A NEW METHOD TO CALIBRATE PRESSURE GAUGES FOR PNEUMATIC APPLICATIONS

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Abstract. The pressure gauges are devices for measuring and monitoring pressure in fluid lines such as air, steam, oil and water. These devices generally support pressure in a diaphragm instrumented strain gauges. The pressure is converted to analog electrical signals, which are then processed and converted into digital signals for data acquisition. These pressure gauges are widely used in mechanical industry, chemical, petrochemical, aerospace, agricultural, medical, etc.. The calibration process following routines described in procedures, which allows for verification of compliance of the results. However, the process is not always automatic and may add uncertainty components and spend a significant time. This work aims to develop a methodology for calibrating pressure gauges, based on best practices, and a computer program capable of managing the automated calibration process. The program will be developed on LabView platform with the implementation of statistical tools to assist in the analysis of calibration device. The pressure gauges used in this work are capable of measuring 200 psi (~ 13.8 bar) and are used in conventional compressed air lines. The calibrations were performed with maximum pressure of 6 bar. The method showed adequate results and allowed for the calibration of gauges in significantly less time than the conventional. In addition, the system features and software developed can be adapted to any kind of calibration of pressure gauges based on strain gauges. The method met the objectives, allowing for quick and reliable calibration of pressure gauges. (Mechatronics, automation, control and metrology)

Keywords: calibration, pressure transducer

1. INTRODUÇÃO

The objective of this work is to develop a new automated methodology for calibrating pressure gauges. During this research, a brief review will be conducted covering the basics foundations of pressure measurement, pressure gauge, calibration methods, and statistical evaluation. The methodology should be easy to understand, feasible, allow for clear analysis of the results, and also have advantages with respect to calibration time, besides the easiness to use the program.

Calibration is a method widely used by research laboratories and companies looking for quality and reliability. Basically, it means to compare the instrument under analysis to a higher standard, i.e. with lower uncertainty. These Labs in turn develop their own procedures to standardize and control the calibration. Among the numerous works related to calibration performed by certified laboratories are the calibration guides developed by INMETRO - National Institute of Metrology, Standardization and Industrial Quality (INMETRO, 2010), and the one developed by EURAMET - European Association of National Metrology Institutes (EURAMET, 2007). Among the works carried out by researchers investigating this issue are those of Bao et al. (2003), Wuest et al. (2007), Kojima, Saitou and Kobata (2007) and Ripper et al. (2009), each one with specific approaches, demonstrating the feasibility of the employment of new methods for calibration.

In order to achieve the objective proposed in this paper, a previous study of different forms of calibration of pressure gauges was develop to define an optimal method for calibrating pressure gauges. For this, we used two pressure gauges with a capacity of 200 psi (13.8 bar) connected to a compressed air network of 6 bar regulated through a manometer. The pressures were determined by software built in LabVIEW 8.2 platform. This software and the setup enable the pressures are measured in two different gauges simultaneously. By varying the pressure in the line where the two gauges mentioned previously were connected we found the adjustment of the gauge to be calibrated, provided the other gauge is calibrated. Using this methodology we determined the fitting curve for the pressure gauge, allowing its calibration.

2. BASICS FOUNDATIONS OF CALIBRATION

Calibration requires the knowledge about the parameter under evaluation, the forms to measure the parameters, and the main methods to treat the results. This topic describes each one of those, focusing on the problem of measuring the pressure.

2.1 Pressure Measurement

Pressure measurement can be performed in two ways, by reference instruments (often mechanical) or by pressure gauges, being the medium in which it works and its required precision the determinant factors to choose the type of instrument utilized (Doebelin, 2004).

The pressure gauges act like sensor and gauge. The second includes the first. Sensor element (elastic) absorbs the deformations, which is transformed in measurable signals by the gauge (Figliola and Beasley, 2006).

The pressure gauges based on strain-gages are widely employed due to their set of unique features, having high accuracy and stability, which make them known like field gauges. Such advantages are due to:

− Small size and mass, an important factor when it is necessary to reduce inertia effects;
− The strain-gage is all linked to basic elastic structure, ensuring high linearity and large range of deformation;
− The low effect of temperature in the equipment;
− The output of the circuit is the variation of its resistance.

