Development of a dynamic standard of pressure
Élaboration d'une étalon de pression dynamique

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Abstract. Based on the fact that there is no reported measurement and calibration capacity for dynamic pressure measurements, a reference standard is statistically characterized from the pressure of the first reflection of the shock wave produced by the expansion of a gas in a shock tube. The direct comparison of the pressure measurements in the stabilization time allows to evaluate the behavior of a pressure transducer by the effect of the validated aperiodic perturbation and thus, to infer its metrological performance in the indirect measurement of the height of the marine waves at depths of up to 25 m, very important in the design of maritime structures. The performance of reference standard was validated for air and 2 m length of the driven section. The results are reported in terms of reproducibility of the pressure in the laboratory by the standard uncertainty pooled, with relative uncertainty of 2,72% for disturbed air pressures equal to 137,01 hPa.

Résumé. Compte tenu du fait qu'il n'y a pas de mesure rapportée et la capacité d'étalonnage pour les mesures dynamiques de la pression, une norme de référence est statistiquement caractérisée à partir de la pression de la première réflexion de l'onde de choc produite par l'expansion d'un gaz dans un tube de choc. La comparaison directe des mesures de pression dans le temps de stabilisation permet d'évaluer le comportement d'un transducteur de pression par l'effet de la perturbation apériodique validée et donc d'en déduire sa performance métrologique dans la mesure indirecte de la hauteur des ondes marines aux profondeurs de jusqu'à 25 m, très important dans la conception des structures maritimes. La performance de la norme de référence a été validée pour l'air et 2 m de longueur de la section entraînée. Les résultats sont rapportés en termes de reproductibilité de la pression dans le laboratoire par l'incertitude standard combinée, avec une incertitude relative de 2,72% pour les pressions d'air perturbées égales à 137,01 hPa.

1 Introduction.

Currently, measurements in dynamic processes are present in the technological, medical and academic sectors [1]. One of its most interesting applications is related to the design of coastal structures from the indirect calculation of the energy transferred by the wind to the surface of the sea [2], which depends, among other variables, on the average height of the waves.

From the simplifications of linear theory, waves can be treated as a progressive wave whose energy density doesn't depend on the wave period or the depth but only on the height and length of the wave:

$$E = \rho_{sw} \times g_l \times \frac{H^2}{8} \times L \qquad (1)$$

Where:

E: Energy density per surface unit of wave train, in J · m^{-1}.

ρ_{sw}: Density of the sea water according to the equation of state of the sea water [3], in kg · m^{-3}.

g_l: Local acceleration of gravity, in m · s^{-2}.

H: Height of the wave, in m.

L: Wave length, in m.

Although the theoretical model allows for simulations prior to design, in reality the wave height is a statistical function, which indirectly determines the average wave height from the pressure measurements performed by a transducer located on the seafloor, and disturbed stochastically by the waves of the sea [4]:

$$H = \rho_{sw} \times g_l \times p^{-1} \qquad (2)$$

Where:

p: Pressure measured by the pressure transducer, in kPa.

The metrological reliability of the generated databases has become an important aspect for researchers and engineers involved with mathematical modeling, who seek a technical - economic balance in their design proposals.

Since in the field of dynamic measurements there are no measurement and calibration capacities (CMC) published by the BIPM [5], it is not possible to make direct comparisons of measuring instruments with internationally recognized standards, as is common practice in measurements quasi-stationary [6].

It has been demonstrated that the metrological parameters resulting from the quasi-stationary calibration of a measurement system do not satisfactorily describe the accuracy of its behavior under dynamic operating conditions [1], but the replacement of the quasi-stationary calibration approach with the dynamic calibration approach, requires the development of a measurement system that allows to define the dynamic pressure.

In the present context, the term "realization" is related to the reproduction of the dynamic pressure not from its definition but by building "... a highly reproducible standard based on a physical phenomenon" [6].

An independent physical phenomenon may be the pressure step that a shock wave produces during the isentropic expansion of an ideal gas. If the gas is dry air, then its value can theoretically be predicted according to the following equation [7]:

$$\begin{aligned} p_5(\tau) - p_1(\tau) = +\frac{7}{3} \times p_1(\tau) \times (M_1^2 - 1) \\ \times [(2 + M_1^2) \\ \times (5 + M_1^2)^{-1}] \end{aligned} \qquad (3)$$

Where:

$p_5(\tau)$: Pressure of the first reflection of the shock wave, in kPa.

