

DYNAMIC PRESSURE CALIBRATION

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Abstract – The sloshing loads in tanks of LNG carriers are assessed during the ship design phase by performing sloshing model tests. GTT have initiated studies to determine parameters influencing pressure sensors sensitivity. The objective is to develop a dynamic pressure calibration method. The selected parameters are the rise time and the discharge time constant. The results in terms of sensitivity and uncertainty of this approach are compared with the more conventional calibration methods.

Keywords: calibration method, dynamic pressure, sensitivity, rise time, discharge time constant, sloshing.

Nomenclature:

FOD: Fast-Opening Device

GTT: Gaztransport & Technigaz

LMD: Dynamic Metrology Laboratory

ST: Shock tube

LNG: Liquefied Natural Gas

1. INTRODUCTION

1.1 Context

LNG is usually stored and transported at -163°C and atmospheric pressure. GTT is the designer of the membrane containment systems for land storage and seaborne transportation of LNG.

During transport by sea, the ship motions induce LNG motions inside the LNG tanks (see Fig. 1). This LNG sloshing might generate impacts on the containment system. The impact loads induced by sloshing are the design loads of the containment system.



Fig. 1. LNG tank of a membrane LNG carrier

Fig. 2. Sloshing Model Tests in GTT lab

Any sloshing assessment performed in GTT relies on sloshing model tests at scale 1/40. The Plexiglas tank is filled with water and a mixture of gases ($\text{SF}_6 + \text{N}_2$) in order that the density ratio between the gas and the liquid matches the real one on board the ship. Six degree-of-freedom motions are accurately imposed to the tank by a Stewart-type platform (hexapod) mimicking pre-calculated ship motions (see Fig. 2), relevantly down-scaled. The tank is instrumented by about 300 pressure sensors grouped by arrays, sampling at 20 kHz. Each sensor is screwed thoroughly into a metallic module in order for the diaphragm of the sensor to be flushed to its inner face. The modules are fixed into dedicated openings of the tank walls at relevant areas. All conditions (fill levels, sea states, wave incidence with regards to the ship route, speed) the ship is expected to face during its life are tested. Measured peak pressures are statistically post-processed. A reliability-based approach is followed enabling to derive the probability of failure for each limit state of the containment system [1]. A summary of the methodology is given graphically in Figure 3.

Sloshing model tests in GTT's lab are also performed for R&D purpose. The main objective of these tests is to better understand sloshing physics and scaling laws for the pressure measurements [2]. These tests can be performed at various scales including scale 1/40, with different kinds of gases and different kinds of liquids. Most of the time, high speed cameras are used during these tests, synchronized with the pressure sensor acquisition. The sampling rate of the pressure acquisition is higher than during the project tests. It is usually around 40 kHz [3].

GTT owns about 1200 PCB dynamic pressure sensors, in piezoelectric technology, to use it during sloshing model tests. Sensor model used is 112A21. The sensor diaphragm measures around 5.6 mm diameter and is in invar whereas the housing is in stainless steel. Otherwise, the IEPE component is integrated, and the sensor is compensated in acceleration. The reliability of the pressure measurements is therefore essential for GTT, both for the projects and for R&D studies [3].

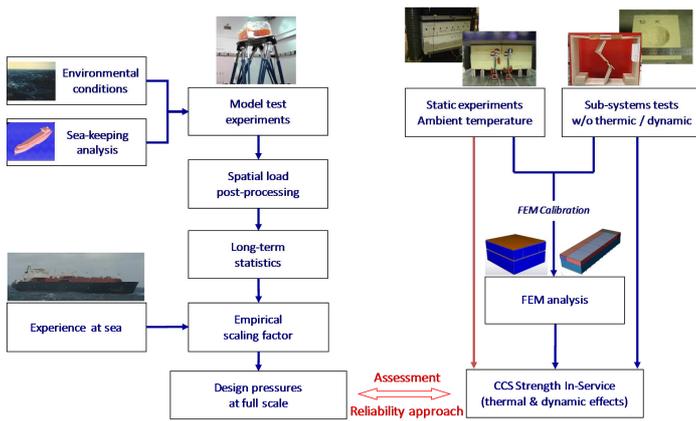


Fig. 3. GTT's methodology for a sloshing assessment of any LNG vessel

1.2 Problem

The determination of the sensor pressure value is derived from a voltage measurement by a calibration factor: the sensitivity value of the sensor. The sensitivity results from the ratio of the output (voltage) on the input (pressure), and, is obtained experimentally by calibration of the pressure sensor. The experiment consists of sending a pressure step and of measuring the output voltage of the sensor. The operation is performed on many levels of pressure, covering the range of the sensor. By definition, the sensitivity of the sensor is the slope of the curve Voltage = f(Pressure) (see Figure 4) [3].

