# Characterisation of Miniature Piezoresistive Pressure Sensors for the Measurement of Slamming Loads.

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**ABSTRACT**

Understanding the effect of highly non-linear wave impact loads on structural integrity is important during Life-of-Type and Life-of-Type extension assessments. Towing tank testing utilising pressure sensors provides a cost effective method of examining these non-linear wave loads within a repeatable, controlled environment.

A survey of the relevant literature reveals many challenges and intricacies associated with the use of pressure sensors for this purpose. In the selection of a sensor, many factors need to be considered that affect the quality of the results obtained such as the sensor type, pressure range, sensitivity, sensor frequency bandwidth, output type, physical construction, size and weight.

This study examines the selection of a suitable pressure sensor to be used during a towing tank trial to measure hydrodynamic loading on a hydro-elastic generic patrol boat model. Prospective sensors were selected and tested for signal-to-noise ratio, dynamic response, photoflash sensitivity and thermal transient response in order to select the most appropriate sensor. Comparisons between results obtained for each sensor revealed some undesirable responses due to environmental influences. The information presented in this paper provides the basis for the selection of pressure sensors for use in scale towing tank or tank sloshing model test programs.

**INTRODUCTION**

The selection of a pressure sensor for scale model towing tank testing requires many factors to be considered. These include the type or construction of sensor, physical size and weight, the output type, media being sensed, pressure range, frequency range and sampling frequency of the output. This study was undertaken as there are currently no relevant standards or procedures for the selection of pressure sensors to measure non-linear wave impact loads in scale model tow tank testing. Previous studies, as outlined below, have used pressure sensors to measure tank sloshing, water impact pressure using wedges, cylinders and scale models which have alluded to issues with acquired pressure data and subsequent follow-on investigations were performed predominantly with Piezoelectric (PE) or Integrated Electronic Piezoelectric (IEPE) sensors.

Rosen et al. [1] found that due to the large number of sensors required, noise caused by coupling of signals between cables highlighted the importance of cable shielding. Thornhill et al. [2] stated that there were relatively high levels of noise in their acquired data and that several sensors failed. Choi et al. [3], Van Nuffel et al. [4] and Pistani et al. [5] found mounting issues related to whether the sensor face was flush with the model surface. If the sensor sits proud of the surface, turbulence will be generated causing incorrect pressure measurements. A sensor sitting recessed will trap air causing variability in the peak pressures that are measured. This is also the case if the measurement face of the sensor is not flush and sits recessed in a duct. The authors from [3, 4, 5] along with Judge et al. [6] and Kim et al. [7] also found that the acquired data contained spikes and level shifts when the sensors were moved between air and water, and vice versa, due to a difference between the water and air temperature. While the majority of studies used piezoelectric pressure sensors, which are known to have temperature sensitivity, Pistani et al. [5] found the same sensitivity in the piezoresistive pressure sensor when the ambient air temperature was the same as the water temperature. The conclusion was that strain gauges in the Wheatstone bridge self-heated due to the applied excitation voltage which locally raised the temperature. When water contacted the sensor it caused the contraction of the metal diaphragm resulting in the spike on the output. Judge et al. [6] experimented with coating the face of the sensor with a thin layer of dielectric grease to isolate the sensor from any temperature variation while still transferring dynamic pressure.

The previous studies show that a wide range of sampling frequencies have been used to measure the pressure caused by wave impacts. Rosen et al. [1] found that the sampling frequency of 2.5 kHz was sufficient for most situations, but on the low side for more extreme impacts. Van Nuffel et al. [4] compared peak pressure measurements and found that a sampling frequency of at least 200 kHz was required to reproduce the signal with approximately 1% error. Repalle et al. [8] found in their tank sloshing experiment that a minimum sampling frequency of 20 kHz was required to measure impact pressure but that 40 kHz is more appropriate.

As there is often a requirement in towing tank experiments to measure both hydrostatic and wave impact pressure, this study was limited to strain gauge or micro-electro-mechanical system (MEMs) based piezoresistive sensors rather than PE or IEPE sensors. PE and IEPE sensors are not suitable for use in measuring static pressure due to the decay in the output signal caused by charge leakage.

## PIEZORESISTIVE PRESSURE SENSORS

A survey of commercially available piezoresistive pressure sensors was undertaken and two prospective sensors were selected due to their small physical dimensions, low weight, frequency bandwidth and diaphragm flush with the sensor face. The sensors selected were the TE Connectivity (Measurement Specialties) XP5 [10] and Keller 2MI [11]. The Endevco 8510C pressure sensor [9] was an existing item in our inventory which was included as a comparison to the XP5 and 2MI sensors.

