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A METHODOLOGY FOR CALIBRATING PIEZOELECTRIC TRANSDUCERS FOR TRANSIENT PRESSURE MEASUREMENTS

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Abstract. *A methodology has been developed to calibrate piezoelectric transducers for transient pressure measurements, in the 500 psi (34,54 bar) - 5000 psi (344,7 bar) range. The transducer has a rising time of less than 5 microseconds and a charge amplifier was coupled to it. The rig was built to pressurize hydraulic oil in small chamber from the atmospheric level to a desired pressure value. A storage oscilloscope was used to measure the rise time of the transducer, together with its output voltage. The setup was built so that a variable rising time for pressurizing the chamber could be obtained in the 2 to 2200 miliseconds range. When plotting the output voltage as a function of rise time, a transducer working range could be selected so that there was no attenuation in its signal. Several pressure values were used to supply data for the calibration procedure, which takes into account the repeatability of the results, the pressure measuring device uncertainty, the voltage uncertainty by the measuring oscilloscope, and the curve fitting to the output voltage versus pressure curve.*

Keywors: Metrology,Piezoelectric transducer,Pressure transducer calibration,Transient pressure measurement, Internal ballistics

1. Introduction

Testing of defence equipment, both for development, as well as for routine monitoring of production and the acceptance procedure for armament and ammunition, requires the use of advanced measurement techniques, together with accurate calibration procedures for increasing reliability of results. In interior ballistics, bad powder ignition can be detected by pressure measurement. Also, if the permissible maximum pressure in the weapon is exceeded, the structure can fail due to overstrain of the material. The duration of this event can be as low as 2 ms, which requires extremely fast transducers.

The calibration of piezoelectric pressure transducer is one of the essential prerequisites for the exact determination of the pressure course in weapons under tests. Due to permanent use and, thus, extremely high stress to which the materials are exposed, sensitivity changes are caused. Therefore, regular recalibrations of piezoelectric pressure transducers are necessary during their life time.

Piezoelectric pressure transducers deliver electric charges, which are proportional to the applied transient pressure, and are converted into voltages by a charge amplifier. For slow static events, this voltage is usually indicated by a digital voltmeter. For fast dynamic events, it is digitized a by a high speed A/D converter and stored for later processing.

(Winkler, 1989) states that it is not possible to derive the sensitivity of pressure transducers from constructional or material data. Therefore, pressure transducer have to be calibrated regularly after manufacturing; partly these recalibration periods are stipulated in standards. During such recalibration the electric charge signal delivered at a known pressure is determined and the sensitivity is calculated therefrom. (Resch, 1987) states that the calibration should always be carried out under conditions similar to those in practical use.

There are two available methods for calibrating piezoelectric transducers, (a) Static Calibration, and (b) Dynamic Calibration.

At the static calibration pressure, (Winkler, 1989), pressure balances (dead weight testers) are used to produce a highly accurate reference pressure. Standard weights with known mass are placed on a piston with a known area. In a hydraulic system, the reference pressures necessary for calibration are generated step by step and are then relieved to atmospheric pressure. The pressure difference serves for determining the sensitivity. The automation of the complete calibration procedure makes it possible to also measure reproducibility and other quantities from the course of the pressure increase and subsequent pressure relief, in addition to the charge variation (Grasberger, 1989). Thus, an extended and objective evaluation of the calibration is possible. This method has the advantage that reference pressures can be built up with high accuracy (better than 0,05 %).

At the dynamic calibration, (Winkler, 1989), the pressure is generated in a hydraulic chamber. The pressure chamber is housed in a measuring head of steel. It is filled with high pressure fluid and is sealed towards outside by a precisely fitted piston. The pressure course is determined by the energy transmission of a falling mass onto the piston, transferring its kinetic energy to the fluid in the chamber, causing its pressure increase. When a maximum pressure value is reached, the piston and impact mass start reverting their motion. As a result, pressure pulses are generated, which correspond to a typical measurement task in ballistics, as far as duration and shape are concerned. (AVL, 1989) claims an uncertainty of ± 2 % in the 1000 to 2000 bar pressure range, and ± 1 % in the 2000 to 8000 bar pressure range, with a reproducibility of ± 0,25 %, for the dynamic calibration.