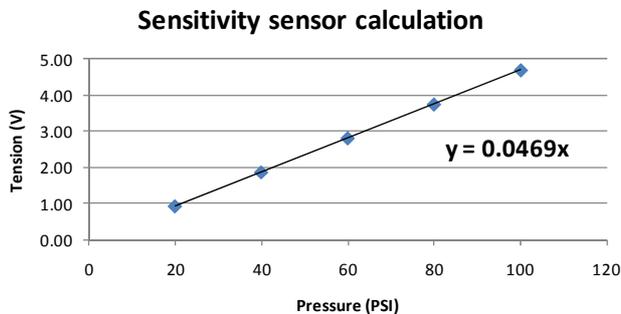


Fig. 4. Sensitivity of a pressure sensor determined by calibration
In this example, sensitivity equals 0.0469 V/PSI.

The impact pressure value depends directly from the sensitivity value. Therefore, it is important to accurately determine the sensitivity of a dynamic pressure sensor and to know the parameters influencing this measure. For the time being, GTT relies on the sensitivity values provided by the sensor manufacturer. They are evaluated by used of a PCB FOD, 903B02 model, with a rise time lower than 5 ms. The fluid used for calibration is the air and the sensor diaphragm is recovered by silicon grease to prevent thermal drift. But these test conditions are not representative of the sloshing impacts, especially because they are made in a homogeneous environment (gas) instead of the heterogeneous environment (liquid and gas) of sloshing tests [3].

As a safety measure, at each time GTT bought a new set of sensors, dedicated wet drop-tests were performed in order

to check the new sensors for liquid impact conditions. Results for different drop heights were compared with previous experimental results with old sensors and with theoretical results from Wagner's theory [4]. Pressure sensors giving results outside a certain range for a given condition were considered as wrong and discarded. Although it was tempting, the drop-tests results have never been used as a real calibration.

Moreover, only a few laboratories and dynamic pressure sensor manufacturers calibrate pressure sensors. Each laboratory has its proper methodology. Consequently, results depend on the laboratory. None of them considers relevant operating conditions with regard to sloshing tests.

1.3 Objectives

GTT decided to develop its own method to calibrate its sensors. This calibration procedure is intended to consider the operating conditions of the sensors during the sloshing model tests and to ensure traceability to the international system unit. Moreover, GTT organises intercomparison between ARTS ET METIERS - ParisTech and PCB Manufacturer to compare result obtained from different methodology [3].

The present article describes results obtained by studying the influence of the rise time and the discharge time constant on the sensitivity of the sensor.

The study is performed in collaboration with the Dynamic Metrology Laboratory (LMD) of ARTS ET METIERS - ParisTech engineering school. The expertise of LMD is the calibration and measurement of dynamic phenomena in general and of dynamic pressures in particular. LMD holds, maintains and operates the French National standard of Laboratoire National de Métrologie et d'Essais (LNE) for the "dynamic pressure".

In a first part, a recalling of pressure sensors characteristics are made, then various equipments used for calibration are presented and finally the results of the study for each parameter are exposed. In conclusion, the influence of each parameter on calibration method will be presented.

2. STATE OF ART

2.1 IEPE characteristics

IEPE stands for "Integrated Electronics Piezo Electric". Piezoelectric pressure sensors measure dynamic pressures and they are generally not suited for static pressure measurements.

The built-in circuit is powered by a constant current source (see Fig. 5). This constant current source may be part of the instrument or a separate unit. The vibration signal is transmitted back to the supply as a modulated bias voltage. Both supply current and voltage output are transmitted via the same cable. The capacitor CC removes the sensor bias voltage from the instrument input providing a zero-based AC signal.

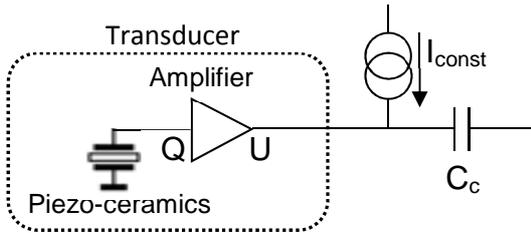


Fig. 5. IEPE principle

The quartz crystals of a piezoelectric pressure sensor generate a charge when pressure is applied. However, even though the electrical insulation resistance is quite large, the charge eventually leaks to zero. In a pressure sensor with built-in ICP electronics, the resistance and capacitance of the crystal and the built-in ICP electronics determine the leakage rate [5].

