dti

PELAMIS WAVE ENERGY CONVERTER

Verification of full-scale control using a 7th scale model

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EXECUTIVE SUMMARY

The Pelamis Wave energy Converter (WEC) is an innovative concept for extracting energy from ocean waves and converting it into a useful product such as electricity, direct hydraulic pressure or potable water. The system is a semi-submerged, articulated structure composed of cylindrical sections linked by hinged joints. The wave-induced motion of these joints is resisted by hydraulic rams that pump high-pressure oil through hydraulic motors via smoothing accumulators. The hydraulic motors drive electrical generators to produce electricity. The complete machine is flexibly moored so as to swing head-on to the incoming waves and derives its 'reference' from spanning successive wave crests.

The Pelamis WEC development programme OPD identified a requirement for an intermediate scale ‘systems’ demonstrator with which to develop and prove the full-scale Pelamis hydraulic, control and data acquisition systems. A 7th scale model was conceived to satisfy the OPD ethos of systematically tackling each aspect of technical risk before committing to a full-scale prototype. It is seen as absolutely critical to the overall success of the technical programme that as little immature technology as possible is incorporated within the first full-scale prototype.

The 7th scale project, which has been part funded by the UK DTI New & Renewable Energy Programme, has successfully demonstrated the complete Pelamis WEC system at 7th scale (see: ‘Pelamis WEC – Intermediate scale demonstration – Final Report’ ETSU V/06/00/188/REP).

It was recognised that the return on the investment made in developing the 7th scale model could be maximised by continuing to use it as a platform to develop and test the next level of control architecture prior to installation on the full-scale prototype. Furthermore, it was thought this work would be most productive and efficient if carried out using wave-tank facilities recently made available at Ecole Centrale de Nantes. In addition, during the programme of work undertaken here it was felt that further control studies using and upgraded version of the 20th scale model also had considerable merit.

To this end, a major program of model upgrades, testing, and analysis was conducted in the Nante Wave Basin. The resulting design improvements, robustness tests, and operational experience have contributed immensely to the full-scale program and provide much increased confidence in the systems now being implemented at full-scale.

PROJECT RATIONALE

Building, commissioning and testing the 7th scale machine was a considerable overhead, both financially and time-wise. OPD are keen to maximise the return to the project on these investments in terms of targeted utilisation to further reduce the risks of the onward programme. A relatively modest investment in a serious tank programme will generate data that will allow the full-scale prototype algorithms, hardware and software to be fully validated.

1. The recent availability of the Ecole Centrale de Nantes wave basin presents OPD with a unique opportunity to expand and consolidate the deliverables from the 7th scale programme
2. OPD's current full-scale joint test rig (V/06/00191) gives confidence in operation of the control and hydraulics systems of a single joint. Wave tank testing confirms this operation in the context of the entire machine under operating conditions, with joint interaction and real hydrodynamic loading.
3. Algorithm testing at 7th scale will significantly reduce the risks of full-scale prototype deployment, particularly in respect of the survivability control mode and increase confidence in power capture algorithms.
4. A range of control variables can be tested under reproducible wave conditions. This is not possible in the unpredictable conditions of sea testing.
5. Mooring response can be monitored.
6. Cost effectiveness: a large range of controlled sea conditions can be repeatably tested more effectively and in much shorter time than in sea trials.

In addition, further tests using an updated computer controlled 20th scale model were proposed. It was felt that there was considerable merit in conducting these tests for the following key reasons:

1. The latest version of the 20th scale model control and drive system allows accurate modelling of the hydraulic characteristics of the full-scale system.
2. Testing using actual control modes can be carried out in extreme wave conditions (not possible with 7th scale in the Nantes Basin)
3. The model will also allow accurate realisation of all partially failed control modes including simulated partial hydraulics failures. This allows numerical predictions to be validated.

PROJECT OBJECTIVES

The project had the following objectives:

A – 7th Scale Testing

Overall objectives

1. Maximise the return on the 7th scale investment to the project in terms of minimising the onward risks.
2. Verify control system hardware, algorithms and software for use in the full-scale prototype.

Specific project objectives

1. Transfer 7th scale full-system model from sea-going use to laboratory use.
2. Test algorithms for maximising power take-off in directional spectra.
3. Confirm transition from power generating to survivability mode.
4. Test failsafe modes for individual joints and entire machine.
5. Make comparisons with results and predictions from numerical studies.

B – 20th Scale Testing

Overall

1. Further verify and improve (where possible) control system algorithms and software for use in the full-scale prototype.
2. Thereby further reduce the technical risk of early full-scale prototype tests.

Specific

1. Test basic control algorithms for general operation & power capture
2. Test algorithms for minimising joint angles in extreme waves
3. Assess transition from power generating to survivability mode.
4. Test failsafe joint controls
5. Test partial failure states
6. Make comparisons with results and predictions from numerical studies.

KEY PROJECT CONCLUSIONS

A – 7th Scale Testing

- The 7th scale model was adapted and enhanced to make the model more suitable for use in a laboratory environment. All changes made were deemed to be satisfactory.
- Tests were carried out over a broad range of conditions and control parameters. The control system was developed during this process in a manner which aimed to maximise both learning and system development, and to increase confidence in control software and algorithms.
- The fundamental control algorithms, running on the central control computer, performed as expected.
- Key aspects of the Pelamis power take-off and control implementation were explored and demonstrated under a range of conditions. The knowledge gained has enabled problems to be understood and solutions to be developed for inclusion in the full-scale programme.
- The effects of failure conditions were demonstrated, and methods of diagnosing and dealing with them were developed. These methods have been incorporated into the full-scale system.
- The operational experience gained during the tests at ECN has provided an invaluable contribution to the design and development of the full-scale control system to be installed on the full-scale prototype.
- Survival control parameters were tested satisfactorily in seas up to ~10metres at full-scale.

B – 20th Scale Testing

- The extra control tests using the upgraded 20th scale model were a valuable addition to the 7th scale trials within this project.
- The use of a high performance digital microcontroller allows complex, non-linear controls to be implemented and fully tested rapidly, without the need for hardware changes or direct intervention on the model. Complex control tests such as those reported would have been almost impossible to achieve without closing the control loop in software.
- It was possible to accurately implement fully representative normal and simulated failed control modes for the full-scale machine. Supervisory joint control can be adapted to the sea size to meet the twin goals of high power and joint angles kept within safe limits.
- The testing further confirmed that effective overall control settings vary in a straightforward way from small to large seas.
- The digital controller facilitated the rapid evolution of a survival mode

that reduced extreme joint angles by 20% over the previous best settings.
- The default mechanical failsafe control mode of the full-scale machine was modelled satisfactorily and tested in waves up to extremes.
- Testing in the failsafe mode confirmed that extreme angles are larger than for the fully active control mode as would be expected. However, performance was still adequate.
- The digital controller also allowed accurate modelling of a various partial hydraulic failures.
- Testing in a range of seas confirmed that partial failure of a single joint has only a small effect on machine performance and extreme joint angles. A large number of partially failed joints results in a larger effect, but survivability and performance are still acceptable.
- All of the results are directly relevant to the full-scale prototype machine, and have been incorporated into the control system development and test programme. OPD will be carrying further testing of this type in due course.

REPORT STRUCTURE

In this report Section A reports work carried out using the 7th scale model during the first phase of the project, Section B, concludes work carried out under the extended scope of this contract using the 20th scale model. The report also refers to reports from the previous programme with the same models.

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SECTION A: 7TH SCALE TESTS

A1. SUMMARY

Work Package (a) spanned the time period from mid March 2003 to the end of April 2003, approximately 7 weeks. Most of the preliminary work was carried out at OPD's premises in Edinburgh, with final model adjustments made, software de-bugged, and installation completed on-site at Ecole Centrale de Nantes (ECN) in France.

Work packages (b) and (c) covered the testing and development of the 7th scale system and the analysis of results. Much of the testing, analysis, and development was done in parallel to maximise technological progress and allow operational experience to guide the development process as much as possible.

The Extended Scope of this contract specified work utilising the 20th scale model for remaining areas for which the smaller model was more appropriate. This work is described in the section following the reporting of the 7th scale work.

Overall objective

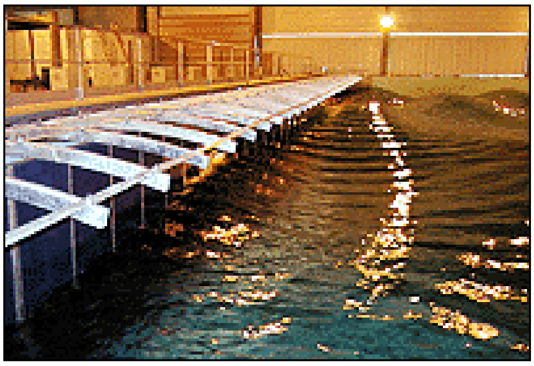
The main objective of the project was to confirm the functionality and robustness of the upgraded control architecture running on a platform functionally similar to the full-scale system, and further the control system design through operational experience in a range of conditions.

It was hoped that testing in a wave tank environment would enable much higher productivity than would be possible through sea-trials where weather and other logistical problems impede concentrated development effort.

Description of the Nantes Facility

The ECN basin, completed in 2002, is widely regarded to be one of the most advanced wave test facilities in Europe. Several key features set it aside from other facilities:

1. The 50m by 30m basin can accommodate full length of 7th scale model. No other facility has previously offered this at an acceptable cost.
2. Wavemaker is state-of-the-art and can generate large regular and irregular waves, representative sea states, and can vary both general wave heading and mixed-wave directional spreading.
3. Good beach absorption allows long tests to be conducted without significant reflection build-up.
4. Nantes is within reasonable travel distance from OPD's offices and workshops.
5. Favourable basin hire rates have been negotiated, with access to the basin divided between model preparation and the actual running of waves, flexibly partitioned on a daily basis.
6. OPD already have a working relationship with ECN, through previous test programmes.



(Above) Wavemaker bank generating directional swell.

