ACTA IMEKO
ISSN: 2221-870X
September 2025, Volume 14, Number 3, 1 - 7

Evaluation of calibration methods of piezoelectric transducers for transient pressure measurement in ballistics tests

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ABSTRACT
The internal pressure generated by the combustion of the propellant in small-caliber ammunition is a significant topic within the defense sector, playing a vital role in both weapon development and ammunition certification. Piezoelectric transducers are utilized to measure the transient pressure curve during internal ballistics, a critical step in enhancing pressure measurement methods for ammunition testing. The accurate calibration of these transducers is essential to ensure the reliability of such measurements. This study examined two calibration techniques: Indirect Dynamic Calibration and Indirect Quasi-static Calibration. To carry out the analysis, three piezoelectric transducers were calibrated using both methods. The results underscored the need for refinements in the second method, particularly in addressing operator influence and resolving issues related to equipment, such as the presence of air in the hydraulic system, leakage, and drift in the measurement system. The findings also revealed multiple sources of uncertainty in both techniques, emphasizing the necessity for adjustments to minimize factors that compromise measurement accuracy.

Section: RESEARCH PAPER

Keywords: ammunition testing, indirect calibration, interior ballistics, piezoelectric transducer, transient pressure measurement

Citation: C. B. C. Felix, K. A. R. Medeiros, C. R. H. Barbosa, Evaluation of calibration methods of piezoelectric transducers for transient pressure measurement in ballistics tests, Acta IMEKO, vol. 14 (2025) no. 3, pp. 1-7. DOI: 10.21014/actaimeko.v14i3.1990

Section Editor: Daniel Ramos Louzada, PósMQI/PUC-Rio, Rio de Janeiro, Brazil

Received November 26, 2024; **In final form** July 30, 2025; **Published** September 2025

Funding: This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Capes) - Finance Code 001.

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1. INTRODUCTION

The measurement of transient pressure, i.e., pressure that varies significantly over a period of time or during a measurement [1], is widely used in the development and monitoring of systems employed in the automotive, aerospace and defence industries [2].

In ballistics, a branch of the defence industry related to the design, testing and evaluation of weapons and ammunition, piezoelectric transducers are employed to measure the internal transient pressure during the combustion process of the propelling charge of ammunition. This measurement method is considered more advantageous in several aspects [3], making it possible to obtain relevant information, such as the maximum pressure inside the weapon's chamber, in addition to the pressure profile over time. This information is useful for the analysis of performance and the safety of ammunition, as well as for the development of weapons [4]. Figure 1 shows an HPI GP6, a

Figure 1. HPI GP6 piezoelectric transducer: instrumentation of a rifle using two units for chamber and muzzle pressure measurement.

piezoelectric transducer, an example in which two units are used to measure transient pressure in the barrel of an automatic rifle.

In general, the demand for measurements with low uncertainty is hindered by the lack of traceability in the calibration methods of transient (non-acoustic) pressure transducers [1], [5], [6]. Traceable calibration, a requirement for quality assurance in laboratories accredited by ISO 17025:2017 [7], generates the need to adapt the calibration methods available for static pressure measuring instruments [5], for example, those that have a traceable standard. Another limiting factor is the lack of normalization of the transient pressure calibration procedures, including the determination of the measurement uncertainty [5], [8].

Concerning the conformity assessment of small-caliber ammunitions, the technical standards dedicated to the standardization of procedures and minimum performance conditions were published by three organizations: (i) the North Atlantic Treaty Organization (NATO), by means of the AEP-97 – Multi-Calibre Manual of Proof and Inspection (M-CMOPI) for NATO Small Arms Ammunition [9]; (ii) the Permanent International Commission (CIP) for the Proof of Small Arms [10]; and (iii) the Sporting Arms and Ammunition Manufacturers' Institute (SAAMI) [11]. These organizations standardize the calibration methods for piezoelectric transducers in addition to the acceptance criteria.

In Brazil, there is no accredited calibration laboratory that is capable of meeting the needs of ballistics testing laboratories regarding the traceability of piezoelectric pressure transducers. Therefore, the acquisition of equipment dedicated to the calibration of piezoelectric transducers, according to the mentioned standardizing organizations, becomes a facilitator for testing laboratories, since calibration procedures can be carried out in the same laboratory where the tests take place, reducing the time and cost of calibration. However, the laboratory must meet the quality requirements of ISO/IEC 17025:2017 concerning the execution of calibration, that is, to prove traceability, including determining the measurement uncertainty of the calibration.