It is not quite clear whether there are differences in behavior of piezoelectric pressure transducers between static and dynamic calibration. However, (Winkler, 1989) show tests in which statically calibrated pressure transducer deviate from each other in their dynamic behavior, in the 0,5 % to 1,5 % range. In particular, at measurements requiring high accuracy, the knowledge about dynamic conformity and dynamic peak pressure accuracy are of great importance.

In Brazil there is no calibration laboratory for piezoelectric transducer. Laboratories that require calibration, usually send their standard abroad, yearly.

The objective of this work is to establish a simple calibration procedure to be used in Brazil, so that a simple calibration verification or even an inexpensive calibration can be regularly performed, thus increasing the reliability of results. As a first step, the methodology was developed for up 5000 psi (344,7 bar), so that the available laboratory setup could be used. The static calibration was chosen for being simpler, and a bourdon manometer replaced a dead weight tester for being less expensive, although less accurate. As a result, the calibration uncertainty was larger than what can be obtained abroad.

A rig was built to pressurize hydraulic oil in a small chamber, from the atmospheric level to a desired pressure value. The output from the charge amplifier was measured with a storage oscilloscope, with a trigger sensitivity of 20 MHz, thus recording the curve shape and its duration, allowing the measurement of the pressure step rise time, which could be varied from 2 ms and up by changing the flow obstruction to the chamber by means of a valve. The operating range of the pressure transducer was determined as having a constant charge amplifier output at the end of the pressure step. The data were statistically analyzed and the uncertainty of measurement was estimated. Then, a curve fitting was done on the data obtained for several pressures, which constitutes the calibration curve of the transducer, together with its uncertainty of measurement.

2. Methodology

2.1 Piezoelectric pressure transducer

Certain piezoelectric crystals, like quartz, Rochelle salt, ammonium dihydrogen phosphate and barium titanate ceramics, if exposed to pressure from all sides, will develop a polarization in a preferred crystal direction; the polarization charge gives rise to an output voltage. They are primarily useful for the measurement of transient pressures of the order of several thousand atmospheres and a time range from a fraction of a second to more than ten microseconds (Lion, 1959). At medium and high pressure fluctuation frequencies, the time response of a piezoelectric transducer depends on the capacitance of the piezoelectric element and on that of the load. They form a voltage divider that is independent of frequency. At low frequencies, the voltage across the load is determined primarily by the reactance of the piezoelectric element, its capacitance and load impedance. The output voltage decreases with decreasing frequency until zero for a steady state applied pressure.

When firing a weapon, the elapsed time between ignition and combustion gas exhaust can be typically 15 ms, according to (Farrar & Leeming, 1983). For portable guns, it can take less than 1 ms. For large artillery tubes, 25 ms. Therefore, the piezoelectric transducer should be able to follow the event without distortion with a time constant much smaller than those values. In order to measure the transducer's ability to handle transients, a parameter called rise time is usually defined as the time delay required before proper output magnitude is reached, after having applied a step input.

When the duration of the event has the same order of magnitude of the piezoelectric pressure transducer rise time, there will be an attenuation of the output voltage. When the event takes too long, leading to a steady state condition, the output voltage will be also distorted. Therefore, for a given pressure transducer, it can be defined a range of duration of an event, in which the output voltage is independent of the fluctuation frequency.

This work deals with the determination of the upper limit of the duration of the event. A rig was constructed in such a way to vary the time required for a liquid to reach a given pressure value, upon application of a pressure step from atmospheric level. A range was chosen so that the output voltage is constant.