(Top-right) View down length of the basin (note length = 50m)

(Right) Waves breaking on basin be

(All pictures courtesy ECN)

A2. 7th SCALE MODEL GENERATION CONFIGURATION

The 7th scale model configuration and design is reported fully in 'Pelamis WEC – Intermediate scale demonstration – Final Report' ETSU V/06/00/188/REP. The configuration is the same as the intended configuration for the first full-scale machine. This is in common with the current configuration of the 33rd and 20th scale models. Standardisation of machine configuration and dimensions is important to allow direct comparison between test results.

Figure A2.1 – General view of the 7th scale machine on test in the Firth of Forth

The approximate dimensions and configuration of the 7th scale machine are as follows:

- Overall length: 17m
- Diameter: 0.5m
- Segments: Four equal length segments
- Joints: Three-off, two degree-of-freedom joints
- Nose: 5m long drooped conical nose
- Tail: Flat

The joint systems are functionally identical to the full-scale design with the same relative ram areas, control valves and accumulator/reservoir sizes. The only key difference is that the rams are external rather than internal and the ram control manifolds could not be mounted directly onto the rams due to scale differences. No hydraulic motor-generator set is included – accurately modelling these at 7th scale is not feasible. Instead, this system is simulated using a pressure compensated flow regulator. This valve delivers a flow-rate proportional to the demand signal, irrespective of the inlet pressure. As far as the control system is concerned this is identical to the motor-generator set. Power for the controllers and control valves was provided by sets of 24V batteries at each joint.

Each joint system has an independent FPGA based controller linked to a common centralised hub comprising an embedded PC104 format computer, and a DSP real time control card. The hub acts as the communication bridge between shore and the individual joint controllers via an external Ethernet or radio modem link, as will be the case for the full-scale machine. This communication link serves both for data acquisition and for access to the joint controllers for remote reprogramming.

Please see 'Pelamis WEC – Intermediate scale demonstration – Final Report' ETSU V/06/00/188/REP for full details.

A3. MODEL HARDWARE UPGRADES

OPD's 7th scale model was built for use in the Firth of Forth, where it has completed several successful sea-trials. Some adaptations were necessary to facilitate its use in a laboratory scenario. Hardware upgrades to reflect recent advances in control architecture were also required.

A3.1 Shore-based power supply

To allow continuous use of the model without recharging the onboard batteries, a DC power supply was assembled. This consists of three 300W switched-mode supplies each supplying a joint-pair with 6A 24V DC. This power supply rack was mounted directly over the model, on the carriage over the ECN basin. This allowed cables to be run to each joint, where a waterproof connection could be made. The model's batteries were disconnected but left in place as ballast to maintain correct trim.

A3.2 Data acquisition system

The 7th scale model has its own facility for logging data via the centralised control system. A laptop was configured to analyse data and custom software was written to allow fast analysis as tests progressed.

Data from the mooring load cells (see below) was logged to a separate computer, provided by ECN. This used industry-standard National Instruments data acquisition hardware and software to collect data. It was synchronised with both the wave generating computer and the model DAQ computer.

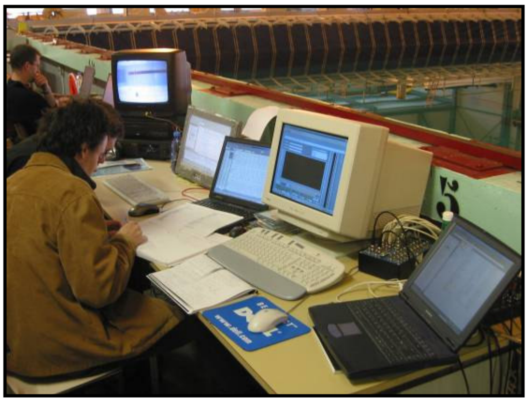


Figure A3.1. Control desk with video, control and DAQ systems

A3.3 Tank mooring build

Previously, the model employed a drift anchor to simulate a mooring during sea trials. This would not have been suitable for use in the tank, so static moorings were assembled to simulate the full-scale geometry. 1000 kg concrete blocks provided by ECN were accurately positioned on the tank floor. Kevlar rope was used to model the main mooring lines, with appropriate springs added to model the full-scale stiffnesses.

The original 7th scale yoke was shortened to allow enough depth for the tether to be modelled. A chain clump weight was constructed from suitably sized chain and steel box section. In the tank, the tether was adjusted so that approx. 50% of the chain rested on the seabed, to reflect the latest full-scale mooring design.

Load cells were designed and manufactured to monitor line tensions. These were mounted in a single assembly that hangs just below the yoke, allowing ease of access in case of failure and a single location to route all signal cables from. The gauges are powered by a Fylde 6-channel strain gauge amplifier unit which also amplifies the signals to a range suitable for the ECN data acquisition system. The Fylde amplifier was positioned on the bridge directly above the model to minimize the distance un-amplified travel.

A3.4 Software development

Considerable changes were made to the control software. The main aim has been to create a system that is fully representative of the proposed full-scale control architecture. The following was accomplished:

- The internal PC104 and DSP, previously used to download programs to the individual joint control FPGA cards and collect data streaming from the joint cards, was replaced by a communications link to an updated external DSP and PC similar to those to be used at full-scale. Mounting the central control processors on the ‘shore’ provides greater flexibility and cable runs to the machine are similar to those in the full-scale machine.
- The software running on the DSP was updated to allow both read and write operations to be performed on registers on the FPGA chips controlling the individual joints. The read/write operations can be performed on a hardware clock cycle thus allowing real-time centralised control of the entire machine from the DSP. This forms a prototype of the system to be constructed for the full-scale machine.
- Control algorithms, developed using the ‘pel’ simulation suite, were adapted to run in real-time on the DSP. Since the 7th scale power take-off system operates in a similar manner to full-scale (except for generation), the control code, once developed on this platform, can be directly applied at full-scale.
- The software running on the PC was updated to include supervisory control of the real-time centralised control algorithm running on the DSP. This allows the setting of parameters such as pressure set-point, spring and damping coefficients, and valve timing delays, without interruption of the centralised control running on the DSP. These parameters are set and the machine’s response monitored by the user through a graphical

user interface (GUI) running on the PC. This interface displays real-time data from the transducers in each of the joints. During initial trials, control parameters will be set by a human user based on data made available through the GUI running on the PC. In future, these parameters will be set automatically in response to changes in machine dynamics (and hence sea-state) by algorithms running on the PC. The GUI running in the 7th scale software is a prototype for the more sophisticated GUI under development for the full-scale machine. The software developments are explained further below.

A4. TRANSPORT & INSTALLATION

A4.1 Transport

The 7th scale model has made previous journeys, to and from sea-trial harbours and exhibition venues. However, account had to be taken of the greater distance and volume of equipment involved.

Suitable crates with polystyrene packing were prepared to allow safe transport of all equipment and a reputable shipping company was identified for shipment of the model and components to ECN. The model, components and tank time were insured against en-route damage or loss. Staff travel was arranged so that OPD staff were on site to receive shipment.

Figure A4.1 Unloading at ECN

Figure A4.2 Transport crates.

A4.2 Pre-installation preparation

Unlike previous tests, the model was going to spend a sustained period in water. With this in mind, several steps were taken to minimize the chance of water ingress:

- All exposed connectors stripped, cleaned and resealed with butyl amalgamating tape.
- The ballast level was checked and trim adjusted.
- Joint position transducers were stripped, cleaned and re-assembled.
- All transducer calibrations and hydraulic pre-charges were checked and modified as required.
- Load measurement transducers were sealed in polyurethane potting compound.
- A new pumping system was installed to evacuate any water. Given the nature of the GRP construction, slight seepage over time is possible.
- Neoprene joint 'jackets' were manufactured and installed, to prevent any hydraulic oil leaking into the tank in the event of seal failures (none occurred). These also act as a fairing for the joint region.

A4.2 Initial trials in the narrow towing tank

Immediately after preparation, the model was installed in ECN's narrow towing tank, adjacent to the workshop area. This allowed ballast to be adjusted and wiring arrangements to be confirmed before final installation in the main wave basin. Tests with small waves were conducted to check progress with software changes and confirm that the hydraulic systems were functioning correctly. At this stage, the newly developed centralised

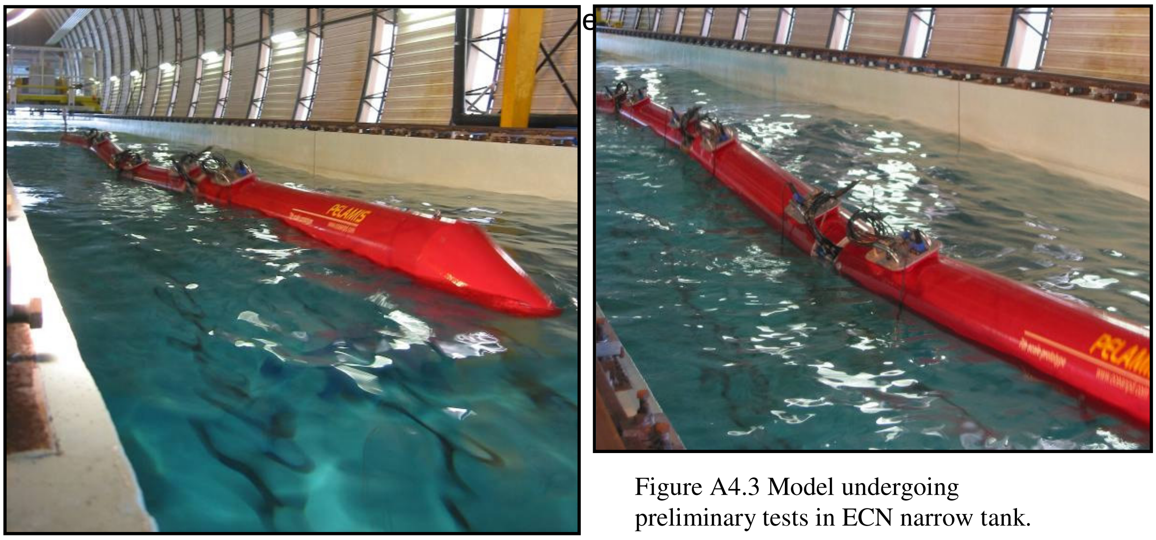


Figure A4.3 Model undergoing preliminary tests in ECN narrow tank.

