TALLINNA TEHNIKAÜLIKOOL

TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of mechanical and industrial engineering

WEDGE DROP TESTS FOR STUDYING SLAMMING EFFECTS

KIILU KUKUTAMISE KATSE LÄMMINGU MÕJU UURIMISEKS

MASTER THESIS

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Tallinn 2021

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THESIS TASK

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Study programme, specialization: MATM02/15 Product development and production engineering, Mechanical engineering
Supervisor(s): PhD student, Saeed Hosseinzadeh,

Thesis title:
Kiilu kukutamise katse lämmingu mõju uurimiseks
Wedge drop tests for studying slamming effects

Lõputöö põhieesmärgid:

1. Preparation of wedge drop test
2. Conducting the drop tests
3. Preliminary analysis of results

Stages and deadlines of the thesis:

Nr	Description of task	Deadline
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2.	Conducting drop tests	01.11.20
3.	Preliminary analysis of results	01.12.20
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PREFACE

This thesis and the ongoing research to which it is connected to, was made possible by the cooperation of TalTech Department of Civil Engineering and Architecture and Small Craft Competence Centre. The work presented in this thesis was carried out in the Small Craft Competence Centre in Kuressaare. The topic of slamming is only a small part of the research conducted under the PRG83 Numerical simulation of the FSI for the dynamic loads and response of ships research grant.

The aim of these experiments is to validate the numerical model developed by Saeed Hosseinzadeh. For this, a drop test rig and variable deadrise angle wedge were prepared. The wedge was manufactured from 5083 H111 aluminium alloy and it had a rigid and elastic side, to compare the dynamic response of the structure. First series of tests were carried out at drop heights between 25 and 200 centimetres with no inclination and incline drop tests between 25 and 100 centimetres. Data was collected from an array of pressure sensors, strain gauges and accelerometers. Video of each test was captured with a camera.

Preliminary analysis of the experiment results showed some issues with negative pressures, which were mostly corrected with small changes in the setup. Comparing the results of different tests showed good repeatability and also agreement with the numerical model developed by the supervisor of this thesis.

The author would like to thank his supervisor Saeed Hosseinzadeh for the opportunity to take part in this research and for sharing his knowledge; his colleagues for their help in preparing and conducting the experiments; his family and friends for their motivation and encouragement.

Wedge drop test, naval architecture, marine engineering, master thesis

1. INTRODUCTION

The aim of this thesis is to carry out wedge drop experiments for validating a numerical model for a variable deadrise angle wedge freefalling into the water and the dynamic response of the structure. This is done to study the slamming effects on a ship structure.

Slamming is a water impact problem on a vessel, defined as an impact between the hull of a vessel and the water surface [1]. Slamming involves local loads changing rapidly in space and time, [2] which are usually a lot larger than other wave loads [2]. It is a challenging problem in hydrodynamics and naval architecture, due the hydroelastic effects, interaction between trapped air pockets and water and complex shapes of the water surface [2].

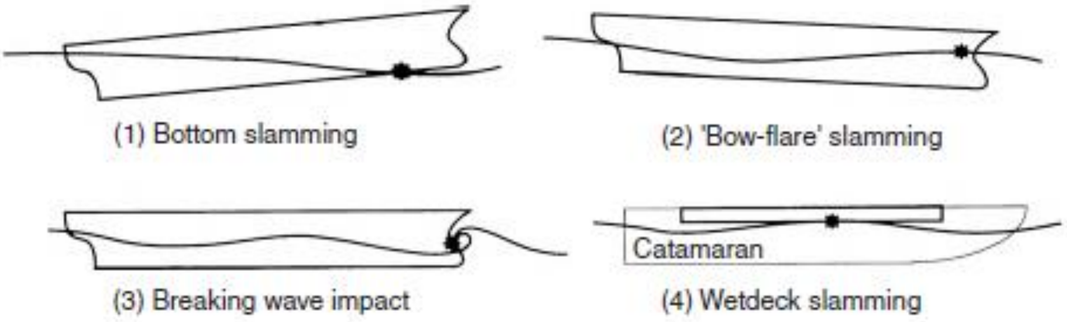


Figure 1. Different types of slamming [2].

Slamming occurs when the combination of relative motion and the relative vertical velocity between the water surface and the hull is above a critical value [1]. For monohulls, the slam usually occurs in the bow area, although stern slamming is also possible. A significant bow flare also increases the occurrence of slamming [1]. Slamming events produce noise and a vibratory response (whipping) but can also cause local buckling and plastic deformations [12][2].

The overall knowledge on wave impacts is to this day rather small, due to the complex nature of the problem. Slamming is a very strongly non-linear problem, heavily dependent on the relative motion and impact angle between the body and the free surface. Another issue is that slamming is a random process, due to the inherent stochasticity of natural seaways. Due to the short duration of impact loads, the hydro-elastic effects are large. The trapping of air may lead to compressible, partially supersonic flows [2].

Two main methods are used for studying slamming effects: numerical models and model tests. Both present their own difficulties. Most often a simplified shape is used for model testing, such as a flat-bottomed body [14], wedge [15] or, in more complicated cases, actual ship models or models of a part of a ship [16]. The main aim of these experiments is to measure the pressure acting on the test body during an impact with water and the resulting deformations caused by it. Due to the very fast nature of these phenomena, measurement equipment must be high quality and reliable. International Towing Tank Conference Association suggests sampling rates for measurement in the order of 100 kHz [17].

In recent years, many studies have been conducted, due to the importance of slamming loads and its effects on marine structures and their operation. Due to the complexity of the problem, it is mostly simplified to a two-dimensional rigid body water entry problem [2].

In most experimental studies, a prismatic shaped wedge is used for the tests. These are usually flat-bottomed or with a symmetric deadrise angle. In an experimental study conducted by Eastridge [13], a wedge with a constant deadrise angle of 20° was dropped from heights of 6, 12, 18 and 24 inches. The results of this study show, that the deflections of the bottom plating are not significant enough, to alter the physics of the flow underneath the wedge. One additional interesting note from this study is that data gathered from strain gauges gave significantly more accurate and reliable results than digital image correlation.

The novelty of the research at hand is the use of a variable deadrise angle wedge, with an elastic and rigid side, which has not been used in previous research. Instead of constant velocity drop tests, e.g. Tveitnes 2008 [17], the test body is allowed to freefall into the water. This is done to reduce the complexity and cost of the setup. The drop height in the current test plan is limited only by the ceiling height of the towing tank where the experiments are conducted. The main aim of these experiments is to compare the gathered data with the developed numerical model, which is not presented in this thesis.

The data recording and initial visual assessment for troubleshooting in this thesis was conducted using the CatmanEASY AP measurement software. For a more thorough analysis Matlab and Microsoft Excel were used, which provided a better way to handle and process the large amount of data gathered. XSens MT Software Suite version

2019.2 was used for gathering separate acceleration data and for exporting it into a text file. All parts and structures were modelled in Solidworks.

2. PREPARATIONS

The preparations for the experiments were done from March to August in 2020. Experiments were conducted between August and October of 2020.

The material used for the wedge is 5083 H111 Aluminium alloy, which is a common alloy used in the ship building industry. The bottom has a variable deadrise angle. The dimensions of the wedge are given in table 1. Drawings of the wedge and stiffener can be found in appendices.

Table 1. Wedge parameters.

Parameter	Value
Length	1500 mm ± 1 mm
Width	940 mm ± 1 mm
Depth	450 mm ± 1 mm
Bottom plating thickness	4 mm
Fore and aft endplating thickness	10 mm
Stiffener height	54 mm
Stiffener base thickness	3 mm
Stiffener flange thickness	4 mm
Fore deadrise angle	30° ± 0.1°
Aft deadrise angle	20 ° ± 0.1°
Weight	53.2 ± 0.1 kg

2.1 Component selection for the experiment

The components for the test were selected in cooperation with the supervisor and researchers working on this project. A big factor for the used equipment was also the availability, because the preparations were at the same time as the COVID-19 induced lockdowns, which slowed down manufacturer response and supply times. The testing rig consists of Norcan profiles and two HepcoMotion 44-1-1796 linear modules. The test specimen is made up of the wedge, support frame inside the wedge, 16 pressure sensors, 20 strain gauges, 3 accelerometers and an Integrated measurement unit (IMU). A GoPro Hero 5 Black action camera was used for capturing video of the tests. A bill of materials is presented in table 2.

Table 2. Bill of materials used for the experiment.

Bill of materials			
Subassembly	**Part**	**Quantity**	**Unit**
Drop rig	Norcan N0116 45*90 mm profile, heavy anodised	30	m
	HepcoMotion 44-1-1796 linear slide modules	2	pcs
	Norcan N1109A 88*43 mm corner brackets	40	pcs
	6061-T6 Aluminium 10*50 mm flatbar	4	m
	M8*30 bolts	160	pcs
	Spring nut M8 RSC zinc coated	160	pcs
Carriage modifications	6061-T6 120*150*5 mm Aluminium beam	6000	mm
	150 mm rubber cart wheels	4	pcs
	Norcan N0116 45*90 mm profile, heavy anodised	2.5	m
	Norcan N1109A 88*43 mm corner brackets	8	pcs
	M8*30 Bolts	20	pcs
	Spring nut M8 RSC zinc coated	20	pcs
Wedge	Wedge	1	pcs
	Norcan N0115 45*45 mm profile, heavy anodised	3	m
	Norcan N1109A 88*43 mm corner brackets	2	pcs
	M8*30 bolts	12	pcs
	Spring nut M8 RSC zinc coated	12	pcs
Measurement system	HBM 1-LY13-6/120 linear strain gauges	20	pcs
	PCB Piezotronics CA102B18 pressure sensor	16	pcs
	Dytran 3176B accelerometer	3	pcs
	Xsens Mti-300-2A8G4-DK inertial measurement unit	1	pcs
	HBM X60 Cold curing two component adhesive	1	pcs
	RG178/U coaxial cable	100	m
	0.14 mm^2 0.131Ω/m wire	400	m
	USB extension cable for IMU	1	pcs
	TE Connectivity S-50 Series 032-0021-0001 connector	16	pcs
	D-SUB HDB 15(M) connector	16	pcs
	DB9 metallic housing for HDB 15 (M) connector	16	pcs
	SCM-SG120 signal conditioning module for strain gauges	4	pcs
	BNC-to-SubHD-15 adapter for accelerometer	3	pcs
	8 pin push-in connector for strain gauges	20	pcs
DAQ system	MX1615B	1	pcs
	MX840A	1	pcs
	MX440A	2	pcs
	MX410B	2	pcs
	CX-22-BW	1	pcs
	FireWire for connection between modules	6	pcs
	Meanwell NDR-240-24 power supply	1	pcs
	Laptop Panasonic Toughbook	1	pcs
Miscellaneous	Silicone tape for covering strain gauges	1	roll
	Electrical tape	3	roll
	Heatshrink tubing	20	m
	HBM DAK2 strain gauge installation kit	1	pcs
	1-LS7 solder terminals for strain gauges	20	pcs
	GoPro Hero 5 Black camera	1	pcs

2.2 Preparation of the wedge

The wedge was produced in Baltic Workboats AS and was delivered to SCC in the beginning of March. Test preparations started in May, when most of the equipment had arrived.

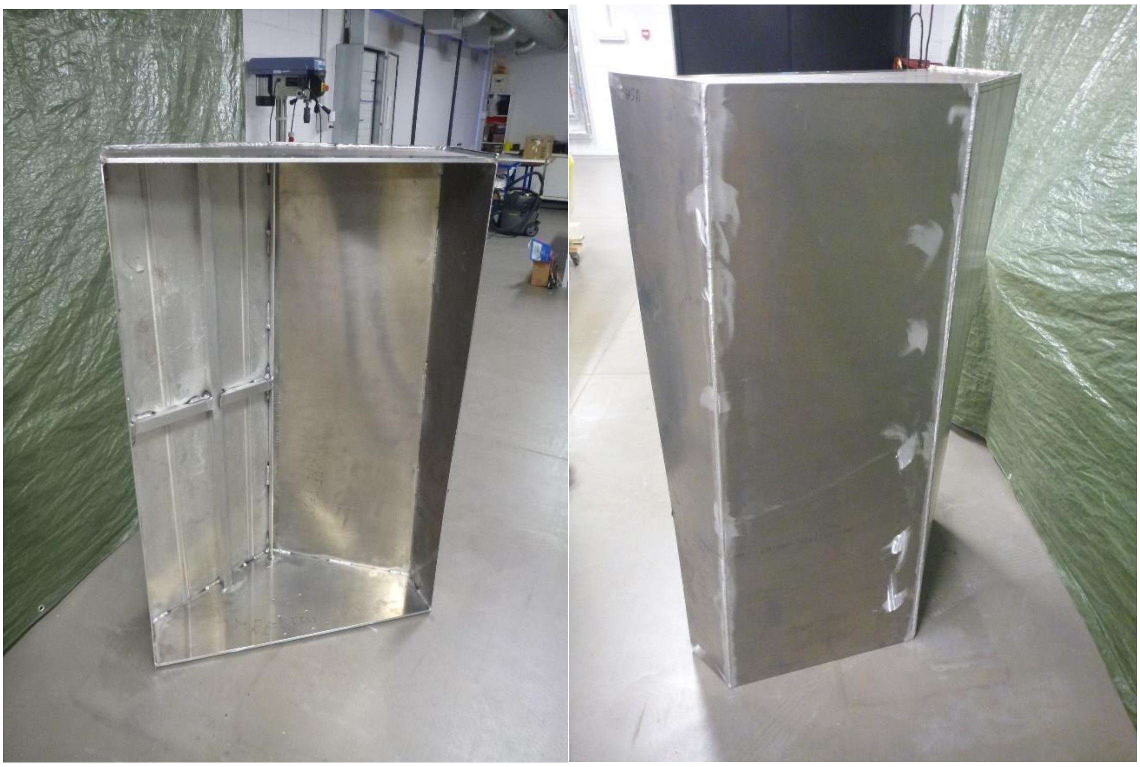


Figure 2 Inside and outside view of the wedge on arrival before preparations.

Four different types of plating are used on the test specimen. The sides and portside bottom plating are made from 4 mm thick 5083-H111 aluminium alloy. Starboard bottom plating is made of 4 mm thick extruded 5083-H111 aluminium alloy panel, with a single longitudinal stiffener. A transverse stiffener is welded to the plating in midship. The dimensions of the stiffeners are 54*35*3*4 mm (Figure 2). Fore and aft end plating is made of 10 mm thick 5083-H111 aluminium alloy. The keel of the wedge is a 60*5 mm 5083-H111 flat bar welded vertically on the connecting line of the starboard and portside bottom plating. The keel line of the wedge was ground down and sanded to remove the weld bead between the two sides of the bottom plating and get a nice sharp edge on the outside surface (Figure 3). The inside of the wedge was kept as it were.

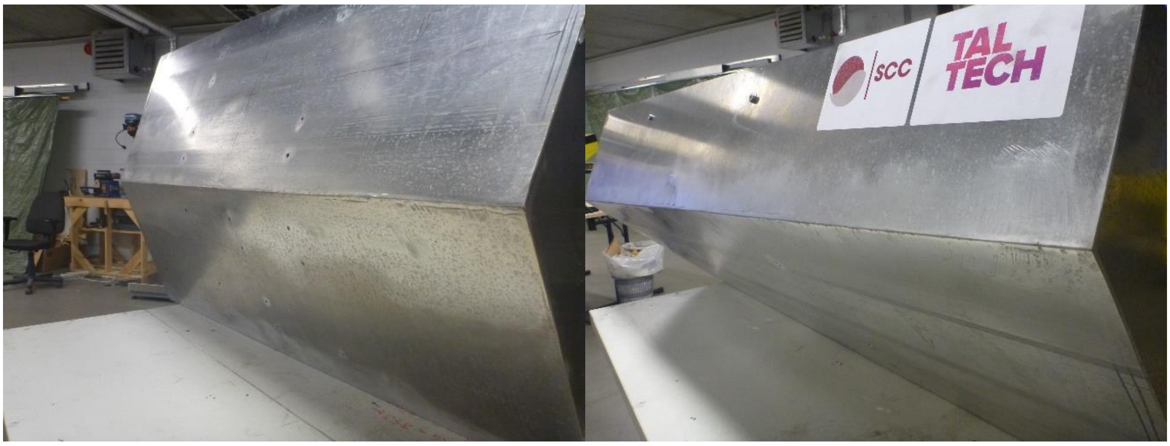
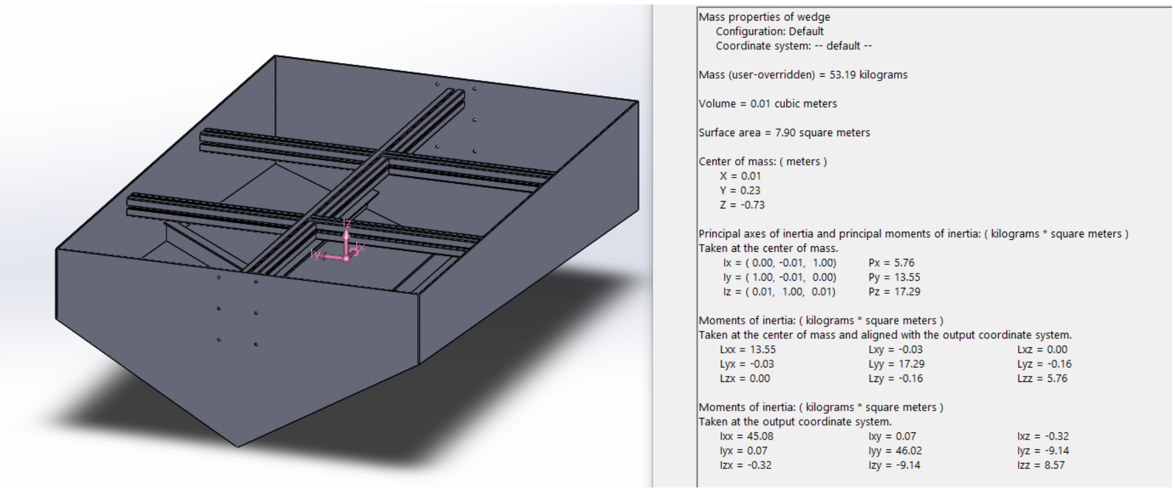


Figure 3. View of the keel and chine of the wedge after sanding and removing the weld beads.