When leakage of a charge (or voltage) occurs in a resistive-capacitive circuit, the leakage follows an exponential decay. A piezoelectric pressure sensor system behaves similarly. The value of the electrical capacitance of the system (in farads) multiplied by the value of the electrical resistance (in ohms) is called the Discharge Time Constant (DTC in seconds).

The discharge time constant is defined as the time required for a sensor to discharge its signal to 37% of the original value from a step change of measure. The discharge time constant of a system relates to the low-frequency monitoring capabilities of a system.

In PCB pressure sensors [6], the discharge time constant of the sensor is set at a fixed value by the built-in circuit. When an ICP sensor is subjected to a step function input, a quantity of charge, Δq is produced proportional to the mechanical input.

Output voltage is $\Delta V = \Delta q/C$ where C is the total capacitance of the sensor electronics. This voltage is then amplified to determine final sensor sensitivity.

The charge signal decays according to the equation:

$$q = Q \cdot e^{(-t/RC)} \quad (1)$$

with :

- q = instantaneous charge (pC)
- Q = initial quantity of charge (pC)
- R = bias resistor value (ohms)
- C = total capacitance (pF)
- e = base of natural log (2.718)
- t = time

Piezoelectric sensor is treated as a linear time invariant system. Then it is evaluated on the basis of the recorded response to the step-function input [7].

The rise time is the time taken by the step to change from a specified low value to a specified high value. Typically, in analog electronics, these values are 10% and 90% of the maximum amplitude of the step.

Excitation by a pressure step is often performed by the aperiodic generator pressure. We list fast opening devices

(FOD) and shock tubes (ST). These means are characterized by a low rise time.

2.2 Shock Tube

The shock tube consists of two elongated chambers, usually of constant cross section, separated by a burst diaphragm (see fig. 6). Initially the gas pressure is higher in one chamber than in the other one. When the diaphragm ruptures the expansion of the high-pressure gas into the low-pressure chamber generates a shock wave which travels faster than the expanding gas. The rise time provided by the shock tube is of the order of nanoseconds [7], [8], and is considered to be an idealized pressure step generating high-frequency content.

The generated pressure step is calculable from gas dynamics provided that the pressure ratio, temperature, driven gas composition and shock wave velocity are accurately known [7].

The low pressure camera contains the working gas. On this last room, the sensor to be calibrated will be installed, either in the wall or in the back tube.

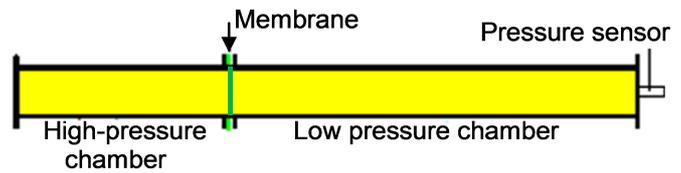


Fig. 6: Simplified illustration of shock tube

The realized pressure step will be held constant during the so-called dwell time which is a function of the shock tube length [5].

2.3 Fast-Opening-Valve Device

In this generator, two chambers with very different volumes are separated by a Fast-Opening-Valve. The sensor to be calibrated is mounted on the smallest cavity, subject to a pressure P_1 . The largest cavity is subject to pressure P_2 , higher than P_1 . Owing to the great difference of volume of the two cavities, the sensor goes to a higher level of pressure (P_2) after opening the separation valve. The pressure increases within a very short time so a nearly perfect step of pressure P_2-P_1 is generated (see fig. 7) [9].

An advantage of the fast opening device, as compared to the shock tube, is that the amplitude of the pressure can be maintained for an arbitrary time. The disadvantage is that the rise time is higher than the one obtained in a shock tube.

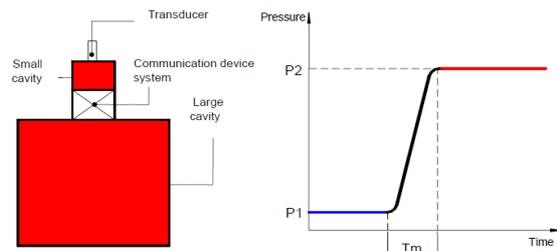


Fig. 7: Synoptic scheme of an FOD and pressure step generated

The French national standards [10] for dynamic pressure, maintained by ENSAM-Paris, consist of four overlapping shock tubes and some fast opening devices, covering the range from 10 kPa to 20 MPa.