The elastic diaphragm is a thin plate of metal (sensor element), in most cases of stainless steel. This membrane is the most critical mechanical component, since such device is responsible to transmit the deformation to the gauge. It is important to emphasize that deformation of the diaphragm should varies linearly with the change in resistance, as any conventional gauge (Window, 1992).

The excitations provided from deformation of sensor element change the resistance in two (or four) arms of Wheatstone bridge, which correspond to gauge element of these strain-gages. This excitation is transmitted to the system of signal processing through the electrical connector.

Other feature of this type of gauge is the presence of a stop bar, which is activated when the pressure exceeds the limit of the gauge (Norton, 1969).

2.2 Calibration of pressure measurement valves

The calibration process aims establish the variables that describe the global function of transference of the equipments (Fraden, 2003). So, if the mathematical model that describes this function is linear, the calibration consists of finding the slope and the intercept of the straight line in the graph.

According with Doebelin (2004), an accurate pressure measurement standard ensures the calibration of instruments of lower accuracy. Such standards are defined in accordance with the pressure range.

One type of calibration is the static calibration, which is performed by direct comparison of measurements obtained by the equipment to be calibrated with the values provided by the instrument of more accuracy (reference instrument), or a standard gauge certified by a laboratory (Figliola and Beasley, 2006).

The procedure of calibration consist of applying known pressure values in the gauge chamber, exposing the gauges simultaneously to the same level of pressure, in order to plot a graph that describes the relation between the pressures of standard gauge and the calibrated gauge. The pair of values is taken after the stabilization of the pressure. The graph obtained plots the calibration curve.

As the curve of static calibration correlates static input and output variables, this curve is valuable for the development of functional relation between the variables. The correlation is obtained through physical reasoning and by applying techniques of curve fitting in the calibration graph.

The term static used in this kind of calibration is because the variables involved in the process are constant; they do not vary with time. So, only the input and output values are considered important (Figliola and Beasley, 2006).

However, there are also dynamic calibrations, for which the variables change with time (or space). In this type of calibration, the value is the rise time and frequency response of pressure gauges. The time dependence of these variables is both in the magnitude and in the frequency (Figliola and Beasley, 2006). These calibrations use a sinusoidal signal or step change as input variables. An electric switching valve is used to generate such step change. Therefore, dynamic calibration correlates the dynamic behavior of known input and output measurement system.

No matter the kind of calibration, this proceeding can be automated in order to improve its quality, organization and accuracy, providing a more detailed report.

To automate a calibration it is required a good understanding of the action of each variable in the process and their interrelationship (Fluke, 1994). Although this process is laborious, it guarantees more consistent measurements, increasing productivity. It also offers automatic documentation and reduction of the procedure cost.

2.3. Curve quality and fitting

According to Vuolo (2000) and Griffiths (2009), to determine the equation of the curve fitting (Y), that match to the static calibration of equipments, is necessary find the parameters a and b, Equation (2) and (3), respectively.

$$Y = ax + b \qquad (1)$$

$$a = \frac{1}{\Delta}\left(S_0.S_{XY} - S_X.S_Y\right) \qquad (2)$$

$$b = \frac{1}{\Delta}\left(S_{X^2}.S_Y - S_X.S_{XY}\right) \tag{3}$$

The equation used to calculate the determinant (Δ) is

$$\Delta = S_\sigma.S_{X^2} - S_X^2 \tag{4}$$

Equations (5) and (6) are needed to determine the average number of uncertainty bars $\left(\overline{N}_{cz}\right)$ and standard deviation $\left(\sigma_{N_{CZ}}\right)$ using on the concept of verisimilitude (Vuolo, 2000).

$$\overline{N}_{CZ} = \frac{2}{3}\upsilon + p = \frac{2}{3}n + \frac{1}{3}p \tag{5}$$

$$\sigma_{N_{CZ}} = \sqrt{n.q.(1-q)} \cong \sqrt{\frac{\overline{N}_{CZ}}{3}} \tag{6}$$

Being υ the degree of freedom that is equal to $n - p$, where n is the number of levels or points and p is the curve parameter (for straight line, $p=2$). So we can check the quality of fit based in the fit curve and uncertainty bars.

