Chapter X
A Low-Cost and Flexible Prototype for Static and Dynamic Calibration of Pressure Measurement Channels

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Abstract

Regarding pressure calibration, it is important to refer that there are several applications where the pressure signals, to be measured, can have large variations in short periods of time. Such applications include, not only, combustion engine monitoring, turbomachinery, aerodynamics, acoustics and ballistics, among others, but also specific industrial and biomedical applications. Thus, this chapter starts with a review of some important issues related with pressure measurements, focusing the main bandwidth limitations associated with the pressure measurement channel that includes, not only, the pressure sensor and associated signal conditioning circuits but also pressure transmission lines, such as pneumatic and capillary tubing, and impulse lines, that is used frequently to perform remote pressure measurements. Then, this chapter includes the hardware and software description of a flexible and low-cost calibration prototype that can be used for static and for dynamic calibration of pressure measurement channels. The last part of the chapter presents two application cases where the performance of the proposed calibration prototype is experimentally evaluated. One of the applications is related with the static

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and dynamic calibration of an industrial pressure transmitter and the other application is related with the calibration of a sphygmomanometer device, largely used for non-invasive blood pressure measurements.

Keywords: pressure sensors, static and dynamic calibration, pressure measurement channel, remote pressure measurements, capillaries, pneumatic tubing.

1. Introduction

Time-varying pressure measurements with high accuracy are essential for numerous applications. Pressure sensors frequently need to be placed at specific distance away from the measuring taps due to temperature values, very high or very low, easy access for maintenance, reliability, robustness against harsh working conditions, among others reasons [1]. The pressure transmission line, such as a capillary, an impulse line or a pneumatic tube, to connect the pressure sensor to the measurement point is, consequently, an important part of the pressure measurement channel. Thus, the accuracy of dynamic pressure measurements can be greatly impacted by the dynamic characteristics of the pressure transmission line, by the internal volume of the pressure transducer, by the material and geometric properties of the connecting transmission line and by the thermodynamic and transport properties of the transmission medium [2]. For these reasons, the frequency response of the transducer must be considered together with the frequency response of the other elements included in the pressure measurement channel. Considering, as an example, that exist only capillary effects, according to National Institute of Standards and Technology [3-5], when high frequency dynamic pressures are to be measured, there are many factors that should be properly taken into consideration. When the pressure signal reaches the sensing device, there are two main types of distortions, namely, the transmitted pressure signal could be affected by phase distortion, altering any time correlations that can exist in the original signal, or the amplitude of the pressure signal could be distorted, selectively in frequency, causing large measurement errors. An example, of the last kind of errors occur if a resonance condition exists within the pressure transmission line and the pressure signal variations activate those resonances [6]. So, the importance of dynamic calibration is not restricted to specific applications, such as military engineering, chemical explosion tests [7], petroleum exploration and well testing [8], gas turbine testing and combustion engine testing [9-10], among others, but are also important in industrial and biomedical applications. One industrial application where dynamic calibration of pressure sensors is crucial is related with the measurement of pressure pulsations in the headbox feed pump of a paper machine [11]. Pressure pulsations, generated at the headbox feed pump, might create unacceptable variations of paper basis weight in the machine direction affecting strongly paper quality and process efficiency. Thus, in pressurized headboxes, pressure measurements must be very accurate and the dynamic characteristics of the pressure measuring channel are critical. Other typical example of dynamic calibration in industrial applications, is related with the need to assure a pump net positive suction head in order to avoid pump performance drop caused by cavitation [12]. It is very important to maintain pump suction pressure as constant as possible. One way to achieve this purpose is to connect the pump suction input to a tank where a constant level control is implemented, using differential or relative pressure measurement transmitter. A last, but also important example of the importance of dynamic pressure measurements in industrial applications, is related with boilers efficiency. Thus, an accurate control of the amount of air is essential to boiler efficiency since too much air will cool the furnace, and carry away useful heat, and with too little air the combustion will be incomplete, unburned fuel will be carried over and smoke may be produced. To avoid these problems, air flow measurement, commonly implemented by differential pressure sensors, is essential to control the blower operating point. Thus, the air flow measurement that is affected by a large number of dynamic disturbances, such as, direction and intensity variations of the wind, must be dynamically accounted to improve boilers' performance. To conclude the importance of dynamic pressure measurements, it is important to also refer biomedical measurement systems. For example, in blood pressure measurements, the dynamic pressure signal contains much more information than the two common steady state values of systolic and diastolic pressures [13] being required to access its dynamic contents. Additionally, in ergonomics area there is an interest to measure the pressure distribution, as well as, the total force between hand and tool during some operations [14]. Furthermore, in physiotherapy, the measurement of foot pressure during the walk is also very important to perform gait analysis requiring the usage of dynamic and accurate pressure sensors [15].

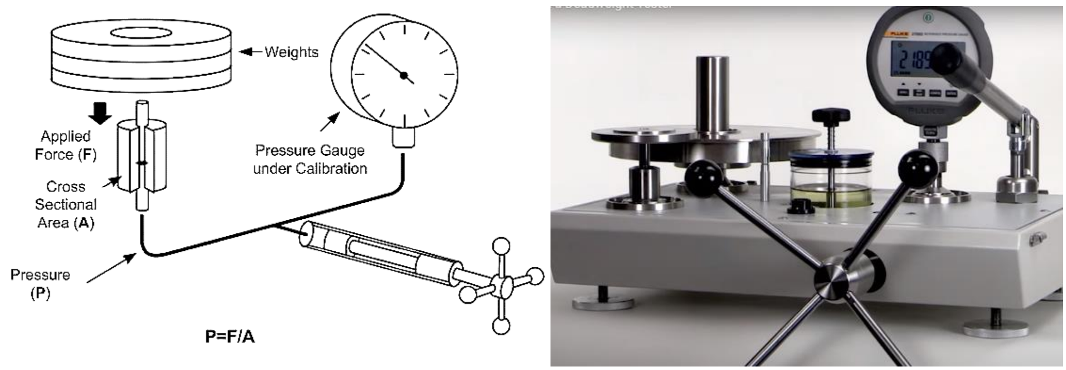
2. Calibration

In general, the performance, accuracy and performance of pressure sensors, in a variety of applications, depend on both static and dynamic calibrations. Static calibration guarantees accuracy in steady-state conditions, while dynamic calibration evaluates the sensor's capacity to react to abrupt pressure changes, being essential for real-world applications where pressure variations happen often.

2.1. Static calibration

The pressure is said to be static when it remains constant for a significant amount of time, generally during several multiples of a complete measurement period. Figure 1 depicts the working principle of a typical deadweight tester for static calibration purposes. The majority of dead weight testers are found in calibration facilities or laboratories across almost all industrial plants. A dead weight tester compares the pressure that a known weight exerts on known surface using directly pressure definition and Pascal's principle. Thus, a dead weight tester has a reservoir chamber filled with oil, that is almost incompressible, a primary piston that carries a known weight, an isolation valve for the oil reservoir, known weights of varying magnitudes, and a secondary piston that applies pressure to the oil in the chamber. The device under calibration is a pressure transmitter, gauge, or a pressostat. It is important to refer that this static calibration method enables an expanded relative uncertainty [16] of some tens of p.p.m., under controlled environmental conditions.