$p_1(\tau)$: Pressure before the arrival of the shock wave (gas not disturbed), in kPa.

M_1: Mach number of the shock wave, dependent on its speed and temperature.

The experimental reproduction of the described perturbation is performed in a shock tube, however, there are discrepancies in the international community regarding its use for metrological purposes: some national metrology institutes (INM) refer to it as the primary standard, while others use it as a measuring system that requires a reference transducer to determine the pressure.

If the shock tube is used as a reference standard, a reasonable doubt arises as to how to calibrate the reference transducer. However, if a high frequency sampling data acquisition system is available, it is possible to perform several measurements during the stabilization time (dwell time) of the first reflection of the shock wave.

During this stabilization time, the pressure variations are minimal and stochastic, so that the accuracy of their measurement can be estimated from the results of the calibration in quasi-stationary regime of the pressure transducer.

The goal of the present work is to present the procedure for estimate the accuracy of the reference standard of dynamic pressure from a statistical model associated with an experimental factorial design, where the effect of the burst of the diaphragm on the pooled standard deviation [8] of the pressure of the first reflection of the shock wave.

2 Materials and methods.

2.1 Pressure measuring system.

For the generation of the experimental data, a dynamic pressure measurement system was developed, consisting of:

- The prototype of shock tube, as generator of aperiodic disturbances of pressure.
- The pressure transducers,
- The analog to digital converter (CAD).
- The software of acquisition and digital recording of the results of the measurements.
- Personal computer (PC).
- Software for processing of metrological and statistical parameters.

Figure 1 shows the shock tube prototype built and installed in the Laboratory of Dynamic Measurements of the Institute of Engineering Research (INII) of the University of Costa Rica (UCR). The device is composed of two tubular polyvinyl chloride (PVC) sections with a constant outer diameter equal to 88.90 mm (3½ in).

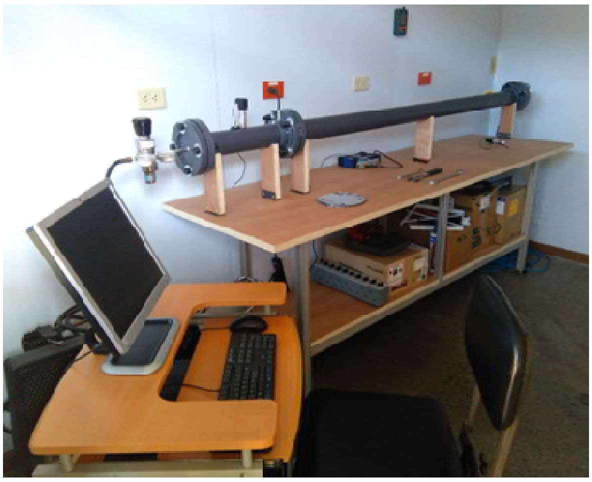


Figure 1. Shock tube prototype. General view.

The wall thickness of the tubes is equal to 7.62 mm, so that their bursting resistance is greater than 6.48 MPa (940 psi), allowing their safe use in the application range.

Figure 2 shows a view of the high pressure chamber of the prototype shock tube, supported by supports (1) on a horizontal table (2) [the bubble level (9) allows its adjustment] to ensure the stability of the system operation.

Each section is joined by movable PVC flanges (3), which guarantee the sealing of the coupling by means of rubber seals and four properly adjusted bolts.

As an operating fluid, air supplied by a reciprocating compressor is used, via the hose (4), to the high-pressure chamber (5), 400 mm in length, by means of a fine adjustment device (6), which allows you to adjust the volumetric flow of air and keep it constant during filling.

