Second Energy Systems Study Group with Industry

5^{th} - 7^{th} December 2018

Innovate UK
Knowledge Transfer Network
THE UNIVERSITY of EDINBURGH
ICMS

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Contents

The organisers gratefully acknowledge sponsoring from the following institutions:

Problems posed by:

1 Study Group Information

The Study Group is an opportunity for industry to gain access to UK excellence in the fields of mathematics, statistics, engineering, and computer science. The format of the group allows for this to be done in a structured, intense session over three days. This Study Group with Industry is being run by the School of Mathematics, University of Edinburgh, the International Centre for Mathematical Sciences, and the Knowledge Transfer Network (KTN) and thankful for funding from ICMS, the University of Edinburgh - Centre for Statistics, the Bayes Centre, and the Maxwell Institute.

1.1 Background

Future energy networks will be characterised by much greater variability and uncertainty: inputs to electricity networks from renewable and solar generation are naturally highly intermittent, while new patterns of demand, e.g. that are required for the recharging of electric vehicles, are likely to be variable and are currently not well understood. Against this, there are significant new technologies available for the management of future systems. These include the management of demand, storage, generation and the networks themselves [1]

The move to cleaner economic growth - through low carbon technologies and the efficient use of resources - is one of the greatest industrial opportunities of our time. By one estimate, the UK's clean economy could grow at four times the rate of GDP. Whole new industries will be created and existing industries transformed as we move towards a low carbon, more resource-efficient economy.

The UK has been at the forefront of encouraging the world to move towards clean growth. We are determined to play a leading role in providing the technologies, innovations, goods and services of this future. [2]

1.2 Who will be attending?

The Study Group will consist of researchers from various fields, including, but not limited to mathematics, statistics, computer science, and engineering. As well as university researchers, we strongly encourage registrations from Ph.D students, postdoctoral researchers and early-stage researchers.

As well as these researchers, the Study Group will be attended by industrial representatives limited to those offering problems to the group. **We are not accepting registrations from any**

1 http://www.icms.org.uk/workshop.php?id=480

2 https://www.gov.uk/government/publications/industrial-strategy-the-grand-challenges/industrial-strategy-the-grand-challenges

industry not directly involved in the problems. In addition to these attendees the Study Group will host a number of Public Sector representatives from UK Research & Innovation. We expect to host around 35 people to this Study Group from across these sectors. Attendees can be found in Section 3.

1.3 How does it work?

The format of the Study Group will be following the highly successful European Study Groups with Industry. Industry present their problems on the morning of the first day to the group. The researchers will ask questions and choose which group they may be able to help with.

The groups (around 10 researchers per group) will move to their own working space. An academic lead will be nominated. They will discuss with the group what aspects of the problem should be addressed, and how these may be approached. It is likely that the group will subdivide, but this will depend on the problem.

It is expected that the industry representatives will be on hand to answer questions, provide access to codes, data and generally ensure that the problem context is clear throughout the Study Group.

Conversations often continue during the evening, as such the Study Group provides dinner for all delegates. This often provides an environment for cross-fertilisation of ideas between groups and disciplines.

Group work continues until the Friday lunchtime for final presentations. It is likely that the Project Lead will provide these presentations. Following the Study Group, the industry presenters will receive a report detailing what was done during the three days. Again, the Project Lead will coordinate this and draw on assistance from members of their team. The Project Lead will aim to get this report to the industrialist by the end of February 2019.

1.4 A Note Regarding Study Group Outputs

For researchers: It should be noted that all work demonstrated at this Study Group should be considered as open disclosure. All codes used to generate results should be made freely available to the working group and industrial partner. If you are not comfortable sharing code, please do not bring it to the Study Group.

For companies: It should be noted that any insight and / or code generated over the course of the Study Group is research output. The research participants offer no guarantees on any code and / or results generated.

1.5 Agenda

	Tuesday 04	Wednesday 05	Thursday 06	Wednesday 07
09:00 onwards		**Registration** (ICMS, Level 5, Bayes Centre)	**Group Work** (See Floor Plan)	**Group Work** (See Floor Plan)
10:00		**Welcome, Introductions and Problem Presentations** (Lecture Theatre, ICMS, Bayes Centre)		
11:00			**Tea and Coffee**	**Tea and Coffee**
11:30		**Group Work** (See Floor Plan)	**Group Work** (See Floor Plan)	**Group Work** (See Floor Plan)
13:00		**Lunch**	**Lunch**	**Lunch**
14:00		**Group Work** (See Floor Plan)	**Group Work** (See Floor Plan)	**Final Presentations** (Lecture Theatre, ICMS, Bayes Centre)
15:30		**Tea and Coffee**	**Tea and Coffee**	**Tea and Coffee**
16:00		**Group Work** (See Floor Plan)	**Group Work** (See Floor Plan)	**FINISH**
17:00				
18:30 onwards	**Drinks Reception** (Motel One Bar)	**Dinner** (Blonde Restaurant)	**Dinner** (Bayes Centre)	

1.6 Do I need to pay?

The organisers are extremely grateful for financial contributions from the University of Edinburgh Centre for Statistics, Bayes Centre, Maxwell Institute, and ICMS so that we are able to cover delegates accommodation and meals for the duration of the Study Group. We do however ask for a nominal payment of £35. Additionally, we do ask that researchers and industrialists cover their own costs for travel to and from the venue. If this is likely to be a major issue, please contact Dawn Wasley

1.7 Pre-Study Group Actions

To make sure the group progresses well, it is important that researchers read and study the problem statements provided by industry prior to the Study Group. It would be helpful for the researchers to have ideas on how they might approach **all** of the problems and be willing to work in any of the groups in case adjustments need to be made to balance capability and numbers in each group.

1.8 Check-in, Accommodation and Dinners

The organisers have arranged for a number of rooms to be held for Study Group members on the Tuesday, Wednesday and Thursday nights at Motel One Edinburgh - Market Street - requests for these should be indicated at registration. These (en-suite) rooms include breakfast. Check-in time on the Tuesday is 15:00. Buffet lunches and dinner on the Thursday night will be available at the Bayes Centre. A conference dinner will be held on the Wednesday evening at the Blonde Restaurant.

For those traveling down on Tuesday, there will be an informal gathering in the evening starting at 18:30 in the bar at the Hotel. It will also be a good opportunity to discuss research ideas and how problems may be addressed in an informal manner.

1.9 Conference Dinner

The dinner on Wednesday will be held at the Blonde Restaurant. There is no dress code, and no cost associated with the dinner. We would ask that people arrive promptly by 18:20 (for a 18:30 start). Additionally, if you have not indicated to the organisers in your registration any allergies, we request that you do so as soon as possible.

2 Study Group Challenges

2.1 A Marine Propulsion Control System : Holy Grail or Maths?

Presenting Institution: Duodrive Ltd.