Fig. 1 Working principle of a typical dead weight tester frequently used for static calibration.



2.2. Dynamic calibration

Even if, till nowadays, there are still no traceable dynamic pressure calibration standards, except for sound pressure, dynamic calibration of pressure sensors can be obtained, in time or frequency domains, using different methods. It is very important to establish de boarder between the cases where static calibration is an acceptable solution, from the cases where dynamic calibration is essential to avoid large measurement errors. Obviously, the line boarder between the need of static or dynamic calibration, depends on the frequency behavior of the measurement channel, on the maximum frequency of the measurement signal and on the maximum calibration error that can be accepted for a given application. Since, the measurement channel is typically modelled as a second order system, which is a common approximation for the pressure measurement channel it makes sense to define the border line according to maximum measurement error that is acceptable in a given application. Thus, considering the transfer function of a second order system defined by:

$$G(s) = \frac{G_0 \cdot \omega_n^2}{s^2 + 2 \cdot \zeta \cdot \omega_n \cdot s + \omega_n^2} \quad (1)$$

where G0 represents the static gain, ζ the damping factor and ω_n the natural frequency. From (1), it can be deduced the relationship between the maximum acceptable error and the damping and natural frequency of the second order system. Figure 2 represents the measurement error amplitudes that are obtained in a dynamic pressure measurement system if only static calibration performed.

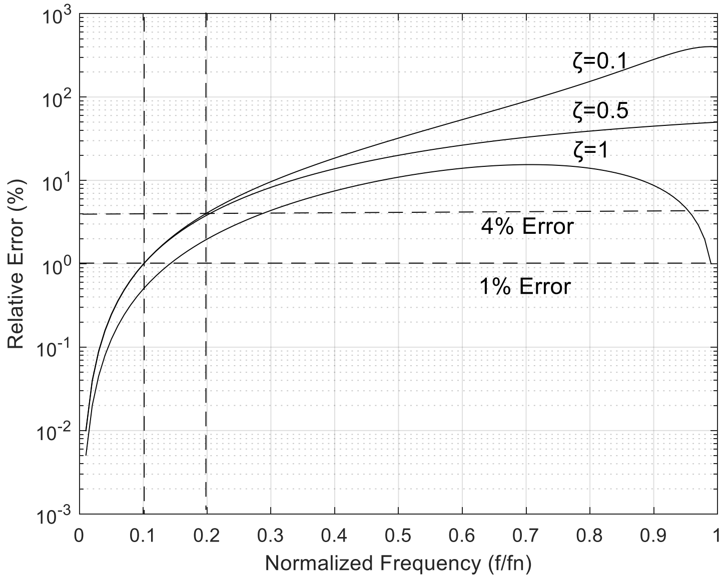


Fig. 2. Relative errors associated with the usage of static calibration when the measurement channel has a second order low-pass filter characteristic (f- signal frequency; fn- measurement channel natural frequency; ζ- damping coefficient).

As it is clearly visible in previous figure, the relative errors that are obtained can be very large if the signals to be measured are affected by channel's behavior in terms of its transfer function characteristics, namely, damping and natural frequency. The relative error as a function of the normalized frequency, for low values of the damping coefficient, is about 1/10 and 1/5 of the pressure channel natural, for an acceptable threshold error equal to 1% and 4%, respectively.

Regarding dynamic calibration methods, the pressure generator may produce either a periodic or an aperiodic pressure. According application requirements, harmonic periodic pressure generators are used in pressure measurements with periodic or repetitive characteristics and, on the other hand, for example, it would make sense to use an aperiodic pressure generator, such as shock tubes, fast opening devices, or falling weights [17] if the measurement system is used to measure impulsive pressure pulses. When a transducer experiences negative step loading stimulus, that means if it is subjected to an abrupt pressure shift from a known static pressure value to either ambient pressure or vacuum, it is recommended to use fast-opening devices, such as a valve that vents the pressure chamber to air pressure or vacuum, respectively. Nowadays, a pressure release time of a few milliseconds can be achieved using this type of devices.

3. Pressure measurement channel

Pressure transmitting lines, usually based on capillaries, pneumatic or impulse lines, are used to enable the location of pressure transmitters away from the process being measured so as to reduce the negative impact of the temperature on the transmitter's performance and operating life. Locating the pressure transmitter away from the process can also reduce the adverse effects of vibration and facilitate access to the transmitter for replacement or, in some cases, enable its adequate maintenance. However, there are also several negative impacts caused by the usage of pressure transmitting lines. Since the measurement points, typically known as pressure taps, are away from the sensor and signal conditioning circuits, being additional sources of errors introduced in the measurement channel. These measurement errors are particularly serious if dynamic pressure measurements are being performed but they also occur, obviously, in static pressure measurements. The response time of a pressure transmitting line is mainly affected by two types of delays: the sonic delay, correspondent to the time that it takes for the pressure signal to travel at the speed of sound through a pneumatic line or through a completely filled line; and the hydraulic delay that depends mainly on the volume of fluid that must be moved in the pressure transmitting line to bring a pressure change in the sensing element of the transmitter. Thus, it is important to underline that the dynamics of a pressure measurement channel does not depends only on the dynamics of the measuring transducer but also on the dynamic of the pressure transmitting line and also on the dynamic characteristics of the signal conditioning circuits. Usually, the natural frequency given in the transducer specifications is only the mechanical natural frequency of the pressure sensing diaphragm without considering the crucial dynamic limitations associated with the capillaries and transducer sensing cavity volume. Considering, as an example, a typical pressure measurement channel, represented in figure 3, the transducer may be dynamically calibrated and even if it is known that all transducer natural frequencies are far above the frequency content of the pressure to be measured, the inclusion of a capillary or pneumatic tube, between the pressure taps and the pressure input ports of the measuring transducer, changes the situation completely by introducing a significant low-frequency dynamic element. In these cases, the pressure signal applied to the pressure transducer does not resembles the pressure signal under measurement, particularly when dynamic pressure signals are at stage. This problem can´t be ignored since the main dynamic limitation are typically associated with the frequency limitations of the capillary or pneumatic tube that interconnects the pressure measuring tap to the sensing transducer cavity volume.

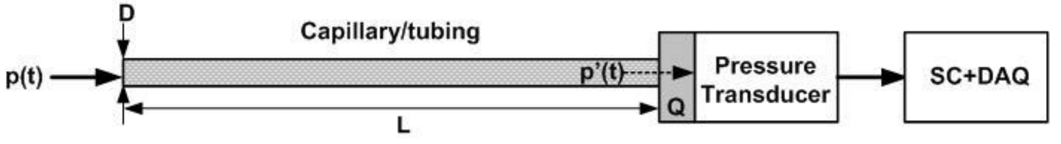


Fig. 3. Pressure measurement channel (p(t)- input pressure signal; p'(t)- pressure signal at the input of the pressure transducer; L- capillary/pneumatic tube length; D- capillary/pneumatic tube diameter; Q- transducer cavity volume; SC- signal conditioning; DAQ-data acquisition).