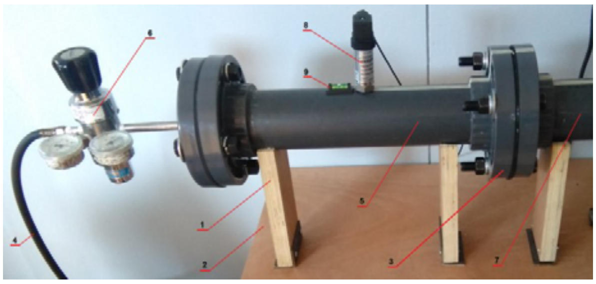


Figure 2. Shock tube prototype. High pressure camera (driver section).

Between the flanges of the high (5) and low pressure (7) chambers is installed an aluminum of 0,1 mm thick diaphragm (see Figure 3), which bursting when its mechanical resistance is overcome by the gas pressure.

Figure 3. Shock tube prototype diaphragm.

To measure the pressure of the rarefaction wave after the diaphragm has burst, the pressure transducer (8) has been installed in the measuring port TP6.

Figure 4 shows the proper configuration of the shock tube prototype validation, where the low pressure chamber (7), of length equal to 2 m, terminates in a blind flange (10), in which the transducer (11) in the measuring port TP5.

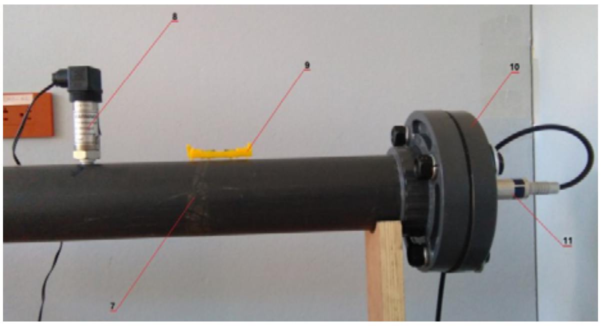


Figure 4. Shock tube prototype. Low pressure chamber (driven section).

When the diaphragm burst occurs, the front of the shock wave first activates the pressure transducer sensor installed in the measuring port TP2 (8), and then to the reference transducer sensor installed 500 mm "downstream" in the measuring port TP5 (11).

The sensors of the pressure transducers are installed on membranes, which when deformed by the action of the shock wave pressure, first converted into analog signals of direct voltage, and then, by means of a transmitter, in electrical signals of electric current of 4 to 20 mA.

Two pressure sensor designs were used:

- The first, of a metallic nature, is installed on a ceramic membrane.
- The second, a silicon semiconductor, is installed on a titanium membrane.

The analog current outputs from the pressure transducers are independently connected to measuring ports of the data acquisition (DAQ) systems, which first condition the measured analog signals and then digitize them synchronized way.

The digitized signals are manipulated by the software whose functions are:

- DAQ configure channels according to the characteristics of the connected transducers and the requirements of the measurement process, for example, its sampling frequency.
- Record the digitized measurements from the electrical transducers in .cvs or .xlsx extension files.

2.2 Experimental design.

The validation of the performance of the prototype shock tube as a generator of aperiodic pressure signals included a pressure transducer, considered as a reference, installed in the TP5 measurement port (see Figure 5).

Figure 5. Experimental design: configuration of the TP5 measuring port.

A factorial type experiment [9] was designed to evaluate the effect of diaphragm rupture (see Figure 3) on the reproducibility of direct pressure measurements for each type of pressure sensor, with the aim of selecting the more suitable to function as a reference standard.

During the measurements the following experimental reproducibility conditions were maintained:

- The pressures p_1 and p_5 are measured experimentally with the reference transducer (11) located in the measuring port TP5 (see Figure 4 of this document).
- The sampling frequency of the data acquisition system is 4.8 kHz.
- Ambient air conditions (temperature and relative humidity) as well as atmospheric pressure were measured at the beginning and at the end of the process.

2.3 Statistical processing of measurements.

Once the parameters of interest are selected, the arrays of air pressure measurements are generated in the low pressure section:

- Matrix p_1, corresponding to the direct measurements of the air pressure before the shock wave disturbance.
- Matrix p_5, corresponding to direct measurements of air pressure after shock wave disturbance.

The matrices are processed statistically according to the following procedure [10]:

- Verification of the concordance of the experimental distribution with the normal one.
- Detection of possible outliers.
- Verification of equality of variances (homoscedasticity).
- Verification of equality of means by analysis of Variance (ANOVA).