Problem Presenter: John Carter

Abstract (Technical Topics and Desired Outcomes): Duodrive Ltd is partnered with the Marine Robotics Innovation Centre, Southampton (UK) and recognises that fuel efficiency and carbon emissions are today's priority in marine propulsion.

In the Marine World there is the "holy grail" of a diesel engine driver where the power output matches exactly that required by the propulsion drivetrain. However modern diesel engines are conceived for the electrical power generation market (so constant speed with varying load) whereas propellers are bound by physics to a cube power law. As almost all gearboxes which drive the propeller are with fixed speed ratios this means the only moment when the engine power matches the demanded propulsion power is at the maximum speed condition. Even worse, in the engine's best operating zone at perhaps 80 % max RPM, it is capable of 3 to 4 times the power demanded by the propeller. As modern diesels shouldn't be loaded at less than 50 % of their peak power, such a condition is a great way to destroy one.

The Duodrive concept is like an eCVT (borrowing from the automotive VOLT or PRIUS drivetrains in electric cars) or electronic CVT but arranged for a marine application. The application for motor vehicles depends on acceleration and braking with the addition of a battery storage which doesn't work with a boat. However the Duodrive design, Varidrivetrain$^{\mathrm{TM}}$, disconnects the engine from the output propulsion speed allowing forward or reverse whilst engine runs at a constant speed - the big question then is whether the control system can realise not only a commercially attractive saving but also simple operation. If one considers single operating points then one sees a saving. To date we are not aware of anyone worldwide considering this concept.

The idea is to oblige the engine to run in its best operating range and to use a control system to coordinate the propulsion speed which can be both variable and reversing with potential to disrupt the conventional reduction or reversing marine gearbox market.

Mathematical challenges: We believe that the core analysis question is focused on knowing how to develop the required control system which could realise a saving which is commercially attractive. That seems to imply a need for the construction of a realistic scale working model or more probably a small prototype which could then generate data/test/improve the control system. As an option, it may be possible to first create a virtual model which would show how to size the respective major components to achieve the goal of saving energy/fuel and to then build the physical prototype to prove and improve the control system.

2.2 Planning Edinburgh City Infrastructure for Uptake of Electric Vehicles

Presenting Institution: Edinburgh City Council

Problem Presenter: Ben Wilson

Abstract (Technical Topics and Desired Outcomes): The city of Edinburgh has ambitious plans for increasing uptake of electric vehicles, in order to improve air quality and reduce carbon emissions. This requires infrastructure developments, including provision of charging points and electricity network capacity, and also taking advantage of synergies with local renewable generation. Availability of energy supply in turn influences where residential and commercial building developments can be sited. Planning background uncertainties include rate of uptake of vehicles, technology growth, and the spatial development of the city itself. The group will scope approaches to these issues, and council analysts will provide data on planning background projections and be available for discussion of uncertainty in these [3].

3 http://www.edinburgh.gov.uk/download/meetings/id/58745/item_71_-_electric_vehicle_infrastructure_business_case

2.3 A Curious Fluid Resonance in a Sloped Channel on a Wave Energy Converter

Presenting Institution: Mocean Energy

Problem Presenter: Cameron McNatt

Mocean Energy is an Edinburgh-based company developing a wave energy converter (WEC), which converters energy in ocean waves into electricity. Our innovation is in the unique geometric shape of a hinged-raft WEC. We describe the geometry as having "wave channels": sloped surfaces on the forward and aft hulls. The geometry induces resonant response in the WEC motions at at-least two wave frequencies, which results in broad-banded wave energy absorption. The design was developed using a computational optimisation routine, based around linear wave-body interaction theory [4], which seeks to minimise the ratio of a parametric "cost" to energy production.

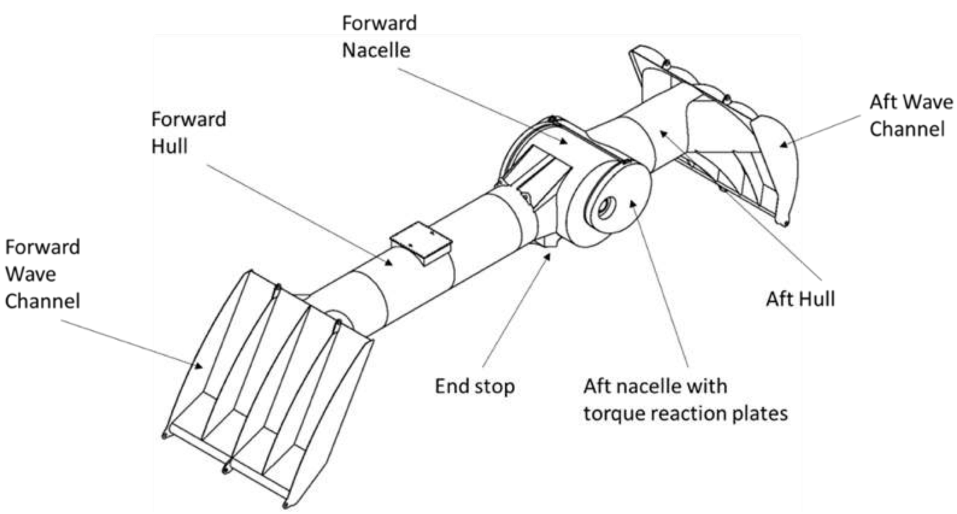


Figure 1: The latest Mocean WEC: M100

We believe that the optimisation has stumbled upon a phenomenon caused by the wave channels that creates a wave resonance with the wave channel; it may be related to the trapped mode phenomenon described by Ursell (1951) [5] . Furthermore, the linear wave resonance can be very large, and so because of nonlinear effects, it is not realisable in practice. Included as Section. A is an excerpt from a report we submitted to our funding body, Wave Energy Scotland.

Mathematical challenges:

- The conditions that we consider are not quite the same as those of Ursell. Is what we have observed a trapped mode?

4 wikiwaves.org/Linear_Wave-Body_Interaction

5 Ursell, F. (1951). Trapping modes in the theory of surface waves. Mathematical Proceedings of the Cambridge Philosophical Society, 47(2), 347-358. doi:10.1017/S0305004100026700

- Can a linear mathematical model of the phenomenon be developed that can be used to predict the linear-wave forces/moments and their frequency dependence?
- Can a mathematical model be developed that can be used to predict the real, nonlinear wave forces/moment and their frequency dependence?

These models would use extremely useful for our technology development. Firstly, they would validate our discovery. Secondly, they would be used in our design approach to develop new WEC geometries by allowing us to better understand the phenomenon and by incorporation into our geometry optimisation routine.