The dynamics of the tubing can be modelled by the Helmholtz resonator model or by the organ pipe model [18], but to obtain accurate information about the dynamic characteristics the measurement channel must be calibrated. The flat frequency bandwidth of the pressure measurement channel depends mainly on the geometry and construction of the pressure sensor, on pressure transmission line dimensions, on the fluid media inside the transmission line and on the output filtering of the conditioning circuits. As a rule of thumb, regarding the frequency bandwidth limitations at the transducer level, it is important to refer that the maximum frequency of the dynamic pressure signal at transducer's input should not exceed one-fifth of the natural frequency of the reference transducer in order to assure measurement errors lower than four percent. Regarding the conditioning circuit response, it is important to underline that damping parameter that is generally used to parametrize the transmitter has a direct impact on the dynamic response of the pressure measurement channel. High damping values filter out process noise at expenses on the useful pressure channel bandwidth. Thus, regarding dynamic calibration, it is important that transmitters' damping is deactivated or, if not possible, that the shortest possible time constant setting is selected. The natural frequency of the capillary plus the sensor cavity of the pressure transducer can be given, approximately by [19-20]:

$$\omega_n = \frac{c}{L \cdot \sqrt{\frac{1}{2} + \frac{4 \cdot Q}{\pi \cdot D^2 \cdot L}}} \tag{2}$$

where: c represents the sound velocity in the medium contained inside the capillary; D represents the internal capillary diameter; Q represents the sensor cavity volume and L represents the capillary length. By its turn, the damping coefficient of the pressure measurement channel can be approximated by [19]:

$$\tau = \frac{16 \cdot \mu}{D^2 \cdot \rho \cdot \omega_n} \tag{3}$$

where: μ represents the capillary fluid dynamic viscosity; D represents the internal capillary diameter; ρ represents the capillary fluid density and ω_n represents the natural frequency of the capillary plus the sensor cavity volume. From (2) and (3), it is possible to conclude that there is a compromise in the product of the damping coefficient times natural the frequency of the pressure measurement channel that does not depend on the capillary length and that varies inversely with the square value of the capillary diameter.

4. Calibration prototype

In the next paragraphs the hardware and software parts of the calibration prototype will be presented. The proposed low-cost prototype can be used as a periodic or aperiodic pressure generator being possible to perform time and frequency characterization of a dynamic pressure measurement channel in the low-medium pressure range. The developed prototype is mainly based on an electro-pneumatic pressure regulator (EPPR) and works, basically, as an arbitrary waveform pressure generator for pressure amplitudes lower than 10 p.s.i.. This pressure range can be extended using EPPR devices with a larger pressure output range. It is also important to underline an innovative capability of the proposed calibrator that consists on its ability to regulate its output according to the real pressure values that are applied to the remote pressure transducer that is under calibration. This advantage is particularly important to avoid errors caused by any fluid leakage that can exist in the pressure measurement channel, namely, in the pressure transmission line that interconnects the pressure measuring tap to the remote transducer. Apart from the previously mentioned benefits, of the proposed prototype, it must be underlined that the accuracy that can be achieved is not as high as the accuracy and measuring range that can be achieved with some commercial dynamic calibrators [21-23] that use, either, time or frequency calibration methods being not possible to use both methods in the same calibrator.

4.1. Hardware

Figure 4 represents the basic block diagram of the electropneumatic pressure regulator (EPPR), used to generate pressure signals for static and dynamic calibration. The main components of the block diagram include: a pneumatic pressure transducer (PT1), a miniature electrovalve with vent capability, used to speed up the pneumatic discharge of air and for zero calibration purposes, a miniature proportional valve (MPV) and some elementary signal conditioning circuits, namely, a comparator and a voltage follower. The setpoint signal, used to define the pressure to be applied to the pressure device under test (PDUT), is generated by a multifunction data acquisition board with 12-bit resolution; a maximum sampling rate of 50 kS/s and a variable DAC output voltage range between 0 and 5 V. The two inputs and three outputs of the EPPR block are, respectively: the control voltage (“setpoint”) of the pressure EPPR output, whose value varies between 0 and 5 V; the air supply (AS); the output pressure monitoring signal (MPS), also variable between 0 and 5 V; the air exhaust outlet (VENT) and the interconnection terminal to the PDUT under test or calibration. Connecting the EPPR device to a PC equipped with a multifunction data acquisition board (PC+DAQ), it is possible to generate calibration signals with different amplitudes, frequencies and waveforms, including arbitrary waveforms. In this way, for each pressure value, required for static or dynamic calibration purposes, the calibration routine sequence include the following steps: the program installed in the PC calculates the corresponding voltage value, for a given pressure value, and the multifunction board output the calibration voltage to the EPPR setpoint voltage input; the EPPR imposes an output pressure value that is a function of the setpoint voltage of the electronic control circuit; the monitoring pressure signal (MPSS) is compared with the pressure signal applied to the PDUT and the difference between these pressure values is compensated by a feedback control loop Regarding the main characteristics of the pressure sensor [24] used for feedback sensing purposes it includes a measuring range between 0 and 5 p.s.i. and a response time of 1 ms.

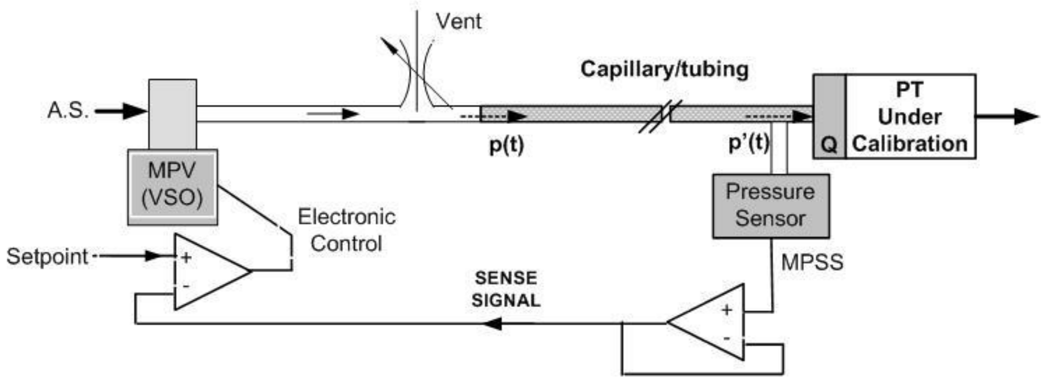


Fig. 4. System hardware block diagram (A.S.- air supply; MPSS- monitoring pressure sensor signal; PT- pressure transmitter; MPV- miniature proportional valve).

An important advantage of the proposed calibration prototype is that it can be used to test field located equipment without need to disconnect the capillaries, or impulse lines, which means that the working conditions of complete pressure channel are not changed during calibration. Additionally, the remote pressure sensing capability of the proposed prototype enables the compensation of the errors associated with pressure drops, such as the typical errors caused by leakages in the pressure transmission line and associated mechanical tubing connectors and interfaces. As limitations of the proposed calibration system, it must be referred that the time response of its components limits the maximum value of the working frequencies to a few hundreds of Hertz and the pressure amplitudes to a few hundreds of kPa.