### Endevco 8510C

The Endevco 8510C piezoresistive pressure sensor uses a micro-machined diaphragm with four small piezoresistors implanted on the surface in a Wheatstone bridge configuration. The

8510C pressure sensor is a vented gauge type and is not sealed on either side of the diaphragm. On the rear of the sensor there is a small tube to allow the air pressure to push against the back of the diaphragm, equalising the force from the front of the diaphragm at ambient pressure. This results in the output of the sensor being centred about the ambient pressure. The sensor face has a diameter of 3.86 mm and an overall length of 19.1 mm. The front of the sensor has mesh covering the face as can be seen in Figure 1a.

There are two reasons for this mesh. It covers the inlet to the sensor and offers mechanical protection while also reducing the amount of high intensity light directly hitting the silicon diaphragm which causes a transient response on the sensor output. The diaphragm is mounted behind the mesh and held in place by epoxy adhesive. As a result, the manufacturer states that while the 8510C pressure sensor can be used in water it should be ‘only for short durations’ and ‘it is best to use de-ionised water or water without normal contaminants found in tap water, which is quite corrosive’ [14]. The manufacturer therefore advised that the sensor then needs to be dried out thoroughly following each immersion. The sensors will be used in a tow tank and it is impractical to fill the tank with purified water for the duration of the testing. It is also impractical to test for short periods and dry each of the pressure sensors out at the end of each session due to the amount of time required to setup and calibrate the sensor suite. Also as a typical tow tank test program can span over many days progressive damage to these sensors may occur which could compromise the acquired data.

**TE Connectivity (Measurement Specialties) XP5**

The TE (Measurement Specialties) XP5 pressure sensor, pictured in Figure 1b, was selected as one of the sensors for further investigation because it is the same physical size and thread pattern as the 8510C. The XP5 is also totally sealed with a flush diaphragm at the sensing face and the range of the sensor can be selected closer to the expected maximum pressure typically observed in scale model testing in towing tanks. The sensor range selected was 104.42 kPa, which was the lowest pressure range at the time. The transducer is completely sealed within a titanium body with a laser welded diaphragm on the face of the sensor and the sensing element is a temperature compensated Wheatstone bridge constructed using micro-machined silicon strain gauges.

(a) (b)

*Figure 1. (a) 8510C pressure sensor; (b) XP5 pressure sensor.*

**Keller 2MI**

The Keller 2MI pressure sensitive element, as shown in Figure 2a, is a micro-machined piezoresistive sensor that is mounted in a stainless steel case and covered in a thin coating of silicone elastomer. The element dimensions are 4.5 mm diameter and 3 mm in height. The small dimensions allow the element to be used in applications where space and weight are important factors and can be used in all gases and liquids that are compatible with silicone elastomer and stainless steel. The 2MI can be used in either constant current or voltage configurations. The end user is to install configuration and external temperature compensation resistors as specified on the supplied calibration sheet.

To enable the sensor element to be easily installed, moved and replaced, the sensor element needs to be mounted in a secondary housing tailored to the particular measurement application under consideration. A secondary housing with locking nut was constructed of aluminium to reduce weight and encloses the temperature compensation and zero adjustment resistors close to the element and allow the transition to a more robust cable. The housing was filled with potting compound to provide mechanical strength and ensure it is fully waterproof. In comparison with the 8510C and XP5 sensors, the finished sensor is larger in diameter at 7 mm and similar in length at 23 mm. The 2MI pressure sensor mounted in the secondary housing that was developed for specific towing tank measurement applications is shown in Figure 2b. The maximum pressure range of the selected sensor was 100 kPa.

(a) (b)

*Figure 2. (a) Keller 2MI sensor element without silicone covering; (b) in housing with locking nut.*

**TESTING METHODOLOGY**

There are currently no standards or procedures for the selection of pressure sensors for use in measuring non-linear wave impact loads in scale model tow tank testing. As a result, a suite of tests was developed to characterise the noise, dynamic, photoflash and thermal transient responses which are relevant to scale model tow tank testing. These responses may be defined as various parameters in the sensor data sheet, but it can be difficult to gain a full understanding on their effect on the acquired data. The testing regime was designed to compare the Endevco 8510C, against the Measurement Specialties XP5 and Keller 2MI sensors for their performance and response in a laboratory setting.

All of the sensors were connected to an Endevco Model 136 bridge amplifier and the analog signal was acquired using a Liberty data acquisition system made by HBM Inc. The GP-8 analog input module has 16-bit resolution and a maximum sampling rate of 100 kilo-samples per second (kS/s) per channel. While there is a large variation in the sampling rates of the previous studies mentioned earlier, a conservative sampling rate of 20 kS/s was selected for this study.

