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Set-up of a sloshing laboratory at the University of Western Australia

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ABSTRACT

A university laboratory has been equipped for carrying out experiments on sloshing dynamics inside tanks. In a first series of runs the measurement of the sloshing pressure on the walls of a rectangular tank at various filling levels were carried out. For this activity the pressure time histories at some specific locations together with the instantaneous position of the tank were recorded. Furthermore, images of the sloshing events with a high speed video camera, have been acquired in synchronization with the other signals.

The design and operation of such a facility involved a number of foreseen activities but also mitigation of least anticipated road blocks. Many of these were resolved on the go. Since the entire activity was to be carried out in a university environment part of the equipment was developed in-house. This approach has the advantage of considerable flexibility but on the contrary unforeseen difficulties can arise.

This paper aims to report on the problems that were faced during the set-up and operation and suitable solutions that were adopted. Some of the topics reported here have to do with the technological aspects of the measuring chain while others are more related to the physics of the flow. The following issues, were of particular importance: 1) signal conditioning; 2) operation of the pressure transducers; 3) choice of the optimal sampling frequency; 4) synchronization of the signals and the images; 5) testing procedure and order of the operations; 6) data storage and test logging.

INTRODUCTION

Sloshing is one of the subjects that has raised significant interest in the scientific community in the past years. The industrial importance is related to the transport and storage of LNG at sea and in general to the transport of any liquid in containers. In civil engineering it is related to impacts on coasts and coastal structures. Furthermore it is a non trivial scientific problem that is still far from being completely understood. The last aspect is probably what makes it interesting and suitable for an experimental activity to be undertaken in a university environment.

Sloshing happens in a particularly extended range of lengths and time scales. Typically sloshing in enclosed containers involves lengths that range from the tank dimensions to the characteristic lengths of the smaller features like entrapped bubbles, small droplets of spray and the complex topology of the breaking free surface. In terms of duration it is important to consider periods that range from the frequency of oscillation of the container, typically of the order of seconds, to the short duration of the pressure impacts that last few milliseconds. Also the pressure ranges from the hydrostatic pressures that are proportional to the filling level height, to the hydrodynamic impact pressures that can be hundreds of time larger.

Presently commercial software and R&D codes still have difficulties in providing reliable results with reasonable computational costs. Data from experimental activity is still needed for tuning up codes and verifying theories. This situation opens the possibility for universities and research institutions to play a role.

This paper discusses the issues encountered during the set up of an experimental laboratory for the study of sloshing phenomena in enclosed containers within a relatively low budget. The results that have been obtained with such a facility during the first tests are encouraging and seem to be in line with the results that

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have been published. The aim is to provide indications for future activities that can be undertaken in this subject.

EXPERIMENTAL SET-UP

Planned activity measurements involved investigating different filling levels of the liquid inside a sloshing tank. The tank also needs to be capable of being filled with different combinations of liquids and gases at pressures above and below the atmospheric to evaluate various ullage pressure sensitivities. A further requirement was to have a set-up that was both capable to carry out the activity for which the project has been funded and also have the necessary flexibility to be utilized again as a university laboratory.

The main quantity of interest to be measured was the pressure time history at several different locations of the tank boundaries. At the same time, images of the impacts of the liquid had to be acquired synchronized with the instantaneous position of the tank.

The tank is mounted on a motion platform that has the capability to perform motions in six degrees of freedom around its starting point and in particular it can be displaced at different combinations of frequencies and amplitudes. The tank has been built with three of its side walls transparent for optical access, and the other three made out of metal, with holes drilled, for hosting the pressure probes. The tank has been fitted with gaskets for it to withstand a positive and negative pressure.

The main difficulty in setting up an experiment for characterizing the sloshing phenomena is the large range that the quantities of interest can span. This issue has repercussions on the entire design and measuring process. The acquisition system will need to be very fast and precise, the transducers will need to have both an extended range and a good resolution, the acquisition of images will need to be resolved in both time and space, the motions of the tank will need to be controlled with precision but also have sufficient amplitude and velocity to generate relevant sloshing in the tank.