4.2. Software

Several procedures for configuring the calibration signal, processing data for evaluating static and dynamic calibration parameters, storing calibration data, and producing calibration reports are all included in the software of the proposed pressure calibrator. Almost all software routines were developed using the LabVIEW graphical program language. Figure 5 represents the front panel of the virtual instrument (VI) that is used to parametrize the pressure signal, used for calibration and testing purposes. The main configuration parameters, displayed in the VI front panel include the pressure signal waveform, its frequency and amplitude, and the offset of the control voltage signal that is applied to the setpoint input of the EPPR device. The main attributes of the pressure calibration signal include the number of bursts, the number of pulses within each burst, the duration of the inter-burst pause, and a burst modulation parameter. In the example represented in figure 5, the pressure calibration signal consists of two burst patterns, seven pressure pulses per burst, a second inter-burst pause, a triangle pattern waveform with frequency equal to 5 Hz, amplitude equal to 1 V and an offset equal to 2.5V.

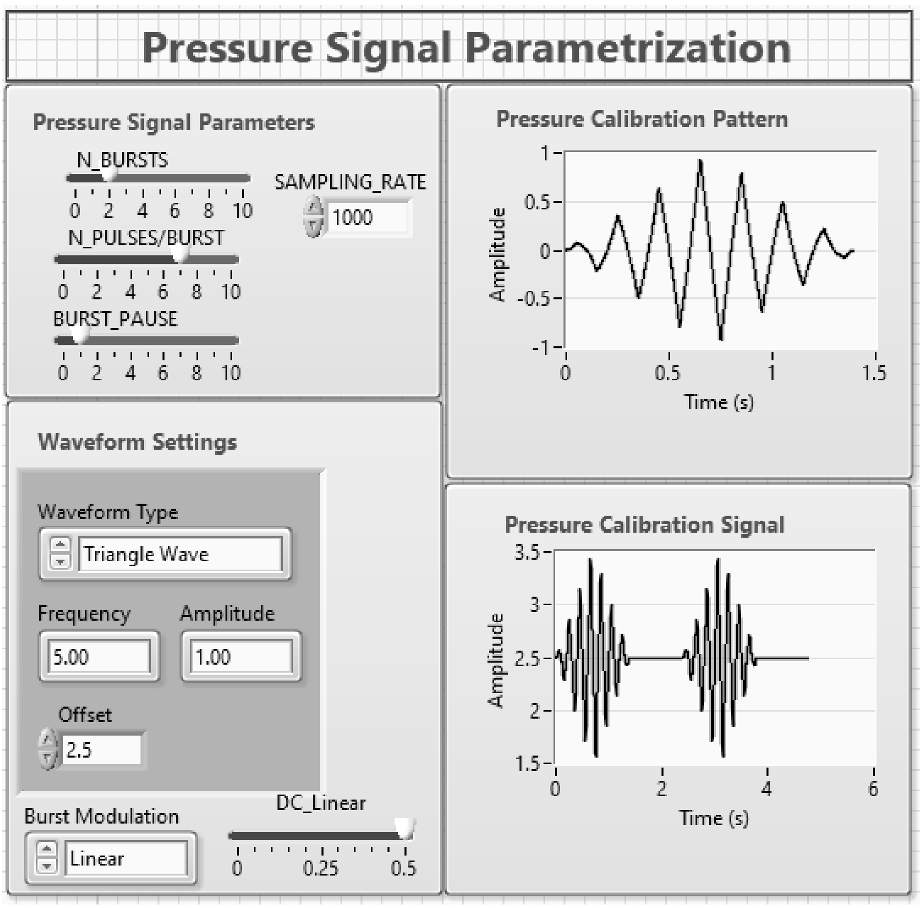


Fig. 5. Front panel of the LabVIEW virtual instrument used to parametrize the calibration pressure signal.

Additional routines of the developed software are used to perform static calibration, diagnostic tests of the hardware, namely of the EPPR device, to collect calibration results from the PDUT and to store measurement and historical calibration data obtained, over the time, for the same PDUT. This data is particularly important in industrial applications to defined the cycle of the routine maintenance tasks and to implement condition-based maintenance. Figure 6 represents the block diagram that implements the main routine of the LabVIEW virtual instrument (VI) previously referred.

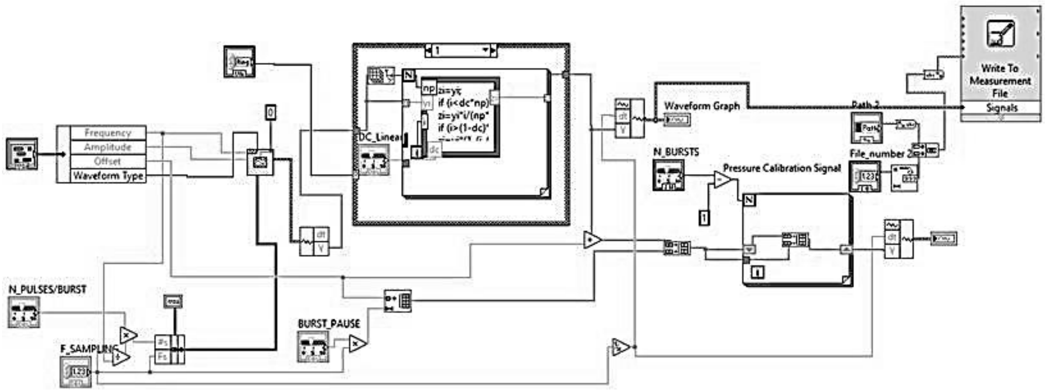


Fig. 6. Block diagram of the LabVIEW virtual instrument used to parametrize the calibration pressure signal.

5. Experimental results

The present section includes two application cases to demonstrate the capabilities of the presented prototype. One case is related with the testing and calibration of a pressure transmitter, connected through a pressure transmission line to our prototype, and the other case is related with the calibration of an automatic oscillometric sphygmomanometer.

5.1. Industrial pressure transmitter

In order to experimentally verify the importance of the frequency characterization of the pressure measurement channel, when pressure dynamic measurements are performed, the proposed calibration prototype was used to generate pressure variations with different waveforms, amplitudes and frequency contents. Both calibration methodologies, in time and frequency domains, were considered. Figure 7 represents the test set up used to perform a dynamic calibration of a pressure transmitter that is remotely connected to the calibrator through a pneumatic tube.

