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DYNAMIC CALIBRATION OF PRESSURE TRANSDUCERS EMPLOYED IN THE AEROSPACE SECTOR – A LITERATURE SURVEY

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Abstract. *This paper presents an overview and current trends concerning dynamic calibration. The research methodology is a literature survey that highlights relevant aspects related to dynamic calibration of pressure transducers. Pressure measurement in non-equilibrium conditions, where the pressure signal varies over time, has applications in many areas, including the aerospace field, which is the authors' area of interest. The study shows the main methods in use nowadays, their advantages, shortcomings and possibilities. The paper also discusses the characterization of the transducers and possible methods for evaluating and expressing the uncertainty in measurement. One of the main problems is the lack of a well-established metrological method to assess the precision of the measurement data. Furthermore, the quantification of the uncertainty is a difficult task due to the lack of traceable dynamic pressure calibration methods. It was observed that shock tubes can be employed as a generator of a-periodic input signals and that the Monte Carlo simulation is appropriate for the estimation of calibration uncertainty.*

Keywords: *dynamic calibration, shock tube, dynamic pressure transducer, uncertainty in measurement.*

1. INTRODUCTION

Sensors, transducers and pressure transmitters are employed in several areas such as: automotive, nuclear, aerospace, robotics, medicine, ballistics, oil and gas and others, whose production processes require accurate monitoring of pressure standards (Hjelmgren, 2002). The development of the aerospace industry has brought the need for the accurate knowledge of each component of a technological product. In this aspect, there is a lack regarding the metrological qualification of pressure sensors and transducers which are to be employed in dynamic conditions. Pressure is said to be dynamic when it varies significantly over a short period of time. An example of aerospace application is the Satellite Launch Vehicle, VLS-1 which uses around 40 transducers in several locations on its outer structure for monitoring the pressure of the surrounding airflow during flight (figure 1).

Figure 1. Example of dynamic measurement. The VLS employs around 40 pressure sensors during flight.
Source: http://www.iae.cta.br

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The technological complexity, inherent risk and high cost of aerospace tests, demand the search for more reliable parameters, traceability of instruments and standardization of metrological procedures for the measurement of physical quantities which vary quickly over time. In this sense, the necessity of understanding the dynamic behavior of a pressure transducer is fundamental for the success of an aerospace mission. For this reason, besides the estimation of a quantity value, it is important to describe faithfully the temporal behavior of that quantity (Diniz, 2003).

Due to the need to accurately determine the response time of a pressure transducer, researchers of the Institute of Aeronautics and Space, IAE, have proposed a study to develop a framework for dynamic calibration of pressure sensors and the evaluation of the associated uncertainty. This paper deals with the first part of the study, which is a literature survey. The bibliographic review highlights relevant aspects related to the characteristics of pressure transducers involved in aerospace applications, points out the existing calibration procedures in dynamic conditions and the methods used for the estimation of the uncertainty in the measurement, which is considered today to be one of the main challenges in this field.

Therefore, in this paper we seek to present the methods employed nowadays in metrological research centers for the calibration of pressure transducers. The aerospace area is emphasized, where shock tubes are cited as suitable laboratory facilities for this kind of calibration, due to the generation of high frequencies and fast changing signals, which are within the operating range of these transducers. Another aim is to present the Monte Carlo simulation as a possible method for the quantification of uncertainties associated to the dynamic calibration, in face of the restrictions of the traditional law of propagation of uncertainty approach (JCGM, 2011 and ISO/GUM, 1998).

In this preliminary work the authors expect to analyze the methods developed so far. Next, through research, the authors intend to supply metrological reliability in dynamic calibration of pressure transducers to the national aerospace area.

