Appendix 1. Platform design details

A1.1 Initial cylinder proposal

A DN400 pipe was selected as a standard available pipe size that would accommodate internal equipment for measurement. The overall length was limited by the size of the test facilities and transport capacity. Properties in Tables A1-1 and A1-2 are taken per standard AS/NZS 1163:2009 – C350 [1] and manufacturer specifications [2].

Table A1-1 Pipe geometry

Property	Value
Outer diameter	406.4 mm
Wall thickness	6.35 mm
Length	12 m

Table A1-2 Pipe and fluid material properties

Property	Value
Steel	
Density	7850 kg/m^3
Young's modulus	2.0e11 Pa
Poisson's ratio	0.25
Water	
Density	1000 kg/m^3

Mass properties in Table A1-1 were calculated by the volume and material density. The endcaps were assumed to be of the size of the inside diameter and the same thickness of cylinder. Added fluid mass is calculated as water displaced by the cylinder. The reserve buoyancy for cylinder with endcaps is calculated as 798 kg.

Table A1-3 Analytical values of structural and added fluid mass

Component	Mass (kg)
Structure	
Cylinder (no endcaps)	747
Endcaps	2 x 6
Total	759
Fluid	
Added Mass	1557

An analytical natural frequency calculation for the first two bending modes was conducted using Equations A1.1 and A1.2 from Blevins [3] for a uniform cylindrical beam with free-free end boundary conditions. Each term is defined in Table A1-4 and mode constants are also taken from Blevins [3]. Endcap structure and mass was not been considered in these calculations. Results for the first two modes are presented in Table A1-5.

$$f_{n_i\,(air)} = \frac{\lambda_i^2}{2\pi L^2}\sqrt{\frac{EI}{m_l}} \qquad A1.1$$

$$f_{n_i\,(water)} = f_{n_i\,(air)}\left(1 + \frac{m_{l(water)}}{m_l}\right)^{-\frac{1}{2}} \tag{A1.2}$$

Table A1-4 Properties for natural frequency calculations

Property	**Value**	
1st Mode constant	λ_1^2	22.37
2nd Mode constant	λ_2^2	61.67
Length	L	12 m
Young's modulus	E	2.0E11 Pa
Second moment of Area	I	159.7E-6 m^4
Structural mass per unit length	m_l	62.3 kg/m
Added mass per unit length	$m_{l\,(Water)}$	129.7 kg/m

Table A1-5 Analytical values of first and second bending mode natural frequencies in air and water

i	$f_{n_i\,(air)}$ (Hz)	$f_{n_i\,(water)}$ (Hz)
1	17.7	10.1
2	48.8	27.8

A natural frequency calculation was also conducted with LS-Dyna [4] in Table A1-6. Note that unlike the analytical calculation, the numerical model does contain endcaps and is therefore expected to have slightly lower natural frequencies compared to the uniform cylinder due to the additional mass. The mode shapes for Bending Mode 1 (BM1) and Bending Mode 2 (BM2) are shown in Figure A1-1 and Figure A1-2 respectively.

Table A1-6 Comparison of natural frequencies in air and water for various mesh resolutions

Model	BM1 Air (Hz)	BM2 Air (Hz)	BM1 Water (Hz)	BM2 Water (Hz)
Analytical	17.7	48.8	10.1	27.8
Numerical	16.9	46.0	10.1	27.7

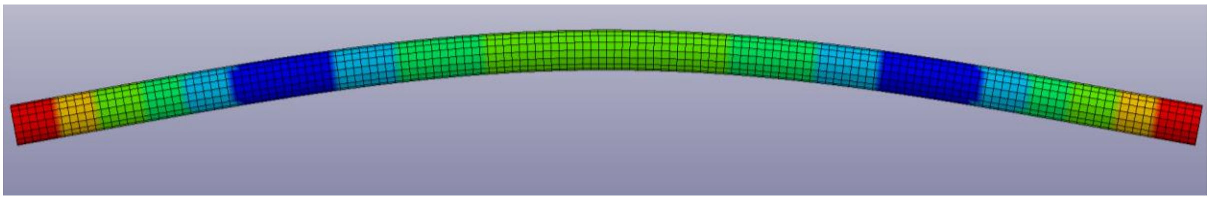

Figure A1-1 First bending mode (BM1)

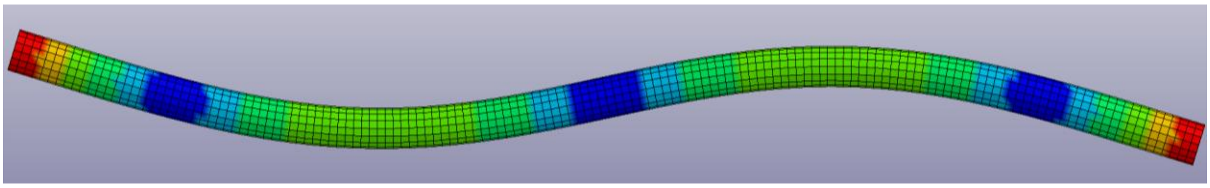

Figure A1-2 Second bending mode (BM2)

The candidate charge size (W) for testing was 250 g of Pentolite at a test depth (D) of 5 m. From the bubble period (T), calculated by Equation A1.3 using k coefficient from Reid [5], the pulsation frequency was obtained, both noted in

Table A1-7. To a induce a large whipping response in the cylinder the structural and bubble pulsation frequencies need to be as close as possible. As there was approximately a 3 Hz difference between these, methods to decrease this difference were explored. There were limitations for adjusting the test depth due to the size of the test area, so modifications were investigated for the cylinder to reduce its bending mode responses.

$$T = K\frac{(W)^{1/3}}{(D+10)^{5/6}} \qquad A1.3$$

Table A1-7 Bubble pulsation period and frequency for 250 g Pentolite at 5 m depth

Period	140 ms
Frequency	7.2 Hz

A1.2 Reduction of natural frequencies

In an effort to lower the natural frequencies, concentrated masses were investigated at key areas along the cylinder length, corresponding with the mode shapes in Figures A1-1 and A1-2. These concentrated masses were formed by creating solid external collars (Figure A1-3) at a length of 80 mm and offset from the cylinder radius by 100 mm (approximately 600 mm outer collar diameter overall). Using the same steel properties as the cylinder, LS-Dyna reported each collar at approximately 100 kg.

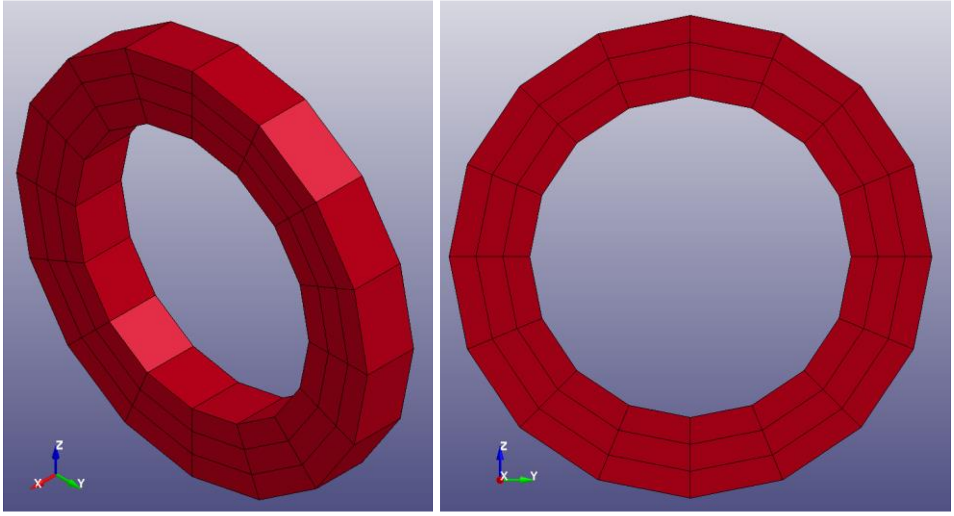

Figure A1-3 Collar model

For a uniform collar size and uniform cylinder, the maximum effective collar length (L_c) can be determined for a given collar diameter (D_c) to maintain neutral buoyancy, taking into account the additional buoyancy effects of the collar. This relationship expressed in Equation A1.4.

$$L_c = \frac{4(m_w - m_s)}{\pi(\rho_{steel} - \rho_{water})(D_c^2 - D_o^2)} \quad , \quad L > L_c > 0 \qquad A1.4$$

With the properties in Table A1-8, the possible collar sizes from Equation A1.4 are shown in Figure A1-4.