This work presents the evaluation of two distinct calibration methods, currently adopted by non-accredited testing laboratories. Regarding the organization of the work, in section 2, the fundamental concepts for the measurement of transient pressure with piezoelectric transducers and the indirect calibration of piezoelectric transducers are presented, highlighting relevant aspects related to ISO/IEC 17025:2017. In section 3, the evaluated indirect calibration methods are presented, detailing the particularities of each method, as well as the specificities of the equipment used. The calibration results using the evaluated methodologies are presented in section 4 and discussed in the subsequent section.

2. BACKGROUND

In this section, the main concepts of the transient pressure measurement chain using piezoelectric transducers are covered, as well as the methods of indirect calibration of piezoelectric transducers.

2.1. Transient pressure measurement by piezoelectric transducers

The sensing element of a piezoelectric transducer is a piezoelectric crystal, which generates an electric charge proportional to the tensile or compressive stress [12]. In the case of piezoelectric pressure transducers, the direct piezoelectric effect enables the measurement of transient pressure by means

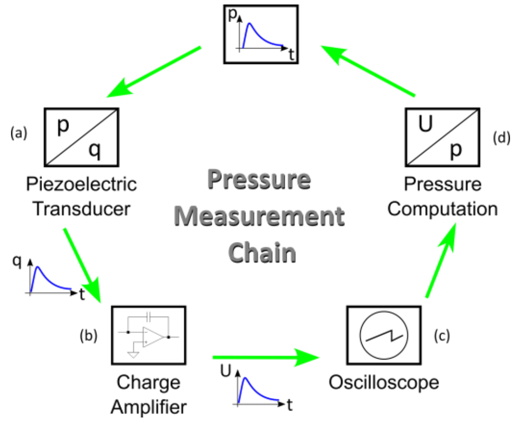

Figure 2. Pressure measurement chain utilizing a piezoelectric transducer: (a) pressure $p(t)$ is converted into electrical charge $q(t)$ by means of the piezoelectric transducer by direct piezoelectric effect; (b) electrical charge $q(t)$ is converted into voltage $U(t)$ by the charge amplifier; (c) voltage $U(t)$ is measured by an oscilloscope; (d) by means of the sensitivity of the employed piezoelectric transducer and the gain of the charge amplifier, the pressure $p(t)$ is calculated. Adapted from [14].

of the generated electric charge, usually measured in picocoulombs (pC), as an effect produced by compression.

Considering that piezoelectric crystals exhibit a rapid response to pressure variations, such materials are applicable to transient pressure measurements. However, such piezoelectric transducers exhibit capacitive behaviour, rapidly discharging the generated electric charge, exponentially following a parameter called the discharge time constant [13]. This prevents piezoelectric transducers from being used for static pressure measurements, and it also hinders the processes of measuring transient pressures and calibrating transducers.

Thus, the measurement of the electric charge originating from the transient pressure produced by the burning of the ammunition propellant is made possible with the use of charge amplifiers, the elementary function of which is to convert the electric charge originating from the piezoelectric effect into an electric voltage proportional to it, thus reducing the discharge effect previously mentioned. A charge amplifier is based on operational amplifiers with an integrator circuit topology, generating an electrical voltage that can then be measured using oscilloscopes or analogue/digital converters. Thus, the transient pressure can be determined by knowing the piezoelectric sensitivity (pC/MPa), which must be determined by a calibration method, and the gain of the charge amplifier (mV/pC). The measurement chain is shown in Figure 2.

Although it is indicated only for transient pressure measurements, depending on the configuration of the charge amplifier, it is also possible to perform pressure measurements with slow variations [15] called quasi-static measurements [16], [17]. A charge amplifier typically presents the topology shown in Figure 3.

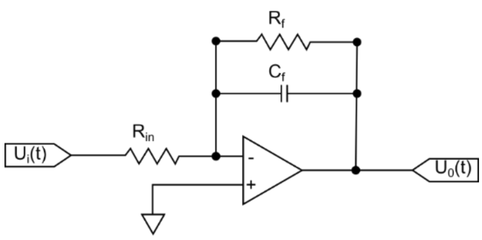

Figure 3. Charge amplifier electric model [18]–[21].

