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Experimental techniques for ballistic pressure measurements and recent development in means of calibration

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Abstract. This paper presents a study carried out with the commonly used experimental techniques of ballistic pressure measurement. The comparison criteria were the peak chamber pressure and its standard deviation inside specific weapon/ammunition system configurations. It is impossible to determine exactly how precise either crusher, direct or conformal transducer methods are, as there is no way to know exactly what the actual pressure is; Nevertheless, the combined use of these measuring techniques could improve accuracy. Furthermore, a particular attention has been devoted to the problem of calibration. Calibration of crusher gauges and piezoelectric transducers is paramount and an essential task for a correct determination of the pressure inside a weapon. This topic has not been completely addressed yet and still requires further investigation. In this work, state of the art calibration methods are presented together with their specific aspects. Many solutions have been developed to satisfy this demand; nevertheless current systems do not cover the whole range of needs, calling for further development effort. In this work, research being carried out for the development of suitable practical calibration methods will be presented. The behavior of copper crushers under different high strain rates by the use of the Split Hopkinson Pressure Bars (SHPB) technique is investigated in particular. The Johnson-Cook model was employed as suitable model for the numerical study using FEM code

1. Introduction

The aim of interior ballistics is to obtain the required velocity to hit the target and inflict the desired damage. The maximum pressure generated by the burn of the propellant inside the ammunition shell must not exceed the yield strength of the weapon barrel. Therefore, it's very important to know the peak pressure value to ensure a safe use of the weapon. Earlier, until the mid of the 1960s, the crusher gauge method, invented in 1860s by Nobel, was the only commonly used and standardized method for gas chamber pressure measurement [1]. A copper or lead cylinder is compressed by a piston fitted to a piston hole into the chamber of the barrel. Under direct effect of the gas pressure generated by the burning of the gunpowder on the base of the piston, the crusher is permanently deformed. The deformed length of the crusher is measured and compared to a conversion table provided by the supplier with each lot of crushers to estimate the peak pressure. The value of maximum pressure is expressed in Copper Units of Pressure (CUP) or Lead Units of Pressure (LUP).

Major drawbacks of this technique are that it has a limited accuracy and gives only the chamber peak pressure value. However, it is still frequently used, since it is simple (there is no further



instrumentation needed), cheap and considered as accurate enough to obtain a rapid estimation of the chamber peak pressure, e.g. in ammunition testing.

Since 1960, piezoelectric transducers have superseded crusher gauges. The discovery of the piezoelectric phenomena was done by Pierre and Jacques Curie in 1880 [2]. Some crystals such as quartz have the capability to produce electric charges when they are squeezed by a mechanical force. This charge is characterized by high impedance. That's why, the use of the piezoelectric technique began effectively in 1935 when a successful application was done by Oerlikon Bührle of Switzerland which was described by Dr. Werner Gohlke in his book published in 1959 on Piezoelectric Technology. The use of piezoelectric pressure measurement in the field of interior ballistics knew a great progress since the development of the charge amplifiers by W.P. Kistler in the 1950s [3].

Today, research and development of piezoelectric pressure measurements are shaped by three main worldwide organizations: NATO (North Atlantic Treaty Organization), C.I.P. (Commission Internationale Permanente pour l'épreuve des armes à feu portatives) and SAAMI (Sporting Arms and Ammunition Manufacturers' Institute). These last two organizations develop proof standards mainly intended to the evaluation of the ammunition for civilian uses. The major differences between the measurement methods defined by these organizations are the transducer fixture points and the measuring techniques. NATO recognizes the direct gas measurement method according to the EPVAT (Electronic Pressure Velocity and Action Time) which it means that the transducer has to be mounted at the case mouth. Both SAAMI and C.I.P. use chamber pressure measurement but C.I.P. uses a transducer which require a hole drilled into the cartridge case and fired by a specific prepared barrel. However, SAAMI employs the so called conformal measurement where the transducer has a similar part as the NATO and C.I.P. sensors except an additional piston is cut in the side of the chamber to conform the cartridge case [4,5,6].

In this paper, a study carried out with the commonly used experimental techniques of high pressure gas chamber measurement is presented. The comparison criteria were the peak chamber pressure, its standard deviation inside specific weapon/ammunition system configurations. Furthermore, a particular attention has been devoted to the problem of calibration. Calibration of crusher gauges and piezoelectric transducers is paramount and an essential task for a correct determination of the pressure inside a weapon. This topic has not been completely addressed yet and still requires further investigations.