Table A1-8 Properties for collar

Property		Value
Displaced water of uniform cylinder	m_w	1557 kg
Structural mass of uniform cylinder	m_s	759 kg
Density of steel	ρ_{steel}	7850 kg/m^3
Density of water	ρ_{water}	1000 kg/m^3
Outer diameter of uniform cylinder	D_o	406.4 mm
Length of uniform cylinder	L	12 m

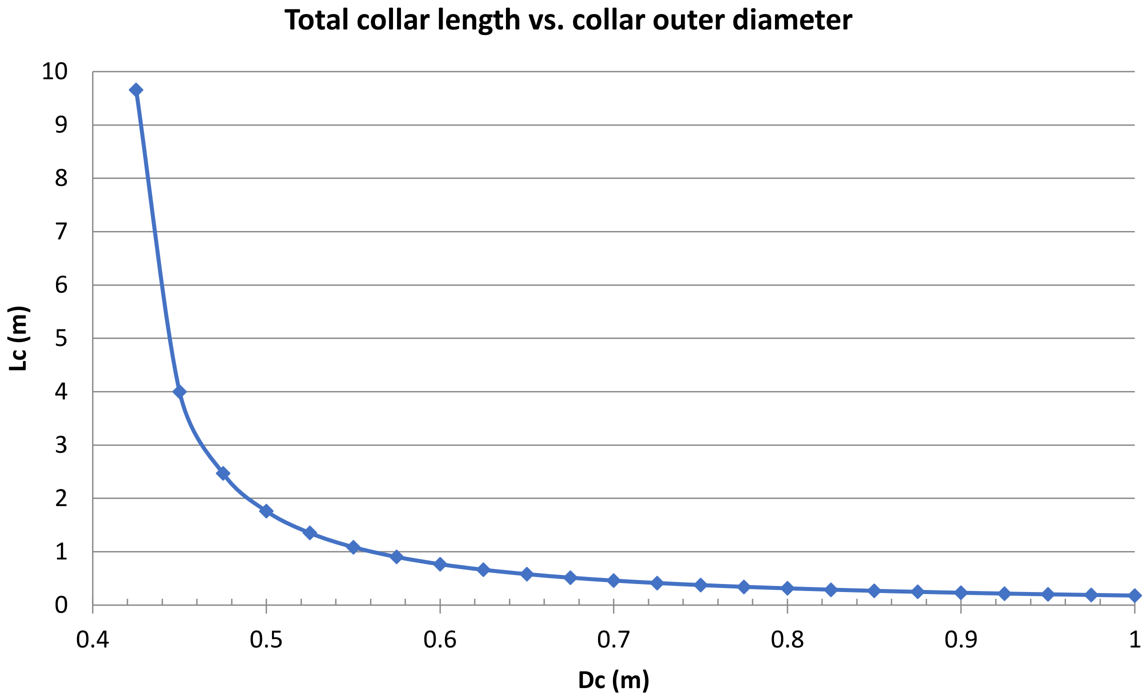

Figure A1-4 Total collar length per diameter

Using the current collar outer diameter of 600 mm allows for a maximum 760 mm total collar length to maintain buoyancy. Utilising the current individual collar length of 80 mm allowed eight collars (an additional 800 kg) while maintaining a reserve buoyancy of approximately 115 kg.

Various configurations were investigated to determine how the distribution of the collars (800 kg) affected the natural frequencies. The first 3 Configurations (Figures A1-5 to A1-7) are targeted primarily at reducing the BM1 frequency while Configurations 4 and 5 (Figures A1-8 and A1-9) are targeted to have an effect on the BM2 frequency, by placing collars away from nodal points (the dark blue areas in Figures A1-1 and A1-2). In Configurations 4 and 5 the middle mass positions correspond with the anti-nodes of the BM2 mode shape (the red areas in Figure A1-2, which was predicted to be 4m from each end.

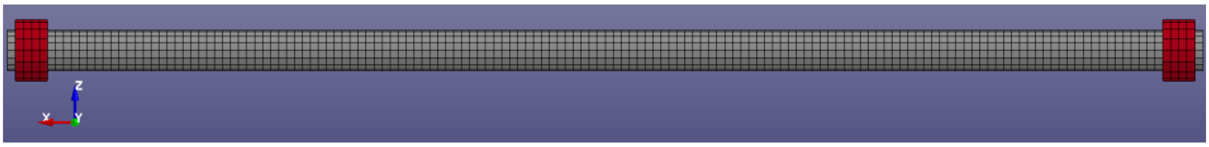

Figure A1-5 Configuration 1 – 4 collars [400 kg] at each end

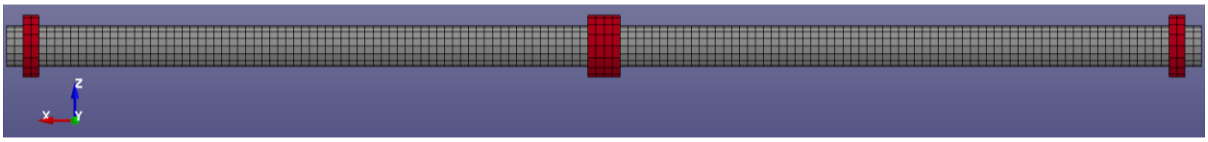

Figure A1-6 Configuration 2 – 2 collars [200 kg] at each end & 4 collars [400 kg] at the middle

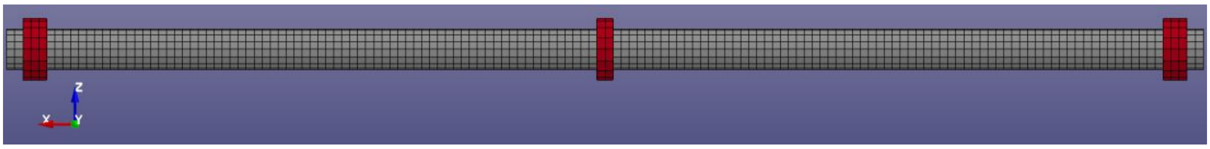

Figure A1-7 Configuration 3 – 3 collars [300 kg] at each end & 2 collars [200 kg] at the middle

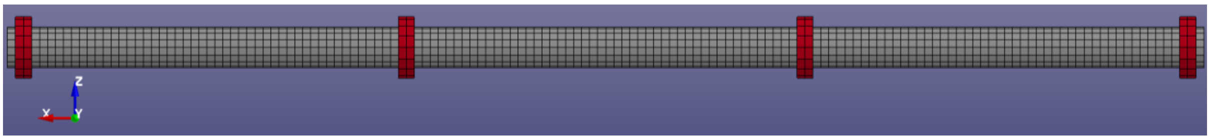

Figure A1-8 Configuration 4 – 2 collars [200 kg] at each end & 2 collars [200 kg] at each peak

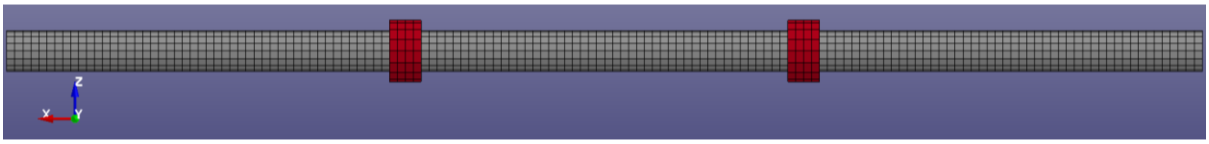

Figure A1-1-9 Configuration 5 – 4 collars [400 kg] at each peak

The natural frequency and added mass of these configurations was calculated from LS-Dyna and presented in Table A1-9.

Table A1-9 Comparison of added mass and natural frequency in water for concentrated mass configurations

Configuration	**Added Mass** (kg)	**1st Water** (Hz)	**2nd Water** (Hz)
Uniform cylinder	1616	9.9	27.0
1	1668	7.1	21.6
2	1670	7.5	23.1
3	1665	7.2	22.4
4	1663	7.6	20.5
5	1685	9.6	22.9

The frequency results are plotted against their mass distribution in Figures A1-10 and A1-11 and trends are fitted to determine the optimum configuration (largest reduction in natural frequency).

All collar configurations have been considered for the BM1 frequency. From these results it is suggested that the best mass distribution for BM1 is to lump all additional mass equally at each end and not use any middle mass collar. For BM2 Configurations 2 and 3 were not considered as the middle mass would act at the node of BM2. Configurations 4 and 5 are designed to behave as their equivalents. From these results it is suggested that the best distribution for BM2 is between a 40 – 60 % distribution (40 % distributed to the peaks and 60 % distributed to the ends) and an even 50 – 50 % distribution (25 % to each peak and the end positions [Configuration 4]).

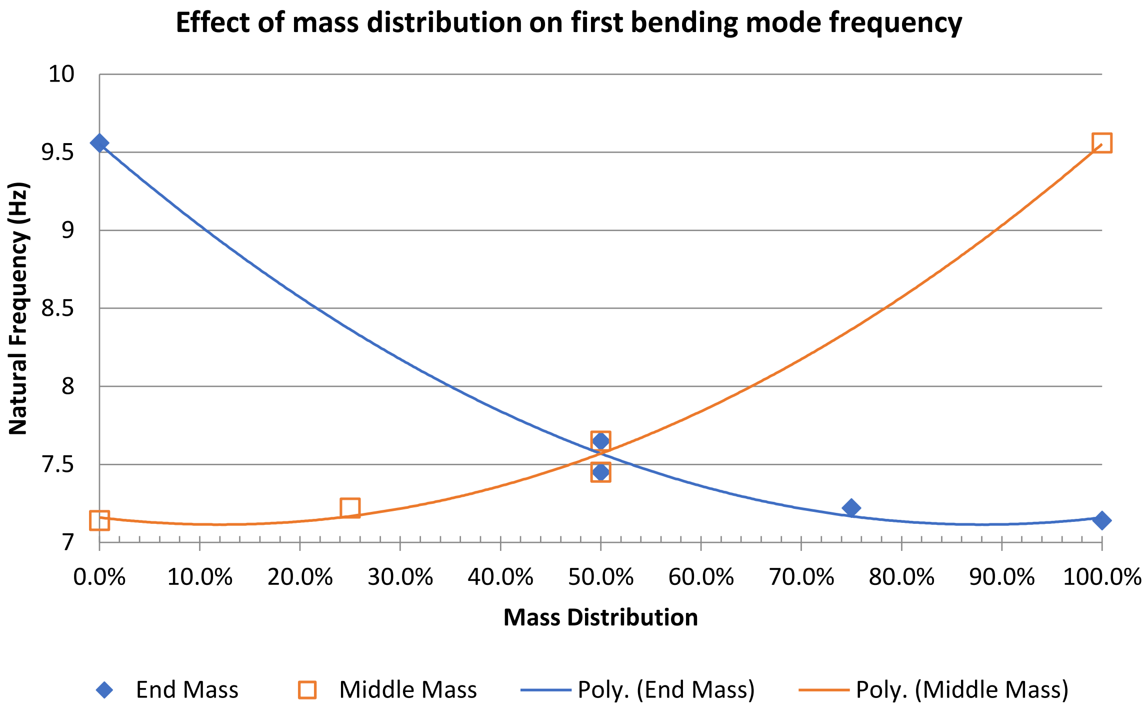

Figure A1-10 Effect of the distribution of concentrated mass on the first bending mode natural frequency