The frame was installed inside and guide sleds in the fore and aft of the wedge. Since the guide sled rollers are very lightly loaded and used only for preventing horizontal movements of the wedge, most of the grease from the bearings was removed before installation, to reduce the rolling resistance. The frame adds stiffness to the sides of the wedge and allows for a loop shackle to be installed for hoisting the wedge up into the testing rig. Holes were drilled in the locations of the pressure sensors and tapped to 3/8 UNF-2A thread. Locations for the strain gauges were progressively wet sanded up to 400 grit and then thoroughly cleaned with acetone and then with a special cleaning solution supplied by the strain gauge manufacturer.

Before the installation of the sensors, the wedge was weighed and the moment of inertia around all three axes determined on the moment of inertia measurement apparatus (henceforth swing), usually used for ballasting the ship models being tested in the Small Craft Competence centre [4]. The initial values for the mass parameters were taken from the 3D model, but these were believed to be inaccurate to some degree, due to the fact that the model is an ideal representation of the wedge, whereas the actual wedge has inaccuracies in manufacturing, welds etc. The linear guide sleds were also installed before measuring the moment of inertia, because these are a constant on the wedge during the testing and account for quite a large percentage of the mass.

The initial values used for setting up the swing can be found by using the mass properties given by the 3D model.



```
Mass properties of wedge
     Configuration: Default
     Coordinate system: -- default --

Mass (user-overridden) = 53.19 kilograms

Volume = 0.01 cubic meters

Surface area = 7.90 square meters

Center of mass: ( meters )
     X = 0.01
     Y = 0.23
     Z = -0.73

Principal axes of inertia and principal moments of inertia: ( kilograms * square meters )
Taken at the center of mass.
      Ix = ( 0.00, -0.01,  1.00)       Px = 5.76
      Iy = ( 1.00, -0.01,  0.00)       Py = 13.55
      Iz = ( 0.01,  1.00,  0.01)       Pz = 17.29

Moments of inertia: ( kilograms * square meters )
Taken at the center of mass and aligned with the output coordinate system.
     Lxx = 13.55               Lxy = -0.03               Lxz = 0.00
     Lyx = -0.03               Lyy = 17.29               Lyz = -0.16
     Lzx = 0.00                Lzy = -0.16               Lzz = 5.76

Moments of inertia: ( kilograms * square meters )
Taken at the output coordinate system.
     Ixx = 45.08               Ixy = 0.07                Ixz = -0.32
     Iyx = 0.07                Iyy = 46.02               Iyz = -9.14
     Izx = -0.32               Izy = -9.14               Izz = 8.57
```

Figure 4. Picture of the 3D model of the wedge with mass properties (Solidworks).

2.3 Preparation of the testing rig

The testing rig was constructed using Norcan 45*90 mm heavy anodised profiles and Norcan 88*43 mm corner triangles. Two HepcoMotion 44-1-1796 linear module rails were installed on the rig. Assembly was done on level ground and checked thoroughly. The mounting holes for the linear guide rails were drilled 0.5 mm oversized, to allow for adjustment of the rails and easy movement of the wedge and to make sure, that there is no binding between the guide sleds and rails.

A manually operated winch was attached to the ceiling, for installing the drop rig and for conducting the tests. The winch was attached so that it is aligned with the centre axis of the rig. The assembled rig and the rig with the wedge installed are shown on figure 5.

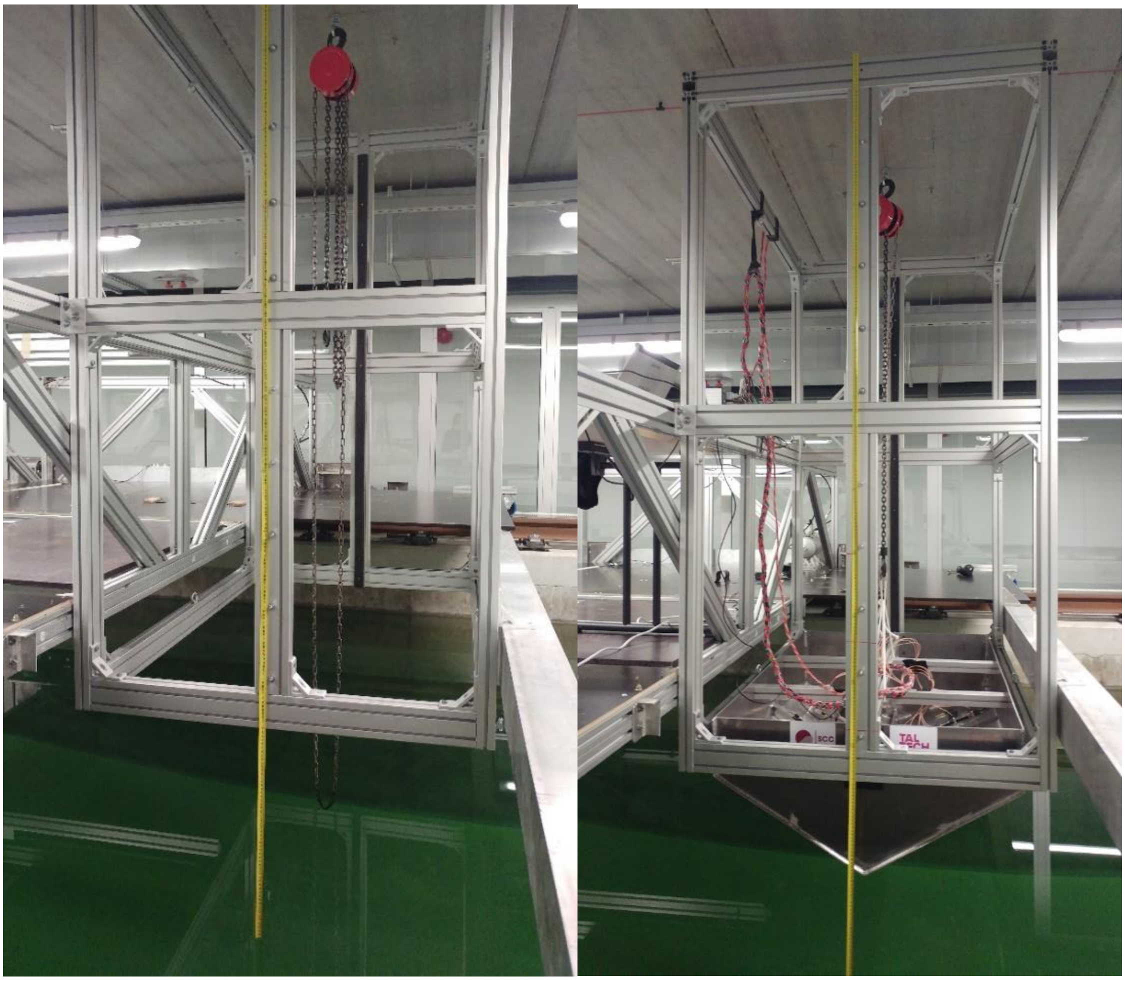


Figure 5. Drop rig installed on the modified carriage (left) and drop rig with wedge installed (right).

The winch was used for mounting the drop rig on the carriage and for hoisting the wedge up to the correct dropping height. Not shown is a movable stop, which is adjusted to the correct height before the tests, which enables the wedge to be lifted to the same height for each test. On one side of the test rig, a measurement tape was installed. For correct positioning of the movable stop, a laser level was placed at the correct height and the wedge hoisted to a height, where the keel of the wedge was aligned with the laser beam. Once in this position, the movable stop was placed on the rig so that the movement of the wedge further upward was not possible.

2.4 Data acquisition and sensors

Forty different sensors were installed on the wedge, for measuring pressure, strain, acceleration and angle of the wedge. Care was taken to ensure that the locations of the sensors on both the starboard and portside bottom plating were at identical distances from the keel and aft plating. Sensor locations were marked with a letter and number designation, where the first letter shows starboard (S) or portside (P), second letter pressure (P) or strain gauge (S) and location number. For example, PS1 is portside strain gauge number 1. Sensor locations are shown on Figure 8.

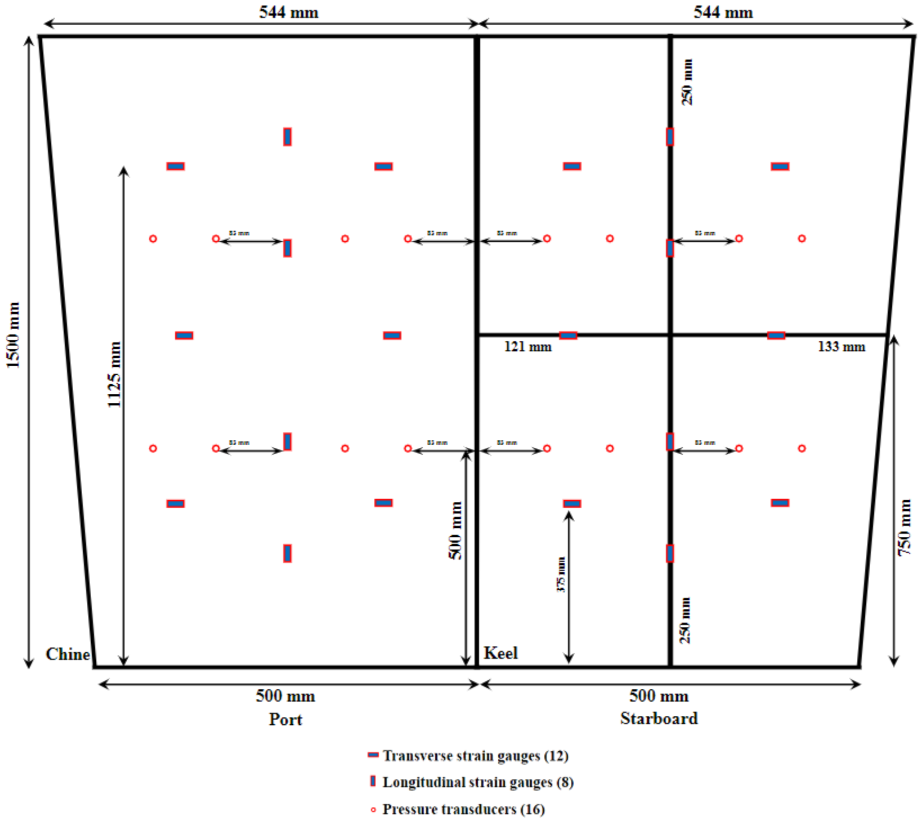


Figure 6. Sensor placement on the bottom plating of the wedge.

Data acquisition schematic for the tests is presented on Figure 7. Note that the blue arrows indicate FireWire connections between the amplifiers and data recorder and red arrows indicate individual sensor connections to the amplifiers. The orange arrow between the laptop and IMU is a USB connection.

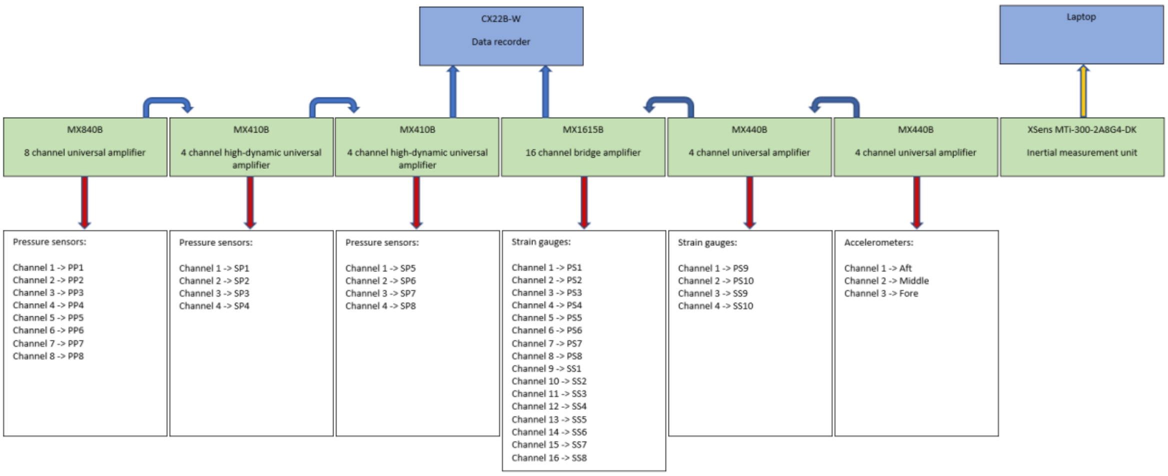


Figure 7. Measurement system schematic.

Data recording was done with an HBM CX22B-W data recorder module. This module uses HBM proprietary CatmanEASY AP software [9], which allows for easy, and in some cases automatic, configuration of sensors. The data was saved to a text (.txt) file in ASCII format with date, time and channel information recorded in the first 38 lines of the file. The file name denotes the drop height, the angle between the water surface and the fore of the keel and the number of the measurement in that height (figure 8). For symmetrical drop tests inclination angle denomination was omitted from the file name.

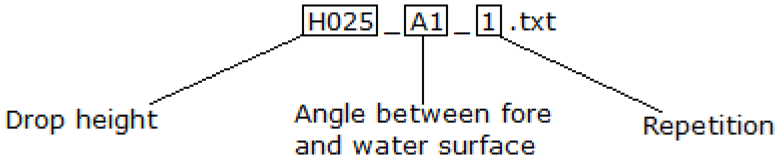


Figure 8. File naming scheme, presented for easier understanding in the discussion section.

Measurement data from the strain gauges was recorded at 40 kHz and the signal reading was zero-balanced before each test. Pressure sensor data was recorded at 100kHz.

2.4.1 Strain Gauges

HBM 1-LY13-6/120 strain gauges were used on the wedge. These are linear strain gauges with one measuring grid and temperature responses adapted to aluminium and with an internal resistance of 120 Ohms [5].

The locations of the strain gauges were wet sanded to 400 grit, to get the surface flat and aid in better adhesion between the strain gauges and the wedge. [6] The strain gauges can be installed with a 2-, 3- or 4-wire configuration. In the current case, 4-wire configuration was used, which allows the errors resulting from cable effects to be electronically compensated for. [7]

Gauges were bonded to the wedge using HBM X60 2-component quick-acting adhesive. Solder tabs were placed under the strain gauge leads, glued to the surface, soldered and excess of the leads removed. Two wires were soldered to each terminal. The gauge and soldering tabs were covered with silicone tape for protection. The wires were taped to the surface of wedge to prevent ripping and breaking of the solder joints. An installed strain gauge is shown on figure 9.

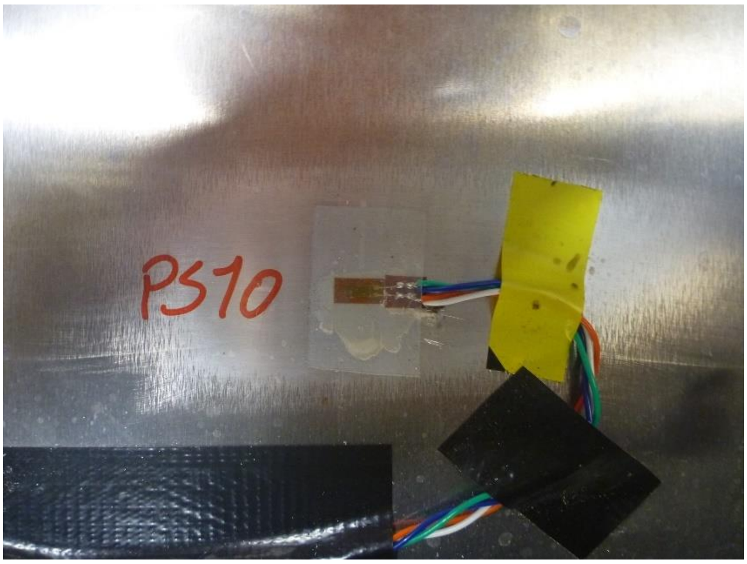


Figure 9. Installed strain gauge (Portside Strain 10).

2.4.2 Pressure sensors

Due to the fast nature of the pressure effects during slamming, a high frequency response pressure sensor was necessary [3]. PCB Piezotronics CA102B18 sensors were selected for this task, due to their robust design and ablative coating on the diaphragm, which reduces the temperature shock and errors in measurement. [10] The sensors are factory calibrated and delivered with a data sheet and calibration data in the form of a linearization (Appendix 2) table for setting up in the data recording software.

