CALIBRATION METHODOLOGY FOR PIEZOELECTRIC PRESSURE TRANSDUCERS USING SUPERSONIC SHOCK TUBES

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Abstract: *The objective of this work is showing a methodology adopted for the calibration of piezoelectric pressure transducers that further on will be utilized on a model inside a supersonic shock tunnel's test section. All the steps and procedures implemented for this calibration will be presented. A comparison will also be established between the calibration data acquired in this experiment and the original data, specified by the manufacturers. From this comparison, a conclusion concerning the effects of time of usage for these kinds of measuring instruments and the experimental error incurred from that will be made.*

Keywords: *calibration, piezoeletric sensor,shock tube.*

1. INTRODUCTION

It is well know that for an experiment to take place all data acquisition equipment must be fully operational, that is, it must be able to collect data properly and with as minimal errors as possible. For this purpose, before experiments can be carried out on the actual model which will be inserted in a supersonic shock tunnel, a calibration is an important step to take place.

The sensors that are being calibrated are piezoelectric pressure transducers on the shock tube. The principle of operation of this pressure transducer is to measure pressure by using the deformation of piezoelectric crystals. The occurrence of this deformation, in specific planes, causes a generation of electrical potential difference or electrostatic charge. With the relation between the stress that deforms these planes and the measured voltage generated by the crystal, it is possible to find the pressure or force for that matter, applied on the crystal (França, 2006).

Therefore, once the calibration of these transducers is done, the experiments can be started on the actual model inside the shock tunnel. With calibration data, we will be able to determine the pressure of the flow along the model with more precision and accurateness compared with an experiment which uses sensors that have not been calibrated for a long period of time.

An earlier model was used in 2008/2009 for the same purpose as the 2010 model: to study the pressure field of a supersonic flow interacting with the model (Damião, 2009). However, in 2008 there was no need to carry out a calibration because the piezoelectric sensors had just been calibrated. With the two year gap between the last calibration and the one made now, we will be able to see the influence of time effects on the sensitivity of these sensors.

2. GOVERNING EQUATIONS

The physical theories utilized for the calibration in a shock tube can be found in any Gas Dynamics literature (e.g, Liepmann e Roshko, 2001). It is important to state that only one equation is relevant for the whole analysis of the calibration range of pressure to choose.

$$\frac{p_4}{p_1} = \frac{p_2}{p} \cdot \left[1 - \frac{a_1 \cdot (\gamma_4 - 1) \cdot \left(M_s^2 - 1\right)}{a_4 \cdot (\gamma_1 + 1) \cdot M_s}\right]^{-\frac{2\gamma_4}{\gamma_4 - 1}} \tag{1}$$

Both values of pressures P_4 and P_1 can be changed in the actual shock tube. Depending on which experiments are being studied, the ratio P_4/P_1 should be adjusted adequately. However, it must be stated that the changes must be made in a way that the ratio P_4/P_1 is different from one another. The results observed if there is 10 *bar* in P_4 and 2 *bar* in P_1 are the same as 5 *bar* and 1 *bar* in P_4 and P_1, respectively. This is an important observation to be taken into account when working with a supersonic shock tube.

3. EXPERIMENTAL PROCEDIMENTS AND APPARATUS

The experiment was performed on a supersonic shock tube which makes part of the shock tunnel T1, shown in Fig. 1. The shock tube is composed of two reservoirs, a high pressure denominated *driver* and a low pressure denominated *driven*. The pressure in both reservoirs can be changed so that different ratios of pressure can be obtained. For practical reasons, only the pressure in the *driver* was varied, maintaining the *driven* pressure constant and equal to the ambient pressure. For the high pressure reservoir, experiments were conducted from pressures ranging from 3 *bar* to 7 *bar* (manometric pressure).

