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DYNAMIC CALIBRATION METHODS FOR PRESSURE SENSORS AND DEVELOPMENT OF STANDARD DEVICES FOR DYNAMIC PRESSURE

Alberto C. G. C. Diniz [1], *Alessandro B. S. Oliveira* [2], *João Nildo de Souza Vianna* [3], *Fernando J.R. Neves* [4]

Laboratório de Metrologia Dinâmica da Universidade de Brasília, LMD-UnB – Brasília, Brazil
[1] adiniz@unb.br [2] abso@unb.br [3] vianna@unb.br [4] ferneves@unb.br

Abstract: This paper presents state-of-the-art research being carried out in Brazil for the development of methods and devices used in the dynamic calibration of pressure sensors. The work is part of an effort set forth to set up a national reference laboratory. The devices developed and their metrological characteristics are presented.

Keywords: dynamic metrology, sensor calibration, pressure.

1. INTRODUCTION

Increasing use of automated systems to control and monitor rapidly varying physical quantities has required the use of sensors and transducers capable of reliably sensing these quantities, so that the time history of their changes can be registered.

Monitoring pressure in turbo machines, detecting cavitation in hydraulic turbines, controlling temperatures in boilers, and measuring pressure at the output of rotors for efficiency tests are examples of applications where the time history of the signal is of great importance or where the fast variation of the physical quantities is frequent.

Dynamic calibration of a sensor is essential to determine its dynamic behavior. The dynamic calibration of sensors has been the object of many research projects in the area of dynamic pressure measurement, seeking to develop reliable and accurate procedures for the determination of the dynamic features of the sensors.

This study looks at the state-of-the-art of research conducted in Brazil to develop methods and means for the dynamic calibration of pressure sensors.

2. DYNAMIC METROLOGY

The manner in which a measured quantity varies with time constitutes important information for many measurement and control processes. Thus, more important than measuring the “value” of the quantity, it is necessary that the sensor, or measurement system, can provide, as an output, a signal that faithfully reproduces the time behavior of the quantity in question.

Today dynamic measurement is present in the most varied areas of science and technology. Pressure levels varying over time are common in the study of the behavior of gas turbines, internal combustion engines, the behavior of aircraft and in many biomedical devices, as in the case of the ones used for diagnosing cardiovascular diseases.

In the aeronautic field, the dynamic measurement of pressure is used in the fire extinguishing systems in turbines and in the measurement of the consumption of the engine.

It must also be taken into account that not only the sensor, but also all the measurement system must be able to determine the dynamic characteristics of the process measured. As well as a sensor capable of “accompanying” the behavior of the signal measured, the measurement system (amplifiers, converters, indicators) must also have a dynamic behavior that does not impair the measurements made. Thus, the transfer function of each component of the measurement system and of the system as a whole must be determined.

The applications of the dynamic measurement of pressure according to the medium where the sensor is installed (if liquid or gas) are grouped in Figures 1 and 2.

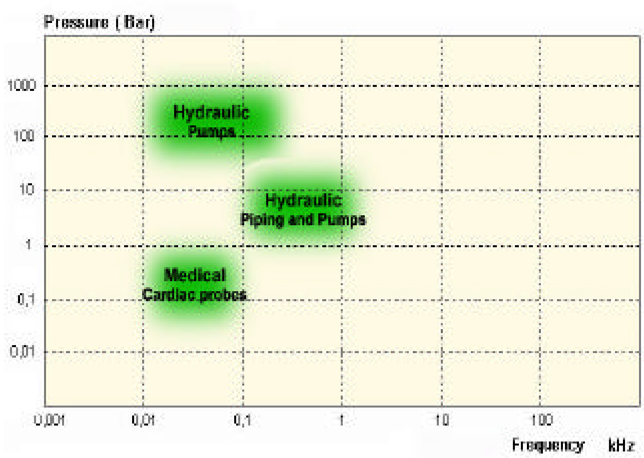

Figure 1. Areas of dynamic measurement of pressure in liquids.

These figures show, for different types of applications, the frequency and pressure zones most frequently found in industry.

