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RESEARCH ARTICLE — OPEN ACCESS

Discontinuity measurement uncertainty evaluation using the Feeler PIG

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Abstract. The Feeler PIG is equipment that uses a geometric sensor to carry out the internal inspection of piping of different sizes. Several experiments on laboratory benches were carried out to evaluate the measuring accuracy of the Feeler PIG, considering a rotating metallic disk with discontinuities machined in its body and a single sensor for the detection of defects. The present work aims to study the measurement uncertainties with the Feeler PIG, through a laboratory experiment, comparing the results found by the device measurements, in a pipe with a nominal diameter of 6" in PVC, with synthetic discontinuities made in a calibrated 3D printer in a laboratory. The tests were based on the operational use of the PIG, in which it moves inside the pipe under different speed conditions and with an arrangement of synthetic discontinuities with 5 different geometries. The methodology used was the same performed in a calibration laboratory, in which the sum of type A and B uncertainties are multiplied by the coverage factor (k), which proved capable of reaching expanded uncertainties of the order of ± 3.1% to 5.0% using a confidence level of 95.45%.

Keywords: Uncertainty evaluation / Feeler PIG / methodology / corrosion in pipelines

1 Introduction

The PIG is equipment widely used in the construction and assembly industry, mainly in the oil and gas segment. This type of equipment, in general, is used for checking corrosion, cracks, dents, cleaning, and fluid separation, among others in ducts [1].

The term PIG, pork in Portuguese, originates in the United States, but the reason for the choice has never been satisfactorily explained. There are several theories, however, the most accepted is because of the sound emitted by the passage of the pig in the duct, producing a noise like the grunt of a pig. Another explanation would be the appearance of the device when it emerges from the pipelines covered in crude oil, resembling a pig in a pigsty. It is highly unlikely that the emergence of the name PIG is an abbreviation of "Pipeline Inspection Gauge" since this term started to be used only when inspections began to be used in the industry [2].

The present work aims to evaluate the measurement uncertainties of the Feeler PIG and the benefits of the application of this equipment to detect the internal corrosion of submarine pipelines.

To detect internal corrosion in pipelines, the devices used must be able to provide three types of information: detect the discontinuity, inform its location, and measure the corrosion. For this purpose, instrumented or intelligent PIGs are used.

This equipment uses the internal fluid pumping energy to move inside the ducts. According to Salcedo [3], they are generally built with a cylindrical body, where the electronics and battery are located, and it is supported by polyurethane cups, they also have an odometer to record distance or position.

2 Feeler PIG

This instrument was developed in Brazil to detect internal corrosion of pipelines. The main motivation for the development of this tool was the inspection of offshore oil production and flow pipelines. There are so-called non-pigable pipelines in the production and refining flow at Petrobras that impose difficulties and limitations on conventional instrumented PIGs, such as ultrasonic and magnetic ones. For this reason, the Feeler PIG was developed to overcome the difficulties in detecting internal corrosion, caused by the presence of salt water transported along with the oil, since external corrosion is detected by

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Fig. 1. Multidimensional Feeler PIG.

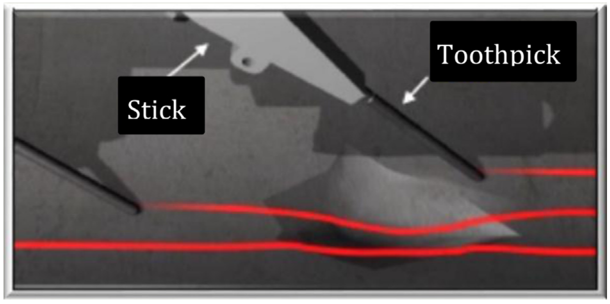

Fig. 2. Toothpick sensors profiling a defective surface.

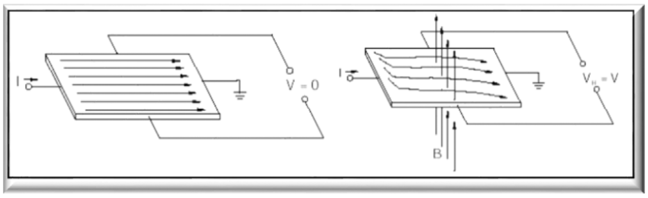

Fig. 3. Hall effect principle.

visual inspection performed by R.O.V – Remotely Operated Vehicle and by the effective against this type of corrosion by cathodic protection [3].