A4.3 Installation in the main wave basin

Following OPD instructions, ECN divers installed the 1000kg concrete clump weights with buoyed-off mooring lines in the tank. The yoke, tether clump weight and load measurement assembly was lowered into place and buoyed-off.

As in sea trials, the model was lifted assembled into two halves on dry land. These halves were then lifted into the tank using overhead cranes. A final mating of spiders and signal cables at the middle joint completed the assembly in the water.

An overhead crane held the tether clump weight, thus maintaining slack in the mooring system so that the yoke could be manipulated by hand and connected to the nose section. A rear yaw restraint line was installed, again to reflect full-scale design.

The shore power supply was installed on the tank carriage above the model and individual joint power cables connected. CAT5 communications cables from the rear of the model were passed up to the carriage and connected to tank-side control computers. Similarly, cables from the mooring load measurement assembly were connected to the signal amplification equipment and the data acquisition computer.

Figure A4.4 View from bridge.
Mooring weight visible bottom right.

Figure A4.5 OPD workshop area at ECN.

Figure A4.5 The two rear sections being craned into the main basin.

Figure A4.6 Joint of middle joint before model is wired to power and DAQ system. Note jackets around joints.

A5. TESTING & ANALYSIS

A5.1 Development during testing and development based on testing experience

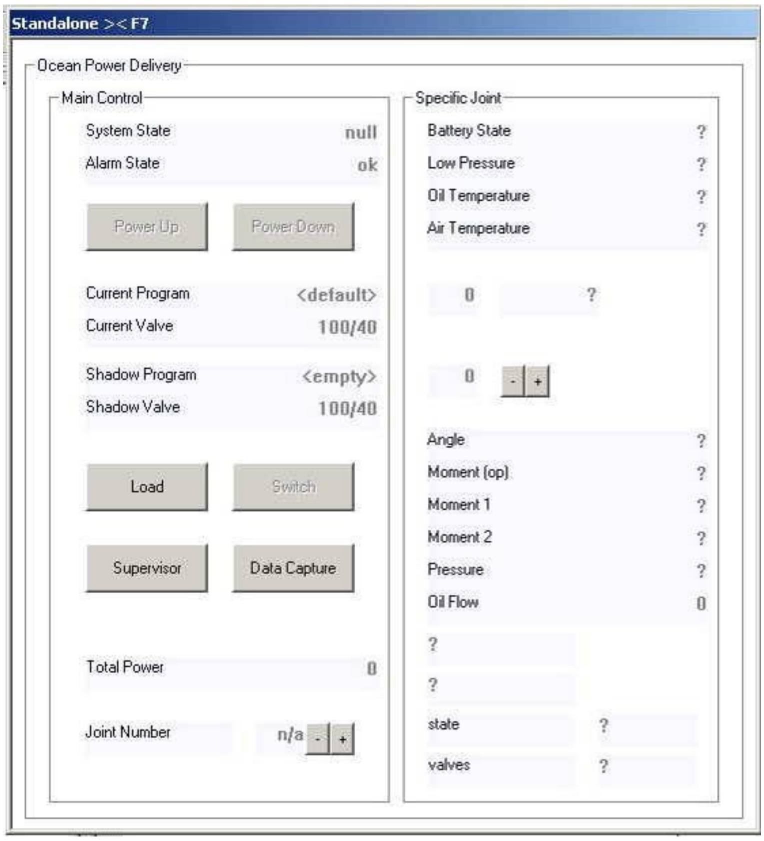
A major benefit of testing the 7th scale model under laboratory conditions was the freedom to develop control software during tests in a relatively *ad hoc* manner. This type of 'trial and error' process is immensely valuable and time efficient during the early stages of development and it is not possible in the difficult, expensive, and unpredictable environment of sea-trials.

For example, the revised control algorithms resulted in the joint systems not to be holding pressure during absorption. The problem was traced to a software bug that factored the programmable interlock time between the operation of control valves. It is far more efficient to test and de-bug software in a tank environment at 7th scale than at sea with a full-scale machine.

All previous work on the 7th scale had concentrated on low level function of both the PTO system and the control hardware. The individual joint control algorithms are written in assembly language running on the FPGA chips on each joint card in isolation. This is the default level of control which it was envisaged the full-scale machine would fall back on if communication between joints and the central controller failed.

The ECN tests served as an impetus to develop the control software to the level required for direct transfer to the full-scale prototype. The control software was completely overhauled in preparation for the ECN tests. The central DSP control hub and the communication architecture (previously responsible only for downloading alterations to assembly code running on individual joint control cards) was extended to allow read-write operations between hub and individual cards to occur at every system sample period. This allows the control algorithm to be run on the central control hub rather than on the individual joint control cards. All information is available to the control algorithm and changes can be made quickly to all control parameters from the graphical user interface.

A picture of the GUI developed for and during the Nantes tests is shown below. The data sampled from transducers is available for each joint by cycling between screens. Control parameters, such as damping coefficients and pressure set-points, can be changed on the fly through a supervisor window available for each joint. Different low-level assembly code programs to run at the FPGA level (to filter signals and control the pressure governing throttle valve) can be downloaded via the 'load' and 'switch' buttons. Data capture files are named and commenced via the 'data capture' button.



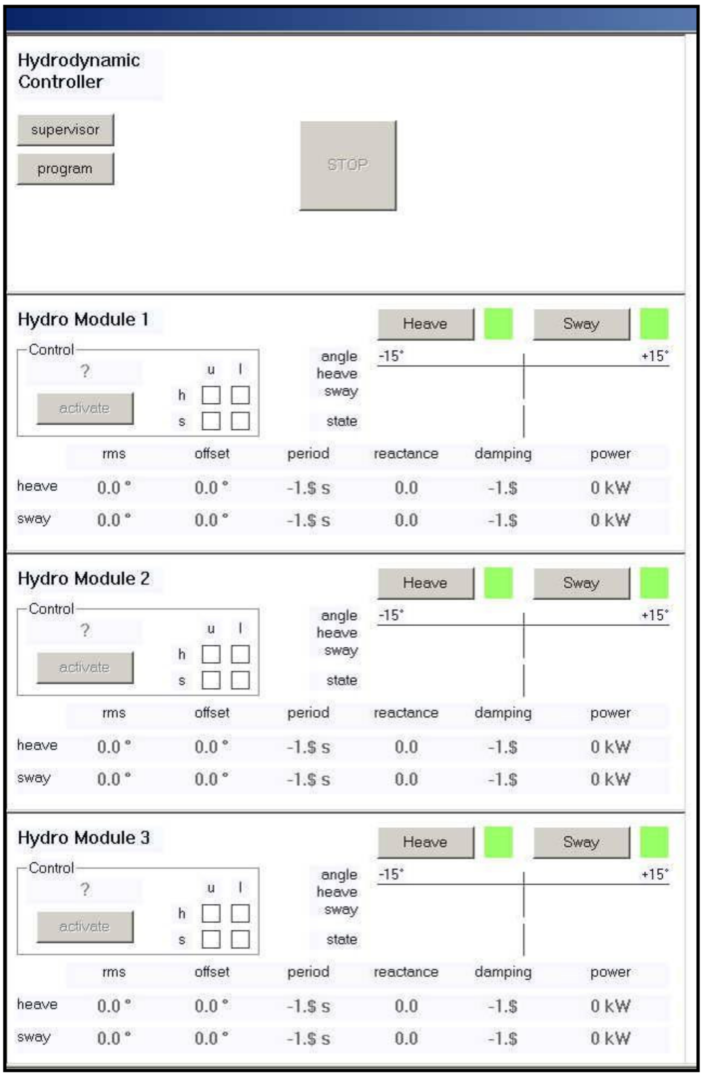
System State null
Alarm State ok
Current Program <default>
Current Valve 100/40
Shadow Program <empty>
Shadow Valve 100/40
Total Power 0
Joint Number n/a

Battery State ?
Low Pressure ?
Oil Temperature ?
Air Temperature ?
0 ?
0
Angle ?
Moment (op) ?
Moment 1 ?
Moment 2 ?
Pressure ?
Oil Flow 0
?
?
state ?
valves ?

Figure A5.1 The 7th scale control system graphical user interface (GUI). Control parameters are input through a dialog box brought up via the ‘supervisor’ button.

The primary value of the tests at ECN was the gaining of operational experience of a wide range of conditions with the flexibility to change control code and develop systems between tests. This method of working is difficult whilst on a small boat at sea in inclement weather.

The design of the full-scale user interface was based in large part on the experience gained during the ECN tests. A screen grab of the GUI for control of the full-scale joint dynamics is shown below. The setting of parameters and download programs through call-up buttons has been retained, but all joints are displayed together in this context for easy reference.



Hydro Module 1

	rms	offset	period	reactance	damping	power
heave	0.0 °	0.0 °	-1.$ s	0.0	-1.$	0 kW
sway	0.0 °	0.0 °	-1.$ s	0.0	-1.$	0 kW

Hydro Module 2

	rms	offset	period	reactance	damping	power
heave	0.0 °	0.0 °	-1.$ s	0.0	-1.$	0 kW
sway	0.0 °	0.0 °	-1.$ s	0.0	-1.$	0 kW

Hydro Module 3

	rms	offset	period	reactance	damping	power
heave	0.0 °	0.0 °	-1.$ s	0.0	-1.$	0 kW
sway	0.0 °	0.0 °	-1.$ s	0.0	-1.$	0 kW

Figure A5.2 The full-scale control system graphical user interface (GUI) for the dynamic (non-generation) side of the control. More detailed information on each axis can be brought up via the 'Heave' and 'sway' buttons.

A considerable problem in monitoring and controlling the Pelamis is displaying information in an effective way that is meaningful and easily interpreted. It was found during these tests that much of the raw data coming up from the machine was very difficult to interpret in the form displayed in the primitive 7th scale GUI. Auxiliary viewing tools, created for the purpose, were used to show time-series and derived values such as mean and rms.