Main requirements The main requirements of the sloshing laboratory can be summarized in: budget, flexibility and accuracy.

Budget is of course a stringent requirement in any activity but sometimes a university has a particularly low budget compared to industrial environments.

The flexibility in operations is requested because the investment is significant and multiple uses of the apparatus are envisioned. It needs to be adaptable to the different activities that will come in the future. This also means that the instrumentation should be suitable to different tasks and not only to the one specific.

Research being the main purpose of the laboratory, the results need to be accurate to a level that new theories can be elaborated or verified based on the results achieved. This is very different from an industrial laboratory where a specific task is usually required to be carried multiple times as part of a production cycle and there might be more need of robustness of the system rather than a very high accuracy of the results.

INSTRUMENTATION

Pressure transducers. The requirement for the pressure transducers is very constraining, the sensors need to be as small as possible, to be able to measure a large range of pressure magnitudes, to perform this task with a good resolution but, most important they need to be compatible with gases, such as air, liquids, such as water and combinations of the two.

The choice was the Kulite model XCL-8M-100-3.5BARA (fig.1 C), also used in (Yung et al., 2009), they are absolute transducers, thus capable of measure the total pressure, with a range of 3.5bar and a diameter of the head of 2mm.

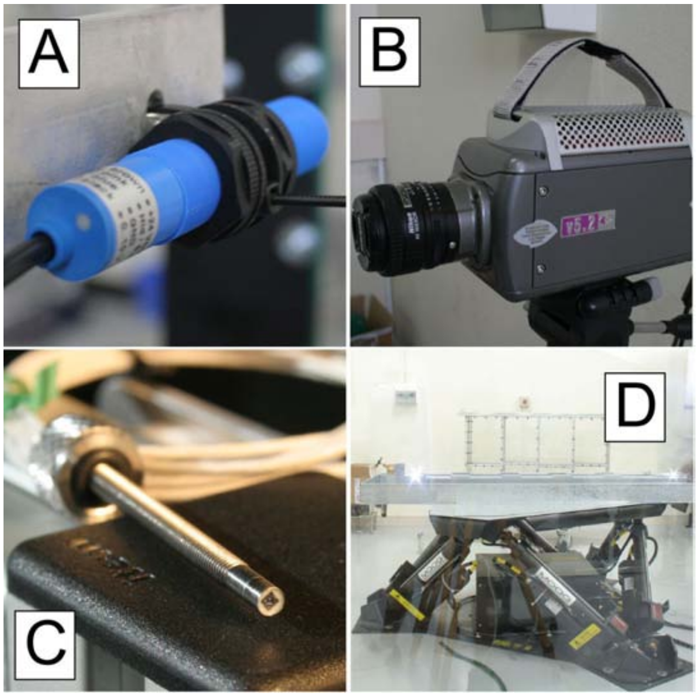

Figure 1: A: the ultrasonic distance probe, B: the fast acquisition camera, C: the miniature pressure transducer and D: the hexapod.

The specifics of these transducers state that they are suitable for measuring the pressure in both in gaseous or liquid phases. We have verified that this is true but they have problems when measuring in a mixed environment where they get in contact with the liquid and gaseous phases alternatively. In our first tests we observed a sudden change in the output signal as soon as the transducer changed from dry to wet conditions. The signal showed a sudden drop of non negligible amplitude just like if the pressure had decreased very fast. In the plot of figure 2 there is an example of this behavior. In that case the transducer was powered with the nominal voltage of 10v and its tip was gently put in contact with the water while the signal was acquired at the frequency of 20kHz. The plot units is in bar and it clearly shows the spikes in the signal when the transducer touches the water, furthermore the signal does not recover its original level after the sensor has been taken out of the liquid. As it can be seen by the plot even after several seconds the signal did not go back to the initial level.