The mechanical structure of the toothpick sensor is a contact rod fixed inside an articulated rod, an axis of rotation of the rod that is fixed to the base of the sensor, and the transducer inside this axis, as in Figure 1. Magnets that provide a magnetic field constant to the set consisting of the shaft and transducer are fixed inside the articulated rod of the toothpick sensor [3].

When there is an angular movement of the articulated rod, which is the result of probing the surface of the duct by the rod, that is, a loss of thickness defect caused by corrosion, the angle of incidence of the magnetic flux on the transducer face changes proportionally to the movement. Thus, this variation in the incidence of magnetic flux will produce an analog output signal from the transducer proportional to the angular movement of the rod [3].

2.1 Hall effect transducer

According to Salcedo [3], the primary measurement element of a toothpick sensor is the measurement of the angular position of the rod with permanent magnets around the Hall transducer as in Figure 2. Therefore, the effective measurement is the intensity of the magnetic flux incident on the face of the Hall transducer that is inside the axis. The main characteristics for choosing this sensor are:
- Temperature resistance, if encapsulated with resin.
- Low cost.
- Absence of moving parts in contact.
- Small size.
- Versatility.

The Hall transducer follows the principle of the Hall effect, that when a thin plate of semiconductor material, carrying current (I), is placed and a magnetic field (B) perpendicular to its surface, a potential difference is generated perpendicular to the current and to the magnetic field as in Figure 3. The output voltage of the Hall element is directly proportional to the magnetic flux density [4].

Sensors type AMR – Anisotropic Magneto Resistive Sensor, implemented in electronic circuit boards, together with the mechanical structures of the toothpick sensor were used.

2.2 Calibration

According to Salcedo [3], the calibration of the PIG is simply a mechanical and manual process operated by technicians, who pass a calibration template individually on each toothpick sensor. This process aims to evaluate measurement errors for all micro geometry sensors, the toothpick sensors, to later be able to use the equipment in the inspection of the duct. This is because the magnets of the internal structure of the toothpick sensor can present varying magnetic field intensity about the others, which combined with the assembly process, mechanical adjustment, and inevitable dimensional differences in manufacturing in the machining of mechanical parts can introduce inaccuracies in the measurement of micro geometry of surface duct.

The components used in the calibration are template and slide guide rail of the template. The first component, the calibration template, is a mechanical part used as a dimensional reference for the sensor's excursion range, which has machined steps with heights defined from the radius of the center of the PIG. The second part, the guide rail, is also mounted according to the radius of the PIG body and is fixed to the vessel support and/or instrumented body to center and slide the calibration template [3].

The calibration of the Feeler PIG has two distinct phases, the first consists of the individual pre-programming of all the transducers of each toothpick sensor and takes place in the pre-assembly of the instrumented PIG. The second phase of calibration starts after all sensors are mounted on the equipment.

In the first calibration phase, the objective is to adjust the sensitivity of the sensor within the toothpick transducer assembly to meet the duct design characteristics, such as internal diameter and wall thickness, configuring the sensor measurement excursion. An operating range is adopted, for a 20% gain in material thickness (welds) and up to 100% loss in duct material thickness (hole duct) for internal corrosion measurement.

In the second calibration phase, the toothpick sensors are submitted to the passage of a reference template, so the values in millimeters of each step are compared with the digitized measurements of each sensor by the onboard electronics. This is done by applying least squares fit to convert the analog measurements into voltage signals from each toothpick sensor to millimeters. The height of each step of the calibration template is machined to represent the range of excursion of the toothpick sensor during the inspection in the duct. Figure 4 shows a crown of the Feeler PIG, without the support cups, in the calibration phase on the bench.

Fig. 4. Feeler PIG calibration on the bench.

3 Measurement method

According to VIM [5], the "method of measurement is the logical sequence of operations, generically described, used in the execution of measurements". In this case, the direct measurement method was used, that is, where the instrument is used to obtain the desired measurement result.

The calibration method consists of a dimensional comparison between the synthetic discontinuity and the measurement detected by the Feeler PIG during the tests as shown in Figure 5. The dimensions of the discontinuity were calibrated by a Laboratory in a reference laboratory.

Fig. 5. Test bench.