2.4 Mathematical Language and Sequential Bundling of Demand-Response Contracts Under Uncertainty

upside

Presenting Institution: Upside Energy Ltd.

Problem Presenter: Meagan Burke, Nick Good

Upside Energy Ltd. provides balancing services to the UK National Grid using a diverse portfolio of electricity assets. These assets are owned by partners and are controlled by Upside's platform according to service agreements, such as response times, power magnitudes, rates of change, cost structure, etc. These conditions are stated into a Demand-Response (DR) contract, which is interpreted as an option for Upside to use for balancing services.

However, these contracts (or offers) might expire frequently and the set of conditions might vary often depending on the asset owner circumstances. For instance, a DR offer may be expressed as "use 1 MWh of battery X for charging and discharging operations from 00:00 to 05:00 hrs for the next 2 days at 10 GBP / MWh". Since these DR opportunities might become available at short notice, the first part of this challenge is to develop a language in which partners (asset owners) can to write their own contracts which allows mathematical reasoning (e.g., formal verification).

Reliability of DR contracts might vary and they are usually bundled to satisfy a given service level. The second part of this challenge is to find an optimal bundling of DR offers, similar to a multistage stochastic unit commitment problem.

2.5 Increasing Maritime Energy Efficiency Through The Application of Analytically Enhanced Predictive Planned Maintenance

Presenting Institution: V.Ships

Problem Presenter: Adrian Box

Abstract (Technical Topics and Desired Outcomes): V.Group is the leading global provider of Maritime Support Services.

Operating around the clock and around the world, V.Group aims to give every client the quality and efficiency they need in every sector, whilst driving transformation within the industry as a whole. Covering crew management, recruitment, quality ship management and technical services, we have an unrivalled industry knowledge, but also critically with respect to this project, the largest ship information database of any commercial entity in the world.

Our database covers all aspects of vessel operational and technical management, such as routes sailed, crew information, purchasing spend and suppliers, maintenance schedules, observations and history - stretching back decades.

The Maritime industry has for many years carried out the majority of its maintenance activities based on a traditional combination of manufacturer's guidelines and time based maintenance interventions. More recently, Condition Based Maintenance (CBM) has been introduced; however, this has not been as widely or extensively adopted as originally envisaged. There are a considerable number of barriers to wider adoption of CBM within the Maritime industry, not least the limited understanding and articulation of the opportunity that CBM represents.

Leaders in the industry are already looking beyond CBM towards Predicative Planned Maintenance (PPM). PPM currently represents the 'holy grail' in terms of maritime maintenance practices, with some major manufactures now even talking in terms of dynamic maintenance scheduling.

Lots of players are engaged in this space but no have so far none have landed a method of taking normal historic records, learning from them and then projecting those learning forward in the form of intervention plans; however, no one else has our database.

We believe that there are significant and real tangible advantages for British Industry to be at the forefront of Maritime PPM creating a value chain around equipment quality rather than low initial cost with hidden high in service life time costs. Arguably however the real value is in efficiency, be it the cost of operation, time lost during unnecessary interventions, cost of unexpected failure.

Thought this collaboration project we have an unique opportunity, for the first time, to team leading and innovative thinkers with the largest Marine Database; we believe this is a game changer.

Recognising the extent of our data, we propose to set a focused challenge utilising a small easily defined data set.

Challenge: All ships are primarily a system of systems. A major and numerous part of the vessels eco systems are pumps.

The vast majority of pumps on-board receive minimal attention, both in terms of maintenance and focus of the engine room staff. The resulting contact points are therefore either for routine intervention (planned maintenance) or in case of breakdown. In many cases planned maintenance interventions result in the unnecessary opening and 'stripping down' of good condition fully operational pumps for inspection - in many cases the pump is 'never the same again'.

The efficiency implications, on numerous levels, of these actions are significant.

The aim of this Study Group challenge is to objectively determine the effectiveness of current pump maintenance routines and based upon these experiences; seek to both predict future interventions (maintenance) and map meantime between failures - in essence the basis of a predictive maintenance algorithm.

Mathematical challenges:

1. What is the most common cause of failure of the pumps on-board our vessels?
    - Which types of pumps fail the most?
    - On which systems are the pumps failing the most?
    - What is our meantime before failure rate? (MBTF)
2. How effective is our maintenance and associated planning?
    - Where is the most common location for pump maintenance? (at sea, in port, in drydock, etc)
    - What is the difference in cost and savings potential between planned and unplanned maintenance?
    - Is our method of maintenance increasing the pump failure rate?
3. Is the procurement process for our pumps effective?
    - Is our purchasing "cost effective" or are we going for the cheapest supplier available?
    - Are the spares being purchased and delivered effectively? (e.g. are we purchasing them in advance or are we doing it in an emergency?)
    - How effective is our internal procurement process? (time between order raised, approved, delivered, etc)
    - Are there any differences between the various suppliers?

4. Is there a human factor involved in the maintenance of our pumps and associated failures?
   - Which ranks are performing maintenance on which pumps?
   - Is there much of a difference between failure rates / cost when overhauled by ship staff or service engineers?

Resources available at the Study Group: We would propose that our data set contain the following parameters:

Vessel and Fleet Particulars, Vessel Position List, Equipment Register and Details, Planned Maintenance System, Running Hours information, Maintenance history, Maintenance assignations, Spares usage, Procurement Information, New purchase pricing, Spare component pricing

3 Participants

	First Name	Surname	Institution
1.	David	Abrahams	University of Cambridge
2.	Douglas	Alem	University of Edinburgh
3.	Ashwin	Arulselvan	University of Strathclyde
4.	Vitali	Avagyan	University of Edinburgh
5.	Andrew	Bedwin	V.Insight
6.	Konstantinos	Belesiotis	V.Insight
7.	Ramzy	Ben-Rehouma	V.Ships
8.	Jim	Berryman	Knowledge Transfer Network
9.	Adrian	Box	V.Ships
10.	Meagan	Burke	Upside Energy Ltd.
11.	Matt	Butchers	Knowledge Transfer Network
12.	John	Carter	Duodrive Ltd.
13.	Aakil	Caunhye	University of Edinburgh
14.	James	Cruise	Heriot-Watt University
15.	Cathal	Cummins	University of Edinburgh
16.	Chris	Dent	University of Edinburgh
17.	Jessica	Enright	University of Edinburgh
18.	Nick	Good	Upside Energy Ltd.
19.	Alastair	Heggie	University of Edinburgh
20.	William	Holderbaum	Manchester Metropolitan University / University of Reading
21.	Gulen	Insay	V.Insight
22.	Joerg	Kalcsics	University of Edinburgh
23.	Marion	Lemery	University of Edinburgh
24.	Andrew	Lacey	Heriot-Watt University
25.	Yuan	Li	University of Birmingham