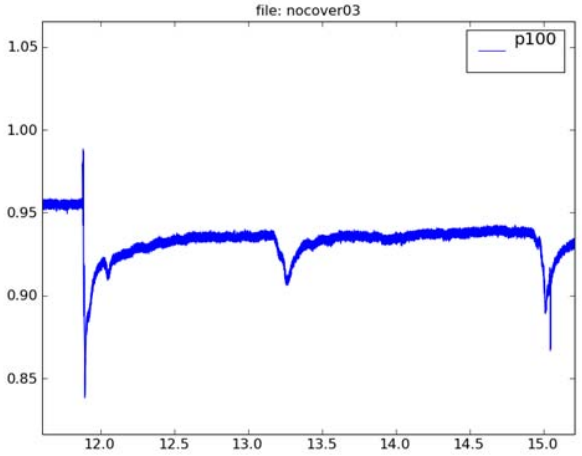

Figure 2: A plot of the signal from the pressure transducer when its tip is gently put in contact with water. The transducer is powered at the nominal voltage of 10v, the sampling rate is 20kHz and the plot is in bar.

The transducers were tested with different liquids, in order to check if this phenomenon was somehow related to the conductivity of the liquid medium, and with liquids at different temperatures, in order to verify the influence of this quantity as well. We came to the conclusion that the phenomenon was related the cooling of the head of the transducer when it touched the liquid, regardless of the temperature of the liquid itself. It seems that the transducers, when they are excited with the nominal voltage, reach a high temperature and, when they come in contact with the liquid, the sudden cooling provokes a contraction of the lamina where the strain gauge is mounted, and consequently changes the response signal. The solution adopted has been to lower the excitation voltage of the transducers down to 12% of the nominal to decrease the sensors operating temperature. This solution we have later found to be similar to the one reported in (Kaminski and Bogaert, 2009).

Then the linearity of the sensors in the range of measurement with the new voltage input has been verified and they performed satisfactorily, in the plot of figure 3 the characteristics of the same pressure transducer with three different excitation voltages are shown. The linearity in the full range is clearly preserved as it is also shown in table 1. The plot is presented with error bars calculated as the average of the signal over 30s of acquisition plus and minus the standard deviation of the signal. Superimposed on the experimental points there is the characteristic linear approximation calculated by means of linear regression method, the coefficients are reported in table 1. The residual was always found to be have a difference below 4×10^{-6} from unity confirming the good linearity of the transducer in the measurement range. The choice felt on the 1.25 voltage level because it has proved to be he less sensitive to the phase change of the medium.

	factory	UWA		
exc. voltage	10 v	10 v	2.5 v	1.25 v
mV/bar	49.409	48.956	12.367	6.143

Table 1: Characteristics of the same sensor for different excitation voltages.

Since also the output voltage was lower, after having decreased the excitation, the output amplification has been increased to a gain of 1000x.

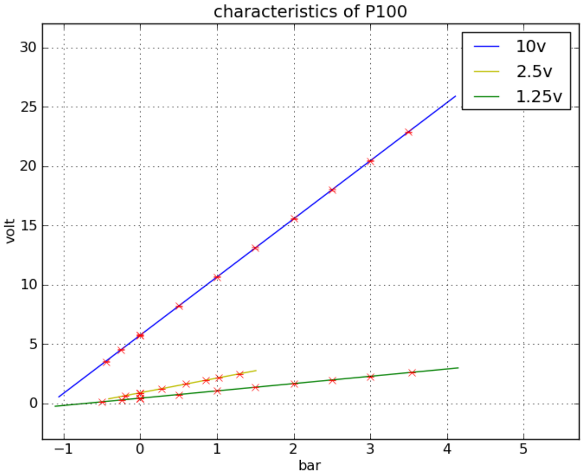

Figure 3: Characteristic lines of one of the transducers tested with different excitation voltages.

