

## **An overview of the dynamic calibration of piezoelectric pressure transducers**

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**Abstract:** Dynamic calibration is a research area that is still under development and is of great interest to aerospace and automotive industries. This study discusses some concepts regarding dynamic measurements of pressure quantities and presents an overview of dynamic calibration of pressure transducers. Studies conducted by the Institute of Aeronautics and Space focusing on research regarding piezoelectric pressure transducer calibration in shock tube are presented. We employed the Guide to the Expression of Uncertainty and a Monte Carlo Method in the methodology. The results show that both device and methodology employed are adequate to calibrate the piezoelectric sensor.

**Keywords:** Dynamic calibration, Pressure transducers, Monte Carlo method.

### **1. INTRODUCTION**

Since the 1960's researchers and members of the metrology community have realised that steady state pressure sensors were unable to capture the pressure variations that occurred in dynamic phenomena [1]. This has stimulated interest in sensors capable of measuring non-stationary pressure variations and how to calibrate such types of sensors.

A strong motivation for the interest in dynamic calibration is its application in the aerospace and military industries, where the reliability of measurements is very important. Schweppe et al (1963) pointed out that programs related to missile and space vehicles required reliable

measurements of pressure signals due to the fact that the values change rapidly [2].

According to Eichstadt (2012) [3], in the automotive industry there is also an important demand for sensors to measure rapid and significant variations in the pressure magnitude. Hjelmgren (2002) [4] cited other areas, such as medicine and robotics, that also need to perform dynamic pressure measurements.

In 1972, in order to standardize the dynamic calibration process of pressure sensors, the American Society of Mechanical Engineers, ASME, published a Guide to Calibrating Pressure Transducers. This document was considered as the state of the art in dynamic calibration of pressure transducers by the Instrumentation Systems and Automation Society, ISA. The ISA

reissued the document in 2002 [5]. This document contains information regarding the properties of pressure transducers in the frequency and time domains, mathematical modelling used in dynamic calibration, devices used for calibration, as well as care to be taken with the electronics of the calibration system. This document does not address any methods of estimating uncertainties associated with pressure transducer measurements.

Currently, the dynamic calibration of pressure sensors mobilizes research centres such as the National Physical Laboratory, NPL, in England [6], the Physikalisch-Technischen Bundesanstalt, PTB, in Germany [7], and large corporations such as Rolls-Royce, Volkswagen and Porsche, which are concerned with improving the dynamic pressure measurement processes.

In this article some concepts regarding dynamic measurements of pressure quantities and issues related to the calibration of pressure transducers under dynamic conditions are discussed. The article is the result of studies carried out by the Institute of Aeronautics and Space, IAE, located in São José do Campos, Brazil.

## **2. DYNAMIC CALIBRATION OF PRESSURE TRANSDUCERS**

The term “dynamic calibration” for a pressure quantity is used to define the process of characterizing a dynamic pressure transducer, determining its properties such as natural frequency, damping, peak time, stabilization time and sensitivity [8].

The procedures to calibrate a sensor to be employed under static pressure conditions are well defined by metrology organizations. In summary, from a calibrated and traceable instrument, we obtain measurements and compare the data with a standard. However, for a dynamic calibration of a piezoelectric pressure

transducer we cannot establish a traceable reference standard which covers all the needs that this calibration demands [8]. For example, we can find the sensitivity of the sensor and compare it with the sensitivity of the standard sensor using different devices, but it is difficult to estimate the peak time or the damping rate of the piezoelectric sensor with the required level of uncertainty so that the dynamic transducer can be considered calibrated.

In dynamic calibration a theoretical signal generated by a device is considered as the standard. Based on the characteristics of this device, a known and repetitive signal is generated which is compared with the signal captured by the transducer under calibration [8].

There are two methods of dynamically characterizing a transducer. In both, a specific type of signal is applied to the analyzed transducer and the response is measured. In the frequency domain method a periodic signal is applied. In the time domain method an aperiodic signal is applied, for example, a step signal [9].

Recently, the authors published a method for characterizing piezoelectric sensors that cover frequency ranges from 1 to 60 kHz and a pressure range from 1 to 1000 kPa [10]. In this method, a shock tube was used as the pressure signal generator to calibrate the sensor. Characteristics such as the rise time, peak time, stabilization time, sensibility, damping and natural frequency were determined, for a Kistler 701A<sup>®</sup> pressure sensor. This sensor is employed in aerospace testing. In this study, we calculated the uncertainties of the main parameters using the Monte Carlo method [11]. We used also the GUM (Guide to the Expression of Uncertainty in Measurement) methodology [12].