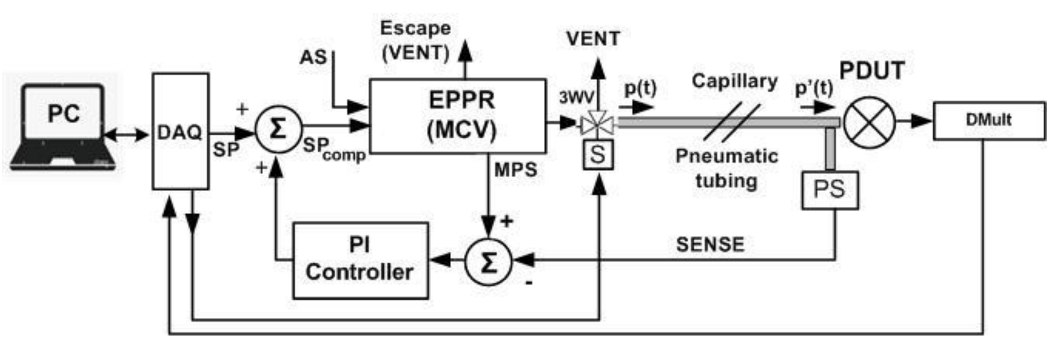


Fig. 7. Testing block diagram used to evaluate the dynamic behavior of a pressure transmitter (PDUT- pressure device under test; SP- setpoint; DAQ- data acquisition board; DMult- digital multimeter; PS- pressure sensor used for pressure sensing purposes; 3WV- 3-way electric solenoid valve; EPPR- electropneumatic pressure regulator; MCV- miniature control valve; PIC- proportional and integral controller; S- 3-way electrical valve control signal).

The main elements of the testing block diagram include: the pressure transmitter to be calibrated [25]; the prototype calibrator previously described; a 3-way electric solenoidal valve [26]; the capillary or pneumatic tubing; the pressure sensor used for remote sensing of PDUT applied pressure; a digital multimeter [27] and a data acquisition board [28]. Experimental tests were easily carried out using flexible pneumatic tubes with different characteristics in terms of lengths, diameters and fluid medium inside the pneumatic tubing. The main specifications of the differential pressure transmitter used for testing purposes includes: a large number of 32 different measuring ranges, varying between a minimum of 0.125 p.s.i. and a maximum of 3200 p.s.i., easily changed by the user by replacing the sensor's diaphragm; an accuracy of ±0.5% of F.S., including non-linearity and hysteresis errors; a very low-pressure cavity volume of 0.004 cu in. and a flat bandwidth frequency equal to 80 Hz, sensor plus its conditioning circuit, when the varying pressure source is close-coupled to the sensor port. Figure 8 represents the natural frequency associated with pneumatic tubes with different lengths and two different internal diameter values. For each pneumatic tube diameter tests were carried out using lengths varying between 50 cm and 300 cm, with increments of 50 cm.

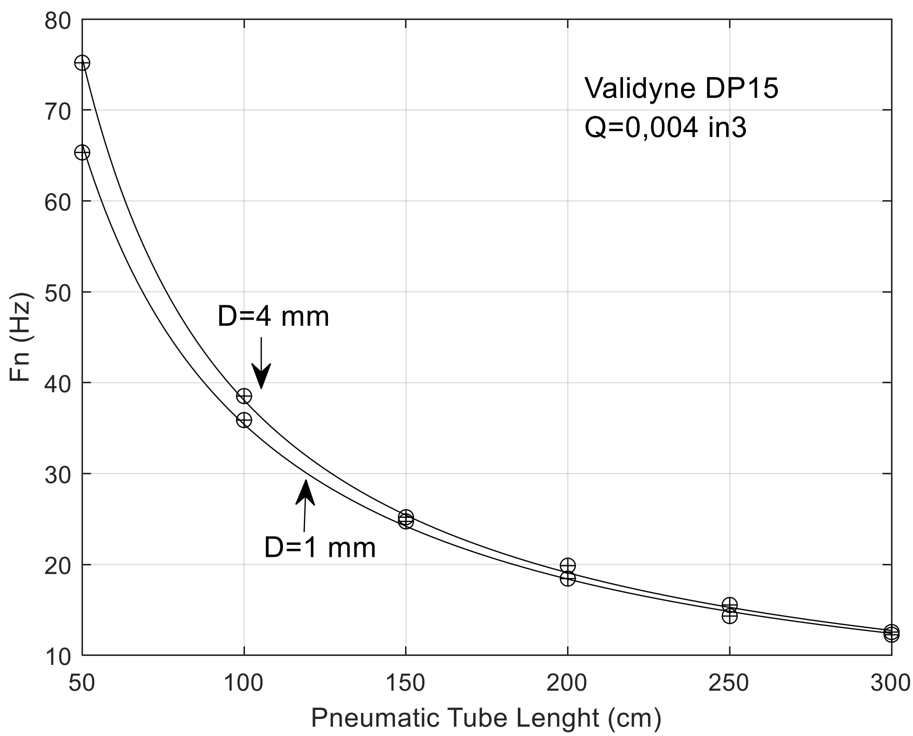


Fig. 8. Natural frequency of the capillary when its length varies between 50 cm and 300 cm and its internal diameter (D) is equal to 1 mm and 4 mm (⊕ symbol- experimental values; continuous line- theoretical expectations).

As expected from (2), the natural frequency imposed by the capillary is inversely proportional to the capillary length being its dependence on capillary diameter very low, since que cavity volume of the PTUD is also very low. By its turn, figure 9 represents the relative error deviation between experimental values and theoretical expectations for the natural frequency and for the same set of experimental points.

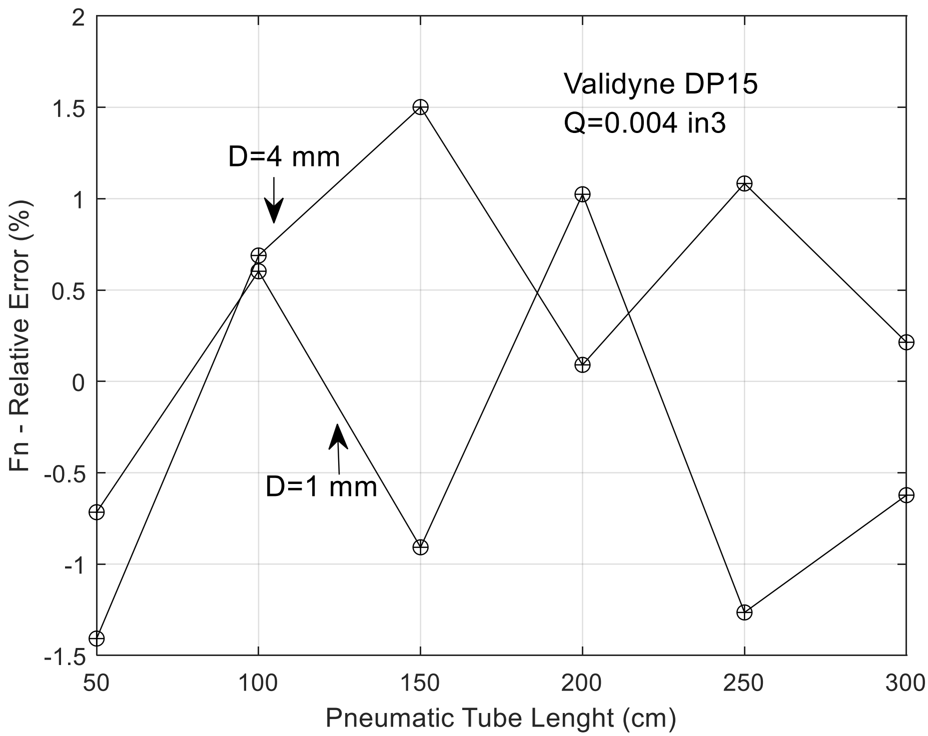


Fig. 9. Relative error deviation between experimental values and theoretical expectations for the natural frequency of the pneumatic tube when its length varies between 50 cm and 300 cm and its internal diameter (D) is equal to 1 mm and 4 mm (⊕ symbol- experimental values; continuous line- linear interpolation values).