To ensure that the curve fitting found match to straight line waited, it is necessary use the Chi-square distribution. The Chi-square distribution models the difference between the expected value and the value obtained and can be calculated with the Equation (7).

$$\chi^2 = \sum_{i=1}^{n}\frac{[y_i - f(x_i)]^2}{\sigma_i^2} = \sum_{i=1}^{n}D_i^2 \tag{7}$$

Where D_i is distance of the experimental points to the fitted curve. This equation describes when the results obtained are very different from the values that you ought to find. So, through the Chi-square distribution it's possible to test the curve fitting and describes whether the values observed agree with the distribution specified or not.

The probability that the dispersion bars cross the fitting line is given by q. Equation (8) shows a reduced form of the the reduced Chi-square, which can be used to evaluate the result of the fitting process.

$$\chi_{red}^2 = \frac{\chi^2}{\upsilon} \tag{8}$$

Where, χ^2 corresponds to the Chi-square found in Tab. 1.

Table 1. Table chi-square.

Degrees of freedom	Right area of critical value										
	0,995	0,99	0,975	0,95	0,9	1	0,05	0,025	0,02	0,01	0,005
1			0,001	0,004	0,016	2,706	3,841	5,024	5,412	6,635	7,879
2	0,010	0,020	0,051	0,103	0,211	4,605	5,991	7,378	7,824	9,210	10,597
3	0,072	0,115	0,216	0,352	0,584	6,251	7,815	9,348	9,837	11,345	12,838
4	0,207	0,297	0,484	0,711	1,064	7,779	9,488	11,143	11,668	13,277	14,860
5	0,412	0,554	0,831	1,145	1,610	9,236	11,070	12,833	13,388	15,086	16,750
6	0,676	0,872	1,237	1,635	2,204	10,645	12,592	14,449	15,033	16,812	18,548
⯑	⯑	⯑	⯑	⯑	⯑	⯑	⯑	⯑	⯑	⯑	⯑

2.4. Propagation and Transfer of Uncertainty

According Vuolo (2000) and INMETRO (2003), assuming a magnitude w in function of other magnitudes x, y and z, represented by w = w(x, y, z). The uncertainties standards are σ_x, σ_y and σ_z, respectively. If the errors are independent between them, the uncertainty standard in w is

$$\sigma_w^2 = \left(\frac{\partial w}{\partial x}\right)^2 \sigma_x^2 + \left(\frac{\partial w}{\partial y}\right)^2 \sigma_y^2 + \left(\frac{\partial w}{\partial z}\right)^2 \sigma_z^2 \qquad (9)$$

Suppose we have a magnitude y measure in function of variable x which is independent $(y = f(x))$. Therefore, x and y should be show in chart with uncertainty bars. The uncertainty of the variable x is transfer to magnitude y, so we will have an increase in uncertainty y resulting in a variance σ_y^2, Equation (10).

$$\sigma_y^2 = \sigma_{y0}^2 + \left(\frac{dy}{dx}\right)_0^2 \sigma_x^2 \qquad (10)$$

Where σ_{y0}^2 is the original variance and $(dy/dx)_0^2 \sigma_x^2$ is the variance representing the transfer uncertainty from x to y along with a preliminary estimate of the derivative (dy/dx).

3. PROCEDURE AND MATERIALS FOR CALIBRATION OF PRESSURE GAUGE

The following text describes the equipment and the software used in the process of automating the calibration process.

3.1. Equipment

For the experiment we used two pressure gauges Sensotec with a maximum capacity of 200 psi (~ 13.8 psi) that are equivalent to the model JTE 708-12 from Honeywell. The pressure control system consists of a proportional valve used for regulating the inlet pressure of the pressure gauges. Its brand is Mannesmann, model DE561 012 062 0. A relay control system brand Finder 10A 250V (24V DC), type 94.74, and an optical sensor that controls the relay 5V, complete the system. These are interrelated and connected to a compressed air line with pressure of 6 bar regulated by a pressure manometer Festo.

