Investigation on gas pressure measurement inside small caliber weapons with piezoelectric transducers

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Abstract: This study carried out at the ballistic laboratory of the Royal Military Academy examined the comparison results between the NATO standard Kistler type 6215, the HPI type GP6 and the SAAMI standard PCB type 117B104 piezoelectric high pressure transducers for the measurement of gas pressure inside a small caliber weapon. To achieve this goal, a barrel of caliber .50 inch manufactured according to military standards was used to fire different types of 12.7x99 mm ammunition [1]. The transducers were installed in the same mounting position in respect to barrel length but displaced by 90 degrees to each other. The exit velocity was also measured to get a reference value.

Results of the study showed that although there was an agreement on the pressure-time curves given by the three ballistic transducers, there were nevertheless, some significant differences in the peak pressure which might be strongly related both to the measuring techniques and the calibration methods.

Recommendations were made to develop in-situ a reliable dynamic calibration method so as to satisfy the demand to cover the whole range in amplitude and frequency. A solution based on the use of a piston in contact with an oil-filled pressure chamber has been developed and tested. The high pressure is obtained by impacting the piston with a mass launched from an air gun. However, this method still requires improvements. Further recommendation can be made to consider measurement uncertainty calculation of the high pulse pressure generator.

Keywords: piezoelectric transducers, high pressure, dynamic calibration, measurement uncertainty.

1. INTRODUCTION

Chamber pressure is the pressure within the chamber of a weapon when ammunition is fired. Knowledge of its maximum value (peak pressure) has become paramount in applications, such as weapon systems development, investigation on ballistic performances of ammunition and safety problems. Given the increasing need of a more reliable method to measure the chamber pressure, some manufacturers have developed their own piezoelectric transducers. Indeed, existing techniques were not good enough and better transducers were needed to achieve this task.

Today, investigating piezoelectric pressure measurement is shaped by many organisations especially NATO, C.I.P. in Europe and SAAMI in USA. The major differences between the pressure measurement methods of these organisations are the measurement point and the measuring techniques. NATO recommends the direct gas measurement method according to the EPVAT (Electronic Pressure Velocity and Action Time) method where the Kistler type 6215 transducer is mounted at the case mouth or over a drilled cartridge. However, both SAAMI and C.I.P. use chamber pressure measurement. Unlike C.I.P. who uses a transducer made by Kistler that requires a hole drilled into the cartridge case and fired by a specific prepared barrel, SAAMI uses a different transducer, called a conformal sensor, made by PCB Piezotronics, where a piston is cut in the side of the chamber to conform the cartridge case [2].

With the advent of different manufacturing techniques of ballistic transducers, few studies have been carried out to compare their capabilities to determine the gas pressure within a weapon chamber. In this study the three types of sensors that are used at ABAL laboratory will be compared regarding the pressure time histories in different types of 12.7x99 mm ammunition fired in small caliber weapon.

Moreover, the dynamic calibration was introduced to achieve a reliable pressure-time measurement. A system has been developed in-situ to cover the whole range in amplitude and frequency.

2. EXPERIMENTAL SETUP

2.1. Characteristics of piezoelectric transducer

Gas pressure inside a small caliber weapon chamber is the most demanding measurement in ballistic testing. At ABAL laboratory, three types of piezoelectric sensors (Standard Kistler type 6215, HPI type GP6 and PCB type 117B104) are used to achieve this purpose. All these sensors are active electrical systems [2,3,4], i.e. no external power supplies are needed to produce the output charge signal.

Kistler type 6215, which has a sensing element made by Quartz (SiO_2), and HPI type GP6, which has a sensing element made by Gallium Phosphate ($GaPO_4$), are both used for direct gas measurement and are based on the transverse piezoelectric effect.

Figure 1 : Piezoelectric transducers

Their fronts are protected by a hard diaphragm which converts the pressure applied by the combustion gases into a mechanical force. This effort directly acts onto the sensing element which delivers an electric charge Q. The relationship between the output Q (pC) and the pressure P (Pa) is given by:

$$Q = K.P$$

Where, the transducer sensitivity K is the main technical characteristic of the piezoelectric transducer and usually expressed in pC/bar (1 bar = 0.1 MPa). The mean sensitivity of the 6215 is 1.4 pC/bar while GP6 has 3 pC/bar.