The figures show the diversity of the ranges of pressure and frequency that must be covered by the pressure sensors in the different fields where they are used.

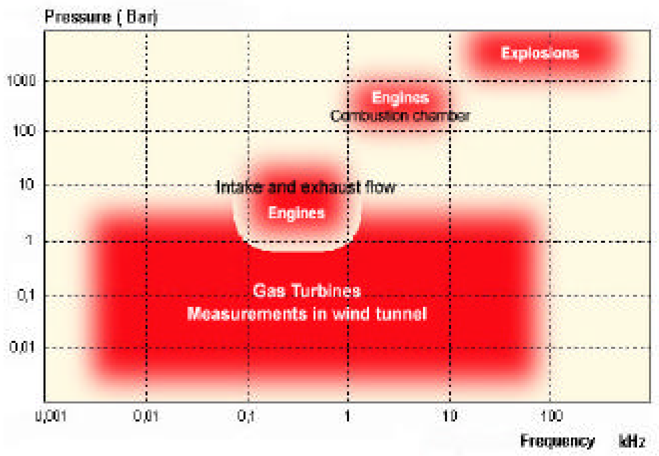

Figure 2. Areas of dynamic measurement of pressure in gases.

The spreading and diversification of the use of dynamic measurement of pressure has required ever more reliable measurement systems. Some applications require, besides static accuracy, that it is possible to determine the characteristics of variation of the signal, such as frequency, wave amplitude and shape, with a high level of accuracy. To do this, the dynamic characteristics of the measurement system must be known, and it must be rigorously calibrated, including the sensor.

3. DYNAMIC CALIBRATION OF SENSORS AND MEASUREMENT SYSTEMS

In most applications pressure sensors are calibrated statically, using standard procedures such as, for example, the “Pressure balance”. In some cases the accuracy of the measurements is estimated from the static calibration of the transducer and from theoretical dynamic characteristics of the system, making sure that the resonance frequency of the sensor (sometimes provided by the manufacturer) is much greater than the frequency of the signal being measured. However, these procedures do not provide information about the dynamic behavior of the sensor, or produce the levels of accuracy required by certain current applications.

The commonly used procedures for dynamic calibration of sensors usually only involve determining some representative characteristics of its dynamic behavior, such as its response time, natural frequency and damping ratio. This information is insufficient for fully characterizing the sensor and its behavior in different frequency ranges.

The ASME published, in 1972, a guide for the dynamic calibration of pressure transducers (ANSI B88.1-1972) [1], which indicates the dynamic properties of sensors that must be included in their calibration, but does not indicate how to characterize the sensor fully. In spite of being an important document for the dynamic calibration of pressure sensors, this guide is not a standard on test procedures, or a recommendation for estimating measurement uncertainties in dynamic processes of pressure measurement. A revised version of this guide has been available since 2002 published by the ISA (ISA-37.16.01-2002) [2], where there is a better description of the methods employed for dynamically calibrating pressure transducers.

The dynamic calibration of sensors or measurement systems involves the determination their dynamic behavior with adequate accuracy. To do this, a system must be used, which produces dynamic pressure, varied over time, in a known, reliable and controllable way. This pressure signal will be used as a reference, or standard, signal for calibration.

For calibrating pressure sensors this signal is obtained by means of dynamic pressure generators. The type of pressure generator used influences both the calibration procedure and the type of sensor that can be calibrated. The dynamic generators of pressure are divided into aperiodic and periodic ones. With few exceptions, the aperiodic generators generate a signal, which is close to a Step Function. The periodic generators, on the other hand, usually generate pressure sine function signals.

In the following discussion the different methods and means of dynamically calibrating pressure sensors developed in the Laboratory of Dynamic Metrology of the University of Brasília (LMD-UnB) are presented. Since 1993 this laboratory has performed research in the field of dynamic metrology and dynamic calibration of pressure sensors. LMD-UnB has a quality system which is adapted to the norm ABNT ISO/IEC 17025 (2001), being accredited by INMETRO and participating in the Brazilian Calibration Network (RBC) since 1999.