2. Experimental techniques for ballistic pressure measurement

2.1. Piezoelectric transducers and measuring chain

Kistler type 6215 and PCB type 117B104 are two different types of piezoelectric transducers often used for pressure measurements inside a barrel of caliber .50 inch [3,7]. As shown in the figure 2 below, the transducer is the first element of a measuring chain which contains other components such as charge amplifier for signal conditioning, data acquisition unit (DAQ) and computer with suitable software for data evaluation and handling.

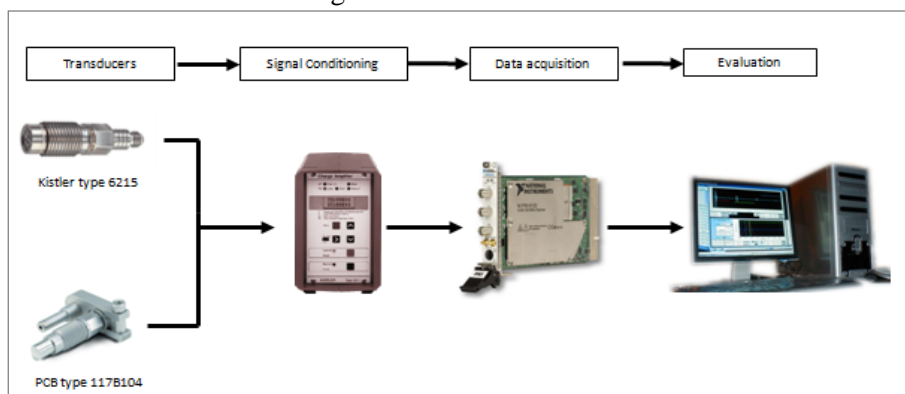


Figure 1. Measuring chain

Calibration of charge amplifier was carried out with a charge calibrator. The data acquisition 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. Here, the sampling frequency was set to 1 MHz to ensure proper signal measurement. The major conversion occurring in the DAQ board is an analog to digital conversion. Filtering was performed at the frequencies of 10 KHz by a 2nd order Butterworth low pass filter. This filter low-cut frequency allows to obtain the most likely pattern of the temporal variation of the gas pressure without losing too much useful information (good compromise). Signal processing was achieved with the suitable software LabVIEW.

2.2. Firing tests setup

2.2.1. Weapon configuration. Firing tests have been performed with an instrumented .50 inch barrel manufactured according to military standards and mounted on a universal ballistic breech with an interchangeable barrel (BMCI). The major advantage of this caliber is the obtaining of a long ballistic cycle which permits to visualize clearly all the events which occur inside the barrel until the exit of the projectile. The piezoelectric transducers and the copper crusher gauge can be installed in the same mounting position in respect to barrel length but displaced by 90 degrees to each other. The copper crusher gauge had a nominal height of 4.91 mm and a nominal diameter of 3.0 mm.

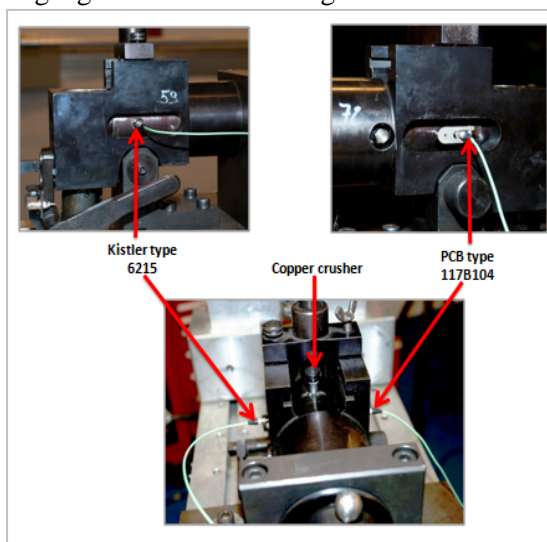


Figure 2. Transducers and crusher installation

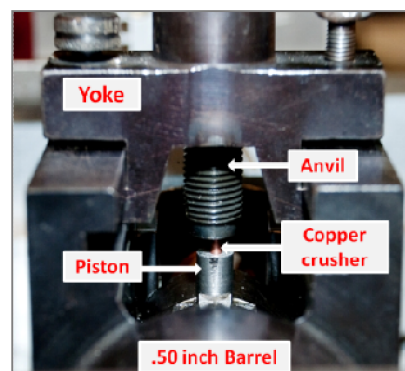


Figure 3. Copper crusher gauge setup.