Kistler type 6215 is the NATO standard sensor approved for ammunition testing and weapon development. Both sensors can be used to achieve pressure measurement in weapon chamber, case mouth or along the barrel. Thus, depending on the measurement configuration, the sensors can be installed with an additional thermal protector shield or diaphragm protection.

Figure 2 : Diaphragm protector Kistler type 6565A and thermal protector shield Kistler type 6567

Both sensors (6215 and GP6) were mounted with thermal protector 6567 on which a slight coating of Kistler type 1063 grease is applied to ensure the adhesion of the sealing ring. Otherwise, the volume within the thermal protector is not filled with grease.

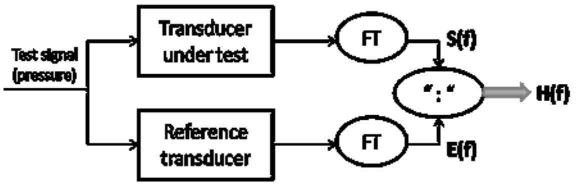
When these transducers are installed in the chamber, the cartridge must be drilled allowing a direct contact between combustion gas and the front diaphragm of the sensor. During the loading of the cartridge in the test weapon, the hole must be carefully aligned with the gas passage.

The conformal PCB type 117B104 sensor has a similar part as the described sensors above, except of the additional piston and the alignment guide (figure 3). The piston has a curved diaphragm. It must conform the shape of ammunition case which is guaranteed by the alignment guide. When the shell expands under the effect of the rising pressure during the combustion cycle, the piston transmits the effect of gas pressure to the transduction element. An electric charge is then generated [2].

Figure 3 : Conformal PCB type 117B104 transducer

2.2. Transducers calibration

Sensors must be calibrated to determine their sensitivity before it will be used in gas pressure measurements. The calibration consists of the knowledge of the relationship between the output signal s(t) (electric charge) and input signal e(t) (pressure) in well-defined conditions, which means the determination of the transfer function.



The transfer function H(f) of the calibration chain is defined as the ratio of the Fourier transform of the output S(f) and the Fourier transform of the input E(f):

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

A dynamic pressure standard for high pressure ballistic transducers has not been developed yet due to the absence of an absolute dynamic system. Thus, dynamic calibration of these transducers with comparison to a reference transducer remains actually the most accurate and reliable way. Therefore, E(f) represents the frequency response of the output signal registered by the measuring chain of the reference sensor.

In 1972, the ASME published a guide for the dynamic calibration of pressure transducers [5]. A revised version of this guide has been available since 2002 published by the ISA where a description of the methods employed for dynamically calibrating pressure transducers is given [6].

A significant amount of work on dynamic calibration has been performed during the last forty years to reach this goal due to the increasing need of accurate pressure measurements [6,7,8,9,10]. Reliable and useful dynamic calibration method must cover the whole pressure and frequency ranges.

Dynamic calibration involves the determination of several properties of pressure transducer such as sensitivity, amplitude and phase as a function of frequency, resonant frequency, damping ratio, rise time and overshoot [6].

2.2.1. Static Calibration

At ABAL laboratory, the calibration of the Kistler type 6215 and HPI type GP6 was performed by the hydraulic high pressure generator Kistler type 6906 which allow a quasi-static calibration. This system generates high pressures up to 10000 bar. The piezoelectric transducer Kistler type 6229AK was selected as the working standard. The calibration chain contains also a Kistler type 6907B calibrator [4].

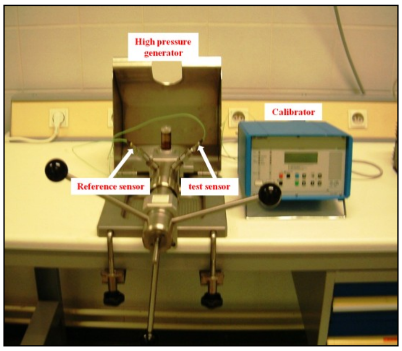


Figure 4 : Quasi-static calibration bench

The transducer to be calibrated was installed in the same pressure chamber as the reference. The pressure was generated by the spindle driven piston. The outputs from the two sensors are recorded simultaneously on the calibrator. The sensitivity and linearity are then calculated.

Calibration of our working standard 6229AK was performed statically in a dead weight tester which is used as a reference standard. Static calibration has the advantage that reference pressures can be built up with high accuracy (<0.05%). A static calibration yields only the sensitivity but it remains the most accurate way although the sensor will be used for dynamic measurement.