**Noise**

Noise is always present in data acquired from sensors to varying extents. It can be generated by many sources including switching power supplies, motors and computers. The noise can be transmitted through the air and picked up with cables or conducted through the power supply. The data sheet for the 8510C sensor states that electrical noise is $5\times10^{-6}$ Vrms and the Model 136 bridge amplifier has electrical noise of $20\times10^{-6}$ Vrms relative to the input plus $1\text{x}10^{-6}$ Vrms relative to the output. Given an average sensor amplifier gain of 42.33 the highest Signal to Noise Ratio (SNR) should be approximately 74 dB. The XP5 and 2MI sensors do not state a noise parameter in the data sheets.

As the 8510C sensor cable is 1.5 m long an 8 m extension cable was used to connect the sensor to the bridge amplifier. This extension cable is unshielded and has unterminated connections to the sensor outputs. Potentially both of these issues could increase the amount of noise, reducing the SNR at the output of the amplifier. A shielded extension cable was constructed and compared with the unshielded variant to examine the difference in the amount of noise exhibited on the output of the bridge amplifier. The XP5 sensor has a cable length of 2 m and therefore also required an extension cable to connect to the amplifier. The effect of using both types of extension cables will be compared. As the 2MI pressure sensor has been constructed with a 10 m cable, only the sensor and bridge amplifier will be compared to the results from the other sensors.

**Dynamic Response**

The dynamic performance of each of the sensors was tested using a PCB Dynamic Pressure Pulse Calibrator. The calibrator generates a step-function pressure pulse of precisely known static air pressure from a large volume reservoir. The pressure of the pulse is set by an input control valve and is displayed on a large dial gauge. The pulse actuation and duration are controlled by a press button which actuates a solenoid valve connected to the test housing.

The 8510C, XP5 and 2MI pressure sensors were tested with pressure pulses at 80 % of the maximum pressure range to gain a better understanding of the frequency response for each of the sensors.

**Photoflash and Light Sensitivity**

High intensity light from a camera flash or strobe light can cause a transient pulse on the output of piezoresistive transducers. This is due to the silicon diaphragm absorbing photons emitted from the flash or high intensity light. These photons excite the electrons of the material that makes up the bridge elements causing a change in the current flow through the piezoresistors. This change in current flow exhibits itself as a positive or negative voltage spike on the output.

As flash photography is often used as a part of the documenting process for towing tank testing, the sensors were tested for photoflash response. The response from the three pressure sensors was measured with the flash at a distance of 1.5 m and rotating the sensor from zero degrees (flash directly facing the diaphragm) through to ninety degrees, in fifteen degree increments. A Canon Speedlite 580 MkII flash module configured in manual trigger mode and a 1/64 second flash duration was used for this test program.

The three sensors were also tested to examine if there is any response due to changes in indoor lighting. The simple test involved placing the sensor perpendicular to a light source for duration of five seconds and then rotating the sensor so that it was parallel to the light for a further five seconds. This was repeated six times to create a test duration of one minute. The distance between the light and sensor was kept at a constant 1.5 m. The light source was a twin tube fluorescent light typical in laboratory lighting.

### Thermal Transient Response

Thermal transient response is the output of the sensor when subjected to a step-function temperature change [13]. This sudden change in temperature can cause a change in the physical stress of the diaphragm and therefore a change in the value of the piezoresistors or microstrain gauges. A change in temperature will also cause a change in the resistance of individual piezoresistors or gauges. An imbalance in the Wheatstone bridge can occur if only part of the bridge is exposed to the thermal transient, resulting in a transient response at the output. Sensors are typically designed with thermal compensation which works only for equilibrium temperature and not thermal transients. As the pressure sensors will be moving between air and water when measuring slamming loads, therefore a minimal response should be exhibited on the sensor output due to the change in media and temperature of the media.

The thermal response was tested by immersing the pressure sensors mounted in the side of an open top enclosure in water to a set level, resulting in an expected hydrostatic pressure change. Various water temperatures were tested to vary the difference between the ambient air and water temperatures and therefore gain an understanding of the thermal response of each sensor. Two mounting positions in the enclosure produce a measured output of approximately 0.12 kPa and 0.31 kPa due to hydrostatic pressure changes alone.

## RESULTS

The following results were measured during the testing program in response to noise, dynamic response, photoflash and light sensitivity and thermal transient response for the 8510C, XP5 and 2MI pressure sensors.

