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DETERMINATION OF MEASUREMENT UNCERTAINTY SOURCES OF A PNEUMATIC SYSTEM OF CALIBRATION OF SHOCK ACCELEROMETERS

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Abstract*. Metrology has been considered an important part for quality control as well as in the processes of industrial and scientific products. However, the development of methodologies and commercial calibration systems might not meet the needs of metrologists who are in search of new measurement techniques and of the fully qualified domain of phenomena involving calibration in their laboratories. Manufacturers of commercial calibration systems use data for result generation in their certificates which can seldom be accessed by the user, creating doubts as to the applied methodologies used to calculate the measurement uncertainties that compose the system. The determination of measurement uncertainty sources in a pneumatic calibration system of shock accelerometers is the study object of this work. In order to know the pneumatic calibration system of shock accelerometer, and the measurement uncertainty sources during calibration, a calculation methodology has been created based on the ISO GUM Guide, the ISO 16063-22 standard and the results presented in the comparative table among the reported data generated by the system manufacturer. In conclusion, the result of the measurement uncertainty estimate for the set of data under study was changed from 1% to 2% in measurements of 20Hz to 2kHz and 3% to 2.7% for shock levels of 2kHz to 10kHz. These results showed to be more adapted and closer to the reality of the instrumentation used in the system, as well as to the environmental conditions of the calibration laboratory, once such data were extracted from previous calibration and technical manuals.*

Key-Words : Shock Transducer, Calibration, Measurement Uncertainty .

1. INTRODUCTION

Accelerometers are vibration transducers that convert a mechanical stimulus into an electrical signal. They are widely used in various fields, such as the automotive industry to drive Air Bags, control and monitoring of vibration in aircraft, spacecraft, missiles, electromechanical machines and even mobile phones as a position sensor. The calibration of this type of transducer is fundamental to the success of space missions, skills and the competitiveness of the industry at large (Ripper at al, 2008). The ISO 16063 family of standards establishes general criteria and procedures for the calibration of vibration and shock transducers. There are three methods to calibrate this type of transducer; the first primary calibration method is done with a laser interferometer or by the method of reciprocity, the second calibration method is accomplished by comparison to a reference transducer, also known as Back to Back method which is discussed in this paper, and the third method involves the use of vibrators with known vibration levels. Accelerometer calibration systems can be implemented using known dedicated instrumentation (PCB Inc.) or implemented shock generation techniques such as electromagnetic launchers (Timpson and Engel, 2012), which are usually used by the military area for the launching of bombs, and they can be an alternative to constructing a calibration system. We can also make use of the systems that are offered in the specialized market. The calibration method that uses comparison techniques has a transducer to be calibrated coupled to a reference transducer so that the same acceleration is generated on both devices and their output signals can be compared, thereby determining its sensitivity.

The shock pneumatic calibration system evaluated in this study (PCB Inc.), makes up the Air Force Metrology System Vibration Laboratory, the SISMETRA, leased in São José dos Campos-SP, in the Institute of Aeronautics and Space DCTA- Dep. of Science and Aerospace Technology. The SISMETRA was created in December 1988 in order to create a metrological hierarchy within the Brazilian Air Force. The Industrial Development Institute (IFI), responsible for the system management, has a structure of central, regional and industry laboratories where all system laboratories follow the ISO / IEC 17025 - General Requirements for the Competence of Testing Laboratories and Calibration and some of these laboratories are accredited by INMETRO. Figure 1 shows the system hierarchy.

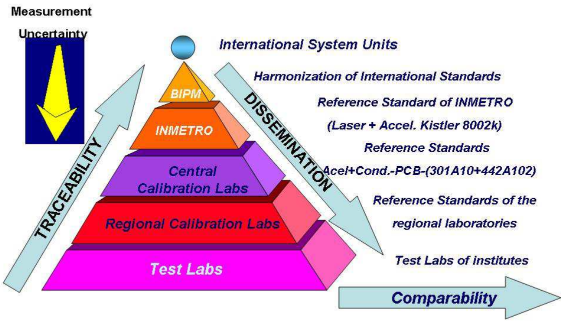

Figure 1 – Hierarchy of SISMETRA

This work aims to evaluate the sources of uncertainty generated by the shock calibration pneumatic system, and validate the methods of calculation using the Guide for Uncertainty Calculation ISO GUM measurement and to ISO 16063-22.

2. THEORETICAL FOUNDATION

2.1 Calibration by comparison

The accelerometer calibration is needed to set the transducer sensitivity, and other parameters such as operating limits, physical, electrical characteristics, and environmental influences that may be determined.