	First Name	Surname	Institution
26.	Gabriel	Lord	Heriot-Watt University
27.	Scott	Marquis	University of Oxford
28.	Simon	Marr	Bayes Centre
29.	Olivier	Masnyk	V.Insight
30.	Peter	McCallum	Heriot-Watt University
31.	Ken	McKinnon	University of Edinbrugh
32.	Cameron	McNatt	Mocean Energy
33.	Simone	Michele	Loughborough University
34.	John	Ockendon FRS	University of Oxford
35.	Sandhya	Patidar	Heriot-Watt University
36.	Ian	Paul	V.Insight
37.	John	Pearson	University of Edinburgh
38.	Emiliano	Renzi	Loughborough University
39.	Chris	Retzler	Mocean Energy Ltd.
40.	Gail	Robertson	University of Edinburgh
41.	Nestor Yuri	Sanchez Guadarrama	University of Edinburgh
42.	Albert	Sola Vilalta	Heriot-Watt University (MIGSAA)
43.	Robert	Timms	University of Oxford
44.	Dawn	Wasley	ICMS
45.	Tim	Weelinck	University of Edinburgh
46.	Amy	Wilson	University of Edinburgh
47.	Ben	Wilson	Edinburgh City Council
48.	Henry	Wynn (Virtual)	London School of Economics

4 ICMS, Edinburgh Information

ICMS is located within the Bayes Centre, 47 Potterrow, Edinburgh EH8 9BT. The map below shows the approximate location of the ICMS in relation to city centre landmarks. Edinburgh has a compact city centre and ICMS is within reasonable walking distance of the main rail and bus stations.

4.1 Travel to ICMS

Train: Edinburgh has several railway stations. Waverley Station is at the east end of Princes Street and is most convenient for visiting ICMS at in Potterrow whether you continue by taxi, by bus or on foot. You can get a number of buses on Princes Street (opposite the Scott Monument) to South Bridge or Nicolson Street. Please consult the Lothian Buses website for full details of services.

Car: ICMS does not have its own car park. There is limited on-street parking in the area. It is expensive and designed for short stays. If, however, you have a Blue Badge for disabled parking the charges are waived.

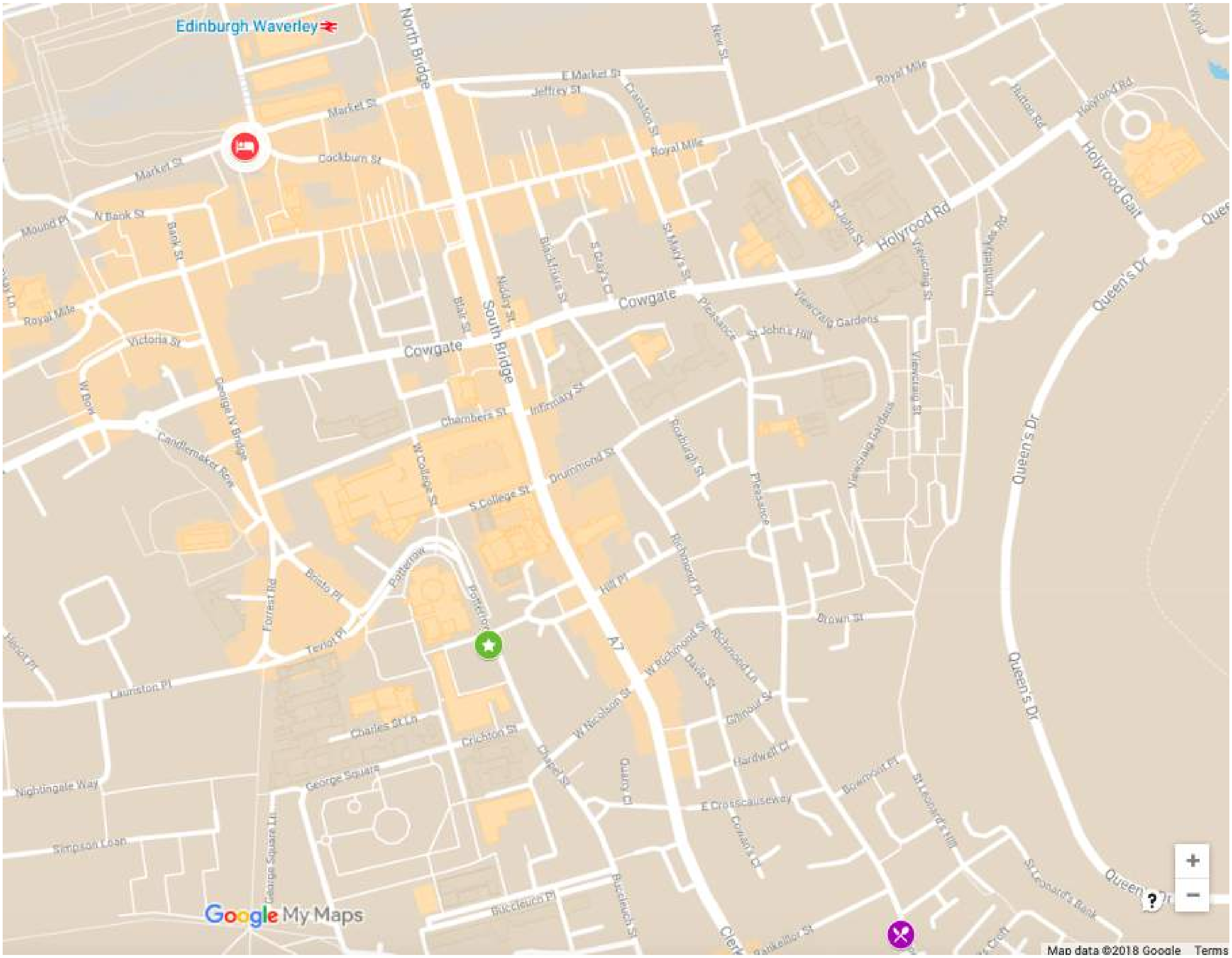
There are two car parks within walking distance of ICMS. One is in Blackfriars Street, just off the Royal Mile and the other is in the at St John's Hill, on the Pleasance. This list shows all city centre car parks, has links to maps for each one and realtime information about the spaces available.

For more information on parking see the City of Edinburgh Council parking web page.

Bus: There are two bus companies in Edinburgh. Links to their sites are given below. Both sites carry timetables. The buses in Edinburgh are not equipped to give change. You should carry a selection of coins in order to have the exact fare.

- **Lothian Buses:** The largest bus company in Edinburgh. Routes 2, 3, 5, 7, 14, 23, 27, 29, 30, 31, 33, 35, 37, 41, 42, 45, 47, 67 and 300 all pass close to ICMS. The fare for any single journey is a £1.70. An all-day pass costs £4.00.
- **First Edinburgh:** First Edinburgh also provide some local bus services in the city and the surrounding towns. Many of their routes will take you to South Bridge and Nicolson Street, which are not far from ICMS. Fares on these buses vary according to distance and are around £1.70.