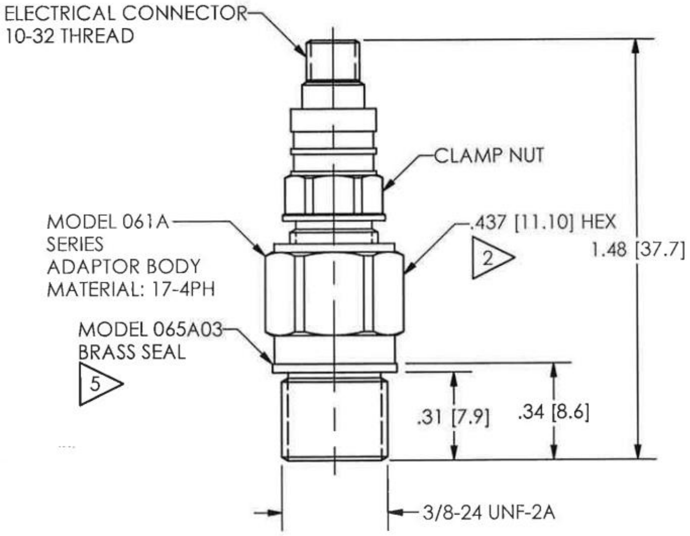


Figure 10. Drawing of PCB Piezotronics CA102B18 pressure sensor. [10]

The connection between the sensors and amplifiers were made with RG178/U coaxial cables, TE Connectivity Straight S-50 series (Microdot 032-0021-0001 equivalent) connector on the sensor side and 15-pin D-SUB type HDB 15(M) connection with housing on the amplifier side.

Since the tools for assembling the Microdot type coaxial cable connectors were not readily available, a DIY solution was found. Drawings of the tools were found on the internet and similar versions were designed and 3D printed.

Figure 11. Picture of assembled coaxial cable with 3D printed assembly tools.

The mounting thread length on the sensor is 0.31 inches (about 7.9 mm). Therefore, when mounting, spacers were initially used. Different spacers were tried, including aluminium, stainless steel and 3D printed ones. 3D printed spacers were made in three different thicknesses were produced: 3 mm, 3.5 mm and 4 mm. Medium strength Loctite thread glue was used on all the threads to ensure that there were no leaks between the threads of the sensor and mounting hole.

Figure 12. Handmade and 3D printed spacers for mounting pressure sensors.

For incline tests two pressure sensors from the fore and two from the aft on the starboard side closest to the chine were removed. These were installed midship on the portside, to better capture the pressure distribution on the elastic side, since the keel impacted the water with this side. Holes left by the removed sensors were plugged with bolts and glued in with thread glue to avoid leaks.

2.4.3 Accelerometers

Accelerometers used for the tests were Dytran 3176B, which is a piezoceramic type sensor. The accelerometers are paired with a signal-conditioning module containing a TEDS (Transducer Electronic Data Sheet) chip, which contains the calibration data for the sensors, therefore not requiring any additional setup.

These were initially installed on top of the inside frame of the wedge, in the fore, middle and aft, but the location was later changed. For that, about 25 mm pieces were cut from an aluminium angle bar, which were glued with two-component epoxy to the keel inside the wedge. The same mounting method was used for all the accelerometers. The accelerometers feature a removable bottom plate, which was used to adhere them to the horizontal part of the bracket and the sensing element was then screwed in [11].

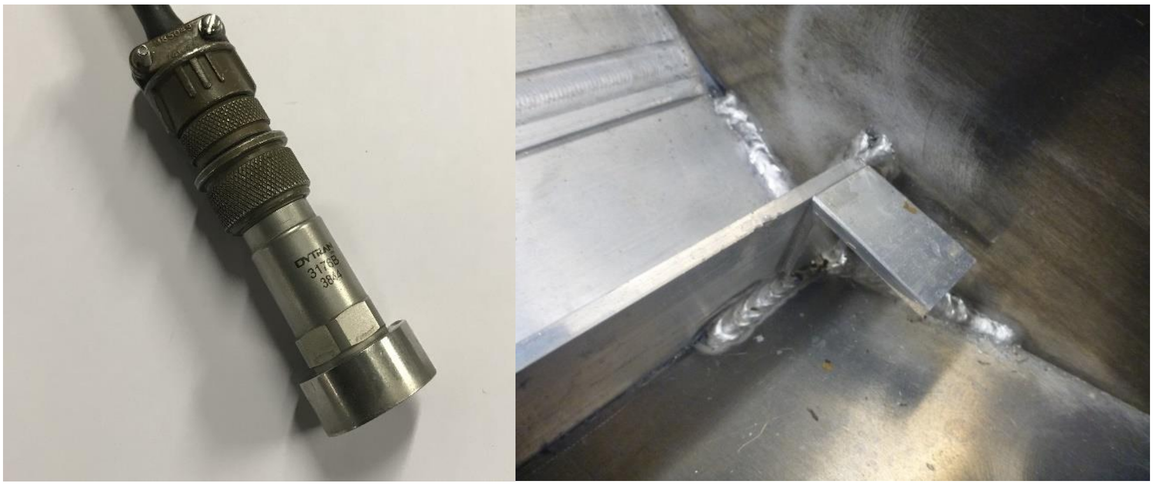


Figure 13. Dytran 3176B accelerometer and angle bracket for mounting in the wedge.

2.4.4 Inertial Measurement Unit

Due to the fact that the accelerometer data from Dytran 3176B sensors showed some inconsistencies, an IMU was also attached to the keel of the wedge to measure acceleration data. For this, an XSens MTi 300 IMU was used, although this device can only capture acceleration data at 1kHz [8]. The IMU cannot be directly connected to the data recording system used for the other sensors, because it is not compatible with the HBM CatmanEASY AP software. Therefore, the IMU was connected via USB to a separate laptop, which was running MT Manager software, specially made by XSens for their sensors. The measurement file was exported to a text (.txt) file for analysis. Unlike other sensors, the signal from the IMU is filtered by default.

For inclination tests, the IMU output was used to determine the inclination of the wedge. The sensor was glued to the keel sideways with epoxy (Figure 14 on the right), so that the vertical acceleration value was taken from the Y-axis of the IMU.

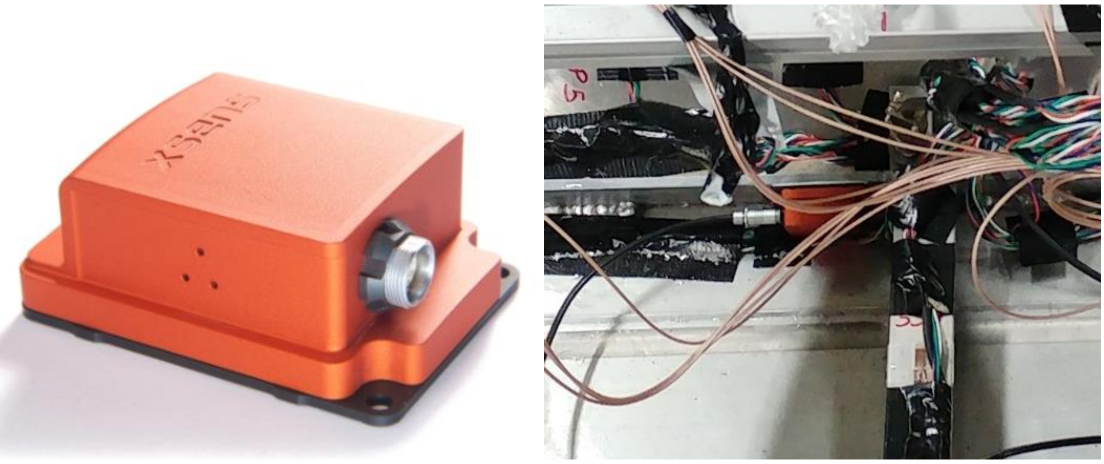


Figure 14. IMU (left) and as installed on the wedge (right).

2.4.5 Data Acquisition system

All the data from the sensors was gathered using a data acquisition (DAQ) system (figure 15). The DAQ consist of:

- MX840B amplifier
- MX440B amplifier
- 2 MX410B amplifiers
- MX1615B strain gauge amplifier
- CX22W Data collection computer
- SCM-SG120 signal conditioning modules for 4 strain gauges

Since the manufacturer supplied power supply is only rated for 30 watts and meant for daisy-chaining up to three devices together through a single power port, a separate DC power supply was used, which could output the necessary 93 watts needed to run the system.

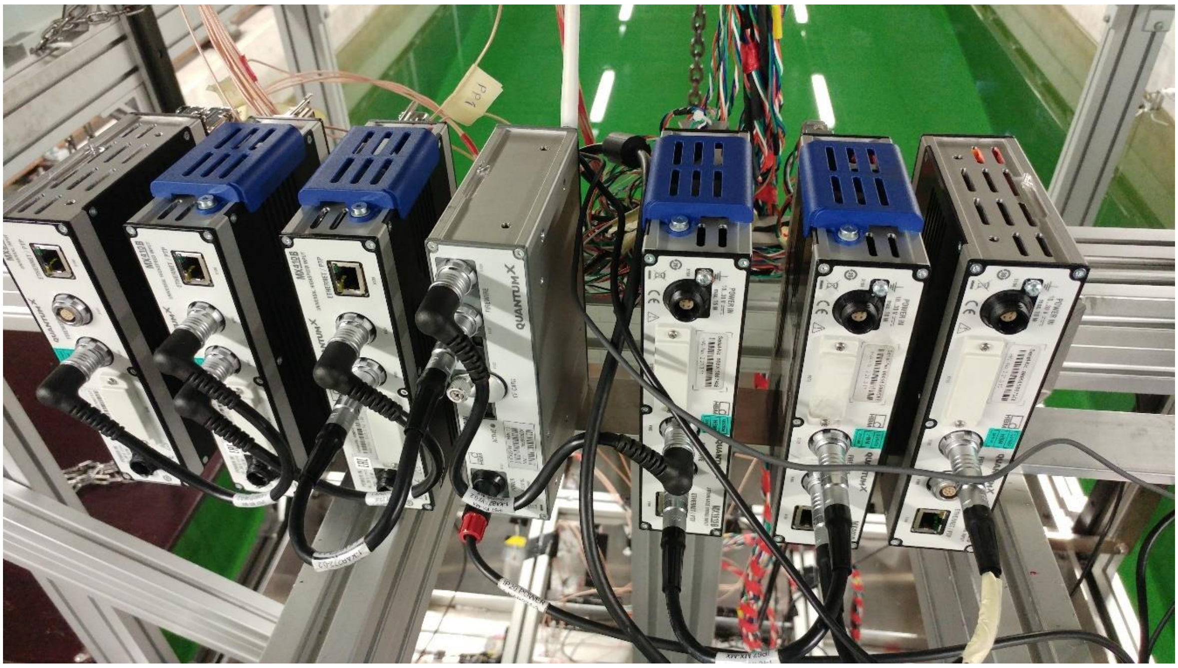


Figure 15. Measurement system as installed.

3. EXPERIMENTS

The preparations and experiments were conducted between May and October of 2020.

Figure 16. Picture from the initial testing of the setup, without measurement equipment installed.

3.1 Conducting the experiments

The test program consisted of even keel and incline drop tests. Wedge was dropped from different heights, from 25 to 200 centimetres, with a 25-centimetre increment. The drop height was measured from the keel of the wedge to the water surface. Incline drop tests were conducted at 5-, 10-, 15-, 20-, 25- and 30-degrees inclination from heights between 25 to 100 cm with a 25 cm increment. Test plans for the symmetric, increased weight symmetric and asymmetric cases are presented in tables 2, 3 and 4. Calculated impact velocities are also given in the rightmost column of each test table. Impact velocity is equal to

$$v_{impact} = \sqrt{2 * h * g}\ ,$$

where

v_{impact} is impact velocity,

h is the height between the keel of the wedge and the water surface and

g is the gravitational acceleration (9.81 m/s^2).

Table 3. Test plan for symmetric drop test with initial weight.

Test Plan (Symmetric)				
First Series				
No.	**Drop Height (m)**	**Weight (kg)**	**Repetition**	**Impact velocity (th)**
Trial test 1	0.25	W_0	1	2.21
			2	2.21
			3	2.21
			4	2.21
			5	2.21
Trial test 2	1	W_0	1	4.43
			2	4.43
			3	4.43
			4	4.43
			5	4.43
3	0.5	W_0	1	3.13
			2	3.13
4	0.75	W_0	1	3.84
			2	3.84
5	1.25	W_0	1	4.95
			2	4.95
6	1.5	W_0	1	5.43
			2	5.43
7	1.75	W_0	1	5.86
			2	5.86
8	2	W_0	1	6.26
			2	6.26

Table 4. Test plan for symmetric drop test with 50% weight increase.

Test Plan (Symmetric, increase weight)				
Second Series				
No.	**Drop Height (m)**	**Weight (kg)**	**Repetition**	**Impact velocity (th)**
1	0.25	1,5W_0	1	2.21
			2	2.21
2	0.5	1,5W_0	1	3.13
			2	3.13
3	0.75	1,5W_0	1	3.84
			2	3.84
4	1	1,5W_0	3	4.43
			4	4.43

Table 5. Test plan for the asymmetric drop test.

Test Plan (Asymmetric)					
Third Series					
No.	**Drop Height (m)**	**Weight (kg)**	**Changed Angle (deg)**	**Repetition**	**Impact velocity (th)**
1	0.5	W0	20	1	3.13
				2	
2	1	W0	20	1	4.43
				2	
3	0.5	W0	15	1	3.13
				2	
4	1	W0	15	1	4.43
				2	
5	0.5	W0	10	1	3.13
				2	
6	1	W0	10	1	4.43
				2	
7	0.5	W0	5	1	3.13
				2	
8	1	W0	5	1	4.43
				2	

For conducting the test, the wedge was tied to the shackle of the winch using nylon rope. It was then lifted to the test height, by hoisting the wedge until it firmly touched the movable stopper and could not rise any higher. Before the test, the arrangement of the cables inside the wedge was checked to reduce the possibility of the cables snagging and damaging the sensors. Water droplets inside the wedge were dried off.

A waiting period between each test ensured that the water surface had calmed down and no visible waves could be seen in the towing tank. Small ripples in the water surface due to droplets falling from the wedge were allowed. To conduct the test, one person operated the computer and another person cut the rope to drop the wedge. This was done to record as little data as possible and avoid unnecessary movement around the area and on the carriage before testing. The length of each measurement was around 10 seconds. If more than one drop was made from the same height, then video was captured only from one single test. For a few tests, underwater video was captured also, but this was unusable for any reasonable analysis.

After each test, the wedge was lifted to the correct height and an initial check of the measurement results were made using CatmanEASY AP analysis module. The aim of these quick checks was to ensure that all the sensors had worked properly and that all the necessary data had been saved. This also allowed for quick troubleshooting and modifications to the setup, if necessary.

For the incline tests, circular mounting slots for the guide sled bolts were milled. The sleds were mounted as close to the axis of the vertical centre of gravity, to reduce the torque on the sleds, avoid slippage and to make achieving the correct angle for the tests easier.

Altogether, 46 individual tests were conducted plus additional tests for troubleshooting and setup checking.

3.2 Issues and solutions

Due to the high sampling frequency and high data rate, data from all the sensors could not be saved at once. Therefore, a decision was made, to measure pressure and strain separately. This issue was later resolved by getting a newer version of the CX22B-W, which allowed for higher data rates and therefore more channels to be measured simultaneously.

Another issue during initial tests was found in the accelerometer data. At the beginning of the drop, very high accelerations were present, as if the wedge were oscillating up and down. Because the accelerometers were installed on top of the inside frame of the wedge and since the rope was also attached to the same frame, once the rope was cut, the tension in the frame was released. This caused the frame to take back its original shape and this oscillation was picked up by the accelerometers. The issue was tried to fix by mounting the accelerometers near the keel with brackets. This produced some improvement at reducing the amplitude of the accelerations after the initial release of the wedge (Figure 17).

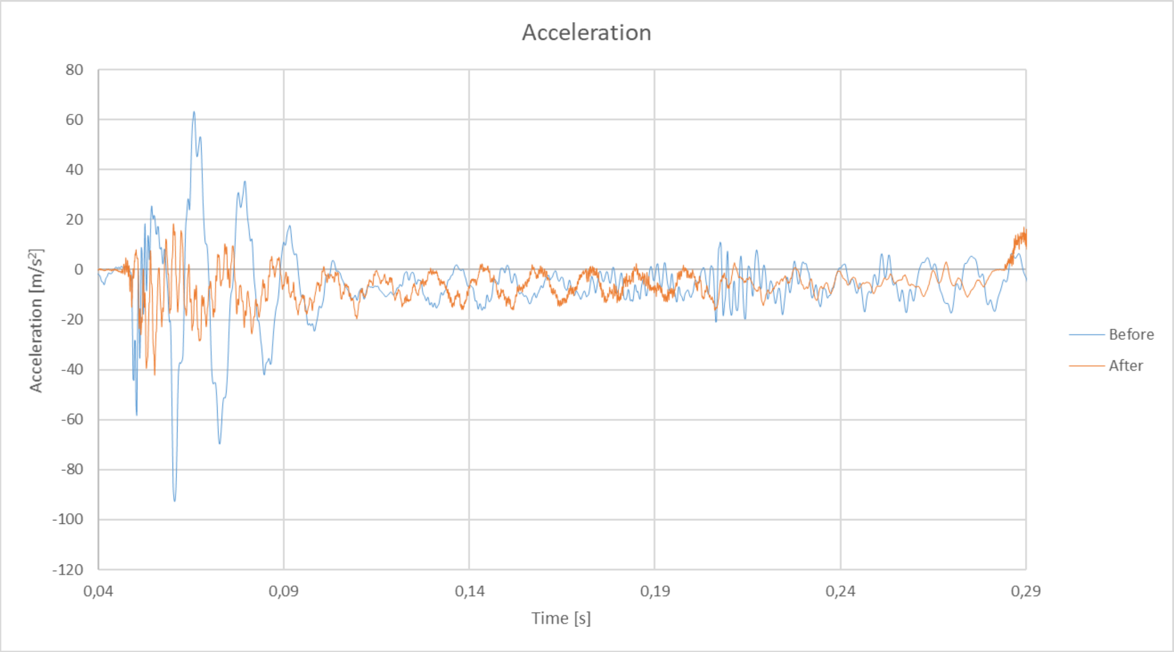


Figure 17. Accelerometer signal during freefall before and after changing accelerometer locations at 25 cm drop height.