A time response characterization of the pressure measurement channel was also performed using a technique known as pressure step down. Basically, this test was carried out by pressurizing the pneumatic tube to a fixed pressure value, in our case equal to 5 p.s.i., and then the 3-way solenoid valve is actuated and the pressure drops abruptly to the atmospheric value. Figure 10 and figure 11 represents theoretical and experimental temporal responses for a pressure step down test for two different cases with different damping coefficients that corresponds to an underdamped and overdamped second order system response, respectively.

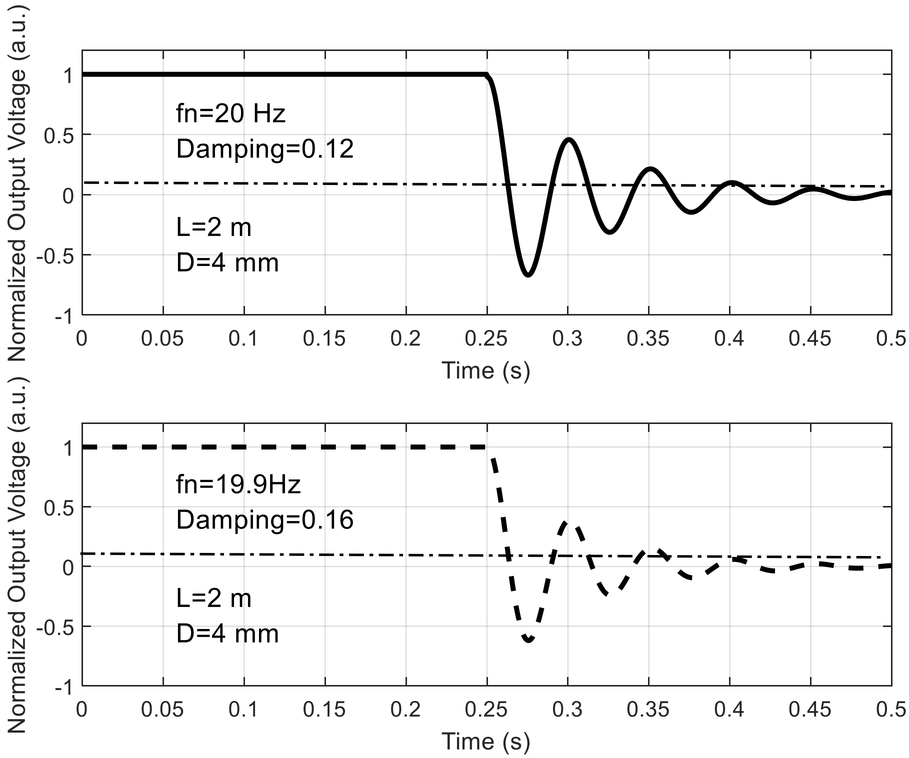


Fig.10. Time response of a pressure channel with a pneumatic tube with 2 m length and 4 mm diameter in an underdamped condition (continuous line- theoretical response; dashed line- experimental response).

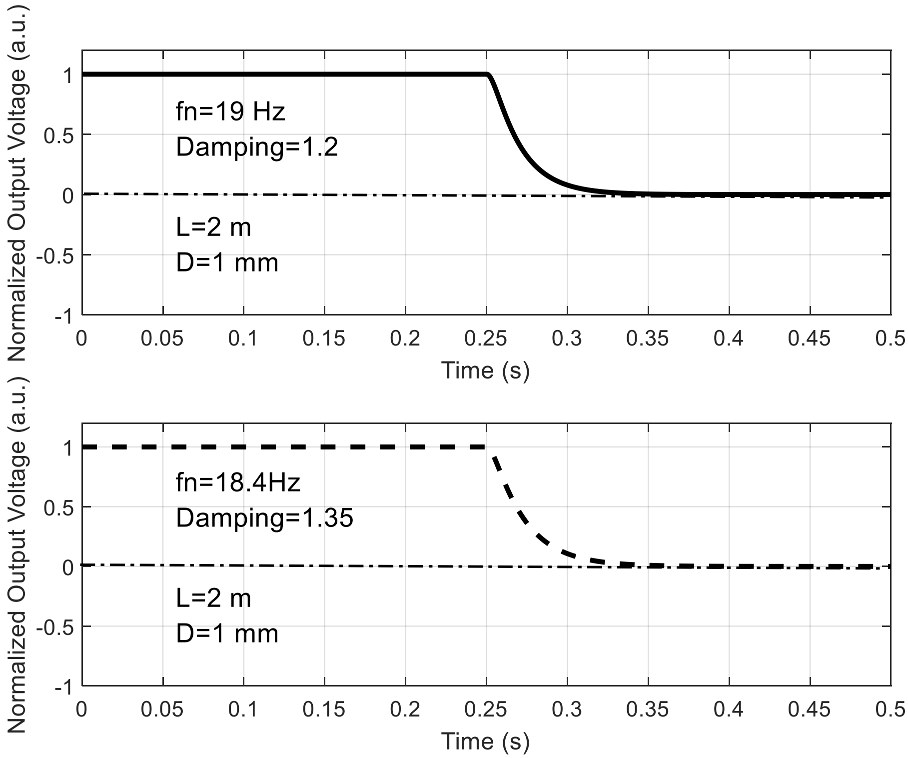
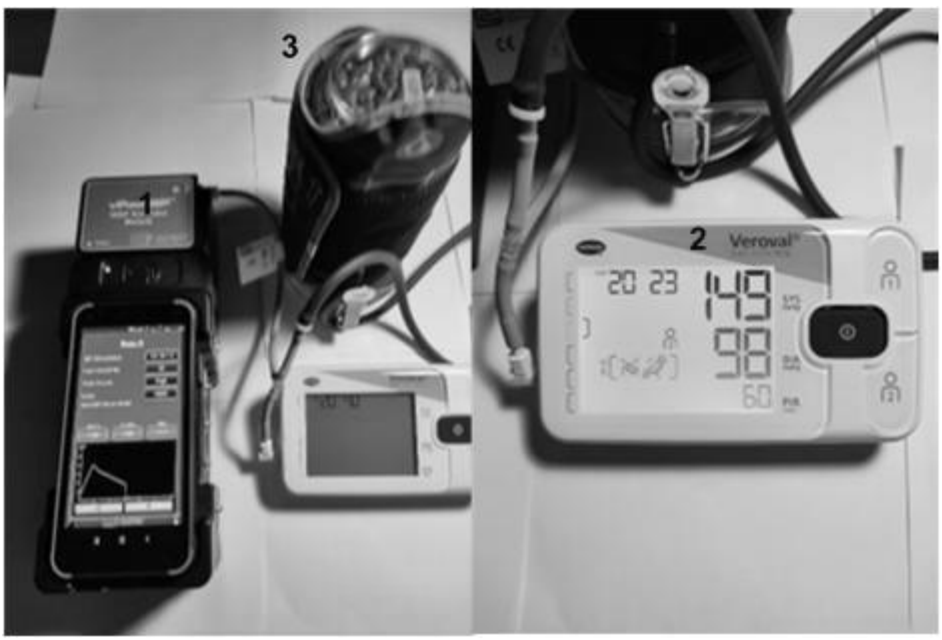


Fig. 11. Time response of a pressure channel with a pneumatic tube with 2 m length and 1 mm diameter in an overdamped condition (continuous line- theoretical response; dashed line- experimental response).

