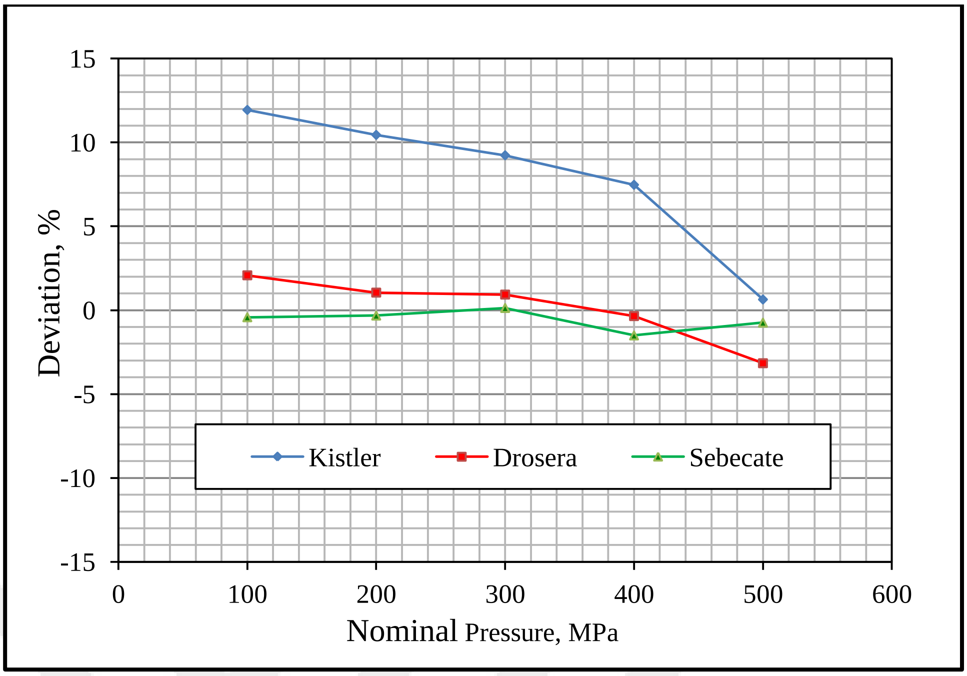


Figure 4.11. Deviation from nominal pressure for reference sensor

The graphs of deviation of pressure values for the test sensor from the reference values for three different oil is seen in Figure 4.11. The expression of a measurement result is satisfactory only if the results include both the value attributed to measurement quantity and uncertainty of the measurement which is associated with that value. Uncertainty is the amount of doubt in a measurement. Uncertainty value should be evaluated for each measurement value. In a dynamic pressure measurement, find the parameters which causes uncertainty should be determined first. For this purpose, measurement should be defined by a mathematical model as given for dynamic pressure measurement in equation (4.7). In the mathematical model, each of parameters are known as uncertainty parameter. Combination of these parameters are known as uncertainty budget. Numerical value of this budget is total standart uncertaint value. Then assign a numerical value for each uncertainty parameter and find summation of these parameters. As a result a standart uncertainty value is evaluated. Model function for dynamic pressure produced in the closed cavity is calculated by equation (4.7) by using the sensitivities of the pressure transducer and signal conditioner.

$$p = \frac{U}{S_{qa} \cdot S_{SC}} R_{FSD} \tag{4.7}$$

where, $\boldsymbol{U}$ is output voltage of measurement chain (pressure transducer and signal conditioner) in Volt, $\boldsymbol{S_{qa}}$ is sensitivity of pressure transducer in pC/MPa, $\boldsymbol{S_{SC}}$ is sensitivity of signal conditioner in mV/pC and $\boldsymbol{R_{FSD}}$ is full scale deflection factor of signal conditioner. Nominal sensitivity of the pressure transducer is 11.93 pC/MPa and its full scale linearity is around 0.17 %. The drift of the sensitivity of the pressure transducer is estimated as 0.25%. Temperature dependence of the sensitivity is assumed 0.1%. The voltage to charge conversion factor of the signal conditioner is $1x10^{-3}$ V/pC and resolution of the signal conditioner is 0.05 MPa.

The uncertainty of the calibration and full linearity of the conditioner is around 0.10% and 0.43% respectively. Measurements were repeated five times for each nominal pressure values. The calculated uncertainty values for the pressure measurements in 3 different oils are given in Table 4.7. Details of uncertainty budget and determination of uncertainty values at 500 MPa in sebacate oil are given in from Table 4.8 to Table 4.12

Table 4.7. Summary of measurement results for the reference sensor range from 100 MPa to 500 MPa

Nominal Pressure	**Type of oil inside the closed chamber**		
	Kistler	**Drosera**	**Sebecate**
[MPa]	**Measurement Uncertainty in % (k=2)**		
100	0.70	0.71	1.01
200	0.73	0.68	1.00
300	0.69	0.67	1.06
400	1.09	0.89	0.80
500	0.72	1.31	1.49

Table 4.8. Uncertainty evaluation at 100 MPa for the oil Sebacate

Uncertainty Evaluation at 100 MPa for the oil Sebacate													
uncertainty resources				**partial uncertaities**					**Sensitivity coefficients**			**partial variances**	
definition	**symbol**	**Estimated value**	**unit**	**symbol**	**Value**	**unit**	**distribution function**	**Multiplier**	**Symbol**	**value**	**unit**	**value**	**unit**
measured value by calibrator	$P_{\text{ölç}}$	1000	bar	0	0.00	0		0	0	0	0	0	0
resolution of calibrator	$d_{\text{çöz}}$	1	bar		0.05	%	Rectangular	0.577	0	1	-	8.32E-04	$(\%)^2$
scale of calibrator	d_{FSD}	500	Bar / Volt		0.00	%	Rectangular	0.577	0	1	-	0.00E+00	$(\%)^2$
measured voltage	V	2.386	V	0	0.17	%	Rectangular	0.577	0	1	-	1.02E-02	$(\%)^2$
load sensitivity of reference pressure sensor	S_{qa}	1.193	pC / bar		0.14	%	Rectangular	0.577	0	-1	-	6.53E-03	$(\%)^2$
drift in pressure sensor sensitivity	d_{drift}	1	-	0	0.25	%	Rectangular	0.577	0	-1	-	2.08E-02	$(\%)^2$
temperature change effect in sensor sensitivity	d_{temp}	1	-	0	0.10	%	Rectangular	0.577	0	-1	-	3.33E-03	$(\%)^2$
conversion coefficient of calibrator	k	1	mV / pC	0	0.10	%	Normal	0.5	0	-1	-	2.50E-03	$(\%)^2$
load conversion linearity of calibrator	d_k	1	0	0	0.43	%	Rectangular	0.577	0	-1	0	6.22E-02	0
repeatability of measurements	d_{rep}	1	-	0	0.39	%	Normal	1	0	1	-	1.51E-01	$(\%)^2$
								TOTAL VARIANCE			u^2c =	2.57E-01	$(\%)^2$
								relative standard uncertainty			uc =	0.51	%
certificate value	P (bar)	1000	U (%)	1.01	k = 2.0			relative expanded uncertainty			U	1.01	%
								(k=2.0 %95 confidence level)					

Table 4.9. Uncertainty evaluation at 200 MPa for the oil Sebacate

Uncertainty Evaluation at 200 MPa for the oil Sebacate													
uncertainty resources				**partial uncertaities**					**Sensitivity coefficients**			**partial variances**	
definition	**symbol**	**Estimated value**	**unit**	**symbol**	**value**	**unit**	**distribution function**	**multiplier**	**symbol**	**value**	**unit**	**value**	**unit**
measured value by calibrator	$P_{\text{ölç}}$	2000	bar	0	0.00	0							
resolution of calibrator	$d_{\text{çöz}}$	1	bar		0.05	%	Rectangular	0.577	0	1	-	8.32E -04	$(\%)^2$
scale of calibrator	d_{FSD}	500	Bar / Volt		0.00	%	Rectangular	0.577	0	1	-	0.00E +00	$(\%)^2$
measured voltage	V	4.772	V	0	0.17	%	Rectangular	0.577	0	1	-	1.02E -02	$(\%)^2$
load sensitivity of reference pressure sensor	S_{qa}	1.193	pC / bar		0.14	%	Rectangular	0.577	0	-1	-	6.53E -03	$(\%)^2$
drift in pressure sensor sensitivity	d_{drift}	1	-	0	0.25	%	Rectangular	0.577	0	-1	-	2.08E -02	$(\%)^2$
temperatur e change effect in sensor sensitivity	d_{temp}	1	-	0	0.10	%	Rectangular	0.577	0	-1	-	3.33E -03	$(\%)^2$
conversion coefficient of calibrator	k	1	mV / pC	0	0.10	%	Normal	0.5	0	-1	-	2.50E -03	$(\%)^2$
load conversion linearity of calibrator	d_k	1	0	0	0.43	%	Rectangular	0.577	0	-1	0	6.22E -02	0
repeatabili ty of measurem ents	d_{rep}	1	-	0	0.38	%	Normal	1	0	1	-	1.45E -01	$(\%)^2$
								TOTAL VARIANCE			u^2c =	0.25	$(\%)^2$
								relative standard uncertainty			uc =	0.50	%
certificate value	P (bar)	2000	U (%)	1.00190 72	k = 2.0			relative expanded uncertainty			U	1.00	%
								(k=2.0 %95 confidence level)					

Table 4.10. Uncertainty evaluation at 300 MPa for the oil Sebacate

Uncertainty Evaluation at 300 MPa for the oil Sebacate													
uncertainty resources				**partial uncertaities**					**Sensitivity coefficients**			**partial variances**	
definition	**symbol**	**Estimated value**	**unit**	**symbol**	**value**	**unit**	**distribution function**	**multiplier**	**symbol**	**value**	**unit**	**value**	**unit**
measured value by calibrator	$P_{\text{ölç}}$	3000	Bar										
resolution of calibrator	$d_{\text{çöz}}$	1	Bar		0.05	%	Rectangular	0.577	0	1	-	8.32E-04	$(\%)^2$
scale of calibrator	d_{FSD}	500	Bar / Volt		0.00	%	Rectangular	0.577	0	1	-	0.00E+00	$(\%)^2$
measured voltage	V	7.158	V	0	0.17	%	Rectangular	0.577	0	1	-	1.02E-02	$(\%)^2$
load sensitivity of reference pressure sensor	S_{qa}	1.193	pC / bar		0.14	%	Rectangular	0.577	0	-1	-	6.53E-03	$(\%)^2$
drift in pressure sensor sensitivity	d_{drift}	1	-	0	0.25	%	Rectangular	0.577	0	-1	-	2.08E-02	$(\%)^2$
temperature change effect in sensor sensitivity	d_{temp}	1	-	0	0.10	%	Rectangular	0.577	0	-1	-	3.33E-03	$(\%)^2$
conversion coefficient of calibrator	k	1	mV / pC	0	0.10	%	Normal	0.5	0	-1	-	2.50E-03	$(\%)^2$
load conversion linearity of calibrator	d_k	1	0	0	0.43	%	Rectangular	0.577	0	-1	0	6.22E-02	0
repeatability of measurements	d_{rep}	1	-	0	0.42	%	Normal	1	0	1	-	1.73E-01	$(\%)^2$
								TOTAL VARIANCE			u^2_c =	0.28	$(\%)^2$
								relative standard uncertainty			u_c =	0.53	%
certificate value	P (bar)	3000	U (%)	1.0568874	k = 2.0			relative expanded uncertainty			U	1.06	%
								(k=2.0 %95 confidence level)					

Table 4.11. Uncertainty evaluation at 400 MPa for the oil Sebacate

Uncertainty Evaluation at 400 MPa for the oil Sebacate													
uncertainty resources				**partial uncertaities**					**Sensitivity coefficients**			**partial variances**	
definition	**symbol**	**Estimated value**	**unit**	**symbol**	**value**	**unit**	**distribution function**	**multiplier**	**symbol**	**value**	**unit**	**value**	**unit**
measured value by calibrator	$P_{\text{ölç}}$	4000	Bar										
resolution of calibrator	$d_{\text{çöz}}$	1	Bar		0.05	%	Rectangular	0.577	0	1	-	8.32E -04	$(\%)^2$
scale of calibrator	d_{FSD}	500	Bar / Volt		0.00	%	Rectangular	0.577	0	1	-	0.00E +00	$(\%)^2$
measured voltage	V	9.544	V		0.17	%	Rectangular	0.577	0	1	-	1.02E -02	$(\%)^2$
load sensitivity of reference pressure sensor	S_{qa}	1.193	pC / bar		0.14	%	Rectangular	0.577	0	-1	-	6.53E -03	$(\%)^2$
drift in pressure sensor sensitivity	d_{drift}	1	-		0.25	%	Rectangular	0.577	0	-1	-	2.08E -02	$(\%)^2$
temperatur e change effect in sensor sensitivity	d_{temp}	1	-		0.10	%	Rectangular	0.577	0	-1	-	3.33E -03	$(\%)^2$
conversion coefficient of calibrator	k	1	mV / pC		0.10	%	Normal	0.5	0	-1	-	2.50E -03	$(\%)^2$
load conversion linearity of calibrator	d_k	1	0		0.43	%	Rectangular	0.577	0	-1	0	6.22E -02	0
repeatabili ty of measurem ents	d_{rep}	1	-		0.23	%	Normal	1	0	1	-	5.19E -02	$(\%)^2$
								TOTAL VARIANCE			u^2_c =	0.16	$(\%)^2$
								relative standard uncertainty			u_c =	0.40	%
certificate value	P (bar)	4000	U (%)		k = 2.0			relative expanded uncertainty			U	0.80	%
								(k=2.0 %95 confidence level)					

Table 4.12. Uncertainty evaluation at 500 MPa for the oil Sebacate

Uncertainty Evaluation at 500 MPa													
uncertainty resources				**partial uncertaities**					**Sensitivity coefficients**			**partial variances**	
definition	**symbol**	**Estimated value**	**unit**	**symbol**	**Value**	**unit**	**distribution function**	**multiplier**	**symbol**	**value**	**unit**	**value**	**unit**
measured value by calibrator	$P_{ölç}$	5000	bar										
resolution of calibrator	$d_{çöz}$	1	bar		0.05	%	Rectangular	0.577		1	-	8.32E -04	$(\%)^2$
scale of calibrator	d_{FSD}	500	Bar / Volt		0	%	Rectangular	0.577		1	-	0.00E +00	$(\%)^2$
measured voltage	V	11.93	V		1.75E -01	%	Rectangular	0.577		1	-	1.02E -02	$(\%)^2$
load sensitivity of reference pressure sensor	S_{qa}	1.193	pC / bar		0.14	%	Rectangular	0.577		-1	-	6.53E -03	$(\%)^2$
drift in pressure sensor sensitivity	d_{drift}	1	-		0.25	%	Rectangular	0.577		-1	-	2.08E -02	$(\%)^2$
temperatur e change effect in sensor sensitivity	d_{temp}	1	-		0.1	%	Rectangular	0.577		-1	-	3.33E -03	$(\%)^2$
conversion coefficient of calibrator	k	1	mV / pC		0.10	%	Normal	0.5		-1	-	2.50E -03	$(\%)^2$
load conversion linearity of calibrator	d_k	1			0.43	%	Rectangular	0.577		-1		6.22E -02	
repeatabili ty of measurem ents	d_{rep}	1	-		0.67	%	Normal	1		1	-	4.49E -01	$(\%)^2$
								TOTAL VARIANCE			u^2_c =	5.56E -01	$(\%)^2$
								relative standard uncertainty			u_c =	0.75	%
certificate value	P (bar)	5000	U (%)	1.49	k = 2.0			relative expanded uncertainty			U	1.49	%
								(k=2.0 %95 confidence level)					

4.3. MEASUREMENT RESULTS ON IMPACT TEST MACHINE

Dynamic pressure measurements have been conducted in impact test machine up to 500 MPa using the setups which are given in Figure 3.43. In this system same pressure sensors are used as in drop mass system measurements. Measurements have been done at 200 MPa, 300 MPa, 400 MPa, 500 MPa. Drosera MS5 and sebacate type oils were used as pressure transmitting media. Measurement results for drosera are given in Table 4.13 and for sebacate given in Table 4.14.