4.2 Campus Map



- Green Star - ICMS, The Bayes Centre, 47 Potterrow, Edinburgh EH8 9BT
- Red Bed - Motel One Edinburgh - 18 Market St, Edinburgh EH1 1BL
- Purple Knife & Fork - Blonde Restaurant, 71 -75 St. Leonard's St, Edinburgh EH8 9QR

5 Supporting Organisations

5.1 Knowledge Transfer Network

Innovate UK
Knowledge Transfer Network

KTN Connects people. To speed up innovation, solve problems and find markets for new ideas. Established to foster better collaboration between science, creativity and business, KTN has specialist teams covering all sectors of the economy - from defence and aerospace to the creative industries, the built environment to biotechnology and robotics. KTN has helped thousands of businesses secure funding to drive innovation. And we support them through their business cycle to see that investment through to success.

Contact(s): Matt Butchers
Website: http://www.ktn-uk.co.uk

5.2 School of Mathematics, University of Edinburgh

THE UNIVERSITY of EDINBURGH

The School of Mathematics is situated in the James Clerk Maxwell Building within the King's Buildings campus, 4 km south of Edinburgh city centre. There are over 50 academic and related staff and around 60 research students.

Contact(s): Chris Dent
Website: https://www.maths.ed.ac.uk/school-of-mathematics

5.3 International Centre for Mathematical Sciences, Edinburgh

ICMS supports research in the mathematical sciences. Its core activity is the development and organisation of international workshops and conferences in all areas of mathematics and these attract leading mathematical scientists from the UK and overseas. In addition to workshops, ICMS is involved in a number of other mathematical activities such as small group research programmes, postgraduate training, journal management and outreach.

Contact(s): Dawn Wasley and Paul Glendinning
Website: http://www.icms.org.uk

Appendix A Wave Channel Theory

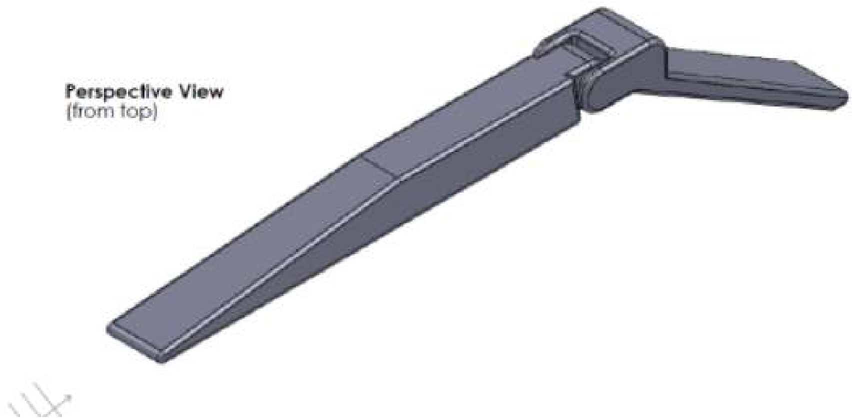


Figure 2: Mocean WEC geometry submitted with WES NWEC1 Application

From its inception, the Mocean WEC has been characterised by sloped surfaces. Fig. 2 shows the geometry that we submitted for our NWEC Stage 1 application. It has sloped faces on both the forward and the aft hulls.

These geometries were found through an optimisation routine using the hydrodynamic software WAMIT. We did *not* design the geometry with the intention of creating a particular effect, and so part of the R&D process has been understanding why the geometries that arose from the numerical optimisation behave as they do.

At the time of our NWEC1 application, we believed the effect of this geometry was to alter the ratios of the mass, added mass, and hydrostatic restoring forces, and to create cross-coupling between modes of motion to tune the resonant response of the WEC to the dominant frequencies of the simulated seas. We still think this is an important aspect of the WEC's performance, but we believe the sloped faces also increased the wave excitation force via a wave resonance.

A.1 Wave Channel Description

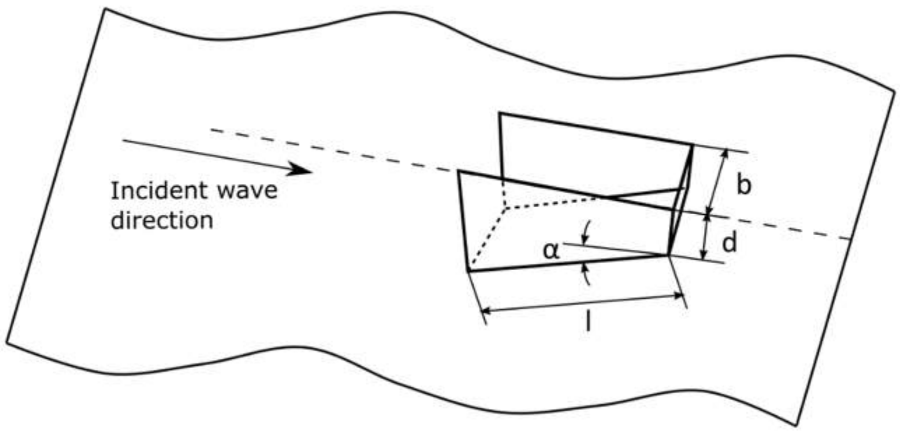


Figure 3: General arrangement of generic wave channel.

Fig. 3 shows the general arrangement of a generic wave channel. It consists of three types of surfaces:

- a sloped base plate,
- side walls,
- an end wall.

There are four parameters that described the geometry:

- width (or beam) of the wave channel: b,
- length of the base plate: l,
- angle of the base plate with respect to calm water surface: α,
- depth of start of slope of plate: d.

A.2 Comparison to Alternative Geometries

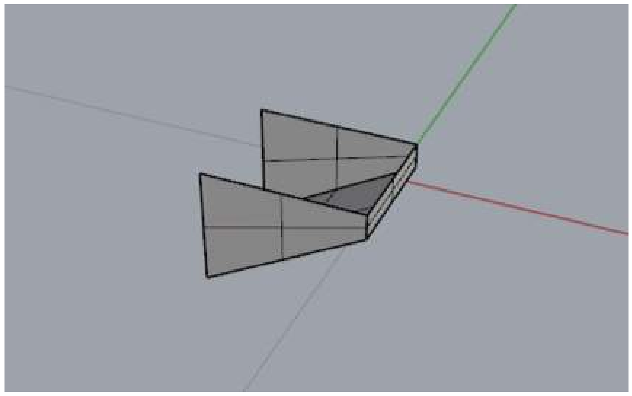


Figure 4: Wave channel used in geometry comparison. Note channel has same dimensions as those tested on the Phase 1a model.