The natural frequencies obtained are a little bit lower than the theoretical expected values. The reason for the difference can easily be justified by the maximum operating speed of the solenoid valve, by the pneumatic tube quality and by the transducer's porting and fittings limitations.

5.2. Non-invasive automatic blood-pressure sphygmomanometer

In order to evaluate the performance of the developed prototype with a well-known biomedical device, a comparison between the calibration results that were obtained with our proposed prototype and the results obtained with an accurate biomedical simulator [29], for a given commercial sphygmomanometer [30] was performed. Regarding the sphygmomanometer unit, that was used to compare experimental calibration results, it is important to refer that it is clinically validated in accordance with a large number of certified entities that includes EN 1060 and EN 81060, the European Society of Hypertension (ESH) and the German Association for High Blood Pressure (DHL), among others. The reference simulator is a modular equipment, very versatile and supports maintenance and calibration of NIBP equipment, from the simplest commercial equipment, for home usage, to very accurate equipment used in hospital intensive care units (ICU). The entire system is controlled by an Android™ device, which allows to perform tests remotely. This equipment has large storage capabilities and includes a large number of specific modules that enables the connection of the simulator with the majority of biomedical equipment available in the market. The NIBP module that was used has the following main specifications: NIBP measurement using the oscillometric simulation method; capability to measure the cardiac rate in the range between 20 and 240 beats per minute (BPM) with an accuracy equal to ±0.25 BPM; minimum diastolic blood pressure measurement capability of 15 mmHg and a maximum systolic pressure measurement capability of 275 mmHg; regulated pressure source in the range between 10.0 and 400.0 mmHg with an accuracy of ±0.5mmHg and a resolution of 0.1mmHg. Figure 12 represents the test setup that was used to calibrate the home blood pressure monitor.



(a) (b)

Fig. 12. Test setup used to calibrate a commercial home blood pressure monitor: (a) equipment interconnections (1- biomedical simulator, 2- home blood pressure monitor, 3- dummy arm used to fix the sphygmomanometer cuff); (b) front view of the home blood pressure monitor with displayed results.

The blood pressure simulator is configured to periodically generate standardized values for systolic and diastolic pressures with a given rate defined by the desired value of BPM. The pressure signal generated by the simulator is applied to the BP monitor, used for comparative purposes, and to a dummy arm that simulates the human body arm that is surrounded by the sphygmomanometer cuff. In this way, the pressure signal generated by the reference simulator is added with the ramp down pressure signal generated by the BP monitor. As an example, the graph represented in the upper part of figure 13 represents the pressure signal generated by the simulator and the graph in the down part, of the same figure, represents the associated BP pulses that are superimposed to the pressure ramp signal variations. The configuration defined for the calibration signal is characterized by the following set of parameters: an inflation speed equal to 15 mmHg/s; a deflation speed equal to 5 mmHg/s; and a sampling rate equal to 1024 S/s.

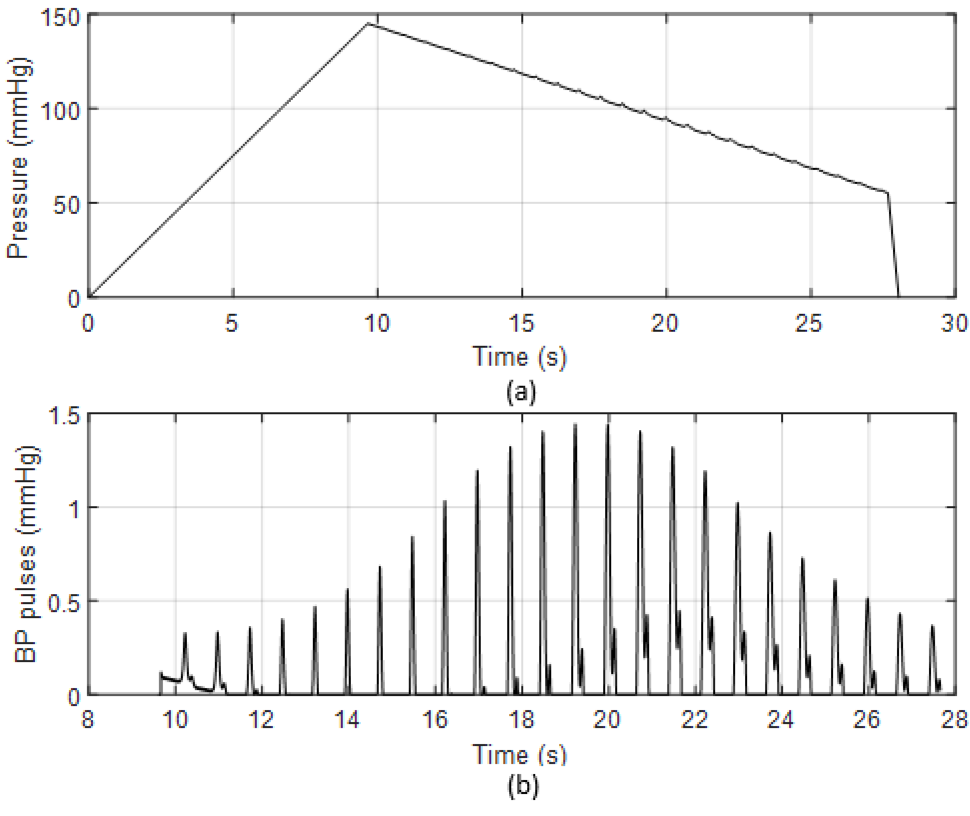


Fig. 13. Simulator calibration signal: (a) pressure applied to the BP monitor; (b) BP pulses included in the pressure signal.

In this experiment the standardized blood pressure signal generated by the simulator is characterized by the following set of parameters: systolic pressure equal to 150 mmHg, diastolic pressure equal to 100 mmHg and a pulse bit rate equal to 60 BPM. After the first calibration, done with the reference simulator, this simulator was replaced by our calibration prototype using the same configuration parameters that were used with the reference simulator. The set of parametrizations used for a comparative evaluation between the BP prototype and the BP simulator includes the following set of values for BPM, diastolic and systolic pressures: 60-30-40; 80-50-60; 100-65-77; 120-80-93; 150-

100-117 and 200-150-167, respectively. Figure 14 and figure 15 represents the measurement results obtained by the BP monitor.