Calibration of the conformal PCB type 117B104 sensor was performed with the PCB type 090B adapter which is similar to the chamber of the test barrel with cartridge and sensor installed. This system was manufactured to take into account the influence of the cartridge material characteristics (hardness and thickness) on the calibration [2].

The sensitivity of PCB type 117B104 was determined with an in-situ made calibration bench. The hydraulic high pressure generator Kistler type 6906B was used to pressurize the cartridge cases within the adapter PCB 090B.

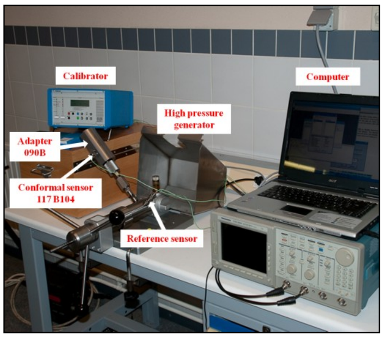


Figure 5 : Calibration bench for the conformal transducer

The determination of the characteristics of ballistic transducers has been limited to static or quasi-static calibration although the events which occur inside a caliber weapon only last a few milliseconds. These calibration methods remain only a comparative method as the input of the system is measured by a reference sensor used as a working standard. The reference sensor is calibrated statically by mean of pressure balance.

2.2.2. Dynamic calibration

One has to note that the calibration should always be carried out under conditions similar to those in practical use. However, static calibration provides reference pressure signal which cannot be compared with a gas pressure curve neither in its duration nor in its shape. Thus, it is obvious that static or quasi-static calibration is usually followed by a dynamic verification since there is till now no dynamic calibration standard available. The aim of this action is to improve the accuracy of the gas pressure measurement.

At ABAL laboratory, the dynamic pressure generator Kistler type 6909 has been used to assess pressure transducer performance in a dynamic environment. 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 [3,6,8,10].

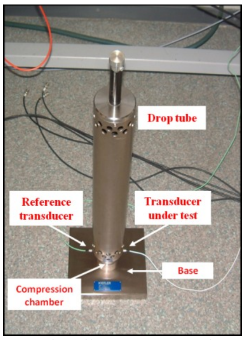


Figure 6 : Hydraulic pressure pulse generator

A pressure pulse is generated when a mass of 5.4 kg falls onto the piston of an oil-filled pressure chamber (adapter). This pulse is similar to a single half cycle of a sine wave; its amplitude depends on the fluid compressibility, the mass, the height of the falling mass, and the piston area. The sinusoidal pressure pulse is characterized by a width of about 5 ms, a rise time about 2 ms and a maximum pressure up to 500 MPa. It acts simultaneously onto test and reference sensors mounted in opposing ports. Therefore, it can be expected that they indicate the "same" pressure as they receive the "same" pressure pulse.

As shown in the following graph, there are differences in pressure signals.

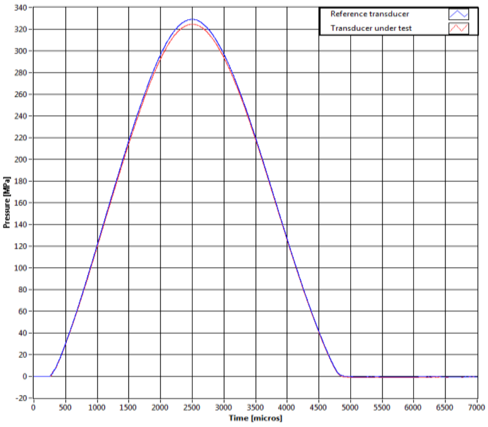


Figure 7 : Typical pressure-time curve given by the hydraulic pulse generator

Although the test was repeated many times, differences still exist between the behaviors of the two transducers. It increases with the increasing of pressure. A difference of around 5 % was observed between maximum pressures. Differences between ascending and descending phases are also inherent to hysteresis phenomena.

Therefore, differences are to be considered between static and dynamic behaviors. Dynamic pressure signal of test sensor (P_{TS}) must be adjust to the reference sensor signal. A polynomial fitting was carried out to achieve this adjustment operation. Indeed, in this case, the dynamic calibration consists of the determination of the coefficients of the polynomial function by comparing pressure-time signals. After that, the polynomial coefficients were used on the stage of signal processing. The obtained chamber pressure (P) is given by:

$$P = a + b.P_{TS} + c.{P_{TS}}^2 + d.{P_{TS}}^3$$

The polynomial degree has to be chosen carefully by comparing the signals of test and reference transducers.