Measurement of the position of the tank. The data from the pressure transducers need to be correlated with the exact position of the tank. For these tests the tank was displaced in one direction only. The feedback provided by the motion platform (hexapod) was not adequate in terms of precision, sampling rate and cannot be logged to the acquisition system. Thus another way of measuring directly the position of the tank had to be found. The first attempt was to derive the position of the tank from the acceleration signal recorded from accelerometers mounted on the motion base. But this approach was not able to provide the required precision in the position of the tank, because of the noise of the signal (a double integration is very sensitive to the amount of noise of the original signal), the range of the accelerometers and the uncertainty in the initial position of the tank.

There are some optical laser instruments that measure the position of object such as the ones reported in (Kuo et al., 2009) but they are too expensive, besides it is not clear what would be the advantage for the measurement of the pressure in achieving such an accuracy in the displacement of the tank. Other techniques are based on filming and image analysis but the response is not immediate. The solution adopted was a direct measurement of the position of the tank by a distance probe based on high frequency sound wave, also called proximity ultrasonic sensor The sensor in our experiments was the model SU1-B1-0A from Micro Detectors (fig.1 A). This option is suitable for measuring displacements in one direction but by adding more probes it can be probably extended to measurement of displacements in more directions. Another advantage is that there was no mechanical contact between the probe and the tank.

The precision achieved is of the order of magnitude of millimeters and the band pass is of the order of kHz, thus in line with the requirements. The transducer itself is a cheap piece of equipment and was quite simple to interface into our acquisition system.

The motion platform. The motion platform, commonly known as hexapod is the main piece of equipment of the laboratory. This device, referred in the literature as a *Stewart platform*, is a six legged robot with a platform mounted on top, capable of performing motions in the six degrees of freedom. The platform is used for moving the tank mounted on it with precision and repeatability. It can be programmed to perform virtually any combination of motions.

Our model was a Moog 6DOF2000E (fig.1 D) that has a payload of 1160Kg and a maximum displacement in surge and sway of ± 0.25m, in heave of ± 0.18m, and ± 22deg for the three rotations.

The system comes with its own software for programming the motion time histories that is limited to sinusoidal displacements in the six DOFs and combinations of them. A small piece of software had to be written for programming more complex motion time histories and have more options. The original Moog software could still be used to convert the motion time histories from a ASCII format expressed in the Cartesian axes into the required binary file format that is actually executed by the hexapod.

The major limitations with this device are related to the performance of the motion platform in terms of the combinations of amplitude and frequencies of the motions that can be achieved, from the tests carried out it has been seen that the platform performed less than it was expected and that there was a non negligible difference between the amplitudes of the motion being requested and the ones being executed. Thus a campaign of test and trial on the output of the hexapod had to be carried out in order to evaluate this difference and have the correct motions executed. The results for one of these tests are shown in figure 4, the test was run without payload and the difference between the programmed motions and the obtained ones is evident.

In order to verify the motion of the hexapod a pair of LEDs were fitted on the machine and long exposure photographs were taken. The images showed the trajectories and were used to assess when the hexapod motion was deviating from the linear operation. An example of the test is shown in the photograph in figure 5.

Another limitation of this system that we point out is the absence of a reliable real time log of the position in space that could be used for recording the actual position of the tank to the acquisition system together with the other signals being acquired. This problem was solved with the aforementioned direct measurement of the position but this solution is currently valid only for one axis.