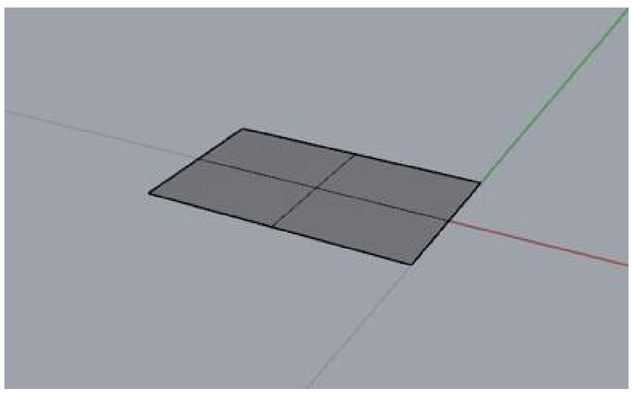


Figure 5: Horizontal plate tested in geometry comparison

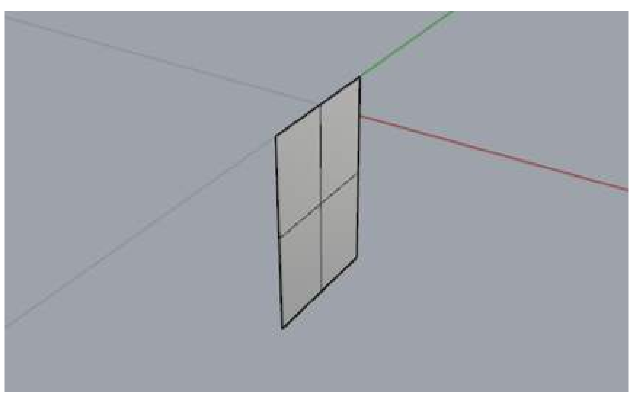


Figure 6: Vertical plate tested in geometry comparison

To describe the impact of the fluid resonance, we will begin by comparing the wave excitation forces on a wave channel (Fig. 4) to those on an equivalent horizontal plate (parallel to the free surface; Fig. 5, and vertical plate (perpendicular to the free surface; Fig. 6. The wave channel has the same dimensions as the channels on the model tested in the Phase 1a testing. The dimensions of all geometries are given in Table. 1.

Table 1: Dimensions of the geometries evaluated in the wave channel comparison

	Width	Length	Angle	Depth	Sidewalls	Area
Units	m	m	*degrees*	m		m^2
Wave channel	0.189	0.280	30	0.038	Yes	0.113
Horizontal Plate	0.189	0.280	0	-	No	0.113
Vertical Plate	0.189	0.280	90	-	No	0.053

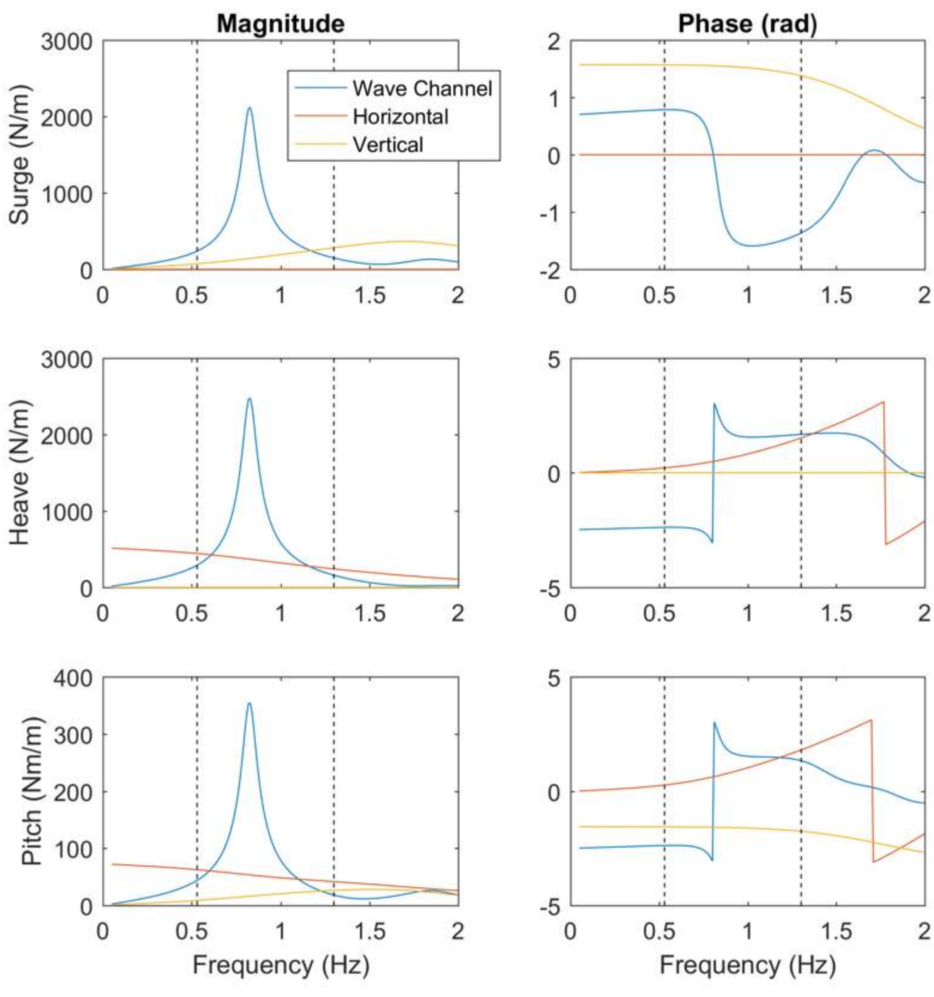


Figure 7: Excitation force and torque on the wave channel, the horizontal plate and vertical plate as a function of frequency. The dashed vertical lines indicate the limits of frequencies that were tested in the Phase 1a regular wave tests.

Fig. 7 shows the wave excitation force and torque (as magnitude per unit wave amplitude, and as phase) on the wave channel, the horizontal plate, and vertical plate as a function of frequency. The dashed vertical lines indicate the limits of frequencies that were tested in the Phase 1a regular wave tests. The torque is about the top of the end wall for the wave channel, the back edge in the horizontal plate, and the top edge in the vertical plate.

The wave channel shows a clear peak in excitation force/torque at a frequency of f = 0.83 Hz, which is not present in the horizontal or vertical plates. The peak is much higher than that on either of the other geometries. The wave channel does have more surface area, but even when the maximum values are normalized by surface area, the wave channel exceeds the other two geometries in peak force and torque; see Table. 2.