Based on the 7th scale experience, the full scale GUI was designed not to display any raw data in numerical form on its main screen, since these were found to be of limited value. Only derived values are displayed in the main window. An emphasis was placed on the development of basic graphical displays within the GUI of the centralised control system. The development of semi-real-time graphical displays to run in parallel with the control system, using data captured by the control system, is underway for inclusion in the monitoring and analysis suite to be housed at EMEC.

A5.2 Actuation delay issues raised

Since the 7th scale hydraulics system is functionally similar to the full-scale system, a number of issues that apply to the full-scale system became apparent during the tests at ECN. One such very important issue is that of valve delays. The valves used to control the flows and pressures in the hydraulic cylinders do not switch instantaneously on command from the control system. A delay exists between the electronic switching of the valve coil and the mechanical motion of the valve. These delays were quantified during laboratory test of the 7th scale test rig and their effects with respect to applied joint restraint understood. However, the effect of these delays on dynamic response with external excitation, rather than prescribed motion as applied by the test rig, can only be determined in the context of the entire Pelamis in waves. Sea-trials did not allow accurate real-time knowledge of the actual wave conditions, or a flexible enough environment, to pin down and address the effects of valve delays - the tank tests at ECN did.

Figure A5.3 With coefficients set above a threshold level, control valve delays can induce instability in still water.

The results above show an example of the critical nature of the delay problem and its importance in the design of the Pelamis control system. Achieving high levels of damping coefficient is particularly important in maximising power capture. An immediate effort was put into addressing the problem while testing at ECN. These tests pointed the way to solutions.

The dynamics of the 7th scale system is more influenced by a given delay time than the full-scale system due to the scaling of time with respect to mass and forces. The effects of delays were reproduced in simulations using a power take-off model verified with the full-scale joint test rig. Solutions have been developed allowing acceptable damping levels to be implemented at full-scale.

A5.3 Regular wave tests

Testing was carried out for a range of regular waves at parameters within the stability threshold of the 7th scale system. Some results from subsequent analysis are given below.

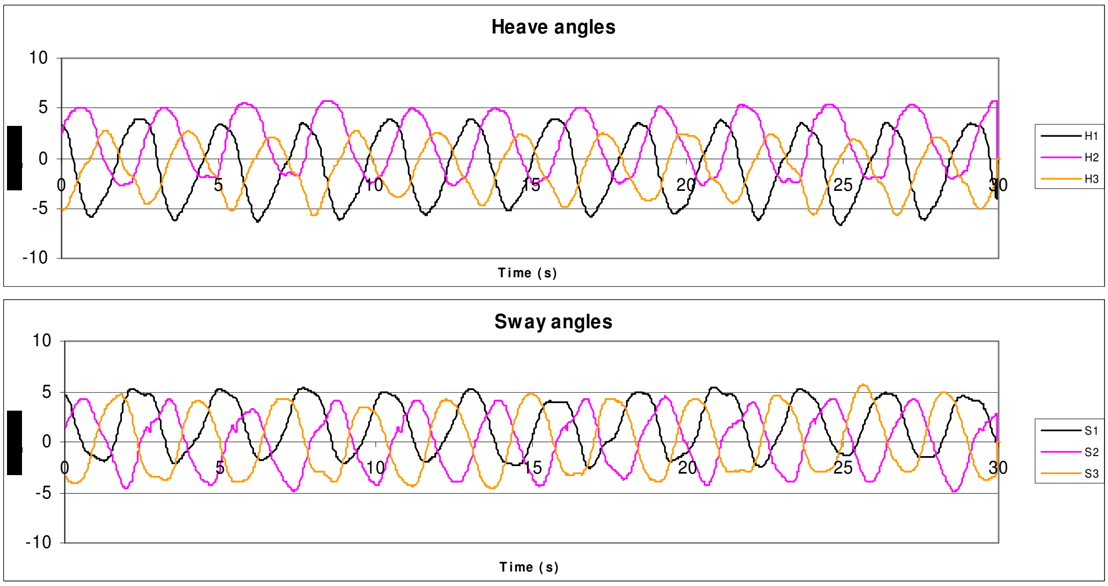
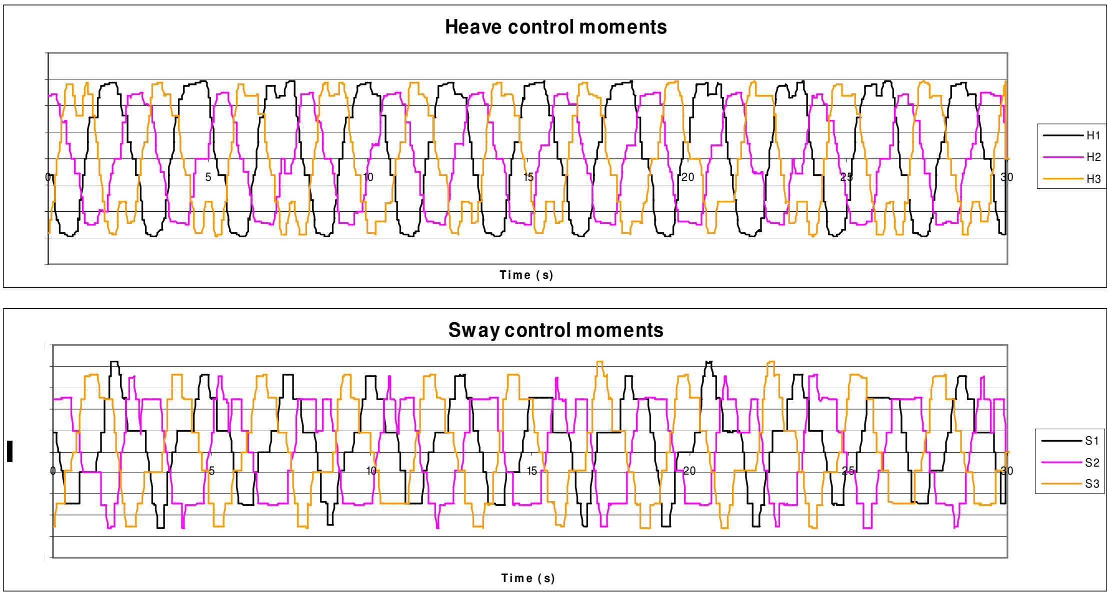


Figure A5.4 Heave and sway joint angles for a regular wave test of 3m and 7s period full-scale.


Heave control moments

Sway control moments

Figure A5.5 Heave and sway moments for the same test.

Figure A5.7 on the following page shows moment traces from a regular wave test of 3m and 7s full-scale. The applied joint moments (derived from control settings) are shown (black) along with the measured moment from the load cells mounted on the joint axes (blue dash). The delay between the demand moment and the applied moment measurement can be seen. Also plotted is the continuous demand moment (orange) which at times exceeds the available joint moment limit.

Figure A5.8 on the page after shows applied impedance functions (moment vs. velocity) for each of the joints during the same regular wave test. The continuous demand function shows the computed function that the joint system should approximate.

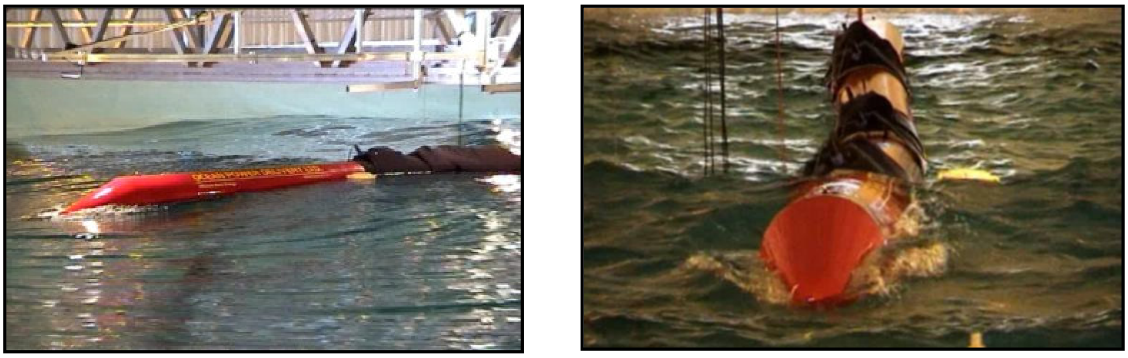


Figure A5.6 Photographs of the machine undergoing testing in the ECN wave basin. Left: from side of nose, Right: from front looking down machine.