4. DYNAMIC CALIBRATION OF PRESURE SENSORS

The dynamic characterization of a pressure sensor can be executed experimentally by exciting it by a periodic signal or by determining the response of the sensor to a step signal. In both cases it is possible to obtain the Transfer Function of the sensor which completely quantifies and qualifies its dynamic behavior. Theoretically, the transfer function would be obtained directly by applying an impulse signal to the input of the sensor. Experimentally it could be implemented by applying a pressure pulse, which would be a good approximation of the impulse signal, in spite of not being perfect. In practice it usually a pressure step is used, since pulse generators are difficult to build and control, not guaranteeing reliability of the standards of calibration.

The response to a step input signal is obtained in tests, using aperiodic pressure generators such as the Shock Tube. This test is mainly applied in the dynamic calibration of sensors destined to measure pressures of high amplitude and frequency.

The frequency response of a pressure sensor can, supposedly, be obtained directly using a periodic pressure generator with varying frequency. But, usually, there are limitations to its range of application.

Thus, pressure generators for dynamic calibration can be classified into two main groups: aperiodic and periodic generators. The former are used in calibration methods in the time domain and the latter for calibration methods in frequency domain.

There are many types of pressure generators for dynamic calibration, but their sphere of application is always limited to a range of pressure and frequency. Below some of these generators developed in the Laboratory of Dynamic

Metrology of the University of Brasília (LMD-UnB) are presented, highlighting their main characteristics and field of application.

5. APERIODIC PRESSURE GENERATORS

Aperiodic Pressure Generators are essential in the dynamic calibration procedures of fast response transducers. With few exceptions, a Step Function signal, generated subjecting a pressure transducer to a step of pressure, creates test conditions that are similar to or more severe than the work conditions experienced by these transducers.

5.1 Fast-Opening-Valve Device

In this generator, two volume cameras with very different (ratios greater than 1/3000) are separated by a Fast-Opening-Valve. The sensor to be calibrated is mounted on the smaller camera, subject to a pressure $\mathbf{p}_1$. Owing to the great difference of volume of the two cameras upon opening the separation valve the sensor goes to a higher level of pressure ($\mathbf{p}_2$), present in the larger camera, in a very short time so that there is a step of pressure $\mathbf{p}_2$-$\mathbf{p}_1$ which is almost perfect [3]. Figure 3 shows the Fast-Opening-Valve Device developed at LMD-UnB, detailing its smaller camera.

The frequency range covered by this device is relatively wide and directly influenced by the gas used in the cameras. Using air as the calibration fluid, the usable frequency range of this particular device extends from 0 to 70 Hz. This limit is defined considering a maximum drop for the pressure signal of about 1%. When using carbon dioxide as calibration gas the upper limit drops to 60 Hz and using helium allows the device to be used up to 100 Hz [3]. In respect to the amplitude of the pressure signal generated, the Fast-Opening-Valve Device does not have great limitations.

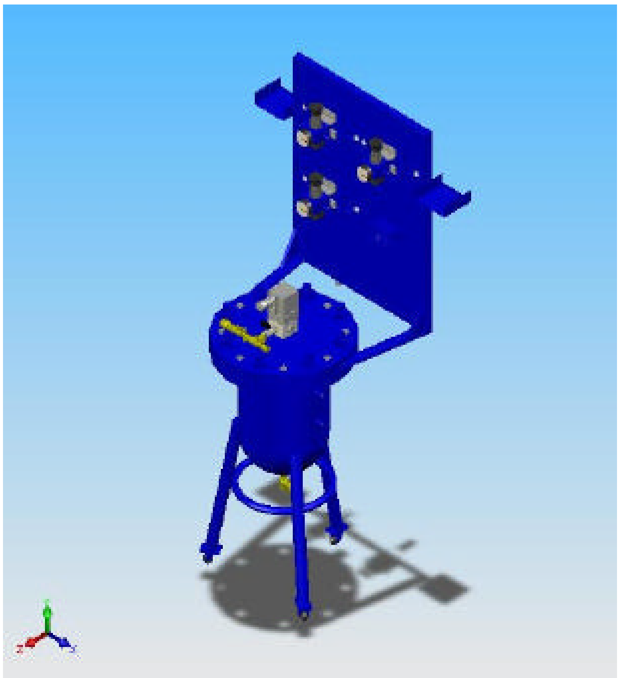

Figure 3. Fast-Opening-Valve Device of LMD-UnB.