The quality of the signal used in the calibration process is a key factor for the success of the

dynamic calibration. The Shock Tube used in this study is located at the Henry T. Nagamazu Laboratory of the Aerodynamics and Hypersonic Division, of the Institute of Advanced Studies, IEAv, Department of Aerospace Science and Technology, DCTA, São José dos Campos, Brazil, and is capable of supplying good repeatability conditions.



Figure 1. Shock Tube [10].

Basically, a shock tube is a device that contains two compartments which are separated by a diaphragm. The first compartment is named the "driver tube" where a gas is stored. The second compartment is the "driven tube" where sensors are located. When the diaphragm is broken by pressure difference, a shock wave is generated and is used as an input step signal in the characterization of the transducers. One can see a schematic view of the main parts of the shock tube with the coupled sensors in Figure 2.



Figure 2. Schematic view of shock tube, diaphragm and sensors [10].

### 3. RESULTS AND DISCUSSIONS

The start of the dynamic characterization process of the sensor occurs before a complete rupture of the diaphragm which separates the driver and driven tubes. Thus, firstly we calculate the

velocity of the front shock wave which passes by sensors P2 and P2' (see Figure 2). Using a theoretical model [13] and based on the value of the wavefront velocity,  $V$ , with initial pressure  $P_1$ , and initial temperature  $T_1$ , of the driver tube the value of the pressure step,  $\Delta P$ , can be estimated.

The dynamic behaviour of the pressure sensor can be represented by a mass-spring system with damping [5]. Thus, the main dynamic characteristics of the sensor, natural frequency and damping, can be obtained experimentally, based on the values of its pick time,  $t_p$ , steady signal,  $x(t_\infty)$ ,  $x(t_{\max 1})$ , and  $x(t_{\max 2})$ . Where  $x(t_{\max 1})$  and  $x(t_{\max 2})$  are two consecutive peaks above the mean value of the steady signal,  $x(t_\infty)$  [4, 5].

An estimation of the uncertainties of the evaluated parameters is an important issue in tests using shock tubes. In order to avoid a large number of experiments, the use of a statistical method such as Monte Carlo in the evaluation of uncertainties can be considered. The experience of the authors is that this strategy has proven to be efficient [8, 10, 11].

Assuming a *t-Student* distribution, we performed  $10^6$  trials for each measurement model to estimate the mean values and uncertainties of the parameters  $\Delta P$ ,  $\zeta$ ,  $\omega_n$ , for a 95% level of confidence, as shown in Table 1.

**Table 1.** Parameters for propagation distributions and estimate values to quantities  $\Delta P$ ,  $\zeta$  and  $\omega_n$ .

Input Parameters	$V, T_1, P_1$	$x(t_\infty), x(t_{\max 1}), x(t_{\max 2})$	$t_p$
Output Parameters	$\Delta P$	$\zeta$	$\omega_n$
Mean values	$5.8 \times 10^2$	$0.58 \times 10^{-1}$	$290 \times 10^4$
Standard deviation	$0.5 \times 10^2$	$0.21 \times 10^{-1}$	$3 \times 10^4$

Uncertainties lower limits	$4.8 \times 10^2$	0	$5 \times 10^4$
Uncertainties upper limits	$6.8 \times 10^2$	$1.1 \times 10^{-1}$	$36 \times 10^4$
Unit	kPa	dimensionless	rad/s

In Table 1, comparing the uncertainties limits shown in line for and five, it can be seen that uncertainties values of the  $\Delta P$  quantities are symmetric (column one). Thus, when using a coverage factor  $k = 2$  [9], we have a coverage interval for  $\Delta P$  value which is similar to the uncertainties limits obtained according to a Monte Carlo Method.

#### 4. CONCLUSION

The aim of this article was to present an overview of the dynamic calibration of pressure transducers and to discuss some of its concepts. The article is the result of studies carried out by the authors in the Institute of Aeronautics and Space (IAE) and Institute of Advanced Studies (IEAv), both part of the Department of Aerospace Science and Technology (DCTA).

A major challenge in dynamic calibration concerns the repeatability of the input pressure signal. In view of this, the entire set of tests must be carefully analyzed: shock tube, data acquisition system, diaphragm construction material, gas used in the shock tube and assumed pressure for the rupture of the diaphragm.

Other precautions such as sensor location, cleaning of the shock tube and the rigidity of its holding can influence the quality of the signal generated, contributing to the uncertainty of the measurements.

The results show that the device and a Monte Carlo methodology employed are adequate to calibrate the piezoelectric sensor. In other words, both a Shock tube and a Monte Carlo Method can

be used for dynamic calibration of the piezoelectric pressure sensor.

More details and references regarding dynamic calibration can be found in the first author's PhD thesis [10].

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