The measurements taken are repeatable, but it seems that the high frequency accelerometers cannot properly capture the freefall of the wedge. Similar issues were reported by Eastridge, where the issue was thought to be due to the bandwidth of the sensor [13]. The IMU seemed to capture the freefall motion better than Dytran accelerometers, although some oscillations in the signal were still present (figure 18).

For future tests, another method for releasing the wedge must be prepared. Improper cutting of the rope for releasing the wedge occasionally resulted in the wedge moving a small amount (figure 19). This made the data from the test unusable and this issue could be mitigated by using a quick-release mechanism, for example similar to Eastridge [13].

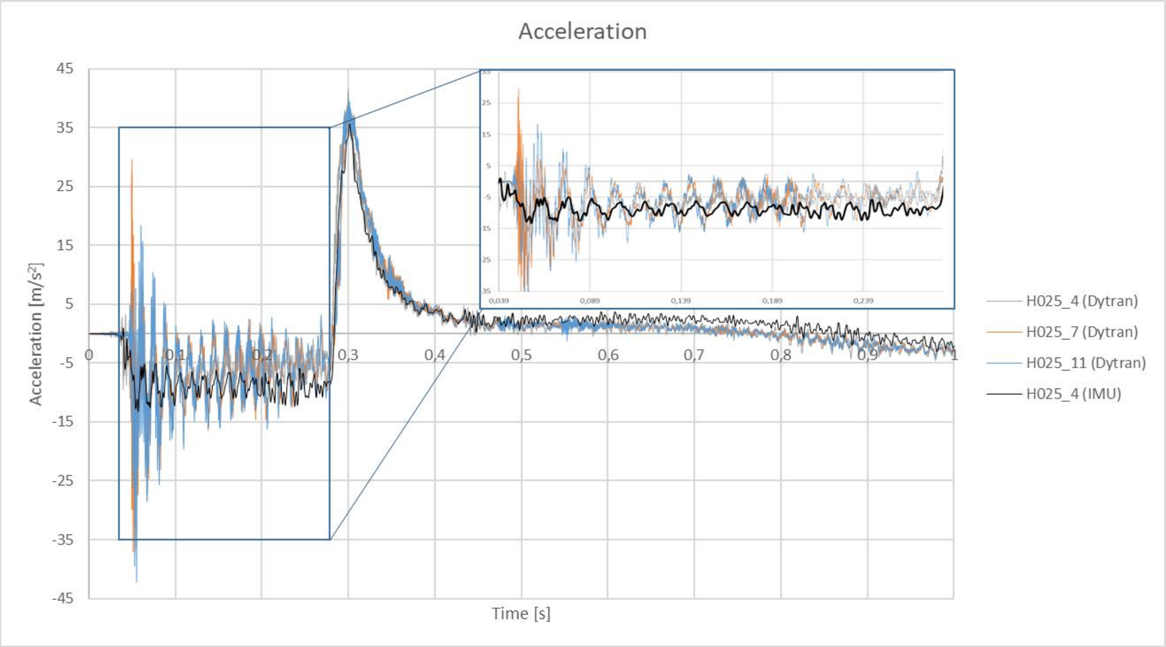


Figure 18. Acceleration data from Dytran 3176B and IMU at 25 cm drop height.

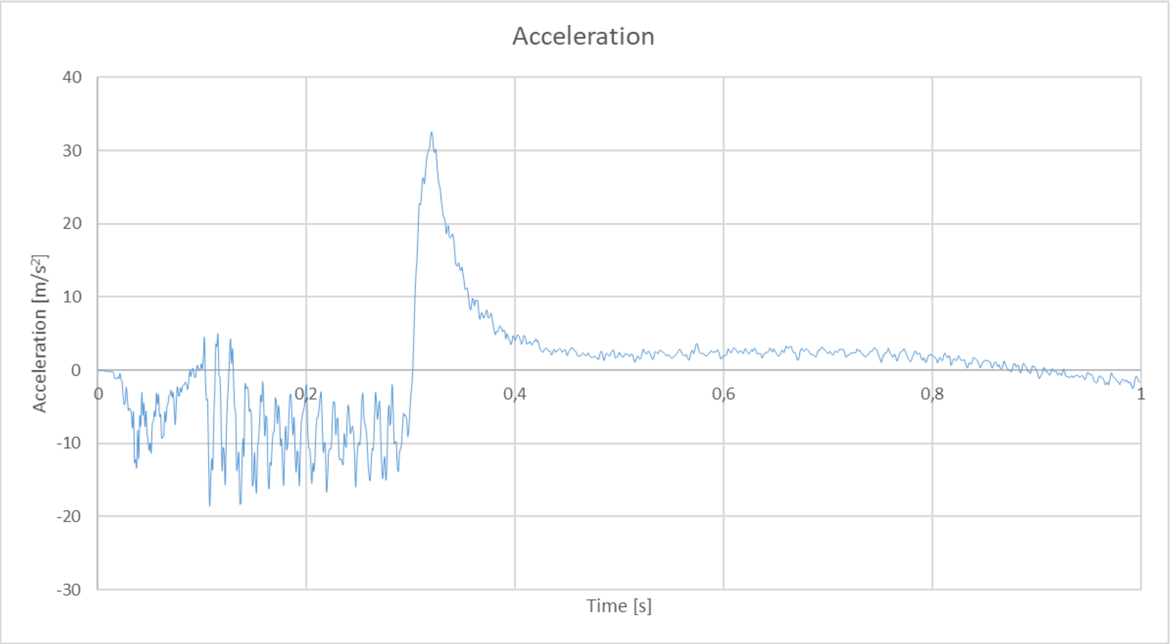


Figure 19. Improper release of the wedge, 25 cm drop height.

Another issue was that some pressure sensors measured negative values during the test (Figure 20). This problem could be caused by many different reasons. One possibility is that the diaphragm of the sensors was not flush or was at angle with the bottom of the wedge. The mounting of all the sensors was checked and some sensors were reinstalled with different washers and spacers. If the sensor diaphragm was at an angle to the bottom plating, the mounting holes were retapped at a slight angle. This allowed for some play in the mounting but necessitated that the sensor be supported while the thread glue dried. For this, modelling clay was pressed against the sensor and the mounting was checked from the bottom.

These fixes helped for a few sensors, but in some locations, the same problem with negative pressures persisted. These sorts of negative pressure issues can sometimes also be caused by temperature shock when the sensor rapidly moves from one environment to another, in this case from air to water. To prevent this, manufacturer recommended procedure is to either cover the sensor diaphragm with electrical tape or with a thin layer of petroleum jelly. Both methods were tried with no positive results.

Negative pressures can also be caused by some other physical phenomena, such as air and water moving past the sensors at high velocities and creating a suction effect. Further research on this topic is needed.

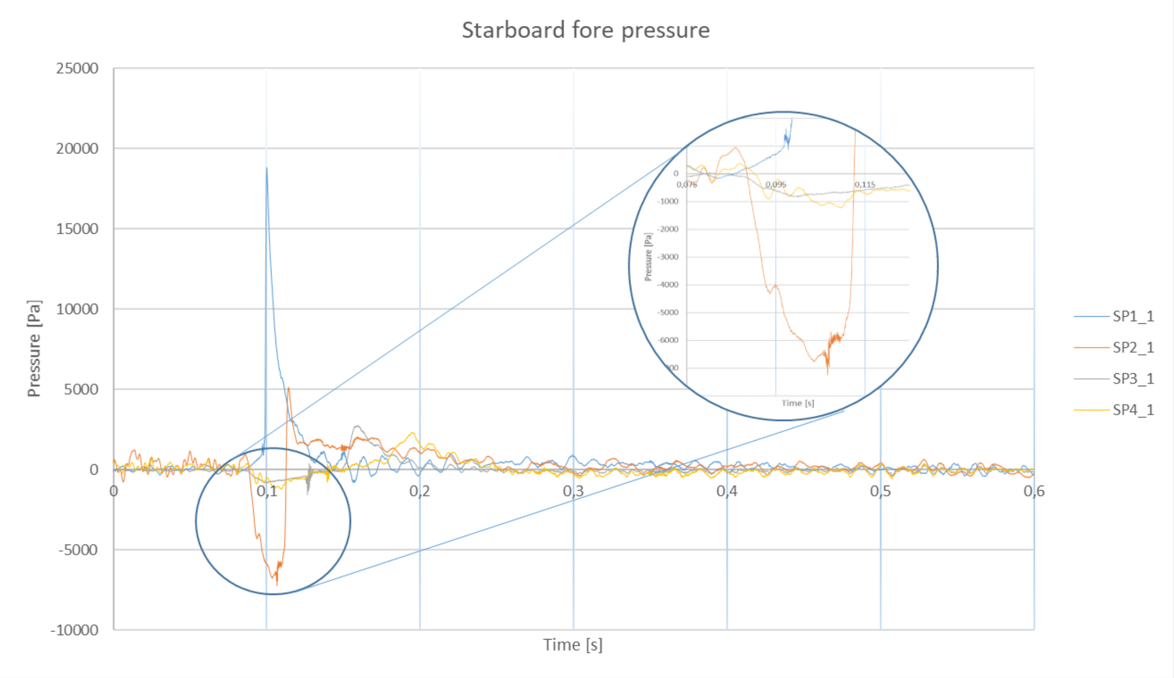


Figure 20. Starboard fore pressure at 25 cm drop height, pressure sensor SP2 showing negative pressure.

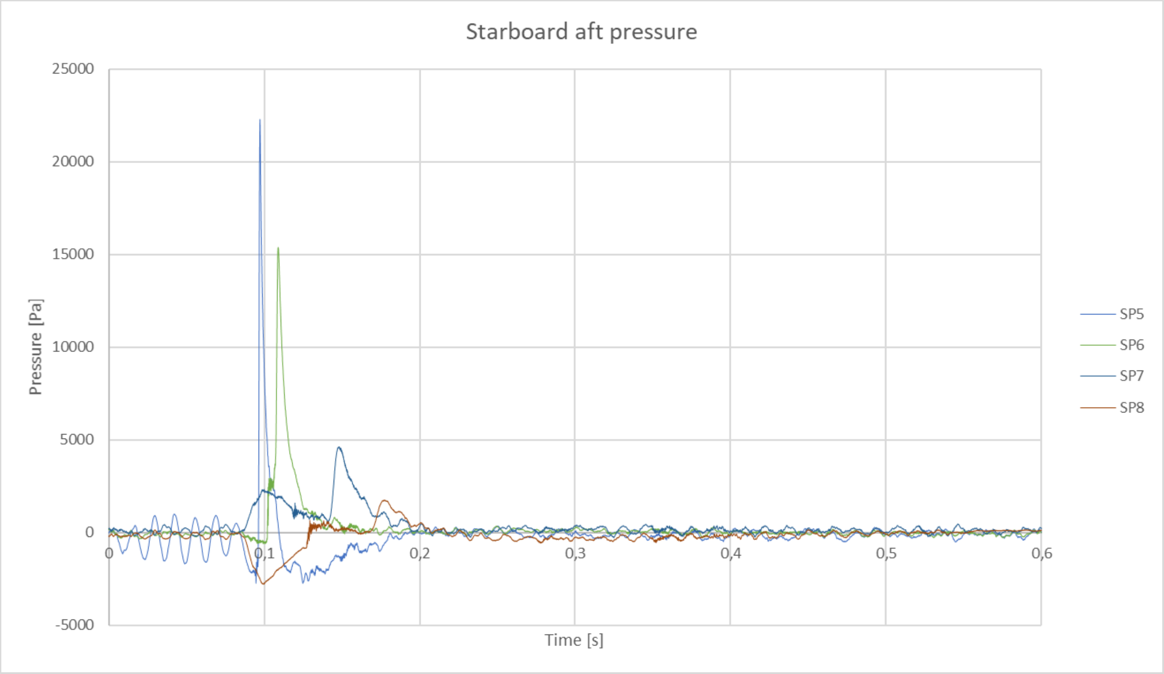


Figure 21. Starboard aft pressure at 25 cm drop height, outermost pressure gauge showing again negative pressures, although less than in the fore.

During drop tests, the water entry of the wedge created vibrations in the drop rig. For symmetrical tests, this effect was minimal, but during non-symmetrical water entry it was very noticeable. The effect on measurement results was negligible. For future testing, the drop rig must be upgraded, with attachment points in the ceiling, sides and bottom of the towing tank, for making the rig more rigid. More effective measures for damping the resulting waves from the impact must be implemented, to reduce the waiting time between tests.

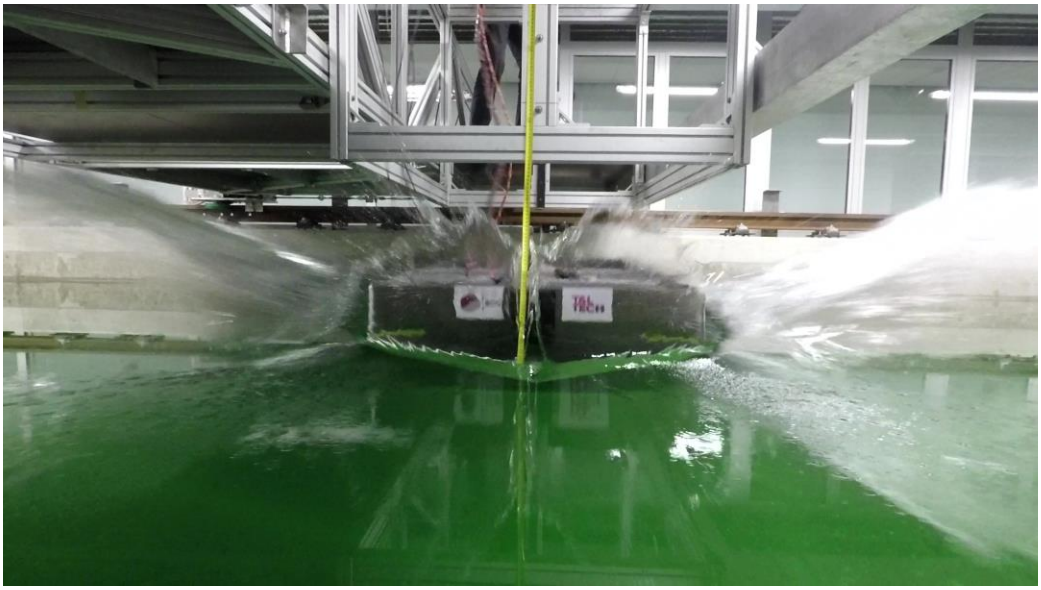


Figure 22. Water entry of the wedge at 50 cm drop height.

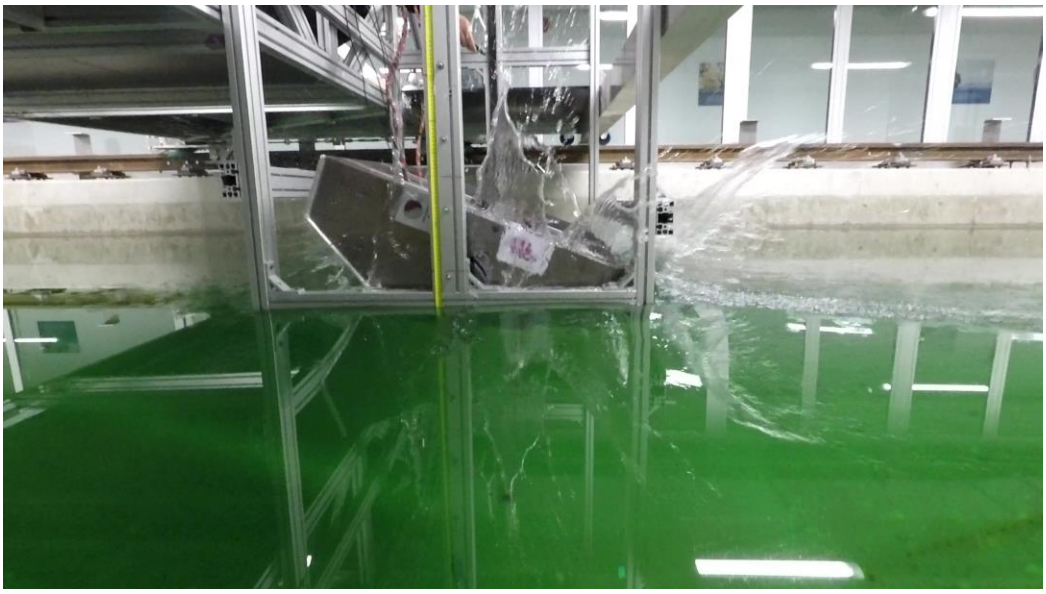


Figure 23. Asymmetrical water entry of the wedge at 50 cm drop height and 25 degree heel angle.