The ANOVA is a powerful statistical tool [11] that allows to estimate, from an experimental design, the reproducibility of the measurements using the standard deviation of p_1 and p_5 pressures.

The above statistical tests were performed using the Minitab 17 application software.

The expanded uncertainty of the pressure of interest has an inferential sense, and for a coverage factor $k_p = 2$ represents a probability of coverage approximately equal to 95%. It is calculated according to the following equation:

$$U_p[\bar{\bar{p}}_{1(5)}] = \pm 2 \times s_p[\bar{\bar{p}}_{1(5)}] \quad (4)$$

Where:

$U_p[\bar{\bar{p}}_{1(5)}]$: Expanded uncertainty of the historical average of evaluated pressure (p_1 or p_5), in hPa.

$s_p[\bar{\bar{p}}_{1(5)}]$: Pooled standard deviation of the historical average of evaluated pressure (p_1 or p_5), in hPa.

$\bar{\bar{p}}_{1(5)}$: Historical average of the historical average of evaluated pressure (p_1 or p_5), in hPa.

In general, the expanded uncertainty of the pressure of interest coincides with its warning limits (LA), and any values outside these limits should be considered as an alert for events that affect the natural variability of the measurement system.

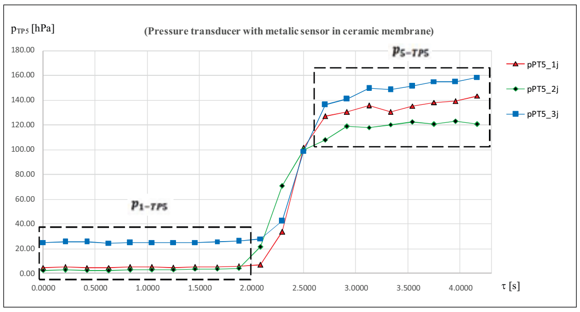
3 Results.

The validation was based on the experimental reproduction of the dynamic pressure p_5 in the prototype of shock tube, through the controlled "firing" at different moments, evaluating the precision, in terms of repeatability and reproducibility within the limits of the Laboratory of Measurements Dynamics, using the techniques of Experimental Design (DOE) [9].

In June 2017 several shots were made on the prototype shock tube, using the pressure transducers with two types of sensors, and the results of the digitized measurements were recorded in .xlsx files (Excel 2007).

3.1 Pressure transducer with metallic sensor in ceramic membrane.

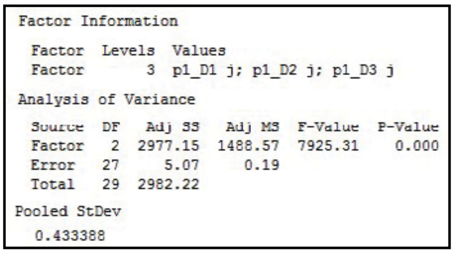
The results of the air pressure measurements before and after being disturbed by the shock wave were as follows:



Graphic 1. Pressures measured in TP5 measuring port by pressure transducer with metallic sensor.

Once the theoretical assumptions of homoscedasticity and normality are satisfied, and considering that there aren't outliers, the ANOVA's shows that there are statistically significant differences between the averages of measurements series of p_1 (Table 1: P-value = 0,000 < α = 0,05) and p_5 (Table 2: P-value = 0,000 < α = 0,05).

Table 1. ANOVA: p_1 measurements on TP5 port.



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Factor Information

 Factor  Levels  Values
 Factor       3  p1_D1 j; p1_D2 j; p1_D3 j

Analysis of Variance

 Source  DF   Adj SS   Adj MS  F-Value  P-Value
 Factor   2  2977.15  1488.57  7925.31    0.000
 Error   27     5.07     0.19
 Total   29  2982.22

Pooled StDev

  0.433388
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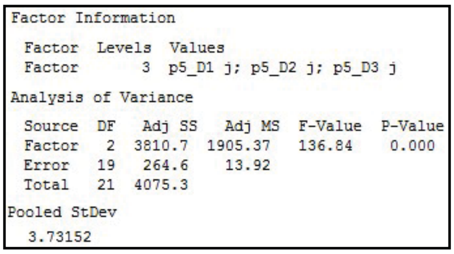
Table 2. ANOVA: p_5 measurements on TP5 port.