Under normal operating conditions, the piezoelectric transducer is extremely stable and its performance does not change with time. However, the sensor can be temporarily or permanently affected by environmental influences or other conditions of misuse that may affect the dynamics of the sensor response. Besides these influences, other factors such as excessive use, accuracy, previous calibrations of information and risks associated with incorrect measures should be considered to determine the calibration cycles. The ISO 10012-1 standard suggests some methods to determine these intervals.

Calibration by comparison with known back to back, is the most common method for determining the sensitivity of piezoelectric accelerometers; Figure 2 shows the mounting of accelerometers. Because both transducers are subject to the same input, this method determines the sensitivity of the accelerometer under test by comparison with the reference sensitivity of the accelerometer, expressed by the relation:

$$Ssut = Sref \bullet (Vsut / Vref) \quad (1)$$

Where: Ssut is sensitivity of Accel. under test (mV/g, mV/(m/s^2); pC/g, ou pC/(m/s^2))
Sref is sensitivity of reference Acel. (mV/g, mV/(m/s^2); pC/g, ou pC/(m/s^2))
Vsut is voltage of Accel. under teste (mV)
Vref is voltage of reference Accel. (mV)

Figure 2 - Back to Back setting

2.2 MAIN SOURCES OF UNCERTAINTY

2.2.1 Mass

The mass of the accelerometer is an important factor in measuring lighter systems of vibration as high masses may significantly change the dynamic behavior of the system. In addition, the mass of the piezoelectric accelerometer is inherently linked to the sensitivity of the same, the larger the mass, the greater the sensitivity. For this reason it is recommended using additional mass on the lower shock levels up to 100 g.

2.2.2 Dynamic range

The piezoelectric accelerometer is linear in operating range due to the performance of the piezoelectric elements. However, in practice, the lower limit of the operating range is determined by the noise present in the measurement system. The upper limit operation becomes nonlinear and determined by the structural behavior of the accelerometer. This accelerometer has a high resonance peak in its frequency response. The displacement between the base and the seismic mass of the sensor increases when the frequency of the applied force approaches the natural frequency of the accelerometer.

2.2.3 Fixing the accelerometer

The accelerometer must be fixed on the surface respecting its axis of maximum sensitivity. Depending on how the accelerometer is fixed, the frequency dynamic range is affected. Moreover, it can damage the sensor and provide misleading measures.

Among the most used fixtures are threaded pins (screws), the epoxy glue, adhesives, permanent magnet, among others.

2.2.4 Influence of environmental conditions

In the piezoelectric accelerometers, the biggest influence on the environmental conditions occurs due to the temperature, as piezoelectric materials lose their properties above a certain temperature, called "Curie temperature" (Endevco®), and present variation in the amount of charge generated due to the variation temperature.

2.2.5 Cables and connections

Cables and connections may introduce some errors in the vibration measures. One is a consequence of the mechanical vibration of the cable and its connections and is known as "Triboelectric effect" (Endevco®) as shown in Figure 3. To avoid this effect, in general, we can attach it to fixed surfaces, reducing the possibility of vibration. Another problem is that very long cables can cause attenuation in the measured signal, especially those of low intensity.

The measurement system grounding is necessary for the proper operation of electrical equipment. However, the grounds of the measuring equipment and equipment where the accelerometer is operating form a loop, thus generating small leakage currents.

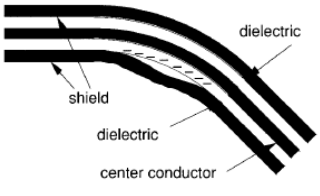

Figure 3 -"**Triboelectric** effect" generated in the coaxial cables

2.2.6 Relative motion

For obtaining the model described in equation (1), it was assumed that the acceleration on the accelerometer to be calibrated is the same as the one applied in the piezoelectric element of the standard accelerometer. At low frequencies, this consideration is valid for the accelerometer housing rigidity is relatively high, making the housing and the piezoelectric element contained inside the housing move up together. However, for higher frequencies, there is a relative movement between the frame of the accelerometer mounted in the reference surface and the piezoelectric element, making a correction necessary. This phenomenon depends directly on the carcass stiffness and mass of the transducer mounted on the standard.

2.2.7 Cross sensitivity

Uniaxial accelerometers are piezoelectric designed to have sensitivity in a single axis. However, due to problems such as uniformity of the piezoelectric material and the assembly of the accelerometer, the axis of maximum sensitivity can present certain displacement of the projected axis, thus generating the so-called "cross sensitivity", as illustrated in Figure 4.