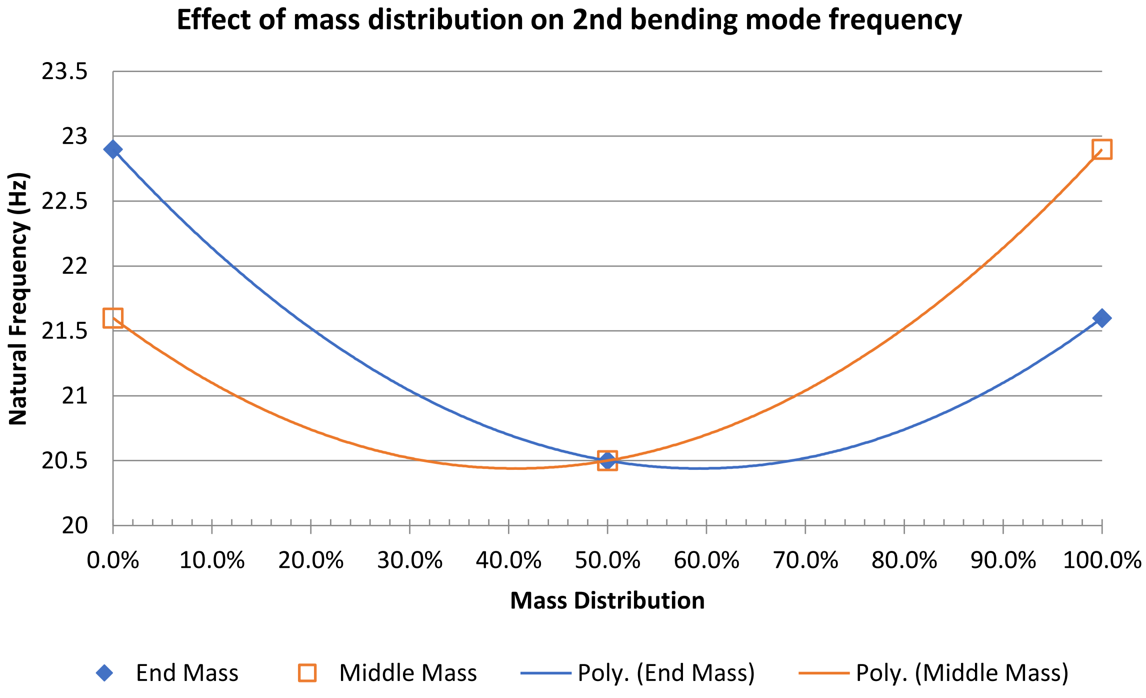

Figure A1-11 Effect of the distribution of concentrated mass on the second bending mode natural frequency

To confirm that collar structure has limited effect on cylinder stiffness, the collars were replaced with equivalent mass elements. It should be noted that although the structural mass is the same, the added mass will only be calculated for the uniform cylinder due to the missing collar structures. This was investigated for Configurations 1 and 3, shown in Figures A1-12 and A1-13 respectively.

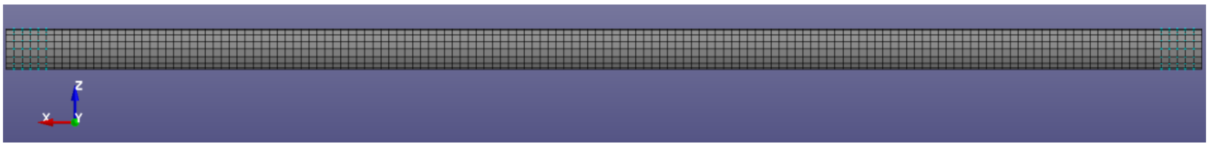

Figure A1-12 Configuration 1 – 400 kg of lumped mass to each end

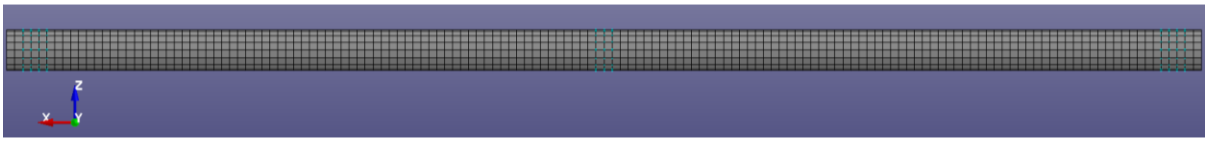

Figure A1-13 Configuration 3 – 300 kg of lumped mass at each end & 200 kg of lumped mass at the middle

The results in Table A1-10 suggest that end collars have no effect on the structural stiffness while middle mounted collars have a small effect. BM2 frequencies remain mostly unchanged which also suggest that the additional stiffness from the collar is only effective at positions of peak bending moment in the structural response.

Table A1-10 Comparison of natural frequencies for collar stiffness

Configuration	**BM1 Air** (Hz)	**BM2 Air** (Hz)	**BM1 Water** (Hz)	**BM2 Water** (Hz)
1 - collar	10.4	34.5	7.1	21.6
3 - collar	9.5	35.5	7.2	22.4
1 - lumped	10.4	34.6	7.2	21.7
3 - lumped	9.4	35.7	7.2	22.5

Demonstrating that Configurations 1-4 were able to reach the desired BM1 frequency of 7.2 Hz, this advice was passed to the manufacturers for their consideration.

A1.3 Candidate design for manufacture

A model was provided with considerations for its manufacture, the key difference being the addition of flanges to the ends and changing how the end masses are applied, shown in Figure A1-14. Now each concentrated mass is offset from the 12m cylinder and is a solid cylindrical body of steel, shown in Figure A1-15.