The triggering was realized using a muzzle flash detector which detects the flash at the exit of the projectile from the muzzle.

2.2.2. Ammunition configuration. The 12.7x99 ammunition filled with the gun powder type .50 inch (WC 860) have been used to achieve the firing tests. A full metal jacket projectile type M33 of 42.5 g is also used for all experiments. The cartridge cases were drilled with a hole of 2.5 mm diameter according to military standards. Obstruction of the hole was done by a heat-resistant adhesive tape. Four types of ammunition from different manufacturers and lot numbers have been selected to illustrate the influence of cartridge case material: FNB 06, PINDAD 86, IVI 10 and EMZ 87. Indeed, It was expected that the conformal pressure measurement depend strongly onto physical parameters like case thickness and hardness. Ammunition case hardness was evaluated using Vickers Diamond Pyramid Hardness test (table1). The sensitivities of the conformal PCB type 117B104 transducer for each type of ammunition type are also listed in the same table 1.

Table 1. Characteristics of ammunition cases

Ammunition	Hardness Vickers HV 100g	Average Sensitivity (pC/bar ^a)
IVI	129.25	1.66
FNB	130.25	1.65
PINDAD	137.75	1.63
EMZ	174.50	1.60

^a bar is a pressure unit is often used for transducer sensitivity (1bar = 0.1 MPa).

The first series of forty shots of each ammunition type have been carried out to compare only the standard Kistler type 6215 and the conformal PCB type 117B104 transducers. While the second series of ten shots was conducted with different gunpowder masses (12 g, 14 g and 16g) to evaluate the Kistler pressure transducer and the copper crushers. All measurements were taken at 21 ±2°C in a completely enclosed shooting test stand free from weather influences. Results of this series have been used in the second part of this paper to study the dynamic behavior of copper crusher gauges.

2.3. Results and discussion

2.3.1. Kistler type 6215 versus PCB 117B104. Figure 4 below shows typical pressure-time curves for the Kistler and PCB transducers when FNB ammunition was fired. 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. As for the Kistler type 6215, the PCB type 117B104 allows to visualize the whole combustion cycle especially the jump of pressure with the departure of the projectile and the two bumps on the top of 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. The conformal sensor 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). When the hardness became high, as for the EMZ ammunition case, irregularities appear in the pressure-time curves, especially regarding the descending branch, which can lead to wrong estimation of the projectile velocity. This phenomenon disappears gradually as the hardness decreases.

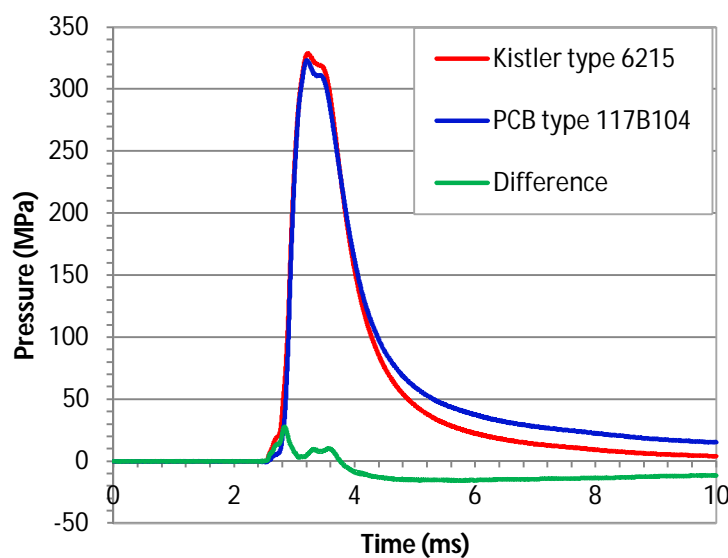


Figure 4. Gas chamber pressure for different transducers

The average peak pressure and its standard deviation for each transducer measurements were determined according to the Guide to the Expression of Uncertainty in Measurement (GUM) [8]. It

was assumed that the maximum pressure follows a normal distribution $N(\mu, \sigma)$ which was confirmed by the normality test of Kolmogorov. The estimator of the mean peak pressure value is given by $\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$ and the estimator of the standard deviation is given by $s = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2}$. The Chi-squared distribution χ^2 was used to determine the maximum standard deviation σ_{max} which is considered more significant to calculate the measurement uncertainty. We know that:

$$\frac{s^2}{\chi_M^2} (n - 1) \leq \sigma^2 \leq \frac{s^2}{\chi_m^2} (n - 1)$$

Then, the maximum standard deviation is given by: $\sigma_{max} = \sqrt{\frac{s^2}{\chi_m^2} (n - 1)}$