2.2.3. Improvement of the dynamic calibrator

The pulse system is an aperiodic pressure generator. It is not an absolute calibration device since the input pressure signal remains unknown except with a reference sensor. This system requires a comparison pressure transducer of known characteristics to monitor the pulse and provide a peak value measurement for the test transducer.

The development of a primary standard for ballistic pressure measurement involves a system which can provide pressure signals quite similar to real one. This system must cover the whole frequency and amplitude ranges of pressure signal measured inside weapon ammunition.

As shown on the figure 7, the pressure-time curves exhibit differences. Next to the curve pattern, other characteristics such as the rise time and the pulse width have to be improved.

At ABAL laboratory, a solution based on the use of a piston in contact with an oil-filled pressure chamber has been developed and tested. The high pressure was obtained by impacting the piston from a mass launched by an air gun. The aim of this set-up was to create a system which generates pressure pulses of high reproducibility and accuracy which are quite similar to real gas pressure variation inside fired ammunition.

The principle of the method is shown on the following figure.

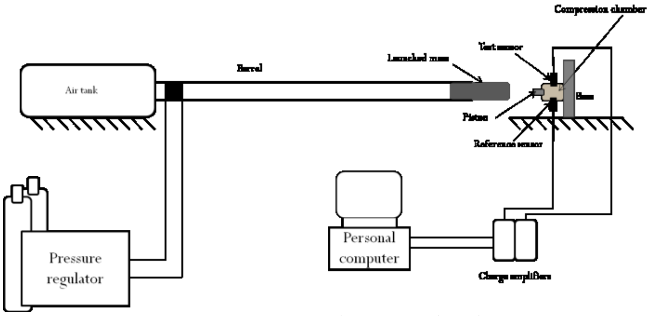


Figure 8 : Dynamic pressure bench

The pressure is generated in compression chamber, which is inside a hard steel structure. It’s filled with high pressure fluid and is sealed towards outside by a piston fitted into the chamber. When the launched mass hits the piston, it transfers its kinetic energy through this piston to the fluid in the chamber. A pressure pulse is then generated and continues to increase until it reaches its maximum value, after which the reverse motion of the piston began [6,10].

By using an adequate mass and velocity, the pressure pulse given by the hydraulic pressure generator can be adjusted to the gas pressure curve in a satisfying manner.

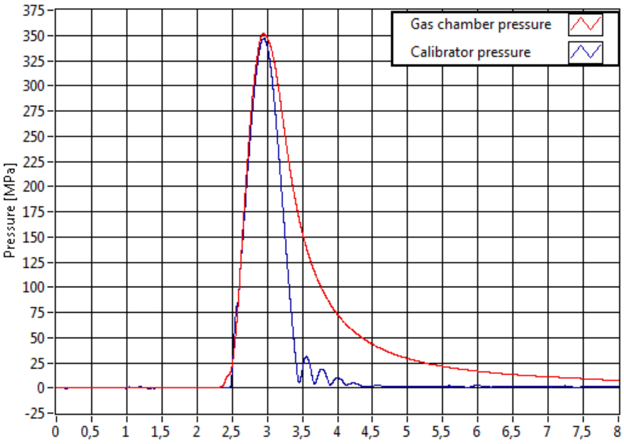


Figure 9 : Comparison between gas chamber and calibrator pressure signals

Moreover, a requirement of all modern systems is that the calibration must be traceable to national or international standards [6,8].

2.3. Weapon configuration

As shown in the following figure, the firing tests have been performed with an instrumented .50 inch barrel manufactured according to military standards and mounted on a universal breech. The major advantage of this caliber was to obtain a longer ballistic cycle which may show clearly all events that occur during the departure of bullet.

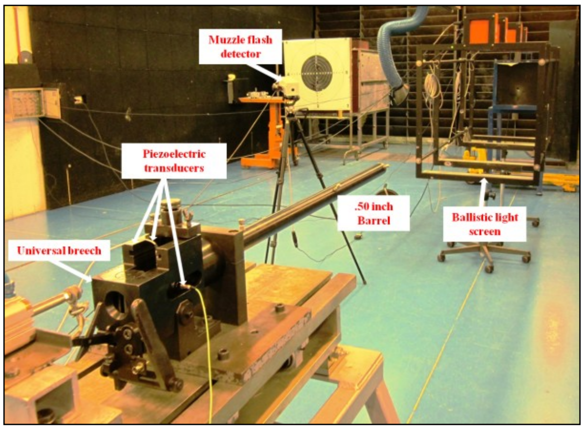


Figure 10 : Materials used to achieve firing test

The barrel has been modified by machining three ports for gas chamber pressure measurement. This differs from standard procedures but it allows comparison between conformal and direct measurements. Furthermore, another port located at the case mouth was used to make pressure measurement according to NATO specifications for ammunition testing.