Table 4.13. Impact test machine measurement results for Drosera

Type of Media	Nominal Pressure (bar)	Test Pressure (bar)	Max. Load (N)	Drop Height (m)	Impact Velocity (m/s)	Drop Energy (J)	Max. Penetration (mm)	Duration Time (ms)
Drosera	2000	2080	3801	0.092	1.340	4.499	2.748	5.691
	3000	2945	5402	0.163	1.787	7.999	3.391	5.386
	4000	3930	7294	0.259	2.252	12.700	4.079	5.120
	5000	5025	9136	0.367	2.681	18.000	4.651	4.907

Table 4.14. Impact test machine measurement results for Sebacate

Type of Media	Nominal Pressure (bar)	Test Pressure (bar)	Max. Load (N)	Duration Time (ms)
Sebacate	2000	2135	3926	5.437
	2000	2135	3926	5.437
	3000	3015	5556	5.151
	4000	4075	7469	4.902
	5000	5115	9362	4.729

Measurements in impact test machine have been repeated 5 times at each nominal pressure value. Impact test machine is controlled by an enhanced sofware program running on a controlling computer. There is load cell located on the bottom end of the dropping mass as well as a accelerator sensor on the dropping mass. So different parameters such as maximum load, drop height, impact velocity, drop energy, maximum penetration of the piston into fluid, duration of dropping time can be measured and recorded as given in Table 4.13 and Table 4.14.

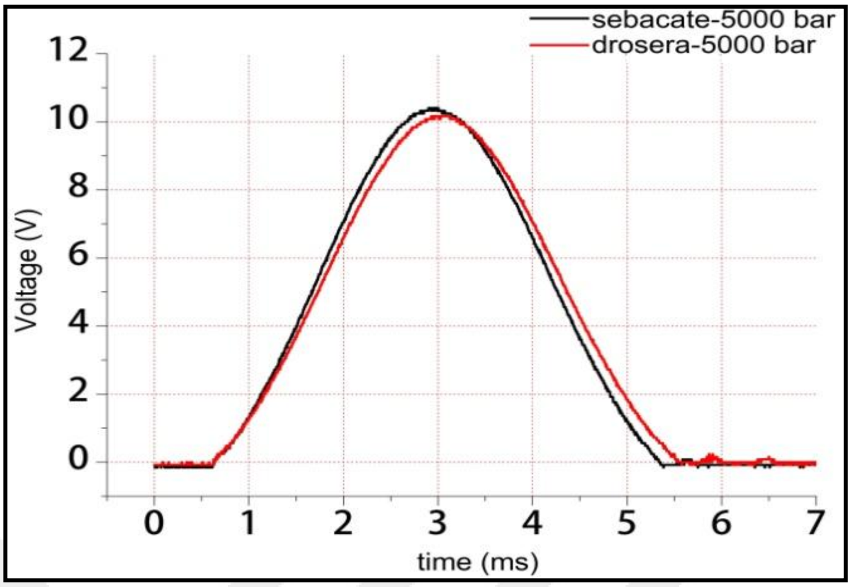


Figure 4.12. Comparison of pressure media effect for 5000 Bar

Figure 4.12 shows the output voltage signals of reference sensor versus time both for sebacate and drosera MS5. The signal is collected from analogue output channel of the charge amplifier as seen in Figure 3.43 by an oscilloscope. By the evaluation of the measurement results as seen in Figure 4.13, it seems that output waveforms look like a half sine signal with a approximate 5 milliseconds to 6 milliseconds period. Analogue output voltages versus time in sebacate media for reference sensor from 100 MPa to 500 MPa are given in Figure 4.13.

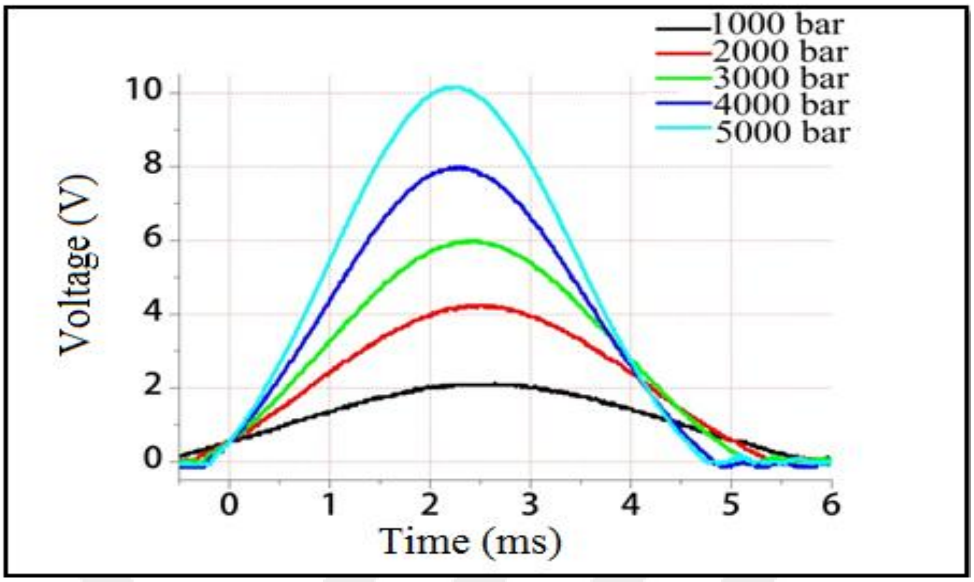


Figure 4.13. Output voltage signals of transducers vs time for impact test machine

Besides the voltage vs. time waveforms, some other additional graphs were drawn based on the data given in Table 4.13. They are force versus time, energy versus time and velocity versus time for each pressure point up to 500 MPa are given in Figure 4.14, Figure 4.15 and Figure 4.16 respectively.

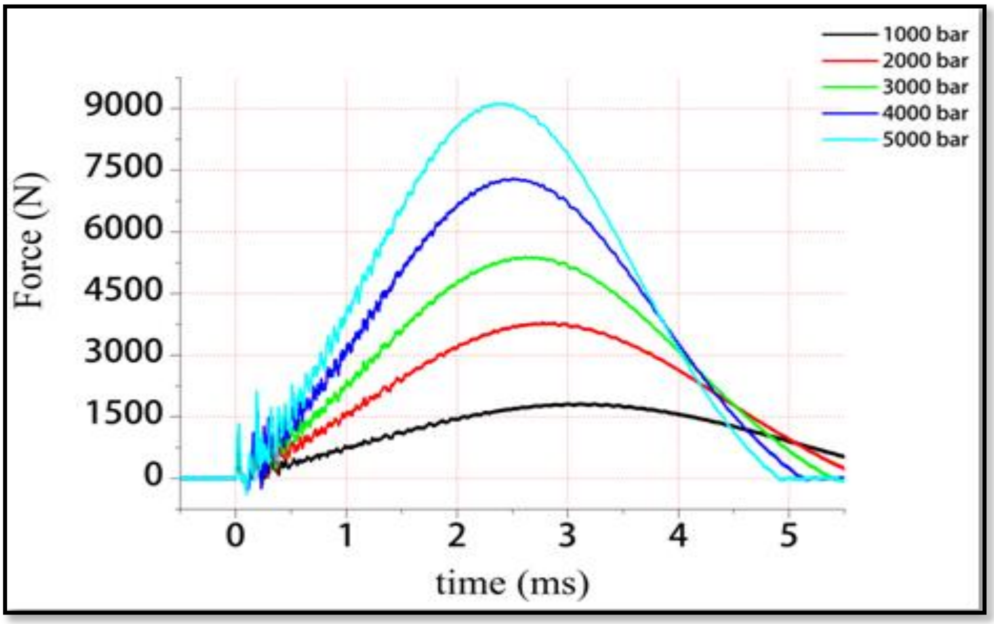


Figure 4.14. Applied force value versus time on impact test machine

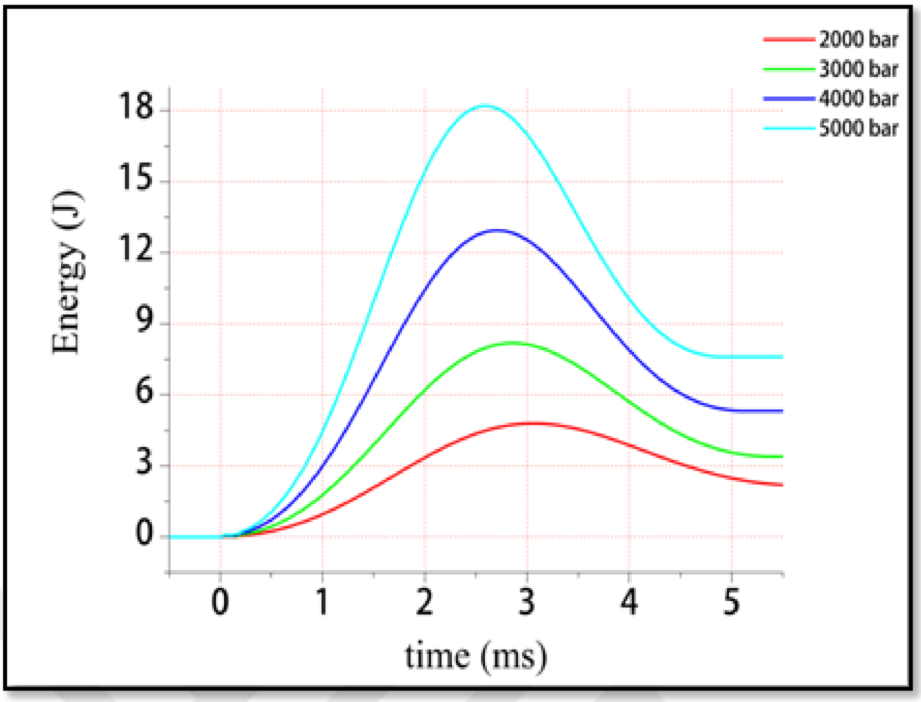


Figure 4.15. Transferred energy value versus time on impact test machine

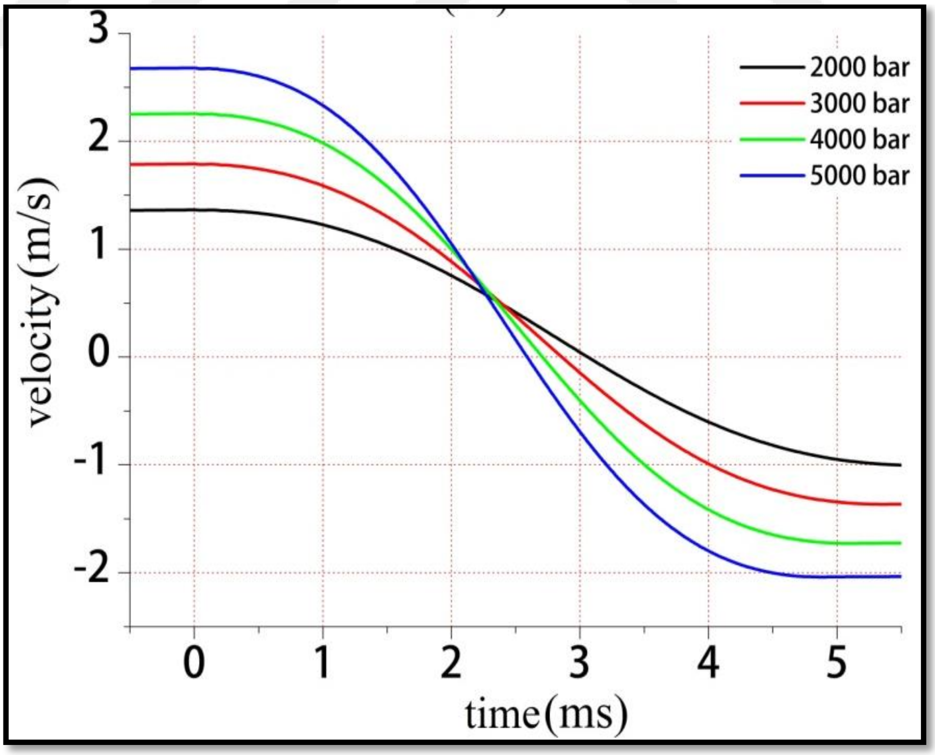


Figure 4.16. Velocity of dropping mass versus time on impact test machine

4.3.1. Calculations of Pressure Sensor Sensitivity by Polynomial Approximation

As mentioned above measurements were performed at nominal pressure values of 100 MPa, 200 MPa, 300 MPa, 400 MPa and 500 MPa. During collection of the data two different sampling rate and resolution used, 250 000 samples/second, 4 bit and 800 000 samples/second, 12 bit. It is clear that the results for the data collected with high sampling rate and resolution is more accurate. In order to determining the peak values of the output signals, corresponding to dynamic pressure, polynomial approximation was made. In this method output signal data which is in the range of 90% of the maximum value of the output signals is taken into account. Using Matlab software parabola " $f(x) = a+bx+cx^2$ " approximation model was applied to output signal pulse.