The following table gives the obtained results of the average (Av.) and the maximum standard deviation (Std.) of peak pressures P_{max} (MPa) for each transducer and ammunition type.

Table 2. Mean and maximum standard deviation of peak pressure

	IVI		FNB		PINDAD		EMZ	
	Av. (MPa)	Std. (MPa)	Av. (MPa)	Std. (MPa)	Av. (MPa)	Std. (MPa)	Av. (MPa)	Std. (MPa)
Kistler type 6215	343.45	9.75	319.86	14.37	333.39	13.21	324.08	12.00
PCB type 117B104	333.00	10.78	311.77	14.12	320.69	16.62	310.28	16.73
Average peak pressure difference (%)	3		2.5		3.8		4.25	

The PCB type 117B104 always gives lower peak pressure values than the Kistler type 6215. The average peak pressure difference usually exceeds 3 %. 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 χ^2 to compare the standard deviation as shown in table 2. Hence, it was concluded that measurements of the two transducers are not statistically different.

Moreover, the expanded uncertainty U (maximum) is given by $U = k\sigma_{max}$. Considering an interval with a confidence level approximately 95%, the relative uncertainty is computed by:

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

Where, P_{am} is the average of the peak pressure values. The relative uncertainties are given in the table 3 below.

Table 3. Relative uncertainties

	Relative uncertainty (%)			
	IVI	FNB	PINDAD	EMZ
Kistler type 6215	5.68	8.98	7.92	7.41
PCB type 117B104	6.47	9.06	10.37	10.78

The results of the conformal transducer depend strongly on the characteristics of the ammunition cases. Indeed, for the conformal PCB type 117B104, the relative uncertainty increases with the ammunition case hardness. The influence was sometimes remarkable, especially when the hardness is relatively high. This can explain the values of the growth of the relative uncertainty which exceeds 10 % with PINDAD and EMZ ammunition cases.

2.3.2. *Kistler type 6215 versus copper crusher gauge.* Table 4 gives the experimental average and the standard deviation of the peak pressure for the piezoelectric Kistler type 6215 and the copper crusher gauges when FNB ammunitions are fired with three different gunpowder masses (12 g, 14 g and 16 g). Copper gauge peak pressures originate from the conversion table provided by the supplier.

Table 4. Results of pressure measurements for different powder masses

	12 g		14 g		16 g	
	Kistler 6215	Copper Crusher	Kistler 6215	Copper Crusher	Kistler 6215	Copper Crusher
Average peak pressure (MPa)	159.15	127.65	251.47	223.27	319.56	291.92
Std. deviation peak pressure (MPa)	14.15	25.51	19.74	21.03	20.64	25.25
Average peak pressure difference (%)	19.8		11.2		8.65	

The peak pressure given by the crusher is always lower than the measured by the Kistler piezoelectric transducer. The difference between values may reach 20 % as for the 12 g powder mass but it is less than 10 % for the higher 16 g powder mass. These significant differences are mainly related to the used supplier conversion table.

Under the effect of the pressure generated by the combustion gas, it deforms plastically under different high strain rates. However, peak pressure values provided by the conversion table are obtained by a quasi-static calibration (10^{-3} - 10^{-1} /s) which do not take into account the dynamic behavior of copper crusher. This statement was also verified experimentally. Therefore, recommendations were made to develop a suitable model dynamic calibration method for the copper crusher gauge. The purpose of this method was to develop a model for the conversion of the deformation in crusher length to maximum pressure. This task was achieved by the investigation of the behavior of the copper crusher at different high strain rates with the Hopkinson Split Pressure Bar (HSPB).

The accuracy of the developed model was verified by a numerical finite element modeling. In this regards, the gas chamber pressure measurements of the transducer Kistler type 6215 was applied to the copper crusher as reference pressure.