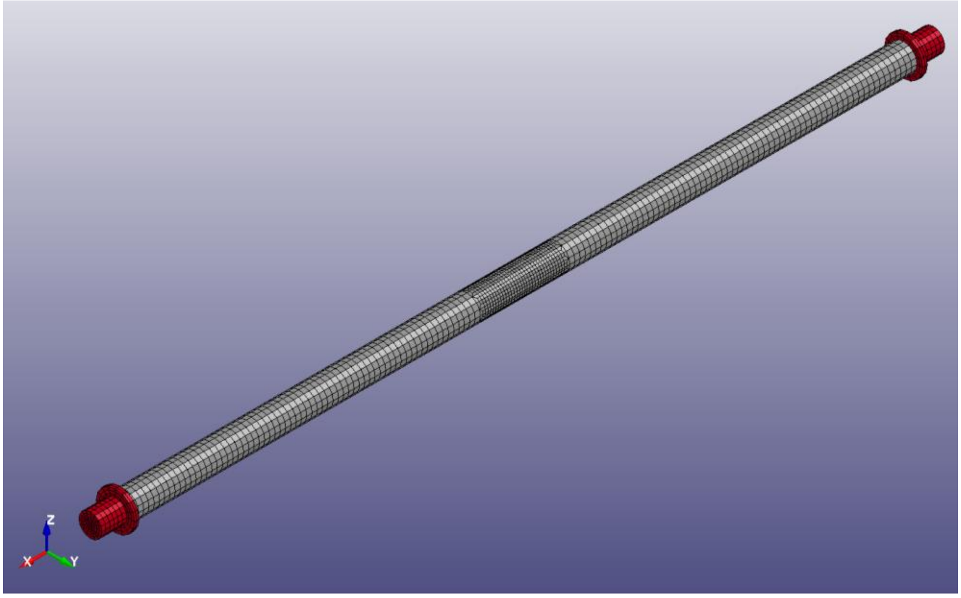

Figure A1-14 Candidate cylinder for manufacturing

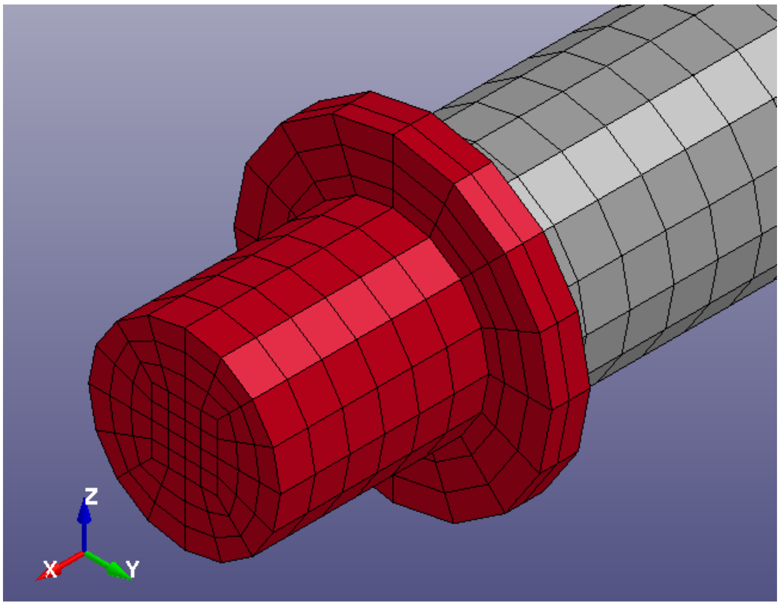

Figure A1-15 End mass and flange

This model was updated with the optimal mass distribution for the first bending mode as discussed previously (50 % distributed to each end). The maximum additional mass allowable was added, taking into account the additional buoyancy provided and a desired reserve buoyancy of approximately 100 kg. This resulted in a total of 570 kg of additional mass being used and a reserve buoyancy of approximately 120 kg. Due to the modification of how the end masses are applied, the natural frequencies of this model are slightly lower than those previously analysed, noted in **Error! Reference source not found.**. As the new frequency was predicted to be lower than that of the bubble pulsations, it was requested that the ends be manufactured in a way to allow mass to be added and removed as desired.

Table A1-11 Natural frequencies for the first two bending modes in air and water of the updated model

Mode	**Air** (Hz)	**Water** (Hz)
BM1	9.4	6.6
BM2	30.8	19.4

A1.4 References

[1] AS/NZS 1163:2009: *Cold-formed structural steel hollow sections* (SAI Global, Australia, 2009).

[2] Austube Mills. *Design Capacity Tables for Structural Steel Hollow Sections*. (Austube Mills, 2013).

[3] Blevins, R. D. *Formulas for Natural Frequency and Mode Shape*. 1st Ed. (Van Nostrand Reinhold Company, 1979).

[4] LSTC. *LS-DYNA R8.0 Keyword Manual*. (Livermore Software Technology Corporation, Livermore, CA, 2015).

[5] Reid, W. D. *The Response of Surface Ships to Underwater Explosions*. Report No.: DSTO-GD-0109, (Defence Science and Technology Organisation, Melbourne, Victoria, 1996).

Appendix 2. Additional measurement systems

A2.1 Accelerometers and velocity meters

Additional measurement transducers were installed in the platform to measure acceleration and velocity responses. The results of these transducers were not considered in the present investigation. A large number of different accelerometer models were used to compare the responses between different models and designs, and for redundancy. Two UERD Velocity meters were installed at each measurement station to directly measure the velocity response in vertical and athwartships directions, and compare against the integrated results from accelerometer transducers. The transducer models, quantity and designation are listed in Table A2-1.

Table A2-1 Pressure and strain measurement transducer details

Transducer	Quantity	Designation	Ref.
Acceleration			
PCB 350B01	5	A1, 3, 5, 7, 9	[1]
PCB 350B21	2	A6, 8	[1]
PCB 350C02	4	A12-13, 18-19, 21-22	[2]
PCB 350B24	6	A14-16	[2]
PCB 350B50 Triaxial	1	A27-29	[3]
PCB 3501A2060KG	3	A2, 4, 10	[4]
PCB 3501A2020KG	3	A17, 20	[3]
PCB 3503A1020KG Triaxial	1	A24-26	[5]
Endevco 7270A-200K	1	A23	[6]
Endevco 7270A-6K	1	A11	[6]
Velocity			
UERD Velocity meter	10	V1-10	[7]

Pacific Instruments 5871 data acquisition systems [8] were used to sample accelerometers. While all velocity meters were sampled through the Elsys TraNET data acquisition system [9]. Both of these systems were located on shore as shown in Figure 3-1 of Chapter 3. All accelerometers and velocity meters were screw mounted on 140x140x20 mm aluminium blocks, machined to the round hull profile and attached by epoxy adhesive. The gauges were located along the hull as described by the polar coordinate system in Figure A2-1, with the coordinates of each transducer listed in Table A2-2.

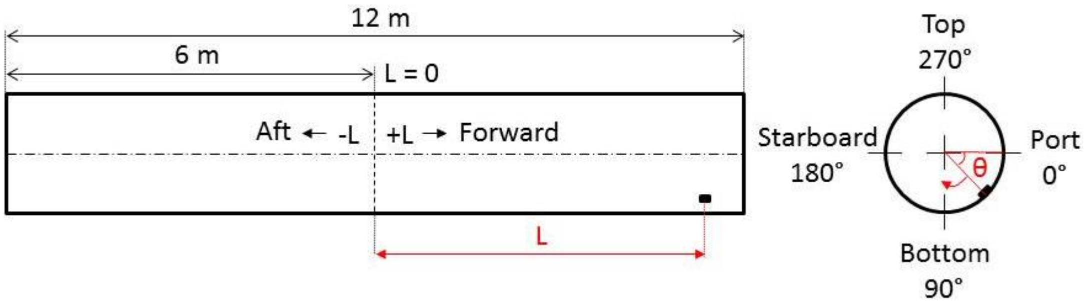

Figure A2-1 Internal arrangement of additional measurement transducers

Table A2-2 Accelerometer and velocity meter details and polar coordinates

Station	**Gauge**	**L** (mm)	**θ°**	**Orientation**
1 Bow	V6	5930	0	Horizontal
	V10	5835	90	Vertical
	A14	5873	356	Horizontal
	A15	5873	4	Horizontal
	A16	5892	90	Vertical
	A27	5873	4	Longitudinal
	A28	5873	4	Vertical
	A29	5873	4	Horizontal
2 2.8 m Fwd	V4	2850	0	Horizontal
	V8	2750	90	Vertical
	A11	2907	356	Horizontal
	A12	2907	4	Horizontal
	A13	2807	86	Vertical
3 Amidships	V1	-50	0	Horizontal
	V2	50	90	Vertical
	A1	7	356	Horizontal
	A2	7	4	Horizontal
	A3	50	352	Horizontal
	A4	50	0	Horizontal
	A5	-107	356	Horizontal
	A6	-107	4	Horizontal
	A7	-75	352	Horizontal
	A8	-25	352	Horizontal
	A9	107	86	Vertical
	A10	107	94	Vertical
	A23	50	4	Horizontal
	A24	-300	180	Longitudinal
	A25	-300	180	Vertical
	A26	-300	180	Horizontal
4 -2.8 m Aft	V3	-2850	0	Horizontal
	V7	-2750	90	Vertical
	A17	-2907	356	Horizontal
	A18	-2907	4	Horizontal
	A19	-2807	86	Vertical
5 Stern	V5	-5930	0	Horizontal
	V9	-5835	90	Vertical
	A20	-5873	356	Horizontal
	A21	-5873	4	Horizontal
	A22	-5778	86	Vertical

A2.2 References

[1] PCB Piezotronics. *Model 350B01 Shear ICP Shock Accelerometer Installation and Operating Manual*. (PCB Piezotronics, Inc., 3425 Walden Avenue, Depew, NY 14043, 2017).

[2] PCB Piezotronics. *Model 350C02 Shear ICP Shock Accelerometer Installation and Operating Manual*. (PCB Piezotronics, Inc., 3425 Walden Avenue, Depew, NY 14043, 2012).

[3] PCB Piezotronics. *Model 350B50 Installation and Operating Manual*. (PCB Piezotronics, Inc., 3425 Walden Avenue, Depew, NY 14043, 2017).

[4] PCB Piezotronics. *Model 3501A2020KG High Amplitude MEMS Shock Accelerometer Installation and Operating Manual*. (PCB Piezotronics, Inc., 3425 Walden Avenue, Depew, NY 14043, 2017).

[5] PCB Piezotronics. *Model 3503A1020KG/ACS-62BT Triaxial High Amplitude MEMS Shock Accelerometer Installation and Operating Manual*. (PCB Piezotronics, Inc., 3425 Walden Avenue, Depew, NY 14043, 2011).

[6] Meggitt Sensing Systems. *Endevco Piezoresistive Accelerometer Model 7270A*. (Meggitt Sensing Systems,, 14600 Myford Road Irvine CA, 2017).

[7] Scavuzzo, R. J. & Pusey, H. C. *Principles and techniques of shock data analysis*. 4th Ed. (Shock and Vibration Information Analysis Center, 2011).

[8] Pacific Instruments. *Series 5800 Conditioning & Transient Recording Systems*. (Pacific Instruments, 4080 Pike Lane, Concord, CA, 2017).

[9] Elsys AG. *TPCX & TPCE Specification*. (Elsys AG, Mellingerstrasse 12, CH-5443 Niederrohrdorf, Switzerland, 2012).

Appendix 3. Mesh refinement study

A3.1 Introduction

10 Meshes are analysed for a simple submerged tube model. This refinement analysis is to determine the most efficient structural mesh for this structure for a series of whipping analyses.

The structure analysed is a 12 m long, 400 mm nominal diameter, 6.35 mm thick cylinder. Endcaps of the same thickness are included to perform analysis on a watertight structure.