## Noise

The SNR for each of the sensors was calculated using the peak-to-peak electrical noise and the maximum peak-to-peak voltage for the full range of the sensor output as shown in Equation 1.

$$SNR(dB) = 20\ log_{10} \frac{Max.Pressure\ _{V\ p-p}}{Measured\ Noise_{V\ p-p}} \qquad (1)$$

In the laboratory bench tests for noise the 8510C, XP5 and 2MI sensors all performed similarly with an average SNR of 65.74, 65.46 and 65.46 dB respectively. There was no increase in noise due to the inclusion of the extension cable or between the original unshielded and shielded version of the cables for both the 8510C and XP5 sensors. As the 2MI was constructed with a 10 m long cable it was not tested with the extension cables. Figure 3 shows the electrical noise on the measured output of the sensors at ambient pressure. While laboratory testing in this case demonstrated no change in noise levels between shielded and unshielded extension cables, shielded cables should be used in noisier environments.

Data acquired during previous test programs that utilised the 8510C sensors found a SNR of between 42.4 and 63.8 dB with an average of 49 dB. When comparing the previously acquired data to the results from the laboratory testing there is reduction of 16 dB in SNR which is due to a 6.3 times increase in the measured noise.

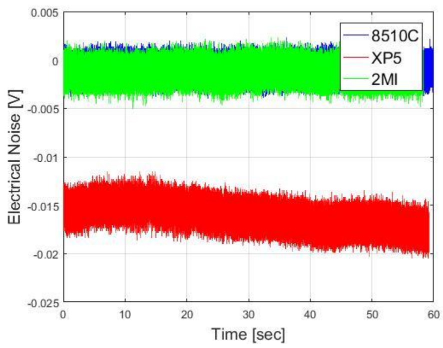



*Figure 3. Pressure sensor noise response of all sensors.*

## Dynamic Response

The dynamic response of the 8510C, XP5 and 2MI sensors were tested with a set pressure pulse corresponding to approximately 80 % of the sensors range. The average measured steady state magnitude of the pressure pulse of the sensors including the peak overshoot is shown in Table 1. A pressure pulse for the 8510C, XP5 and 2MI sensors is shown in Figures 4a, 5a and 6a respectively. A magnified view of the pressure pulse peak for the 8510C, XP5 and 2MI sensors is shown in Figures 4b, 5b and 6b respectively. The overshoot for the 8510C and 2MI pressure sensors had a decaying oscillation with a measured frequency of 9.7 and 9.1 Hz respectively, which decayed within 0.7 of a second. The XP5 decayed from the overshoot with no oscillation and was still trending down at the end of the pressure pulse. It is estimated that the decay would reach a steady state in approximately 1.2 seconds. The measured response of the XP5 sensor after the negative going edge of the pulse also overshot the original zero pressure by 1 kPa returning to zero 1.2 seconds later. The spikes at the start and end of the measured pressure pulses for all sensors were caused by the actuation and release of the PCB pulse calibrator solenoid.

| Sensor | Pressure Pulse (kPa) | Av. Steady State (kPa) | Peak Overshoot (kPa) |
|---|---|---|---|
| 8510C | 275.8 | 274.42 | 0.4 |
| XP5 | 82.74 | 81 | 1.35 |
| 2MI | 82.74 | 83.2 | 0.16 |

*Table 1. Dynamic Pressure Pulse measurements for all sensors.*

As shown, the 8510C and 2MI sensors matched the pressure pulse more closely and were within approximately 0.5 % of the set pressure for the pulse when compared to the XP5 which was 2.1 %.

(a) (b)

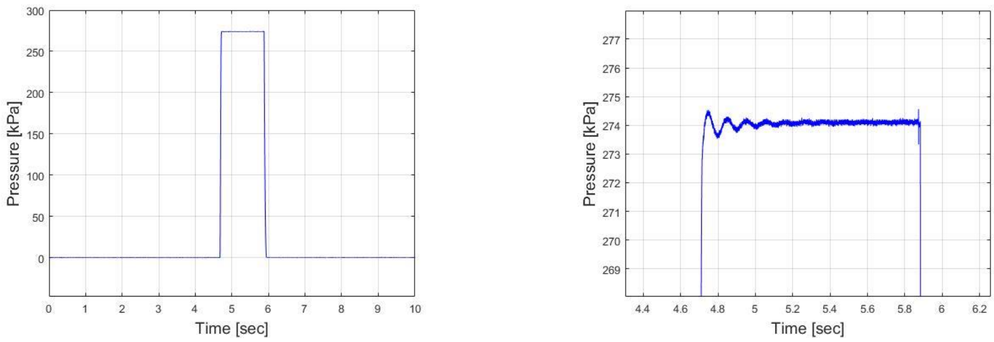



*Figure 4. (a) Pressure Pulse response for 8510C sensor; (b) magnification of the peak.*

(a) (b)

