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Research Article

Design and Manufacturing of a Dynamic Pressure Standard Based on Dropping Mass Principle

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Abstract

Dynamic pressure measurements are constantly used in areas such as combustion analysis in the engine cylinder, automotive industry, turbomachinery, aerodynamics, fluid power and control, production processes and within medicine. In these applications, the pressure values range from a few pascals to a few gigapascals, while the frequency ranges studied start below 1 Hz and extend to 1 MHz. Since dynamic pressure calibrators are not commercially available, laboratories working in the field of dynamic pressure measurements have developed some calibrator devices in line with their own needs. Hydraulic and pneumatic shock tubes, pulse and sine wave generator devices can be given as examples of such devices. Even deadweight testers can be included in the class of such devices by using the instantaneous pressure relief method in the negative direction. This study, it is aimed to develop a dynamic pressure device to be used in the calibration of dynamic pressure sensors and to make progress in calibration methods. To develop the aforementioned system, the working method of material testing machines working with the principle of mass reduction was used. The measuring range of the device planned to be produced is aimed to be up to 500 MPa.

Keywords: Dynamic pressure, drop mass system, dynamic pressure calibration, pressure calibrator.

Kütle Düşürmeli Prensibe Dayanan Dinamik Basınç Standardının Tasarımı ve Üretilmesi

Öz

Dinamik basınç ölçümleri, motor silindirinde yanma analizi, otomotiv endüstrisi, turbo makineler, aerodinamik, akışkan gücü ve kontrolü, üretim süreçleri ve tıp gibi alanlarda sürekli olarak kullanılmaktadır. Bu uygulamalarda, basınç değerleri birkaç paskaldan birkaç gigapaskal'a kadar değişirken, çalışılan frekans aralıkları 1 Hz'nin altında başlar ve 1 MHz'e kadar uzanır. Dinamik basınç kalibratörleri piyasada bulunmadığından dinamik basınç ölçümleri alanında çalışan laboratuvarlar kendi ihtiyaçları doğrultusunda bazı kalibratör cihazları geliştirmiştir. Hidrolik ve pnömatik şok tüpleri, darbe ve sinüs dalga üreteci cihazları bu tür cihazlara örnek olarak verilebilir. Negatif yönde anlık basınç tahliye yöntemi kullanılarak ölü ağırlık test cihazları bile bu tür cihazların sınıfına dahil edilebilir. Bu çalışmada, dinamik basınç sensörlerinin kalibrasyonunda kullanılacak bir dinamik basınç cihazının geliştirilmesi ve kalibrasyon yöntemlerinde ilerleme sağlanması amaçlanmıştır. Söz konusu sistemi geliştirmek için kütle azaltma prensibi ile çalışan malzeme test makinelerinin çalışma yöntemi kullanılmıştır. Üretilmesi planlanan cihazın ölçüm aralığının 500 MPa'ya kadar olması hedefleniyor.

Anahtar Kelimeler: Dinamik basınç, Kütle düşürmeli sistem, Dinamik basınç kalibrasyonu, Basınç kalibratörü.

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1. Introduction

Measurement 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 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.

The lack of a metrological infrastructure for dynamic mechanical quantities has been recognised for some time, and several 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 of relying on statically calibrated reference transducers to provide the instantaneous pressure values. The available devices cover ranges up to 800 MPa [2]. Dynamic pressure sensors have a wide area of usage both in measurement and in controlling processes 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 have a mechanical structure. In the case used in the measurement of a dynamic parameter effect, the transducer will be subjected to some effects. These effects can be made as deflected, vibrated, resonated, conducted sound signal, experienced stress and strain, and transferred force and motions. Structures of sensors behave differently at the different spectrum of frequencies at low, medium, and high districts of frequencies [3, 4]. While some pressure transducers are suitable for static pressure measurements some others can be used in dynamic pressure measurements. In a dynamic process, one of the most important components of a dynamic pressure transducer is the response time of a pressure transducer. Response time parameters should be thought about seriously in the selection of a convenient pressure transducer during pressure measurement applications [1]. Pressure sensors with a piezoelectric structure generate electric charges, which are proportional to the applied input transient pressure [5]. Generated charges converted into electrical signal values by a connected charge amplifier. A common example design of a piezoelectric pressure transducer is given in Fig. 1a and Fig. 1b [6]. An example of a dynamic pressure sensor in quartz structure is given in Fig. 1c.