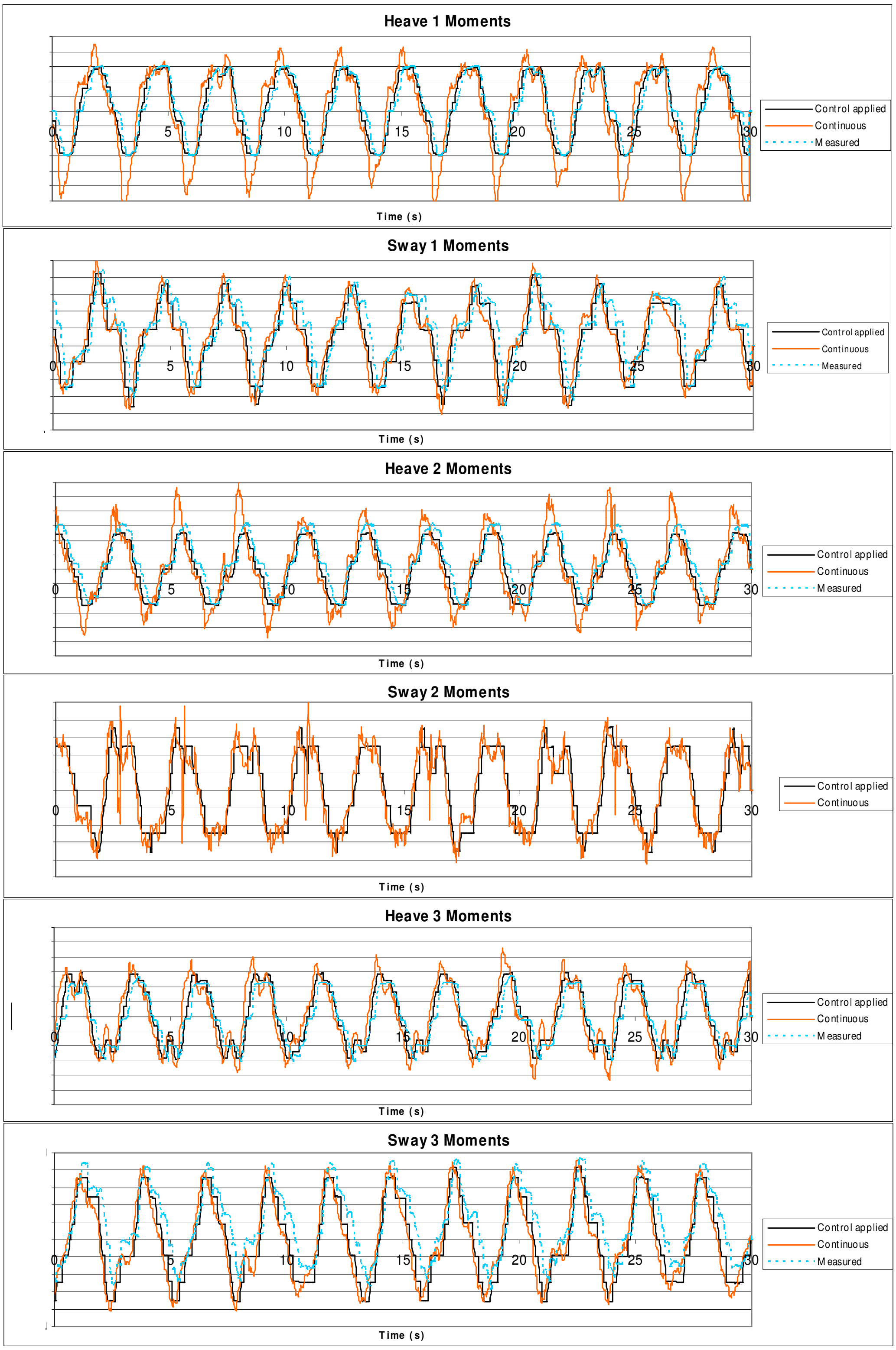


Figure A5.7 – Regular wave demand (balck & orange) & measured (blue) moment traces

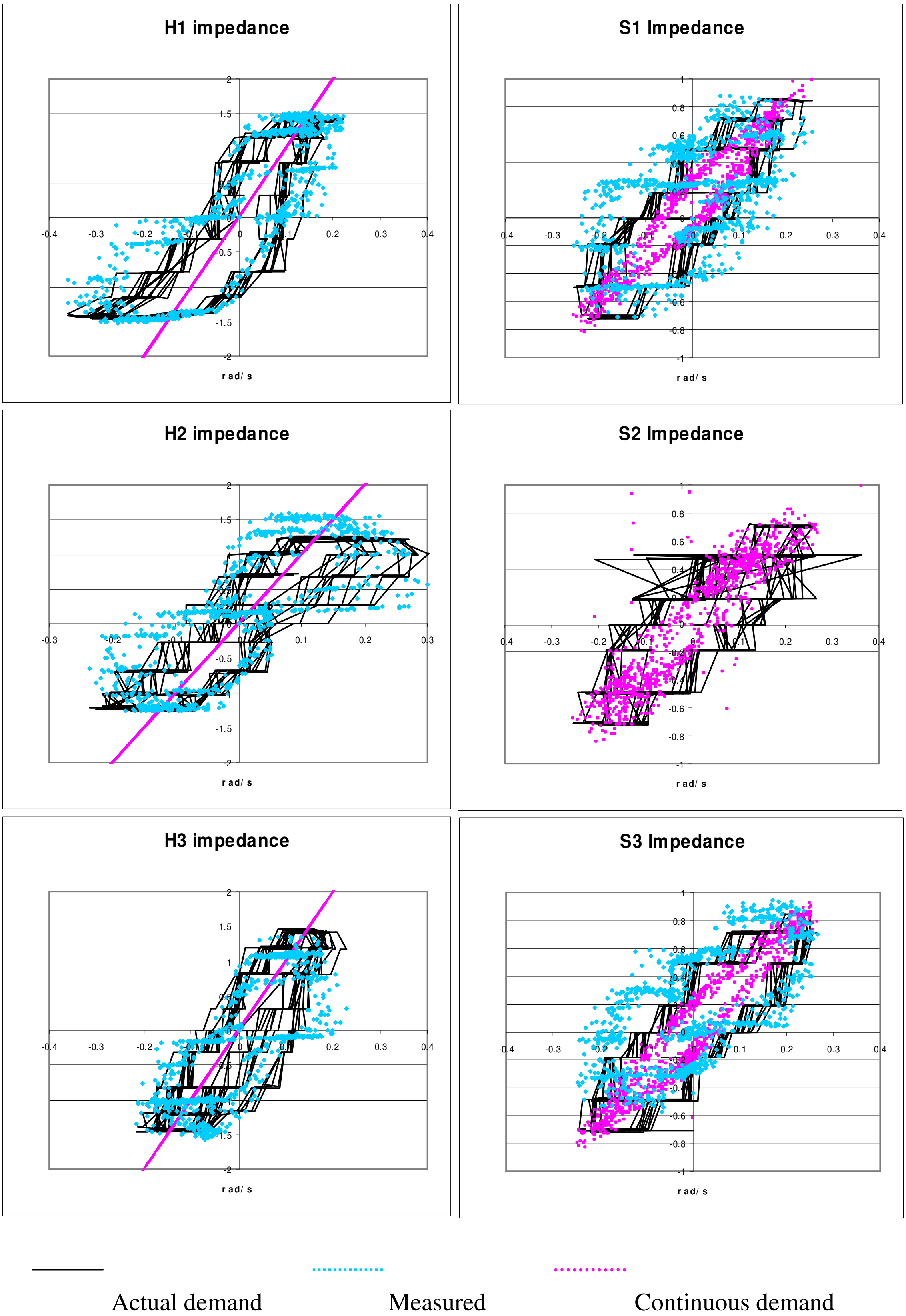


Figure A5.8 – Joint impedances for the same tests as shown in Figure A5.7

A5.4 Irregular wave tests

Tests were carried out in a range of irregular waves. The control algorithms were found to behave as expected.

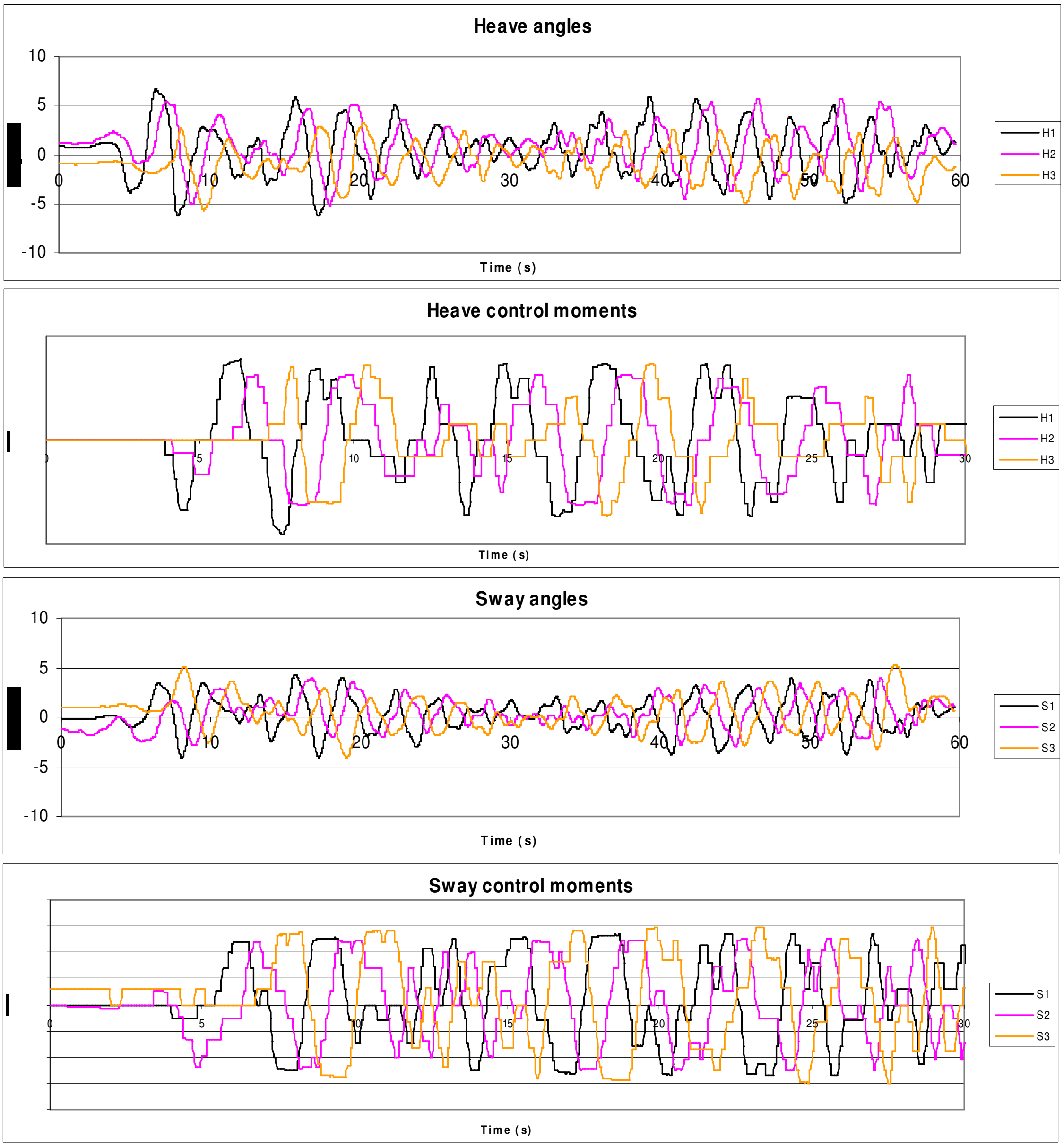


Figure A5.9 – Example joint responses in irregular waves

A5.5 Failure modes

The treatment of faults and failure conditions is important to the survival and efficacy of Pelamis. The 7th scale machine underwent genuine communications, transducer and valve faults in its hydraulic system during tests, and dealing with these faults from information only available to the control system gave invaluable experience to guide further design of the control system and interface for full-scale, and also directly to personnel in advance of launching the full-scale prototype. The inclusion of specific transducers and alarm conditions in the monitoring software, and also automated responses to those conditions, were made in response to the experience gained while testing the 7th scale model at ECN. For example, the full-scale control software allows dynamic reassignment of valves to isolate valve failures, and each ram chamber has pressure measurement to allow faults to be quickly and accurately diagnosed and dealt with.