The output voltage $e_0(t)$ for a unit step input is given by:

$$e_0(t) = \frac{R_\mathrm{f}}{R_\mathrm{in}}\left(e^{-\frac{t}{R_\mathrm{f}\,C_\mathrm{f}}} - 1\right) = \frac{R_\mathrm{f}}{R_\mathrm{in}}\left(e^{-\frac{t}{\tau}} - 1\right). \quad (1)$$

The time constant $\tau = R_\mathrm{f}\,C_\mathrm{f}$ determines the charge and discharge rates of the charge amplifier [22], that is, the initial output voltage will be zero, reaching $-R_\mathrm{f}/R_\mathrm{in}$ according to the exponential function with time constant τ. The limit for the duration of charge measurements can be set in the interval $0 < t < 0{,}02\,\tau$, for an error limit of $2\ \%$, for example [22].

Because charge amplifiers are components of the transient pressure measurement chain, this equipment should be used both in the ammunition testing and in the calibration of piezoelectric transducers. Calibration, in turn, involves the determination of piezoelectric sensitivity by measuring the electric charge produced by applying a known pressure [9] originating from a traceable standard (direct calibration) or measured by a reference transducer (indirect calibration). As previously mentioned, the application of static pressure does not produce the desired effect on piezoelectric transducers. Thus, a dynamic event is inserted in the calibration process with a certain duration, influencing the time constant τ determined by the charge amplifier. Generally, for the calibration of piezoelectric transducers used in ballistics tests, when the desired pressure is obtained, a relief valve is quickly opened, characterizing a negative step with a certain duration of time [1], [9], [10].

In order to reduce measurement errors, CIP and NATO, for example, recommend that charge amplifiers used in calibration be configured to perform quasi-static measurements [9], [10], that is, the time constant be set to "long". Such a configuration, in practice, generates the phenomenon called drift, which would be an electric charge originating in the measurement chain that has no relation to the measuring [22]. The drift has linear behaviour and is independent of the force applied to the transducer and should be taken into account in the calculation of the measurement uncertainty [23].

2.2. Indirect calibration of piezoelectric transducers

The conformity assessment of small-caliber ammunition is carried out based on standards published by NATO, CIP, and SAAMI. In standard pressure tests, pressure can be measured by means of piezoelectric transducers, and the HPI GP6 transducer (Figure 1), for example, is certified to perform pressure measurement according to CIP and NATO. The said transducer has a sensing element of gallium phosphate and is capable of measuring pressures between 0 and 600 MPa.

There are two ways to perform transient pressure measurements in indirect calibration, allowed by the three organizations. The first is the pressurization of the cylinder by means of a piston and the measurement of electric charge at the moment of pressure relief performed by opening a valve, characterizing a negative step [1]. For this measurement, attention should be paid to configuring or selecting the charge amplifier with a time constant τ appropriate to the duration of the dynamic event. In this work, this method will be called Indirect Dynamic Calibration (IDC).

The second method consists of measuring the charge continuously during the pressurization of the cylinder, and the charge amplifier must be configured or selected with long time constant τ, which in the case of the PCB 443B102 charge amplifier, for example, would be equivalent to τ greater than 10^5 s [24]. This method may be called Indirect Quasi-static Calibration (IQsC). Figure 4 illustrates the pressure variation and calibration points that characterize the two processes.

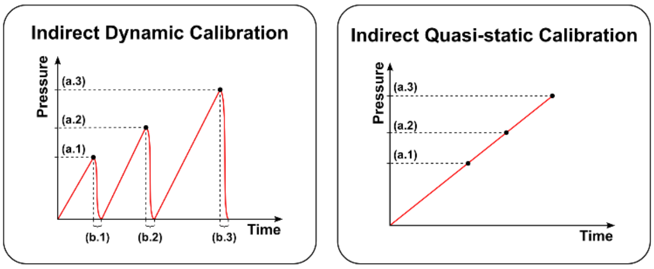

Figure 4. Pressure time diagrams for IDC and IQsC: (a) electric charge is measured at each predefined pressure level; (b) a negative step is applied by fast pressure release.