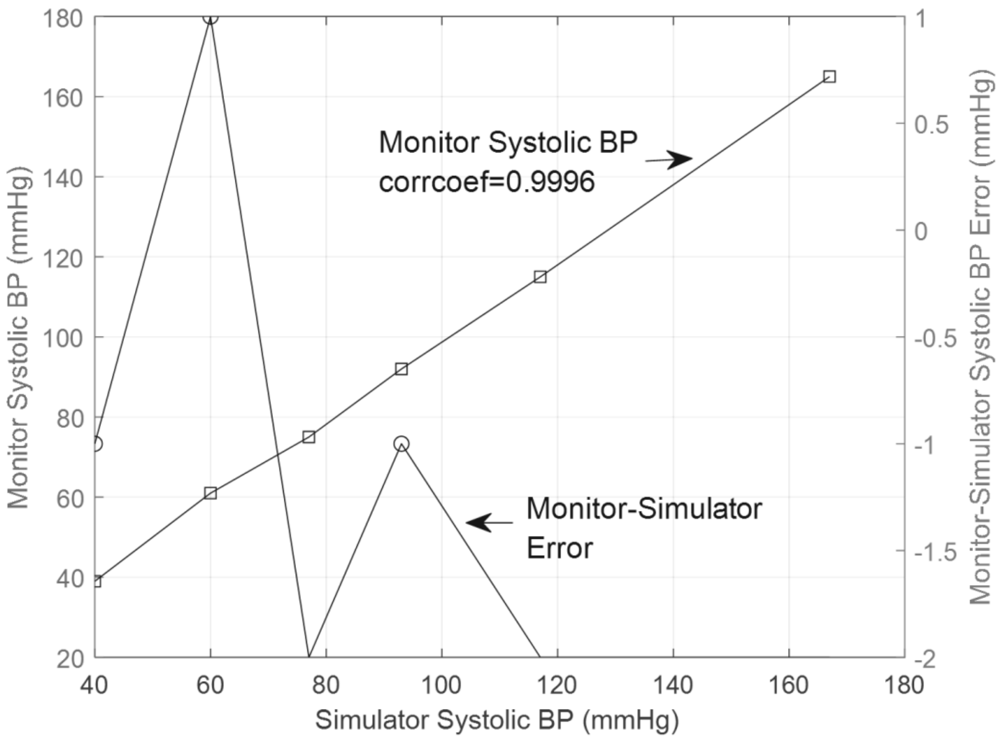


Fig. 14. Measurement results obtained by the BP monitor using the simulator to perform calibration.

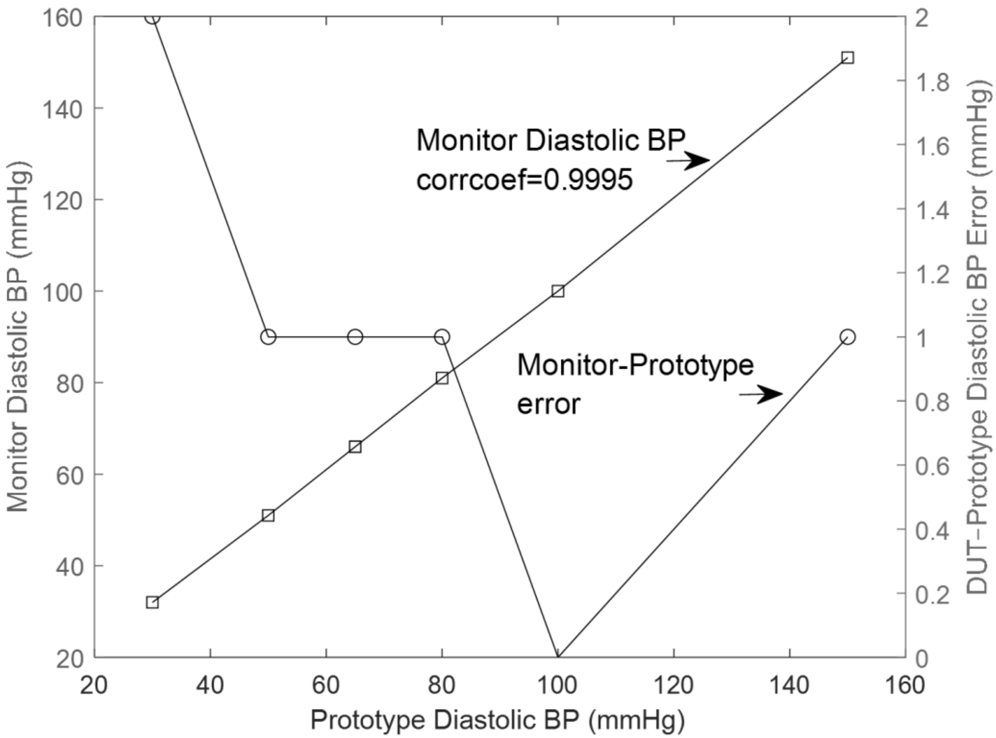


Fig. 15. Measurement results obtained by the BP monitor using the prototype to perform calibration.

The comparative results obtained with both calibrators, using the same values for systolic and diastolic pressures, are in conformity with the monitor BP measurements and the absolute error, obtained with each one of the calibrators. The absolute error is lower than 2 mmHg, which corresponds to a relative error almost equal to 1.4 % relatively to the pressure measurement range that is equal to 140 mmHg. It is important to refer that this error is lower than the one associated with the technical specification of the BP monitor that is equal to 3 %, being also verified that the maximum BPM relative error is lower than the technical specification value, which is equal to 5 %. Moreover, it is also important to underline that the correlation coefficient values that were obtained, between both calibrators and the BP monitor were better that 0.9995.

6. Conclusions

This chapter paid a special attention to static and dynamic calibration of pressure measurement channels. Regarding dynamic calibration, it is very important to analyze the frequency response of the different elements that are included in the pressure measurement channel. Whenever the measurement channel includes pressure transmission lines that are frequently used to interconnect pressure sensors to the conditioning circuits of the pressure transmitters, these transmission lines are, usually, the key element that imposes the greatest restrictions in terms of pressure channel bandwidth. In the second part of the chapter a low-cost and flexible calibrator protype, that can be used to perform static and dynamic pressure calibrations and devices' testing, is presented. The chapter ends with two application examples where dynamic calibration is important. One example is related with the calibration of an industrial pressure transmitter and the other example is related with the calibration of a home blood pressure monitor. In the industrial application example, a particular attention is dedicated to the bandwidth limitations that are associated with the capillaries that are frequently used to interconnect the remote pressure measurement taps to the pressure transmitter. In the second example a comparison, in terms of accuracy, is established between the proposed prototype and a certificated calibrator. As expected, the measurement errors that are obtained with the proposed prototype calibrator are a little bit higher than the errors that are obtained with a certificated biomedical calibrator. However, those results achieved the expected goals, in terms of accuracy, and further improvements are possible to obtain, in a near future, using faster speed 3-way valves and hardware components with better time and frequency performances.

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