The test was performed with varying speeds of 0.2, 0.5, 1.0, and 1.5 m/s, the speeds were defined based on previous works carried out by Salcedo [3], Costa [6], and Medeiros [5]. For each speed, 16 runs were performed for data collection, the definition of the number of runs took into account the number of measurements that were performed on the synthetic discontinuities at the time of calibration.

The discontinuities were positioned on the external face of the PVC tube of nominal diameter 6" to start the passages of the Feeler PIG. A total of 20 holes with a diameter of 25 mm were drilled to accommodate the discontinuities. The pipe was fixed to the supports through load straps on benches with a wooden tops. To ensure that the discontinuities were not ejected with the passage of the PIG, due to the force exerted by the sensors on the inner wall of the tube, nylon clamps were installed around its perimeter to prevent this effect (Fig. 5).

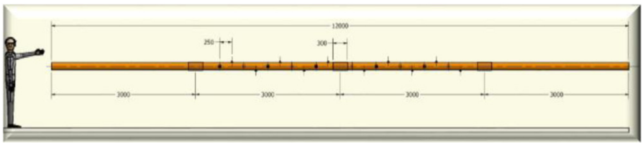

Fig. 6. Side view of the test bench with the sectors.

As shown in Figure 6, the bench was designed in 3D software and consisted of four tube rods of a nominal diameter of 6" measuring 3000 mm in length each. In addition, 3 sleeves with a nominal diameter of 6" and 300 mm in length were used to connect the tubes, totaling 12,000 mm of bench width in total.

The bench was divided into 5 sectors, each consisting of 4 discontinuities of the same dimensions, separated by 250 mm. The purpose of this sectorization was to obtain the largest possible amount of data in the same run, that is, in one passage of the Feeler PIG, 4-dimensional information is collected from each sector, totaling 20 data collections.

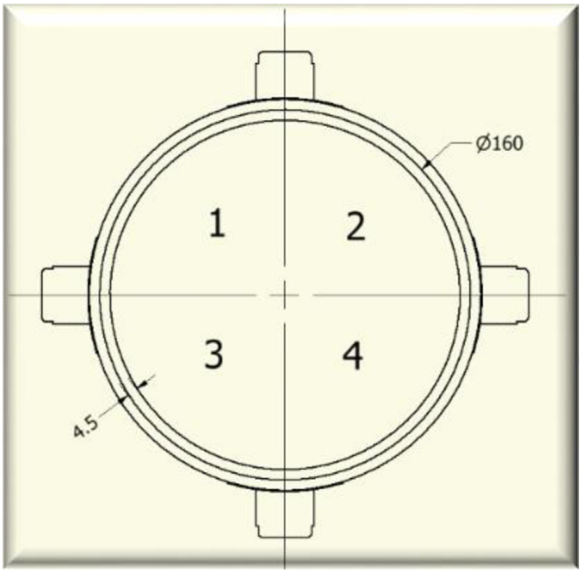

Fig. 7. Quadrant division.

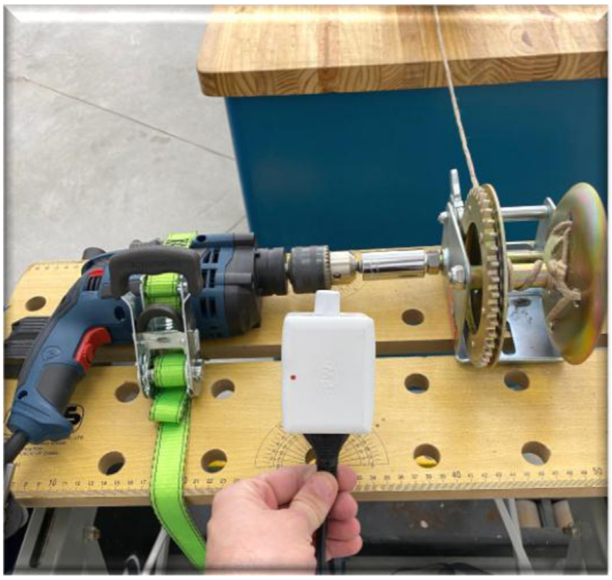

Fig. 9. Device designed to pull the Feeler PIG.

Fig. 8. Front view of the test bench.