4. DISCUSSION

In the following section, analysis of the measurement results is presented. Due to the large amount of data collected, in this thesis only one drop height (25 cm) and not all of the tests are analysed.

4.1 Acceleration, velocity and displacement

The acceleration data gathered from the IMU was used to plot out the acceleration. Speed and displacement of the wedge were calculated based on the acceleration. Speed is the integral of acceleration with respect to time

$$v = \int \boldsymbol{a\,dt}$$

and displacement is the integral of speed respect to time

$$s = \int \boldsymbol{v\,dt}\,,$$

a quick and simple calculation in MS Excel can be made to find the velocity and displacement. Velocity is found as

$$v = v_{initial} + a * t_s.$$

where

v – instantaneous velocity,

a – acceleration,

t_s – sample time.

Based on the theoretical calculation, impact velocity for a 25-centimetre drop height should be 2.215 m/s. Calculation based on acceleration measurements gives an average impact velocity of 2.13 m/s. Negative sign of the impact velocity and displacement denotes the movement in the negative vertical direction.

The displacement value on water entry for water entry is taken at same time point when maximum speed occurs. Note that maximum acceleration on impact and maximum velocity do not occur at the same point in time. The difference between theoretical and calculated velocity based on measurements can be attributed to the errors in measurement and the friction between the sleds and guide rails.

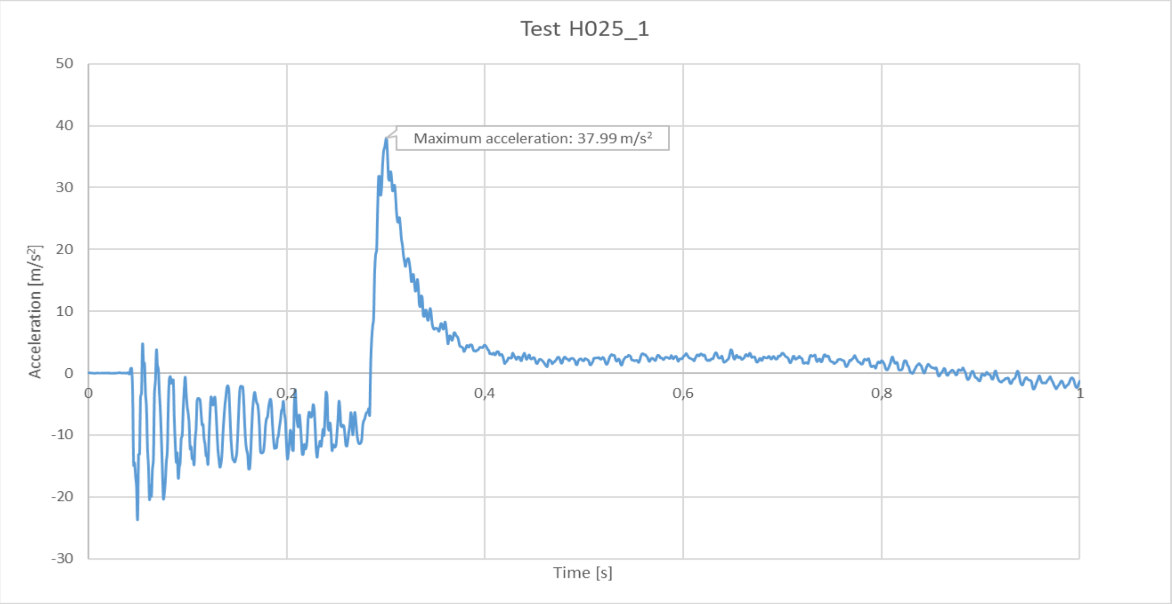


Figure 24. IMU acceleration data from a 25-centimetre height symmetrical drop test at weight W0.

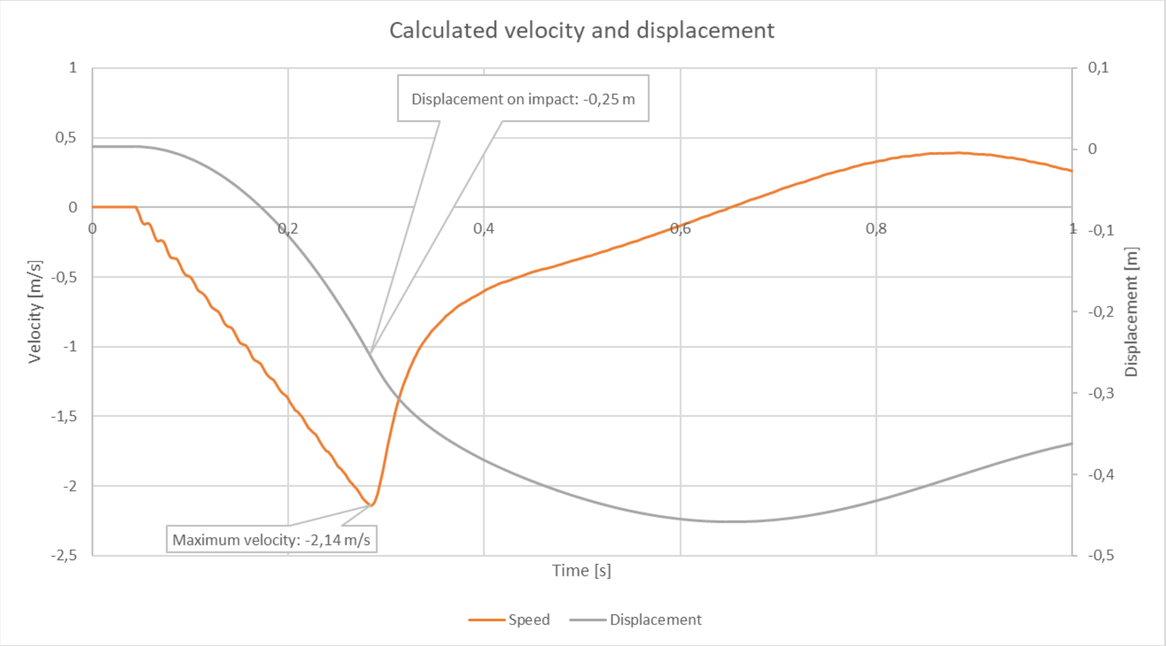


Figure 25. Calculated velocity and displacement graphs.

4.2 Repeatability

Acceleration measurement results from the IMU show good consistency between runs. The data from each test is as repeatable as the measurements from Dytran accelerometer, but the free fall acceleration is captured better with the IMU. As mentioned before, the IMU has built-in filtering, which cannot be disabled, unlike the purpose-built Dytran accelerometers.

Velocity and displacement calculations based on acceleration data are consistent between runs, with only minor differences caused by calculation errors.

Table 6. Measured and calculated data from twelve tests at weight W0 and 25 cm drop height.

Test number	Max acceleration on water entry	Max velocity	Displacement on entry to water
H025_1	37,99	-2,14	-0,25
H025_2	36,60	-2,13	-0,25
H025_3	35,40	-2,12	-0,25
H025_4	35,61	-2,13	-0,25
H025_5	34,60	-2,12	-0,25
H025_6	35,30	-2,13	-0,25
H025_7	34,43	-2,14	-0,26
H025_8	35,02	-2,12	-0,26
H025_9	34,89	-2,11	-0,25
H025_10	33,80	-2,12	-0,26
H025_11	34,90	-2,12	-0,25
H025_12	37,74	-2,12	-0,25
Average	35.52	-2,13	-0.25

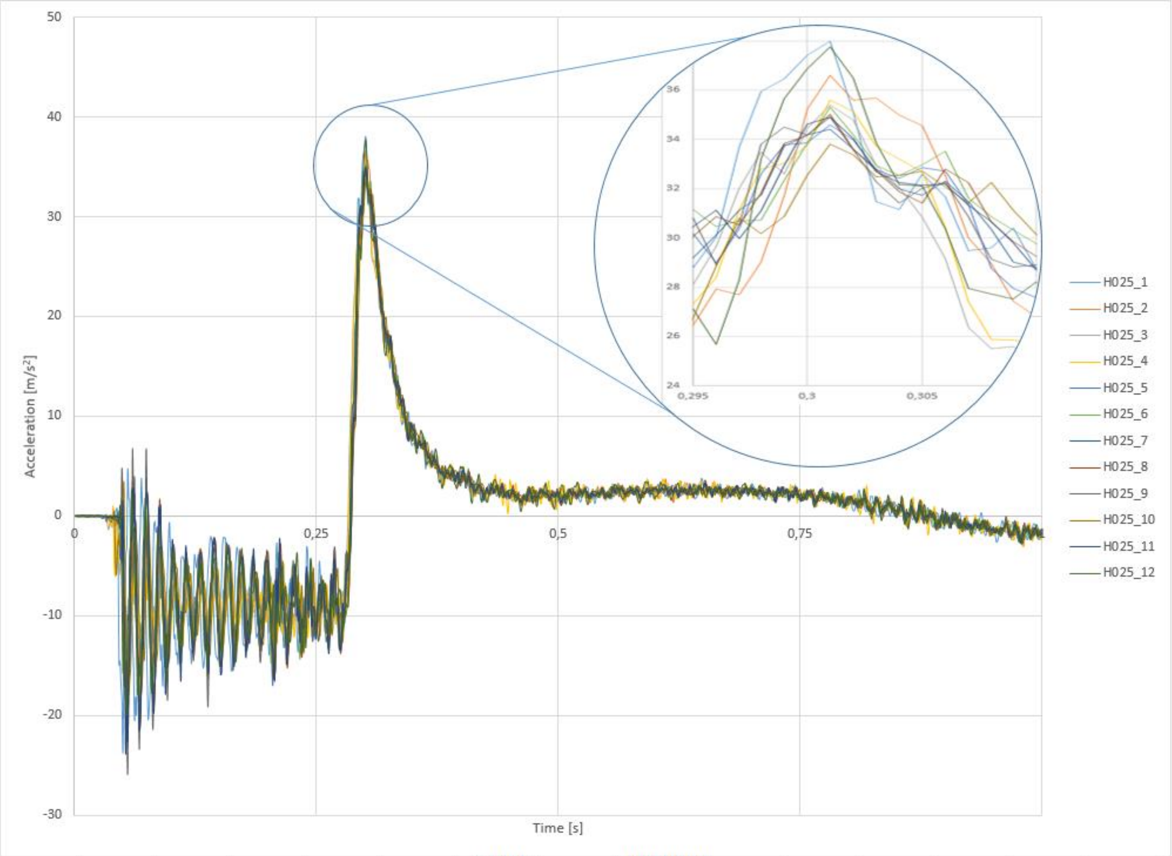


Figure 26. IMU acceleration measurement results from 12 symmetrical tests at 25 cm drop height.

4.3 Pressures

Pressure measurement data from different individual tests shows consistent results. The pressure near the keel is the highest and quickly decreases closer to the chine. On the rigid side of the wedge, pressures are constantly higher than on the elastic portside, although issues with negative pressures are more prevalent in the starboard (figures 27 and 28). In the fore of the wedge, where the deadrise angle is larger, pressures are consistently a bit smaller than in the aft (Figure 29), which becomes more evident in larger drop heights.

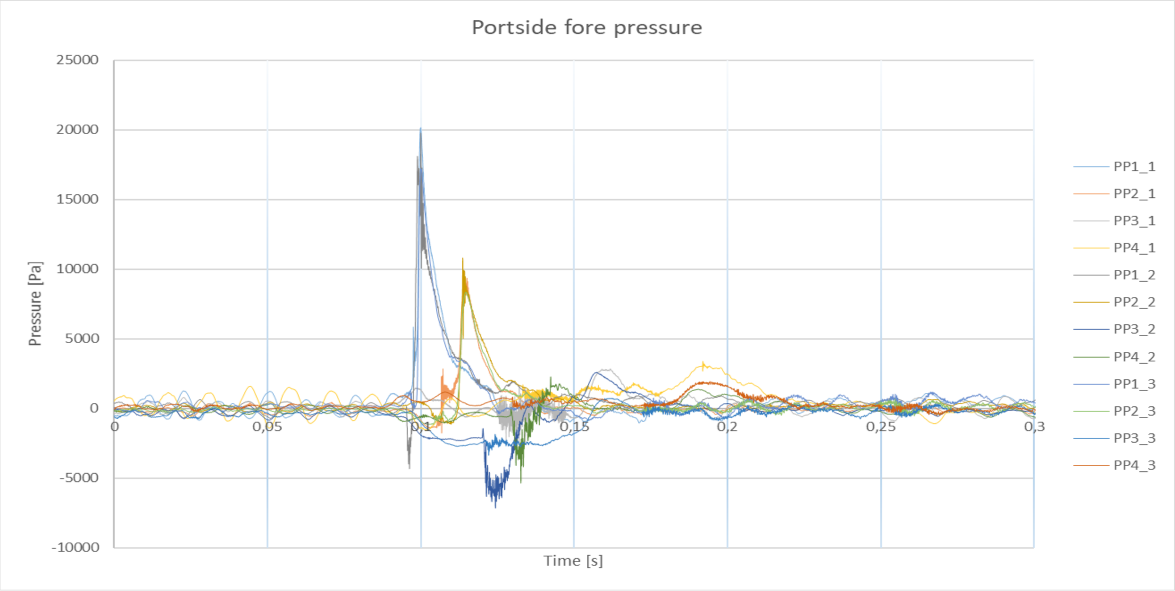


Figure 27. Plotted measurement results from portside fore pressure sensors PP1 to PP4 from three different tests at 25 cm drop height.

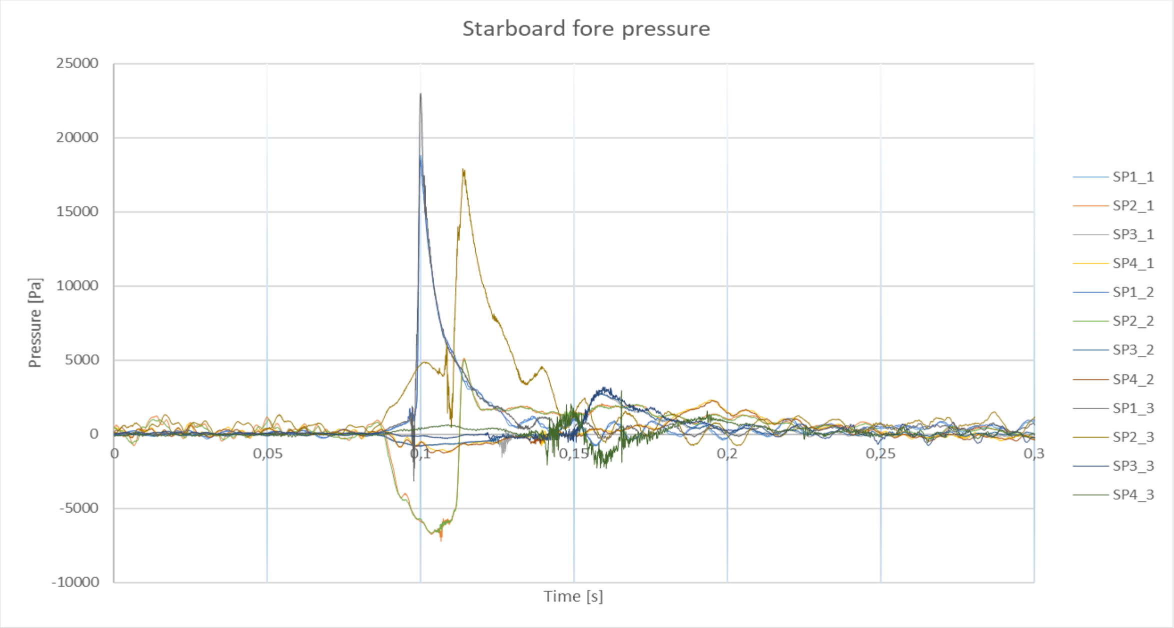


Figure 28. Plotted measurement results from starboard fore pressure sensors SP1 to SP4 from three different tests at 25 cm drop height.