3. EXPERIMENTATION

To calibrate dynamic pressure sensor, we need to apply as input, a pressure step with a short rise time. The step has to be as low as possible relative to the discharge time constant, to have a negligible error.

To quantify the error during calibration with a finite rise time, analog and numerical simulations were performed by varying the rise time of the input step and the discharge time constant.

3.1 Analog simulation

At the input of an analog simulator, whose transfer function is high pass type filter of the first order, we apply a given rise time step. The corresponding output is shown in fig. 8. To a unit amplitude input, the maximum value of the response is less than the value of the input.

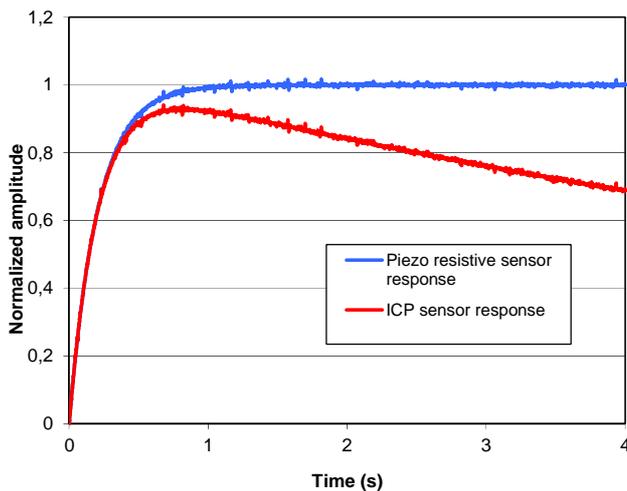


Fig. 8: Response of a piezo resistive sensor and an ICP sensor to a pressure step

To quantify the error introduced by the effect of the rise time for a given discharge time constant, the maximum achieved by the response is recorded for each rise time. The fig. 9 shows the result of simulation.

The rise time is the time taken by the step to change from 10% to 90% of the maximum amplitude of the step. The discharge time constant is defined as the time from the intersection of the tangent at the origin and the time axis.

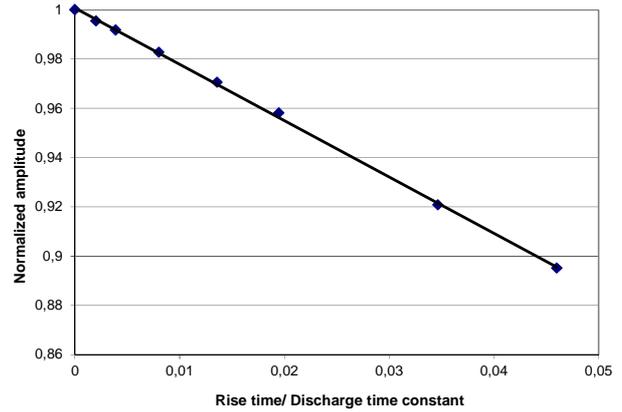


Fig. 9: Maximal of amplitude obtained with a step function of the ratio rise time/Discharge time constant

The maximum amplitude of the response to a unit step is represented versus the ratio between the rise time and the discharge time constant. The error is a substantially linear function for a given rise time and discharge time constant.

For example, for a discharge time constant of 2 seconds which is the typical value of test sensors, a rise time of 0.004 s to the input pressure step introduces an error less than 0.5% on the determination of the sensibility.

Given the analog noise, measurements are delicate when the error approaches zero. To explore this area more precisely, a numerical simulation study needs to be performed.

3.2 Numerical simulation

The approach used in the numerical simulation (MATLAB) is identical to the analog simulation. At the input of a module representing a first order high-pass type filter, we apply a given rise time step. Fig. 10 gives typical responses.

As a digital noise is very low, the maximum measurement is easier and allows to explore more precisely the area where the error is very small.

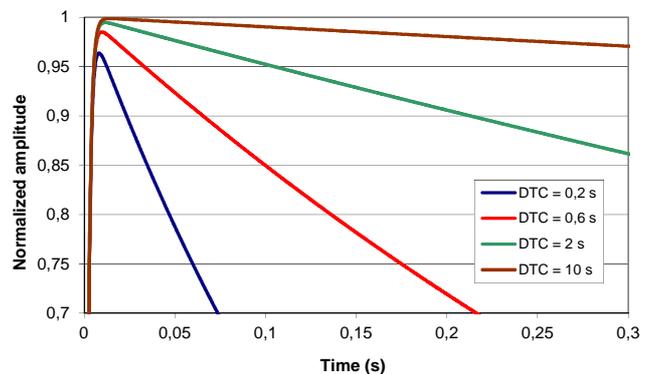


Fig. 10: Response to a step for different discharge time constants (Rise time : 4 ms)

Fig. 11 shows the maximum value for different rise times versus the discharge time constant. The lower the discharge

time constant is, the higher the error is. The lower the step of the rise time is, the lower the error is.