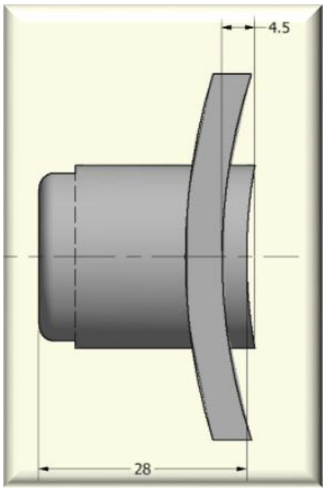

Fig. 10. Modeling with Autodesk Inventor Software.

A helical positioning of the synthetic discontinuities was adopted so that each quadrant of the pipe was covered by a part of each dimension (Fig. 7). This methodology was adopted to test the maximum number of sensors of the Feeler PIG during its passage.

One run is characterized when the Feeler PIG is positioned at the entrance of the pipe and is towed through an alternating current motor, which has a dimmer to control the motor rotation, as shown in Figure 8. A rope is used between the motor and the PIG to of towing the equipment inside the pipeline. When the PIG reaches the other end of the tube, 1 race is characterized.

The speed was calculated indirectly, that is, through the passage time of the Feeler PIG inside the pipe. A chronometer was used, marking the time from the start of the engine to the arrival of the PIG at the end of the pipeline.

3.1 Operator

The tests were performed by 2 technicians from the research center and 1 analyst specialized in the interpretation of data provided by the RTScan program, which is the software developed by the research center for PIG data acquisition.

3.2 Equipment

To move the equipment inside the PVC pipe, a device capable of pulling the PIG at different speeds was designed and assembled. For this, an electric drill coupled to a manual winch, and an electronic dimmer to vary the rotation of the drill and rope were used (Fig. 9).

From the moment the electronic dimmer was activated, the alternating current motor of the drill began to rotate at the speed equivalent to the current generated by the device. Using a coupling through a multidimensional socket, the

Fig. 11. Synthetic discontinuities facing the inside of the PVC piping.

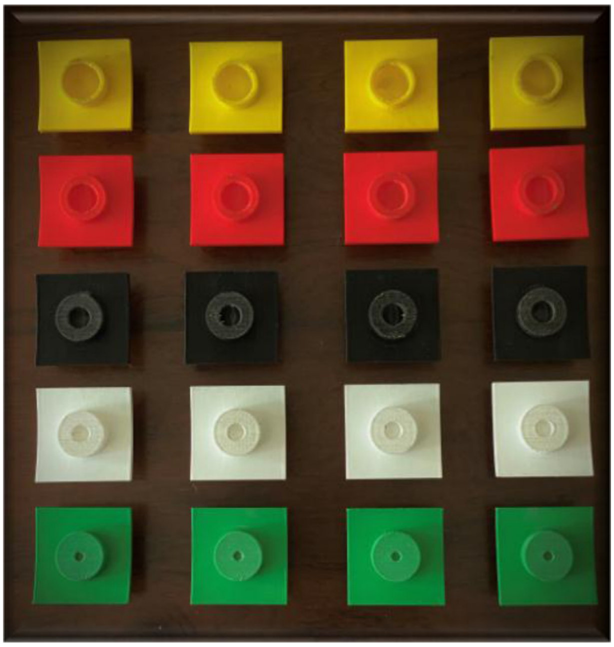

Fig. 12. 3D printed synthetic discontinuities.

manual winch pulled the rope that was housed in its spool, thus performing the displacement of the pig, as the end of the rope was coupled to the front of the equipment.

For the simulation of corrosion defects in the pipe, synthetic discontinuities were modeled in 3D, using Autodesk Inventor software (Fig. 10) so that it was millimetric coupled to the external face of the tube and also designed so that the modeled part faced the pipe internal wall, with the purpose that the PIG would only detect the mapped imperfections (Fig. 11).

The 3D printing method was used to make the parts for the simulation of discontinuities, as it has a better cost-benefit ratio. The printing technique was fabrication with fused filament (FFF) as shown in Figure 12. The fabrication

Table 1. Test parameters.