A5.6 Survival mode control

The 7th scale machine was tested under adapted 'survival' control parameters resulting from previous iterative tests of the 20th scale model in extreme conditions. The 7th scale machine is much too large for the tank to produce extreme waves for actual survival testing. However, the observed performance was seen to be satisfactory in the largest mixed seas producible. Joint angle offsets in particular were found to be controlled well and response shared effectively between joints as per the 20th scale tests in similar conditions.

Survival control of this type has been validated for application on the full-scale machine, using the same fundamental control code and systems.

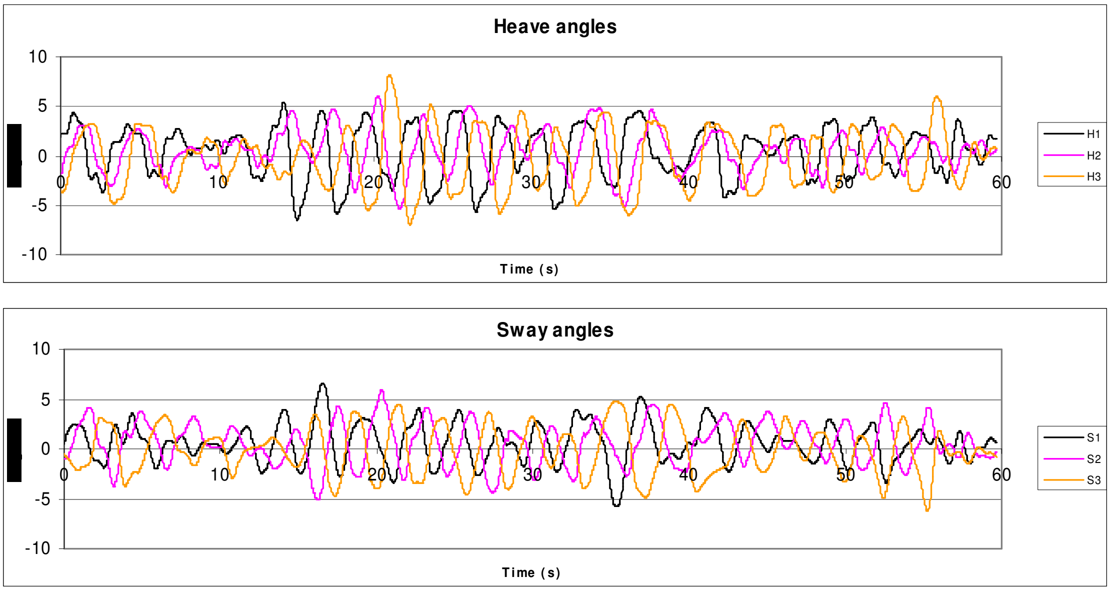


Figure A5.10 – Examples of the joint response with survival settings in large irregular waves of up to ~10metres height at full-scale. Note the effective sharing of response between all joints.

A6. CONCLUSIONS FROM 7TH SCALE TRIALS

- The 7th scale model was adapted and enhanced to make the model more suitable for use in a laboratory environment. All changes made were deemed to be satisfactory.
- The control architecture was overhauled to provide centralised control to reflect the aims of the full-scale development programme. These changes successfully provided a test-bed for the centralised control system to be used on the full-scale Pelamis prototype.
- Tests were carried out over a broad range of conditions and control parameters. The control system was developed during this process in a manner which aimed to maximise both learning and system development, and to increase confidence in control software and algorithms.
- The basis of the full-scale control and communications software was tested and de-bugged using the 7th scale platform in a realistic but controllable environment.
- The fundamental control algorithms, running on the central control computer, performed as expected.
- Key aspects of the Pelamis power take-off and control implementation were explored and demonstrated under a range of conditions. The knowledge gained has enabled problems to be understood and solutions to be developed for inclusion in the full-scale programme.
- The effects of failure conditions were demonstrated, and methods of diagnosing and dealing with them were developed. These methods have

been incorporated into the full-scale system.

- The operational experience gained during the tests at ECN has provided an invaluable contribution to the design and development of the full-scale control system to be installed on the full-scale prototype.
- This operational experience will prove invaluable for OPD personnel for the forthcoming trials of the full-scale prototype.
- Survival control parameters were tested satisfactorily in seas up to ~10metres at full-scale.
- Increased confidence in the complete system, and valuable specific technological improvements, justify the investment made in testing the 7th scale system at ECN.

SECTION B: 20TH SCALE TESTS

B1. INTRODUCTION

The first part of this report covered the verification of the full-scale prototype (FSP) control using the 7th scale model. This report extends that work using the Mk.2 20th scale model in the Nantes wave basin, in order that extreme waves could be modelled. A number of model modifications and upgrades were implemented allowing the features of the FSP control system to be

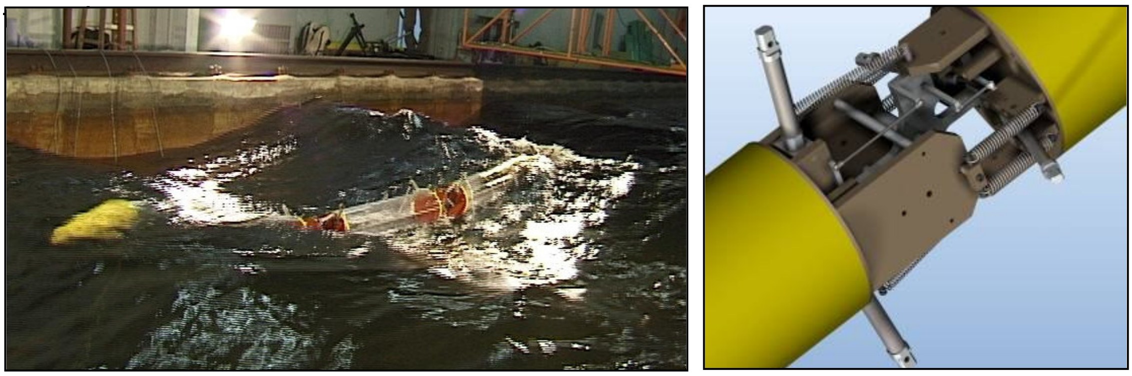


Figure B1.1 Mk1 20th scale model under test and joint detail showing water dampers

The Mk.2 20th scale model was a major development of the original model at this scale. The original model had water filled dampers to crudely simulate the full-scale hydraulic system. Control of the damping level was effected using needle valves and various other flow impedances. This was hard to set-up resulting testing with only a few ‘control’ settings. The Mk2 20th scale model followed the precedent of the 33rd scale, using closed loop servo motors driving through gear segments to allow arbitrary joint restraint to be applied. The joints were controlled using a high-speed microcontroller to allow a wide array of control settings and strategies to be accurately modeled, and non-linear characteristics such as moment limiting. The model had previously been tested extensively in the Nantes tank in this configuration to supply design verification data for the WS Atkins full-scale prototype verification process.

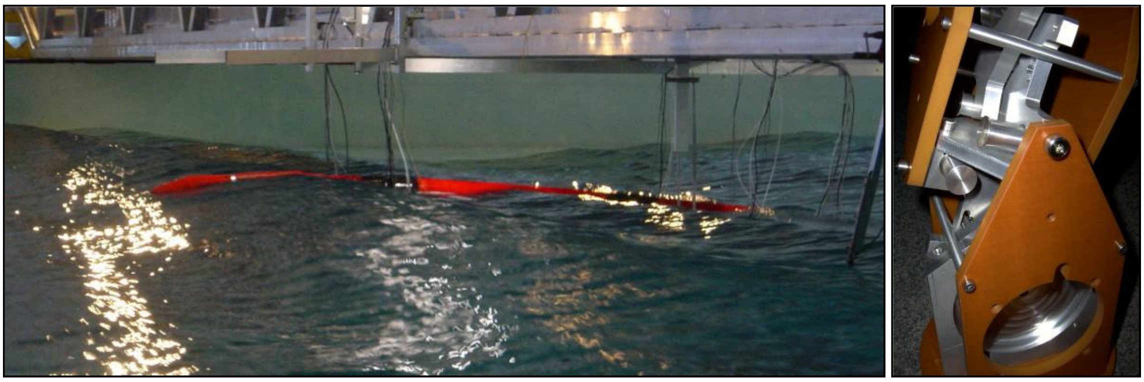


Figure B1.2 Mk2 20th scale model under test and new servo-mechanical joint during build

B1.1 Model preparation & upgrades

A new model controller box was built. It contained similar instrumentation to that used with the earlier version, but with a new faster microcontroller. This allowed more sophisticated control strategies to be implemented, and the full-scale control modes to be simulated more closely. The previous microcontroller only allowed linear control, i.e. linear springs and dampings. The real control on the full-scale joints is more complex, the new microcontroller was fast enough to fully simulate the full-scale hydraulics in real time.

Each model joint was assembled and tested on the bench. The scaling of the model is such that the forces are 'handleable' – i.e. a person can drive the joint by hand against the full force that can be developed by the motor. The simulated full-scale active and the fail-safe controls could be tested both by instrumentation and by 'feel', the latter proving just as useful.

In addition, a fourth joint unit was fabricated and assembled as a spare, this was used in the tests because of water damage to one of the existing joints. The Pelamis model comprises 4 cylinder sections with 3 joints. The previous model had used perspex cylinders with end-caps held in by tie-rods. These were prone to leak through the tie-rod fixings, and so were replaced with purpose built fibre-glass sections which were watertight, opaque and easier to see in the wave-tank, and had cavities on the underside so that ballast modules could easily be installed and changed.