Operation of the Fast-Opening-Valve Device developed at LMD-UnB is uncomplicated and the device has good repetitiveness. Considering only the magnitude of the pressure signal, the uncertainty of measurement of the signal generated, for a confidence of 95%, is less than 2.5% of the pressure level generated. The quality of the signal can be seen in Figure 4, for air as calibration gas. The upper and lower limits of the uncertainty of the signal generated can be seen in the figure.

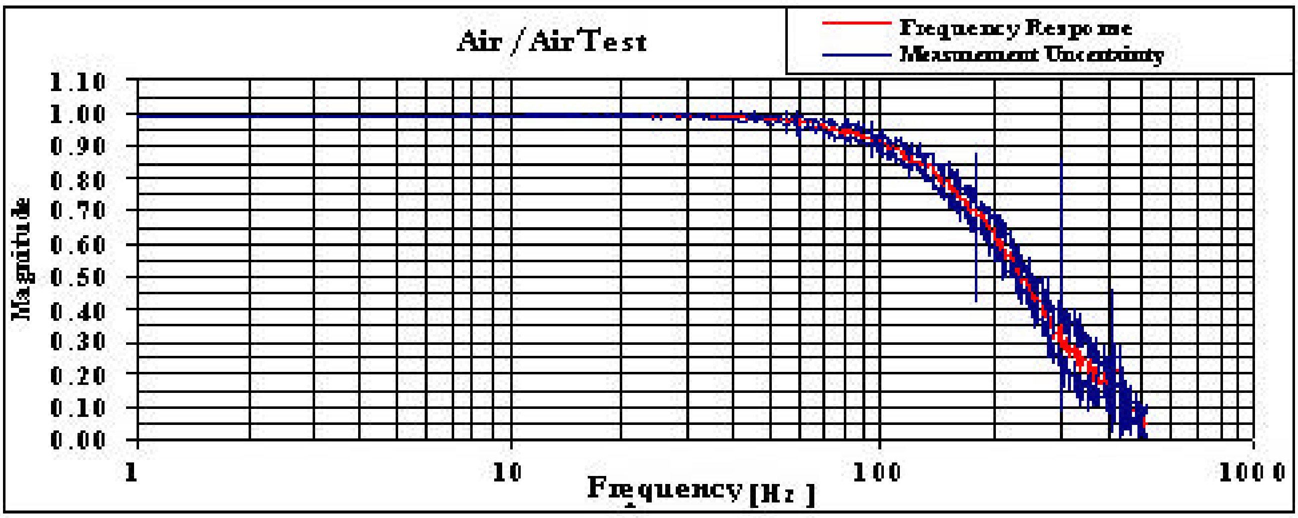

Figure 4. Magnitude of the Frequency Response Function of the Fast-Opening-Valve Device of LMD-UnB.

5.2. Shock Tube

A Shock Tube is an excellent device for the dynamic calibrating of temperature and pressure sensors [4]. The Shock Tube is composed of two cameras with different pressure levels, separated by a membrane. Upon tearing the membrane, a shock wave propagates along the tube reaching the sensor to be calibrated, which is assembled on the tube wall or on the back of the tube. These two possibilities allow calibrations with continuous pressure steps and different amplitudes.

Figure 5 shows the Metrological Shock Tube developed at LMD-UnB.