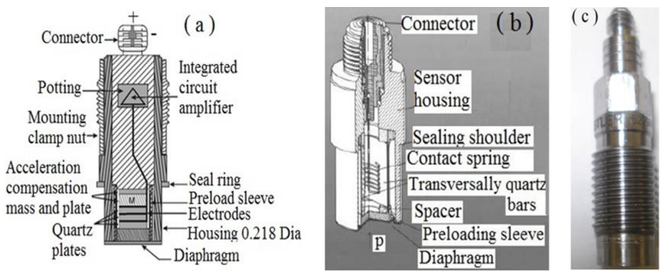

Fig.1 Structure of a typical piezoelectric pressure transducer (a) [7], (b) [8] , (c) [9]

The 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 using a pressurization system based on bottled nitrogen, using either single or double diaphragms up to a pressure range of 1.4 MPa. A Plastic shock tube of 0.7 m driver section and 2 m driven section is shown in Fig. 2a and dynamic transducers connected to shock tube is seen in Fig. 2b. Burst aluminium diaphragm is given in Fig. 2c [47].

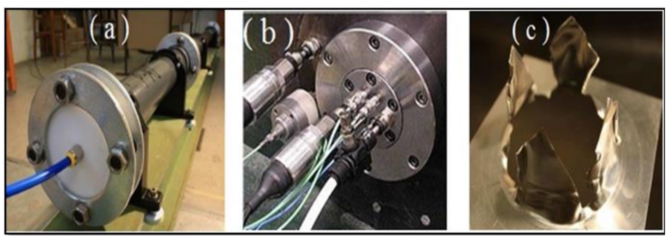

Fig. 2 Shock tube [10]

The structure of a shock tube is composed of a cylindrical plastic tube with a uniform cross-section area. The diaphragm separated the tube into two volumes [3, 11, 12]. From one end gas is sent to the first volume. Test sensors are connected into a second volume. Increased pressure destroys the diaphragm and the shock wave reaches test sensors that have been connected to another end of the tube. The rise time of the pressure step because the shock wave is about the nanosecond range [3, 13]. Therefore a shock tube is considered as an idealized pressure step including all frequency spectrums above the low-frequency limit.

Another method is the negative pressure drop method. In this method, a pressure balance is used as a reference instrument and so reference pressure is calculated based on the pressure balance working principle which is pressure equals force per unit area. After the system is pressurized immediately, the pressure line is vented to atmospheric pressure and a simultaneous negative pressure drop is applied on the dynamic pressure sensor as seen in Fig. 3.

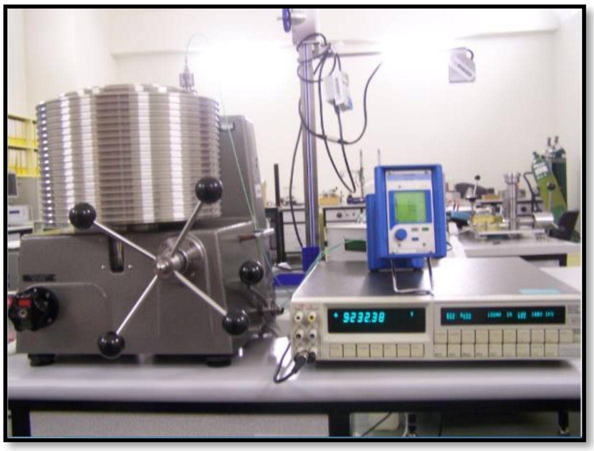

Fig. 3 Negative pressure drop system by pressure balance

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 the drop weight method

2. Material and Method

2.1. Design of Mechanical Part

At present, traceable primary standards do not exist in dynamic pressure metrology. There are some secondary systems to produce dynamic pressure, but they all have no metrological traceability. Applications for which these requirements are needed include the 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. Maximum acceleration and/or velocity of dropping mass will be measured 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 from the dropping mass system were given and presented clearly in the following sections.