The model, its control and instrumentation, spares and tools were packed and shipped to the ECN wave basin in Nantes. On site the joints were retested, revealing a number of faults including failed adhesive on a strain-gauge on a mooring block and a motor pinion, and intermittently contacting BNC cables. These faults were repaired and installation in the tank commenced. Moorings for the model were placed in position by divers.

The model was fully assembled in the work area by the side of the wave basin, craned into position in the basin, launched and attached to the moorings, whereupon all electrical connections were made to the control and data acquisition electronics. A digital video (DV) format camera was utilised at several locations to record the model response in waves, and a further analog (VHS) underwater camera was installed to provide a view of the moorings and model underside, and clarify the mooring dynamics.

Figure B1.3 Model with control and data wiring with approaching wave

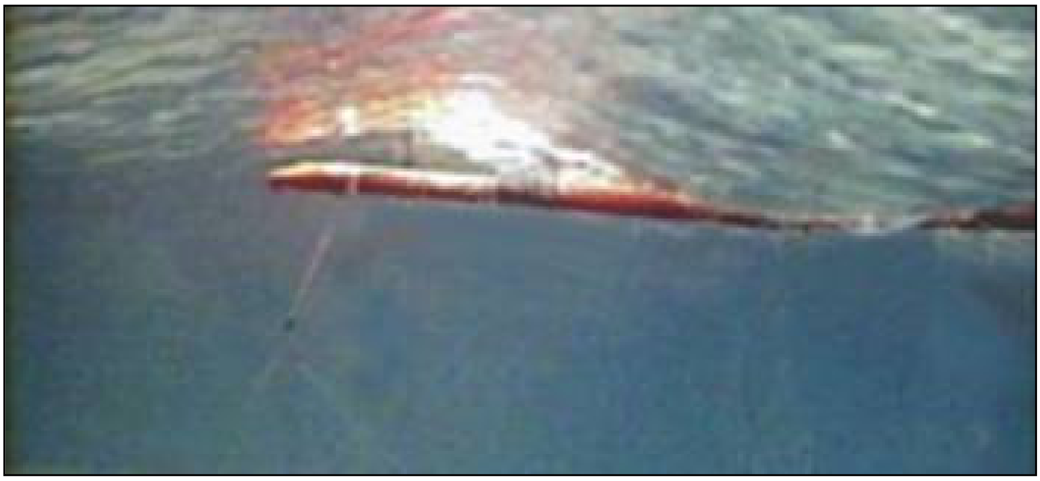


Figure B1.4 Underwater view of model in 14m, 7.2s (at full-scale) wave, showing dynamic submergence

B2. TESTING & ANALYSIS

B2.1 Waves

The model was tested in regular waves, irregular waves, and focused waves up to a height of 23m. The regular waves provide simple cases for comparison with numerical models; the irregular waves comprised a set of Bretschneider spectra of nominal significant steepness of 1/16, a little steeper than the 1/19.7 for Pierson-Moskowitz; they allowed the model to be tested in both power producing and survival mode; the focused waves tested the model's ability to survive the most extreme individual waves. The wavemakers in the ECN wave basin have not yet been fitted with the expected upgrade to provide wave absorption. Where appropriate, we mitigated this by sampling for a sufficiently short period to exclude reflections from the wavemakers. We had planned to test in directional seas, but the rapid build-up of cross-waves between the basin sides prevented this. Again, we would expect absorbing wavemakers to help suppress cross-waves. Consequently, all tests were carried out in unidirectional waves.

B2.2 Mooring

Although not specified in the original work package, the model was also tested with two configurations of mooring. Comparison of the results is contributing significantly to our understanding of the interaction of mooring and the main structure.

1. The original mooring design, as deployed at EMEC for the full-scale prototype
2. A new configuration with an omni-directional capability, designed to be easier and cheaper to deploy and use

This new mooring has a lower spring rate and was observed to have a significant effect on the machine dynamics in extreme seas. The behaviour of the nose of the machine is critical, a less forcefully restrained nose does not dive as deep into extreme waves, so increasing the extent to which the machine rides the waves and hence increasing the joint angles. In irregular waves (the largest sea, Tp 15.4s, Hs 11.8m) both heave and sway angles on the first joint increase by about 10-15%, with negligible changes on other joint axes. However, in particular extreme focused waves the angle range on all joint axes can increase by more than this.

B2.3 Control

The new controller code allowed springs, dampings and moment limits to be set for each of the joints while the model was operating, the values being set from the keyboard of a dedicated PC. The model could also be switched instantaneously from its simple linear control to simulated full-scale hydraulic control, which precisely models the restraint characteristics of the full-scale prototype machine. It was not, as had been hoped, possible to accurately model valve delays due to insufficient time resolution in the microcontroller. Two further programs controlled the model in failure modes: passive failsafe mode, and half-circuit failure mode, again with *on-the-fly* adjustment of key parameters.

The full-scale design uses hydraulic rams to provide various levels of moment to oppose the wave-induced motion of the joints. These levels and the ultimate moment limits, were implemented in the 20th scale model. Figure B2.1 shows the command and measured moment records for the middle heave joint in a regular wave with a 7.2s period and height of 4.0m, the measured moments closely follow the command moments. There is a small amount of ‘ringing’ response in the measured moment following each instant of level switching due to the mechanical response of the drive system of the model. There is also an offset between command and measured moment, of opposite sign for the rising and falling waveforms. This is due to motor friction opposing the direction of motion. It is typically less than 10% of the maximum moment.

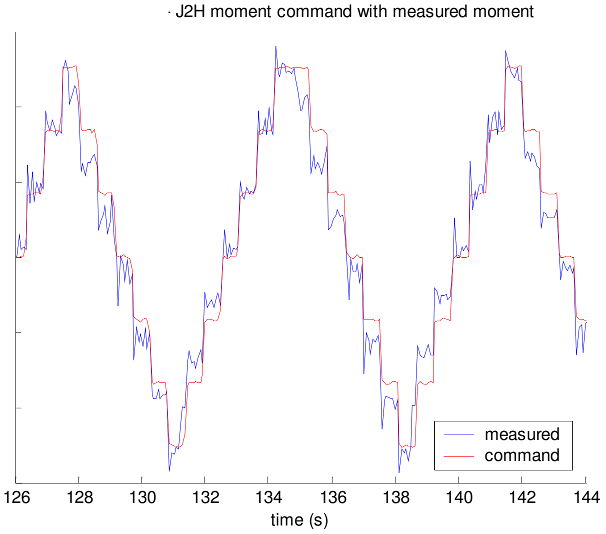


Figure B2.1 Moment command and measured moment compared

B2.4 Power and survival controls

Previous tests and numerical modeling have shown that a good control strategy for high power in small seas is to maximise the damping ratio at each joint, thus promoting resonant sway motion. For survival conditions in large seas we want to reduce both power and maximum joint angles - this can be accomplished with a low damping ratio and varying the damping along the length of the machine.

In this work package our then current best survival control was refined by making incremental changes designed to reduce the angles on all the joints until superior settings in extreme conditions were found. Figure B2.2 shows the changes in root-mean-square joint angle for each joint axis. The mean reduction was 20% for the new setting. The results are for the original mooring design, in an irregular wave of Tp 15.4s, Hs 11.8m, significant steepness 1/16.

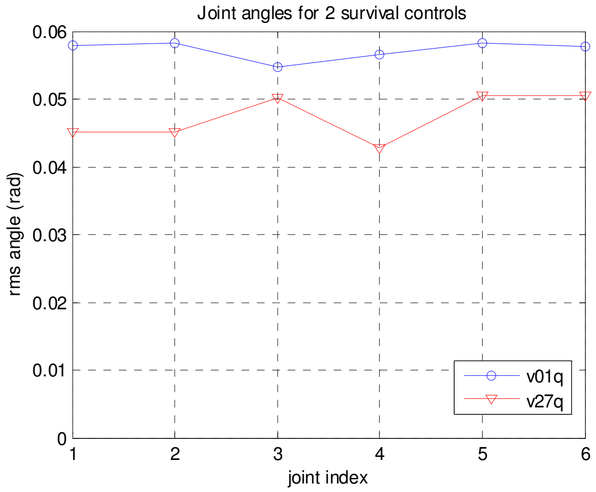


Figure B2.2 Reduction in rms joint angles from the old survival control (blue) to the new settings (red)

The model was then tested with the new experimental mooring in a broad set of irregular waves. In each sea the goal was to maximise power absorbed while keeping the joint angles within their mechanical limits. Figure B2.3 shows shows the rms angles with wave height – the sway angles are enhanced in the small seas by setting a high damping ratio, all the angles tend to a limit in the largest seas.

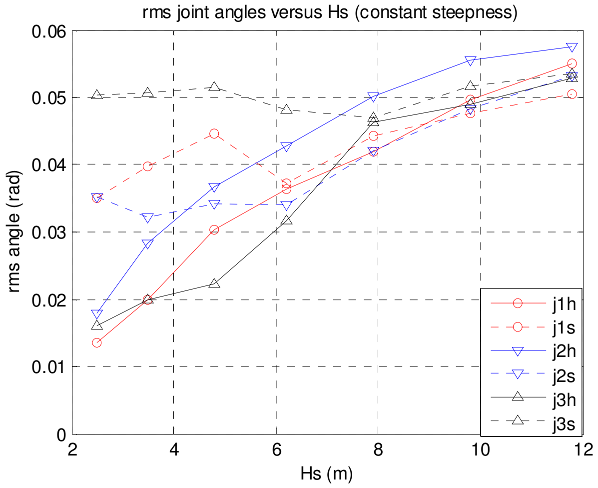


Figure B2.3 Joint angles in increasing sea size, with transition from power to survival control

These tests confirmed the power and survival settings in small and large seas respectively, and showed that in intermediate seas the optimum damping changed smoothly between the two extremes. These results add confidence to the current supposition that optimum control can be accomplished by means of a look-up table based on sea-size. Further work could clarify the independent contributions of period and wave height.