2. APPLICATION OF PRESSURE TRANSDUCERS IN THE AEROSPACE AREA

Several examples of pressure measurements that are performed with the intention to capture dynamic phenomena can be found in Hjelmgren, 2002. The list of applications includes combustion engines, turbo-machinery, aerodynamics, acoustics, production processes, robotics, medicine, ergonomics, blast waves, ballistics, etc. He highlights that “the lack of traceability for dynamic pressure measurements in industry results in less than-optimal measurement quality leading to increased costs in terms of reduced quality, increased scrapping and reduced competitiveness”.

In his doctoral thesis, the author Eichstädt (2012) proposes a framework for the evaluation of uncertainty in dynamic measurements. He reinforces that despite the growing importance for industry and metrology, the traceability of dynamic calibration is still not properly addressed. An interesting point is cited in this reference, which is that “the World Trade Organization, WTO, has recognized that the international comparability in measurement is a significant barrier to trade” and that comparability starts with traceability.

Many applications of dynamic pressure transducers are mentioned by Sprovieri (2010), such as:

- Hydrostatic testing in engine envelopes aiming to check for structural leaks;
- Rocket motor burning bench test to evaluate parameters such as the propellant burning rate;
- Evaluation and reevaluation of in-flight performance parameters;
- Rolling control system(s) where the pressure sensor can identify a rolling motion of the vehicle and trigger an action to eliminate the undesirable rotation;
- Cold gas system(s) in which, similarly to the rolling motion control system(s), a small thrust is generated by the release of nitrogen, thus controlling the rotation in subsequent stages of the rocket.

For Damião (2010), the use of robust and calibrated pressure sensors is crucial in hypersonic propulsion tests and experiments carried out in shock tubes and shock tunnels, as is the case of the Direct Energy Air Spike, DEAS, a high-energy flow experiment. Follador (2005), reports that these experiments reveal the airflow changings around a model under test by applying a laser pulse against the air upstream of the model. Salvador (2006) also reports the application of piezoelectric pressure transducers to measure the transit time of the incident shock wave in a DEAS test in hypersonic shock tubes.

3. CONSIDERATIONS ABOUT DYNAMIC CALIBRATION OF PRESSURE TRANSDUCERS

According to the *Guia de Calibração de Transdutores de Pressão* (INMETRO, 2010), pressure can be considered as the result of the effect of the impact force of the molecules of a fluid, liquid or gas, on the walls of a container in which the fluid is contained. Anderson (2001) defines pressure as the normal force per unit area exerted on a surface due to the time rate of change of momentum of the gas molecules impacting on that surface. If we consider a point in a volume of gas, the pressure p at this point is defined according to eq. (1):

$$p = \lim_{dA \to 0}\left(\frac{dF}{dA}\right) \tag{1}$$

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where *dA* is an incremental area around the point, *dF* is the force on one side of *dA* due to pressure.

Equation 1 states that the pressure *p* is the limiting form of the force per unit area where the area of interest has shrunk to zero around the point.

In the case of a moving stream, three different pressures can be measured: static pressure, which is a consequence of just the purely random motion of the molecules, dynamic pressure, which is the pressure equivalent to the direct kinetic energy of the flow, and stagnation pressure, which is the pressure where the stream is decelerated to zero velocity. The unit of pressure in the International System of Units is the pascal (Pa), but other units are also used such as bar, equal to 10^5 Pa, pound-force per square inch, psi, equal to 6894.76… Pa, millimeter of mercury, equal to 133,322... Pa, etc. (INMETRO, 2010). The most common units used for pressure measurements in space applications, besides the pascal, are bar and psi (Sprovieri, 2010).

As stated by White (2002), the pressure measuring instruments can be classified according to the following categories:

– Based on gravity: barometers, manometers and dead weight piston;

– Elastic deformation: Bourbon tube, diaphragm, extensometer (strain-gage);

– Behavior of gases: gas compression (McLeod), thermal conductance (Pirani), molecular impact (Knudsen) ionization, thermal conductivity;

– Electrical Output: resistance (Bridgman), extensometer diffuse, capacitive, piezoelectric, resonant frequency.