Generally, manufacturers inform the maximum deviation of sensitivity to the mounting axis generated by the cross sensitivity, given in percentage and direction. This information is experimentally obtained after the fabrication of the accelerometer.

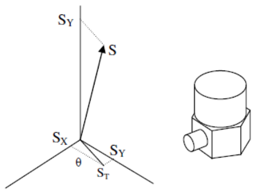

Figure 4 - Representation of Cross Sensitivity

2.2.8 Harmonic distortion

The accelerometers are fixed in relation to the reference surface. However, at high frequencies, vibrating movements may exist between the accelerometers and the reference surface, and between the standard and the unknown accelerometer, the roughness of the surfaces, the temperature variation and the applied torque, generating harmonic distortion on output waveform as shown in figure 5.

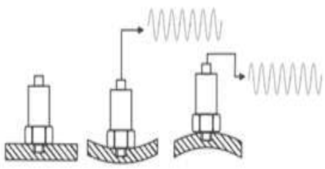
Figure 5 - Harmonic distortion

2.3 Estimation of measurement uncertainties

All calibration requires the specification of an estimate of measurement uncertainty, which must be associated with a certain level of coverage. The current rules require that the calculation of this uncertainty is made and expressed according to Guide to Measurement Uncertainty Expression (ISO GUM). Whereas all random variables involved in measurement are statistically independent, the square of the combined uncertainty concerning indirect measurements, obtained by divisions of non-correlated measurements are estimated by summing the squares of the standard uncertainties relating associated with each input variable, given by:

$$\left[\frac{u(X_1/X_2)}{X_1/X_2}\right]^2 = \left[\frac{u(X_1)}{X_1}\right]^2 + \left[\frac{u(X_2)}{X_2}\right]^2 \quad (2)$$

Or

$$u_R^2(X_1/X_2) = u_R^2(X_1) + u_R^2(X_2) \quad (3)$$

These expressions can be generalized to any number of divisions; then you can write:

$$u_R^2 = u_R^2(X_1) + u_R^2(X_2) + \cdots + u_R^2(X_n) \quad (4)$$

When non-correlated measurements of various input quantities are combined by a continuous and differentiable mathematical function, whatever it may be, it is possible to estimate the uncertainty of the combination by a general expression, given by:

$$G = f(X_1, X_2, \cdots, X_n) \quad (5)$$

Where: G = quantity to be determined by indirect measurement;
f = continuous and differentiable mathematical function;
X_n = nth input quantity that is being combined.

The combined uncertainty of G magnitude can be estimated by:

$$u^2(G) = \left(\frac{\partial f}{\partial X_1} u(X_1)\right)^2 + \left(\frac{\partial f}{\partial X_2} u(X_2)\right)^2 + \cdots + \left(\frac{\partial f}{\partial X_n} u(X_n)\right) \quad (6)$$

Where: $u^2(G)$ is the square of the combined uncertainty of the magnitude to be determined by indirect measurement;
f is the continuous mathematical function that relates G derivable with the input quantities;
$\left(\frac{\partial f}{\partial Xn}\right)$ is the partial derivative of the function f with respect to Xn input variable, also called sensitivity coefficient associated with Xn input variable;
$u(X_n)$ is the standard uncertainty of the input variable umpteenth that is being combined.

The degree of freedom ν_{ef}, can be obtained from Welch-Satterthwaite equation given by:

$$\frac{u_c^4}{\nu_{ef}} = \frac{u_1^4}{\nu_1} + \frac{u_2^4}{\nu_2} + \ldots + \frac{u_n^4}{\nu_n} \quad (7)$$

where: u_n is the relative standard uncertainty of the umpteenth source of uncertainty and ν_n is the number of degrees of freedom of the umpteenth source of uncertainty. The expanded uncertainty is calculated based on the combined uncertainty from the equation:

$$U = u_c * t \quad (8)$$

Where: U is the expanded uncertainty; t is the Student factor corresponding to the actual number of degrees of freedom and confidence of 95.45%.

After identifying the major sources of uncertainty, the value of each one of them could be extracted through tests and consultations with the manufacturer's manuals and consultations with their respective calibration certificates.