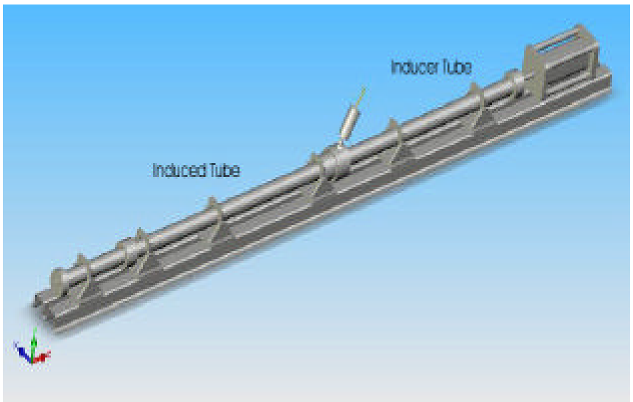

Figure 5. Dimensions of the Metrological Shock Tube of LMD-UnB.

Two examples of signals generated for calibration are shown in Figures 6 and 7, for measurements on the tube wall and back of the tube.

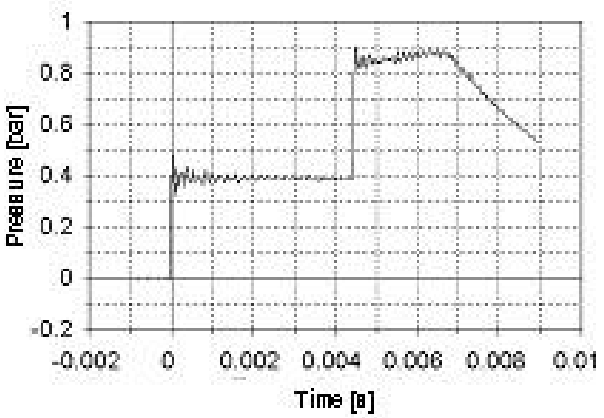

Figure 6. Steps of pressure obtained on the wall of the Metrological Shock Tube of LMD-UnB.

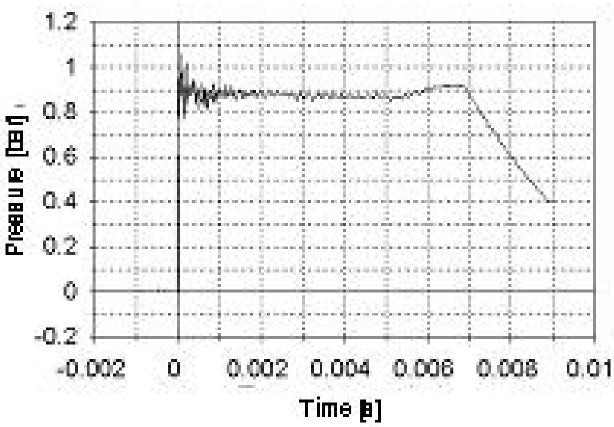

Figure 7. Steps of pressure obtained at the back of the Metrological Shock Tube of LMD-UnB.

The step generated is considered perfect within the metrological conditions required for calibrating sensors and transducers [5]. With the Metrological Shock Tube developed it is possible to generate a step of pressure at the back of the tube with an average duration of 6.8 [ms] with pressures varying 0.1 through 10 [bar]. The uncertainties estimated for the signal generated for different frequency ranges are shown in Table 1.

Table 1 – Measurement uncertainties of the Shock Tube of LMD-UnB.

Frequency band	Expanded uncertainty
200 – 1.000 Hz	1.5 %
1.001 – 3.000 Hz	2.5 %
3.001 – 8.000 Hz	12.5 %
8.001 – 10.000 Hz	30.0 %

The Shock Tube allows the calibration of high frequency sensors at quite varied amplitudes, as the maximum pressure limit is a function of the mechanical resistance of the structure of the tube.

The limits for use of the shock tube, as well as the uncertainties of the signal generated can be modified if different gases are used as a medium for propagating the shock wave. It was found that the use of air, as a calibration fluid, allows ranges of frequencies and measurement uncertainties within those required by the majority of applications of pressure sensors in normal industrial applications, such as the measurements made in internal combustion engines [6]. It was also found that the deformation of the diaphragm, under pressure, affects the quality of the signal generated and so must be considered, depending on the pressure difference between the two cameras [7].