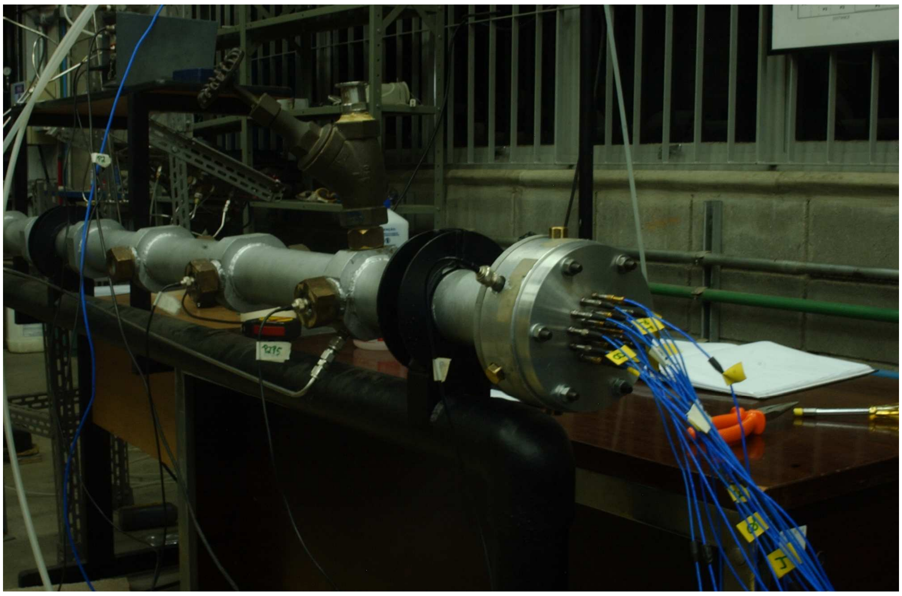

Figure 1. Shock tube T1 with 21 PCB sensors at the end of the low-pressure reservoir.

Each condition of pressure represents one point in the calibration curve. For the procediments adopted here, not more than four points were necessary to draw a reliable curve. The pressure conditions were, 3 *bar*, 4 *bar*, 5 *bar* and 7 *bar* for the *driver* (manometric pressure). All of data acquisition/analysis and experimental procedure for each condition can be considered the same. Few things vary from one condition to another, and if necessary, will be specified throughout this article.

To separate the *driver* from the *driven*, plastic papers were used as diaphragms since the difference in pressure was not very high. The only exception of this configuration was in the fourth condition, where two sheets of plastic diaphragms were needed to stand the pressure gradient. For the rupture of the diaphragm, a metallic spike at the end of the *driver* section was used. To make it work, injection of compressed air is applied at the end of the spike, so it can move forward. The use of this apparatus makes it very fast for the experiment to start, so that once the pressure for a specified condition is attained, the same condition can be repeated in the same way, with little or no difference at all from the other trials.

3.1. Shock tube instrumentation

The only physical quantity analyzed is pressure. For this reason, the shock tube was instrumented purely with piezoelectric sensors. Two types of sensors were used: KISTLER sensors and PCB sensors. All sensors were positioned in the *driven* section of the shock tube.

Three KISTLER sensors are used in the experiment; the first two of them are used to measure the speed of the normal incident shock wave while the last one is used to measure the standard reservoir (stagnation) pressure value. In other words, the value of pressure measured from this sensor is the most reliable and will be the reference throughout the calibration. From now on, the pressure measured by this standard sensor will be denominated P_5.

The KISTLER sensors are positioned perpendicular to the flow inside the shock tube. The denomination of the sensors by order of encounter with the normal incident shock wave is: P_2P_2, P_2P_5 and P_5.

There is also the PCB type of sensors. These are the sensors which will be calibrated in the experiment. They are positioned at the end of the shock tube, in opposite direction to the flow on the tube. In that configuration, the pressure registered by this sensor will be the same pressure captured by the P_5 sensor. Twenty one PCB sensors were used in this experiment.

3.2. Amplifiers and oscilloscopes

All sensors were connected to amplifiers and oscilloscopes so that data could be correctly treated. Two YOKOGAWA DL 750 Scope Corder oscilloscopes and two PCB PIEZOTRONICS SENSOR SIGNAL CONDITIONER MODEL SERIES 481 amplifiers were used in this calibration.

4. EXPERIMENTAL DATA ANALYSIS

It is not the purpose of this article to show all graphical results from each of the twenty one sensors calibrated. For this reason, a global analysis will be done, gathering the most important information from all sensors and analyzing it. Sensor PCB number 1 will be used as example for all the experimental proceedings. A KISTLER sensor results will be explained, given its importance in the experiment.

Figure 2 shows the first two KISTLER sensors signals, as the moving incident normal shock wave developed inside the shock tube passes by them.