It is worth mentioning that this study emphasizes pressure measuring instruments with electrical output, specifically piezoelectric and piezoresistive sensors, due to their importance for the aerospace industry.

Regarding terminology, some questions arise when dealing with sensors, transmitters and transducers. The International Vocabulary of Metrology, VIM, (JCGM 200, 2012), defines a transducer as a measuring device that provides an output quantity, which has a specific relation to the input quantity. The same vocabulary defines a sensor as an element of a measuring system that is affected by a phenomenon, body or substance carrying a quantity to be measured. In the definition proposed by Albertazzi (2008), the transducer, as well as the sensor, is a part of a measuring system generating a measurement signal generally proportional to the value of the measurand. The definition of transmitters is not mentioned in VIM, however, transducers and transmitters have equivalent definitions according to the Guide for Calibration Transducer / Pressure Transmitter (INMETRO, 2010). For pressure devices related to this article the adopted terminology for transducer is that as stated by JCGM 200, 2012.

There is a wide variety of pressure measuring instruments, designed for several purposes. They are designed to operate in static and dynamic conditions and in different amplitude and frequency ranges. Depending on the intended application, the amplitude regime is in the low vacuum, vacuum, medium pressure or high pressure. The demand in frequency in medicine for blood pressure measurements is up to 20 Hz and in ballistics the frequency content can reach some several hundred kHz (Hjelmgren, 2002). The transducers for aerospace application, the object of this study, are basically piezoelectric-type and piezoresistive-type which can be used to measure pressures up to 15 MPa, as is the case for combustion tests (Sprovieri, 2010).

Some applications of pressure transducers require only static calibration, since they will be used to measure a time-invariant value of pressure. If pressure is time-dependent, it is said to be dynamic because it varies significantly over a short period of time demanding a dynamic calibration. The dynamic pressure can be defined as the change in the signal value in the order of 63.2% of the original size in less than one second of time interval (Diniz et al, 2003). Many instruments are calibrated under static conditions but are employed in dynamic measurements, in part due to the lack of standard calibration procedures, methods for assessment of uncertainty in measurement and metrological traceability through calibration of other measurement standards, measuring instruments, or measuring systems.

According to Sprovieri (2010) static calibration of pressure transducers have established procedures. It is carried out primarily by the use of deadweight testers and there is an extension of published guides and documents for standardization. In such cases the qualification of sensors is well defined, their static characteristics are known and the uncertainties of measurement are estimated according to the conventional approach recommended by the ISO/GUM (1998). Therefore, regarding static calibration, the improvement of its processes is the only thing required in order to make them more efficient (Albertazzi, 2008).

Literature shows that the first reports on dynamic calibration took place in the sixties (Coulter, 1967). Afterwards, a guide for the dynamic calibration of sensors was published (ANSI B88. 1-1972) which was reprinted by the Instrumentation, Systems and Automation Society, ISA (2002), describing the methods for the calibration of pressure transducers. However, there is still no standardization of procedures for dynamic calibration. The estimation of associated uncertainties is presented as a major barrier in this area (Santos, 2012).

According to Diniz, *et al*. (2003), one of the major challenges for dynamic calibration of pressure transducers is to be able to determine the pressure value for different frequencies with a high level of confidence in the measurement. Currently, what we have are different methods and means of calibration for each operating frequency range, which makes the process time consuming and moreover costly. In other words, there is a lack of versatility in the methods of dynamic calibration because one calibration method employed for low frequency signals could hardly be used in devices that work on higher frequencies, *i.e.* for each type of transducer, the calibration process is dynamically different, increasing time and cost.

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Diniz *et al* (2003) emphasize the research growth on dynamic calibration in the Dynamics Metrology Laboratory (LMD) of the Brasilia University (UNB), resulting from the cooperation with the *Laboratoire National de Métrologie et d'Essais* (LNE), Paris, a leading laboratory in this area. These two research centers have developed different generators and work together to supply traceability to an extended range of amplitude and frequency. The ranges cover much of the spectrum of industrial operation, however, they still do not meet the needs of aerospace applications.