3. CALIBRATION SYSTEM DESCRIPTION

The studied calibration system is based on the specifications of ISO 16063-22 standard "Methods for the calibration of vibration and shock transducer". Figure 6 shows the system containing a projectile driven by pneumatic valves, one of the transducers comparison system (back to back) and an acquisition system and signal conditioning. Both transducers are mounted on a base where the reference transducer is coupled. The control panel provides buttons that are used to regulate and adjust the pressure valve that sets the amplitude and duration of the generated pulse, and fires a projectile generating pre-established level of shock. Table 1 sets out the relationship between the pulse duration, type of the base sleeve and the drive pressure for each shock level. The data acquisition system collects data from the transducers generating the measurement results according to Table 2.

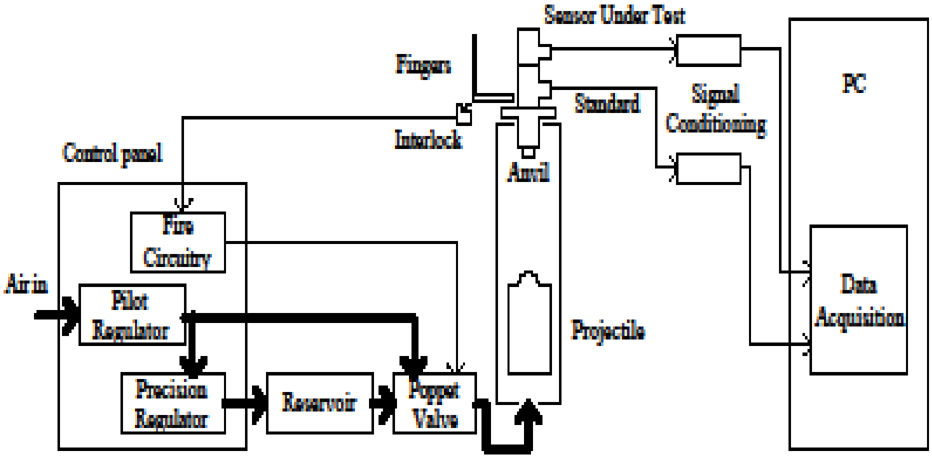

Figure 6 - shock pneumatic system

Table 1. Guidelines for choosing anvils and padding

Shock(g)	Pulse (ms)	Base (Anvil)	Padding	Pressure do Drive (psi)
20-50	3	Inox	1/4 Rubber	15-25
50-300	1.5	Inox	1/4 Rubber	20-30
100-500	1	Inox	1/8 Rubber	20-35
200-1,5k	0.5	Inox	1/8 Felt	20-35
500-2k	0.5	Aluminum	1/8 Rubber	20-40
1k-10k	0.1	Aluminum	1/8 Felt	20-40

4. RESULTS

Figure 7 shows the result of an average of three shock pulses generated by the calibration system, with intensities of approximately 5000 g and pulse duration 0.25ms, as shown on Table 2. The graph is generated from the calibration system software, where the transducer under test is represented by the graph blue curve and the reference transducer is defined by the color red. The results of Table 2 show good repeatability of the measurements, making the percentage of the standard deviation of the measurements stay below 0.1%, and keeping the level of uncertainty in the measurement low, showing that the system complies with the technical specifications of the manufacturer.

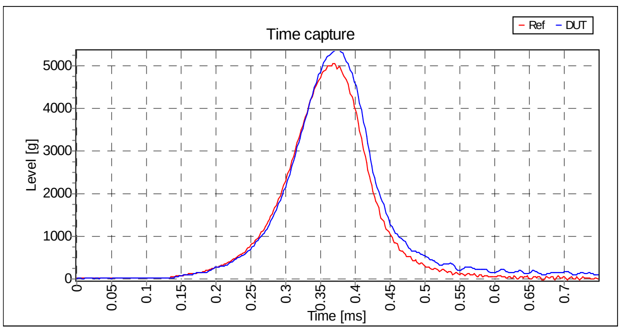

Figure 7 - the calibration system response curve.

Reference level = 5030.54 g

Table 2 - Accelerometer Calibration Results under test

Generated Value [g]	**Measurements [g]**	**Sensitivity [pC/g]**	**Tendency [%]**	**Duration [ms]**	**Z.Sh. [%]**	**$U_{95\%}$ [%]**

5000	4965.86	3.115	-0.17	0.252	2.246	3
5000	4995.71	3.121	0.04	0.248	2.228	3
5000	5030.54	3.124	0.13	0.25	2.242	3

In order to study the methodology used by the system manufacturer of the calculations for determining the measurement uncertainty sources Table 3 was created. This table displays a comparison with three numerical sets. The first set consists of the calculation spreadsheet calibration system, the second set was defined with information and examples described in ISO 16063-22 standard, and the third number set, aim of this study, was taken from technical manuals, calibration data and manufacturer`s data, in order to adjust the values to the reality of the Laboratory. It can be seen that the uncertainty of the results of the three sets differ from each other, because this different information comprising one source of uncertainty. An important source of uncertainty, the uncertainty related to measurements, which is the average standard deviation, was considered only in the third set of data. However, we can see that its contribution is small, since the measurements have a repetitive behavior.