Table 2: Peak force/torque per area for the three geometries considered in the comparison

	Peak surge force per area	Peak heave force per area	Peak pitch torque per area
Units	$kN/m/m^2$	$kN/m/m^2$	$kNm/m/m^2$
Wave channel	18.8	22.0	3.1
Horizontal plate	0	9.7	1.4
Vertical plate	6.9	0	0.5

A.3 Wave Fields

In this section, the wave fields of the three geometries are compared and the wave field of the wave channel is examined in more detail.

Fig. 8 shows the wave fields of the three geometries held fixed for the wave frequency, f = 0.83 Hz, which is the frequency of the peak of the wave channel force curves. The column on the left shows the wave elevation at an instant in time (t = 0) and the column on the right shows the wave elevation magnitude.

The wave channel causes a significant disturbance in the wave field. In the left-hand column, one can see the that for the wave channel, the wave crests are disturbed from being long and straight, while for the other two geometries, the crests are still mostly straight. In the right-hand column, the plot of the wave elevation magnitude shows that the wave channel creates significant standing wave crests, which are manifested as parabolic ridges around the geometry. However, the other two geometries show little impact on the wave field (magnitude plot is mostly green).

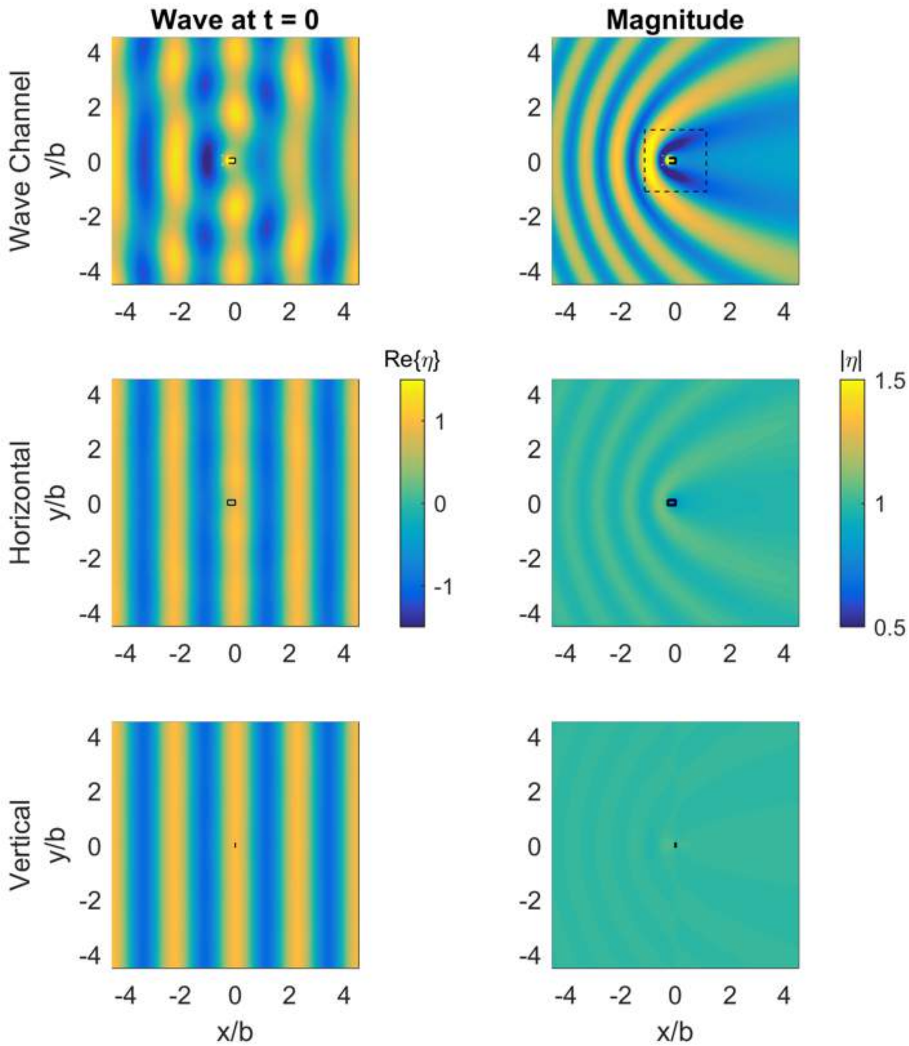


Figure 8: Wave fields of the three geometries held fixed for the wave frequency, f = 0.83 Hz. The column on the left shows the wave elevation at an instant in time (t=0), and the column on the right shows the wave elevation magnitude.

Fig. 9 shows a close-up of the wave channel wave field. The close-up location is indicated by the dashed line in the wave channel magnitude plot in Fig. 8; note that the colour scales between the two plots are very different. In Fig. 9, we see that the magnitude of the wave inside the channel goes up to 14 times the incident wave amplitude.

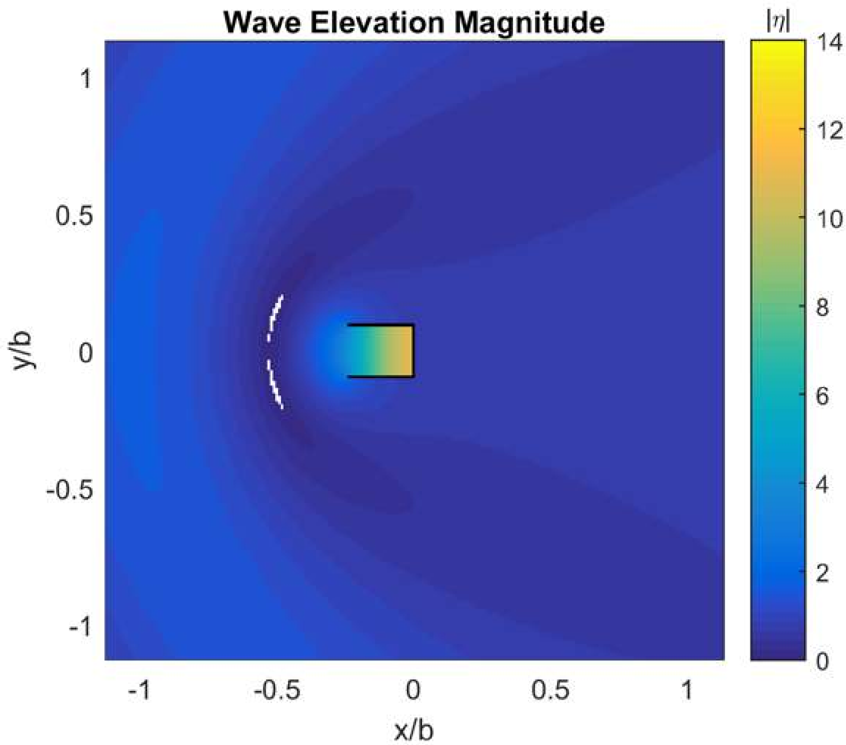


Figure 9: Close-up of the wave channel wave field. The close-up location is indicated by the dashed line in the wave channel magnitude plot in Fig. 8; note that the colour scales between the two plots are very different.