In the calibration processes, from the electric charge q_k measurements corresponding to the n different predefined pressure levels P_k, the piezoelectric sensitivity d is defined by the angular coefficient of the line with null intercept, determined by means of least squares curve fitting [9], [10]:

$$d = \frac{\sum_{k=1}^{n} P_k \cdot q_k}{\sum_{k=1}^{n} P_k^2}. \quad (2)$$

The curve fitting is a key part of classifying the piezoelectric transducer for service life. For NATO, the transducer's sensitivity should not vary more than $\pm\ 2\ \%$ from the sensitivity determined in the previous calibration, and $\pm\ 10\ \%$ from the original calibration [9]. In addition, the linearity error, i.e., the maximum vertical distance between the measured charge and the curve fitting, relative to the maximum charge corresponding to the full scale q_Fs, shall not exceed $\pm\ 1\ \%$ [9], [10]. The linearity error can be determined using the following expression:

$$L = \frac{(q_k - d \cdot\ P_k)_\mathrm{max}}{q_\mathrm{Fs}}\ \%\,. \quad (3)$$

The indirect calibration of the transducers adopted by the three organizations is commonly performed by testing laboratories, thus reducing time and cost in this essential step for performing ballistics tests. Laboratories must comply not only with the requirements related to the normative bases but also with quality assurance, in the case of laboratories accredited according to ISO/IEC 17025:2017. In this way, for example, the accredited testing laboratory that wishes to calibrate piezoelectric transducers must meet the requirements related to the calibration activity.

As a matter of priority, the laboratory must ensure the traceability of the measurements performed in the calibration procedures, that is, it must have sufficient information regarding the calibration of all instruments related to the transient pressure measurement chain used in the process: reference transducer, charge amplifier, oscilloscope or A/D converter. Despite the lack of a transient pressure reference standard [1], the accredited laboratory must be able to establish the traceability of measurements to the International System of Units (SI) [7].

In addition to the calibration of the instruments employed, the laboratory must be able to determine the measurement uncertainties, both in the calibration procedures and in the measurements during the tests. The calculation of the measurement uncertainty should mainly consider the influence of the charge amplifier, especially in the calibration processes, in which the drift will have great relevance if the time constant τ is configured as long (quasi-static charge measurements) [23].

Commonly, the calibration of piezoelectric transducers used in ballistics tests can be carried out with the use of commercial equipment designed for such activity, such as the B630 Calibration Unit (HPI B630), manufactured by HPI GmbH, which employs the IQsC method, and the Model K9905D High Pressure Calibration System (TMS K9905D), developed by The Modal Shop, Inc., which uses the IDC method. The HPI B630 is equipped with a two-channel AVL B692 A01 charge amplifier, a hydraulic cylinder pressurized by means of a piston automated by a step motor and a reference piezoelectric transducer, and the calibration process is fully controlled by the HPI B3000 Ballistic Workframe software (version 2.44) [25].

In the TMS K9905D, the IDC is performed by manually pressurizing a hydraulic cylinder by means of the main four-wheel handles, with the reference calibration pressure determined by a Viatran 345EGSPW pressure transmitter and the dynamic event inserted into the process by manually opening a dump valve. The charge is measured by the single-channel PCB 443B102 charge amplifier [26].

Both systems are commercialized for the calibration of piezoelectric transducers, meeting the regulatory bases related to small-caliber ammunition. The possession of such equipment, together with the establishment of a calibration plan for the instruments included in the measurement chain, should not be a sufficient condition for quality assurance in the calibration processes. In addition, the laboratory needs to ensure that the technical staff has the competence to perform such activities, that is, has the capacity to perform the calibration activity with the necessary training and supervision for the correct execution according to the established methods [7], [27].

3. EVALUATION OF INDIRECT CALIBRATION METHODS

This section aims to present two calibrations of HPI GP6 transducers performed in different laboratories with IQsC and IDC methods. However, although these laboratories perform pressure tests for ammunition certification, it should be noted that they do not have the accreditation granted in Brazil by INMETRO/CGCRE.

3.1. Indirect Quasi-static Calibration (IQsC)

The HPI B630 equipment employs the IQsC method to perform the calibration of HPI GP6 transducers, using an HPI GP8 reference transducer, the latter with gallium phosphate sensing element and pressure measurement capacity of up to 800 MPa.

The HPI B3000 software previously performs a check of the drift present in the measurement chain by measuring the charge with the depressurized cylinder. According to the manufacturer, the drift related to the charge amplifier is less than 0.05 pC/s [25]. In the verification, it is indicated that the drift obtained in 2 s is less than 1 pC. If the value is higher, it is recommended to replace the cables connecting the transducer with the charge amplifier or even clean and dry the connectors [28].