A HPI 5QP6000M piezoelectric pressure transducer was chose for demonstrating this methodology, having a rise time much smaller than the duration of the event, with the following features:

Table 1: HPI 5QP6000M piezoelectric pressure transducer specifications

PARAMETER	UNIT	VALUE
Measuring range	bar	0 to 6000
Sensitivity	pC/bar	2.2
Linearity	% FSO	≤ 1
Natural frequency	kHz	≥ 200
Rise time	μs	≤ 2
Capacitance	pF	1.5

2.2 Measuring System

A rig was constructed to calibrate the pressure transducer. It consists of a small 0,8 cm^3 chamber full of oil, connected to the following components :

- A pumping system with a capacity for pressurizing the chamber up to 12000 psi (827,4 bar), upstream of the chamber. It consists of an alternative pump and a control system that shuts it off when the target pressure is reached.
- A calibrated bourdon manometer, between the chamber and the pumping system, for measuring the steady state target pressure in the chamber.
- A fine adjustment valve, downstream of the chamber, for reducing its pressure to the atmospheric level. By controlling its opening, it is possible to vary the time rate of depressurization of the chamber, and, thus, changing the duration of the event.
- The piezoelectric pressure transducer to be calibrated and a charge amplifier to output the generated voltage.
- A storage oscilloscope to register and measure fast events.

2.3 Data acquisition and processing procedure

A procedure was developed to acquire data e process them, for each pressure set at the chamber, and used to build the transducer calibration curve for the whole pressure range. All uncertainty calculations follow (ISO GUM, 1995), and are referred to 95,45 % confidence level. It consists of the following steps:

- Set a given pressure in the pumping system, and measure the output voltage by the scope for n rise times of the event, by varying the opening of the valve.
- For each valve opening and set pressure, measure the output voltage (V) and the rise time (T_r) three times, for determining the repeatability of the measuring procedure, calculating the average value (V_m), maximum value (V_{max}) and minimum value (V_{min}). Using the experiment characterized by the maximum difference (V_{max} – V_{min}), the marker uncertainty (U_m) can be calculated as :

$$U_m = (V_{max} - V_{min})/2 \quad (1)$$

- The minimum time required for the output voltage to go from zero to a constant maximum value is measured by the scope and is called rise time
- For each set pressure, plot the output voltage (each one represented by the average value of three measurements) as a function of the rise time.
- Because of the fact that at lower frequencies (higher rise times) there is an attenuation of the output voltage, consider only those points, sequentially ordered, with the same value. In order to reduce the influence of the judgement on the choice, select several sets of points and calculate the average and the standard deviation. Choose the set that has the smallest standard deviation, thus representing the output voltage (V) and its standard uncertainty of reading (u_{exp}).
- Apply Chauvenet's criterium (Holman, 1971) to the set of points, discarding off the bad ones.
- Calculate the expanded uncertainty of reading (U_{exp}) by multiplying the standard uncertainty of reading (u_{exp}) by t (t-student, with the number of points – 1).
- Calculate the expanded uncertainty of measuring the voltage with the oscilloscope (U_{scope}) by calibrating it against a multimeter.
- Calculate the combined uncertainty of voltage measurement (U_V) as :

$$u^2 = (U_{exp}/2)^2 + (U_{scope}/2)^2 + (U_m / 3^{0.5})^2 \quad (2)$$

$$U_V = 2.\, u \quad (3)$$

- Thus, each pressure and uncertainty ($P \pm U_P$) is related to the output voltage of the piezoelectric transducer and uncertainty ($V \pm U_V$), thus defining the calibration of the transducer.

2.4 Interpolation of the calibration points

A calibration curve for the transducer can be obtained by fitting a polynomial by the least square method. The advantage of using this procedure is that the overall behavior of the transducer can be obtained at points not experimentally determined during the calibration, besides providing the overall uncertainty of measuring the pressure, which includes other factors not taken into account. For simplicity, a straight line can be fitted do data points:

$$P = k.V + b \quad (4)$$

When calculating the overall uncertainty of measuring pressure with the transducer, the following standard uncertainties can be calculated, (Orlando, 2003) :

- Output voltage standard uncertainty : $u_V = U_V /2$
- Pressure standard uncertainty : $u_P = U_P /2$
- Square root of the sum of squares of the deviation from the mean value given by the fitting : u_{fit}

The combined uncertainty (u) and the expanded uncertainty (U) can be calculated as :

$$u^2 = (u_P)^2 + (u_{fit})^2 + (k.u_V)^2 \quad (5)$$

$$U = t.u \quad (6)$$

3. Experimental setup

3.1 Test chamber

A setup was built, consisting of a 0,8 cm^3 chamber, full of oil.