Schematic presentation of the fitted curve for the output signal data for transducer is seen in Figure 4.17.

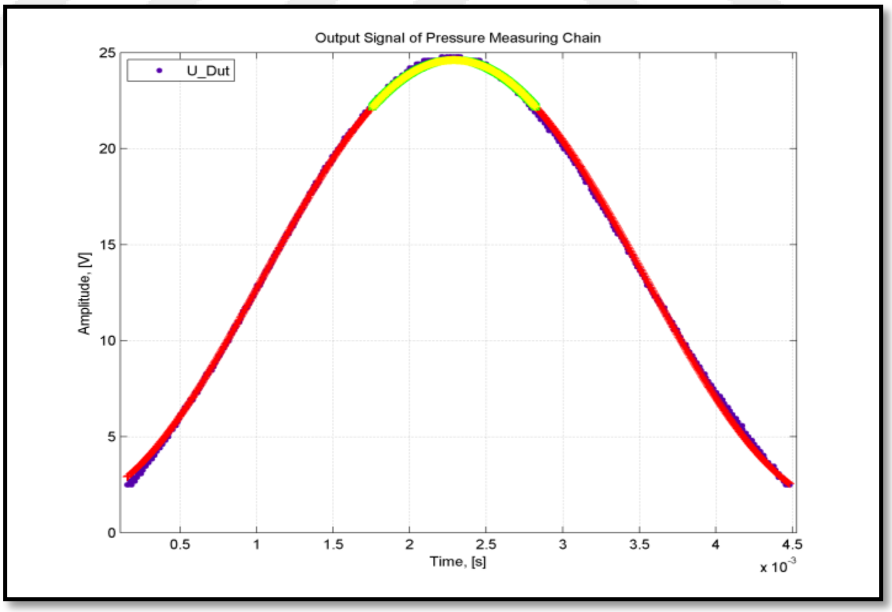


Figure 4.17. Schematic presentation of the fitted pulse for for the 90% of the maximum peak value

Then the sensitivity of the pressure transducer being calibrated was calculated using equation (4.8).

$$S_{dut} = S_{ref} \frac{U_{dut,peak}}{U_{ref,peak}} \tag{4.8}$$

where, S_{dut} is sensitivity of the calibrated transducer, S_{ref} is sensitivity of the reference transducer, $u_{dut,peak}$ is maximum peak value of output of calibrated transducer and $u_{ref,peak}$ is maximum peak values of output of the reference transducer. Calculated sensitivity results are given in Figure 4.18 and Figure 4.19.

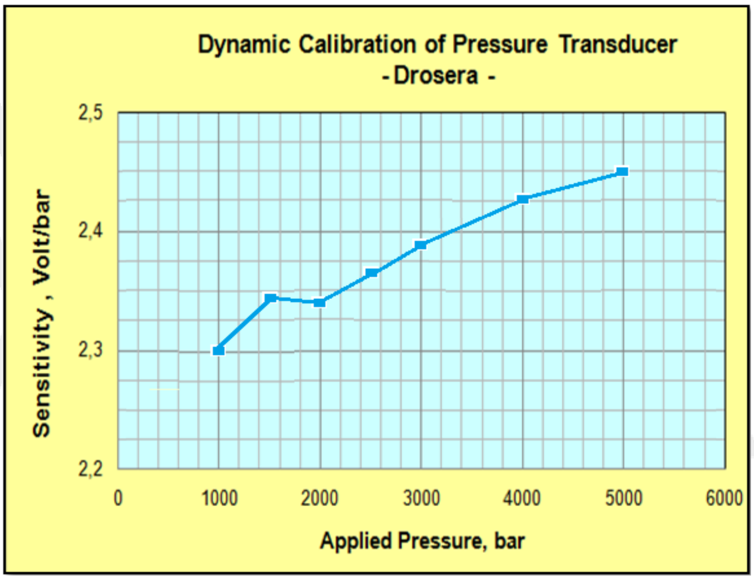


Figure 4.18. Dynamic sensitivity values of measurements for Drosera MS5 media

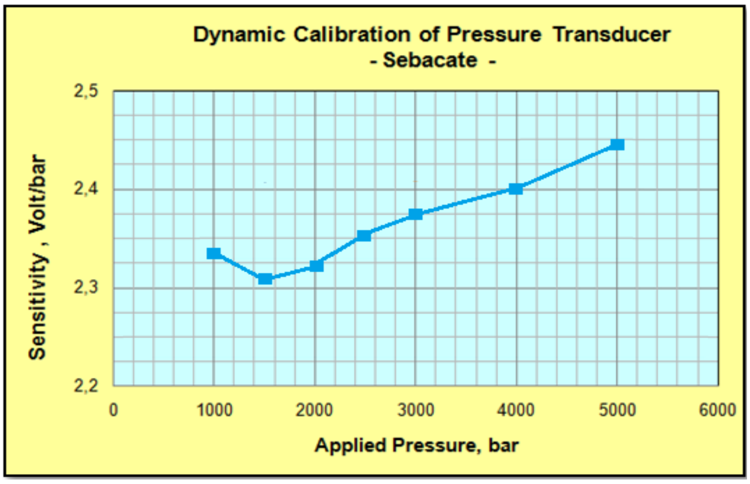


Figure 4.19. Dynamic sensitivity values of measurements for sebacate media

5. DISCUSSION

In the case of dynamic pressure calibrations of mechanical quantities, it has been recognised that lack of a metrological infrastructure appears. Some of national metrology institutes and comercial entities have attempted to remedy for this challenging dynamic area. However the solutions offered so far have often lacked traceability.

This thesis study has two significant contributions to dynamic pressure calibration area. First, a dynamic pressure generator is manufactured based on drop mass principle. It allows to generate repeatable dynamic pressure pulse signals to be used in calibrations of dynamic pressure sensors. For this purpose, three different types of transmitting oil is specified to be used in the manufactured drop mass system. In case of using Kistler 1053 oil as results appeared in Table 4.3 we get relatively worse repeatable results comparing to results given in table Table 4.4 for Drosera MS5 and Table 4.5 for Sebacate oil. Graphical illustrations for these pressure values specified in these tables are given in Figure 4.5 to Figure 4.7 and summary drawing for three oils is given in Figure 4.11. It is seen that biggest deviation between reference and test sensor is revealed in Kistler 1053 oil. It is evaluated that different results are obtained because oils have different physical and chemical specifications.

Second contribution is producing an uncertainty budget and uncertainty value which is attributed to measured nominal pressure value for reference sensor for coverage factor k=2 which corresponds to confidence level 95%. In the thesis study aim was to reach a 1% accuracy in the measurement uncertainty. In tables from Table 4.8 to Table 4.12, measurement uncertainty budget parameters are identified starting from pressure values 100 MPa to 500 MPa for the oil Sebacate. In Table 4.10, while uncertainty is calculated about 1.06% as in Table 4.12 uncertainy is about 1.49% which is the biggest one out of all tables. If uncertainty parameters are evaluated, biggest contribution to uncertainty due to repeatability error. By increasing the number of the measurements, results will be approach to majority or mean. So, it will be possible to decreasing the uncertainty about 1% for all measuring range up to 500 MPa.

For the verification of drop mass system comparison measurements were done between the drop mass system and modified impact test machine. Table 4.13 and Table 4.14 includes the results taken from impact test machine for different oils. When the figure 4.12 and figure 4.13 are evaluated, it is seen that similar output signals were obtained from the dynamic sensors in case of impact test machine when comparing to from Figure 4.8 to Figure 4.10.

Figure 4.13 and Figure 4.14 show that pressure and force signals termination points in time axis are different for each pressure points. These differences because of the mass drops further before stopping with the transmission oil media. This increase in drop implies lower deceleration and therefore lower peak force and peak pressure but a longer impact period and these reductions in force and pressures, and increase in duration, are apparent in measurements in Table 4.13 and in Table 14. Also, evaluating the Figure 4.15 and 4.16, it is seen that maximum energy is transfered to piston from dropping mass when the velocity of piston and dropping mass is zero.

Sensitivity parameter is defines the amount of electrical load to be produced by a dynamic sensor corresponding to applied pressure. So, one of the important reason for calibration of a sensor is to find the sensitivity of test sensor against to reference one. Test sensor's output signal data which is in the range of 90% of the maximum value of the output signal is taken into account. A parabola approximation model was applied to output signal pulse. Then the sensitivity of the pressure transducer being calibrated was calculated using equation (4.8). In Figure 4.18 and in Figure 4.19 calculated sensitivity of test sensor is given versus pressure in different oils. For same test sensor, calculated sensitivity differs maximum 1% between two different oils because of different physical and chemical specifications of oils.

As a result of this thesis research, newly developed dynamic pressure generator can be used in dynamic pressure sensor calibrations.

6. CONCLUSION

In this paper, two methods for dynamic pressure measurements are presented. Firstly, new developed dynamic pressure standard was presented. Since it uses drop mass working principle, it is also known as drop mass system. Designing parts of the system and manufacturing stages of these parts detailed. Some series of dynamic pressure measurements have been done on this drop mass system using reference and test dynamic pressure transducers. Measurements were carried out at hydraulic media using different types of oils with different physical and chemical properties. Measurement pressure values were 100 MPa, 200 MPa, 300 MPa, 400 MPa and 500 MPa. Measurements have been repeated 5 times at each pressure value to determine the repeatablility parameter which is involving in uncertainty budget. Drop mass system produces half sine signals with approximately 5 milliseconds signal period. Similar signals were observed at the output of both reference and test sensors which were under measurement. Amplitude of output signals were linearly proportional to applied pressure. Drop mass system has a possibility of setting drop height into a certain distance and it is possible to define number of desired measurement cycles by entering in control display. This options provide operator to do repeatable measurements which provide trustable measurements on dynamic pressure transducers.

In the measurements, range of the relative error for all fit types is found within 1%. Relative error increases due to the pressure increase. This is probably the limitation of transducer's operating range. Bias occurs between result obtained for fluids drosera MS5 and sebacate. It is assumed that this is not only resulted from fluid but also the different sampling rate and resolutions of the measurement setups and also leakage and temperature effects.

The second utilized an impact test machine, which works based on the same principle as the drop mass system. In this method impact test maching was fitted with a piston-cylinder unit, so it is essentially converted it into a drop mass system for making dynamic pressure transducer calibrations. Using the modified impact test machine, measurements were performed in different oil media at different pressure points like in the first method as in drop mass system. Repetitive measurement were done at 100 MPa, 200 MPa, 300 MPa, 400 MPa and 500 MPa . Impact test machine also gives how much energy transfered to piston, velocity of dropping mass, applied force by dropping mass, etc. parameters as well as transducer output voltage versus applied dynamic pressure.

The measurement results thus obtained from two different systems were compared via comparison measurement graphics of output voltages versus time. Observed differences between the two systems' output voltage values at each pressure point were attributed to the drop mass system and the consequent difficulties in achieving the same pressure at repeated measurements. Nonetheless, given that the observed variance between measurements taken from the two systems were about 15% at 200 MPa and 5% at 300 MPa, 400 MPa and 500 MPa. So, it is concluded that the impact test machine may be used as a drop mass system for the reliable calibration of dynamic pressure transducers.

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APPENDIX A: FRONT PANEL AND BLOCK DIAGRAM FOR LABVIEW SOFTWARE FOR DATA ACQUISITION