3. Dynamic calibration of copper crusher gauges

3.1. Crusher material modeling

Two different strength models were considered for the copper material of the crushers. An experimental study was performed in order to obtain the necessary parameters of each.

A first considered model was the Zerilli-Armstrong model [9], which in its version for face-centered cubic materials (FCC) like copper is given by:

$$\sigma = C_0 + C_2 \sqrt{\varepsilon_p} e^{-C_3 T + C_4 \ln(\dot{\varepsilon}) T}$$

With σ the stress, ε_p the plastic strain, $\dot{\varepsilon}$ the strain rate, T the temperature, and finally C_0 , C_2 , C_3 , C_4 the material parameters fitted to the real material behavior.

The second considered strength model was the Johnson-Cook model [10], which originally was developed to model the mechanical behavior of body-centered cubic materials (BCC), as steels for instance. Nevertheless, the Johnson-Cook model is a very versatile model that has often been used outside its original scope, typically with satisfactory results. Its mathematical expression is given by:

$$\sigma = \left[A + B \varepsilon_p^n \right] \left[1 + C \ln \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left[1 - \left(\frac{T - T_r}{T_m - T_r} \right)^m \right]$$

With A, B, C, n and m the material parameters to determine, and $\dot{\varepsilon}_0$ a reference strain rate (chosen as 1 s^{-1}). T_m and T_0 are respectively the melt temperature of the considered material and a reference

temperature. Based on the melt temperature of pure copper, T_m was chosen at 1357 K, whereas the reference temperature T_0 was chosen at room temperature (294 K).

The material parameters for the Johnson-Cook model described above were determined using the SHPB. It is one of the few known setups nowadays for studying material behavior at high strain rates [11,12]. A compressive longitudinal wave is produced by a projectile impacting the input bar. This wave is transported through the bar and once it reaches the specimen interface, a part of the waves is reflected, and a part is transmitted. These three waves are recorded with strain gauges glued on the input and output bar.

The ABAL laboratory setup consists of 2 m long input and output bars with a diameter of 30 mm and made out of high-strength steel. A double set of strain gages was used on both the input bar and the output bar to eliminate any influence of parasitic bending of the bars. The signals coming from the strain gages were sampled at 10 MHz and recorded using a digital acquisition system. The final stress-strain curves of each test were obtained using the typical relationships between the strains in the input and output bar and the deformation history of the sample, which are integrated in a custom data analysis software implemented in a LabVIEW environment.

The cylindrical samples used for the experiments were made out of the same material as the original copper crushers used in the ballistic experiments, but had slightly different dimensions in order to have a good signal-to-noise ratio for the SHPB testing. The samples had respectively a height and diameter of 10 mm and 7.2 mm.

In total 11 dynamic compression tests were performed in a strain rate range of approx. 650 s^{-1} up to 1400 s^{-1} . The final strains varied correspondingly from approx. 0.1 up to 0.25, comparable to the strains achieved in the copper crushers during a typical pressure measurement. All samples had an initial temperature corresponding to room temperature.

A typical stress-strain curve (true strain rate 1181 s^{-1}) is shown in Figure 5. The pseudo-elastic part of the curve was removed using a 0.2 % offset criterion as used for quasi-static tensile and compression testing.

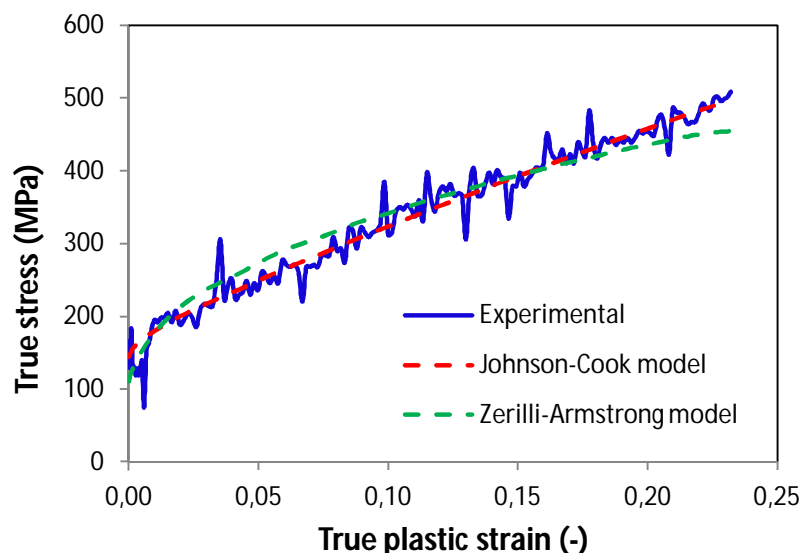


Figure 5. Comparison between an experimental stress-strain curve and the modeled results