Each mesh is defined by the number of elements about the circumference (*C*) and along the length (*L*) of the cylinder, as shown in Figure A3-1. For geometry considerations, the number of *C* elements had to be divisible by 4 and 6.

Table A3-1 Cylinder meshes

Mesh	C	L	L/C	Elements
24_60	24	60	2.50	1752
24_120	24	120	5.00	3192
24_180	24	180	7.50	4632
24_240	24	240	10.00	6072
24_300	24	300	12.50	7512
36_120	36	120	3.33	5058
36_180	36	180	5.00	7218
36_240	36	240	6.67	9378
36_300	36	300	8.33	11538
36_320	36	320	8.89	12258

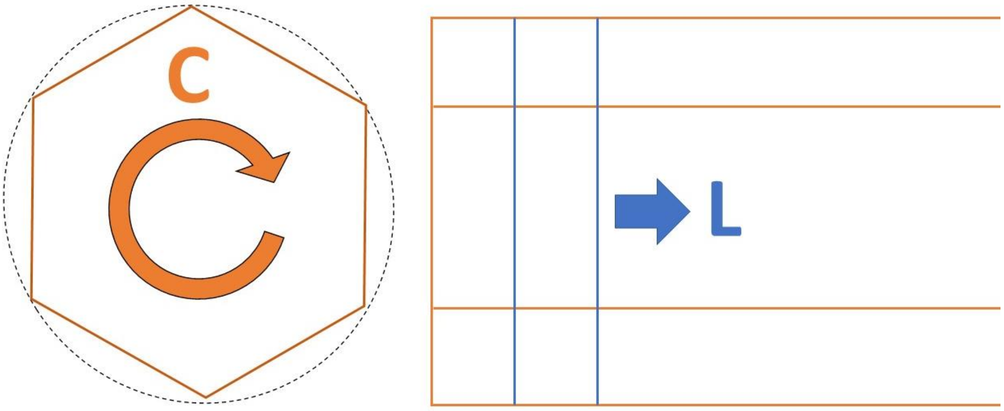

Figure A3-1 Mesh definitions

The suitability of each mesh was assessed by the accuracy of structural mass, added fluid mass and natural frequencies. A shock wave impact analysis was also performed for a convergence study and comparison of CPU runtime to achieve the result.

A3.2 Mass study

The mass of the cylinder and endcaps was calculated analytically from the geometry, assuming a material density of 7850 kg/m^3. The masses are listed in Table A3-2.

Table A3-2 Analytical mass of cylinder and endcaps

Component	**Mass** (kg)
Cylinder	751.8
Endcaps	12.9
Total	**764.7**

The mass of the FE model was dependent on the *C* mesh density for the cylinder, as first-order elements can only approximate curvature from their faceted geometry. The mass of the cylinder section (no endcaps) for the two *C* mesh densities (24 and 36) was compared in Table A3-3 and it was found both provided an accurate total mass, within an error of less than 0.3 %.

Table A3-3 Comparison of FE mass for each C mesh density

C	**Tube Mass** (kg)	**Error**
24	750	-0.2 %
36	751	-0.1 %

A3.3 Added mass

Blevins [1] advises that added mass may be approximated by the displacement of the cylinder so long as it is of sufficient distance from any boundary (considered in the same order of magnitude) and has a slenderness ratio (*L/r*) greater than 10. With the nominal radius $R = 0.2\ m$, the relative distance to the free surface (*F*) and ground (*G*), and the slenderness ratio compared to the overall length (*L*) are compared.

$$F = 5\ m \qquad F/r = 25$$

$$G = 10\ m \qquad G/r = 50$$

$$L = 12\ m \qquad L/r = 60$$

From these comparisons it is shown that the scenario can be assumed to be free from boundary effects and the slenderness ratio is well above 10. Therefore, the added mass could be approximated from the cylinder displacement.

At the outer surface of the cylinder ($R = 0.2032\ m$) the added mass $m_f = 1557\ kg$. The USA code calculates added mass from the mid-shell plane as opposed to outer surface, therefore at $R = 0.2\ m$, $m_f = 1508\ kg$. The difference of 49 kg was considered negligible when considered over the entire length of 12 m, resulting in a difference of approximately 4.1 kg/m.

The USA added mass results for each mesh are plotted in Figure A3-2, compared to the number of elements in the FE model. Both circumferential mesh densities converge at a lower added mass of approximately 1470 kg, a difference of approximately 3 % from the analytical value. Detailed results of individual meshes are listed in Table A3-4 and all meshes within 3 % of the calculated value were considered acceptable for further analysis.

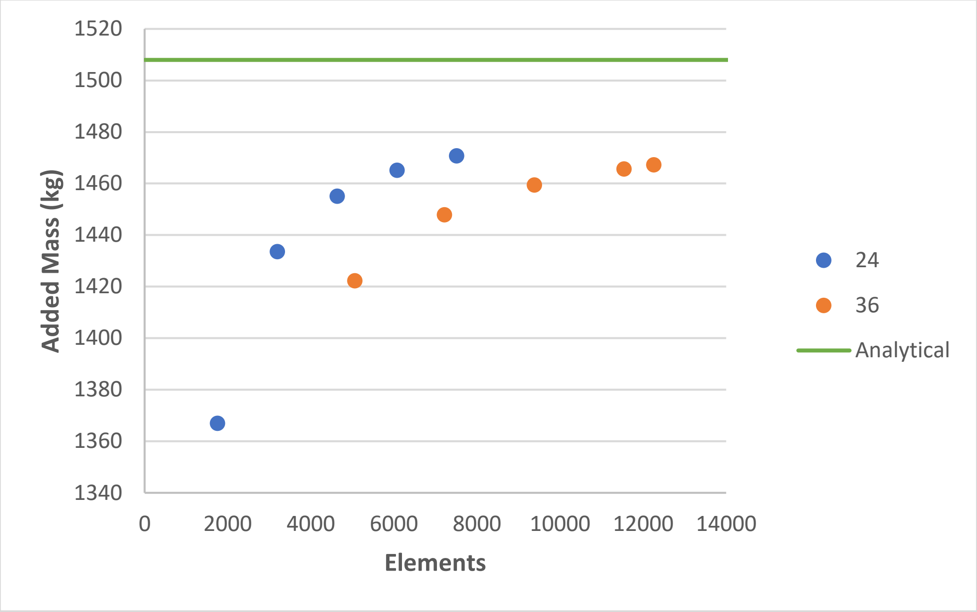

Figure A3-2 Convergence of added mass per number of elements

Table A3-4 Added mass results for each FE mesh

Mesh	m_f (kg)	Error
24_60	1367	-9.35%
24_120	1434	-4.93%
24_180	1455	-3.51%
24_240	1465	-2.84%
24_300	1471	-2.47%
36_120	1422	-5.68%
36_180	1448	-3.98%
36_240	1459	-3.22%
36_300	1466	-2.80%
36_320	1467	-2.70%

A3.4 Natural frequency analysis

Due to the endcap mass being as than 1% of the beam mass, it was assumed that the cylinder responds as a free-free beam section with uniform mass. The first two natural frequencies in air were calculated using Blevins [1] formula:

$$f_n = \frac{\lambda_n^2}{2\pi}\sqrt{\frac{EI}{mL^3}} \qquad A3.1$$

E = 200 GPa $\qquad \lambda_1 = 4.730041$

I = 1.59693E-4 m^4 $\qquad \lambda_2 = 7.853205$

The resulting bending mode frequencies in air from Equation A3.1 are:

$$f_1 = 17.66 \text{ Hz}$$

$$f_2 = 48.67 \text{ Hz}$$

For simple uniform cross sections, the immersed natural frequency can be approximated from air frequencies [1] using the formula:

$$Wet\ f_n = \frac{f_n}{\sqrt{1+\frac{m_f}{m}}} \qquad A3.2$$

where,

$$\sqrt{1+\frac{m_f}{m}} = 1.72393$$

The resulting wet modal frequencies from Equation A3.2 for the first two bending modes are:

$$Wet\ f_1 = 10.24\ \text{Hz}$$

$$Wet\ f_2 = 28.23\ \text{Hz}$$

The results from a *weteig* analysis using the USA code are compared for each frequency response in Figure A3-3 and Figure A3-4. For the first bending mode response, the *C = 24* mesh densities appear to converge towards the analytical value while the *C = 36* mesh densities converged slightly higher.