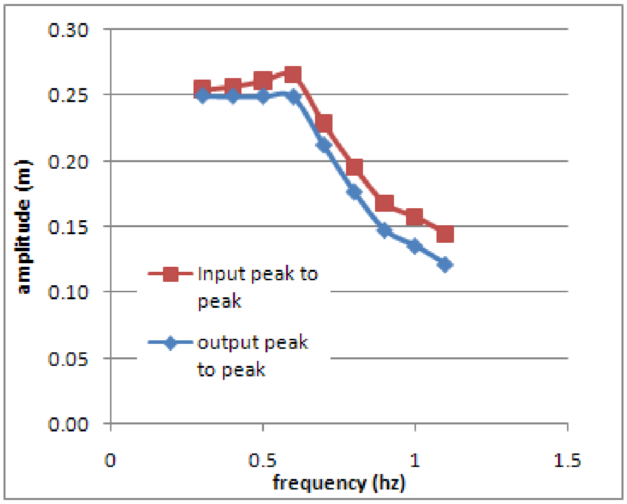

Figure 4: Difference between input motions and obtained ones.

Fast camera. A fast camera model Phantom v5.2 (fig.1 B) capable of acquiring up to 1000fps at the maximum resolution of 1152 × 896 pixels, monochrome, was used for filming the instants of the impact of the water on the side walls of the tank. The camera can be driven by an external signal and this capability has been used for synchronizing the acquisition of the images with the position of the tank.

In figure 6 one example of the results that can be obtained with this setup is shown. The two photographs on top are extracted by the movie filmed by the camera, the plot below shows the pressure trace from one sensor together with the pulses generated by the system and delivered to the camera. A total number of 150 pulses where programmed in that case with an interval of 1/100s between each other. Since to each pulse corresponds the acquisition of one frame by simply counting the acquired pulses a correspondence to the images and the exact instant in which they have been recorded can be made. In the case shown the first image has been taken when the sloshing wave was still far from the wall. The second image is taken 0.14 seconds later when the wave impacts the wall and the pressure peak is registered. The two instants are highlighted in the plot.

Figure 5: Long exposure photograph taken while the hexapod is in motion. The two leds on the sides show the trajectory of the base which is not linear and is different in the two locations.

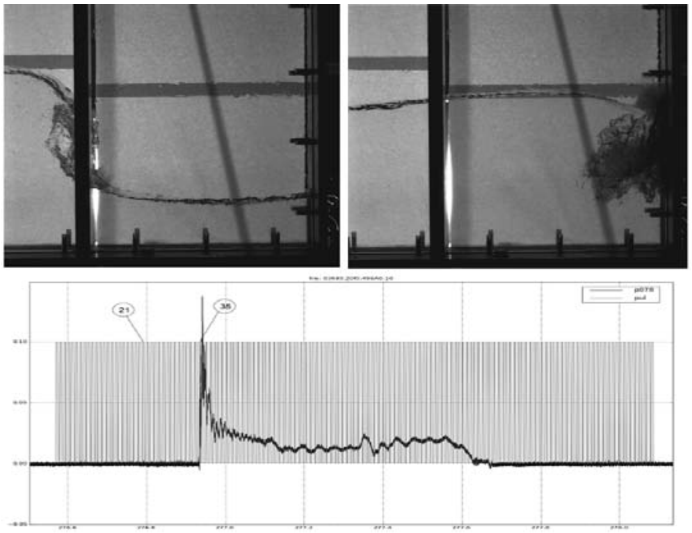

Figure 6: Two frames from the camera acquisition, the pulses on the plot allow perfect positioning in time relative to the pressure time history, shown in plot below.

The camera on board memory of 12Gb allows the recording of roughly 6000 images at the maximum resolution. The possibility to acquire each image with a pulse signal gives the user maximum control over the instant at which each image is acquired. After the internal memory of the camera is filled the images need to be downloaded to a computer and this process takes around 25 minutes on a standard ethernet connection.

The camera proved to be reliable and the software provided by the manufacturer gives full access to all its functions. A sufficient illumination of the scene has to be provided in order to decrease the exposure time, we have used a pair of 500W halogen lamps.