The resulting parameters for both models are given in Table 5 and compared with literature values [13] for pure copper (OFHC). It can be observed that the crusher material shows a much more pronounced strain hardening than OFHC copper, which could most likely be explained by the crusher material being a copper alloy (instead of the initially assumed pure copper material). As in the case of the Johnson-Cook model the temperature sensitivity exponent, m , did not converge to any meaningful

physical value (which can be attributed to the fact that all testing was done at room temperature), its value was set arbitrarily to 1. A representative comparison between an experimental stress-strain curve and the modeled curves is given in Figure 5 as well. Even if it was developed for BCC materials, the Johnson-Cook model fits the experimental curve better than the Zerilli-Armstrong model, especially for the beginning and the end of the curves. The Johnson-Cook strength model was hence preferred to the Zerilli-Armstrong model for the subsequent finite element modeling.

Table 5. Johnson-Cook and Zerilli-Armstrong model parameters

Johnson-Cook model					
	A (MPa)	B (MPa)	C (-)	n (-)	m (-)
Own result	119	935	0.049	0.89	1
Literature	90	292	0.025	0.31	1.09
Zerilli-Armstrong model					
	C₀ (MPa)	C₂ (MPa)	C₃ (-)	C₄ (-)	
Own result	107	853	0.0054	0.000681	
Literature	65	890	0.0028	0.000115	

3.2. Numerical Modeling

The finite element modeling was carried out with the ANSYS Workbench 14 [14]. If the strength model is accurate enough, the permanent deformation of the crusher Δl_{sim} could be compared to the reference permanent deformation Δl_{ref} corresponding to the initially applied peak pressure P_{peak} (using the conversion table), and to the experimentally obtained average residual deformation Δl_{exp} . If the simulated permanent deformation corresponded to the reference permanent deformation, the developed model could be assumed to be correct.

Both piston and crusher were modeled using a Lagrangian mesh and implementing the previously fitted Johnson-Cook model as the strength model. The piston's inertia could be hence evaluated. The measured pressure-time curve was taken as the input "true" pressure. The equation of state was obtained from the material models for OFHC copper, as available in the ANSYS material library. No failure model was considered.

The final deformations of the copper crusher as a function of the powder mass are given in table 6.

Tableau 6. Comparison between reference, simulated and experimental permanent deformation.

Powder mass (g)	P_{peak} (MPa)	P_{crusher} (MPa)	Δl_{ref} (mm)	Δl_{sim} (mm)	Δl_{exp} (mm)
12	159.15	127.65	0.69	0.64	0.49
14	250.15	218.4	1.35	1.29	1.1
16	319.6	292	1.80	1.73	1.6

With increasing powder mass, the residual deformation increases as well, as expected. It is also clear that the simulated residual deformations correspond better to the reference deformations than to the average experimental deformations. However, they are still less than the reference deformations. The reasons of these differences are certainly two: the piston's inertia and the strength model which originate from the developed calibration method. Indeed, the Johnson-Cook model was determined at different strain rates. The question was then raised about the choice of the required strain rate of the deformation of copper crusher. One of the possible solutions consists of the estimation of this parameter from the pressure-time curve. Once this has been done, the appropriate stress-strain curve has to be used to convert the deformation in the length of the crusher to a maximum pressure.

4. Calibration of piezoelectric pressure transducers

4.1. Calibration of ballistic pressure transducers

Calibration is a procedure to find the relationship between a known input $e(t)$ and a measured output $s(t)$ in well-defined conditions [15], which means the determination of the transfer function.