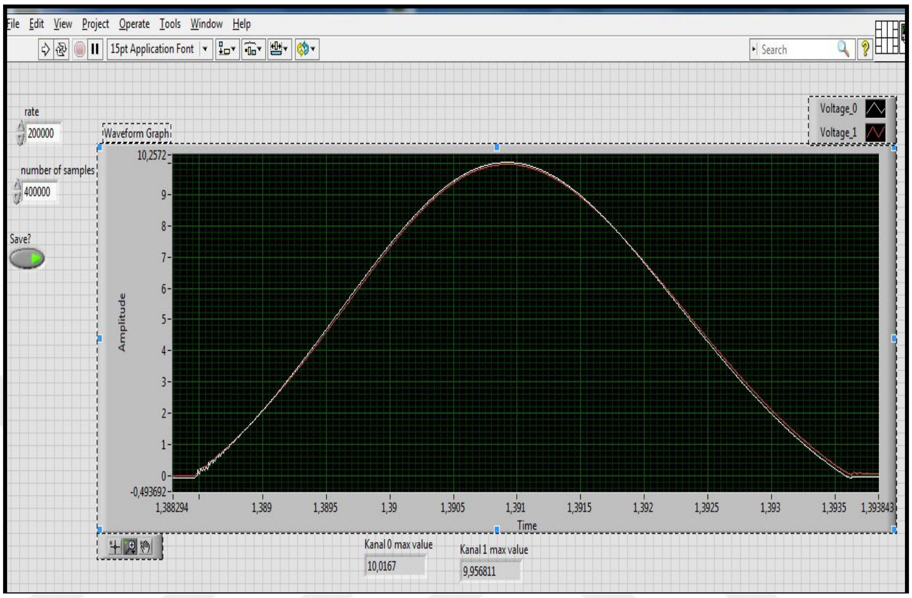


Figure A.1. Front panel

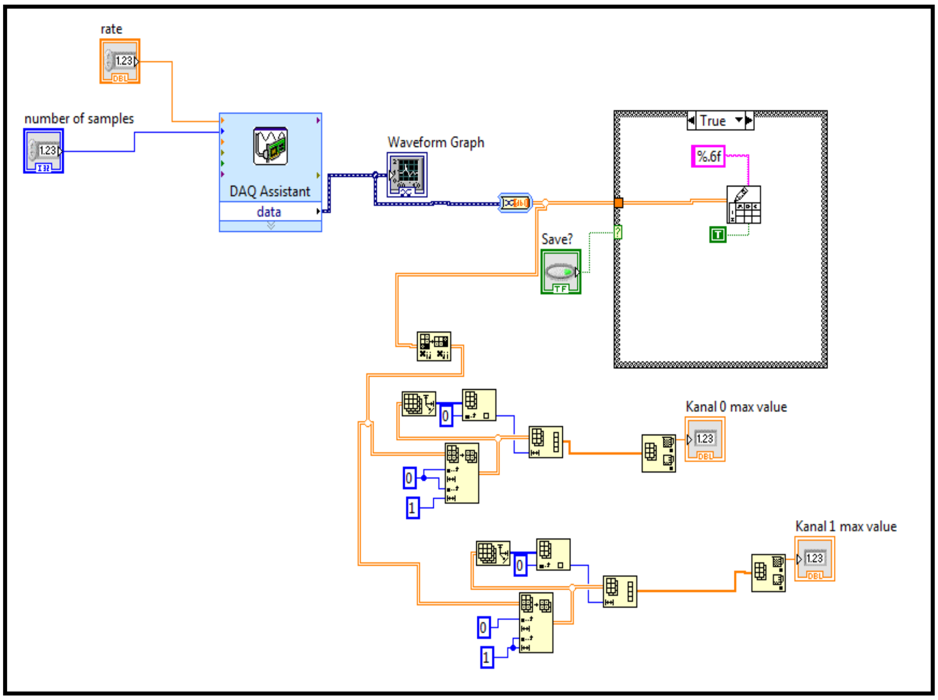


Figure A.2. Block diagram

APPENDIX B: PLC CONTROL PROGRAM

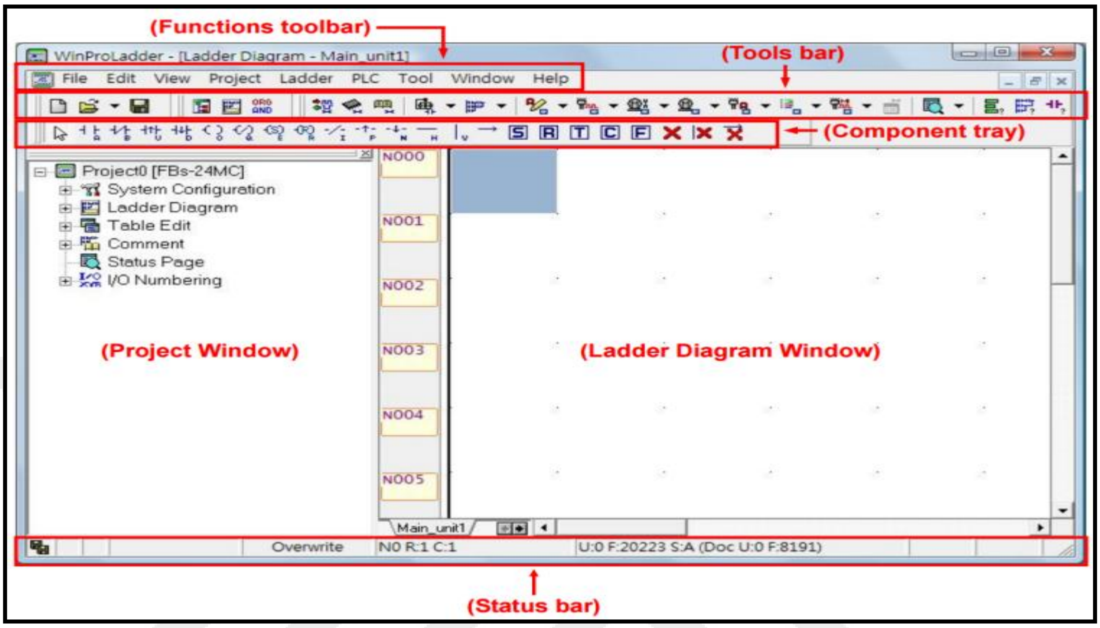


Figure B.1. Operation desktop

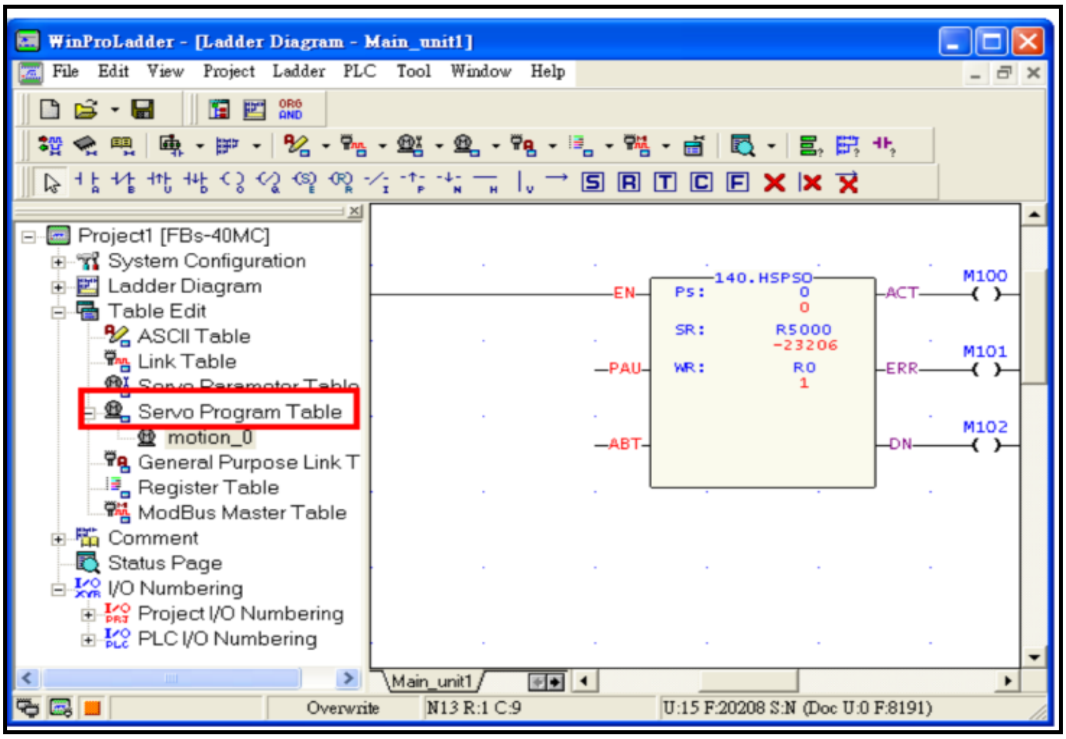


Figure B.2. Servo program table

APPENDIX C: INTOUCH CONTROL PANEL PROGRAM INTERFACE

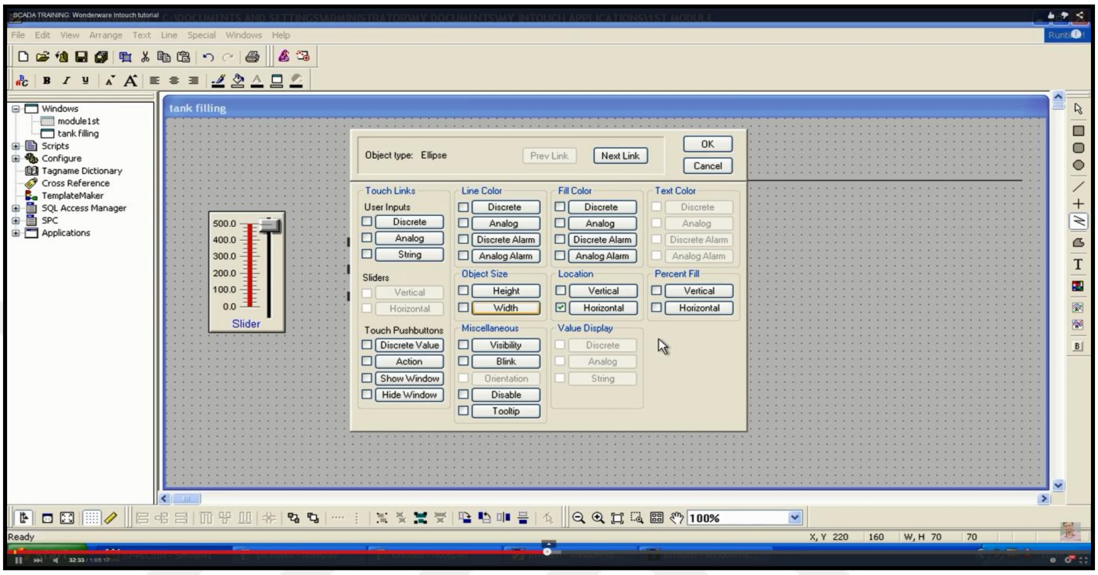


Figure C.1. Intouch control panel program design panel 1

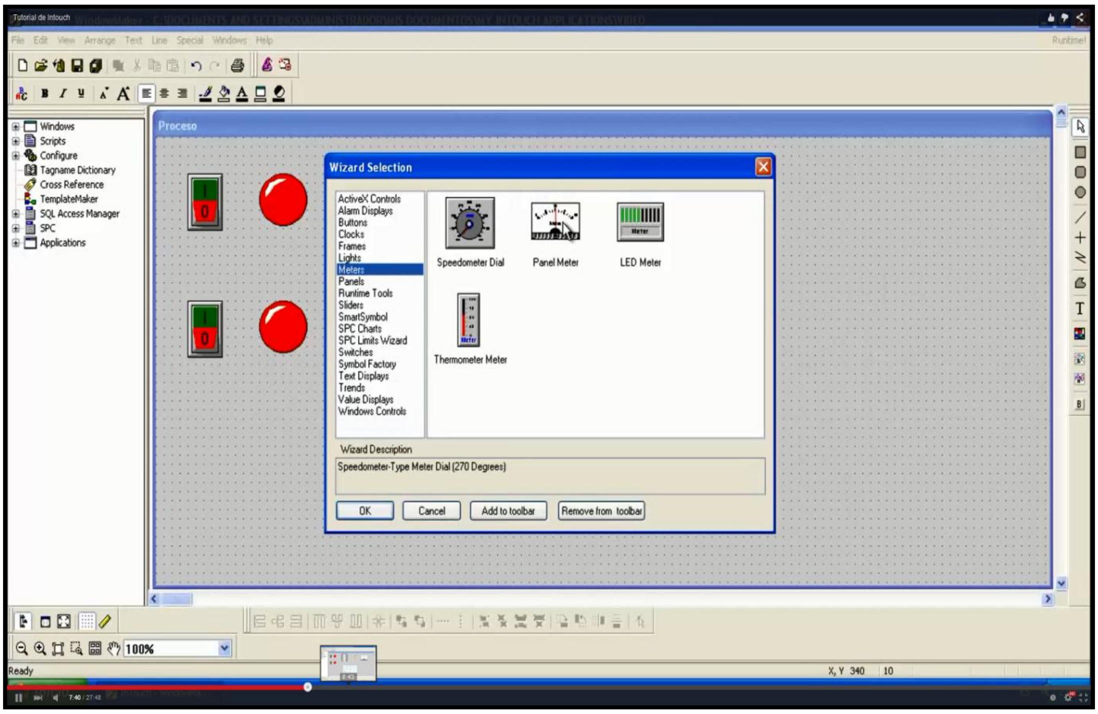


Figure C.2. Intouch control panel program design panel 2

APPENDIX D: TECHNICAL DATASHEET OF SENSOR 6213BK

Pressure – PAG

KISTLER

1 ... 2

Quarzkristall-Hochdrucksensor
Capteur de haute pression à quartz
Quartz High-Pressure Sensor

6213B

Frontdichtender Hochdrucksensor, geeignet für ballistische und hydraulische Druckmessungen bis 10'000 bar.

Durch die patentierte Anti-Strain-Konstruktion unempfindlich gegen unterschiedliche Anzugsmomente und Einbaubedingungen. Der Sensor zeichnet sich durch eine sehr gute Linearität von ≤±0,5 %, eine extrem hohe Lebensdauer und durch eine gute Langzeitstabilität aus.

Aufgrund seiner hervorragenden Messeigenschaften bestens geeignet als Referenzsensor für Kalibrieranlagen.

Capteur de haute pression à étanchéité frontale pour mesurer des pressions balistiques et hydrauliques jusqu'à 10'000 bar.

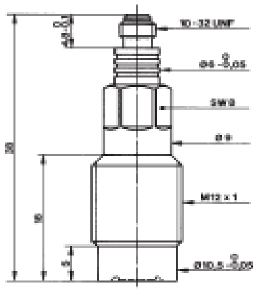
Grâce à la construction brevetée "Anti-Strain", le capteur est insensible aux couples de serrage différents et aux conditions de montage. Il se distingue par sa très bonne linéarité de ≤±0,5 %, une durée de service extrêmement grande et une bonne stabilité à long terme.

A cause de ses excellentes propriétés, ce capteur est avantageusement utilisé comme capteur de référence pour systèmes d'étalonnage.

Front sealing high pressure sensor for ballistic and hydraulic pressure measurements up to 10'000 bar.

Thanks to patented Anti-Strain construction, the sensor is not critical to different tightening torques and mounting conditions. It excels by its excellent linearity of ≤±0,5 %, an extremely high life and a good long-time stability.

Due to its excellent measuring properties, this sensor is advantageously used as a reference sensor for calibrating systems.