The dynamic pressure facilities of some set-ups operate according to the “drop mass” principle. A drop mass system is given schematically in 3 dimensional (3D) picture of the drop mass system in Fig. 4. 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. The drop mass system is consists of three main parts. A first part is a mechanical unit. The second one is the control unit and the third part is called the data logging and sensor configuration unit.

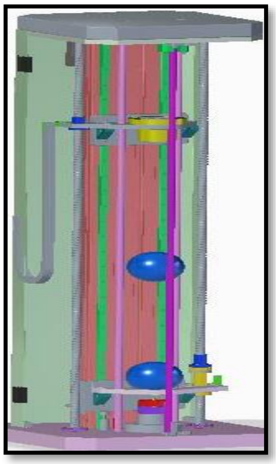

Fig. 4 Three-dimensional (3D) view of the drop mass system

Dynamic pressure measurement standard also known as drop mass system. To improve a dynamic pressure measurement standard based on the drop mass principle, this study was conducted. An electromagnet was designed for keeping the holding sphere ball. Copper wire was rolled around a conducting cylindrical metal. When it is worked at a 24-volt direct current (DC), quite a powerful electromagnet will be obtained. The purpose of usage of the electromagnet is to catch the sphere ball and lift it to a certain height for the free-falling head. The electromagnet is shown in Fig. 5.

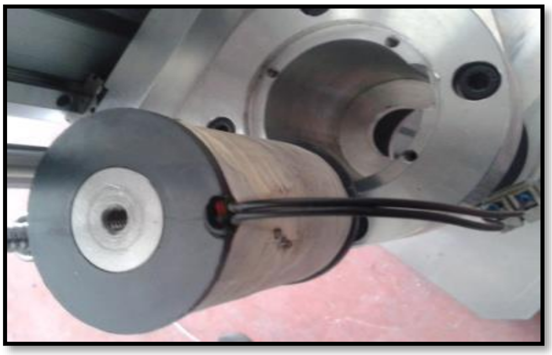

Fig. 5 The electromagnet of the system

The Piston-cylinder unit is one of the important parts of the drop mass system. The cylinder is a cylindrical part with a hole along it to allow the piston insert to be inside. The inner surface of the cylinder should be machined very sensitively as well as the piston's surface. Piston and cylinder are shown in Fig. 6.

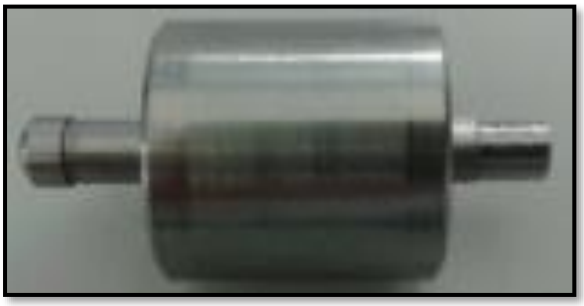

Fig. 6 piston-cylinder unit

Basement and roof metal plates were designed. Designs of lower and upper plates were given Fig. 7. They are approximately square and made of iron. There are some holes both in the basement and in the roof plates. Holes in the corner of the triangle shape for holding security rods. Security rods start from the roof and stand along with the drop mass system and finish in the basement plate. 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 belts. So, infinite screw gets rotation from servo engines to move electromagnet and dropping mass rebound or dropping mass holder system.

Piston-cylinder and reference and test sensors are located in a closed chamber. It has an approximate volume of 0.5 cm^3. During the experiments, different transmitting oils were filled into this volume. Fig. 7. shows the whole drop mass-based dynamic measuring standard. The main trunk is located between the 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.