6. PERIODIC PRESSURE GENERATORS

In the case of periodic generators, a sine pressure signal of known frequency is applied to the transducer to be calibrated. The steady state response of the sensor for a series of frequencies can be obtained and thus the Frequency Response curve determined directly. In some cases, depending on the system used, this means that the test can take quite a long time.

These generators are particularly suited for the calibration of sensors designed small pressure amplitudes and low frequencies.

The best-known periodic generators are the cavity ones, which can operate in a resonating or a non-resonating mode and the Liquid Column Generator. The principle of operation of this sensor relies on submitting a column of liquid to sine function acceleration.

6.1. Liquid Column Periodic Generator

Shutte, Cate and Young [8] proposed using a column of liquid accelerated vertically by means of a sine function signal as a periodic pressure generator. In this case, the pressure generated is a function of the height of the column, the density of the fluid and the acceleration to which the column is submitted.

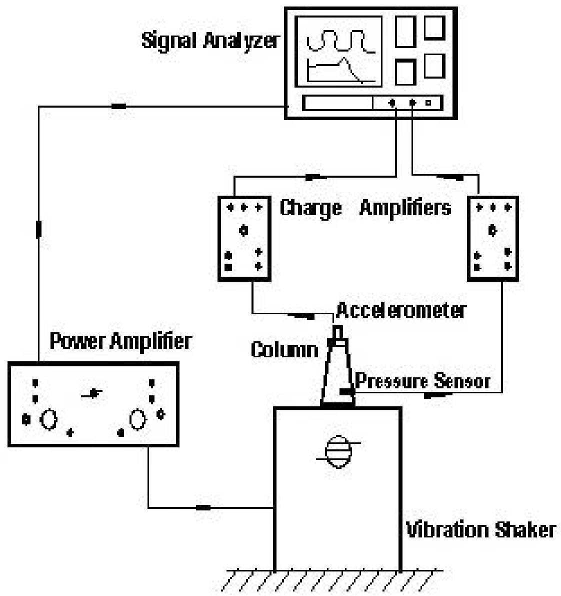

Figure 8. Schematic drawing of the Liquid Column Periodic Generator of LMD-UnB.

Based on this concept, the generator developed at LMD-UnB uses a conical column with a cylindrical cavity, which is filled with a liquid and mounted on a shaker. The shaker accelerates the column with a sine function of controlled frequency a amplitude. This is measured using an accelerometer fixed over the structure of the column. The sine signal of the resulting pressure is registered. The calibration of the sensor is done comparing the pressure signal with the acceleration forced on the column. The liquid in the cavity, in this case, is the calibration medium. The signal in the accelerometer is used as a reference.

Results obtained are influenced not only by the amplitude and frequency range of the input signal, but also by the properties of the liquid used [9].

Considering metrological limitations, the use of the Liquid Column Shaker is limited to pressures lower than 35 [mbar], within a frequency range of 40 through 1900 Hz [10].

The limits of the frequency span of the generator are defined by the level of the response signal generated, considering the average value of the amplitude in steady state and a maximum variance of 5% around it. Different frequency ranges are obtained for different filling liquids. Thus, for Oil SAE-40 the frequency range goes from 60 Hz to 1300 Hz, whereas for Glycerine this interval is between 40 Hz and 950 Hz. The low viscosity of water means that its use as a filling liquid limits the use range of the generator to 350 Hz. The widest frequency range was obtained using Polydimethylsiloxane (PDMS) as calibration liquid. For PDMS the frequency use range is between 40 Hz and 220 Hz.

Figure 9 shows the Frequency Response Function of the liquid column generator of LMD-UnB using Polydimethylsiloxane (PDMS) as calibration liquid. PDMS is an organic polymer of silicone available in different viscosities. They have few alterations in the chemical properties in a wide range of temperatures, low steam pressure and high resistance to oxidation. In this case, PDMS with a viscosity of 1000 [centistokes] was used, which has at 25°C, a density of 0.977 kg/m^3 and Surface Tension of 21.5 [din/cm].