Particular aspects of the methods and means used in dynamic calibration of pressure transducers, evaluation of associated uncertainties by employing the Monte Carlo method will be shown in the following sections.

3.1 Method and means in dynamic calibration of pressure transducers

A sensor may be dynamically characterized in two ways: the harmonic and the transient approaches, Damion (2006). The first requires periodic pressure generators which supply periodic signal such as sine-wave functions, whose magnitude variation is repeated at regular time intervals. The latter generates aperiodic pressures. Mathematically, this function could be obtained by generating an impulse signal at the input of the sensor. Experimentally, this would be done by applying a pressure pulse which would be a good approximation of the impulse signal. In both cases it is possible to obtain the transfer function, which fully describes and quantifies the sensor.

An input signal or stimulus provides a response signal or output. According to Diniz et al (2003), a possible way of exciting transducers would be by applying a sinusoidal periodic pressure signal. For this type of excitation it is necessary to obtain the permanent response of the sensor in a series of frequencies in order to find the frequency response to the sinusoidal input. This makes the test time-consuming. The main periodic generators are those of cavity which operate in resonant or non-resonant modes. Another periodic generator is the liquid column type whose liquid is accelerated by a signal from an accelerometer used as a reference. The liquid column generator can be used to calibrate sensors, especially up to 35 mbar, in a working range between 40 Hz and 1900 Hz.

The second form of transducer excitation is via an aperiodic signal. To produce this type of signal, which works in the time domain, the most commonly used methods are the shock tube, the quick-opening device and the closed pump. The first two are used at frequencies up to 100 Hz and 400 Hz respectively and the closed pump is used for the low and medium frequencies, as shown in Figure 2a and 2b (Diniz et al, 2003).

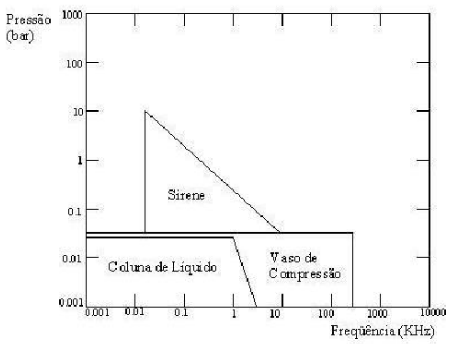

Figure 2a. Amplitude and frequency domain of periodic generators. Source: Diniz, *et al*, (2003).

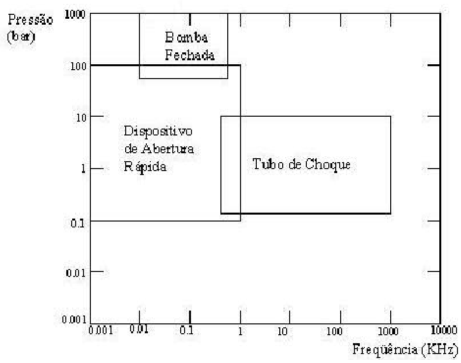

Figure 2b. Amplitude and frequency domain of aperiodic generators. Source: Diniz, *et al*, (2003).

As noted in Figure 2b, and presented in literature (Damion, 2006), the shock tube is the most suitable method of dynamic pressure generation when required to simultaneously deal with high frequencies and amplitudes, as is the case for testing and calibration of pressure sensors for space application. So far literature has not presented a standard methodology for implementing this type of calibration. However, some tests have been conducted, such as Damian (2010), who used the shock tube device to calibrate a PCB brand sensor for carrying out experiments in hypersonic propulsion. Other applications of the shock tube in the dynamic calibration may be found in Damion (2006), Diniz et al (2003) and Leódido (2009), amongst others.

According to Liepman and Roshko (1957) the shock tube device consists of two pressure chambers separated by a diaphragm. The first chamber, known as driver, is separated from the rear pipe, which is called driven, through a diaphragm which permits one to maintain different pressures in each chamber of the tube, as shown in figure 3a.