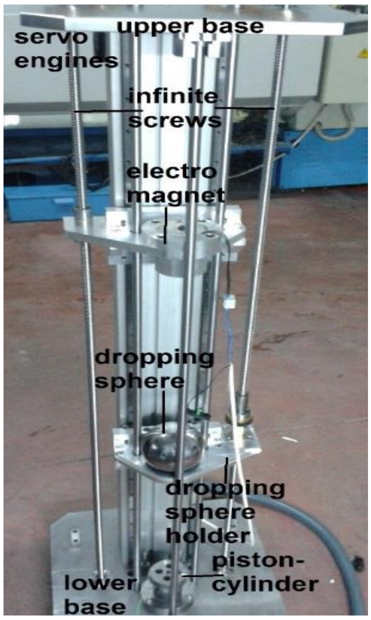

Fig. 7 Drop mass system

2.2. Design of Control Unit

Dynamic pressure measurement standard is controlled by a programmable logic controller (PLC). The movement of the rebound system and the electromagnet is done by two servo motors. PLC unit, control touch screen display, servo motor drivers and power unit is located in a rectangular prism box. PLC control program is given in Appendix B. The control display is located onto the cover of the box and PLC, drivers of servo engines and power unit are located inside the box.

Inside parts of the control unit PLC was located as given in Fig. 8. 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 the electromagnet, sudden lifting of the rebound system which gets triggered from the microphone are some of the logic and conditional operations which are done by PLC. For each measurement setup, an impact mass is released and freely falls onto the 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 at the same speed. The distance travelled together is relatively small which is about 0.5 mm

Fig. 8 PLC control unit

Reference and test sensors and amplifiers should be configured before the experiment. Configuration software is shown in Fig. 9. Before the measurement, in the configuration stage, measurement ranges and sensitivity values of both sensors is specified. The output voltage of the sensors is scaled. For data acquisition and sensor configuration, different computers and software were used.

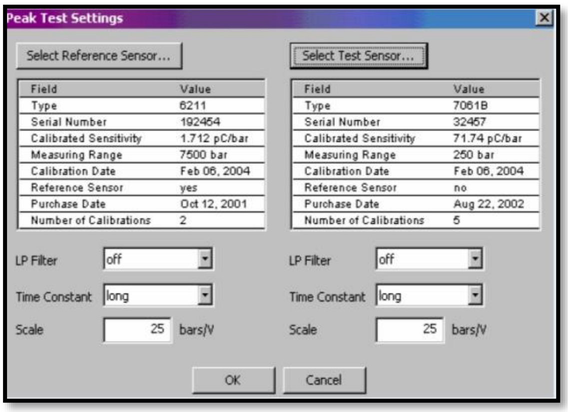

Fig. 9 Data acquisition software interface

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 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. Fig. 10 shows the dynamic pressure measurement calibration schedule.

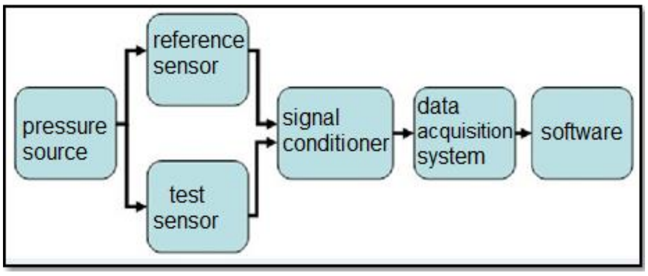

Fig. 10 Dynamic pressure measurement calibration schedule [14]

3. Results and Discussion

Drop mass system working principle is drawn schematically as in Fig. 11. Dropping mass creates an 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.