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Factor Information

 Factor  Levels  Values
 Factor       3  p5_D1 j; p5_D2 j; p5_D3 j

Analysis of Variance

 Source  DF  Adj SS   Adj MS  F-Value  P-Value
 Factor   2  3810.7  1905.37   136.84    0.000
 Error   19   264.6    13.92
 Total   21  4075.3

Pooled StDev

 3.73152
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The initial historical values of the parameters that characterize the prototype shock tube as secondary standard are shown in Table 3:

Table 3. Parameters of shock tube prototype.

Parameter	Unit of measure	$\bar{\bar{p}}_i$	$s_p(\bar{\bar{p}}_i)$	$\pm U_p(\bar{\bar{p}}_i)$
Air pressure before disturbance	hPa	11,126	0,4334	0,8668
Air pressure after disturbance	hPa	137,006	3,7315	7,4630

Where:

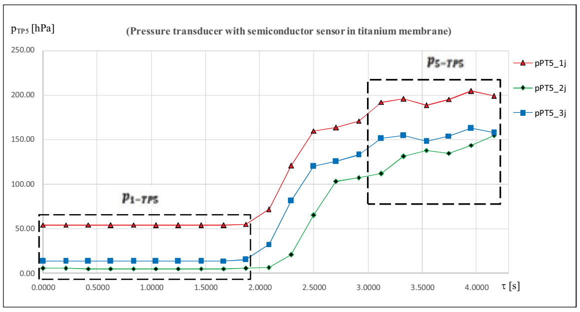
$\bar{\bar{p}}_i = \bar{\bar{p}}_{1(5)}$.

$s_p(\bar{\bar{p}}_i) = s_p[\bar{\bar{p}}_{1(5)}]$.

$U_p(\bar{\bar{p}}_i) = U_p[\bar{\bar{p}}_{1(5)}]$.

3.2 Pressure transducer with silicon semiconductor sensor in a titanium membrane.

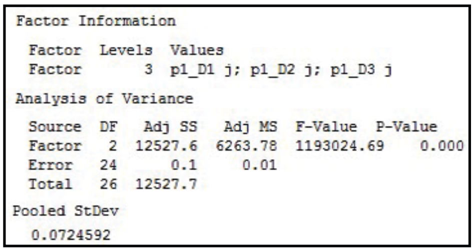
The results of the air pressure measurements before and after being disturbed by the shock wave were as follows:



Graphic 2. Pressures measured in TP5 measuring port by pressure transducer with silicon semiconductor sensor.

Once the theoretical assumptions of homoscedasticity and normality are satisfied, and considering that there aren't outliers, the ANOVA's shows that there are statistically significant differences between the averages of measurements series of p_1 (Table 4: P-value = 0,000 < α = 0,05) and p_5 (Table 2: P-value = 0,000 < α = 0,05).

Table 4. ANOVA: p_1 measurements on TP5 port.



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Factor Information

  Factor  Levels  Values
  Factor       3  p1_D1 j; p1_D2 j; p1_D3 j

Analysis of Variance

  Source  DF   Adj SS   Adj MS    F-Value  P-Value
  Factor   2  12527.6  6263.78 1193024.69    0.000
  Error   24      0.1     0.01
  Total   26  12527.7

Pooled StDev

  0.0724592
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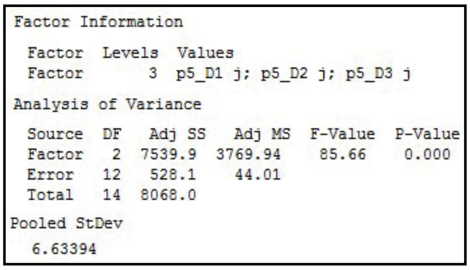
Table 5. ANOVA: p_5 measurements on TP5 port.