The transducers were installed in the same mounting position in respect to barrel length but displaced by 90 degrees to each other according to manufacturer's instructions. This experience allows the comparison of the sensor measurements without the influence of the measurement point.

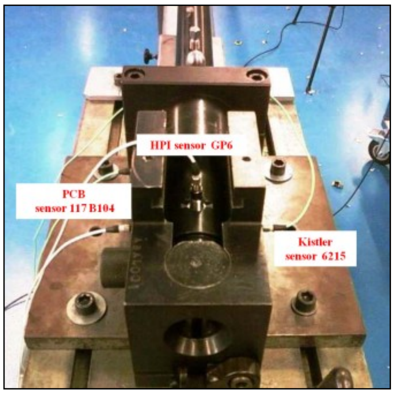


Figure 11 : Transducers fixture

Moreover, a ballistic light screen was used to measure projectile velocity. This measurement has been taken at 4 m from the barrel muzzle to avoid the influence of intermediate ballistics. The triggering was realized using a muzzle flash detector which can detect the flash when the bullet leaves the barrel.

2.4. Ammunition

Four types of ammunition from different manufacturers and lot numbers have been selected to illustrate the expected influence of cartridge material: FNB 06, PINDAD 86, IVI 10 and EMZ 87. Indeed, the conformal pressure measurement may depend strongly onto some physical parameters like case thickness and hardness. They are all 12.7x99 mm cartridges filled with 16 g deterred gun ball powder type .50 inch. This load is considered as an optimal mass which leads to a projectile velocity around 920 m/s and a maximum gas chamber pressure of 320 MPa. A full metal jacket projectile type M33 of 42.5 g is also used to achieve all experiences. Cartridges were conditioned at 21 ±2°C.

Moreover, case hardness was evaluated using Vickers Diamond Pyramid Hardness test. The sensitivities of the conformal PCB type 117B104 transducer for each type of ammunition are listed in the following table.

Ammunition	**Hardness Vickers HV 100g**	**Average Sensitivity** pC/bar
IVI	129.25	1.66
FNB	130,25	1.65
PINDAD	137.75	1.63
EMZ	174.50	1.60

Table 1 : Characteristics of cartridge cases

To achieve pressure measurement, the cartridge case was drilled with a hole of 2.5 mm diameter to expose the transducer temporarily to gas pressure. Obstruction of the hole was achieved by a heat-resistant adhesive tape. Forty successive firing tests for each ammunition type have been made for the comparison of pressure transducers.

All measurements were taken in a completely enclosed shooting test stand free from weather influences.

2.5. Data acquisition and analysis

The signals delivered by the piezoelectric pressure (charge mode sensors) are low amplitude generally expressed in pico-Coulomb (pC) and very high impedance. Thus, a charge amplifier was needed. This device is characterized by high input impedance and has the ability to measure very small charges without modifying them.

The charge amplifier consists of a high-gain inverting voltage amplifier with a MOSFET or J-FET at its input to achieve high insulation resistance. Charge amplifier is typically two-stage device. The first stage is a very high gain operational amplifier employing capacitive feedback (C_r) which converts a charge to a voltage. The second stage provides voltage gain [4].

In practice, a feedback resistor (R_r) is placed across the capacitor to prevent it from charging. The system low frequency response is then determined by the time constant (R_rC_r) that is independent of circuit capacitance. For sufficiently high open loop gain, the cable and transducer capacitances can be neglected. Therefore, the output voltage $\mathbf{V_0}$ depends only on the input charge **q** and the range capacitance $\mathbf{C_r}$.

$$V_0 = \frac{-q}{C_r}$$

Charge amplifier Kistler type 5011B with scale factor of 100 MPa/V was used. The pressure is then obtained multiplying the output voltage by a factor of 100.
The components of the measuring chain are showing in the figure below.