Table 3 - Results of measurement uncertainty calculations for pneumatic calibration system accelerometers.

			1st Set		2nd Set		3rd Set	
			System 9525C		Example of standart		Studied	
			20-2kg urel,i (y) [%]	2k-10kg urel,i (y) [%]	20-2kg urel,i (y) [%]	2k-10kg urel,i (y) [%]	20-2kg urel,i (y) [%]	2k-10kg urel,i (y) [%]
Reference	Description							
1	Calibration of Certificate	Normal (k= 2)	0.250	1.300	0.500	0.500	0.950	1.300
2	Uncertainty Type A						0.100	0.100
3	Relative Motion	Rectangular	0.026	0.491	0.250	0.500	0.000	0.000
4	Transverse Accel. POP+DUT+301A12	Esp. raiz(1/18)	0.042	0.127	0.150	0.300	0.115	0.035
5	Temperature 23 +/- 3 ºC	Rectangular	0.228	0.228	0.500	0.500	0.214	0.214
6	Drift (1 year)	Rectangular	0.119	0.119	0.100	0.100	0.119	0.119
7	Influence of Gravity (SHEAR)	Rectangular	0.000	0.000	0.000	0.000	0.000	0.000
8	Non-linearity of the reference transducer	Rectangular	0.115	0.058	0.050	0.250	0.058	0.058
DUT								
9	Mounting parameters of the DUT	Rectangular	0.194	0.245	0.200	0.200	0.193	0.193
10	Mounting base deformation	Rectangular	0.029	0.029	0.200	0.200	0.029	0.029
Conditioner								
11	DUT e Ref. (Charge)Amplifier	Normal (k = 2)	0.058	0.058	0.200	0.200	0.000	0.000
12	Ratio between 2 inputs (pulse)	Normal (k = 2)	0.057	0.057	0.200	0.200	0.039	0.039
13	Distortion acceleration (shock =0)	Rectangular	0.000	0.000	0.000	0.000	0.000	0.000
14	Non-linearity of the amplifier	Rectangular	0.098	0.098	0.100	0.100	0.098	0.098
15	Temperature	Rectangular	0.058	0.058	0.200	0.200	0.058	0.058
Algorithm								
16	algorithm Influence	Normal (k = 2)	0.144	0.312	0.200	0.540	NA	NA
17	Residual Effects- Noise(Cables)	Rectangular	0.017	0.017	0.100	0.200	0.017	0.017
		Uc K=1	0.47	1.48	0.93	1.21	1.02	1.34
		U95% K=2	0.95	2.96	1.85	2.41	2.04	2.70

5. CONCLUSION

In this study, a comparison of three methods for determining the measurement uncertainty sources inserted in a pneumatic shock calibration system was shown. It is possible to see through the results, a not very significant difference between the expanded uncertainties of the three sets, which happened due to the different values for the same source of measurement uncertainty. The calculation of the studied group differs from the others when it adds uncertainty concerning the average of the measurements, and disregards the influence of the calculation algorithm (item 16 of the table), as this source requires a more detailed study as the methodology to calculate the sensitivity of the accelerometer is not informed.

Data from the standard accelerometer calibration certificate are the source of uncertainty that most contributes to increase in values in the calculating of the expanded uncertainty, followed by the contribution of the assembly of the transducers and environmental conditions.

The end result of the measurement uncertainty estimate for the data set under study was changed from 1% (generated by the system) to 2% for measurements from 20 to 2000 g and 3% (generated by the system) to 2.7% for Shock levels of 2000g to 10000g. These results showed to be more adapted and real, approaching the instrumentation reality used in the system as well as the environmental conditions of the calibration laboratory, since they are data extracted from previous calibrations, technical manuals and knowledge of what was being measured. The final sensitivity of the calibration of the sensor under test is: (3.12 +/- 0.084) pC / g or according to the international system of units SI (0.318 +/- 0.008) pC / ms^2 for a coverage factor of 95.45 %.

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