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Factor Information

  Factor  Levels  Values
  Factor       3  p5_D1 j; p5_D2 j; p5_D3 j

Analysis of Variance

  Source  DF   Adj SS   Adj MS  F-Value  P-Value
  Factor   2   7539.9  3769.94    85.66    0.000
  Error   12    528.1    44.01
  Total   14   8068.0

Pooled StDev

  6.63394
```

The initial historical values of the parameters that characterize the prototype shock tube as secondary standard are shown in Table 6:

Table 6. Parameters of shock tube prototype.

Parameter	Unit of measure	$\bar{\bar{p}}_i$	$s_p(\bar{\bar{p}}_i)$	$\pm U_p(\bar{\bar{p}}_i)$
Air pressure before disturbance	hPa	24,499	0,0725	0,1449
Air pressure after disturbance	hPa	165,496	6,6339	13,2679

4 Discussion.

As a result of the execution of the experimental design, values related to the performance of the shock tube as reference standard were obtained. The present discussion focuses on the interpretation of the following metrological parameters obtained experimentally:

4.1 Air pressure before disturbance.

Currently the air pressure at rest is not a controllable parameter in the prototype of the shock tube. During the installation of the diaphragm, the low pressure section (driven section) was filled with air to the ambient thermodynamic parameters, which varied within the following limits:

Table 7. Limits environmental conditions during shooting in the prototype shock tube.

	t_a	HR_a	p_{at}
	°C	%	hPa
Average	24,6	70,8%	879,3
Variation	2,6	7,4%	1,7

Where:

t_a: Temperature of the ambient air.

HR_a: Relative humidity of the ambient air.

p_{at}: Atmospheric pressure.

Considering that:

- The accuracy reported by the manufacturers of both pressure transducers is the same and equal to 0.25% of the maximum of their measuring range (2 068,43 hPa),
- The resolution uncertainty of the DAQ is negligible (24 bit).

The expanded uncertainty of the measurement of resting air pressure depends on the reproducibility of its measurements.

Table 8. Difference of resting air pressure measurements between both pressure transducers.

	Δp_1	$u_{EMP}(p_1)$	$s_p(\bar{\bar{p}}_1)$	$\pm U_p(\Delta p_1)$
Type of sensor	hPa	hPa	hPa	hPa
Metallic on ceramic membrane	13,37	3,0	0,4334	6,03
Semiconductor on titanium membrane			0,0725	5,97

Where:

Δp_1: Difference of the measured air pressure at rest between both pressure transducers.

$u_{EMP}(p_1)$: Standard uncertainty associated with the inaccuracy of the pressure transducer.

$s_p(\bar{\bar{p}}_1)$: Pooled standard deviation of the historical average of p_1 (see Table 3).

$\pm U_p(\Delta p_1)$: Expanded uncertainty of the measurement difference between both pressure transducers ($p \approx 95\%$).

The difference of p_1 measurements obtained between both pressure transducers can not be explained by the expanded uncertainty for a 95% confidence probability.

Under this circumstance, the relative uncertainty of both pressure transducers in the measurement of air pressure at rest is compared.

Table 9. Relative uncertainty of pressure measurement of air at rest.

	$u_r(\bar{\bar{p}}_1)$
Type of sensor	%
Metallic on ceramic membrane	3,90%
Semiconductor on titanium membrane	0,30%

Where:

$u_r(\bar{\bar{p}}_1)$: Relative uncertainty of the historical average of p_1. It's calculated according to the following equation:

$$u_r(\bar{\bar{p}}_1) = \frac{s_p(\bar{\bar{p}}_1)}{\bar{\bar{p}}_1} \qquad (5)$$

When the gas is at rest (quasi-stationary measurements), the pressure transducer with the semiconductor sensor mounted on a titanium membrane behaves better metrologically compared to the pressure sensor with ceramic membrane metal sensor.

However, the dynamic behavior will decide the selection of the pressure transducer which, together with the prototype shock tube, will function as a reference standard.

4.2 Pressure of disturbed air.

As measurements of the air pressure at rest, the expanded uncertainty of measuring air pressures disturbed by the shock wave depends on the reproducibility of their measurements.

Table 10. Difference of pressure measurement of disturbed air between both pressure transducers.