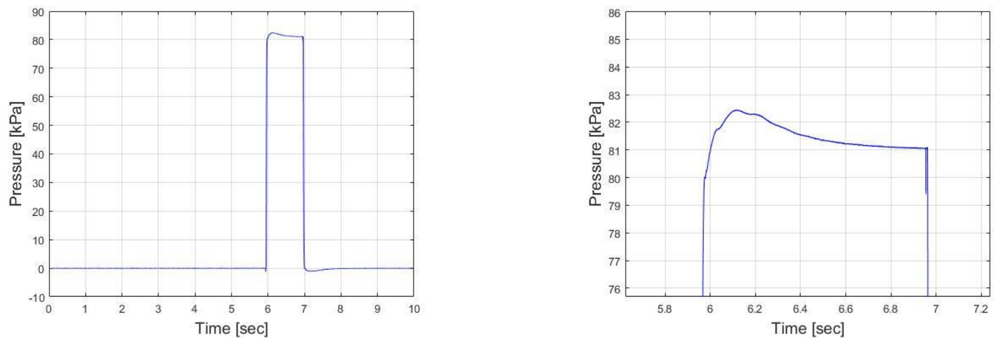



*Figure 5. (a) Pressure Pulse response for XP5 sensor; (b) magnification of the peak.*

(a) (b)

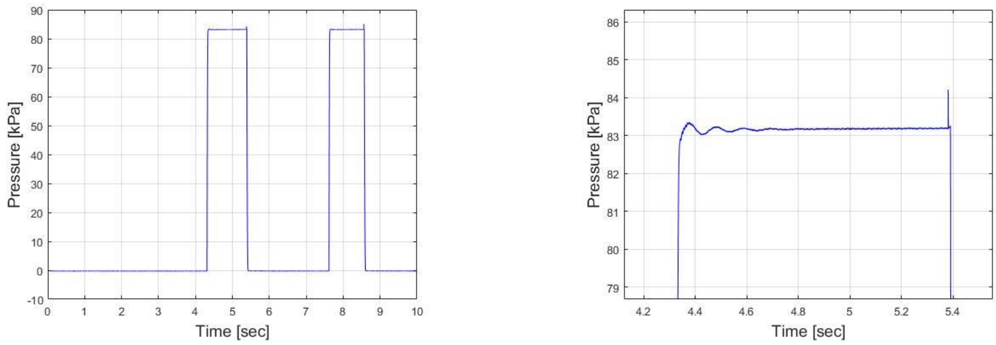



*Figure 6. (a) Pressure Pulse response for 2MI sensor; (b) magnification of the peak.*

The response from the three sensors was underdamped, with the XP5 sensor being more heavily damped than the 8510C and 2MI sensors. The higher damping factor of the XP5 sensor may be due to the increased mass of the diaphragm and may contribute to the lower dynamic frequency when compared to the 8510C and 2MI sensors. The useable dynamic frequency bandwidths for the 8510C, XP5 and 2MI sensors are calculated as 64 kHz, 21.6 kHz and 60 kHz respectively, using a general industry 'rule of thumb'. This 'rule of thumb' states that, 20% of the natural frequency is the useable bandwidth of piezoresistive and piezoelectric pressure sensors due to the change in gain of the sensor exceeding 5% as the dynamic frequency approaches the natural frequency [10, 12 & 13]. As a result, the signal from each sensor should be filtered to remove high frequency components of the signal before the data acquisition system and folding due to the Nyquist theorem. Typically manufacturers will only define the natural or resonant frequency in datasheets, so care needs to be taken to ensure that the maximum frequency expected during testing is lower than 20% of the natural or resonant frequency.

**Photoflash and Light Sensitivity**

The results for the 8510C sensor in Table 2 show that the high intensity light from the flash was measured at all angles except for 90 degrees. At 90 degrees the light output is parallel to the diaphragm and was blocked from hitting the diaphragm by the construction of the sensor. The level of response varied, as the angle between the flash and the sensor increased due to the mesh covering the duct leading to the sensor diaphragm blocking the light more effectively at some angles. The magnitude of the measured spikes varied from -0.77 to -23.13 kPa, which is 0.22 – 6.7 % of the total range of the sensor but in the negative direction.

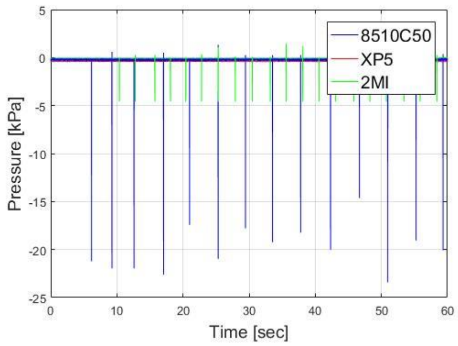
The 2MI pressure sensor diaphragm is sealed using a thin layer of silicone elastomer to protect it from the media being sensed which allows some of the light through to the sensor diaphragm. The measured photoflash response, as shown in Table 2 and Figures 7a and 7b, was constant at -4.59 kPa across all angles except for 90 degrees, which produced a response of -0.4 kPa. The constant response is because the silicon attenuates the light rather than blocking it.