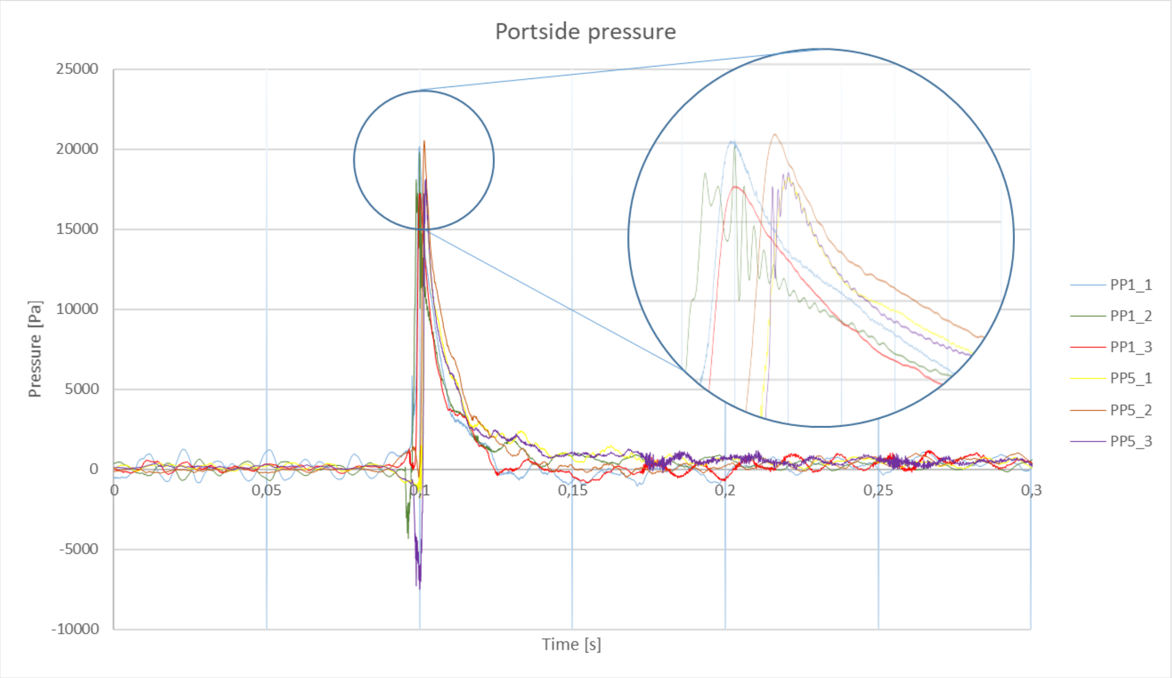


Figure 29. Pressure in the fore (PP1) and aft (PP5) of the wedge at 25 cm drop height for three different tests.

Pressure measurements from the sensors closest to the chine are of very little interest at this drop height. As seen on figures 26 and 27, peak pressures are up to ten times lower than near the keel and cause relatively little effect to the deformations of the test specimen.

4.4 Strain

Measurements from strain gauges show consistent deformation of the wedge during tests. The largest strains were measured at locations PS8 and SS8, where the deformation reached or exceeded 100 μm/m (Figures 30 and 31). These strain gauges are situated closest to the areas with the highest pressure (further aft from pressure sensors PP5 and SP5). As expected, strain in the starboard bottom plating was considerably lower overall. Strain in the midship on the rigid side was negligible for 25 centimetre drop heights is negligible (Figure 32).

As with the Dytran accelerometer data, the strain gauge measurement data is unfiltered. For further analysis, filtering must be applied.

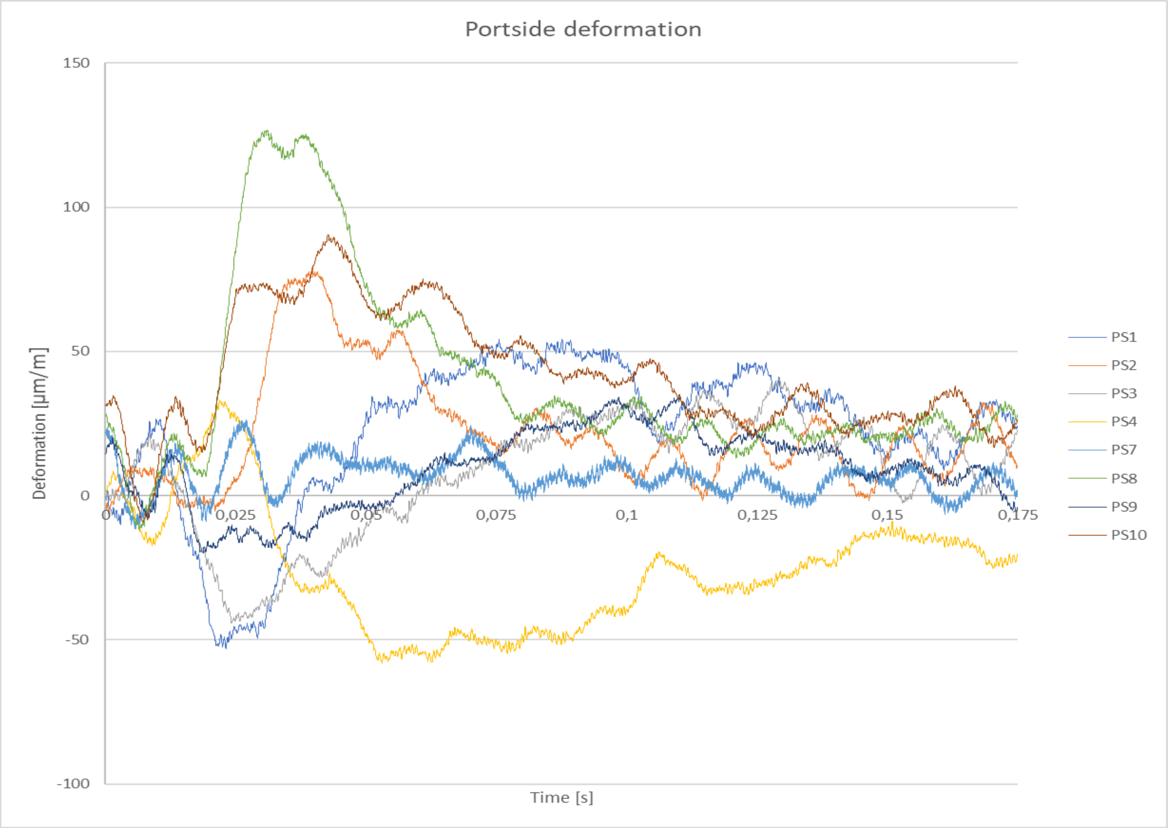


Figure 30. Deformation in the elastic bottom plating at 25 cm drop height.

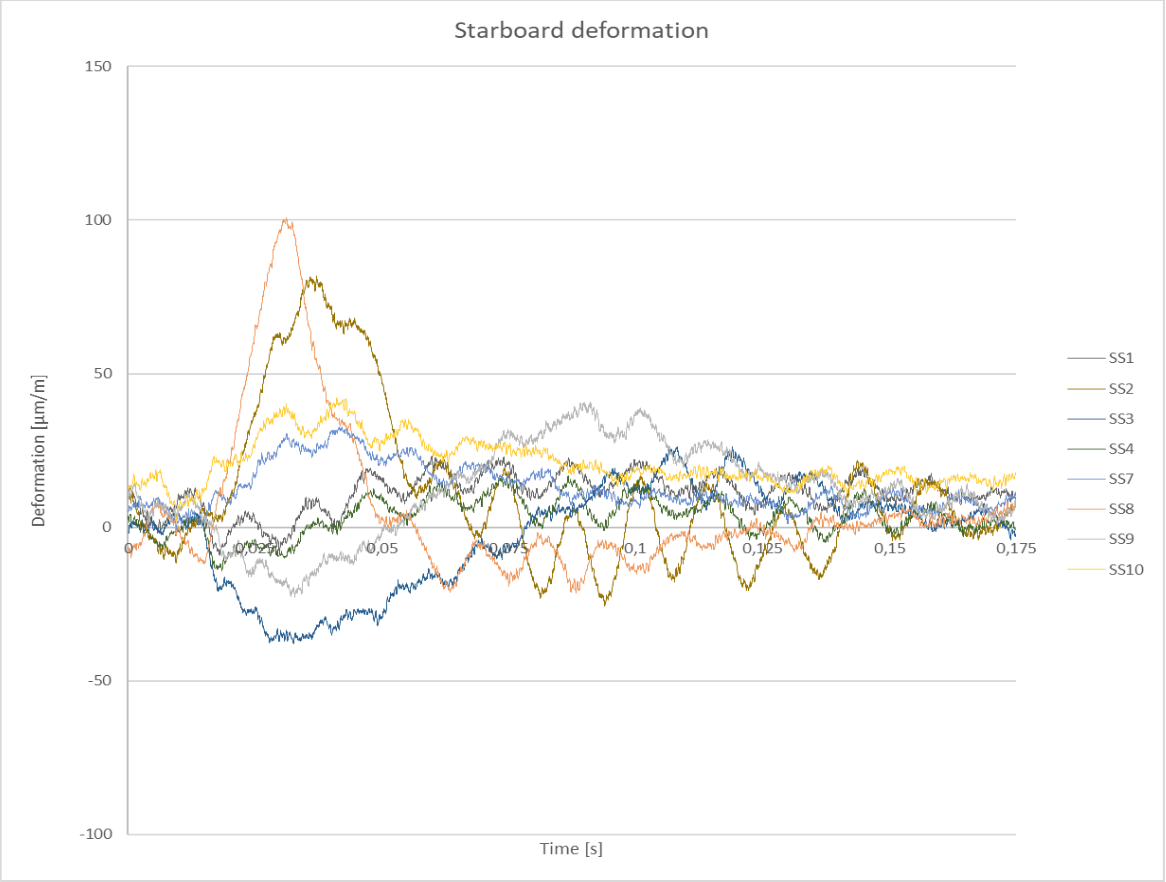


Figure 31. Deformations in the rigid bottom plating at 25 cm drop height.

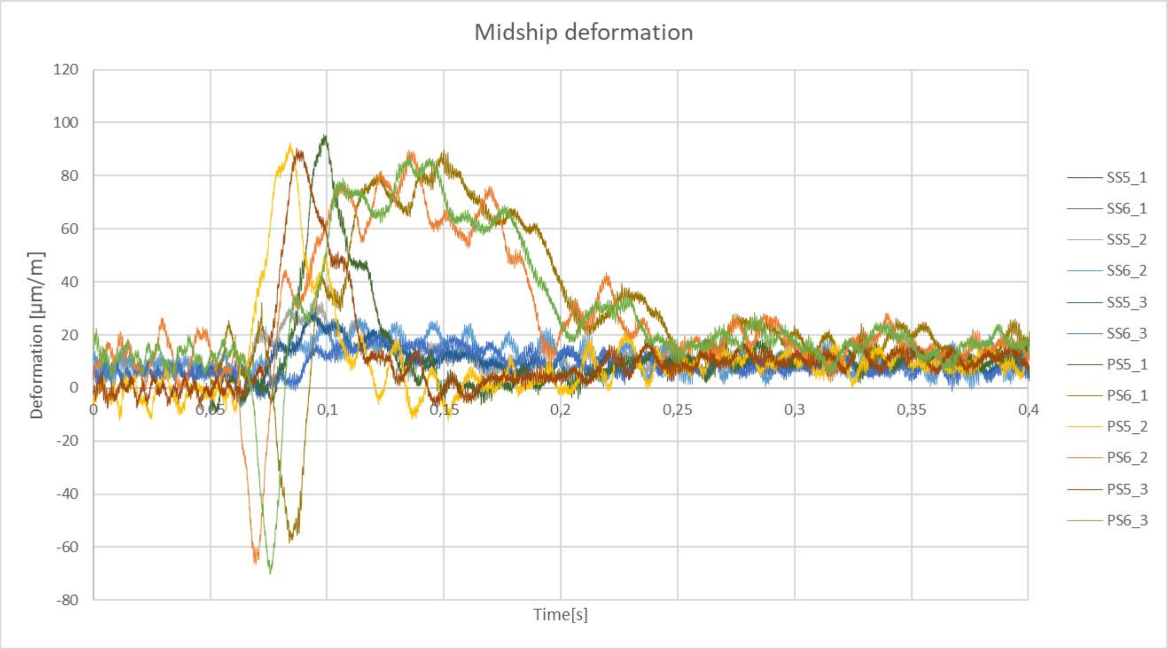


Figure 32. Midship deformations for three tests at 25 cm drop height.

4.5 Further developments

In this thesis, a very brief overview of the results is given. Further analysis of these measurements is conducted, in order to properly validate the numerical model. Already a few ideas have arisen for how to develop the numerical model and for its further validation. More experiments for studying slamming phenomena are planned, for example oblique drop tests, where the wedge is dropped into the water so, that it also has a horizontal velocity component. However, this is more difficult than vertical drop tests, due to the complexity of the dropping rig and its mounting. In addition, for future experimentation, changes in some of the sensors and other instrumentation has to be made, in order to get better results and to reduce the testing time.

It would be advisable to use a different type of acceleration sensor for capturing the signal during freefall better. For a more accurate analysis, a high speed camera should be used for Digital Image Correlation. This would allow for a better visual analysis of the spray formation.

CONCLUSION

The aim of this thesis was to conduct an experimental study on slamming effects. For this, a variable deadrise angle aluminium wedge was dropped into water from 8 different heights between 25 and 200 centimetres and the resulting pressures and deformations were measured. Additionally, asymmetric drop tests were conducted, where the heel angle of the wedge was changed from 0 to 20 degrees in 5-degree increments. Measurement instrumentation consisted of 20 strain gauges, 16 pressure transducers, accelerometers and an inertial measurement unit.

Main time of the work went into preparations of the wedge, drop rig and instrumentation. The rig was made of aluminium profiles and attached to the towing carriage in the towing tank. Guide rails were attached to the rig for guiding the wedge vertically. The wedge was made of 5083 H111 aluminium alloy, with a bottom plating thickness of 4 mm.

Problems with the noisy signal of the accelerometers and negative relative pressures measured by the pressure sensors required a lot of troubleshooting and downtime. The issues with the accelerometers persisted and no adequate solution was found. Pressure transducer problems were mostly solved and physical alteration of the pressure sensor mounting seemed to yield the best results.

Initial analysis of the measurement results showed mostly expected pressures and deformations. Accelerations measured by the IMU were used to calculate the velocity and displacement of the wedge, which gave adequately accurate results, although a higher frequency measurement with a better accelerometer would be more suitable. A deeper analysis of all the results is needed in order to properly validate the numerical model.

Future work on this problem should also include oblique drop tests, were the wedge enters the water with a vertical and horizontal velocity component. Many components of the measurement system should be revised and a high-speed camera should be used to better capture the water entry for visualization and for measuring the velocity.

KOKKUVÕTE

Käesoleva lõputöö eesmärk oli läbi viia eksperimentaaluuring lämmingu mõju uurimiseks. Selleks kasutati mitteprismaatilist, muutuva kiilsusnurgaga, mida kukutati vette kaheksalt erinevalt kõrguselt vahemikus 25 kuni 200 cm ning mõõdeti vette sisenemisel kiilu põhja all tekkivaid rõhkusid ja põhjaplaadistuses tekkivaid deformatsioone. Lisaks viidi läbi asümmeetrilised kukutamise katsed, kus kiilu kreeninurka muudeti viie kraadi kaupa vahemikus 5 kuni 20 kraadi. Mõõtmiseks kasutati 20 deformatsiooniandurit, 16 rõhuandurit, kiirendusandureid ja inertsiaalandurit.

Suurem osa ajast panustati kiilu, kukutamise rakise ja mõõteinstrumentide ettevalmistamisele. Rakis valmistati alumiiniumprofiilidest ning kinnitati mudelkatsebasseini vankri külge. Juhtsiinid kinnitati rakise külge kiilu vertikaalseks suunamiseks. Kiil valmistati 5083 H111 alumiiniumisulamist, ning põhjaplaadistuse paksus oli 4 mm.

Mõõtmiste käigus esines probleeme kiirendusandurite halva signaaliga ning rõhuandurite poolt mõõdetud negatiivsete rõhkudega, mille tõrkeotsing nõudis palju aega. Kiirendusandurite probleemidele ei leitud lahendust. Rõhuandurite näiduprobleemid said enamjaolt lahendatud ning kõige tõhusamaid tulemusi tõi kaasa andurite kinnituse füüsiline muutmine.

Mõõtetulemuste esialgne analüüs näitas enamasti oodatud tulemusi nii rõhkude kui deformatsioonide osas. Inertsiaalanduriga mõõdetud kiirenduste baasilt arvutati kiirused ja siirded. Tulemused olid rahuldavad, kuigi kõrgema mõõtesagedusega kiirendusandur annaks täpsemaid tulemusi. Arvutusliku mudeli valideerimiseks on vajalik mõõteandmete täpsem analüüs.

Tulevikus peab töö antud teemal jätkama kaldus kukutamise katsetega, kus kiilu langemisel vette on sellel nii vertikaalne kui ka horisontaalne kiirus. Mitmed mõõtesüsteemi osised on tarvis välja vahetada ning vaja on kasutada kõrge kaadrisagedusega kaamerat, et paremini jäädvustada kiilu vette sisenemise hetke nii visualiseerimiseks kui ka kiiruse mõõtmiseks.