For signal acquisition and control, we used an acquisition board National Instruments NI PCI 6229 -16 Bit, 250 kS/s, 32 analog inputs with a block of connections. We also used a signal conditioner model CB 68LP and an amplifier Measurement Instruments, Model 2160. Figure 3 shows the complete system used in the experiment.
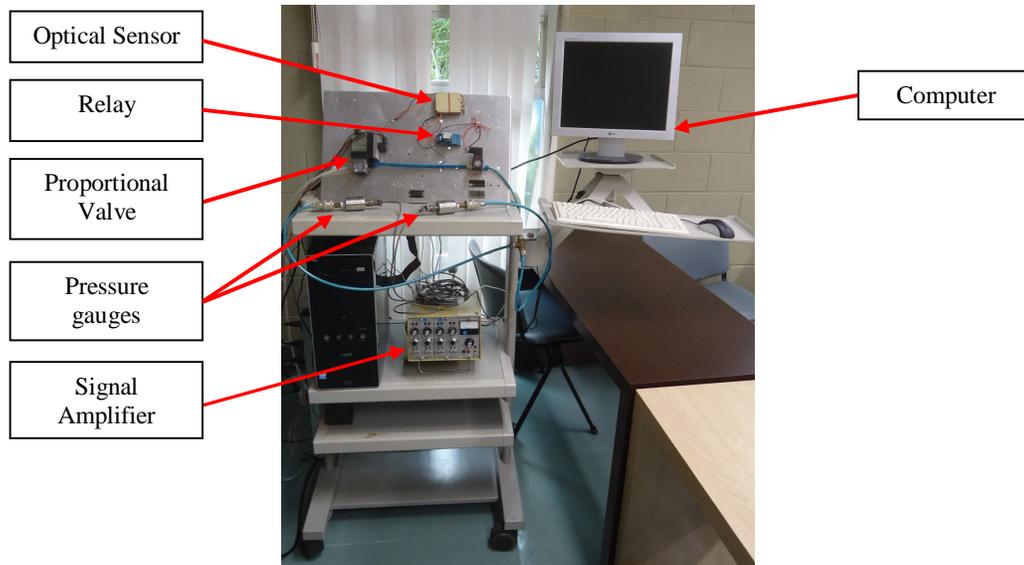
Figure 3. System to monitoring signals and calibrate the pressure gauges.

3.2. Program to analyze the data and calibrate the gauges

The program for calibration of pressure gauges was developed in LabVIEW 8.2 platform. The front page of the program introduces data of the title, author, institution, release, and date of development of the program.

Figure 4 shows the second page of the program, which presents the drivers of the program for calibration of the pressure gauges. This is used to set the variables of input on the program (input voltage (V), output voltage (V), Calibration Factor (mV/V), excitation voltage (V), amplification, and capacity meter (psi)). It has a button to control the proportional valve. It also has charts (Pressure Gauge Signal 1 and 2) and indicators (Gauge 1 and 2) to identify the balance and control the voltage signal sent by the valves.

The program controls automatically the opening of the proportional valve, which corresponds to the pressures level. Therefore, it is important to highlight that the number of steps is fixed in twelve levels, being six of rise and six of descent. The increment in each step is a function of the final and initial pressures.