1 : 1

Technische Daten	Données techniques	Technical Data		
Bereich	**Gamme**	**Range**	bar	0 ... 10'000
Kalibrierter Bereich	**Gamme étalonnée**	**Calibrated range**	bar	0 ... 8'000
Kalibrierter Teilbereich	**Gamme partielle étalonnée**	**Calibrated partial range**	bar	0 ... 1'000
Überlast	**Surcharge**	**Overload**	bar	11'000
Ansprechschwelle	**Seuil de réponse**	**Threshold**	bar	<0,02
Empfindlichkeit	**Sensibilité**	**Sensitivity**	pC/bar	–1,2
Eigenfrequenz	**Fréquence propre**	**Natural frequency**	kHz	>150
Anstiegszeit	**Temps de montée**	**Rise time**	µs	2
Linearität für Bereich und Teilbereich	**Linéarité** pour gamme et gamme partielle	**Linearity** for range and partial range	% FSO	≤±0,5
Beschleunigungsempfindlichkeit	**Sensibilité aux accélérations**	**Acceleration sensitivity**	bar/g	<0,01
Stossfestigkeit	**Résistance au choc**	**Shock resistance**		
axial	axiale	axial	g	25'000
normal zur Achse	normale à l'axe	transverse	g	10'000
Temperaturkoeffizient der Empfindlichkeit	**Coefficient de température** de la sensibilité	**Temperature coefficient** of the sensitivity	%/°C	≤±0,03
Betriebstemperaturbereich	**Gamme de température d'utilisation**	**Operating temperature range**	°C	–50 ... 200
Kapazität	**Capacité**	**Capacitance**	pF	≈5,5
Isolationswiderstand bei 20 °C	**Résistance d'isolement** à 20 °C	**Insulation resistance** at 20 °C	Ω	>10[13]
Anzugsmoment	**Couple de serrage**	**Tightening torque**	Nm	40
Gewicht	**Poids**	**Weight**	g	18

1 bar = 10^5 Pa (Pascal) = 10^5 N · m^{-2} = 1,0197... at = 14,503... psi; 1 g = 9,80665 m · s^{-2}; 1 Nm = 0,73756... lbft; 1 g = 0,03527... oz

000-042m-07.92 (D803.6213Bm)

Kistler Instrumente AG Winterthur, CH-8408 Winterthur, Switzerland, Tel. (052) 224 11 11 Kistler Instrument Corp., Amherst, NY 14228-2171, USA, Phone (716) 691-5100

Figure D.1. Page 1 of techical datasheet for Kistler sensor of model 6213BK

2

Beschreibung

Die Frontdichtung stellt gegenüber der bisher verwendeten Schulterdichtung eine erhebliche technische Verbesserung dar. Die wichtigsten Vorteile der Frontdichtung sind eine wesentlich geringere mechanische und thermische Belastung des Sensors, kein Einbauspalt (kleines Totvolumen) und eine stark reduzierte Flächenpressung in der Dichtpartie.

Anwendung

Für alle ballistischen Messungen und Messanordnungen und als Referenzsensor bestens geeignet. Trotz des extrem grossen Messbereiches eignet sich der Sensor bestens für die Druckmessung relativ geringer Drücke von einigen hundert bar.

Montage

Zur Montage des Sensors genügt ein M12x1 Gewindeloch mit präzis bearbeiteter und mittels Reibwerkzeug Typ 1300A23 nachgeriebener Dichtfläche (Fig. 1). Der Einbau kann ohne besonderen thermischen Schutz lediglich mit dem Dichtring Typ 1100 erfolgen (Fig. 2).

Zur Verlängerung der Lebensdauer des Sensors und zur Erhöhung der Messgenauigkeit empfehlen wir die Verwendung des Thermoschutzschildes Typ 6563A mit eingesetzter Thermoschutzplatte Typ 1181 (Fig. 3).

Weitere Hinweise siehe B3.6213B.

Zubehör

Zubehör	Typ
• Thermoschutzplatte	1181
• Thermoschutzschild	6563A
• Dichtung	1100
• Verschlussstück	Z13195
• Adapter zu Druckgenerator 6905A	6923

Kabel: siehe Datenblatt 15.011.

Montagezubehör

Montagezubehör	Typ
• Spezialbohrer	1341
• Gewindebohrer M12x1	1355
• Reibwerkzeug	1300A23
• Drehmomentschlüssel	1371B
• Steckschlüssel SW8	1373

Ausführungen

Typ 6213BK für Kalibrierzwecke mit Linearität ± ≤0,3 %

Typ 6213B1 Set bestehend aus 6213B inkl. Einbauwerkzeug Typen 1341, 1300A23, 1855 und 1373

Description

Comparée à l'étanchéification sur épaulement utilisée jusqu'ici, l'étanchéification frontale représente une amélioration technique importante. Les avantages principaux qui en résultent sont une sollicitation mécanique et thermique considérablement réduite du capteur, pas de fente de montage (volume mort réduit) et une pression superficielle fortement réduite dans la partie d'étanchéification.

Application

Utilisation pour mesures balistiques et configurations de mesure et comme capteur de référence. Malgré sa gamme de mesure extrême, le capteur peut très bien être utilisé pour mesurer des pressions relativement basses de quelques centaines de bar.

Montage

Un seul taraudage M12x1 avec surface de joint usinée avec précision avec l'outil à plan dresser type 1300A23 suffit pour la fixation du capteur (fig. 1). Le montage peut s'effectuer sans protection thermique particulière, uniquement avec le joint d'étanchéité type 1100 (fig. 2).

Pour prolonger la durabilité du capteur et pour augmenter la précision de mesure nous recommandons l'usage d'un bouclier thermique type 6563A avec plaque de protection type 1181 (fig. 3). Pour toute information complémentaire, consulter la fiche B3.6213B.

Accessoires

Accessoires	type
• Plaque de protection thermique	1181
• Bouclier thermique	6563A
• Joint d'étanchéité	1100
• Obturateur	Z13195
• Adaptateur pour générateur de pression 6905A	6923

Câble: voir notice technique 15.011.

Accessoires de montage

Accessoires de montage	type
• Mèche spéciale	1341
• Taraudage M12x1	1355
• Outil à plan dresser	1300A23
• Clé dynamométrique	1371B
• Clé à douille à ouverture 8 mm	1373

Modèles

Type 6213BK pour une utilisation à des fins d'étalonnage, avec une linéarité ± ≤0,3 %

Type 6213B1. Set comprenant la version 6213B, ainsi que les outils de montage de types 1341, 1300A23, 1855 et 1373.

Description

Compared to the shoulder sealing used so far, the front sealing technically improves the sensor considerably. The resulting main advantages are a considerably lower mechanical and thermal stress of the sensor, no mounting gap (small dead volume) and a largely reduced surface pressure in the sealing part.

Application

Use for all ballistic measurements and measuring configurations and as a reference sensor. Despite its extremely large measuring range, the sensor is best suited for measuring relatively low pressures of several hundred bar.

Mounting

To mount the sensor, a threaded hole M12x1 with accurately machined contact face, which has been finished with the surface finishing tool Type 1300A23, is sufficient (Fig. 1). The sensor can be fitted without special thermal protection, using only the sealing ring Type 1100 (Fig. 2).

For prolongation of sensor life and for increasing the measuring accuracy we recommend the use of the thermal protection shield Type 6563A with mounted thermal protective plate Type 1181 (Fig. 3).

Further information is porvided in B3.6213B.

Accessories

Accessories	Type
• Thermal protective plate	1181
• Thermal protective shield	6563A
• Sealing joint	1100
• Locking tappet	Z13195
• Adapter to pressure generator 6905A	6923

Cable: see data sheet 15.011.

Mounting Accessories

Mounting Accessories	Type
• Special drilling tool	1341
• Screw tap M12x1	1355
• Surface finishing tool	1300A23
• Torque wrench	1371B
• Tubular socket wrench hex. 8 mm	1373

Versions

Type 6213BK for calibration purposes with linearity of ± ≤0,3 %

Type 6213B1 set consisting of 6213B including mounting tools Types 1341, 1300A23, 1855 and 1373.

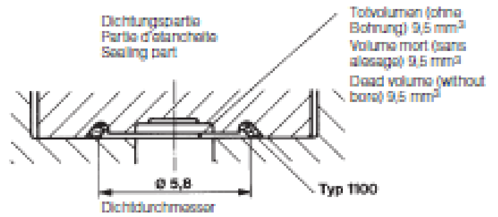


Fig. 2

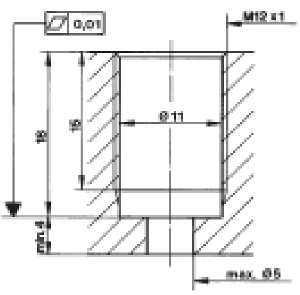


Fig. 1

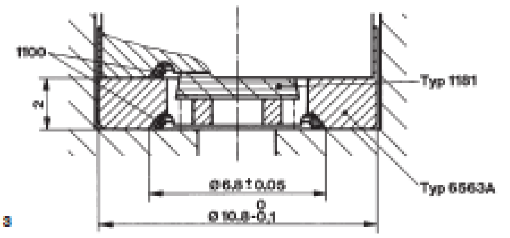


Fig. 3

000-042m-07.92 (D803.6213Bm)

Figure D.2. Page 2 of techical datasheet for Kistler sensor of model 6213BK

APPENDIX E: CALIBRATION CERTIFICATE FOR SENSOR 6213BK

KISTLER
measure. analyze. innovate.

Kalibrierschein DRUCK
Calibration Certificate PRESSURE

Type 6213BK **Serial No. 1862472**

Kalibriert durch / Calibrated by	Datum / Date
E. Weniger	12.05.2010

Referenzgeräte / Reference Equipment	Typ / Type	Serien-Nr. / Serial No.
Gebrauchsnormal / Working Standard	Budenberg 1200 [1734 Budenberg 6000 [120C	17346 12005
Ladungskalibrator / Charge Calibrator	Kistler 5395A	441991

Umgebungstemperatur / Ambient Temperature °C	Relative Feuchte / Relative Humidity %
23	42

Messergebnisse Results of Measurement

Druck / Pressure bar	Ladung / Charge pC	Empfindlichkeit der Stufe / Sensitivity of Step pC / bar
8000	-9562,9	-1,195
7000	-8355,9	-1,194
6000	-7145,4	-1,191
5000	-5959,8	-1,192
4000	-4761,0	-1,190
3000	-3573,6	-1,191
2000	-2381,8	-1,191
1000	-1188,8	-1,189
500	-593,90	-1,188
200	-236,82	-1,184
100	-118,42	-1,184

Aus der Stufenkalibrierung berechnet
Calculated by the step wise calibration

Bereich / Range bar	Empfindlichkeit / Sensitivity pC / bar	Linearität / Linearity ≤ ± %FSO
0 ... 8000	-1,193	0,14
0 ... 1000	-1,188	0,07

Messverfahren **Stufenweise Kalibrierung mit Totgewichtsanlage**
Measurement Procedure Stepwise Calibration, with dead weight tester

Kistler betreibt die SCS Kalibrierstelle Nr. 049, akkreditiert nach ISO 17025. SCS Kalibrierzertifikate sind auf Bestellung erhältlich.
Kistler operates the SCS Calibration Laboratory No. 049, which is accredited per ISO 17025. SCS Calibration Certificates are available on request.

Bestätigung Confirmation

Das oben durch die Seriennummer identifizierte Gerät entspricht der Vereinbarung der Bestellung und hält die Herstelltoleranzen gemäss den Spezifikationen der Datenblätter ein. Dieses Dokument erfüllt die Anforderungen von EN 10204 Abnahmeprüfzeugnis "3.1". Alle Messmittel sind auf nationale Normale rückverfolgbar. Das Kistler Qualitätsmanagement System ist nach ISO 9001 zertifiziert. Dieses Dokument ist ohne Unterschrift gültig.
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Figure E.1. Calibration certificate of Kistler sensor of model 6213BK

APPENDIX F: TECHNICAL DATASHEET OF SENSOR 6229AK

Pressure – PAG

KISTLER

1 ... 2

Quarz-Hochdrucksensor
Capteur de haute pression à quartz
Quartz High-Pressure Sensor

6229A

Frontdichtender Hochdrucksensor, speziell geeignet für Druckmessungen an hydraulischen Systemen, z.B. Brennstoff-Einspritzpumpen von Dieselmotoren.

Durch die patentierte Anti-Strain-Konstruktion unempfindlich gegen unterschiedliche Anzugsmomente und Einbaubedingungen. Der Sensor zeichnet sich durch eine gute Linearität, eine extrem hohe Lebensdauer und durch eine gute Langzeitstabilität aus.

Dank hervorragender Messeigenschaften bestens geeignet für das Messen relativ geringer Drücke von einigen hundert bar.

Capteur de haute pression à étanchéité frontale pour mesures de pressions dans systèmes hydrauliques, p.ex. pompes d'injection de carburant pour moteurs Diesel.

Grâce à la construction brevetée "Anti-Strain", le capteur est insensible aux couples de serrage différents et aux conditions de montage. Il se distingue par sa bonne linéarité, une durée de service extrêmement grande et une bonne stabilité à long terme.

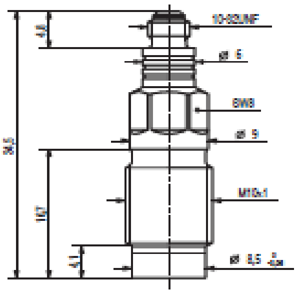
A cause de ses excellentes propriétés, ce capteur est avantageusement utilisé pour mesurer des pressions relativement basses de quelques centaines de bar.

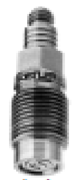
Front sealing high-pressure sensor especially for pressure measurements in hydraulic systems, e.g. fuel injection pumps of Diesel engines.

Thanks to patented Anti-Strain construction, the sensor is not critical to different tightening torques and mounting conditions. It excels by its good linearity, an extremely long lifetime and a good long-time stability.

Due to its excellent measuring properties, this sensor is advantageously used for measuring relatively low pressures of several hundred bar.