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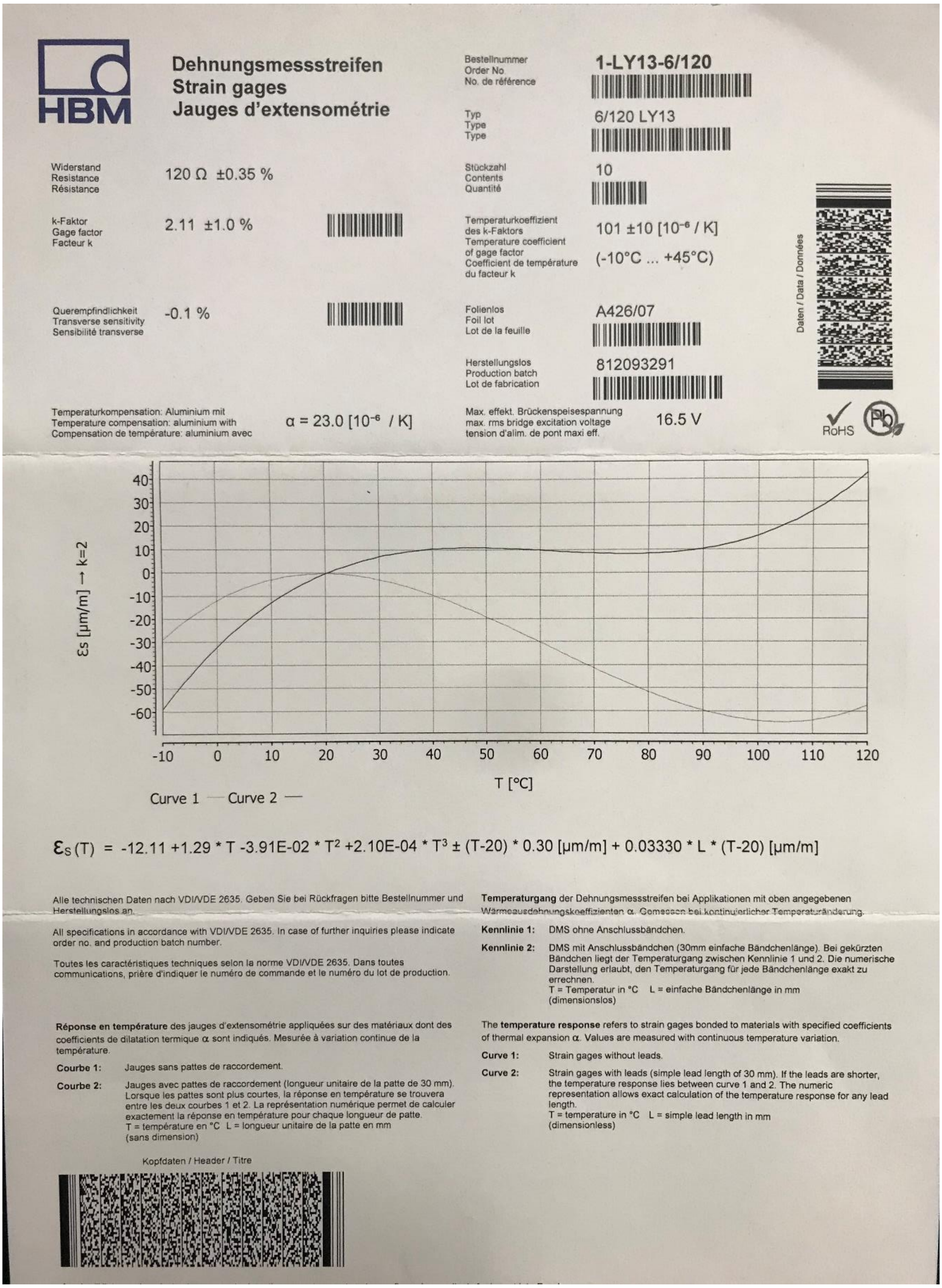
APPENDICES

Appendix 1 HBM 1-LY13-6/120 Strain Gauge data sheet



HBM

Dehnungsmessstreifen
Strain gages
Jauges d'extensométrie

Bestellnummer Order No No. de référence	**1-LY13-6/120**
Typ Type Type	6/120 LY13
Widerstand Resistance Résistance	120 Ω ±0.35 %
Stückzahl Contents Quantité	10
k-Faktor Gage factor Facteur k	2.11 ±1.0 %
Temperaturkoeffizient des k-Faktors Temperature coefficient of gage factor Coefficient de température du facteur k	101 ±10 [10⁻⁶ / K] (-10°C ... +45°C)
Queremfindlichkeit Transverse sensitivity Sensibilité transverse	-0.1 %
Folienlos Foil lot Lot de la feuille	A426/07
Herstellungslos Production batch Lot de fabrication	812093291
Temperaturkompensation: Aluminium mit Temperature compensation: aluminium with Compensation de température: aluminium avec	α = 23.0 [10⁻⁶ / K]
Max. effekt. Brückenspeisespannung max. rms bridge excitation voltage tension d'alim. de pont maxi eff.	16.5 V

Daten / Data / Données

RoHS

$$\varepsilon_S(T) = -12.11 + 1.29 * T - 3.91E\text{-}02 * T^2 + 2.10E\text{-}04 * T^3 \pm (T-20) * 0.30\ [\mu m/m] + 0.03330 * L * (T-20)\ [\mu m/m]$$

Alle technischen Daten nach VDI/VDE 2635. Geben Sie bei Rückfragen bitte Bestellnummer und Herstellungslos an.

All specifications in accordance with VDI/VDE 2635. In case of further inquiries please indicate order no. and production batch number.

Toutes les caractéristiques techniques selon la norme VDI/VDE 2635. Dans toutes communications, prière d'indiquer le numéro de commande et le numéro du lot de production.

Réponse en température des jauges d'extensométrie appliquées sur des matériaux dont des coefficients de dilatation termique α sont indiqués. Mesurée à variation continue de la température.

Courbe 1: Jauges sans pattes de raccordement.

Courbe 2: Jauges avec pattes de raccordement (longueur unitaire de la patte de 30 mm). Lorsque les pattes sont plus courtes, la réponse en température se trouvera entre les deux courbes 1 et 2. La représentation numérique permet de calculer exactement la réponse en température pour chaque longueur de patte.
T = température en °C L = longueur unitaire de la patte en mm
(sans dimension)

Temperaturgang der Dehnungsmessstreifen bei Applikationen mit oben angegebenen Wärmeausdehnungskoeffizienten α. Gemessen bei kontinuierlicher Temperaturänderung.

Kennlinie 1: DMS ohne Anschlussbändchen.

Kennlinie 2: DMS mit Anschlussbändchen (30mm einfache Bändchenlänge). Bei gekürzten Bändchen liegt der Temperaturgang zwischen Kennlinie 1 und 2. Die numerische Darstellung erlaubt, den Temperaturgang für jede Bändchenlänge exakt zu errechnen.
T = Temperatur in °C L = einfache Bändchenlänge in mm
(dimensionslos)

The **temperature response** refers to strain gages bonded to materials with specified coefficients of thermal expansion α. Values are measured with continuous temperature variation.

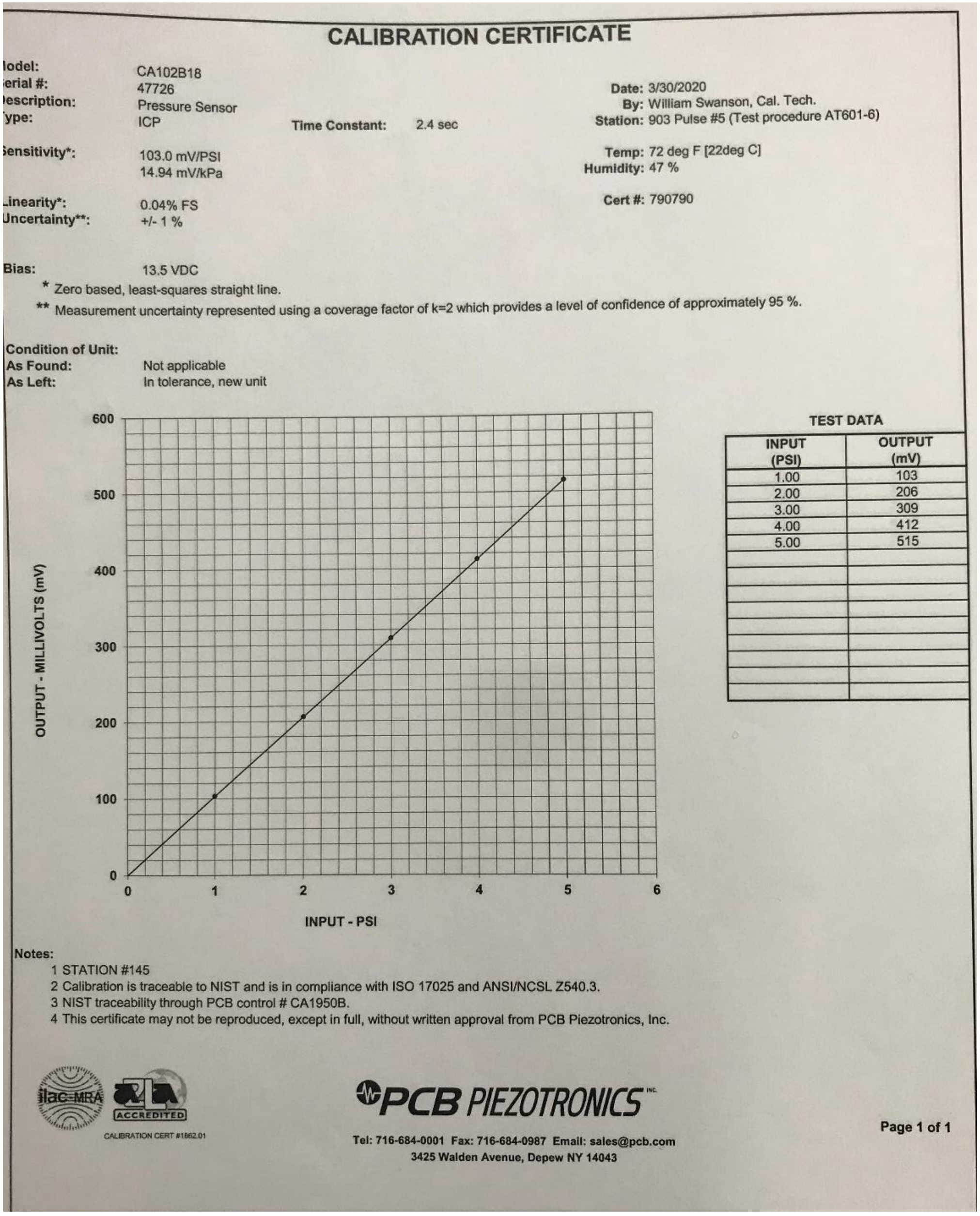
Curve 1: Strain gages without leads.

Curve 2: Strain gages with leads (simple lead length of 30 mm). If the leads are shorter, the temperature response lies between curve 1 and 2. The numeric representation allows exact calculation of the temperature response for any lead length.
T = temperature in °C L = simple lead length in mm
(dimensionless)

Kopfdaten / Header / Titre

APPENDICES

Appendix 2. Example of PCB Piezotronics data sheet and calibration info



CALIBRATION CERTIFICATE

lodel: CA102B18
erial #: 47726
escription: Pressure Sensor
ype: ICP
Time Constant: 2.4 sec

Date: 3/30/2020
By: William Swanson, Cal. Tech.
Station: 903 Pulse #5 (Test procedure AT601-6)

ensitivity*: 103.0 mV/PSI
14.94 mV/kPa

Temp: 72 deg F [22deg C]
Humidity: 47 %

inearity*: 0.04% FS
Jncertainty:** +/- 1 %

Cert #: 790790

Bias: 13.5 VDC

* Zero based, least-squares straight line.
** Measurement uncertainty represented using a coverage factor of k=2 which provides a level of confidence of approximately 95 %.

Condition of Unit:
As Found: Not applicable
As Left: In tolerance, new unit

TEST DATA

INPUT (PSI)	OUTPUT (mV)
1.00	103
2.00	206
3.00	309
4.00	412
5.00	515

Notes:
1 STATION #145
2 Calibration is traceable to NIST and is in compliance with ISO 17025 and ANSI/NCSL Z540.3.
3 NIST traceability through PCB control # CA1950B.
4 This certificate may not be reproduced, except in full, without written approval from PCB Piezotronics, Inc.

ilac-MRA ACCREDITED
CALIBRATION CERT #1862.01

PCB PIEZOTRONICS INC.
Tel: 716-684-0001 Fax: 716-684-0987 Email: sales@pcb.com
3425 Walden Avenue, Depew NY 14043

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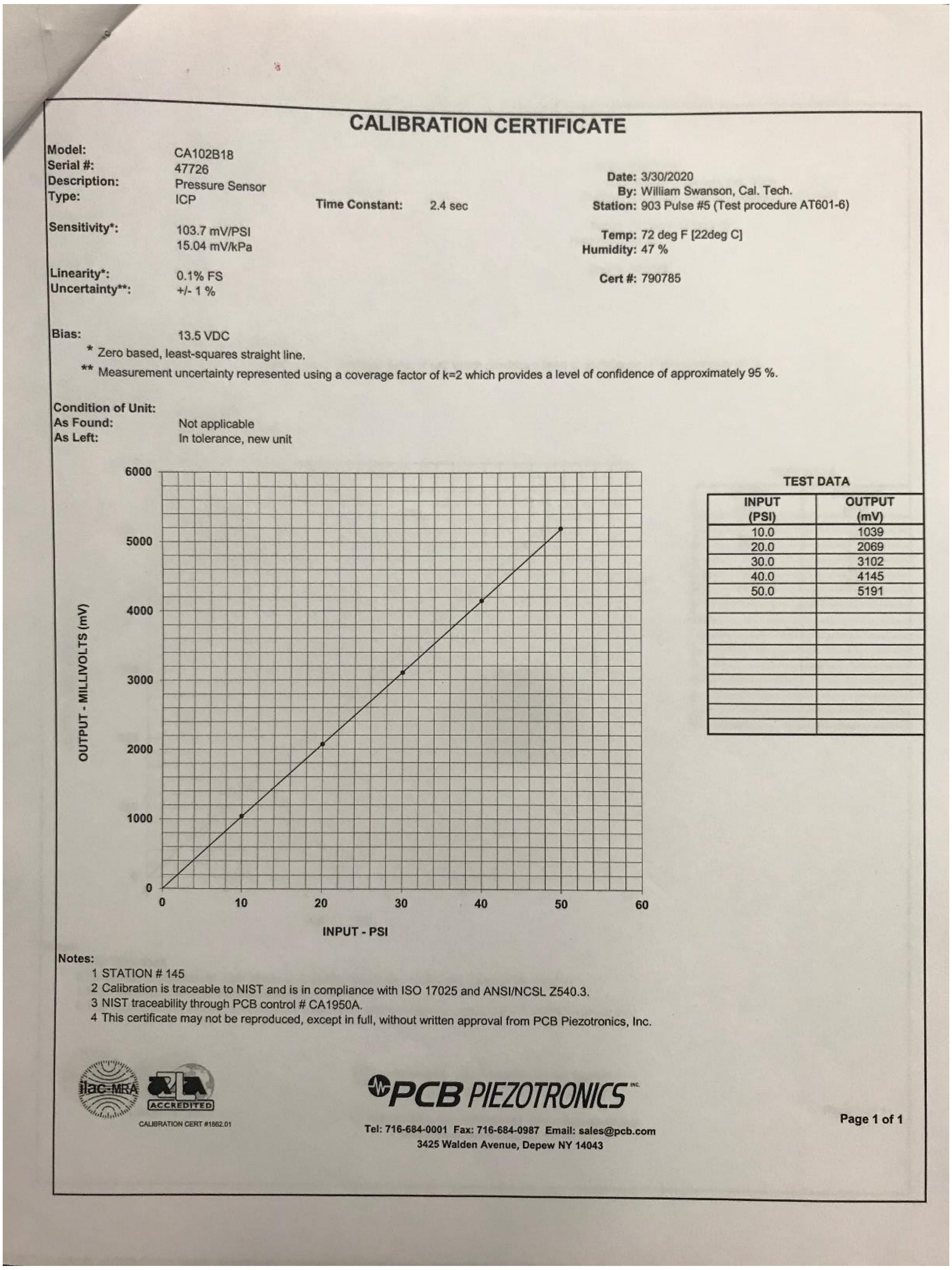
APPENDICES

Appendix 3. Example of PCB Piezotronics data sheet and calibration info



CALIBRATION CERTIFICATE

Model: CA102B18
Serial #: 47726
Description: Pressure Sensor
Type: ICP
Time Constant: 2.4 sec

Date: 3/30/2020
By: William Swanson, Cal. Tech.
Station: 903 Pulse #5 (Test procedure AT601-6)

Sensitivity*: 103.7 mV/PSI
15.04 mV/kPa

Temp: 72 deg F [22deg C]
Humidity: 47 %

Linearity*: 0.1% FS
Uncertainty:** +/- 1 %

Cert #: 790785

Bias: 13.5 VDC

* Zero based, least-squares straight line.
** Measurement uncertainty represented using a coverage factor of k=2 which provides a level of confidence of approximately 95 %.

Condition of Unit:
As Found: Not applicable
As Left: In tolerance, new unit

TEST DATA

INPUT (PSI)	OUTPUT (mV)
10.0	1039
20.0	2069
30.0	3102
40.0	4145
50.0	5191

Notes:
1 STATION # 145
2 Calibration is traceable to NIST and is in compliance with ISO 17025 and ANSI/NCSL Z540.3.
3 NIST traceability through PCB control # CA1950A.
4 This certificate may not be reproduced, except in full, without written approval from PCB Piezotronics, Inc.