Speed (m/s)	Holes diameter × depth (mm)	Colors of synthetic discontinuities
0.2	5 × 2.5	Green
0.5	9 × 4.5	White
1.0	12 × 6	Black
1.5	16 × 8	Red
	20 × 12	Yellow

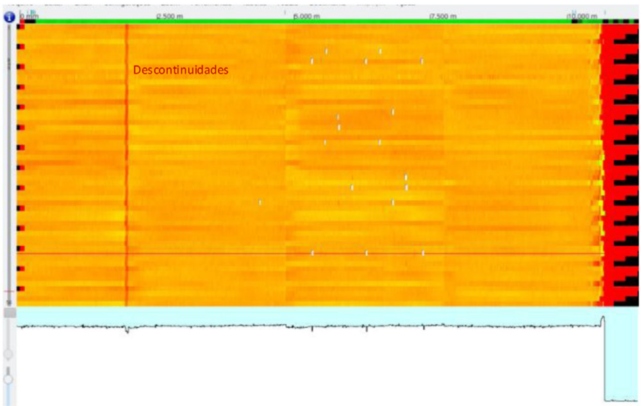

Fig. 13. Image generated by RTScan Software for speed 0.2 m/s.

technique starts with heating filaments of plastic material such as polylactic acid (PLA), until reaching a semi-solid state and then exiting through the extruder nozzle. This extrusion forms layers from the movement of the printer in the X, Y, and Z axes. It is important to highlight that the application of this method was a pioneer in the academic environment on PIG, as it was not found in other publications researched on the subject.

Table 1 shows the dimensions of the synthetic discontinuities used, their colors, and the speeds adopted.

The dimensions of the pieces were based on Salcedo [3], Costa [6], and Medeiros [4], only the 20 × 12 mm dimension was chosen by the author together with the research center, as it is a conventional dimension in the industry.

To guarantee the dimensions of the printed discontinuities, the parts were sent for calibration. As well as the use of 3D printed parts, the dimensional calibration of the discontinuities used is a differential in this work.

4 Results

RTScan is the software developed by the research center for PIG data acquisition. This software was used to analyze the results of the runs performed by Feeler PIG. Figure 13 shows the image of the scan performed by the equipment at a speed of 0.2 m/s, where the white pixels represent the synthetic discontinuities. In the following image, the running direction is from left to right.

Table 2. Values found in the test.

Speed (m/s)	Hole depth × diameter (mm)	Standard average value depth × diameter (mm)	Average value found by PIG depth × diameter (mm)
0.2	2.5 × 5	2.55 × 4.71	1.75 × 3.69
	4.5 × 9	4.60 × 8.48	3.56 × 7.70
	6 × 12	6.08 × 11.72	4.56 × 9.47
	9 × 16	8.10 × 15.64	4.15 × 12.46
	12 × 20	12.15 × 19.74	2.4 × 5.36
0.5	2.5 × 5	2.55 × 4.71	1.58 × 4.26
	4.5 × 9	4.60 × 8.48	2.63 × 6.54
	6 × 12	6.08 × 11.72	4.14 × 10.70
	9 × 16	8.10 × 15.64	4.80 × 12.64
	12 × 20	12.15 × 19.74	2.75 × 6.50
1.0	2.5 × 5	2.55 × 4.71	0.51 × 1.64
	4.5 × 9	4.60 × 8.48	1.70 × 5.14
	6 × 12	6.08 × 11.72	3.22 × 9.66
	9 × 16	8.10 × 15.64	4.49 × 13.44
	12 × 20	12.15 × 19.74	1.22 × 3.22
1.5	2.5 × 5	2.55 × 4.71	0.75 × 3.76
	4.5 × 9	4.60 × 8.48	2.25 × 8.56
	6 × 12	6.08 × 11.72	3.56 × 11.98
	9 × 16	8.10 × 15.64	3.96 × 13.76
	12 × 20	12.15 × 19.74	1.44 × 4.84

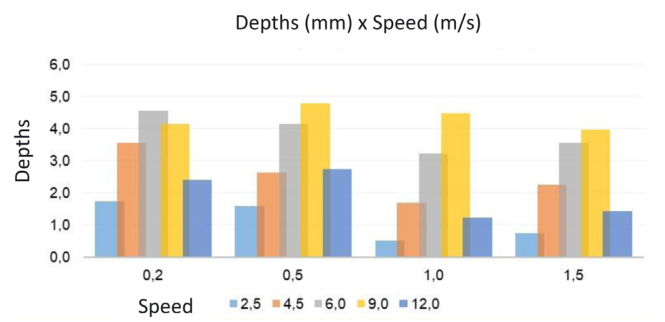

Fig. 14. Depths measured by PIG for $v = 0.2$; 0.5; 1.0; 1.5 m/s.