- **Hohe Eigenfrequenz**
  Fréquence propre élevée
  Built-in temperature compensation
- **Lange Lebensdauer >10^7 Zyklen (bei 3000 bar)**
  Durée de service prolongé >10^7 cycles (à 3000 bar)
  Long life >10^7 cycles (at 3000 bar)
- **Auch mit eingebautem Impedanzwandler erhältlich**
  Disponible aussi avec convertisseur d'impédance incorporé
  Available with built-in ased impedance converter, too





1 : 1

Technische Daten | **Données techniques** | **Technical Data***

Technische Daten	Données techniques	Technical Data	Unit	Value
Bereich	**Gamme**	**Range**	bar	0 ... 5000
Kalibrierter Teilbereich	**Gamme partielle étalonnée**	**Calibrated partial range**	bar	0 ... 500
Überlast	**Surcharge**	**Overload**	bar	6000
Empfindlichkeit	**Sensibilité**	**Sensitivity**	pC/bar	–2,5
Eigenfrequenz	**Fréquence propre**	**Natural frequency**	kHz	>200
Anstiegszeit	**Temps de montée**	**Rise time**	µs	1
Linearität für alle Bereiche	**Linéarité** pour toutes les gammes	**Linearity** for all ranges	% FSO	≤±1
Beschleunigungsempfindlichkeit	**Sensibilité aux accélérations**	**Acceleration sensitivity**		
axial	axiale	axial	bar/g	<0,004
normal zur Achse	normale à l'axe	transverse	bar/g	<0,01
Stossfestigkeit	**Résistance au choc**	**Shock resistance**		
axial	axiale	axial	g	10'000
normal zur Achse	normale à l'axe	transverse	g	5'000
Temperaturkoeffizient der Empfindlichkeit	**Coefficient de température** de la sensibilité	**Temperature coefficient** of sensitivity	% /°C	+ 0,02
Betriebstemperaturbereich	**Gamme de température d'utilisation**	**Operating temperature range**	°C	–50 ... 200
Kapazität	**Capacité**	**Capacitance**	pF	≈8
Isolationswiderstand bei 20 °C	**Résistance d'isolement** à 20 °C	**Insulation resistance** at 20 °C	TΩ	50
Anzugsmoment	**Couple de serrage**	**Tightening torque**	Nm	20
Gewicht	**Poids**	**Weight**	g	12
Lebensdauer (Anzahl Lastwechsel 0 ... 3000 bar)	**Durée de service** (nombre de sollicitations 0 ... 3000 bar)	**Service life** (number of load cycles 0 ... 3000 bar)		>10^7

1 bar = 10^5 Pa (Pascal) = 10^5 N · m^{-2} = 1,0197... at = 14,503... psi; 1 g = 9,80665 m · s^{-2}; 1 Nm = 0,73756... lbft; 1 g = 0,03527... oz

* In all Kistler documents, the decimal sign is a comma on the line (ISO 31-0:1992).

000-044m-11.97 (D803.6229Am)

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Figure F.1. Page 1 of techical datasheet for Kistler sensor of model 6229AK

Beschreibung

Die Frontdichtung stellt gegenüber der bisher verwendeten Schulterdichtung eine erhebliche technische Verbesserung dar. Die wichtigsten Vorteile der Frontdichtung sind eine wesentlich geringere mechanische Belastung des Sensors, kein Einbauspalt (kleines Totvolumen) und eine stark reduzierte Flächenpressung in der Dichtpartie.

Description

Comparée à l'étanchéification sur épaulement utilisée jusqu'ici, l'étanchéification frontale représente une amélioration technique importante. Les avantages principaux qui en résultant sont une sollicitation mécanique considérablement réduite du capteur, pas de fente de montage (volume mort réduit) et une pression superficielle fortement réduite dans la partie d'étanchéification.

Description

Compared to the shoulder sealing used so far, the front sealing technically improves the sensor considerably. The resulting main advantages are a considerably lower mechanical stress of the sensor, no mounting gap (small dead volume) and a largely reduced surface pressure in the sealing part.

Anwendung

Druckmessung an hydraulischen Hochdrucksystemen, z.B. Brennstoff-Einspritzpumpen von Dieselmotoren.

Application

Mesure de pressions dans systèmes hydrauliques à haute pression, tels que pompes d'injection de carburant pour moteurs Diesel.

Application

Pressure measurements in hydraulic high pressure systems, e.g. fuel injection pumps of Diesel engines.

Montage

Zur Montage genügt ein Gewindeloch M10x1 mit präzis bearbeiteter und mittels Reibwerkzeug Typ 1300A25 nachgeriebener Dichtfläche (Fig. 1).

Ein spezieller Adapter Typ 6533A... ermöglicht die direkte Montage an eine angebohrte Einspritzleitung (siehe Fig. 2).

Für die Montage ist unbedingt die Betriebsanleitung B3.6229 zu beachten.

Montage

Un seul taraudage M10x1 avec surface de joint usinée avec précision avec l'outil à plan dresser Type 1300A25 suffit pour la fixation du capteur (fig. 1).

Un adaptateur spécial type 6533A... permet le montage direct sur un conduit d'injection (voir fig. 2).

Lors du montage la Notice d'emploi B3.6229 doit être consultée.

Mounting

To mount the sensor, a threaded hole M10x1 with accurately machined contact face which has been treated with a surface finishing tool Type 1300A25 is sufficient (Fig. 1).

A special adapter Type 6533A... allows the direct mounting onto a spot drilled injection (see Fig. 2).

For the mounting procedure the Operating Instructions B3.6229 must be observed.

Zubehör

Zubehör	*Typ*
• Dichtung	1100
• Verschlussstück	6449
• Adapter zu Druckgenerator 6905A	6925
• Bridenadapter	6533A...

Kabel: siehe Datenblatt 15.011
Bridenadapter: siehe Datenblatt 4. 015

Accessoires

Accessoires	*Type*
• Joint d'étanchéité	1100
• Obturateur	6449
• Adaptateur pour générateur de pression 6905A	6925
• Adaptateur à bride	6533A...

Câble: voir notice technique 15.011
Adaptateur à bride: voir notice technique 4.015

Accessories

Accessories	*Type*
• Sealing joint	1100
• Locking tappet	6449
• Adapter to pressure generator 6905A	6925
• Clamp adapter	6533A...

Cable: see data sheet 15.011
Clamp adapter: see data sheet 4.015

Montagezubehör

Montagezubehör	*Typ*
• Spezialbohrer	1327
• Gewindebohrer M10x1	1353
• Reibwerkzeug	1300A25
• Drehmomentschlüssel	1300A11
• Mauleinsatz	1300A29
• Steckschlüssel SW 8 (nur notwendig bei Tieflochmontage)	1300B41

Accessoires de montage

Accessoires de montage	*Type*
• Mèche spéciale	1327
• Taraud M10x1	1353
• Outil à plan dresser	1300A25
• Clé dynamométrique	1300A11
• Fourche Insert	1300A29
• Clé à douille à ouverture 8 mm (seulement pour le montage dans des Alésages profonds)	1300B41

Mounting Accessories

Mounting Accessories	*Type*
• Special drilling tool	1327
• Screw tap M10x1	1353
• Surface finishing tool	1300A25
• Torque wrench	1300A11
• Fork wrench insert	1300A29
• Tubular socket wrench hex. 8 mm (only for mounting in deep holes)	1300B41

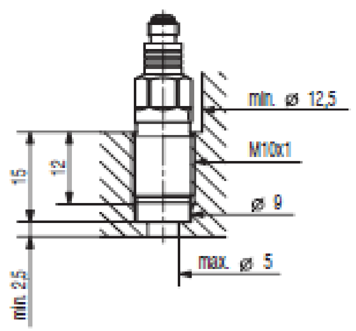

Fig. 1

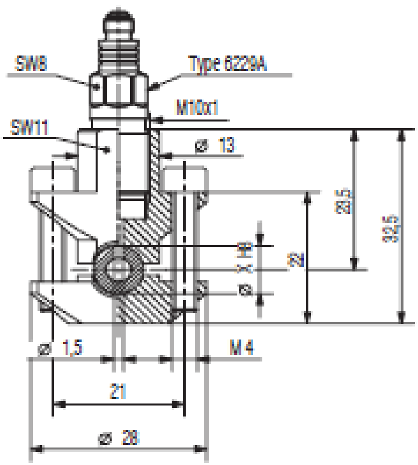

Fig. 2

000-044m-11.97 (DB03.6229Am)

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Figure F.2. Page 2 of techical datasheet for Kistler sensor of model 6229AK

APPENDIX G: CALIBRATION CERTIFICATE FOR 6229AK

KISTLER

measure. analyze. innovate.

Kalibrierschein DRUCK
Calibration Certificate PRESSURE

Type **6229AK** Serial No. **1831227**

Kalibriert durch / Calibrated by	Datum / Date
U. Köhler	25.01.2010

Referenzgeräte / Reference Equipment	Typ / Type	Serien-Nr. / Serial No.
Gebrauchsnormal / Working Standard	Kistler 6213B-6000bar	612552
Ladungskalibrator / Charge Calibrator	Kistler 5395A	441991

Umgebungstemperatur / Ambient Temperature °C	Relative Feuchte / Relative Humidity %
23	35

Messergebnisse Results of Measurement

Kalibrierter Bereich / Calibrated Range bar	Empfindlichkeit / Sensitivity pC / bar	Linearität / Linearity ≤ ± %FSO
0 ... 5000	-2,402	0,17
0 ... 2000	-2,400	0,17
0 ... 500	-2,408	0,09

Messverfahren / Measurement Procedure: **Kontinuierliche Kalibrierung, Vergleichsverfahren** / Continuous Calibration, Comparison Method

Kistler betreibt die SCS Kalibrierstelle Nr. 049, akkreditiert nach ISO 17025. SCS Kalibrierzertifikate sind auf Bestellung erhältlich.
Kistler operates the SCS Calibration Laboratory No. 049, which is accredited per ISO 17025. SCS Calibration Certificates are available on request.

Bestätigung Confirmation

Das oben durch die Seriennummer identifizierte Gerät entspricht der Vereinbarung der Bestellung und hält die Herstelltoleranzen gemäss den Spezifikationen der Datenblätter ein. Dieses Dokument erfüllt die Anforderungen von EN 10204 Abnahmeprüfzeugnis "3.1". Alle Messmittel sind auf nationale Normale rückverfolgbar. Das Kistler Qualitätsmanagement System ist nach ISO 9001 zertifiziert. Dieses Dokument ist ohne Unterschrift gültig.
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Figure G.1. Calibration certificate of Kistler sensor of model 6229AK

APPENDIX H: TECHNICAL DATASHEET OF CALIBRATOR 6907B

Accessories – XKE

KISTLER

1 ... 4

Kalibriergerät
Etalonneur
Calibrator

6907B...

Tragbares, mikroprozessorgesteuertes Kalibriergerät für Sensoren.

Zusammen mit den von Kistler angebotenen Referenzsensoren und Druckgeneratoren können komplette Anlagen für die dynamische Funktionskontrolle und quasistatische Kalibrierung von Drucksensoren erstellt werden.

Für das Erstellen von Kalibrierscheinen und zum Speichern der Kalibrierdaten steht eine zusätzliche PC-Software zur Verfügung.

Das Messgerät kann auch zur zweikanaligen Spitzendruckerfassung oder als 2-Kanal-Ladungsverstärker mit stufenlos einstellbaren Messbereichen und hohem Bedienungskomfort eingesetzt werden.

Etalonneur portatif pour capteurs, commandé par microprocesseur.

Associé aux capteurs de référence et aux générateurs de pression de la marque Kistler, cet étalonneur permet le montage d'installations complètes, destinées au contrôle de fonction dynamique et à l'étalonnage quasistatique de capteurs de pression.

Pour établir des certificats d'étalonnage et pour mémoriser les données d'étalonnage, un logiciel supplémentaire pour ordinateurs personnels est disponible.

De plus, l'étalonneur peut aussi être employé pour la mesure de pressions de crête dans 2 canaux ou comme amplificateur de charge à 2 canaux avec des gammes de mesure réglables en continu, permettant une mise en œuvre aisée.

Portable, microprocessor-controlled calibrator for sensors.

Kistler offers along with reference sensors and pressure generators also complete systems for dynamic function testing and quasistatic calibration of pressure sensors.

Additional PC software is available for producing calibration certificates and for storing calibration data.

Moreover, this measuring instrument can also be used for 2-channel peak pressure measurements or as a user-friendly 2-channel charge amplifier with continuously adjustable measuring ranges.

- **Universelles Kalibriergerät für dynamische Funktionskontrolle und quasistatische Kalibrierung**
  Etalonneur universel pour l'étalonnage dynamique et quasistatique
  Universal calibrator for dynamic and quasistatic calibration
- **Hohe Messgenauigkeit**
  Haute précision de mesure
  High measuring accuracy
- **Leistungsstarke Software für das Auswerten und Verwalten von Kalibrierdaten und das Erstellen von Protokollen**
  Logiciel très performant pour traiter et gérer les données d'étalonnage et pour établir des prises en procès-verbal
  Powerful software for processing and managing calibration data and for establishing editing reports
- **CE-konform**
  Conforme au CE
  Conforming to CE

000-382m-04.99 (D816.6907m)

Konformität mit EG-Richtlinie	Conformité à la Directive CE	Conformity to EC Directive	
EMV Störaussendung	CEM Emission	EMC Emission	EN 50081-1
EMV Störfestigkeit	CEM Immunité	EMC Immunity	EN 50082-1
Sicherheitstechnische Anforderungen	Règles de sécurité	Safety requirements	EN 61010-1

Beschreibung

Der Aufbau besteht aus einem 2-Kanal-Ladungsverstärker mit zusätzlichen analogen Spitzenwertspeichern, ADC, Mikroprozessor, einem LCD-Display sowie den Schnittstellen RS-232C und IEEE-488.

Die Bedienung ist vollständig menügeführt und kann sowohl manuell über die Frontplatte als auch über die Schnittstellen erfolgen.

Die Messwerte können in den Einheiten bar, psi, N oder M.U.** (mechanische Einheiten) auf dem Display angezeigt werden. Die Messwerte werden jedoch nicht automatisch umgerechnet.

Description

L'étalonneur se compose d'un amplificateur de charge à 2 canaux avec des mémoires pour valeurs de crête analogiques, convertisseur numérique-analogique, microprocesseur, LCD et les interfaces RS-232C et IEEE-488.

La commande est complètement automatisée par menu et peut être effectuée par l'intermédiaire de la plaquette frontale ou des interfaces.

Les valeurs de mesure sont affichées au choix en bar, psi, N ou (unités mécaniques) M.U.** Cependant des valeurs mesurées ne sont pas converties automatiquement.

Description

The calibrator consists of a 2-channel charge amplifier with analog peak value memories, ADC, microprocessor, LCD and RS-232C and IEEE-488 interface.

The operation is completely menu-controlled and can be effected via the front plate as well as the interfaces.

The measured values are displayed optionally in bar, psi, N or M.U.** (mechanical units) on the LCD. However the measured values are not automatically converted.