B2.5 Fail-safe mode

When there is a failure of electronic control in the FSP it drops into fail-safe mode; the rams pump passively and motion is opposed by the full available moment – it can be thought of as a moment-limited infinite damping. Out with a central 'dead-band' the rams is controlled using a set of mechanically operated valves that maintain restraint on the joint while ensuring that they stay near the centre of their stroke.

When modelling this arrangement numerically (or using the servo-mechanical joints on the 20th scale model) calculations must be made in finite time-steps; the rams thus apply finite impulses of fixed size. For small velocities around zero these impulses are unlikely to be exactly matched to the load, so the velocity will be over-corrected, i.e. reversed. The same happens on the next time-step, and the system oscillates. The time steps can be made smaller, but this does not eliminate the oscillation, only decreases its period. The same happens physically in the 20th scale model because of the velocity feedback loop: the effective time-step is the reciprocal of the loop bandwidth. The full-scale machine does not suffer in this way – it effectively has infinitesimal time-steps as the hydraulics are reacting passively. To avoid this oscillation in the model the restoring moment is switched on only when the velocity goes outside a 'dead band' around zero velocity – an effective solution but which compromises the accuracy of the control model to a certain extent. This reduces the time for which full moment is applied to the joint and, for a given sea-size, and results in larger angles than would be expected in the full-scale design.

The model was tested in a focused wave (Tp 15.0s, Hs 3m, focused wave height 16.9m) with best survival control and in fail-safe mode. The joint angles (in radians) in this wave are shown in Figure B2.4 fail-safe control (red curve) and best active survival control (blue curve).

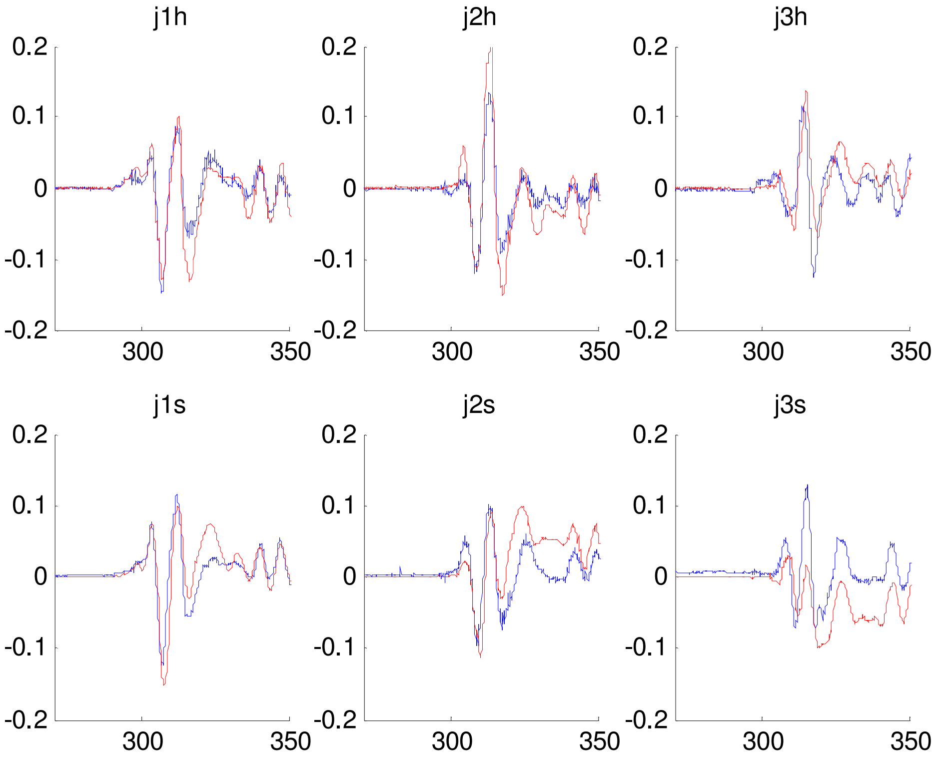


Figure B2.4 Extreme joint angles during the passage of an extreme wave for passive 'fail-safe' control (red) and best active survival control (blue)

The scale model has demonstrated an implementation of the fail-safe mode that, in large focused waves, can lead to somewhat larger joint angles than the best survival control. However, the model implementation is imperfect: because of the velocity dead-zone, maximum moment is applied for only part of the time that it should be. The full-scale prototype fail-safe is considerably better because the maximum moments are applied with no delay. Further research will continue to improve the overall surviviability of the machine in active and passive modes.

B2.6 Hydraulic half-circuit failure

The Pelamis hydraulic systems incorporate a number of features that enhance the robustness and survivability of the system in partial failed conditions. Further tests in this series were carried out to investigate the wave limits for various failed conditions.

One of these partial failure systems is the equivalent of dual circuit brakes on a car. Half of the hydraulics in the joint module can fail completely without loss of restraint on each joint axis. However, the maximum moment that the system can apply about each axis is reduced. With reduced moment to oppose hydrodynamic forces, joint angles would be expected to be larger. Tests indicated that the survivable extreme wave height drops by 30-40% with all joint axes in the partially failed condition.

However, with the half-circuit failure implemented on just one joint axis, changes in joint angle are much less severe. Figure B2.5 shows the joint angle range (minimum to maximum) for each joint axis on the ordinate of the graph, against the index of the failed joint axis along the abscissa. The wave is a focused irregular wave of Tp 15s and Hs = 3.0m, and a focused wave height of 16.9m. Only failure on joint 1 heave increases the maximum angle among all joints by more than 5%.

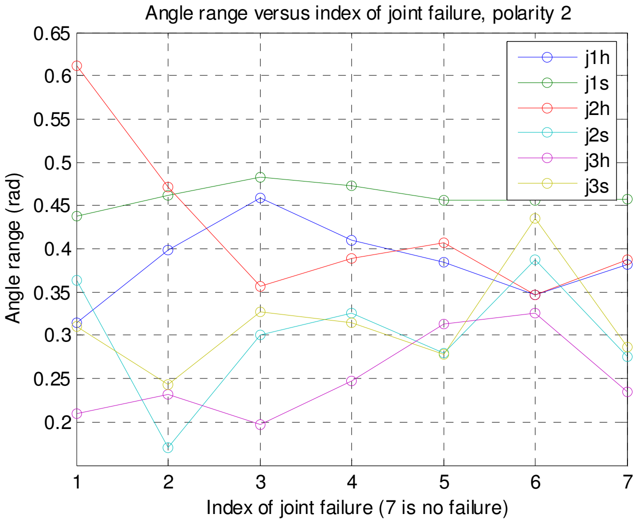


Figure B2.5 Joint angles plotted against the location of joint failure

B3. MODEL DECOMMISSIONING AND MAINTENANCE

Rather than performing the crane launch in reverse, it proved about twice as fast to remove the model from the wave basin by dismantling the joints and cylinder sections while still in the water, removing the sections one at a time up to the carriage above the tank. Once ashore, segments and joints were electrically disconnected, checked for leaks and electrical and mechanical integrity. All proved intact. The model was then fully dismantled and repacked in the crates for the return shipment.

B4. CONCLUSIONS FROM THE 20TH SCALE TRIALS

- The extra control tests using the upgraded 20th scale model were a valuable addition to the 7th scale trials within this project.
- Apparently small changes in mooring can lead to significant changes in machine response, the mooring and machine response were found to be more interdependent than previously thought.
- The use of a high performance digital microcontroller allows complex, non-linear controls to be implemented and fully tested rapidly, without the need for hardware changes or direct intervention on the model. Complex control tests such as those reported would have been almost impossible to achieve without closing the control loop in software.
- It was possible to accurately implement fully representative normal and simulated failed control modes for the full-scale machine. Motor friction led to a small but acceptable inaccuracy in the moment levels – about 10% of full-scale.
- Supervisory joint control can be adapted to the sea size to meet the twin goals of high power and joint angles kept within safe limits.
- The testing further confirmed that effective overall control settings vary in a straightforward way from small to large seas.
- The digital controller facilitated the rapid evolution of a survival mode that reduced extreme joint angles by 20% over the previous best settings.
- The default mechanical failsafe control mode of the full-scale machine (enabled on complete loss of power to the system) was implemented on the digital controller and thoroughly tested. The model scale implementation is imperfect because of the finite control loop-bandwidth. However, the algorithm achieved was deemed to be conservative representative of the full-scale system.
- Testing in the failsafe mode confirmed that extreme angles are larger than for the fully active control mode as would be expected. However, performance was still adequate.
- The digital controller also allowed accurate modelling of a various partial hydraulic failures.
- Testing in a range of seas showed that partial failure of a single joint has only a small effect on machine performance and extreme joint angles.
- A large number of partially failed joints results in a larger effect, but survivability and performance are still acceptable.
- All of the results are directly relevant to the full-scale prototype machine, and have been incorporated into the control system development and test programme. OPD will be carrying further testing of this type in due course.

PROJECT CONCLUSIONS

The following overall project conclusions can be drawn:

- Valuable additional tank testing using both the 7th & 20th scale models has been carried out
- Both models were configured to make them representative of the full-scale machine & control system
- A number of control system stability & operability issues were successfully tackled.
- Satisfactory operation of all aspects of the control algorithms has been demonstrated in a broad range of seas up to extremes.
- It was confirmed that operation of the machine in various partially failed conditions was investigated – performance was found to be satisfactory.
- All of the testing, analysis and results are directly relevant to the success of the full-scale prototype programme, justifying the investment in the programme.
- The programme has resulted in significantly inproved confidence all aspects of the Pelamis WEC control system, and the response of the machine in a broad range of wave conditions and control states.

RECOMMENDATIONS FOR FURTHER WORK

- A thorough exploration of the effects of changing the mooring configuration, and the response in extreme waves should be conducted. This is likely to lead to reductions in joint angles in extreme waves, thus improving survivability.
- A general optimisation of the hydraulic system components should be carried out to improve the resolution of restraint to the joint axes – this is expected to improve power production in small seas.
- A study of further improvements to the power and survival control settings should be conducted, and exploration of the benefits of the differential moment limits applied to each joint.