In static calibration, the ratio of output and input is constant and gives the sensitivity of the sensor. In the dynamic calibration, the ratio leads to a complex function $H(f)$ which is defined as the ratio of the Fourier transforms of the output $S(f)$ and the input $E(f)$ [16,17,18]:

$$H(f) = \frac{S(f)}{E(f)} = \frac{\int_0^{\infty} s(t)e^{-j2\pi ft} dt}{\int_0^{\infty} e(t)e^{-j2\pi ft} dt}$$

In the most of cases, the measured signals are sampled and non-periodic. Discrete Fourier Transform (DFT) is then used to compute the transfer function, also known as the Frequency Response Function (FRF). The FRF allows the full characterization of pressure transducers both in the static and the dynamic regimes. Dynamic calibration involves the determination of several properties of the pressure sensor such as the FRF (amplitude and phase), resonant frequency, damping ratio, rise time and overshoot [16]. In 1972, the ASME published a guide for the dynamic calibration of pressure transducers [19]. 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 [20]. A diversity of periodic and aperiodic generators is described. These systems allow the characterization respectively of the harmonic and transient response of pressure sensors. Periodic pressure signals have low amplitude and limited bandwidth while aperiodic generators produce pressure signals with high amplitude and large bandwidth (several hundred kHz). Aperiodic generators include shock tube, quick-opening valve devices, explosive devices (close bombe), and the drop weight devices (hammer and ball). They create step-like pressures or single pressure pulses similar to a half-sine wave [16,18,20]. Each pressure generator has its range of operation. The choice of the required device is then determined by the conditions of use of the sensor to be calibrated.

Until today, a pressure primary standard for the dynamic calibration of high pressure sensors does not exist yet. Few national institutes of metrology such as LNE, NPL and NIM have developed a series of shock tubes to achieve this challenge but no one of these systems was able to satisfy entirely the needs [17,18]. Further work is still required because the generated pressure step signals have some limitations especially in amplitude (several tens MPa) and the low limit of frequency which remains significantly high. Also a reference pressure sensor still needed to measure the output in most of the cases which is generally calibrated statically.

In the field of interior ballistics, the need of reliable dynamic calibration techniques for piezoelectric high pressure sensors has been increasing in the last years since accurate dynamic measurements of gas chamber pressure became paramount in many applications. The best way still a static calibration followed by a dynamic verification. First of all, only the working standard is calibrated statically, by the use of a pressure balance as primary standard, which allows a step-wise calibration. Then, a quasi-static calibration of the piezoelectric transducer is fulfilled by a high continuous pressure generator. Finally, its dynamic behavior is checked against the “dynamic” working standard. These procedures are explained in the figure 6 below [21].

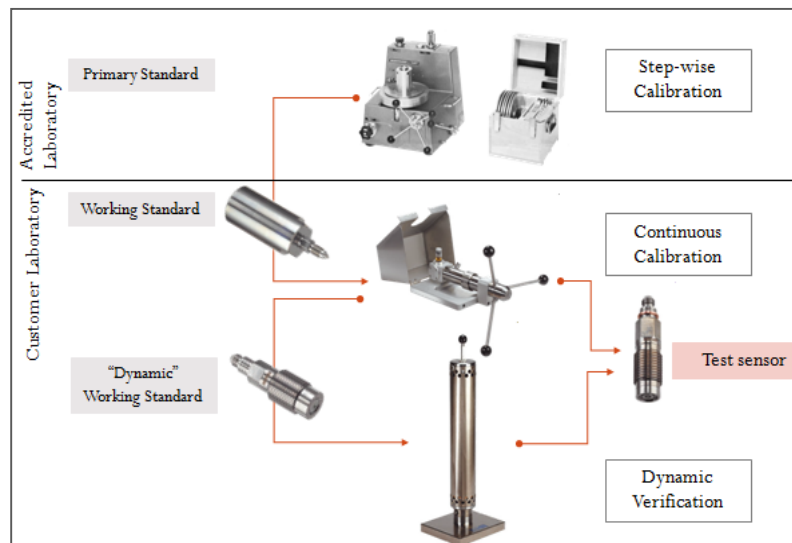


Figure 6. Calibration of piezoelectric pressure transducer

4.2. Development of dynamic calibration generator

The aperiodic pressure pulses generator produces a single half-cycle sine wave with high amplitude (several hundred MPa). However, the frequency bandwidth of this system is not wide enough to characterize the high pressure transducers. This limitation is essentially due to the big width of the generated pressure pulse. In theory, an ideal system will generate an ideal impulse signal. The transfer function of the sensor can be directly derived by computing the Fourier transform of the measuring chain response. A system like this does not exist. However, it is possible to produce a pseudo-Dirac function which allows to reach high frequencies.