Other characteristic of the program is that it saves and reads automatically the data files generated as ".lvm" (Data Files, Archives of Standard Deviation and Average Pressure in the Standard Gauge), reducing the time and the operations made by the user.
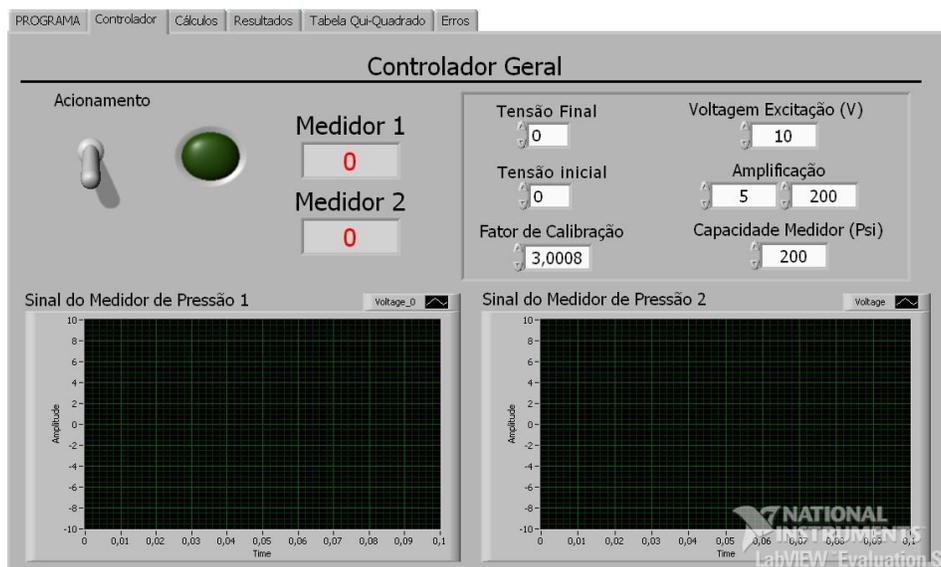
Figure 4 – Second page of the program for calibration of pressure gauges.

Figure 5 shows the third page of the program presents the calculations of the average read voltage on the pressure gauge to be calibrated (Average Yi (V)) and the standard uncertainty read voltage (Sigma i). After this, the calculation of Sx, Sx², Ssig, Sy and Sxy are needed to determine the adjusted parameters the curve. The sigma x represented the standard desviation that is use to calculate the transfer of uncertainty DP y + x, being that (dy/dx) was considered equal to 1.

Média Yi(V)	Sigma i	Sx	Sx²	Ssig	Sy	Sigma x	DP y + x	Sxy
0,00637	0,0073	-229,183	0.157383	3,34E+5	2,12E+3	0,001731	0,303462	-1,459
-0,22	0,0065	38833,5	4105,63	3,67E+5	-8,03E+4	0,00165	0,0033	-8538,3
-1,97	0,0094	246271	227555	2,67E+5	-5,24E+5	0,001937	0,303874	-4,844E+5
-3,74	0,0094	468217	820835	2,67E+5	-9,93E+5	0,001935	0,00387	-1,7505E+6
5,5	0,0066	937581	2,1165E+6	3,64E+5	2E+6	0,001658	0,003316	5,1565E+6
-7,26	0,0053	1,44407E+6	4,91355E+5	4,24E+5	-3,03E+6	0,001535	0,00307	-1,0487E+7
-9,02	0,0047	1,96347E+6	8,29679E+5	4,65E+5	-4,13E+6	0,001467	0,302934	-1,7709E+7
-7,26	0,0048	1,55603E+6	5,29632E+5	4,57E+5	-3,32E+6	0,001479	0,302958	-1,1296E+7
-5,5	0,00043	1,2654E+6	3,28569E+5	4,6E+5	-2,76E+6	0,001429	0,302856	-6,9587E+6
-3,74	0,0073	588373	1,02621E+5	3,32E+5	-1,24E+6	0,001735	0,0047	-2,1836E+6
-1,98	0,0086	269571	251675	2,89E+5	-5,72E+5	0,001861	0,303722	-5,338E+5
-0,2	0,0090	27572	2900,04	2,55E+5	-5,6E+4	0,00190	0,00396	-6053,9
0,02	8900761	26522214	4,31E+5	1,89E+7	0,020906	0,040702	5,6574E+7

Somatório

Figure 5 – Third page of the program for calibration of pressure gauges.