The diaphragm can be suddenly ruptured due to the initial pressure of the driver tube. A shock wave (incident) is generated and propagates through the region of the driven tube (region 1in figure 3). Behind the shock wave, the pressure abruptly rises to a new value, resulting in a positive pressure step. At the same time, an expansion wave propagates on the opposite side, and after that, several other expansion waves are formed, giving rise to an expansion fan, as show in region 4 of figure 3b. A contact surface is settled down in the driven, where the pressure and velocity are equal on both sides of the surface. The shock and expansion waves are reflected when they reach the end of the

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respective reservoirs. When the incident shock wave is reflected, it returns towards the contact surface and is reflected again, represented in region 5.

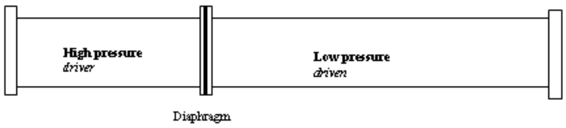

Figure 3a: Schematic diagram of the shock tube.
Source: Matthews, *et al* (2011). Adapted.

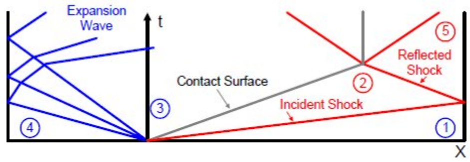

Figure 3b. Shock waves in the tube.
Source: Follador (2005).

The generated pressure step at the driven section of the shock tube can be employed as an input signal to calibrate pressure sensors, at known pressure and frequency ranges. Several parameters must be measured to calculate the step pressure amplitude. In shock tubes, the shock wave propagates at a speed relative to a coordinate system. The shock wave velocity is estimated from the measurement of two sensors “p1” e “p2” located at the bottom of the *driven* region. A third sensor, “p3”, is positioned downstream to measure the stagnation pressure P_0. The transducer “p4” to be calibrated is positioned at the end of the tube, as shown in Figure 4.

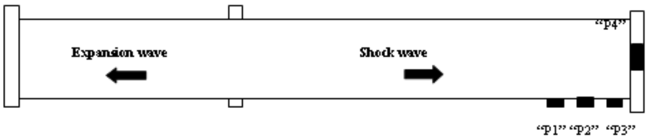

Figure 4. Shock wave generated after the rupture of the diaphragm and positioning of sensors in the shock tube.
Source: Matthews, *et al* (2011). Adapted.

In the shock tube, the input signal of the system is a step pressure. The amplitude of the step (ΔP) is estimated from the measurement of the initial pressure, P_1 and temperature T_1 in the driven section of the shock tube, and shock wave velocity V_s, (ISA, 2002):

$$\Delta P = \frac{7}{3} P_1 \left[\left(M_s^2 - 1 \right) \left(\frac{2 + 4M_s^2}{5 + M_s^2} \right) \right] \qquad (2a)$$

where M_s is expressed by:

$$M_s = \left(\frac{V_s}{344.5} \right) \sqrt{\left(\frac{298}{273 + T_1} \right)} \qquad (2b)$$

Eqs. (2a) and (b) are valid when the fluid in the tube is air.

Figure 5 shows the calibration experiment of 21 PCB brand piezoelectric pressure sensors. The laboratory facility is the shock tube T1 of the Aerothermodynamics and Hypersonics Laboratory “Professor Henry T. Nagamatsu” of the *Instituto de Estudos Avançados*, IEAv, in São José dos Campos. The sensors to be calibrated are mounted at the end of the shock tube and connected to a data acquisition system (Damião, 2010).