From there, the system can start the calibration process, initiating the pressurization of the cylinder. The HPI B3000, from an estimate determined by the volume of the cylinder and the displacement of the piston performed by the step motor, determines the approximate pressure developing in the process. With this, it also verifies whether the pressure measured by the reference transducer is equivalent to the pressure estimated by the software. If there is no match, the software indicates failure in the process, which can be attributed to high drift, the presence of air bubbles in the system, or oil leakage. In the last two cases, the bleeding procedure should be performed according to the user manual [25].

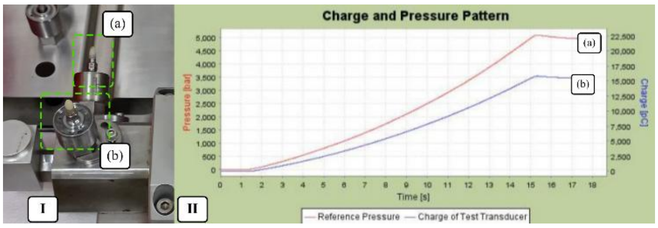

Figure 5. (I) Installation events of the two transducers on the hydraulic cylinder: (a) reference transducer and (b) transducer under calibration. (II) Pressure and charge chart at IQsC process: (a) pressure measured by the reference transducer and (b) electric charge measured by the transducer under calibration [25].

At the end of the calibration process, the software, from the pressure determined by the reference transducer, determines the sensitivity of the transducer being calibrated, its calibration table with the predetermined pressures and the electric charge measurements, the sensitivity determined by the angular coefficient of the curve fitting and the linearity error obtained. Figure 5 shows HPI B630, highlighting the installation events of the two transducers in the hydraulic cylinder, and illustrates the curves of pressure and electrical charge measurements generated in the IQsC process.

3.2. Indirect Dynamic Calibration (IDC)

For calibration with the use of TMS K9905D, illustrated in Figure 6, the IDC method is performed by means of manual pressurization of the hydraulic cylinder, that is, the operator must turn the wheel until the digital panel indicates the desired pressure for calibration. The reference pressure is measured by means of a Viatran 345EGSPW pressure transmitter. At the instant the pressure is obtained, the operator must quickly open the dump valve, characterizing a positive step, at the instant when the maximum electrical charge originated by the piezoelectric transducer in calibration is measured by the charge amplifier and the A/D converter.

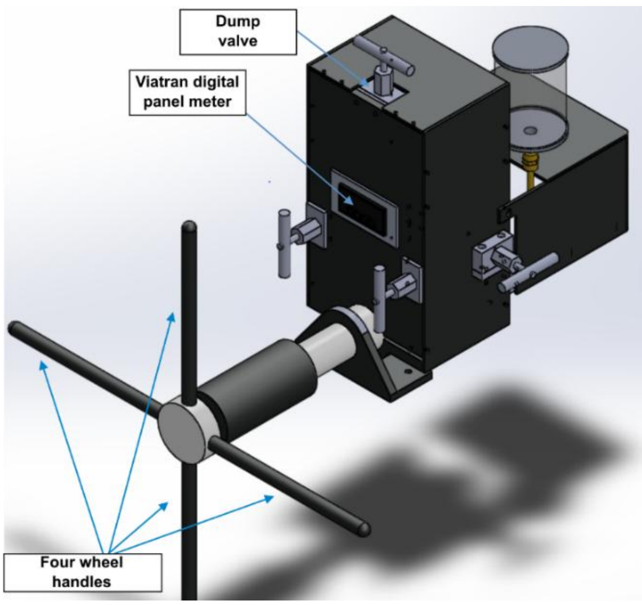

Figure 6. TMS K9905D calibration system [26].

Table 1: Transducers used in the evaluation of calibration methods.

	Model HPI GP6		
Serial number	6336	6795	6931
Original sensitivity	33.00 pC/MPa	33.84 pC/MPa	34.04 pC/MPa

In the case of the TMS K9905D, there is no fault-checking process in the calibration system. Thus, unless there is a procedure to check for such failures, the measurements of electric charge and pressure are subject to inaccuracies related to the possibility of high drift, air bubbles or leaks in the hydraulic system. According to the manufacturer, the drift related to the charge amplifier is less than $0.03\ \mathrm{pC/s}$ [24].