Figure 6 presents the calculations of the determinant Δ, the determination coefficient R² and the parameters a and b for the adjusted curve. In the upper right is the graph of Average Read Voltage (V) X Pressure (bar). In the lower region of the page we show the calculation of the quality of the adjusting using the Least Squares Method and the calculations of Reduced Chi-square. Using the Method of Maximum Likelihood we need to input the data of the levels and the number of the points that do not cross the adjusted straight line. To use the reduced chi-square is necessary to place the Q2 upper and Q1 lower limit, which can be found in the table on the fifth page of a program (similar to the Table 1). For this we need to know the percentage of confidence that can be determined by the area at the right of the critical value available in the table. In the upper central region we have Read Voltages (V), which was acquired from the standard pressure gauge and at its right the Pressure (bar) determined by the equation:

$$P = \frac{FSC \times V}{EV \times CF \times A}$$

(11)
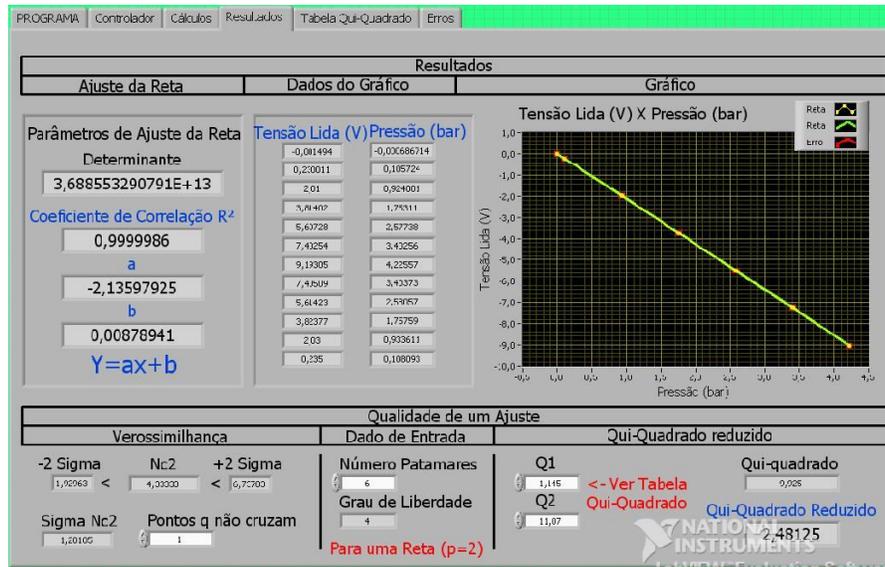
Figure 6. Fourth page of the program for calibration of pressure gauges.

In Equation (11), P is the pressure, FSC is the total capacity of the pressure gauge, V is the read voltage, EV is the excitation voltage, CF is the calibration factor and A is the amplification. This formula is used with a previous calibration chart, that came with the transducer.

This calculation is performed automatically by the program, and the user need only to input the data in the Controller and Results page of the program, according to the units in each field. The page called "Erros" of the program shows the errors boxes generated by input or output channel and data of the program. It also shows the errors identify boxes in the readings of the program, mainly those generated by the acquisition of signals from the pressure gauges.

4. RESULTS AND DISCUSSION

As we can see by the adjusting parameters the straight line generated by the program is different for each gauge. Table 2 shows the results of the parameters a and b from comparison between the pressure gauges 1 and 2 performed by the program. To check the results we used the Equation (2) and parameters a and b extracted from Table 2. The value of x is the pressure (P) found from the pressure gauge to be calibrated, which is given in Equation (12).

$$x = P = K.TL \tag{12}$$

Table 2. Parameters a and b from the program for calibration of the pressure gauges.

Parameters	Value
a	-2.136
b	0.009

K is the calibration factor resulting from the program, TL is the read voltage from the pressure gauge to be calibrated in volts, and Y is the average read voltage in volts (Average Yi (V)). The last parameter is found for the standard gauge. Thus, the calibration factor K determined is equal to 0.468. The calibration factor resulting from the calculation is 0.459. This corresponds to an approximate fit with a small difference in one pressure gauge from the other.