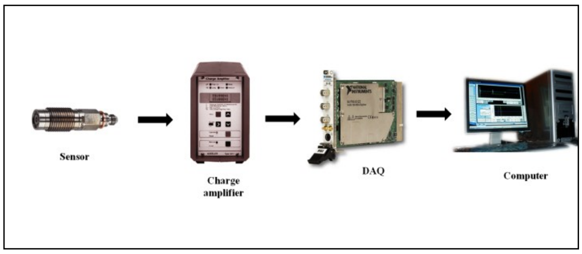


Figure 12 : Pressure measuring chain

Calibration of charge amplifier was carried out with a charge calibrator. The data acquisition (DAQ) board consists in a multi-channel device of four high speed digitizers. Each digitizer has two channels in parallel with a resolution of 14 bits and a maximum sampling rate of 100 MHz. The major conversion occurring in the DAQ board is an analog to digital conversion. In addition, the LabVIEW software was used for signal processing.

3. RESULTS

3.1. First results

The graph below shows a sample of the obtained pressure-time curves collected from the three described sensors when FNB ammunition was fired. Data was sampled at 10^6 samples per second. With respecting Shannon criteria, a faster sampling rate will ensure proper signal measurement.

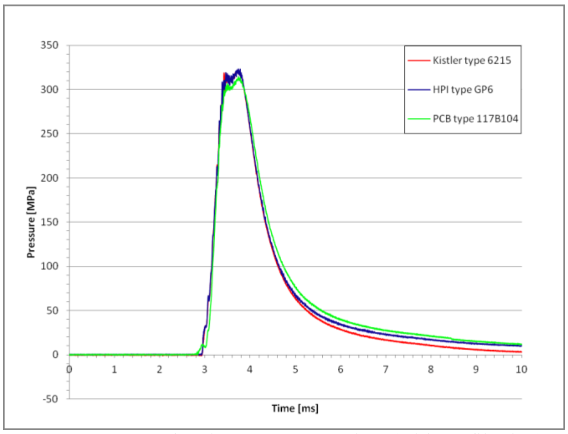


Figure 13 : Gas chamber pressure vs. time (without filtering)

The shape of pressure time curve given by the three sensors are highly similar: rising until a peak value, and then an exponential-like decay to a pressure elevated ambient. Thus, some parameters such as peak pressure and rise time may be determined from these graphs.

As for the 6215 and GP6 transducers, the PCB type 117B104 allows to visualize the whole combustion cycle especially the two bumps on the curve when the peak pressure is reached which is due to the use of a deterred ball powder. Nevertheless, some differences still exist. This concerns mainly the values of the peak pressure which are slightly different.

Comparing to the 117B104, the differences with the 6215 and the GP6 transducers was noticed also in the expansion phase of the ballistic cycle. The pressure measures given by this sensor remain slightly greater than the 6215 and GP6 measures. It exhibits also a slower rate of decay once the peak pressure has been reached. This may be due to the permanent deformation of cartridge case which continues to urge the sensor at the end of ballistic cycle (residual pressure).

Despite the measurement of the gas pressure according to the standard procedures, oscillations still exist on the pressure-time signal. These oscillations are created by the very fast pressure changes and the cavity volume of the mounting hole of the transducer, which acts like Helmholtz resonator, and create the so-called pipe oscillations.

3.2. Filter choice

In the field of interior ballistic, the peak pressure is the most important parameter especially for ammunition testing and the safety test. However, the presence of oscillations in the obtained pressure-time signals makes its determination one of the crucial tasks for ballisticians. Oscillations can lead to incorrect read of the peak pressure. Thus, the way to estimate its value was opened.

There are two ways to eliminate the effect of pipe oscillations: change the dimensions of the mounting hole or filtering. Filtering may be the only way to suppress pipe oscillations since the pressure path is specified in standards. The ideal filter may remove “unnecessary” data points from a data set, while having little effect on the important data. However, when using a filter, a cutoff point must be determined in which the filter will begin removing data.

There are three types of low pass filter which can be used. The main type of filter that was considered for use was the Butterworth filter. A Butterworth filter has a relatively steep response curve which gets steep as the order is increased. An advantage of using this filter is that it does not affect the data on the side of the cutoff in which the data is desired to remain untouched.

Frequency domain transformation of the pressure signal can be computed by Fast Fourier Transform (FFT). Filtering was performed at four frequencies (5 KHz, 10 KHz, 15 KHz and 20 KHz) by a 2^{nd} order Butterworth law pass filter as showed in the graph below.