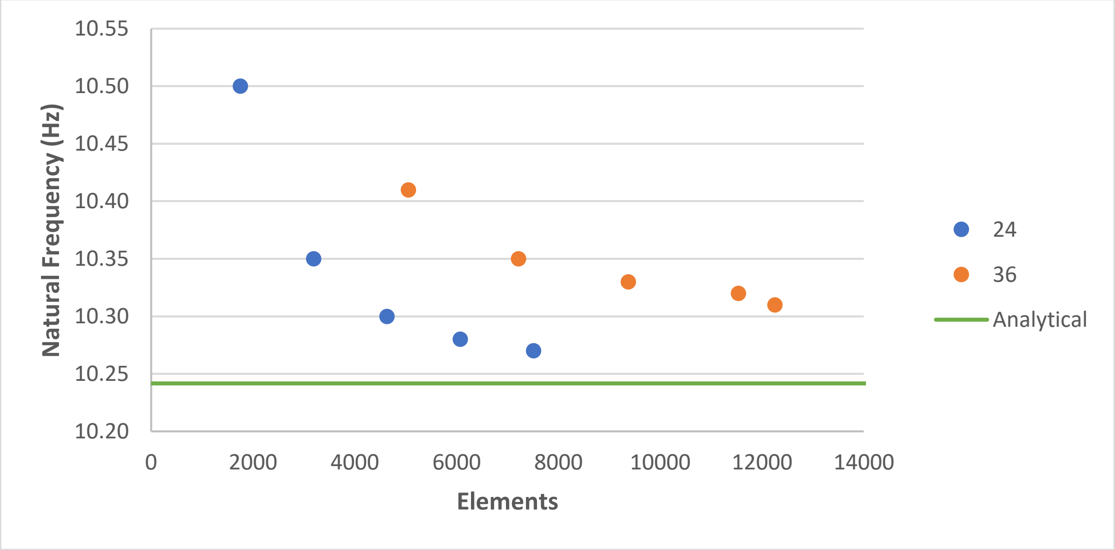

Figure A3-3 Convergence study of for the first wet bending mode response per number of elements

For the second bending mode response the *C = 24* meshes tended to slighlty under predict in their convergeance while the *C = 36* meashes converged towards the anlaytical value. It should be noted however that the scale of the convergeance for the second bending mode is much smaller that for the first bending mode, and both mesh densities converge with in 0.1 Hz of the anlytical solution.

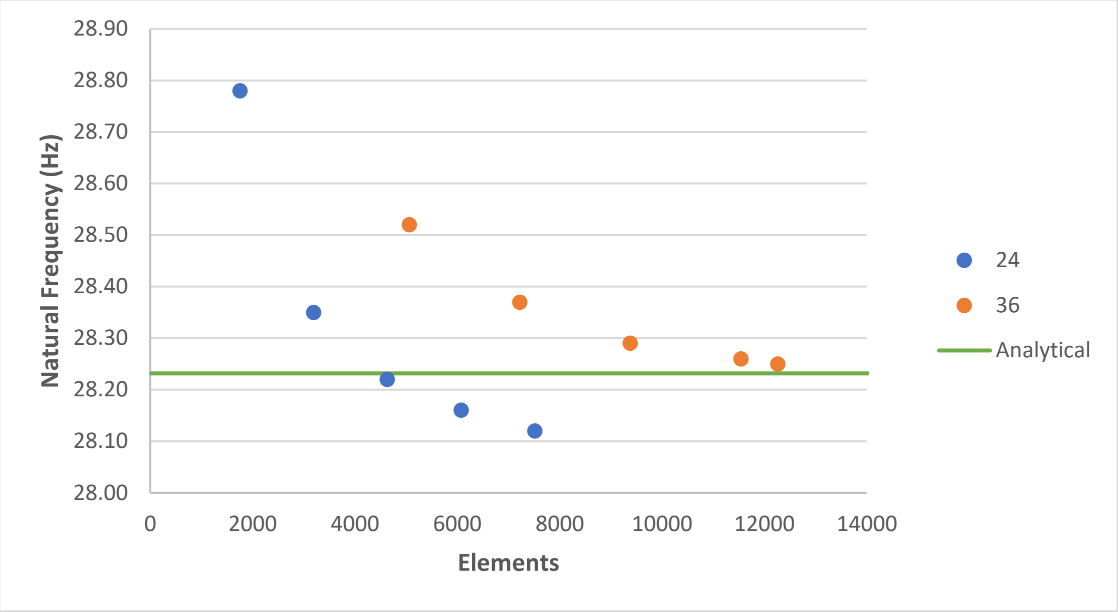

Figure A3-4 Convergence study of for the second wet bending mode response per number of elements

Detailed result for each mesh are listed in Table A3-5 and show that all meshes were within 3 % of the anlytical solutions for both bending mode frequencies. Meshes within 1 % of the analytical values were considered adequate for further analysis.

Table A3-5 Wet frequency results for each FE mesh

Mesh	**Wet f_1** (Hz)	**Error**	**Wet f_2** (Hz)	**Error**
24_60	10.50	-2.52%	28.78	-1.94%
24_120	10.35	-1.06%	28.35	-0.42%
24_180	10.30	-0.57%	28.22	0.04%
24_240	10.28	-0.37%	28.16	0.25%
24_300	10.27	-0.28%	28.12	0.40%
36_120	10.41	-1.64%	28.52	-1.02%
36_180	10.35	-1.06%	28.37	-0.49%
36_240	10.33	-0.86%	28.29	-0.21%
36_300	10.32	-0.76%	28.26	-0.10%
36_320	10.31	-0.67%	28.25	-0.07%

A3.5 Peak Stress Analysis

A shock analysis was performed with the USA code, applying loads from a 250 g Pentolite charge at a stand-off distance of 1.3 m. The analysis was cut-off prior to any bubble loading.

Comparison of the peak strain measured from each mesh is plotted against the number of elements in the FE model in Figure A3-5. Both circumferential mesh densities converge at a peak stress of approximately 330 MPa, with the $C = 36$ meshes already steady and the $C = 24$ meshes rapidly approaching this value with an overall element count of approximately 6000, corresponding to mesh 24_240.

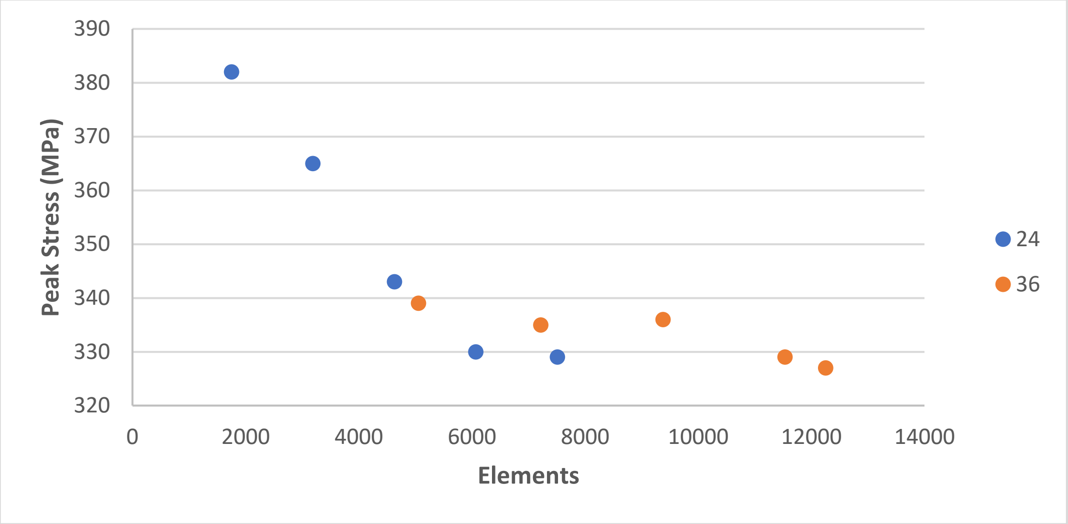

Figure A3-5 Convergence study of peak stress from shock loading analysis per number of elements

The runtime for each of these meshes is compared in Figure A3-6, where it is shown that most the least accurate meshes with a C = 36 density had similar computational requirements as the most meshes of the accurate C = 24 density.

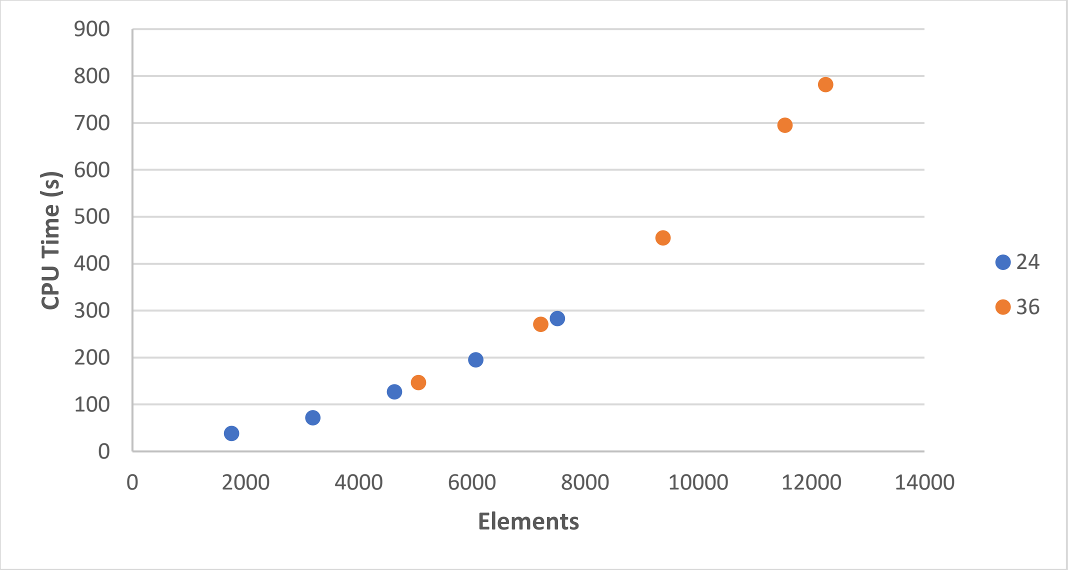

Figure A3-6 Comparison of CPU runtime against number of elements

Based on the demonstrated converged of both meshes with an element count greater than 6000, and from previous criteria satisfaction, mesh 24_240 demonstrated the most efficient results and will be used to conduct validation and further numerical studies of the submerged whipping platform.