Figure 1 : Test Chamber, control valve and piezoelectric pressure transducer

3.2 Oscilloscope

- Digitizing oscilloscope HP 54501A
- Repetitive bandwidth : 100 MHz
- Trigger sensitivity : 20 MHz
- Sample rate : 10^6 samples/s
- Maximum vertical sensitivity : 5 mV/division
- Vertical resolution : 8 bits
- Rise time : 3,5 ns
- Vertical gain accuracy : ± 1,5 %
- Time base accuracy : ± 0,005 %

The oscilloscope was calibrated at PUC-Rio, against a HP34401-A multimeter, in parallel to a voltage source. For interpolation purposes, a curve fitting can be done on data by Eq. (7). Table (2) shows the calibration curve of the voltage (V) as a function of the scope indication (S), together with the uncertainty of measurement (95,45 %) with the scope.

$$V = k.\ S \quad (7)$$

Table 2: Calibration of the digitizing oscilloscope HP 54501A

Range (mV)	Scale (mV/division)	k	Uncertainty (mV)
4000	1000	1,004961319	38,4
2000	500	1,009757193	17,5
1000	200	1,008961264	5,9
500	100	1,008472143	3,1

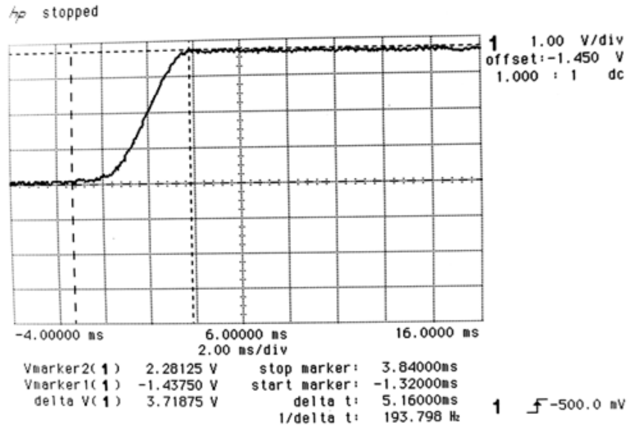

Figure 2: Oscilloscope showing test

3.3 Charge amplifier

- Kistler Model 5004 Dual Mode charge amplifier

Figure 3: Charge amplifier

3.4 Manometer

- Bourdon manometer 0 – 400 kgf/cm^2, Class 0,5 %.
- Smallest division: 2 kgf/cm^2.

The manometer was calibrated using as a standard a pressure balance (dead weight tester) XIAN in the 0,3 to 60 MPa range, traceable to INMETRO laboratory , with un uncertainty of ± 0,015 % (95,45 %). The calibration was performed in the Temperature and Pressure Laboratory of PUC-Rio, at 11 points, using 3 cycles of loading and unloading pressure. A second degree polynomial was fitted to the data points by the least square method, resulting in the following calibration curve Pressure (P) as a function of Manometer Indication (M), both in kgf/cm^2.

$$P = -6E\text{-}06M^2 + 0{,}1019M - 0{,}104 \tag{8}$$

with a maximum expanded uncertainty of ± 1,2 kgf/cm^2 (0,12 MPa). Readings were made with a visual interpolation to half the smallest division (1 kgf/cm^2).

4. Results

Figure (4) shows a set of data points taken for 500 psi (34,5 bar) pressure. It can be seen that the output voltage is approximately constant, after having eliminated points with attenuation. Therefore, in this range, the output voltage from the piezo electric transducer is independent of frequency. Figure (5) shows the procedure for choosing points in the frequency independent range. It can be seen that the standard deviation remains approximately constant. For higher values of the rise time, it started to increase due to voltage attenuation.