**) M.U. = Mechanical Unit (Mech. Einheit, z.B. bar, N, g) / M.U. = Mechanical Unit (unite mecanique, p.ex. bar, N, g) / M.U. = Mechanical Unit (e.g. bar, N, g)

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Figure H.1. Page 1 of techical datasheet for Kistler calibrator of model 6907B

2

Technische Daten	Données techniques	Technical Data*		
Anzahl Messkanäle	**Nombre des canaux de mesure**	**Number of measuring channels**		2
Messbereich	**Gamme de mesure**	**Measuring range**	pC	±10 … 999'900
Sensorempfindlichkeit (4stellig)	**Sensibilité du capteur** (4 chiffres)	**Sensor sensitivity** (4 digits)	pC / M.U.	0,01 … 9'999 **)
Massstab	**Echelle**	**Scale**	M.U. / V	0,001 … 9'999'000
Ausgangsspannung	**Tension de sortie**	**Output voltage**	V DC	±10
Ausgangsstrom	**Courant de sortie**	**Output current**	mA	<±5
(kurzschlussicher)	(protégé contre les court-circuits)	(short-circuit protected)		
Ausgangsimpedanz	**Impédance de sortie**	**Output impedance**	Ω	10
Isolationswiderstand am Eingang	**Résistance d'isolement à l'entrée**	**Insulation resistance at input**	TΩ	>100
Frequenzbereich (–3dB, Filter off)	**Gamme de fréquence** (–3dB, Filter off)	**Frequency limit** (–3dB, Filter off)	kHz	≈0 … 200
Tiefpassfilter (–3dB)	**Filtre passe-bas** (–3dB)	**Low-pass filter** (–3dB)	kHz	0,01 … 30 ±10 %
Butterworth 2-pol., 8-stufig	Butterwoth à 2 pôles, à 8 étages	Butterworth, 2 pol., 8 stages		
(je nach Messbereich)	(selon gamme de mesure)	(acc. to measuring range)		
Zeitkonstante *Long*	**Constante de temps** *Long*	**Time constant** *Long*	-	-
(τ = Rg · Cg) *Medium*	(τ = Rg · Cg) *Medium*	(τ = Rg · Cg) *Medium*	s	1 … 10'000
Short	*Short*	*Short*	s	0,01 … 100
Linearität	**Linéarité**	**Linearity**	%	≤±0,05
Fehler im Messbereich ***)	**Erreur dans la gamme de mesure** ***)	**Error in the measuring range** ***)		
≤±99,9 pC FS	≤±99,9 pC FS	≤±99,9 pC FS	%	≤±3
≤±999,9 pC FS	≤±999,9 pC FS	≤±999,9 pC FS	%	≤±1 (2)
≥±999,9 pC FS	≥±999,9 pC FS	≥±999,9 pC FS	%	≤±0,5 (1)
Fehler der ermittelten Sensorempfindlichkeit (2 s)	**Erreur de la sensibilité déterminée du capteur (2 s)**	**Error of the determined sensor sensitivity (2 s)**	%	±≤0,8
(Referenzsensor Lin. ≤±0,3 % FSO)	(Capteur de référence Lin. ≤±0,3 % FSO)	(Reference sensor Lin. ≤±0,3 % FSO)		
Ausgangsstörsignal	**Interférence à la sortie**	**Output interference**	mV_{rms}	<1,5
Störsignal durch Eingangskabel-kapazität	**Interférence due à la capacité d'entrée du câble**	**Interference due to cable capacitance**	pC_{rms}/pF	$<2 \cdot 10^{-5}$
Drift (Leckstrom des MOSFET) bei 25 °C	**Dérive** (courant de fuite du MOSFET) à 25 °C	**Drift** (leakage current of MOSFET) at 25 °C	pC/s	<±0,03
Spitzenspeicher	**Mémoire valeurs de crête**	**Peak value memory**		
Wiederholfrequenz	Fréquence de répétition	Repetition frequency	Hz	<10
Dachbreite des Druckimpulses	Palier de l'impulsion de pression	Top width of pressure pulse	µsec	>5
Speicher pro Kanal (Spitzenwerte)	Mémoires par canal (valeurs de crête)	Memories per channel (peak values)		15
Parallele Schnittstelle IEEE-488	*Interface parallèle IEEE-488*	*Parallel interface IEEE-488*		
Serielle Schnittstelle RS-232C	*Interface sériel RS-232C*	*Serial interface RS-232C*		
Allgemeines	*Général*	*General*		
Temperaturbereich	**Gamme de température**	**Operating range**		
für Spezifikationen	pour spécifications	for specifications	°C	15 … 35
für Funktion	pour fonction	for function	°C	–10 … 50
Spannungsversorgung	**Alimentation**	**Power supply**	V AC	230 / 115
(umschaltbar)	(commutable)	(switchable)	%	+15 / –22
			Hz	48 … 62
Leistungsaufnahme	**Puissance absorbée**	**Power consumption**	VA	29
Abmessungen (DIN 41494, Teil 5)	**Dimensions** (DIN 41494, partie 5)	**Dimensions** (DIN 41494, part 5)		
Breite (Frontplatte)	Largeur (plaquette frontale)	Width (front panel)	213,2 mm	(42 TE)
Höhe (Frontplatte)	Hauteur (plaquette frontale)	Height (front panel)	128,7 mm	(3 HE)
Tiefe (ohne Anschlüsse)	Profondeur (sans connexions)	Depth (without connections)	229,5 mm	
Mit Gehäuse (und mit Anschlüssen)	Avec boîtier (et avec connexions)	With case (and with connections)	236 x 151 x 260 mm	
Gewicht	**Poids**	**Weight**	kg	5
Anschlüsse	**Connexions**	**Connections**		
Netz 2 P + E	Secteur 2 P + E	Mains 2 P + E	Type	IEC 320C14
Messkreis erdfrei (Schutzklasse I)	Circuit de mesure sans terre (Classe de protection I)	Measuring circuit ground-free (Degree of protection I)		
Externes Operate	Operate externe	External Operate	3polig / 3 broches / 3 pins	Klemme / borne / terminal (Phoenix)
Max. Spannung zwischen Netzerde und Signal Common	Tension max. entre terre du secteur et Signal Common	Max. voltage between mains ground and Signal Common	V_{eff}	≤50
Messeingang	**Entrée de mesure**	**Measuring input**	Type	BNC neg.
Spannungsausgang	**Sortie de tension**	**Voltage output**	Type	BNC neg.
Anzeige (Parameter)	**Affichage** (paramètres)	**Display** (parameters)		
4zeilige, 20stellige Dot-Matrix-LCD	"Dot matrix" LCD à 4 lignes et 20 caractères	4-line, 20-character LCD dot matrix		

**) = M.U. Mechanical Unit (Mech. Einheit, z.B. bar, N, *g*) **) = M.U. Mechanical Unit (unité mécanique, p.ex. bar, N, *g*) **) M.U. = Mechanical Unit (e.g. bar, N, *g*)

000-382m-04.99 (DB16.6907m)

* In all Kistler documents, the decimal sign is a comma on the line (ISO 31-0: 1992)

***) Die Fehlerangaben gelten für ein Jahr nach Auslieferung. Anschliessend sollte das Gerät jährlich nachkalibriert werden; andernfalls sind die in den Klammern angegebenen Werte massgebend.

***) Les erreurs indiquées sont valides pour une année après livraison. Après ce délai, l'instrument doit être réétalonné chaque année; sinon les valeurs indiquées entre parenthèses sont valables.

***) Errors specified are valid for one year after delivery. Then the instrument must be recalibrated each year; otherwise the values specified within brackets are valid.

Kistler Instrumente AG Winterthur, CH-8408 Winterthur, Switzerland, Tel. (052) 224 11 11 Kistler Instrument Corp., Amherst, NY 14228-2171, USA, Phone (716) 691-5100

Figure H.2. Page 2 of techical datasheet for Kistler calibrator of model 6907B

3

Rückseite **Côté arrière** **Rear side**

Anwendung

Für das Nachkalibrieren von piezoelektrischen Drucksensoren bis 700 bar zusammen mit Druckgenerator Typ 6904 und Referenzsensoren.

Für die Kalibrierung von Sensoren mit Druckbereich >700 bar wird der Druckgenerator Typ 6905A verwendet. Für die dynamische Funktionskontrolle von Hochdrucksensoren wird zusätzlich der Typ 6909 benötigt.

Sollte bei der dynamischen Kontrolle eine Veränderung der Sensorempfindlichkeit festgestellt werden, kann der Sensor mit Hilfe des Druckgenerators Typ 6905A quasistatisch nachkalibriert werden. Auf diese Weise können zeitintensive quasistatische Kalibrierungen auf ein Minimum beschränkt werden.

Funktionen

Dynamische Funktionskontrolle

Die Kalibrierung erfolgt durch den Vergleich des Testsensors mit einem Referenzsensor.

Beide Sensoren werden einem sinusförmigem Druckimpuls von einigen Millisekunden ausgesetzt.

Die beiden Druckspitzen und deren Differenz in % und in mechanischen Einheiten werden am Kalibriergerät angezeigt und können über die Schnittstellen abgerufen werden.

Zum Aufzeichnen der Druckkurven kann zusätzlich ein 2-Kanal-Speicheroszilloskop an den analogen Messwertausgängen angeschlossen werden. Die Druckkurven können mit der PC-Software ausgewertet und in einer Datenbank gespeichert werden.

In dieser Betriebsart kann das Gerät auch als 2-Kanal-Ladungsverstärker verwendet werden.

Quasistatische Kalibrierung

Die Kalibrierung erfolgt durch den Vergleich des Testsensors mit einem Referenzsensor.

Beide Sensoren werden in den Druckgenerator eingebaut und der Druck wird durch Drehen der Spindel langsam erhöht.

Der im Kalibriergerät eingebaute 2-Kanal-Ladungsverstärker wandelt die von den beiden Sensoren abgegebenen Ladungen in proportionale Spannungen um. Der Mikroprozessor vergleicht die digitalisierten Spannungswerte insgesamt 40mal über den eingestellten Kalibrierbereich und errechnet daraus die Empfindlichkeit und Linearität des Testsensors.

Die ermittelten Werte sowie die 40 Stützwerte werden am LCD-Display angezeigt und können über die Schnittstellen abgerufen und mit der PC-Software ausgewertet und dargestellt werden.

Application

S'utilise avec le générateur de pression Type 6904 et les capteurs de référence pour réétalonner des capteurs de pression piézo-électriques jusqu'à 700 bars.

Pour l'étalonnage de capteurs destinés à la mesure de pressions supérieures à 700 bars, c'est le générateur de pression de type 6905A qui est utilisé. Pour le contrôle dynamique du fonctionnement des capteurs haute pression, le type 6909 est également nécessaire.

Lorsqu'une déviation de la sensibilité du capteur est détectée lors du contrôle dynamique, ce capteur peut être réétalonné quasistatiquement avec le générateur de pression type 6905A, ce qui permet de réduire les étalonnages statiques nécessitant beaucoup de temps à un minimum.

Fonctions

Contrôle dynamique du fonctionnement

Lors de l'étalonnage on compare un capteur à tester avec un capteur de référence.

Les deux capteurs sont soumis à une impulsion de pression de forme sinusoïdale d'une durée de quelques millisecondes.

Les deux crêtes de pression et leur différence en % et en unités mécaniques sont affichées par l'étalonneur et peuvent être appelées via les interfaces.

Pour enregistrer les courbes de pression, un oscilloscope à mémoire et à 2 canaux peut être branché sur les sorties analogiques. Les courbes de pression peuvent être évaluées avec le logiciel pour ordinateurs personnels et entrées dans une banque de données.

Dans ce mode d'utilisation, l'instrument peut aussi être employé comme amplificateur de charge à 2 canaux.

Etalonnage quasistatique

Lors de l'étalonnage on compare le capteur à tester avec un capteur de référence.

Les 2 capteurs sont installés dans le générateur de pression puis la pression est augmentée lentement en tournant la broche du générateur.

L'amplificateur de charge à 2 canaux incorporé dans l'étalonneur convertit les charges électriques générées par les 2 capteurs en des tensions proportionnelles. Le microprocesseur compare les deux tensions 40 fois sur toute la gamme d'étalonnage réglée et en déduit la sensibilité et la linéarité du capteur testé.

Les valeurs mesurées ainsi que les 40 valeurs de référence sont affichées sur LCD et peuvent être appelées via les interfaces et évaluées et représentées avec le logiciel pour ordinateurs personnels.

Application

For recalibrating piezoelectric pressure sensors up to 700 bar together with pressure generator type 6904 and reference sensors.

The pressure generator Type 6905A is used for calibrating sensors with a pressure range >700 bar. Type 6909 is additionally needed for dynamic function testing of high pressure sensors.

If a change of the sensor sensitivity is detected during dynamic checking, the sensor can be recalibrated quasistatically with the pressure generator Type 6905A. This allows to reduce time-consuming static calibrations to a minimum.

Functions

Dynamic function check

Calibration is made by comparing the performance of a test sensor with a reference sensor.

Both sensors are exposed to a sinusoidal pressure pulse of several milliseconds.

Both pressure peaks and their difference in % and in mechanical units are displayed on the calibrator and can be called via the interfaces.

To record the pressure profiles, an additional 2-channel storage oscilloscope can be connected to the analog outputs. The pressure curves can be evaluated by means of the PC software and stored in a data base.

This mode of operation allows to use the calibrator as a 2-channel charge amplifier, too.

Quasistatic calibration

Calibration is made by comparing the performance of a test sensor with a reference sensor.

Both sensors are mounted into the pressure generator then the pressure is slowly increased by turning the spindle.

The 2-channel charge amplifier built into the calibrator converts the electric charges generated by both sensors in proportional voltages. The microprocessor compares both digitized voltages 40 times over the adjusted calibration range and derives the sensitivity and the linearity of the test sensor.

The measured values as well as the 40 reference values are displayed on the LCD and can be called via the interfaces and evaluated and displayed by means of the PC software.

000-382m-04.99 (D816.6907m)

Figure H.3. Page 3 of techical datasheet for Kistler calibrator of model 6907B

Zur Aufzeichnung der Kalibrierkurve kann ein X-Y-Schreiber an die Messwertausgänge angeschlossen werden.