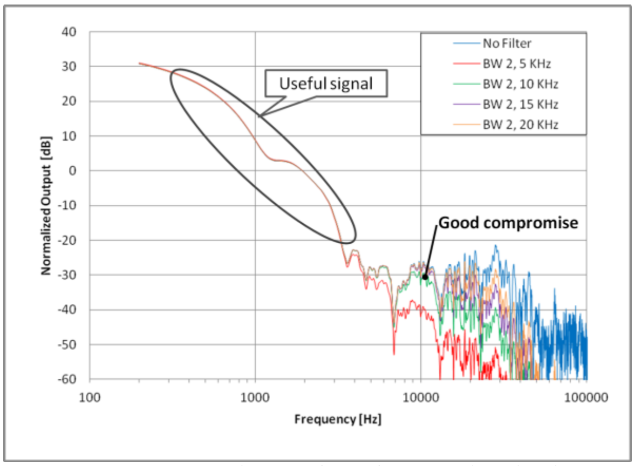


Figure 14 : Fast Fourier Transform of pressure-time signals

Figure 14 shows that the useful signal (without attenuation) is clearly still exist beyond a frequency equal to 5 KHz. Thus, filtering the pressure signal from a frequency of 10 KHz could meet the needs. It is clear that going below this frequency will lead the losing of too much information (signals become too smooth). However, the amplitude of pipe oscillations will increase gradually beyond it [4].

The figure below shows pressure-time curves with the use of different frequency levels.

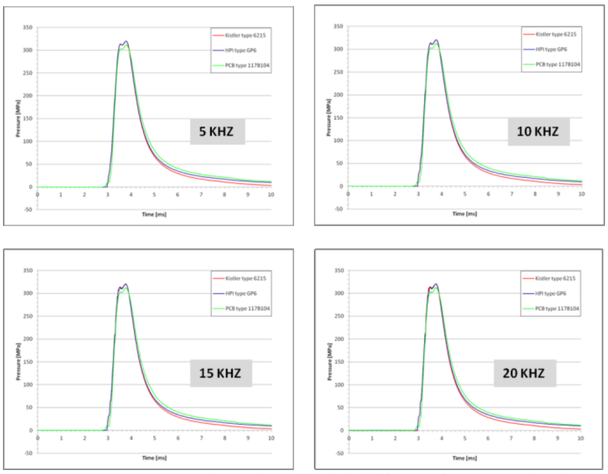


Figure 15: Pressure-time signals with different frequency levels

Although it doesn’t suppress completely pipe oscillations, the frequency of 10 KHz may be considered as an optimum filter level. The use of this frequency is suitable for all pressure-time signals given by the three piezoelectric transducers. It allows to obtain the most likely pattern of the temporal variation of the gas pressure without losing too much useful information (good compromise).

3.3. Discussion

According to the Guide to the Expression of Uncertainty in Measurement (GUM) published by ISO in 1993 [11], there are two procedures for measurement uncertainty estimation: Type A method and Type B method. In our case, Type A method which is based on the application of statistical methods to a series of repeated measurements was applied since when our measurement process was repeated while keeping as well as possible the same conditions to ensure a good repeatability.

In order to get a result close to the “right value”, which remains unknown, the mean peak pressure and its standard deviation for each transducer measurements were determined.

According to the central limit theorem, which states that under mild conditions the sum of a large number of random variables is distributed approximately normally, it was assumed that the maximum pressure follows a normal distribution N(μ,σ) which was confirmed by the normality test of Kolmogorov.

The estimator of the mean peak pressure value is given by:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

The estimator of the standard deviation is given by:

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})}$$

The Chi-squared distribution $\mathcal{X}^2$ was used to determine the maximum standard deviation σ_{max} which is considered more significant to calculate the measurement uncertainty.

We know that:

$$\frac{s^2}{\mathcal{X}_M^2}(n-1) \leq \sigma^2 \leq \frac{s^2}{\mathcal{X}_m^2}(n-1)$$

Then, the maximum standard deviation is given by:

$$\sigma_{max} = \sqrt{\frac{s^2}{\mathcal{X}_m^2}(n-1)}$$

The following tables show the obtained results for each sensor and ammunition type.