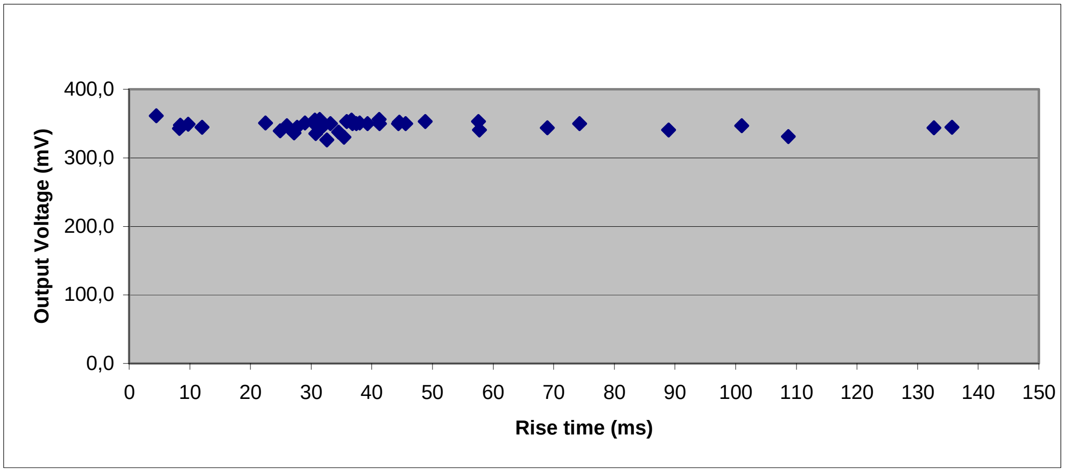

Figure 4: Output voltage as a function of rise time por 500 psi (34,5 bar)

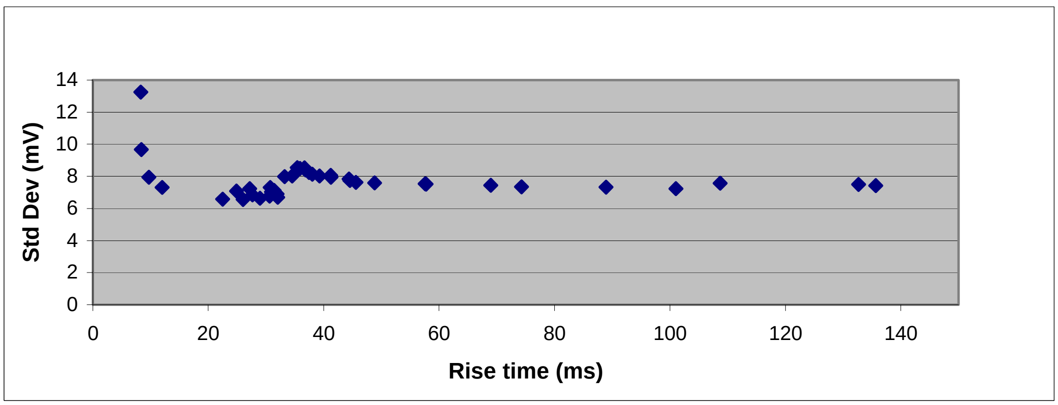

Figure 5: Standard deviation as a function of number of rise time data points for 500 psi (34,5 bar)

The data were taken at 10 points, and the lowest and highest rise times were registered for validity of frequency range. Table (3) presents the raw data, that is, measured values before applying the calibration curves.

Table 3: Raw data

RISE TIME (ms)		PRESSURE	PRESSURE	VOLTAGE
LOWEST	HIGHEST	psi	MPa	mV
4,5	135,7	500	3,45	347
3,1	26,0	1000	6,89	723
5,7	66,8	1500	10,34	1092
3,2	51,7	2000	13,79	1489
2,9	135,0	2500	17,24	1836
2,5	122,3	3000	20,68	2190
2,9	118,0	3500	24,13	2476
1,9	9,5	4000	27,58	2952
1,9	11,8	4500	31,03	3304
5,1	94,7	5000	34,47	3666

After having calibrated all the measuring equipment, all data were taken, corrected and statistically processed. Table (4) presents the statistical analysis used for each pressure. Table (5) shows the combined uncertainty for the voltage measurement with the oscilloscope, Eq. (2). Table (6) shows the pressure and voltage values, both corrected by Eq. (8) and Eq. (7), respectively, together with their uncertainties.