At the end of the procedure, the pressures and the corresponding maximum electrical charges are used to calculate the sensitivity, by means of the angular coefficient of the fitted curve, and the linearity error is determined.

4. RESULTS

The calibrations were performed with three different transducers using the two calibration methods previously described. Table 1 shows the serial numbers of the transducers used.

The results of the calibrations of the transducers using the IQsC and IDC methods allowed to determine not only the sensitivity, the deviation from the original sensitivity, and the linearity error necessary for the classification of the transducers regarding their lifetime, but also the uncertainty of the least squares curve fitting u_{fit} and the standard uncertainty of the calculated sensitivity u_{d}, which were determined according to the following expressions:

$$u_{\mathrm{fit}} = \frac{1}{n-1}\sqrt{\sum_{i=1}^{n}[P_i - P(q_i)]^2} \tag{4}$$

$$u_{\mathrm{d}} = \sqrt{\frac{{u_{\mathrm{fit}}}^2}{\sum_{i=1}^{n} q_i^2}}, \tag{5}$$

where n represents the number of measurements, P_i is the pressure corresponding to the level i, and the pressure $P(q_i)$ is calculated by means of the expression obtained by the curve fitting for the charge q_i.

Results for Indirect Dynamic Calibration (IDC)

Using the method described in section 3.2, the transducers were calibrated at 8 (eight) pressure levels, ranging from 50 MPa to 400 MPa, with two replicates at each pressure level. Table 2 and Table 3 present the results for each transducer by both calibration methods.

From the results obtained, it is clear that, according to the IDC method, since the linearity error obtained was higher than the limit determined by the normative base ($\pm 1\ \%$), the three calibrated transducers failed. It is also noted that the uncertainties of the curve fitting u_{fit} and of the sensitivity u_{d} present values higher than those obtained with the IQsC method.

Figure 7 shows the linearity errors calculated for each calibration point using the IQsC method.

The graph in Figure 8 shows the linearity errors obtained for each calibration point according to the IDC method. It is observed that for all transducers, there are at least 4 (four) points with linearity errors greater than ± 1 %.

Table 2: Results for calibration by IQsC.

Transducer	6336	6795	6931
Sensitivity	32.169 pC/MPa	33.727 pC/MPa	34.183 pC/MPa
Deviation from original sensitivity	2.52 %	0.33 %	0.42 %
Maximum linearity error	0.28 %	0.92 %	-0.69 %
Uncertainty of fit (u_{fit})	21.66 pC (0.11 %)	46.93 pC (0.23 %)	45.29 pC (0.22 %)
Standard uncertainty of sensitivity (u_d)	0.0176 pC/MPa	0.0382 pC/MPa	0.0378 pC/MPa

Table 3: Results for calibration by IDC.

Transducer	6336	6795	6931
Sensitivity	33.063 pC/MPa	33.888 pC/MPa	34.475 pC/MPa
Deviation from original sensitivity	0.19 %	0.14 %	1.28 %
Maximum linearity error	3.46 %	-3.20 %	5.13 %
Uncertainty of fit (u_{fit})	228.35 pC (1.15 %)	250.43 pC (1.23 %)	213.99 pC (1.03 %)
Standard uncertainty of sensitivity (u_d)	0.2261 pC/MPa	0.2473 pC/MPa	0.2113 pC/MPa

5. CONCLUSION

This study presented the evaluation of two distinct methods of calibration of piezoelectric transducers used in ballistics tests:

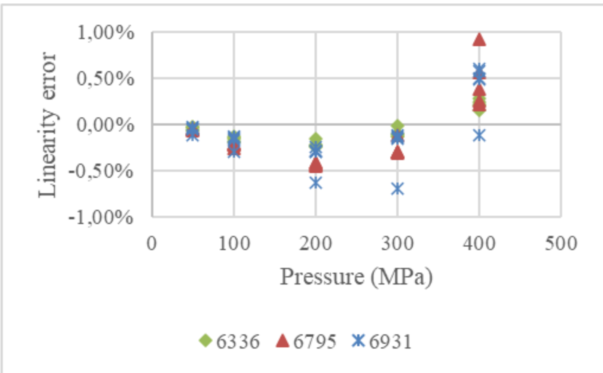

Figure 7. Linearity error for each pressure measurement in IQsC.