The XP5 sensor has a diaphragm that is covered by a thin layer of titanium, which blocks light and is therefore not affected by photoflash as shown in Table 2 and Figures 7a and 7b.

| Flash Angle (deg) | 8510C50 (kPa) | XP5 (kPa) | 2MI (kPa) |
|---|---|---|---|
| 0 | -21.54 | 0 | -4.59 |
| 15 | -13.8 | 0 | -4.59 |
| 30 | -23.13 | 0 | -4.59 |
| 45 | -19.32 | 0 | -4.59 |
| 60 | -18.34 | 0 | -4.59 |
| 75 | -0.77 | 0 | -4.59 |
| 90 | 0 | 0 | -0.4 |

*Table 2. Pressure sensor flash response of all sensors.*

(a) (b)



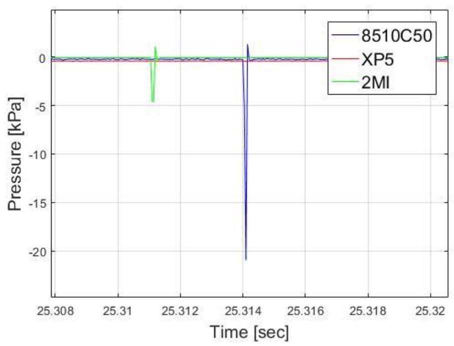




*Figure 7. (a) Pressure sensor flash response of all sensors; (b) zoom of single flash.*

When testing the response of the 8510C sensor to fluorescent lights the negative peaks shown in Figure 8a was due to weight of the sensor diaphragm causing deformation during rotation. A more consistent result showing level shifts due to an increase in light hitting the diaphragm would be expected if the 8510C was sensitive to fluorescent light. As the titanium diaphragm of the XP5 blocks all light, the negative peaks shown in Figure 8a are also due to the movement of the sensor. A more accurate test for these two sensors would be to leave them in position and block the light with an opaque cover.

There was a small level shift of 13 Pa from the 2MI sensor when it was rotated towards or away from the fluorescent light at 1.5 m as shown in Figure 8b. This variation on the output of the sensor is the equivalent of a 1.3 mm change in hydrostatic pressure.

(a) (b)

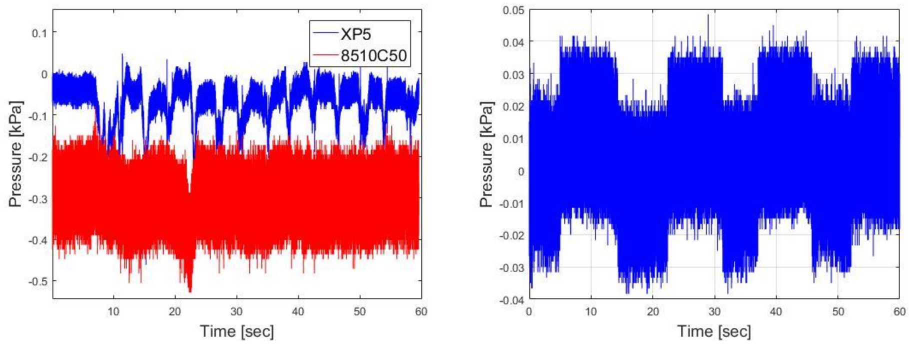



*Figure 8. Fluorescent Light response at a distance of 1.5 m of (a) 8510C and XP5 pressure sensors; (b) 2MI pressure sensor.*

**Thermal Transient Response**

The 8510C and XP5 pressure sensors were mounted in the side of an enclosure which was placed in the water causing the sensors to be submerged to a depth of 31.5 mm and 11.5 mm. The increase in water pressure should produce an expected measured pressure of 0.31 kPa and 0.12 kPa respectively. The test involved placing the sensors in the water and allowing them to stabilise for approximately 50 seconds before stopping the acquisition system. A second test involved removing the sensors from the water and allowing them to stabilise for a further 50 seconds. The two tests were repeated three times with the average response for the 8510C sensor shown in Table 3. Figures 8a and 8b show the measured response of the 8510C when it is placed in and removed from water.