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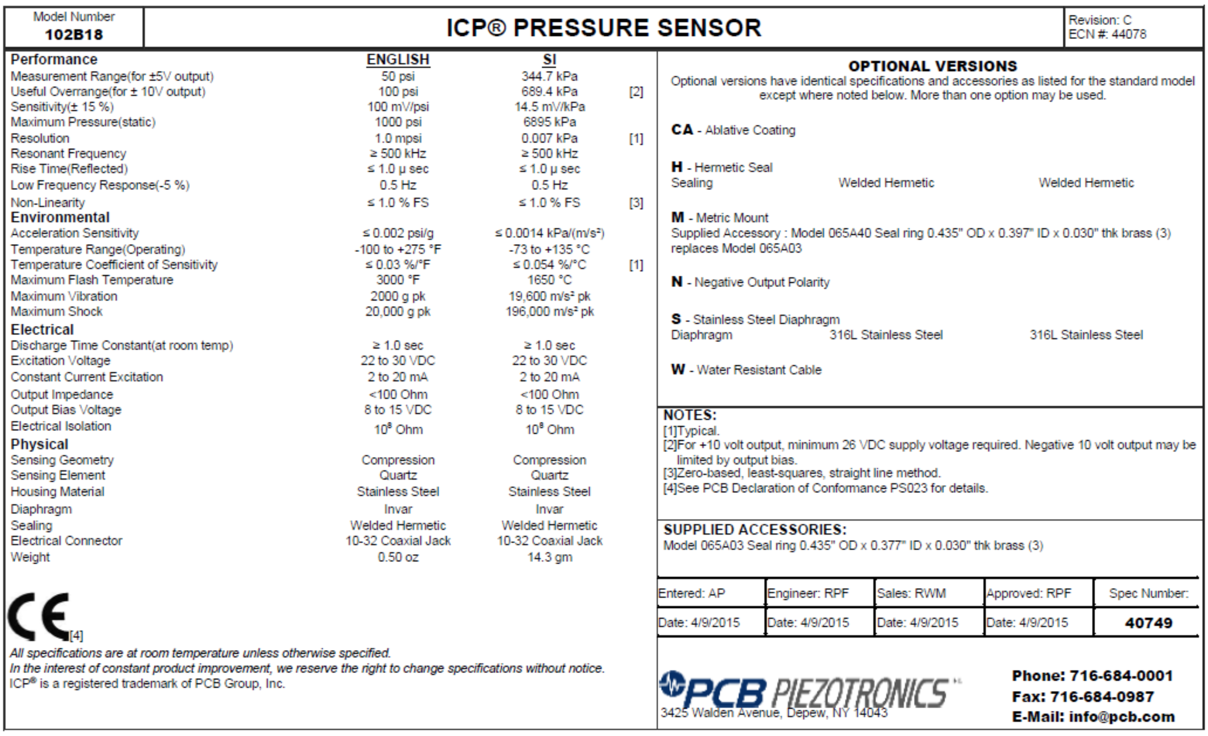
Appendix 4. PCB Piezotronics CA102B18 Data sheet



Model Number **102B18**	**ICP® PRESSURE SENSOR**	Revision: C ECN #: 44078

Performance	**ENGLISH**	**SI**	
Measurement Range(for ±5V output)	50 psi	344.7 kPa	
Useful Overrange(for ± 10V output)	100 psi	689.4 kPa	[2]
Sensitivity(± 15 %)	100 mV/psi	14.5 mV/kPa	
Maximum Pressure(static)	1000 psi	6895 kPa	
Resolution	1.0 mpsi	0.007 kPa	[1]
Resonant Frequency	≥ 500 kHz	≥ 500 kHz	
Rise Time(Reflected)	≤ 1.0 μ sec	≤ 1.0 μ sec	
Low Frequency Response(-5 %)	0.5 Hz	0.5 Hz	
Non-Linearity	≤ 1.0 % FS	≤ 1.0 % FS	[3]
Environmental			
Acceleration Sensitivity	≤ 0.002 psi/g	≤ 0.0014 kPa/(m/s^2)	
Temperature Range(Operating)	-100 to +275 °F	-73 to +135 °C	
Temperature Coefficient of Sensitivity	≤ 0.03 %/°F	≤ 0.054 %/°C	[1]
Maximum Flash Temperature	3000 °F	1650 °C	
Maximum Vibration	2000 g pk	19,600 m/s^2 pk	
Maximum Shock	20,000 g pk	196,000 m/s^2 pk	
Electrical			
Discharge Time Constant(at room temp)	≥ 1.0 sec	≥ 1.0 sec	
Excitation Voltage	22 to 30 VDC	22 to 30 VDC	
Constant Current Excitation	2 to 20 mA	2 to 20 mA	
Output Impedance	<100 Ohm	<100 Ohm	
Output Bias Voltage	8 to 15 VDC	8 to 15 VDC	
Electrical Isolation	10^8 Ohm	10^8 Ohm	
Physical			
Sensing Geometry	Compression	Compression	
Sensing Element	Quartz	Quartz	
Housing Material	Stainless Steel	Stainless Steel	
Diaphragm	Invar	Invar	
Sealing	Welded Hermetic	Welded Hermetic	
Electrical Connector	10-32 Coaxial Jack	10-32 Coaxial Jack	
Weight	0.50 oz	14.3 gm	

CE[4]

All specifications are at room temperature unless otherwise specified.
In the interest of constant product improvement, we reserve the right to change specifications without notice.
ICP® is a registered trademark of PCB Group, Inc.

OPTIONAL VERSIONS

Optional versions have identical specifications and accessories as listed for the standard model except where noted below. More than one option may be used.

CA - Ablative Coating

H - Hermetic Seal

Sealing	Welded Hermetic	Welded Hermetic

M - Metric Mount
Supplied Accessory : Model 065A40 Seal ring 0.435" OD x 0.397" ID x 0.030" thk brass (3) replaces Model 065A03

N - Negative Output Polarity

S - Stainless Steel Diaphragm

Diaphragm	316L Stainless Steel	316L Stainless Steel

W - Water Resistant Cable

NOTES:
[1]Typical.
[2]For +10 volt output, minimum 26 VDC supply voltage required. Negative 10 volt output may be limited by output bias.
[3]Zero-based, least-squares, straight line method.
[4]See PCB Declaration of Conformance PS023 for details.

SUPPLIED ACCESSORIES:
Model 065A03 Seal ring 0.435" OD x 0.377" ID x 0.030" thk brass (3)

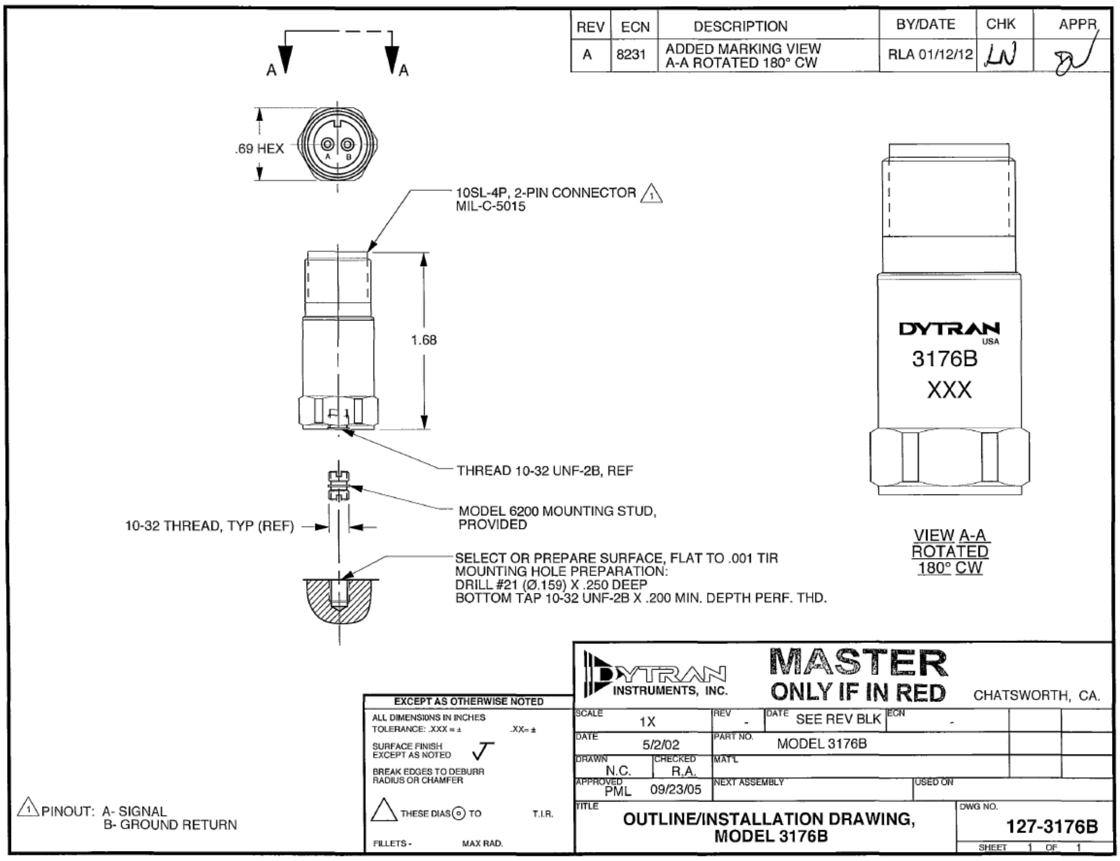
Entered: AP	Engineer: RPF	Sales: RWM	Approved: RPF	Spec Number:
Date: 4/9/2015	Date: 4/9/2015	Date: 4/9/2015	Date: 4/9/2015	**40749**

PCB PIEZOTRONICS
3425 Walden Avenue, Depew, NY 14043

Phone: 716-684-0001
Fax: 716-684-0987
E-Mail: info@pcb.com

APPENDICES

Appendix 5. Dytran 3176B Accelerometer Data sheet



REV	ECN	DESCRIPTION	BY/DATE	CHK	APPR
A	8231	ADDED MARKING VIEW A-A ROTATED 180° CW	RLA 01/12/12	LN	

1 PINOUT: A- SIGNAL
B- GROUND RETURN

EXCEPT AS OTHERWISE NOTED
ALL DIMENSIONS IN INCHES
TOLERANCE: .XXX = ± .XX= ±
SURFACE FINISH EXCEPT AS NOTED √
BREAK EDGES TO DEBURR RADIUS OR CHAMFER
△ THESE DIAS ⊙ TO T.I.R.
FILLETS - MAX RAD.

DYTRAN INSTRUMENTS, INC.
MASTER
ONLY IF IN RED
CHATSWORTH, CA.

SCALE 1X	REV -	DATE SEE REV BLK	ECN -
DATE 5/2/02	PART NO. MODEL 3176B		
DRAWN N.C. / CHECKED R.A.	MAT'L		
APPROVED PML 09/23/05	NEXT ASSEMBLY	USED ON	
TITLE OUTLINE/INSTALLATION DRAWING, MODEL 3176B		DWG NO. 127-3176B	SHEET 1 OF 1

Model Number 3176B	PERFORMANCE SPECIFICATION	DOC NO PS3176B
	IEPE ACCELEROMETER	REV A, ECN 12601, 04/04/16

- HIGH SENSITIVITY
- ELECTRICALLY ISOLATED
- HERMETICALLY SEALED

		ENGLISH		SI	
PHYSICAL					
Weight, Max.		1.6	oz	44	grams
Connector	Type	MIL-C-5015		MIL-C-5015	
	Pins	2-PIN		2-PIN	
Mounting Provision		Tapped 10-32 Hole		Tapped 10-32 Hole	
Material (Case/Connector)		300 Series S.S.		300 Series S.S.	
Element Type		Piezoceramic, Planar Shear		Piezoceramic, Planar Shear	
PERFORMANCE					
Sensitivity, ±5% [1]		100	mV/g	10.2	mV/m/s²
Range F.S for ± 5 Volts Output		±50	g	±490.5	m/s²
Frequency Response, ±10%		0.3 to 10,000	Hz	0.3 to 10,000	Hz
Mounted Resonant Frequency		> 27	kHz	> 27	kHz
Equivalent Electrical Noise Floor		0.00002	Grms	0.0002	m/s² rms
Amplitude Non-Linearity, Max. [2]		±2	% F.S.	±2	% F.S.
Maximum Transverse Sensitivity		5	%	5	%
Strain Sensitivity @ 250/μσ		0.0001	g/με	0.001	m/s²/με
ENVIRONMENTAL					
Maximum Vibration		500	G's, peak	4905	m/s² peak
Maximum Shock		5000	G's, peak	49050	m/s² peak
Temperature Range		-60 to +250	°F	-51 to +121	°C
Seal		Hermetic		Hermetic	
ELECTRICAL					
Supply Current Range [3]		2 to 20	mA	2 to 20	mA
Compliance Voltage Range		+20 to +30	Volts	+20 to +30	Volts
Output Impedance, Typ.		200	Ω	200	Ω
Output Bias Voltage		+11 to +13	VDC	+11 to +13	VDC
Discharge Time Constant		0.9 to 2.0	Sec	0.9 to 2.0	Sec
Output Signal Polarity		Positive for Acceleration Toward Top		Positive for Acceleration Toward Top	
Electrical Isolation, Ground Pin to Case		10	GΩ, min	10	GΩ, min

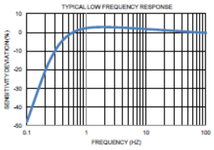
This family also includes:

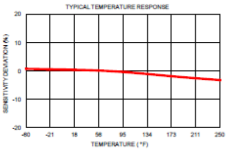
Model	Sensitivity	Range F.S ± 5 Volts	Max Vibration/Shock	Resonant Frequency

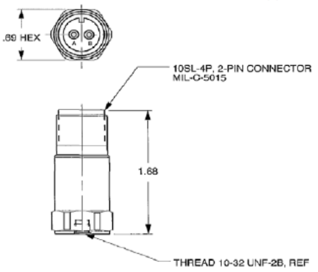
Refer to the performance specifications of the products in this family for detailed description

Supplied Accessories:
1) Accredited calibration certificate (ISO 17025)
2) Mouting Stud Model 6200S, 10-32 to 10-32

Notes:
[1] Measured at 100Hz, 1 Grms per ISA RP 37.2
[2] Measure using zero-based straight line method, % of F.S. or any lesser range.
[3] Do not apply power to this system without current limting, 20 mA MAX. To do so will destroy the IC charge amplifier.







Units on the line drawing are in inches, units in brackets are in millimeters. Refer to 127-3176B for more information.

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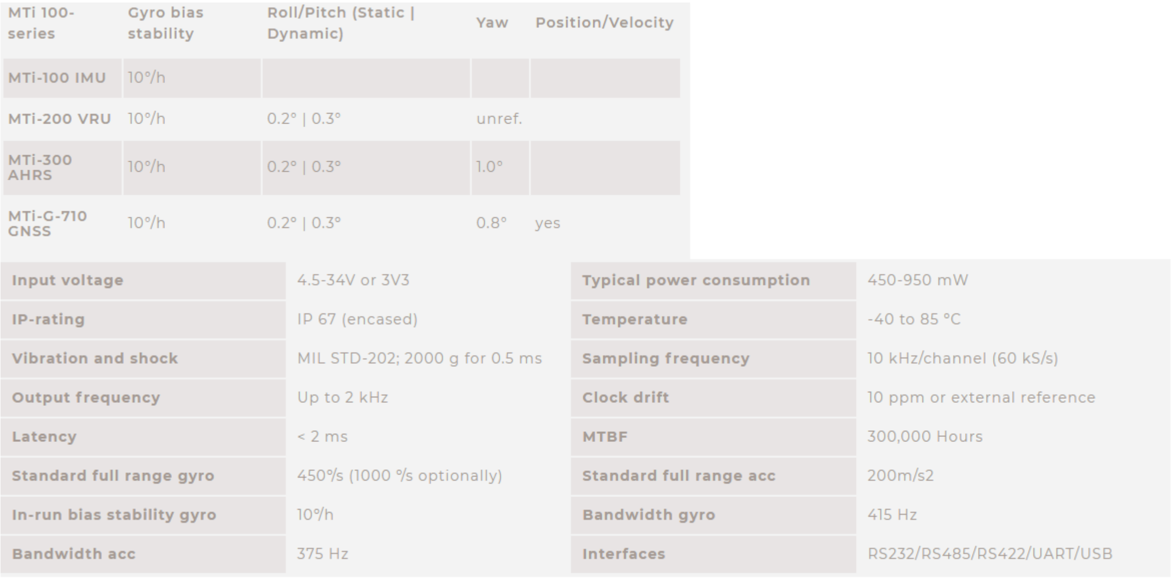
Appendix 6. XSens MTi Series Inertial Measurement Unit Data sheet



MTi 100-series	Gyro bias stability	Roll/Pitch (Static | Dynamic)	Yaw	Position/Velocity
MTi-100 IMU	10°/h			
MTi-200 VRU	10°/h	0.2° | 0.3°	unref.	
MTi-300 AHRS	10°/h	0.2° | 0.3°	1.0°	
MTi-G-710 GNSS	10°/h	0.2° | 0.3°	0.8°	yes

Input voltage	4.5-34V or 3V3	**Typical power consumption**	450-950 mW
IP-rating	IP 67 (encased)	**Temperature**	-40 to 85 °C
Vibration and shock	MIL STD-202; 2000 g for 0.5 ms	**Sampling frequency**	10 kHz/channel (60 kS/s)
Output frequency	Up to 2 kHz	**Clock drift**	10 ppm or external reference
Latency	< 2 ms	**MTBF**	300,000 Hours
Standard full range gyro	450°/s (1000 °/s optionally)	**Standard full range acc**	200m/s2
In-run bias stability gyro	10°/h	**Bandwidth gyro**	415 Hz
Bandwidth acc	375 Hz	**Interfaces**	RS232/RS485/RS422/UART/USB