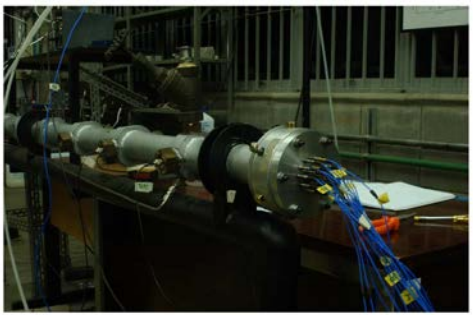

Figure 5: Pressures sensors under calibration, connected at the end of the shock tube T1. Source: Damião (2010).

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3.2 Uncertainties in Dynamic Calibration and the Monte Carlo Method

According to ISA standard 37.16.01 (2002), there are properties of transducers that are general either for static or dynamic calibration. Other properties are specific to dynamic pressure measurements. Each property is an error source and contributes to the uncertainty in measurement, along with other sources already known as those related to the resolution of the measuring instrument, hysteresis, linearity, temperature change, etc.

The characterization of a transducer is performed by basically measuring the following properties:

− Sensitivity: this property measures the ratio of the change in transducer output to a change in the value of the measured quantity;
− Amplitude response: amplitude of the transfer function versus frequency, often called the frequency response;
− Phase Response: phase of the transfer function versus frequency;
− Resonance frequency: the frequency at which the transducer responds with the maximum output amplitude;
− Ringing frequency: number of oscillations per unit of time. The frequency of free oscillations in the transducer output results from a changing in the input signal. Figure 6 shows a stabilized frequency different from the initial frequency;
− Damping ratio: damping coefficient of the wave excitation of the transducer;
− Rise Time: the time required for the output of a transducer to rise from 10% of its initial value to 90% of the final value;
− Overshoot: the amount that the output exceeds the final steady output value. In Figure 6, this property can be observed at the first peak of the wave.

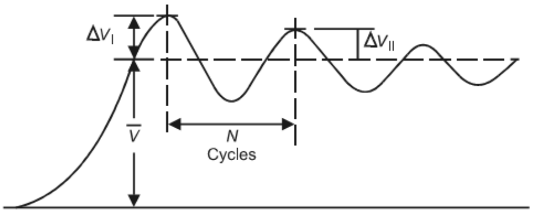

Figure 6: Measured properties of a pressure transducer. Source: ISA 37.16.01 (2002).

Each of the above mentioned properties will produce an effect that will have a direct influence on the transducer calibration. Proakis and Manolakis (1996) describe the transfer functions and mathematical models for each property of the transducers for treatment and analysis of these signals.

A mathematical model which describes most of the pressure transducers is provided by second order differential equation, represented by a system consisting of a mass, *m*, spring constant, *k*, and damping, *c* (Hjelmgren, 2002 and ISA, 2002). The governing differential equation for this transducer model is represented below:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F(t) \tag{3}$$

where $F(t)$ is the external load caused by the acting pressure.

This equation can be written as:

$$\ddot{x}(t) + 2\zeta\omega_0\dot{x}(t) + \omega_0^2 x(t) = \frac{F(t)}{m} \tag{4}$$

where ω_0 is the undamped natural frequency natural and ζ is the relative damping defined by:

$$\omega_0 = \sqrt{\frac{k}{m}} \quad , \quad \zeta = \frac{c}{2m\omega_0} \tag{5}$$

In studies of dynamic responses of linear measuring systems, the Laplace Transform is used to derive the transfer function. The Laplace transfer function is defined as the ratio of the Laplace Transform of the output q_o to the Laplace Transform of the input q_i. The transfer function of Equation (4) is:

$$\frac{q_o}{q_i}(s) = \frac{K\omega_0^2}{s^2 + 2\zeta\omega_0 s + \omega_0^2} \tag{6}$$

where:

$q_o(s)$ is the Laplace Transform of the output;

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$q_i(s)$ is the Laplace Transform of the input;
K is the sensibility in steady-state regime;
ω_0 is the system's natural frequency in radians/second (Eq. 5);
s is a complex variable = $i2\pi f$
ζ is the damping ratio, damping ratio between real and critical damping given by Eq. (5).