	Δp_5	$u_{EMP}(p_5)$	$s_p(\bar{\bar{p}}_5)$	$\pm U_p(\Delta p_5)$
Type of sensor	hPa	hPa	hPa	hPa
Metallic on ceramic membrane	28,49	3,0	3,7315	9,56
Semiconductor on titanium membrane			6,6339	14,55

Where:

Δp_5: Difference of pressure measurement of disturbed air between both pressure transducers.

$u_{EMP}(p_5) = u_{EMP}(p_1)$: Standard uncertainty associated with the inaccuracy of the pressure transducer.

$s_p(\bar{\bar{p}}_5)$: Pooled standard deviation of the historical average of p_5 (see Table 3).

$\pm U_p(\Delta p_5)$: Expanded uncertainty of the measurement difference between both pressure transducers ($p \approx 95\%$).

In these circumstances, other parameters that characterize the performance of the prototype shock tube are compared to select the type of sensor that will work with this as a reference standard.

Table 11. Another parameters of shock tube prototype.

	$u_r(\bar{\bar{p}}_5)$	$\bar{\bar{\tau}}_{1-5}$	$\bar{\bar{n}}_{p5}$	$\bar{\bar{\tau}}_5$	$\bar{\bar{f}}_5$
Type of sensor	%	ms	samples	ms	Hz
Metallic on ceramic membrane	2,72%	1,18056	7	1,31944	757,8947
Semiconductor on titanium membrane	4,01%	1,52778	6	0,83333	1199,9999

Where:

$u_r(\bar{\bar{p}}_5)$: Relative uncertainty of the historical average of p_5. It's calculated according to the following equation:

$$u_r(\bar{\bar{p}}_5) = \frac{s_p(\bar{\bar{p}}_5)}{\bar{\bar{p}}_5} \qquad (5)$$

$\bar{\bar{\tau}}_{1-5}$: Historical average of reaction time of the pressure transducer to step-type disturbance Δp_{1-5}.

$\bar{\bar{n}}_{p5}$: Historical average of number of samples recorded by the DAQ at the time of pressure stabilization p_5.

$\bar{\bar{\tau}}_5$: Historical average of stabilization time of pressure p_5.

$\bar{\bar{f}}_5$: Historical average of frecuency of the shock tube prototype. It's calculated according to the following equation:

$$\bar{\bar{f}}_5 = (\bar{\bar{\tau}}_5)^{-1} \qquad (5)$$

From Table 11 it is inferred that the pressure sensor with metallic sensor mounted on ceramic membrane behaves dynamically better to characterize the experimental step-like perturbation reproduced by the prototype of tube of shock.

This does not mean that the pressure transducer with titanium membrane semiconductor sensor is not able to measure dynamic events, but its inertia is higher compared to the selected pressure transducer.

The values of relative uncertainty of the pressure measurement as well as the stabilization time of the first reflection of the shock wave are comparable with those reported by other authors [1].

5 Conclusions and recommendations.

In general, the results of the statistical tests applied show that for a level of statistical significance α = 5 %, the pressure values depend on the diaphragm factor, but not the variability of its series of measurements.

The prototype shock tube together with the metal sensor pressure transducer installed in a ceramic membrane, is the reference standard of the Laboratory of Dynamic Measurements of the University of Costa Rica (UCR).

Its metrological characteristics are as follows:

Table 12. Reference standard of dynamic pressure. Metrological characteristics.

$\bar{\bar{p}}_1$	$s_p(\bar{\bar{p}}_1)$	$\bar{\bar{p}}_5$	$s_p(\bar{\bar{p}}_5)$	Unit of measure
11,13	0,072	137,01	3,732	hPa

It is recommended:

R1. Applying this procedure to higher burst pressures to increase the amplitude validated prototype shock tube.

The increase in the amplitude of the burst pressure of the diaphragm is achieved by using sheets of the same material but of a greater thickness or another type of material.

R2. Check the effect of atmospheric air humidity on the reproducibility of the air pressure disturbed by the first reflection of the shock wave (p_5), and in the stabilization time.

R3. Feed the matrices p_1 and p_5 to quantify the asymptotic limits of the corresponding pooled deviations.

4R. To evaluate the dynamic behavior of the pressure transducer selected as reference standard in other aperiodic devices, in order to quantify the reproducibility between laboratories.

Acknowledgements

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