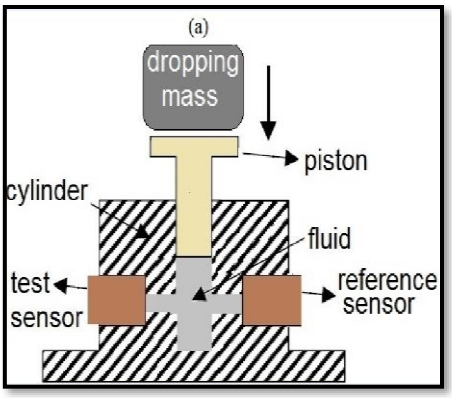

Fig. 11 Drop mass system working principle

While reference sensor has a pressure measurement range up to 800 MPa as the test sensor has a pressure range up to 500 MPa. Specifications of reference and test sensors are given in Table 1.

Table 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. The 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. The duration of a produced pressure peak is about milliseconds.

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. The energy conservation equation assumes that all the potential energy is converted to compression energy and pressure is constant. The used equations for dynamic pressure drop mass system were given in equations (1) to (4).

$$F = m.a = P.A \quad (1)$$

$$P_{max} = m\frac{a_{max}}{A} \quad (2)$$

$$E_{potential} = m.g.h = P_{max}.A.\Delta_x \quad (3)$$

$$P_{max} = \frac{m.g.h}{A.\Delta_x} \quad (4)$$

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 the object (m)
Δ_x : maximum piston displacement (m)

The Piston-cylinder unit is seen in Fig. 12. To obtain the pressure, the sphere ball falls onto the piston. So, the hardness of the piston and sphere ball is an important parameter.

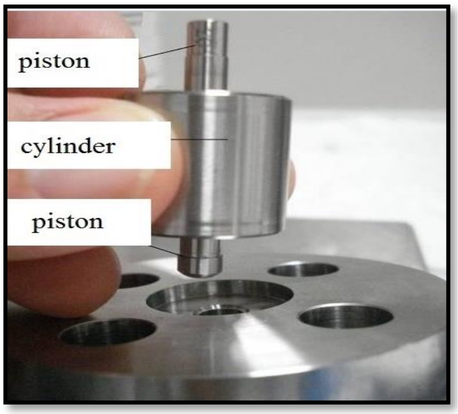

Fig. 12 piston-cylinder unit

Piston-cylinder unit positioned under the vertical axis of the free-fallen sphere ball. At each pressure measurement, the sphere ball is left to free fall. So it hits onto the piston. Sphere's hardness is also measured. Also to make some calculations such as free-fall height mass of the sphere should be known. The mass of the sphere is measured. If the sphere ball is a sphere enough, it is said that a central collision is happening between the ball and piston. To be sure that the ball and the piston are concentric, a thin steel rod is used to adjust the centres of the ball and the piston.

Reference and test sensors are screwed, and the piston-cylinder unit is inserted into a 0.5 cm^3 closed volume chamber which was filled with pressure transmitting oil. A closed chamber equipped with a piston-cylinder unit and reference and test sensors is given in Fig. 13.

Fig. 13 Piston-cylinder with reference and test sensors

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 and reference and test sensor measurement results in sebacate media are given in Table 2. The deviations for test values from the reference pressure for the pressure transmitting oil media sebacate is also illustrated in Fig. 14 and Fig. 15 [15].

Table 2. 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

Fig. 13. Oil-filled closed chamber equipped with the piston-cylinder unit, reference and test sensors. Drop mass standard system provides us with computer-controlled and repeatable dynamic data. Dynamic pressure constituted in a closed cavity is sensed and measured using two piezoelectric pressure transducers, named reference and test transducers. This volume can be filled with different types of oils as pressure transmitting media. The piston is directly located in line with the vertical axis of free dropped spherical. Load outputs coming from dynamic sensors through the load-carrying cable are connected into amplifier channels 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. Outputs of the 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 a reference. Because the reference transducer has a pressure range up to 800 MPa and the test transducer can measure the pressure up to 500 MPa, measurements were performed up to 500 MPa starting from 100 MPa with the step of 100 MPa. The data sampling rate was 200 kHz and a 300 K sample was taken for each mass drop. The drops

were repeated five times for each height and outputs of the signal conditioner were measured using a computer-controlled NI DAQ board.