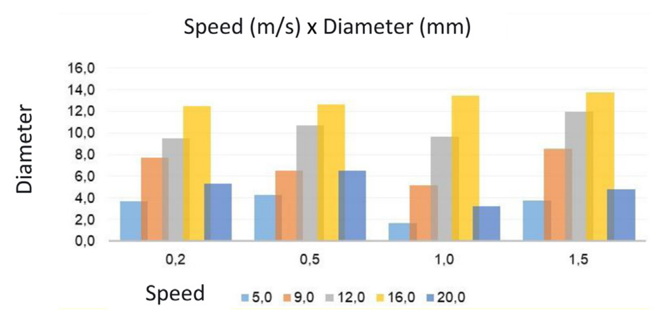

Fig. 15. Diameters measured by the PIG for $v = 0.2$; 0.5; 1.0; 1.5 m/s.

4.1 Uncertainty evaluation

During the execution of the test, 16 runs were performed per speed, totaling 64 runs. After the end of the experiment, 1280 measurements were collected, as 20 dimensions are collected in one pass of the PIG, as there are 4 equal discontinuities divided into 5 sections. The spreadsheet used to perform the uncertainty evaluation is attached to this work.

It was decided to calculate the uncertainty separately from the depth and diameter because if the volume criterion were adopted, the results would not be considered fair.

The discontinuity values shown in Table 2 are the average results collected by the equipment during the runs.

Figures 14 and 15, the blue bar with a depth of 12 mm and a diameter of 20 mm. The values are below the expected graphically as they stop the trend. This phenomenon occurs because of the deceleration of the PIG at the end of the run, thus causing cancellation in the detection of discontinuities located at the end of the pipe.

According to Mendes and Rosário [7], the measurement error (E) is characterized as the result of a measurement (X) minus the reference value (VR), which characterizes the measurement trend.

$$E = X - VR. \tag{1}$$

The error used for the calculations was the relative error (Er), which by definition is the measurement error divided by the reference value of the measurement object

$$Er = \frac{X - VR}{VR} \times 100(\%). \tag{2}$$

Table 3. Average of relative error.

Speed (m/s)	Hole depth × diameter (mm)	Average relative error depth × diameter (%)
0.2	2.5 × 5	–31.28 × −21.57
	4.5 × 9	–22.47 × −9.10
	6 × 12	–24.99 × −19.20
	9 × 16	–48.82 × −20.58
	12 × 20	–80.26 × −72.88
0.5	2.5 × 5	–38.05 × −9.59
	4.5 × 9	–42.87 × −22.86
	6 × 12	–31.89 × −8.70
	9 × 16	–40.74 × −19.37
	12 × 20	–77.38 × −67.07
1.0	2.5 × 5	–79.89 × −65.19
	4.5 × 9	–62.97 × −39.35
	6 × 12	–47.08 × −17.51
	9 × 16	–44.51 × −14.08
	12 × 20	–89.93 × −83.18
1.5	2.5 × 5	–70.44 × −20.42
	4.5 × 9	–51.16 × 1.04
	6 × 12	–41.52 × 2.24
	9 × 16	–51.16 × −12.08
	12 × 20	–88.13 × −75.47

Table 4. Final uncertainties.

Speed (m/s)	Hole depth × diameter (mm)	Expanded uncertainty ± (%) depth × diameter
0.2	2.5 × 5	3.30 × 4.10
	4.5 × 9	3.38 × 5.01
	6 × 12	3.29 × 4.35
	9 × 16	3.40 × 4.35
	12 × 20	3.36 × 4.14
0.5	2.5 × 5	3.26 × 3.81
	4.5 × 9	3.37 × 4.11
	6 × 12	3.28 × 4.14
	9 × 16	3.44 × 4.75
	12 × 20	3.48 × 4.62
1.0	2.5 × 5	3.22 × 3.59
	4.5 × 9	3.34 × 4.06
	6 × 12	3.26 × 4.27
	9 × 16	3.73 × 4.72
	12 × 20	3.18 × 3.33
1.5	2.5 × 5	3.22 × 4.22
	4.5 × 9	3.13 × 4.08
	6 × 12	3.20 × 3.78
	9 × 16	3.34 × 4.92
	12 × 20	3.24 × 3.83

In Table 3, it can be seen that the deeper the discontinuity, the greater the error, this is because the smaller the diameter and the deeper the discontinuity, the worse its detection will be since the inclination of the rod does not allow the sensor tip to reach the bottom of the hole.