At an ambient air temperature of 22°C and water temperature of 21°C the response from the 8510C sensor when it was placed in the water showed a step change with an average of 0.25 kPa. When the enclosure was removed from the water the sensor showed an average negative step change of 0.43 kPa. This response is 0.18 kPa larger than when the enclosure was placed in the water showing the effect of a change in the thermal compensation on the output of the sensor. The test was repeated in air and water temperatures of 21°C and 3°C respectively at the same water depth. The 8510C sensor showed a step change when the sensor was placed in the water with an average pressure response of 0.3 kPa. When the sensor was removed from the water it showed an average negative step change of 0.15 kPa. The step change is 0.15 kPa smaller than when the sensor was placed in the water which again shows the effect of a change in the thermal compensation.

When the XP5 sensor was placed in the water the output showed an average initial change of -18.35 kPa which trended up towards an average value of -10.5 kPa over 40 sec. On removal from the water the XP5 sensor had a large negative change of -10.2 kPa before a large positive change of 20.1 kPa. The output of the sensor stabilised at an average -0.18 kPa upon removal from the water. When the test was repeated at air and water temperatures of 21°C and 3°C respectively the response was similar to the previous test with a smaller magnitude on immersion and a larger magnitude on removal from the water. The average response for the XP5 sensor is shown in Table 3. The measured responses when placed in and removed from the water are shown in Figures 9a and 9b.

The large change in the output of the XP5 pressure sensor is due to the effect of the difference in the thermal conductivity between water and air on the sensor. The micro-machined strain gauges in the Wheatstone bridge self-heat due to the current passing through the gauges. The water conducts the heat away from the diaphragm more efficiently than air causing contraction of the metal diaphragm and also a change in resistance of the strain gauges. If the sensors were used in one media or if the thermal conductivity of the two media was more closely matched, the large difference in the response due to a change in media would not be experienced.

| Temperature difference Air to Water (deg) | Average Sensor response into water (kPa) | | Average Sensor response out of water (kPa) | |
|---|---|---|---|---|
| | 8510C | XP5 | 8510C | XP5 |
| 1 | 0.19 | -10.88 | -0.47 | 3.64 |
| -1 | 0.25 | -18.35 | -0.43 | 9.92 |
| -18 | 0.3 | -8.68 | -0.15 | 5.47 |

*Table 3. 8510C and XP5 average measured output when placed in and removed from water at different temperatures.*

(a) (b)

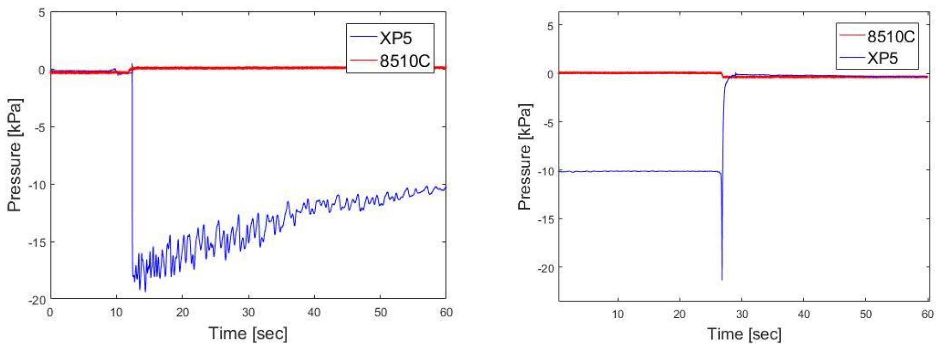



*Figure 9. Hydrostatic response of 8510C and XP5 for (a) immersion in water; (b) removal from water.*

The thermal response test for the 2MI pressure sensors was carried out at a different time as they were not available when the 8510C and XP5 sensors were tested. The testing for the 2MI sensor was carried out using similar methodology as detailed below.

The 2MI pressure sensor was mounted in the side of an enclosure which was placed in water causing the sensor to be submerged to a depth of 30 mm resulting in an expected measured pressure change of 0.29 kPa. At an ambient air temperature of 22.5°C and water temperature of 20.4°C, the measured response from the 2MI when placed in the water showed an average step change of 0.35 kPa as shown in Figure 10a. When the enclosure was removed from the water, the measured response showed a step change of -0.31 kPa, as shown in Figure 10b. The difference between the two results was due to a change in the thermal compensation of the sensor. The test was repeated with air and water temperatures of 22.1°C and 21.3°C respectively and a water depth of 26 mm with an expected measured pressure of 0.26 kPa.

The average response of the 2MI sensor is shown in Table 3 which indicates it is the least affected due to thermal effects.