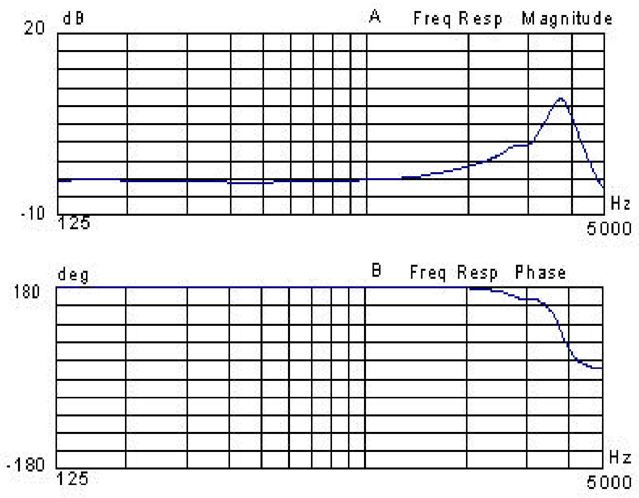

Figure 9. FRP of the Liquid Column Pressure Generator of LMD-UnB.

The generator developed is capable of generating a sine pressure signal as required at different levels of pressure and frequency within its operating range. The signal generated has a stability level covering a reasonable range of frequencies, with good repetitiveness and being little affected by external influences. Consequently it is applicable for the dynamic calibration of pressure sensors. The pressure signal generated has an uncertainty (for a confidence of 95%) of ? 0.92 mbar for the amplitude, and of ? 5% for the phase angle [11].

7. FIELD OF USE OF PRESSURE GENERATORS FOR DYNAMIC CALIBRATION

All the pressure generators have their ranges of operation very well defined, and it is the operating range and the conditions of use of the sensor to be calibrated which determine the choice of a dynamic calibration device.

The range for use of aperiodic pressure generators is quite wide, covering practically all the area of industrial use of pressure sensors. The Quick-Opening-Valve Devices cover the lowest frequency ranges whereas the Shock Tubes covers the highest frequencies. Generally speaking, the periodic generators act at the low levels of amplitude. So, the devices generating an aperiodic signal can operate at the high amplitude levels, whereas the devices generating a periodic signal work at the low levels of amplitude.

The pressure generators available at LMD-UnB for the dynamic calibration of pressure sensors cover the ranges of pressure and frequency indicated in Figure 10.

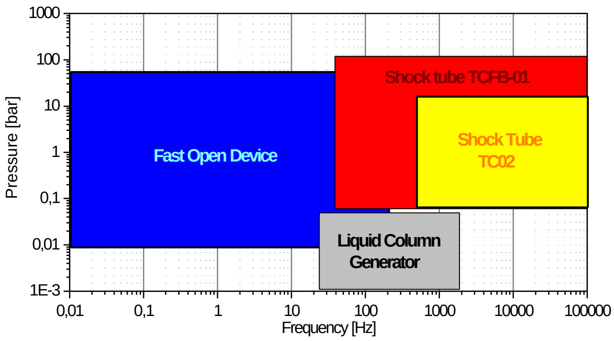

Figure 10. Field of use of the pressure generators of LMD-UnB.

8. CONCLUSION

Taking into account the increase in the levels of metrological quality required for measurements made in industry, aiming at both the development of products and the evaluation of conformity, dynamic metrology is also undergoing sharp growth.

Aware of this need the Laboratory of Dynamic Metrology of the University of Brasília LMD-UnB has developed, over the last ten years, methods and means for dynamically calibrating pressure sensors.

This paper has presented some of the results obtained from these studies, highlighting the equipment developed for the dynamic calibration of pressure sensors.

The research undertaken has allowed the development of Brazilian competence in the dynamic calibration of pressure sensors, as part of an effort to create a laboratory of national reference in the dynamic calibration of sensors.

The equipment developed was extensively tested and evaluated to ensure the requirements and reliability for metrological applications. The tests and evaluations were performed according to international standards, making adaptations for the case of dynamic measurements, in the situation that standards do not exist.

The uncertainties associated with the signals generated and the calibration procedures are satisfactory for the current applications of dynamic metrology. These values are within the same range of those at European laboratories.

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