To find the average number of uncertainty bars $\left(\overline{N}_{cz}\right)$ we applied the method of likelihood. We considered the number of points and the curve parameter equal to 6 and 2, respectively. Thus we found the value of $\overline{N}_{cz}$ equal to 4.33 and $\sigma_{N_{cz}} = 1.20135 = 1$. With this, we have only one uncertainty bars crossed the fitted straight line. This corresponds to a fitting curve with bad fit. Thus, it was necessary to use a chi-square method with higher accuracy than the method of likelihood.

To determine the chi-square we also used points number and adjusting parameters equals to 6 and 2. The degrees of freedom are equal to 4, so the values of Q1 and Q2 that define the confidence interval of 90% to chi-square corresponds

to 1.145 and 11.070, but the reduced chi-square is equal to 0.1145 and 1.1070, respectively. The reduced chi-square determined by programa is equal to 2.4812. This value is outside the range of acceptable value for chi-square reduced, so the adjustment can be considered good. However, there is a possibility that the uncertainties were overestimated or underestimated. In addition, there is chance that straight line is an inappropriate function to be adjusted. Figure 7 shows the graph of Read Voltage (V) X Pressure (bar).
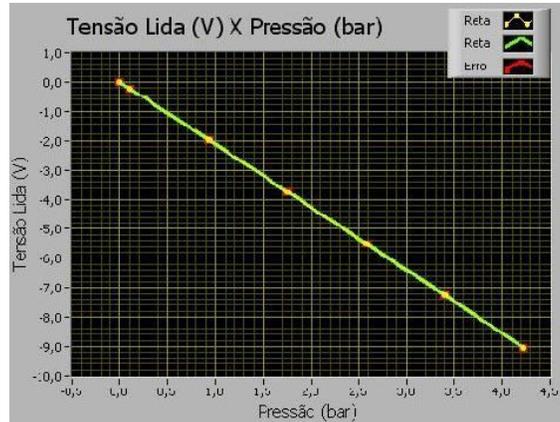
Figure 7. Read Voltage (V) X Pressure (bar) chart from the program of calibration of the pressure gauges.

Figure 7 shows the distribution of points that appears in yellow, the straight line through them generated in green and uncertainty bars in red. The line has the parameters a and b. The determination coefficient R² obtained when comparing the two pressure gauges is 0.9999986, corresponding to an adjustment of the line in 99.99%. Thus, the fit is considered adequate, because it is above 95%, which is the value of reference.

5. CONCLUSIONS

The program developed meets the objectives established by this work, providing a quick and reliable calibration of pressures gauges. This calibration is automated, thus, do not require all laborious operations of fitting curve. Another advantage is that the program allows the measurement of the pressure on two pressures gauges simultaneously and saves such measurements to posterior analyze. Besides, the variation of the pressure levels is automatic, allowing for more precise adjustment.

When comparing the two set of data, we obtained a good fit in both the straight line. The determination coefficients R² calculated using the program had value equal to 99.99% for both sets of data.

Using the parameters a and b presented by the program we calculate the calibration factor (K), which resulting value is equal to 0.468. The value found for the calibration factor (K) calculated using the formula of pressure, Equation (9), is equal to 0.459, which is the value we reported as corrected, once it came from a previous calibration using standard methods. Checking the fitted straight line we can conclude that the results we got are adequate.

Through the method of likelihood we estimated the value of $\overline{N}_{CZ}$, i.e., the average number of uncertainty bars that cross the line, which is equal to 4.33. For this calculation, we considered the number of points and curve parameter equal to 6 and 2, respectively. According with this way of looking the results, the fit is not adequate because only one uncertainty bars crossed the fitted straight line ($\sigma_{N_{CZ}} = 1.20135 = 1$).

Using the chi-square method, the value of chi-square is approximately 9.925 and reduced chi-square is 2.4812. The later is out of the limits: (Q1) of 1.145 and (Q2) of 11.070 for a confidence interval of 90% and 4 degrees of freedom, determined by Table 1 of Chapter 2. As the value of chi-square is between the range of Q1 and Q2, we can assume that fitting curve has a good fit.

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