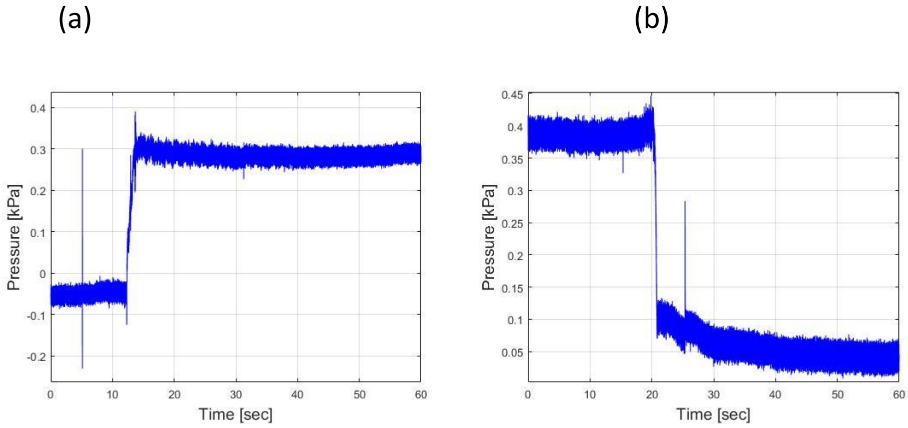



*Figure 10. Hydrostatic response of 2MI for (a) immersion in water; (b) removal from water.*

| Temperature difference Air to Water (°C) | Water Depth (mm) | Sensor response into water (kPa) | Sensor response out of water (kPa) |
|---|---|---|---|
| 0.8 | 26 | 0.28 | -0.24 |
| 2.1 | 30 | 0.35 | -0.31 |

*Table 3. Hydrostatic response of 2MI pressure sensor.*

During discussions with the supplier of the XP5 sensors about the thermal transient response, a suggestion was made to coat the sensor surface with a compound that would isolate the face of the sensor but still allow transmission of the pressure force. Judge et al [6] mentioned that this may be a viable technique for removing the spikes in the acquired data caused by thermal transients. Coating the gauges with PVC tape, dielectric grease and RTV silicone were considered as ways of isolating the sensor that could be applied during the towing tank testing program. As the sensors are intended to test slamming pressures at speeds of up to 2.5 m/s, coating the sensors only in grease was dismissed because of the chance of being removed during a run. It was considered that the application of PVC tape and RTV silicone could damage the sensors due to adhesion to the face of the sensor. Hence a thin layer of grease was applied to the face of the sensor before applying the tape or silicone. To reduce the effect of self-heating due to the amount of current flowing through the micro-machined strain gauges in the Wheatstone bridge, the sensor excitation voltage was reduced from 10 V to 5 V. This reduction in the excitation voltage halved the current flowing through the bridge and therefore reducing the amount of heat produced by the micro-machined strain gauges.

The testing demonstrated that the reduced excitation voltage and coating the XP5 sensor with PVC tape reduced the transient response but it also reduced the sensitivity of the sensor so that no hydrostatic response was measured. The response from the sensors with the reduced excitation voltage and coated with RTV silicone was very inconsistent. Some results demonstrated a thermal response similar to the uncoated sensor, while other tests demonstrated a response more closely matching the expected output. There was no discernible correlation between actual output and RTV silicone thickness. In addition the RTV silicone requires 24 hours to fully cure which would cause long delays in setting up the sensors and therefore this treatment option was not considered viable for towing tank measurement applications.

Dynamic air pressure pulse testing was undertaken with a sensor coated with grease and RTV silicone. The results showed that the response was more critically damped most likely due to the increase in the mass of the diaphragm causing a reduction in the frequency bandwidth of the sensor.

**CONCLUSIONS**

This paper describes the study examining the selection of a suitable pressure sensor to be used during a towing tank trial to measure hydrodynamic loading on a hydro-elastic generic patrol boat model. A survey was conducted of relevant literature which revealed many challenges and issues when using pressure sensors to measure highly non-linear wave impact loads in scale model towing tank testing. As there are no standards or procedures available to guide selection of pressure sensors for this purpose, a test program was developed to characterise the noise, dynamic, thermal transient and photoflash responses which are relevant to scale model tow tank testing.

The results of the study of three piezoresistive sensors for noise, dynamic, photoflash and light sensitivity and thermal transient responses showed that while some pressure sensors have the benefits of being completely isolated from any light effects, they may demonstrate a large transient thermal response when immersed or removed from water rendering them unsuitable for the intended application. For pressure sensors that do not have an opaque covering over the diaphragm to block light, care needs to be taken due to the effects of photoflash response and light sensitivity on the piezoresistors in the sensors Wheatstone bridge. As a result it is important to have a thorough understanding of the sensor design and responses to ensure that the most applicable sensor is chosen in relation to the particular testing application under consideration. The results of the study show that the Keller 2MI pressure sensor is the most appropriate of the sensors examined for the measurement of non-linear wave impact loads in scale model tow tank testing.

Information in this report can be used as guidance for selection of piezoresistive pressure sensors for scale model tow tank testing where wave impact loads are to be measured.

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