Un traceur peut être branché sur les sorties de mesure pour tracer la courbe d'étalonnage.

A plotter can be connected to the outputs for plotting the calibration curve.

Kalibrierkette für das Kalibrieren von Hochdrucksensoren >700 bar

Chaîne d'étalonnage pour capteurs haute pression >700 bar

Calibration chain for calibrating high-pressure sensors >700 bar

Hydraulic High Pressure Generator
Type 6905A

Impulse Pressure Generator
Type 6909

Calibrator .
Type 6907B...

PC-Software
Type 2831A

Kalibrierkette für das Kalibrieren von Sensoren bis 700 bar

Chaîne d'étalonnage pour capteurs de pressions inférieures à 700 bar

Calibration chain for calibrating high-pressure sensors up to 700 bar

Hydraulic Pressure Generator
Type 6904

Calibrator
Type 6907B...

PC-Software
Type 2831A

Zubehör	*Typ / Art.-Nr.*
• Hochdruckgenerator	6905A
• Druckgenerator	6904
• Druck-Impulsgenerator	6909
• Referenzsensor	6213BK
• Referenzsensor	6229K
• Referenzsensor	7061BK
• Referenzsensor mit SCS Kalibrierschein	6961A250 6962A2000 6963A8000
• Präzisions-Ladungskalibrator	5395A

Kabel siehe Datenblatt 15.035.
Adapter und mechanisches Zubehör siehe Datenblatt 16.6905 und 16.6909

Accessoires	*Type / Art. N°*
• Générateur de haute pression	6905A
• Générateur de pression	6904
• Générateur d'impulsions de pression	6909
• Capteur de référence	6213BK
• Capteur de référence	6229K
• Capteur de référence	7061BK
• Capteur de référence avec SCS certificat d'étalonnage	6961A250 6962A2000 6963A8000
• Amplificateur de charge à précision	5395A

Câbles, voir notice technique 15.035.
Adaptaterus et accessoires mécaniques, voir notices techniques 16.6905 et 16.6909

Accessories	*Type / Art. No.*
• High pressure generator	6905A
• Pressure generator	6904
• Pressure pulse generator	6909
• Reference sensor	6213BK
• Reference sensor	6229K
• Reference sensor	7061BK
• Reference sensor with SCS calibration certificate	6961A250 6962A2000 6963A8000
• Precision charge calibrator	5395A

Cables, see data sheet 15.035.
Adapters and mechanical accessories, see data sheets 16.905 and 16.6909

000-382m-04.99 (D816.6907m)

Figure H.4. Page 4 of techical datasheet for Kistler calibrator of model 6907B

APPENDIX I: CALIBRATION CERTIFICATE OF 6907B

Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

PTB

Kalibrierschein
Calibration Certificate

Gegenstand: *Object:*	Ladungsverstärker
Hersteller: *Manufacturer:*	Kistler Instrumente AG Postfach 304 8408 Winterthur Schweiz
Typ: *Type:*	5015 A 1000
Kennnummer: *Serial No.:*	4326662
Auftraggeber: *Applicant:*	UME Pressure Laboratoies TÜBITAK Gebze Yerleskesi P.O. Box 54, 41470 Gebze Kocaeli TURKEY
Anzahl der Seiten: *Number of pages:*	4
Geschäftszeichen: *Reference No.:*	PTB-1.33-4068343
Kalibrierzeichen: *Calibration mark:*	PTB 13002/14
Datum der Kalibrierung: *Date of calibration:*	2014-03-05

Im Auftrag
On behalf of PTB
Dr. Holger Christian Schönekeß

Braunschweig, 2014-03-05
Siegel
Seal

Im Auftrag
On behalf of PTB
Heinz Hertel

391 00A I

Kalibrierscheine ohne Unterschrift und Siegel haben keine Gültigkeit. Dieser Kalibrierschein darf nur unverändert weiterverbreitet werden. Auszüge bedürfen der Genehmigung der Physikalisch-Technischen Bundesanstalt.
Calibration Certificates without signature and seal are not valid. This Calibration Certificate may not be reproduced other than in full. Extracts may be taken only with the permission of the Physikalisch-Technische Bundesanstalt.

Figure I.1. Page 1 of calibration certificate of Kistler calibrator 6907B

Physikalisch-Technische Bundesanstalt

PTB

Seite 2 zum Kalibrierschein vom 2014-03-05, Kalibrierzeichen: PTB 13002/14
Page 2 of the Calibration Certificate dated 2014-03-05, calibration mark: PTB 13002/14

Kalibriergegenstand:

Der Ladungsverstärker vom Typ Kistler 5015 für die Messgröße elektrische Ladung.

Kalibrierverfahren:

Die Messwerte wurden mit dem beim Hersteller rückgeführten Präzisionsladungsverstärker vom Typ Kistler 5395A Prüfmittelnummer PTB-1.33-0035 nach Kalibrieranweisung des Herstellers ermittelt.

Messergebnisse:

Die Kalibrierung umfasst die Messgröße Ladung *Q*. Nach der Selbstkalibrierung des Monitors des Ladungskalibrators und der Messung der Nullpunktspannung wurde eine Messserie be 8 verschedenen Ladungen mit jeweils 1 Messwert durchgeführt.

Messunsicherheit:

Die angegebene Messunsicherheit ist die Standardunsicherheit der Messung multipliziert mit einem Erweiterungsfaktor k = 2. Sie wurde gemäß dem "*Guide to the Expression of Uncertainty in Measurement*" (ISO, 1995) ermittelt. Der Wert der Messgröße liegt im Regelfall mit einer Wahrscheinlichkeit von annähernd 95% im zugeordneten Werteintervall. Die erweiterte Messunsicherheit beinhaltet jedoch keine Langzeitstabilität.

Umgebungsbedingungen:

Temperatur	(21± 1) °C
Relative Feuchte	(60 ± 5) %

Messbedingungen:

Vor der Messung wurde die Messleitung auf einen ausreichenden Isolationswiderstand ($\geq 1 \cdot 10^{13}\ \Omega$) geprüft.

Besondere Bemerkungen:

Auf dem Ladungsverstärker wurde eine Prüfmarke angebracht.

Figure I.2. Page 2 of calibration certificate of Kistler calibrator 6907B

Physikalisch-Technische Bundesanstalt

PTB

Seite 3 zum Kalibrierschein vom 2014-03-05, Kalibrierzeichen: PTB 13002/14
Page 3 of Calibration Certificate dated 2014-03-05, calibration mark: PTB 13002/14

Kalibriermesswerte

Nullpunktspannung in V = -0,0006

Einstellung		Messwert	Abweichung	Ergebnis
Kalibrator	Verstärker	in V	in %	
50 pC	5,0 pC/V	10,021	0,21	i.O.
100 pC	10,0 pC/V	10,022	0,22	i.O.
500 pC	50,0 pC/V	10,027	0,27	i.O.
1000 pC	100,0 pC/V	10,035	0,35	i.O.
5000 pC	500 pC/V	10,010	0,10	i.O.
10000 pC	1000 pC/V	10,033	0,33	i.O.
50000 pC	5000 pC/V	10,027	0,27	i.O.
100000 pC	10000 pC/V	10,047	0,47	i.O.

Die **erweiterte Messunsicherheit** beträgt gemäß ISO guide to the expression of uncertainty in measurement ± **0,47 %** (Erweiterungsfaktor k = 2 bei einer Wahrscheinlichkeit von 95 %).

Figure I.3. Page 3 of calibration certificate of Kistler calibrator 6907B

Physikalisch-Technische Bundesanstalt

PTB

Seite 4 zum Kalibrierschein vom 2014-03-05, Kalibrierzeichen: PTB 13002/14
Page 4 of the Calibration Certificate dated 2014-03-05, calibration mark: PTB 13002/14

Die Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig und Berlin ist das nationale Metrologieinstitut und die technische Oberbehörde der Bundesrepublik Deutschland für das Messwesen. Die PTB gehört zum Geschäftsbereich des Bundesministeriums für Wirtschaft und Technologie. Sie erfüllt die Anforderungen an Kalibrier- und Prüflaboratorien auf der Grundlage der DIN EN ISO/IEC 17025.

Zentrale Aufgabe der PTB ist es, die gesetzlichen Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI) darzustellen, zu bewahren und weiterzugeben. Die PTB steht damit an oberster Stelle der metrologischen Hierarchie in Deutschland. Die Kalibrierscheine der PTB dokumentieren eine auf nationale Normale rückgeführte Kalibrierung.

Zur Sicherstellung der weltweiten Einheitlichkeit der Maßeinheiten arbeitet die PTB mit anderen nationalen metrologischen Instituten auf regionaler europäischer Ebene in EURAMET und auf internationaler Ebene im Rahmen der Meterkonvention zusammen. Dieses Ziel wird durch einen intensiven Austausch von Forschungsergebnissen und durch umfangreiche internationale Vergleichsmessungen erreicht.

The Physikalisch-Technische Bundesanstalt *(PTB) in Braunschweig and Berlin is the National Metrology Institute and the supreme technical authority of the Federal Republic of Germany for metrology. The PTB comes under the auspices of the Federal Ministry of Economics and Technology. It meets the requirements for calibration and testing laboratories as defined in DIN EN ISO/IEC 17025.*

The central task of PTB is to realize, to maintain and to disseminate the legal units in compliance with the International System of Units (SI). PTB thus is at the top of the metrological hierarchy in Germany. The calibration certificates issued by PTB document a calibration traceable to national measurement standards.

PTB cooperates with other national metrology institutes - at the regional European level within EURAMET and at the international level within the framework of the Metre Convention - with the aim of ensuring the worldwide coherence of the measurement units. This aim is achieved by an intensive exchange of the results of research work and by comprehensive international comparison measurements.

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38116 Braunschweig
DEUTSCHLAND

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10587 Berlin
DEUTSCHLAND

Figure I.4. Page 4 of calibration certificate of Kistler calibrator 6907B

APPENDIX J: CALIBRATION CERTIFICATE OF 6907B

TÜBİTAK SAGE

TÜBİTAK SAGE KALİBRASYON LABORATUVARI

SAGE
09-15

Uygulanan/Set Değer *Applied/Set Value*	Ölçülen Değer *Measured Value*		Alt Limit *Lower Limit*	Üst Limit *Upper Limit*	Hata *Error*	Ölçüm Bel. *Meas. Unc.*
DCV						
0.0000 V	0pC/0.00114	V	V	V	V	5.8e-005 V
1.000 V	1010pC/1.0064	V	V	V	V	5.8e-004 V
2.000 V	2020pC/2.0257	V	V	V	V	5.8e-004 V
3.000 V	3030pC/3.0431	V	V	V	V	5.8e-004 V
4.000 V	4050pC/4.0568	V	V	V	V	5.8e-004 V
5.000 V	5070pC/5.0735	V	V	V	V	5.8e-004 V
6.000 V	6100pC/6.1019	V	V	V	V	5.8e-004 V
7.000 V	7120pC/7.1209	V	V	V	V	5.8e-004 V
8.000 V	8140pC/8.1427	V	V	V	V	5.8e-004 V
9.000 V	9170pC/9.1768	V	V	V	V	5.8e-004 V
10.000 V	10200pC/10.2004	V	V	V	V	5.8e-004 V

✓ Ölçülen değer üretici toleransları içindedir   × Ölçülen değer üretici toleransları dışındadır.

Ölçüm Belirsizliği:
Measurement Uncertainty

Beyan edilen genişletilmiş ölçüm belirsizliği, standart belirsizliğin, k=2 olarak alınan genişletme katsayısı ile çarpımı sonucunda bulunan değerdir ve %95 oranında güvenilirlik sağlamaktadır.
The reported expanded uncertainty of measurement is stated as the standard uncertainty of measurement multiplied by the coverage factor k=2, which for a normal distribution corresponds to a coverage probability of approximately 95%.

Gerektiğinde yorum:
Remarks

Belge No:201-002244
Güncelleme:12

TÜBİTAK SAGE PK 16 06261 Mamak/ANKARA T +90 312 590 90 00 F +90 312 590 91 4 8
www.sage.tubitak.gov.tr

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Figure J.1. Page 1 of calibration certificate of Kistler calibrator 6907B

SAGE

08-15

TÜBİTAK SAGE KALİBRASYON LABORATUVARI

Uygulanan/Set Değer *Applied/Set Value*	Ölçülen Değer *Measured Value*	Alt Limit *Lower Limit*	Üst Limit *Upper Limit*	Hata *Error*	Ölçüm Bel. *Meas. Unc.*	
ACV						
0.9955 V @ 160 Hz	0.99237 V	0.98558 V	1.00542 V	-0.00313 V	1.2e-004 V	✓
1.991 V @ 160 Hz	1.9903 V	1.9711 V	2.0109 V	-0.0007 V	6.1e-004 V	✓
2.9864 V @ 160 Hz	2.98350 V	2.95657 V	3.01624 V	-0.00290 V	5.7e-004 V	✓
3.9818 V @ 160 Hz	3.97800 V	3.94202 V	4.02158 V	-0.00380 V	6.4e-004 V	✓
4.9773 V @ 160 Hz	4.97200 V	4.92758 V	5.02702 V	-0.00530 V	7.2e-004 V	✓
5.9728 V @ 160 Hz	5.96480 V	5.91315 V	6.03245 V	-0.00800 V	7.9e-004 V	✓
6.9683 V @ 160 Hz	6.96200 V	6.89868 V	7.03792 V	-0.00630 V	8.6e-004 V	✓

✓ Ölçülen değer üretici toleransları içindedir

× Ölçülen değer üretici toleransları dışındadır.

Ölçüm Belirsizliği:
Measurement Uncertainty

Beyan edilen genişletilmiş ölçüm belirsizliği, standart belirsizliğin, k=2 olarak alınan genişletme katsayısı ile çarpımı sonucunda bulunan değerdir ve %95 oranında güvenilirlik sağlamaktadır.

The reported expanded uncertainty of measurement is stated as the standard uncertainty of measurement multiplied by the coverage factor k=2, which for a normal distribution corresponds to a coverage probability of approximately 95%.

Gerektiğinde yorum:
Remarks

Belge No:991-002244
Güncelleme:12

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Figure J.2. Page 2 of calibration certificate of Kistler calibrator 6907B