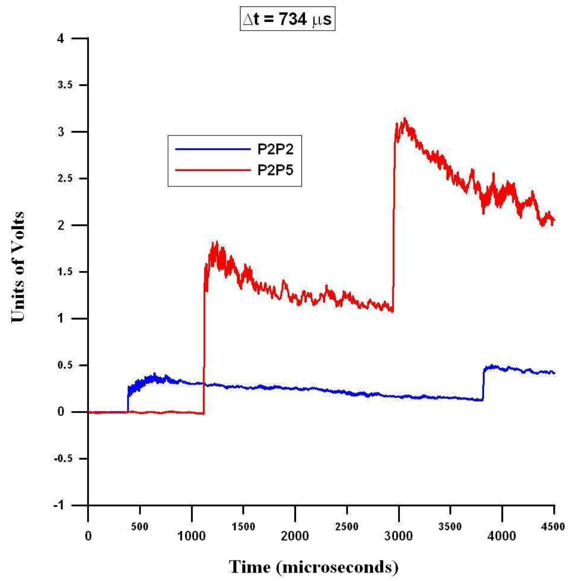

Figure 2. KISTLER sensors signals P_2P_2 and P_2P_5

Notice that once the shock wave passes P_2, the pressure in that region increases, producing a step like signal. After traveling a distance of 314 millimeters the wave passes through P_2P_5, producing the same kind of signal (in the figure it looks different, but it is only because of the different gains in the amplifiers used in each sensor). After that, the wave is reflected in the end of the shock tube and passes through sensor P_2P_5 first, and then P_2. That is why when looking at the signals in Fig. 2, it shows first a raise on signal P_2, then P_2 P_5, P2 P_5 again and finally P_2.

Figure 3 shows the third KISTLER signal, which represents the reservoir pressure P_5 produced by the normal shock wave.

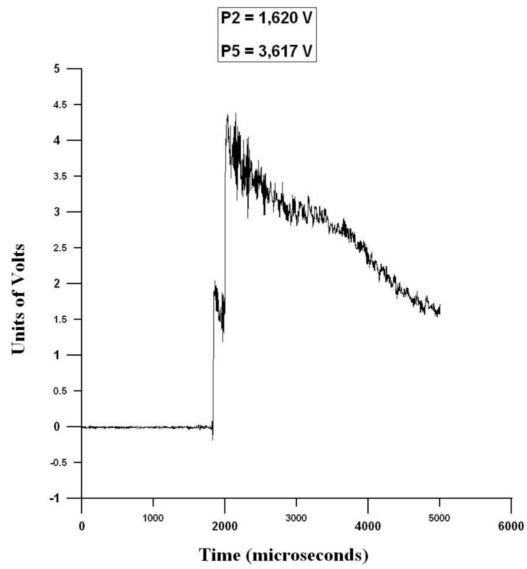

Figure 3. Pressure sensor P_5 signal

Once the wave passes through P_5, like with the other two KISTLER sensors (P_2 and P_2P_5), the pressure in the region is increased. But just after passing P_5, the wave encounters the end of the shock tube, reflecting and moving back towards the beginning of the shock tube. Therefore, shortly after passing P_5, the normal shock wave passes this sensor again, increasing the pressure for the second time. Physically, this second pressure raise is exactly equals to the stagnation pressure of the flow. The reason is directly connected to the fact that the boundary condition at the end of the tube is the "no flow" condition, that is, the gas behind the shock wave after the reflection must be stagnated (where the sensor is located). Since the PCB sensors are all located at the end of the shock tube and in a direction opposite to the flow, they will also measure this stagnation pressure P_5. This is the reason why it is important to make P_5 the standard pressure in this experiment, so that the correct pressure measured by KISTLER sensor can be compared to the PCB sensors and the output signal they give.

In shock tunnel experiments, the reservoir pressure P_5 is very important because it is what generates the flow that will enter the test section of the tunnel. Depending on the convergent-divergent nozzle used on the test section, different numbers of Mach can be obtained inside the tunnel.

As mentioned earlier on this article, four experimental conditions were considered for this calibration, where each condition is represented by a point in a calibration curve.

Each condition was repeated four times so a pattern could be clearly seen from the results. Once the data could be considered reliable, a point was drawn on the calibration graph. Figure 4 shows the results obtained for sensor number one.