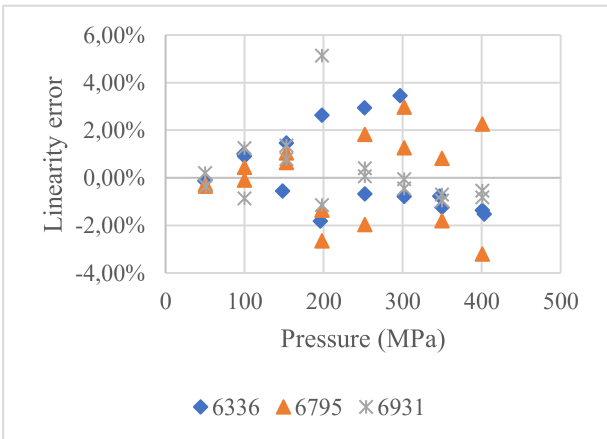

Figure 8. Linearity error for each pressure measurement in IDC.

the IQsC and the IDC. In both procedures, commercial equipment was used, the HPI B630 and the TMS K9905D, both intended for the indirect calibration of these transducers. In the process of conformity assessment of ammunition, the calibration of piezoelectric transducers is fundamental, since it will determine the sensitivity of the instrument, that is, the relationship of pressure with the electric charge measured, employing the transient pressure measurement chain, detailed in Figure 2.It also provides data necessary for the classification of the transducer according to lifetime, by means of the linearity error and the deviation from the original sensitivity.

In a superficial analysis, it is important to emphasize that the cause of the transducer's rejection should not be imputed to the method employed. As highlighted in section 3.2, the TMS K9905D equipment is not automated, but is run manually by the operator. In addition, there is no checking procedure for drift in the measuring chain and leakage or air bubbles in the hydraulic system. Probably, such aspects may be directly related to the greater uncertainty obtained with the IDC method compared to the IQsC method.

The IQsC method used in the HPI B630 has an automated drift and hydraulic system verification procedure, and pressurization is performed by a software-controlled motor, reducing the operator's influence on calibration. Although the latter presents smaller uncertainties, in this case, it is not possible to determine which procedure is correct. Since the equipment does not have the proper calibration, that is, within the deadlines determined by the respective manufacturers and by the normative basis of ballistics tests, it would not be possible to guarantee that any of the calibrations carried out could be adopted by a laboratory accredited by ISO/IEC 17025:2017.

Given the results, the main issue to be solved is reducing the risk of undue rejection of transducers or their inappropriate use in ballistics tests. The undue rejection can generate an increase in the costs of the laboratory, imposing the acquisition of new piezoelectric transducers. Improper approval may mean the use of a transducer with improper functioning, that is, with linearity error higher than the limit determined by the normative basis, or even the use of inadequate sensitivity, inserting a large portion of systematic error in the transient pressure measurements.

To reduce such risks, it would be useful to adopt transducer checking procedures. ISO/IEC 17025:2017 requires testing laboratories to check if it is "necessary to maintain confidence in the performance of the equipment" [27]. In the verification of charge amplifiers, it is possible to use standard signal generators as reference material [22].

For the piezoelectric transducers, as there is no transient pressure reference standard, the issue could be solved by comparing it with another measurement method accepted by NATO and the CIP. In this context, it can be suggested that the measurement of pressure is realized by means of copper crushers, a technique in which copper cylinders are used to determine the maximum pressure developed in the burning of the propelling charge of ammunition [3], [29]–[32]. The cylinders are compressed by a piston that moves as the internal pressure rises. From the final length of the copper cylinder, the maximum pressure is determined by conversion tables corresponding to the copper cylinder used. Simultaneous measurement by means of a copper crusher and piezoelectric transducers can be a way to verify the reliability of piezoelectric transducer calibrations. This possibility can be researched in future studies.

AUTHORS' CONTRIBUTION

Methodology: C.B.C.F. and C.R.H.B.; investigation: C.B.C.F., K.A.R.M., and C.R.H.B.; writing (original draft preparation): C.B.C.F.; writing (review and editing): C.B.C.F., K.A.R.M., and C.R.H.B.; supervision: K.A.R.M. and C.R.H.B. All authors have read and agreed to the published version of the manuscript.

ACKNOWLEDGEMENT

The authors thank the Brazilian funding agencies CNPq, FINEP and FAPERJ for the financial support provided. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Capes) - Finance Code 001. The CAEx (Centro de Avaliações do Exército) is sincerely thanked for their valuable support in the experiments and collaborations conducted during the production of this scientific article.

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