A solution based on the use of a piston in contact with oil-filled pressure chamber has been developed and tested. The high pressure was obtained by impacting the piston with projectiles launched by an air gun. The aim of the setup was to create a system which may generate narrow pressure pulses with high accuracy. The change of projectile length leads to create pulses with different width. Figure 7 gives an overview of the obtained results. A maximum pressure of 500 MPa can easily be reached but the narrowest generated pressure pulse has a width of 0.4 ms.

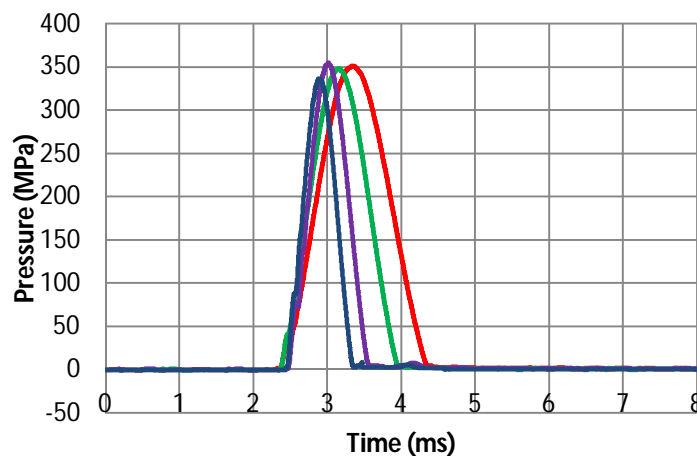


Figure 7 : Different pressure pulses

The amplitude and the phase of the FRF are estimated by the following expression:

$$H(f) = \frac{G_{SS}(f)}{G_{SE}(f)}$$

Where $G_{SS}(f)$ and $G_{SE}(f)$ are respectively the Power spectrum of the measuring chain response of the reference transducer and the Cross power spectrum of the measuring chain response of the tested and the reference transducers.

Results show that the system has a limited frequency bandwidth. The low limit frequency and the high limit frequency are respectively 100 Hz and 4 kHz which are obtained for a maximum deviation of 2.5 % of the amplitude ratio. As the FRF was estimated using a reference transducer calibrated statically to measure the input pressure pulse, this method is still also a comparison calibration method.

The way to improve the developed system was identified by the use of Hopkinson pressure bar device as shown in the figure 8 below.

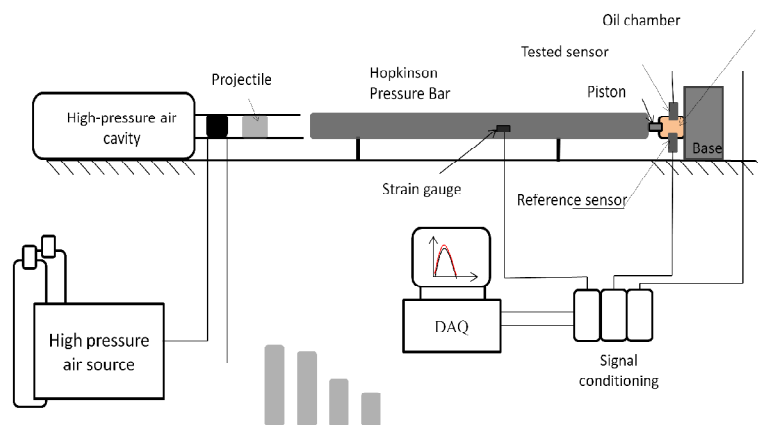


Figure 8. Setup of the dynamic calibration

This dynamic pressure generator produces a pseudo-Dirac pressure wave. It allows to reach a quit high frequency and has wide frequency bandwidth as it was approved in the recent study made by Zhang et al. [22]. Finite element modelling was also carried out to develop a numerical model for the described setup.

5. Conclusion

Gas chamber pressure measurement is one of the most demanded measurements in ballistic testing. Experimental method usually used to measure this physical quantity were reviewed and compared to elucidate on the typical measurement differences one can find between the results of not only crusher and piezoelectric measurements, but also between the different piezoelectric measurement techniques. Furthermore, as the accuracy of pressure measurement depends strongly on the calibration method, a big amount of this work was dedicated to the problems of dynamic calibration to develop in-situ reliable techniques for both copper crusher and piezoelectric transducers. Further works still needed to improve the accuracy of the behavior model for copper crusher gauges and the generated pressure pulses frequency bandwidth for dynamic calibration of piezoelectric high pressure transducers.

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