Sensors	Mean of P_{max} (MPa)			
	IVI	FNB	PINDAD	EMZ
Kistler type 6215	343.45	319.86	333.39	324.08
HPI type GP 6	339.15	320.00	326.95	318.29
PCB type 117B104	333.00	311.77	320.69	310.28

Table 2 : Mean values of peak pressure

Sensors	Maximum standard deviation of P_{max} (MPa)			
	IVI	FNB	PINDAD	EMZ
Kistler type 6215	9.75	14.37	13.21	12.00
HPI type GP 6	9.07	14.25	15.93	15.73
PCB type 117B104	10.78	14.12	16.62	16.73

Table 3 : Maximum standard deviation of peak pressure

Despite the HPI type GP6 has a greater sensibility than the Kistler type 6215, good agreement was observed between the two transducers but not always with the conformal PCB type 117B104. The deviation between the 6215 and GP6 is around 2 %, however it reaches 5 % between direct and conformal transducers. In addition, the agreement between pressure and velocity was better with the 6215 and GP6 types than with the 117B104 type.

To compare statistically the results given by the transducers, hypothesis tests were carried out. The tests were based on the use of the Chi-squared distribution $\mathcal{X}^2$ to compare the standard deviation as shown in table 3. The comparison results allow to conclude that the measures given by the three transducers are not statistically different.

Moreover, the expanded uncertainty U (maximum) is given by:

$$U = k\sigma_{max}$$

The value of the extending factor k is chosen according to the level of confidence requested; generally k=2 or 3. Considering an interval with a confidence level approximately 95% means that the relative uncertainty is given by:

$$U_{rel} = \frac{2\sigma_{max}}{P_{am}}$$

Where, P_{am} is the average of the peak pressures of a sensor. The calculated relative uncertainties are given in the following table.

Sensors	Relative uncertainty (%)			
	IVI	FNB	PINDAD	EMZ
Kistler type 6215	5.68	8.98	7.92	7.41
HPI type GP 6	5.34	8.91	9.74	9.88
PCB type 117B104	6.47	9.06	10.37	10.78

Table 4 : Relative uncertainties (maximum)

It was expected that the results of the conformal transducer depend strongly on the characteristics of the ammunition cases. Nevertheless, this influence was sometimes very strong, especially when the hardness is relatively high. This can explain the values of the relative uncertainty which exceed 10 % with PINDAD and EMZ ammunitions cases.

Moreover, strange variations were observed in the pressure-time curves given by the conformal transducer, mainly with the EMZ ammunition case. This phenomenon disappears gradually as the hardness decreases. The Figure 16 below shows the results obtained with the conformal 117B104 transducer for the four considered ammunition cases.

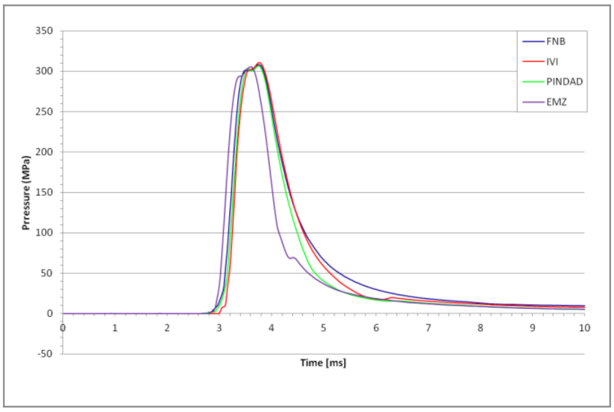


Figure 16 : Pressure-time curves for all ammunition cases

Non-regular pressure-time curves, especially regarding the descending branch, can lead to wrong estimated values of the projectile velocity.

4. CONCLUSION

Investigations on gas pressure measurement were carried out at ABAL laboratory to compare the most often used ballistic pressure transducers. The comparison criteria were essentially the peak chamber pressure and its standard deviation.

It's impossible to determine exactly how precise either the direct and conformal transducer methods are, as there is no way to know exactly what the pressure is. Nevertheless, the combined use of direct and conformal measurements can improve accuracy.

Moreover, differences between 6215, GP6 and 117B104 transducers were still observed despite the use of the same working standard for quasi-static and dynamic calibration. Indeed, none of the used techniques is totally similar to the real process.

Further work on the dynamic calibration aims to improve the used calibration system in order to obtain pressure pulses of high reproducibility with a high rise time, high maximum pressure and short pulse duration similar to the real gas pressure patterns in weapon ammunition. Evaluating the measurement uncertainty is essential to improve the reliability of the system.

5. REFERENCES

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