Acquisition system. The acquisition system comprises two Agilent U2331A data acquisition devices mounted into a U2781A chassis that provides synchronization between the two. Each of the data acquisition devices is capable of acquiring a maximum of 64 channels. The maximum sampling rate depends on the number of channels and goes up to 3MSa/s for a single channel at a resolution of 12 bits. The devices are also capable of generating output signals and this functionality has been very useful in the design of the measurement chain, specifically it has been used for driving the camera. Another useful feature is that the starting instant of the signal generation can be triggered upon the values of another signal. The synchronization chassis gives to the system the possibility to have all the signals in input and output sharing the same time basis.

Measurement chain

In order to perform reliable measurements, a proper measurement chain, that connects all the different instruments and brings together all the signals, has to be designed and put in operation. Extensive tests have to be conducted to assess its performance, levels of noise and errors.

In this regard a crucial role is played by the signal conditioner cards for the pressure transducers. They have been designed and built at the university and are capable of supplying an excitation voltage variable between 1 and 10 volts. The output signal is amplified with a user defined gain than can vary between 1x, 10x, 100x and 1000x. Lately also a gain of 500x had to added in order to extend the range of pressures that could be measured; the fact that the cards were designed here made the change viable. The cards are also equipped with a low band pass filter with a cut off frequency of 10kHz. The filter, together with a opportune choice of the sampling frequency, ensures that the aliasing effect is avoided and preserves the measurements from high frequency noise.

The set of cards, one for each sensor to be acquired, is hosted into the slots of a rack that provides the insulation from external interferences, the cabling of each card to the acquisition system and power to the all system.

Cables, connectors and interface boards for connecting and disconnecting the pressure transducers to the system have also been designed and built in the workshop of the School of Mechanical Engineering at UWA.

In the photograph of figure 7 the instruments described till now are shown in the environment of the laboratory while the schematic drawing of figure 8 shows the connections and the data flow.

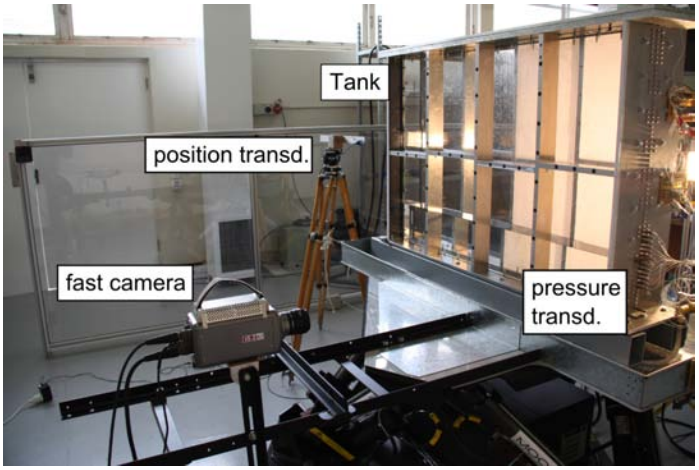

Figure 7: The sloshing laboratory at the University of Western Austalia.

The test matrix

The setting up of the instruments, tests, and preliminary measurements took eight months to complete.

The planned activity required to measure, in the first phase with water and air at atmospheric pressure, the pressures on 17 different locations on the side wall and top lid of the tank, for ten different filling levels, for six different combinations of amplitude and frequency, adding up to a total of 60 different runs. The sampling frequency was set to 40kHz (as in (Yung et al., 2009)) for 10 minutes that, multiplied by the total of 19 channels acquired contemporaneously, and added up to the 12Gb of images from each run made the storage of the data a problem to be solved. The analysis of such a large amount of data required also an optimization of the codes.