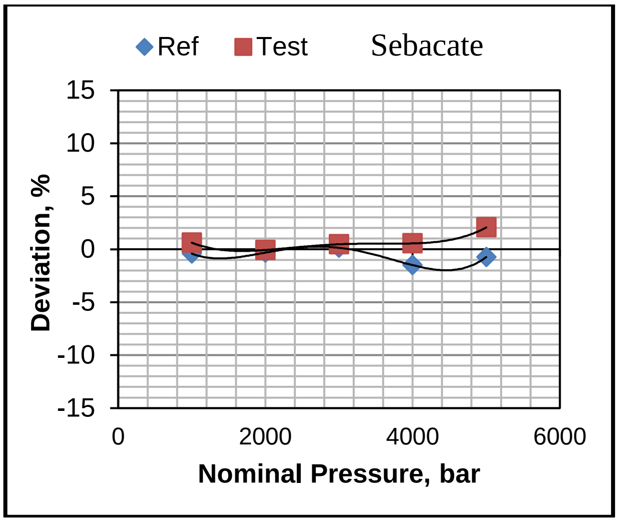

Fig. 14 Deviation for reference and test sensors versus pressure in sebacate oil

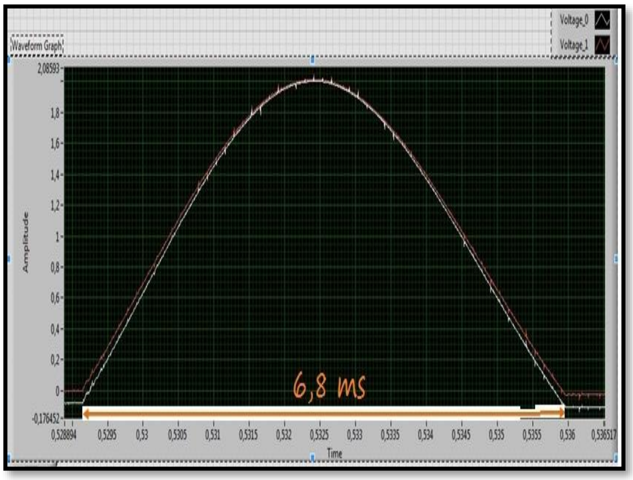

Fig. 15 Electrical outputs of reference (in white) and test channel (in red)

4. Discussion and Conclusions

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

This study has two significant contributions to the dynamic pressure calibration area. First, a dynamic pressure generator is manufactured based on the drop mass principle. It allows the generation of repeatable dynamic pressure pulse signals to be used in calibrations of dynamic pressure sensors. For this purpose, the oil type sebecate was used as transmitting oil is specified to be used in the manufactured drop mass system. The sensitivity parameter is defining the amount of electrical load to be produced by a dynamic sensor corresponding to applied pressure. So, one of the important reasons for calibration of a sensor is to find the sensitivity of the test sensor against 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.

As a result of this research, a newly developed dynamic pressure generator was manufactured and characterised to use in dynamic pressure sensor calibrations. Two methods for dynamic pressure measurements are presented. Firstly, new developed dynamic pressure standard was presented. Since it uses a drop mass working principle, it is also known as a drop mass system. Designing parts of the system and manufacturing stages of these parts are 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 the oil named sebecate. 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 repeatability parameter which is involved in the 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. The amplitude of output signals was linearly proportional to applied pressure. Drop mass system has the possibility of setting drop height into a certain distance and it is possible to define several desired measurement cycles by entering in control display. These options provide an operator to do repeatable measurements which provide trustable measurements on dynamic pressure transducers.

In the measurements, the 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 the transducer's operating range. It is assumed that this is not only resulted from fluid but also the different sampling rate and resolutions of the measurement setups and leakage and temperature effects.

5. Acknowledge

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