A3.6 References

[1] Blevins, R. D. *Formulas for Natural Frequency and Mode Shape*. 1st Ed. (Van Nostrand Reinhold Company, 1979).

Appendix 4. Numerical model details

A4.1 LS-Dyna Structure

The following code describes the LS-Dyna structural model, including part and material data. The ***Element_Shell**, ***Element_Solid**, and ***Node** keywords have been partially removed for brevity of the bound format. The full keywords are available on the attachment and/or CD in the 0_WH3.k file. Full details of all the LS-Dyna keywords are available in the LS-Dyna manuals [1].

```
*KEYWORD
*TITLE
$# title
Whipping Hull, Units = MKS
*PART
$# title
Hull_Aft
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
         1         1         1         0         0         0         0         0
*SECTION_SHELL_TITLE
Shell
$#   secid    elform      shrf       nip     propt   qr/irid     icomp     setyp
         1        16       1.0         2       1.0         0         0         1
$#      t1        t2        t3        t4      nloc     marea      idof    edgset
   0.00635   0.00635   0.00635   0.00635       0.0       0.0       0.0         0
*MAT_ELASTIC_TITLE
Steel
$#     mid        ro         e        pr        da        db  not used
         1    7850.0   1.90E11      0.25       0.0       0.0         0
*PART
$#                                                                         title
Webs
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
         2         2         1         0         0         0         0         0
*SECTION_SHELL_TITLE
Webs
$#   secid    elform      shrf       nip     propt   qr/irid     icomp     setyp
         2         2       1.0         2       1.0         0         0         1
$#      t1        t2        t3        t4      nloc     marea      idof    edgset
     0.006     0.006     0.006     0.006       0.0       0.0       0.0         0
*PART
$#                                                                         title
Hull_Fwd
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
         3         1         1         0         0         0         0         0
*PART
$#                                                                         title
BlockMesh4
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
         4         3         1         0         0         0         0         0
*SECTION_SOLID_TITLE
Solid-8NR
```

```
$#   secid    elform       aet
         3         3         0
*PART
$#                                                                         title
BlockMesh5
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
         5         3         1         0         0         0         0         0
*PART
$#                                                                         title
RigidMass_Aft
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
         6         4         2         0         0         0         0         0
*SECTION_SOLID_TITLE
Solid
$#   secid    elform       aet
         4         1         0
*MAT_RIGID_TITLE
Rigid-Steel
$#     mid        ro         e        pr         n    couple         m     alias
         2    7850.0   2.00E11      0.25       0.0       0.0       0.0
$#     cmo      con1      con2
       0.0         0         0
$#lco or a1        a2        a3        v1        v2        v3
       0.0       0.0       0.0       0.0       0.0       0.0
*PART
$#                                                                         title
RigidMass_Fwd
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
         7         4         2         0         0         0         0         0
*ELEMENT_SOLID
$#   eid     pid      n1      n2      n3      n4      n5      n6      n7      n8
    5881       4    5817    5829    5830    5818    5848    5849    5831    5819
...
    7152       7    7465    7505    7597    7601    7466    7506    7598    7602
*ELEMENT_SHELL
$#   eid     pid      n1      n2      n3      n4      n5      n6      n7      n8
       1       1       4       5      50      49       0       0       0       0
...
    5880       2    7637    5651    5675    5675       0       0       0       0
*ELEMENT_MASS_PART
$#   pid         addmass         finmass    lcid
       1             0.0             430       0
       3             0.0             430       0
*NODE
$#   nid               x               y               z      tc      rc
       1            -6.0        0.141421       -0.141421       0       0
...
    7642        5.907115       -0.227015        0.131067       0       0
*END
```

A4.2 USA boundary

The USA boundary is activated by the ***Boundary_USA_Surface** keyword. The USA ***Set_Segment_Title** keyword defines the nodes that will form the DAA elements during the USA solution. This has been partially removed for brevity of the bound format. The full keywords are available on the attachment and/or CD in the 0_USA.k file.

```
*KEYWORD
*TITLE
$# title
Whipping Hull, Units = MKS
*BOUNDARY_USA_SURFACE
$#    ssid    wetdry     nbeam
         1         1         0
*SET_SEGMENT_TITLE
USA
$#     sid       da1       da2       da3       da4    solver
         1       0.0       0.0       0.0       0.0MECH
$#      n1        n2        n3        n4        a1        a2        a3        a4
      7418      7450      7442      7394       0.0       0.0       0.0       0.0
...
       254       255       279       278       0.0       0.0       0.0       0.0
*END
```

A4.3 Analysis and output controls

The analysis and output controls were defined in the LS-Dyna model. 21 ***Set_Shell_List_Title** keywords were defined to represent each of the strain gauge locations, where S1 – S3 and S4 – S6 were all taken at one respective location. These have been partially removed for brevity of the bound format. The full keywords are available on the attachment and/or CD in the 0_USA_run.k file.

```
*KEYWORD
*TITLE
$# title
Whipping Hull, Units = MKS
*CONTROL_ENERGY
$#    hgen      rwen    slnten     rylen
         2         1         1         2
*CONTROL_HOURGLASS
$#     ihq        qh
         1       0.1
*CONTROL_OUTPUT
$#   npopt    neecho    nrefup    iaccop     opifs    ipnint    ikedit    iflush
         1         0         0         0       0.0         0         0         0
$#   iprtf    ierode     tet10    msgmax    ipcurv      gmdt   ip1dblt      eocs
         0         0         2         0         0       0.0         0         0
$#   tolev    newleg    frfreq     minfo    solsig    msgflg    cdetol
         2         0         1         0         0         1      10.0
*CONTROL_RIGID
$#     lmf      jntf    orthmd     partm    sparse    metalf    plotel     rbsms
         0         0         0         0         0         0         0         0
*CONTROL_SHELL
$#  wrpang     esort     irnxx    istupd    theory       bwc     miter      proj
      20.0         1        -1         0         2         1         1         0
```

```
$# rotascl    intgrd    lamsht    cstyp6    tshell
       0.0         0         0         0         0
$# psstupd   sidt4tu     cntco    itsflg    irquad
         0         0         2         0         2
$#  nfail1    nfail4   psnfail    keepcs     delfr   drcpsid    drcprm
         1         1         0         0         0         0       1.0
*CONTROL_SOLID
$#   esort   fmatrix   niptets    swlocl    psfail   t10jtol
         1         0         0         1         0       0.0
$#   pm1     pm2     pm3     pm4     pm5     pm6     pm7     pm8     pm9    pm10
       0       0       0       0       0       0       0       0       0       0
*CONTROL_TERMINATION
$#  endtim    endcyc     dtmin    endeng    endmas
       1.0         0       0.0       0.0       5.0
*CONTROL_TIMESTEP
$#  dtinit    tssfac      isdo    tslimt     dt2ms      lctm     erode     ms1st
       0.0       0.9         0       0.0   -5.0E-6         0         0         0
$#  dt2msf   dt2mslc     imscl    unused    unused     rmscl
       0.0         0        -3                           0.0
*DATABASE_ELOUT
$#      dt    binary      lcur     ioopt   option1   option2   option3   option4
    1.0E-5         0         0         1         0         0         0         0
*DATABASE_GLSTAT
$#      dt    binary      lcur     ioopt
     0.001         0         2         1
*DATABASE_MATSUM
$#      dt    binary      lcur     ioopt
     0.001         0         0         1
*DATABASE_BINARY_D3PLOT
$#      dt      lcdt      beam     npltc    psetid
     0.002         2         0         0         0
$#   ioopt
         0
*DATABASE_FORMAT
$#   iform   ibinary
         0         0
*DATABASE_EXTENT_BINARY
$#   neiph     neips    maxint    strflg    sigflg    epsflg    rltflg    engflg
         0         0         0         1         1         1         1         1
$#  cmpflg    ieverp    beamip     dcomp      shge     stssz    n3thdt   ialemat
         0         0         0         1         1         3         2         0
$# nintsld   pkp_sen      sclp     hydro     msscl     therm    intout    nodout
         0         0       0.0         0         2         0    STRAIN    STRAIN
$#    dtdt    resplt
         0         0
*DATABASE_HISTORY_SHELL_SET
$#     id1       id2       id3       id4       id5       id6       id7       id8
         2         9        13        17        21         0         0         0
         5        10        14        18        22         0         0         0
         7        11        15        19        23         0         0         0
         8        12        16        20        24         0         0         0
*DEFINE_CURVE_TITLE
Timestep
$#    lcid      sidr       sfa       sfo      offa      offo    dattyp     lcint
         1         0       1.0       1.0       0.0       0.0         0         0
$#                a1                  o1
                 0.0           1.00e-006
               0.006           1.00e-006
```

```
              0.0061           2.00e-004
                 1.0           2.00e-004
*DEFINE_CURVE_TITLE
Output
$#    lcid      sidr       sfa       sfo      offa      offo    dattyp     lcint
         2         0       1.0       1.0       0.0       0.0         0         0
$#                  a1                  o1
                 0.0           1.00e-005
               0.006           1.00e-005
              0.0061               0.002
                 1.0               0.002
*DEFINE_CURVE_TITLE
Mass Scaling
$#    lcid      sidr       sfa       sfo      offa      offo    dattyp     lcint
         3         0       1.0       1.0       0.0       0.0         0         0
$#                  a1                  o1
                 0.0                 0.0
               0.006                 0.0
              0.0061                 1.0
                 1.0                 1.0
*SET_PART_LIST_TITLE
Mass Scaling Parts
$#     sid       da1       da2       da3       da4    solver
         3       0.0       0.0       0.0       0.0MECH
$#    pid1      pid2      pid3      pid4      pid5      pid6      pid7      pid8
         2         4         5         0         0         0         0         0
*SET_PART_LIST_TITLE
All
$#     sid       da1       da2       da3       da4    solver
         1       0.0       0.0       0.0       0.0MECH
$#    pid1      pid2      pid3      pid4      pid5      pid6      pid7      pid8
         1         2         3         4         5         6         7         0
*SET_SHELL_LIST_TITLE
S1,2,3
$#     sid       da1       da2       da3       da4
         2       0.0       0.0       0.0       0.0
$#    eid1      eid2      eid3      eid4      eid5      eid6      eid7      eid8
      2905         0         0         0         0         0         0         0
...
*SET_SHELL_LIST_TITLE
S24
$#     sid       da1       da2       da3       da4
        24       0.0       0.0       0.0       0.0
$#    eid1      eid2      eid3      eid4      eid5      eid6      eid7      eid8
        55         0         0         0         0         0         0         0
*END
```