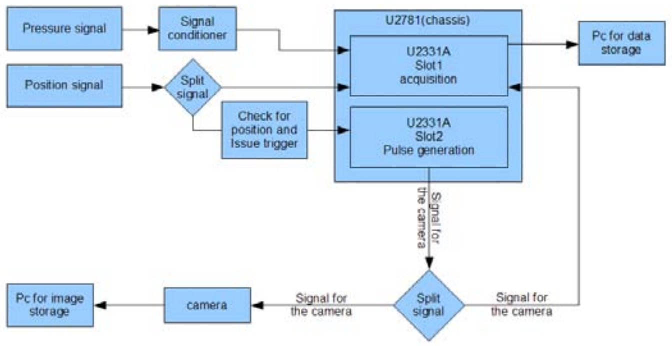

Figure 8: Schematic drawing of the connections

The sampling frequency has been chosen as an optimal compromise between the capabilities of measuring the short duration pressure pulses and the space required for storing the obtained files.

Two computers with Windows XP system were used for storing the data from the acquisition system and from the camera. A third computer was attached to the hexapod for generating the time histories, finally all the data were transfered to external USB hard drives.

Particular attention was devoted to designing the procedure and in optimizing the order of operations for two main reasons. Firstly the time needed for switching from one configuration to the next one was minimized. Secondly the possibilities of errors was reduced and a quality control on every condition that was going to be tested was established.

All the operations involved in the preparation of one test condition were performed and analyzed for evaluating the time needed and their difficulty. Each of these actions needed to be repeated several times in order to change the setup from one test condition to the other and complete the test matrix. The overall time can be reduced if the longest ones are performed a minimum number of times. These set of actions can be seen in the same way as a program to be run. Then the fastest operation can be put in the inner cycle of the program, the one that is going to be executed more times, and the slowest operations as part the outer cycle.

In practical terms the easiest operation that has to be carried out for changing setup from one condition to the other was the change of the combination of frequency and amplitude of the motion of the hexapod. This operation simply implied uploading the correct time series to the computer.

The next operation in order of simplicity was to change the filling level in the tank, this implied attaching the water hose, opening some valves and measuring the correct level. Thus it had to be done only when all the possible combinations of motions that were to be tested for a particular filling level were executed.

The most expensive operation was to change the location of the pressure transducers along the tank, because the tank needed to be emptied at least partially, the sensors had to be disconnected, dismounted and repositioned, all the configuration files needed to be updated to keep track of the changes and then the tank had to be filled again to the proper level.

It is evident that this operation had to be performed only when every other possible condition that uses the same positions of the sensors and the same filling level had been tested.

After having considered all the aforementioned issues the resultant test matrix had the test conditions ordered in a sequence that optimized the overall time spent to complete the entire activity with the minimum number of operations.

Data analysis was performed by means of code written in house. Most of the programs have been written in the Python language. Python itself is a multi platform programming language that it not oriented to any particular application but together with the scientific modules such as SciPy, NumPy, Matplotlib, ReportLab and others provides a open source free to use environment suitable for research purposes, and most important for us, free of license and upgrade costs. These important characteristics made the language environment easy to install, to distribute to students, to maintain and to develop.

Programs written in Python have been used in each of the test phases mainly for: quick analysis and report after each run; for post processing of the data, including frequency analysis and plotting; for programming the signals used in driving the camera and the time series for the hexapod motions; for calibration of the instruments.

Conclusions

During the course of one year, with a team consisting of one expert researcher, the aid of a research fellow and couple of PhD students and the support frame provided by a senior academic, the UWA laboratory has been set up to perform sloshing experiments. This, in the constrains of the budget. The main part of the activity required by the sponsored project has also been competed.

The second part of the activity, focuses on the use of combination of liquid and gasses different from water and air, for which additional design and procedures have been carried out, and will be completed soon.

Upon the project completion, the School of Mechanical Engineering will be left with a motion base, a fast acquisition camera, a number of pressure transducers and acquisition system that will be used for other educational and research purposes.

The activity performed for the sponsor has been judged satisfactory.

The authors think that what is described in this paper shows a positive example of collaboration between industrial and educational institutions worth to be noted. This relation had positive outcomes for all: the university has increased its capability of carrying out research works in the future and the industry had shed some light on the physics involved in such a complex phenomena as sloshing.

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