Table 4: Statistical analysis of the experimental data

Pressure	Pressure	Voltage	Number of runs	Standard Deviation	U Eq. (6)
psi	MPa	mV		mV	mV
500	3,45	347	42	6,8	14
1000	6,89	723	29	6,1	13
1500	10,34	1092	32	15,6	33
2000	13,79	1489	32	18,2	38
2500	17,24	1836	35	45,9	95
3000	20,68	2190	20	62,9	135
3500	24,13	2476	29	60,2	126
4000	27,58	2952	23	41,2	87
4500	31,03	3304	12	36,0	81
5000	34,47	3666	30	29,8	62

Table 5: Uncertainty of voltage measurement with the scope, Eq. (2)

PRESSURE	PRESSURE	U_{exp}	U_m	U_{osc}	u_V	U_V
psi	MPa	mV	mV	mV	mV	mV
500	3,45	14	1,563	3,11	7,18	14
1000	6,89	13	15,63	5,93	11,44	23
1500	10,34	33	7,80	17,46	19,00	38
2000	13,79	38	23,44	17,46	24,89	50
2500	17,24	95	78,13	38,38	68,33	137
3000	20,68	135	46,88	38,38	75,04	150
3500	24,13	126	46,88	38,38	71,33	143
4000	27,58	87	46,88	38,38	54,88	110
4500	31,03	81	46,88	38,38	52,35	105
5000	34,47	62	15,63	38,38	37,72	75

Table 6: Calibration of the piezoelectric pressure transducer (corrected values)

PRESSURE (MPa)		VOLTAGE (mV)	
P	U_P	V	U_V
3,47	0,12	350	14
7,03	0,12	729	23
10,58	0,12	1102	38
14,11	0,12	1504	50
17,62	0,12	1845	137
21,12	0,12	2200	150
24,61	0,12	2488	143
28,08	0,12	2966	110
31,53	0,12	3320	105
34,98	0,12	3684	75

For interpolation purposes, a curve fitting can be done on the data by the Eq. (4); Pressure (P), in MPa, as a function of voltage (V), in mV, which is measured during an application:

k = 0,0095 MPa / mV

b=0,1376

u_{fit}= 0,33651 MPa

The overall combined uncertainty of measuring pressure (u) from the voltage output, can be calculated by the Eq.(5) and the expanded uncertainty (U) is calculated by multiplying the combined uncertainty (u) by t-student (t=2,32 for 10 points), as it is showed in Eq. (6). Table (7) presents the overall combined uncertainty of measuring pressure (u) from the voltage output:

Table 7: Calibration curve and uncertainty measurement with the piezoelectric pressure transducer

OUTPUT VOLTAGE (mV)	PRESSURE (MPa)	
INPUT DATA	VALUE	UNCERTAINTY
MEAN VALUE	Eq. (4)	Eq. (6)
350	3,47	0,81
729	7,09	0,83
1102	10,64	0,90
1504	14,47	0,96
1845	17,72	1,70
2200	21,10	1,83
2488	23,85	1,76
2966	28,40	1,45
3320	31,78	1,40
3684	35,25	1,15

As usual in pressure transducer application, the transducer uncertainty is referred as the ratio between the maximum uncertainty and the maximum pressure transducer, or 1,83 / 35,25 = 5,2 %

5. Conclusions

A methodology has been developed for calibrating piezoelectric pressure transducers. It uses a Class 0,5 bourdon manometer as a pressure standard and a digitizing oscilloscope as a measuring system. Obviously, lower uncertainties can be obtained if a dead weight tester is used. Lower uncertainties can be obtained too if a more accurate voltage measuring system can be used. Even so, this methodology is useful for verifying calibration or performing an inexpensive one.

6. Aknowledgements

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