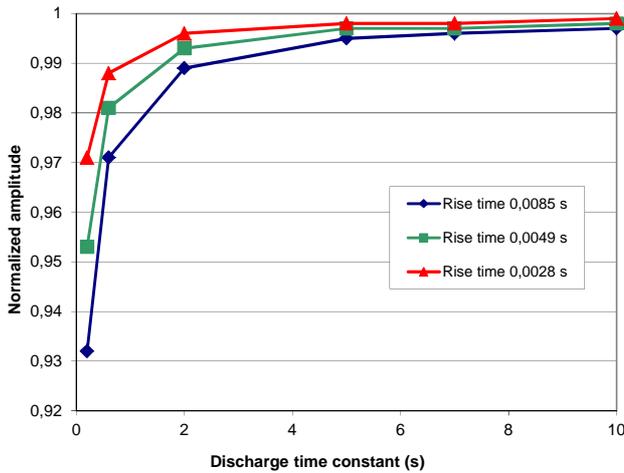


Fig. 11: Maximum value for different rise times versus the discharge time constant (Discharge time constant: 2 s)

Fig. 12 gives the results of numerical simulation based on the ratio of the rise time and the discharge time constant. Regardless of the rise time and the discharge time constant, the error is a linear function.

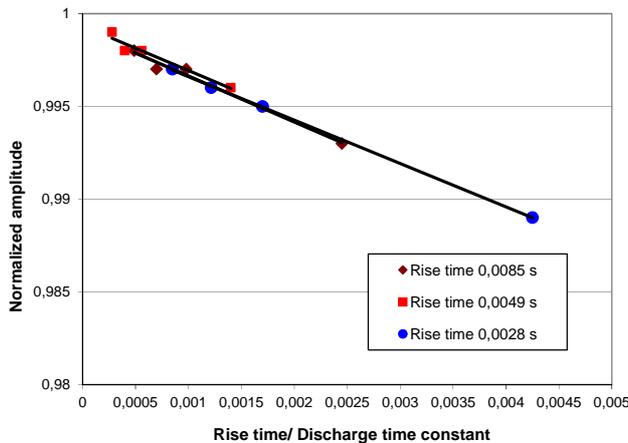


Fig. 12 : Maximum value versus the ratio Rise time/Discharge time constant

Fig. 13 shows the comparison between the analog simulation and numerical simulation. The two approaches showed very similar results.

The linearity and the slopes are almost equal in a relatively wide range of the ratio (rise time/discharge time constant). These properties are independent of the "shape" of the input step.

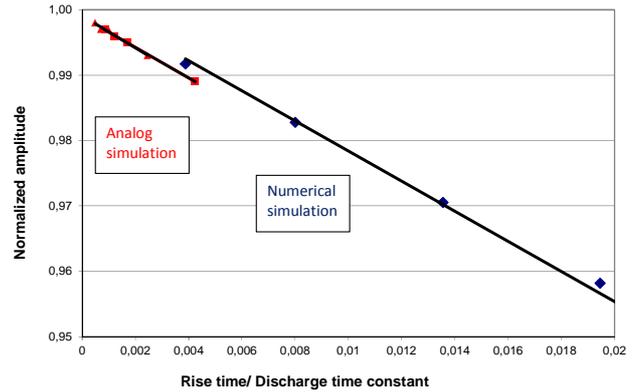


Fig. 13: Comparison between analog and numerical approach

During a sensor calibration, provided that the acquisition is adequate (sampling frequency and recording time), the calculation of the rise time and the discharge time constant is possible. Knowing the ratio of these two parameters can allow a correction on the sensitivity of the sensor under test.

4. CONCLUSION

This study allows to see the effect of the rise time and the discharge time constant on the sensitivity. Whatever the kind of simulation, analog for long times and numerical for short times, curves are linear and slopes are similar. During calibration, it is necessary to quantify these two parameters to minimize sensitivity errors. Moreover, knowing the ratio rise time/discharge time constant allows to correct during the test, sensor sensitivity.

Finally, it should be noted that the conditions for acquisition of the entire measurement chain must be taken into account and in particular the input coupling (DC / AC). Indeed, an alternative coupling decreases the equivalent discharge time constant. For a given rise time, it may also cause a significant error in the value of the pressure peak.

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