Due to the difficulty in measuring the various parameters related to dynamic measurements, and assessing all sources of uncertainty related to this process, a reasonable proposal would be to apply the method of Monte Carlo simulation for analyzes of uncertainty, as proposed by Matthews et al (2011) and Eichstädt (2012).

As Supplement JCGM (2008), to the ISO/GUM (1998), calls attention to different approaches to evaluate uncertainties. The ISO/GUM describes the law of propagation of uncertainties based on the Gaussian distribution with the goal of providing a confidence interval for the mean measured result. The JCGM is concerned with the propagation of probability distributions functions, PDFs, through a measurement model, by employing the Monte Carlo method.

According to INMETRO, the statement of measurement uncertainty through the ISO/GUM is quite safe and complete, but when the uncertainty is large or asymmetric or when the correlations between the different measurements are difficult to characterize, analytical methods might not be adequate. In these cases, a numerical simulation can be employed, among which is the Monte Carlo method.

For Fernandes (2005), the basic principle of the application of Monte Carlo method consists in establishing a probability distribution function (PDF) model, which responds to a random variable, and taking a sample of that random variable at a sufficiently large number of times, which corresponds to carrying out interactions.

According to Piratelli Filho (2010) and JCGM (2008), the evaluation of uncertainty using the Monte Carlo method is accomplished by the following steps:

− Define the output quantity Y, the measurand;
− Determine the input quantities X_i, $i = 1,\ldots, n$, upon which Y depends;
− Establish a mathematical model for the measurand Y as a function of the input quantities X_i;
− Assign probability distribution functions (Gaussian, rectangular, triangular, etc.), to the input quantities;
− Propagate the probability distribution functions through the model to obtain the probability distribution function for Y.

Use the Monte Carlo method to accomplish the last stage. The number of Monte Carlo interactions must be chosen (for example, 10^6 trials). After performing these steps, one can use the PDF for Y to obtain the estimate of the expectation of the measured quantity, its associated uncertainty and a coverage interval with a specified probability.

For Jornada (2007), the advantages of the Monte Carlo method over the conventional approach proposed by the ISO/GUM for evaluating the measurement uncertainty, are that the Monte Carlo method eliminates the inconvenient calculation of partial derivatives of the model. It does not require model linearity and can be used to validate the ISO/GUM method. However, its main disadvantage is the fact that the quality of the result depends on the quality of the algorithm used to generate random numbers, the number of interactions, in addition to requiring the use of software.

4. CONCLUSIONS

This paper presented the problem of dynamic calibration of pressure transducers used in the aerospace industry, particularly with respect to the lack of reliability regarding to the calibration of pressure transducers subject to rapid signal variations over short time intervals. An introduction presenting the goals of this paper, its relevance and the methodology to be employed was shown. Subsequently, a review of literature which deals with the main concepts related to pressure, pressure gauges, static and dynamic pressures, and the main systems and methods available to carry out dynamic calibration of pressure transducers was presented.

Periodic and aperiodic pressure generators were discussed, as well as their applications and operation ranges. It was identified that aperiodic generators, especially the shock tube device, are the most suitable for carrying out dynamic calibration of pressure transducers for the aerospace industry, since they are capable of simultaneously generating pressure levels and frequency ranges suitable for the needs in this field.

Important subjects as transducers characterization and the related methods for evaluating and expressing the uncertainty of measurement were discussed, along with current trends of the dynamic calibration of pressure transducers in the aerospace sector in order to present an overview. It was also observed that the quantification of uncertainties in the dynamic calibration is a major difficulty due to the lack of measurement standards and standardized procedures for this type of operation.

In conclusion, it was observed that the calibration of pressure transducers used in aerospace sector using aperiodic pressure generating devices, such as shock tubes, for example, would be quite appropriate. We also conclude that using the methodology based on Monte Carlo simulation would be a viable alternative for calculating the uncertainty in calibration.

5. ACKNOWLEDGEMENTS

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