For several reasons, mainly economic, the number of repetitions of measurement is reduced, typically varying between three and ten.

Therefore, the type A measurement uncertainty (ua) with normal probability distribution is obtained by, where S is the standard deviation and n is the number of measurements:

$$ua = \frac{S}{\sqrt{n}}. \tag{3}$$

Uncertainties of this type are determined from ancillary information and external to the measurement process.

The resolution of the standard, and resolution of the normal probability distribution, where the parameters of the standard were taken from its calibration certificate and the resolution of the PIG, the rectangular distribution was used, were considered as type B uncertainties, since the probability distribution is the same within a certain range.

$$u\ resolution = \frac{resolution}{\sqrt{3}}. \tag{4}$$

The standard uncertainty of the result of a measurement, when this result is obtained through the values of several other quantities, being equal to the positive square root of a sum of terms, which constitute the variances or concordances of these other quantities, weighted according to how much the measurement result varies with changes in these quantities [7].

The equation expresses the combined uncertainty (uc) through the vector sum of the PIG resolution uncertainty ($rpig$) and the standard uncertainty (cp), it is the number taken from the 3D parts calibration certificate.

$$uc = \sqrt{u^2(rpig) + u^2(cp)}. \tag{5}$$

When a smaller number of measurements is made, in this case, 16, this distribution is approximated to a normal, applying the T-Student expressed in Table 4.

The best way to combine the different components of uncertainty is by tabulating the standardized uncertainties of each type, using the concept of effective degrees of freedom to determine the coverage coefficient that corresponds to a statistical confidence of 95.45%. This determination is based on the Welch-Satterwaite equation (calculated effective degree of freedom).

$$V_{ef} = \frac{{u_c}^4(x)}{\sum_{i=1}^{n} \frac{{u_i}^4(x)}{v_i}}. \tag{6}$$

To determine the coverage factor (k), it is necessary to determine the number of effective degrees of freedom (V_{ef}) [8]. The effective number of degrees of freedom is the number of degrees of freedom associated with the combined standard uncertainty (uc). Using Table 4 of the T-Student, a coverage factor (k) of 2.18 is adopted, with a confidence level of 95.45%.

The expanded uncertainty (U) is obtained by multiplying the combined standardized uncertainty (U_c) by the coverage factor (k). The factor (k) is identified in the T-Student Table, for 95.45% of probability, and defined by the value of the effective degree of freedom (V_{ef}), [8]. Table 4 explains the final uncertainties found.

$$U = k.u_c. \tag{7}$$

The expanded uncertainties presented in Table 4 expose values between ± 3.1% and 5.0%. It is important to note that the experiment presented in this dissertation analyzed the values measured by the Feeler PIG simulating the operating conditions of the equipment, unlike previous works, where the test was performed on a rotating bench under ideal conditions.

5 Conclusion

The present work had the objective of studying the measurement uncertainties of the PIG, through laboratory experiments, comparing the results found by the passage of the PIG in PVC piping, with synthetic discontinuities, and comparing these results with the real dimensions of the pieces.

Several experiments on laboratory benches were carried out to evaluate the measuring capacity of the PIG, considering a rotating metallic disk with discontinuities machined in its body and a single sensor for the detection of defects. It is worth mentioning that this work used the operational principle of the equipment and considered a range of variables present during its use, resulting in information outputs closer to reality than the previous tests.

The principle used proved capable of reaching uncertainties in the order of ± 3.1 to 5.0% using an expanded uncertainty obtained with a confidence level of 95.45%. However, there are still some problems found in the current state of the test bench that limit performance, mainly in determining the average speed of the PIG during the test.

From the analysis of the validation experiments of the system, it can be verified that it was able to perform the function of detection of corrosion defects in the order of millimeters.

In the worst case possible, it was noticed that the smallest diameter discontinuities are the ones that have the worst results because it refers to the biggest errors found during the tests. One of the lessons learned during the test was that for more accurate measurement of time, an automatic instrument is needed to time the passage of the PIG.

In summary, it is possible to conclude that the developed system has the potential to be used as a Feeler PIG calibration bench. With the creation of a laboratory methodology, it is possible to certify the bench for calibration with traceability.

Regarding the equipment, it enables measurement with high resolution and speed, it is a robust system, with great possibilities for improvement.

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