A4.4 Damping models

The three damping methods investigated during the numerical validation in Chapter 5 are detailed in the following sections. All damping models were appended to the analysis and output control keyword file (0_USA_run.k) for their respective analyses.

A4.4.1 Rayleigh Damping

The Rayleigh Damping model used a constant mass damping parameter of $\alpha = 2.52$, where the ***Define_Curve_Title** parameter *a1* represents time in seconds and *o1* is α. The stiffness damping parameter β was also constant and was defined directly as *coef* in the ***Damping_Part_Stiffness_Set** keyword. All model parts were damped.

```
*DEFINE_CURVE_TITLE
Damp Alpha
$#    lcid      sidr       sfa       sfo      offa      offo    dattyp     lcint
         4         0       1.0       1.0       0.0       0.0         0         0
$#                a1                  o1
                 0.0             2.33375
                 1.0             2.33375
*DAMPING_PART_MASS_SET
$#    psid      lcid        sf      flag
         1         4       1.0         0
*DAMPING_PART_STIFFNESS_SET
$#    psid      coef
         1  5.796E-5
```

A4.4.2 Frequency Range Damping

The frequency range damping model varied for each event, based on the charge size *W* and longitudinal stand-off distance *L*. These ***Damping_Frequency_Range** keyword variations are listed for each scenario in the following sections.

W = 250 g, L = 0.0 m or -2.8 m

```
*DAMPING_FREQUENCY_RANGE
$#   cdamp      flow     fhigh      psid     blank    pidrel      iflg
      0.04       5.0       8.0         0         0         0         0
```

W = 43 g, L = 0.0 m or -2.8 m

```
*DAMPING_FREQUENCY_RANGE
$#   cdamp      flow     fhigh      psid     blank    pidrel      iflg
      0.02       5.0      25.0         0         0         0         0
```

W = 250 g, L = -4.3 m

```
*DAMPING_FREQUENCY_RANGE
$#   cdamp      flow     fhigh      psid     blank    pidrel      iflg
      0.02      15.0      45.0         0         0         0         0
```

W = 43 g, L = -4.3 m

```
*DAMPING_FREQUENCY_RANGE
$#   cdamp      flow     fhigh      psid     blank    pidrel      iflg
      0.01      15.0      25.0         0         0         0         0
```

A4.4.3 Combined Rayleigh and Frequency Range Damping

The combined Rayleigh and Frequency Range Damping model used a constant mass damping parameter of *α = 2.52* for the Rayleigh model, where the ***Define_Curve_Title** parameter *a1* represents time in seconds and *o1* is *α*. Unlike the previous frequency range damping models in section A4.4.2, the same ***Damping_Frequncy_Range** keyword was used for all events.

```
*DEFINE_CURVE_TITLE
Damp Alpha
$#    lcid      sidr       sfa       sfo      offa      offo    dattyp     lcint
         4         0       1.0       1.0       0.0       0.0         0         0
$#                a1                  o1
                 0.0                2.52
                 1.0                2.52
*DAMPING_PART_MASS_SET
$#    psid      lcid        sf      flag
         1         4       1.0         0
*DAMPING_FREQUENCY_RANGE
$#   cdamp      flow     fhigh      psid     blank    pidrel      iflg
      0.01      40.0     120.0         0         0         0         0
```

A4.5 USA input

USA inputs changed for each event. Event 1 is shown in the example code while all modified variables for other events are detailed in Table A4-1.

The PHS-BUB model is hard coded for the charge mass (wgtchg) to be input as American pounds (lb), while all other quantities are compatible with SI units and must correspond with the same unit system from LS-Dyna. The charge coordinate system (*xc*, *yc*, *zc*) is specified according to the LS-Dyna coordinate system, where the model origin was located at the centroid of the cylindrical hull. Therefore, the *yc* quantity was obtained from the sum of the hull radius (0.2032 m) and the strand-off distance *R* in meters, and the *xc* quantity was equal to the longitudinal stand-off distance *L* in meters. The charge was always aligned with the platform centroid axis plane with its normal vector to the free surface, and therefore *zc = 0.0 m* for all events. Details of all USA keywords are found in the USA manual [2].

Table A4-1 USA inputs for each event

Event	**W** (g)	**L [xc]** (m)	**R [dist]** (m)	**R + 0.2032 [yc]** (m)	**wgtchg** (lb)	**eqwgtf**
E1	250	0.0	1.8	2.0032	0.5511	1.11
E2	250	0.0	1.5	1.7032	0.5511	1.11
E3	250	0.0	1.3	1.5032	0.5511	1.11
E4	43	0.0	0.8	1.0032	0.0948	1.19
E5	250	-2.8	1.3	1.5032	0.5511	1.11
E6	43	-2.8	0.8	1.0032	0.0948	1.19
E7	250	-4.3	1.3	1.5032	0.5511	1.11
E8	43	-4.3	0.8	1.0032	0.0948	1.19
N1	250	-2.8	1.8	2.0032	0.5511	1.11
N2	250	-4.3	1.8	2.0032	0.5511	1.11
N3	250	-2.8	1.5	1.7032	0.5511	1.11
N4	250	-4.3	1.5	1.7032	0.5511	1.11
N5	43	0.0	1.0	1.2032	0.0948	1.19
N6	43	-2.8	1.0	1.2032	0.0948	1.19
N7	43	-4.3	1.0	1.2032	0.0948	1.19
N8	43	0.0	0.7	0.9032	0.0948	1.19
N9	43	-2.8	0.7	0.9032	0.0948	1.19
N10	43	-4.3	0.7	0.9032	0.0948	1.19
N11	150	0.0	1.5	1.7032	0.3307	1.11
N12	150	-2.8	1.5	1.7032	0.3307	1.11
N13	150	-4.3	1.5	1.7032	0.3307	1.11
N14	150	0.0	1.3	1.5032	0.3307	1.11
N15	150	-2.8	1.3	1.5032	0.3307	1.11
N16	150	-4.3	1.3	1.5032	0.3307	1.11
N17	150	0.0	1.1	1.3032	0.3307	1.11
N18	150	-2.8	1.1	1.3032	0.3307	1.11
N19	150	-4.3	1.1	1.3032	0.3307	1.11

```
*keyword
*title ="Whipping Hull USA”
$ -------------------
*usa_solution, flumas
$ -------------------
*fluid_density = 1000.00
*fluid_sound_speed = 1500.
*symmetry_free_surface
$ depth, cxfs, cyfs, czfs,    patm, gravac
      5,  0.0,  0.0,  1.0, 101E+03,   9.81
*symmetry_bottom
$ distb, cxbr, cybr, czbr, bnorm
     11,  0.0,  0.0, -1.0,  0.65
*control, autcrv=true
$ -------------------
*usa_solution, augmat
$ -------------------
*daa_formulation, daa2=0.5, option=hybrid_direct
$ -------------------
*usa_solution, timint
$ -------------------
*control_lsdyna_interface, usa_coupling=new
*integration
     0.000    4.5e-6
     0.030    4.5e-6
     0.031    9.0e-6
     1.000    9.0e-6
*control, nbstps=50000
$ -------------------
*incident_pressure, TYPE=phs-bubble, UNITS=mks, DIST=1.8,
OPTION=INCLUDE_BOTTOM_EFFECTS
$ xc,     yc,  zc
 0.0, 2.0032, 0.0
$ wgtchg, cf drag,   convft, bubcut, movbub, buoyan,      name,
eqwgtf
  0.5511,    0.33, 3.280833,    0.3,      2,      0, Pentolite,
1.11
$ migrat, depth, cxfs, cyfs, czfs
       1,   5.0,  0.0,  0.0,  1.0
*eof
```

A4.6 References

[1] LSTC. *LS-DYNA R10.1 Keyword Manual*. (Livermore Software Technology Corporation, Livermore, CA, 2018).

[2] LSTC. *USA LS-DYNA Users Manual - USA Release 7.5.3*. (Livermore Software Technology Corporation, Livermore, CA, 2018).