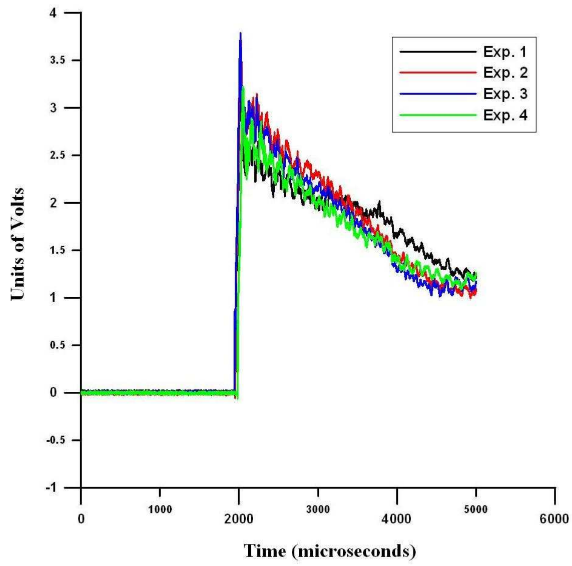

Figure 4. Four experimental results for condition one, in sensor number 1

As it can be seen in graph from Fig. 4, the experimental results proved to be very repetitious, which, needless to say, is very good. An average value for the peak of the signal was calculated and then drawn in the calibration curve for sensor number 1. The other sensors proved to have the same repeatability as sensor number 1.

After doing the same analysis for all four conditions, a calibration curve was made. A straight line passing through the origin was used to adjust the experimental points, where the criteria utilized for this fit was least squares. A straight line passing through the origin was the best fit because physically, if there was no pressure gradient felt by the sensor, there would be no signal as an output. Figure 5 shows the curve for sensor number 1.

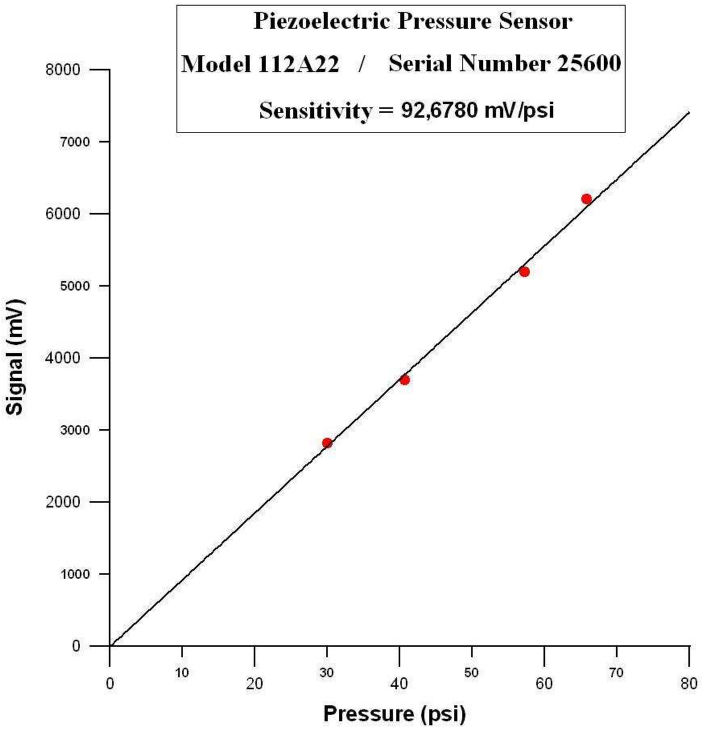

Figure 5. Calibration curve for sensor number 1

4.1. Data comparison

After all calibration curves were in hand, for all 21 sensors, a comparison was made for some of the sensors with the first calibration results, when the sensors were first used. This comparison will be able to show the effects that time have over the sensor's sensitivity. The last calibration done on the 21 sensors was 2 years ago.

Table 1 shows 5 different sensors calibration data for c

Table 1. Calibration comparison for 5 sensors.

Sensor	First Calibration Sensitivity		Last Calibration Sensitivity		Error (%)
1	96,61	mV/psi	92,68	mV/psi	4,07
3	99,73	mV/psi	96,84	mV/psi	2,89
11	103,7	mV/psi	96,58	mV/psi	6,86
15	101	mV/psi	100,75	mV/psi	0,25
21	103,9	mV/psi	99,35	mV/psi	4,38

As can be seen in Tab. 1, the error varies from 0,25% to 6,86%. That means that if the old calibration was used, the experimental results would necessarily be erroneous and with errors of as much as 6,86%.

5. CONCLUSIONS

From the analysis made on the data collected in the supersonic shock tube, it was observed the real importance of establishing equipment calibration cycles. These cycles will have to be periods of less than 2 years, since it was observed sensitivity errors of up to 6,86%. A good "rule of thumb" is to recalibrate on an annual basis.

It is also good practice to recalibrate after exposure to any severe temperature extreme, shock, load, or other environmental influence, or prior to any critical test (PCB Piezotronics).

6. ACKNOWLEDGEMENTS

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