This fluid behaviour is further elucidated by watching videos. Two videos are submitted with this deliverable:

- `MOE-10039-D20waveChanAnim.avi` - animation of the wave field around the wave channel geometry considered here at a frequency of 0.83 Hz, which is the frequency of max wave force/torque.
- `MOE-10040-D20waveChanExper.avi` - slow motion video of the physical tests that Mocean carried out between NWEC1 and NWEC2. The video shows a model held fixed through and overhead load cell. The dimensions of the wave channel are: b = 0.20 m, l = 0.20 m, d = 0.03 m, α = 20°. The video shows a regular wave results at a frequency of 0.84 Hz. These experiments are described in two Mocean internal reports: "Mocean Small-scale Excitation Force Tests - Feb 2017" and "Mocean WEC, Wave Excitation Tests, UoE Hydraulics 20 m Flume - March 2017".

Both videos show a single wave cycle, and are best viewed by setting the video player to "Repeat".

In the wave channel animation, one sees a fluid behaviour inside the wave channel that is clearly not physically possible.

In the experimental video, one sees that the wave amplitude inside the channel is much higher than that of the ambient wave that passes by on the outside of the channel. The wave amplitude is limited by steepness wave breaking, a fluid jet formation, and overtopping of the end of the channel.

We conclude that the wave channel geometry causes a fluid resonance inside the wave channel. This results in increases in wave excitation forces. Linear models, which do not inherently have any constraints on wave elevation predict wave elevations and forces that are not physically obtainable.

A.4 Wave Forces on Various Angles

It is interesting to test the impact of altering wave channel dimensions on the wave forces. While not all parameters will be considered here, since the model in the physical tests could easily be adjusted to change the base plate angle, we will consider this.

Fig. 10 shows a plot of the wave channel excitation torque for the wave channel geometry previously considered at various wave channel angles. The plot is normalized by the values of frequency and torque of the channel at 30°. One can see that as the angle decreases, the peak of the torque increases, gets narrower and moves to lower frequencies. The opposite is true as the angle increases.

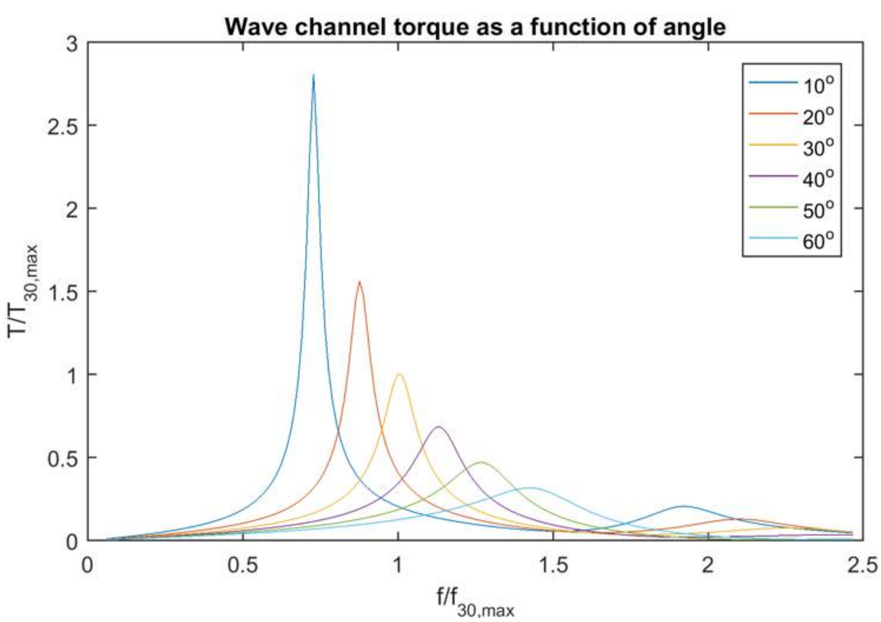


Figure 10: Wave channel excitation torque at various wave channel angles.

A.5 Ursell's Trapped Mode Theory

Ursell's paper, "Trapping modes in the theory of surface waves" (1951), was the first to describe (to our knowledge) the phenomenon of a wave trapped mode in water waves. He describes a trapped mode as:

> *"a mass of fluid bounded by fixed surface and by a free surface of infinite extent may be capable of vibrating under gravity in a mode (called a trapping mode) containing finite total energy."*

That is, trapped waves are waves that do not propagate away from the body to infinity, but exist locally, and it the absence of viscosity would persist for all time.

Interestingly, the first example of a trapped modes Ursell gives is for a semi-infinite channel with a sloped beach, which is a geometry very similar to the Mocean wave channel.

While we are not clear as to whether Ursell's theory is related to the behaviour we see in the wave channel, we feel that it may be, and that his work is important to understand. And so, we rederived the theory presented in 4 to get it into coordinates that we are familiar with, and to ensure that we understand it correctly (the Ursell work was somewhat confusing because it did not contain a diagram).

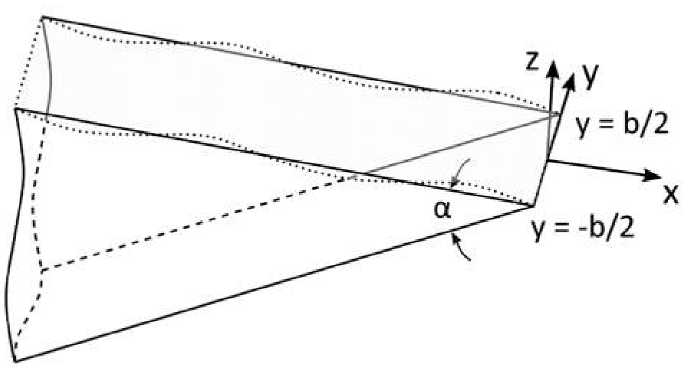


Figure 11: Geometry of Ursell for which wave trapped modes can occur.

Fig. 11 shows Ursell's geometry (in our coordinates system and parameter definition) for which wave trapped modes can occur. Ursell gets a solution for the wave elevation:

$$\eta(x, y) = A \exp(k \cos\alpha \cdot x) \cos ky \tag{1}$$

where A is a complex amplitude, and k is the wave number, where the wavelength, $\lambda = 2\pi/k$, is related to the channel width by:

$$\lambda = \frac{b}{n}, \qquad n = 1, 2, 3, ... \tag{2}$$

That is, only wavelengths where n times the wavelength is equal to b can exist. These represent standing waves between the two sidewalls.

He also gives a relationship between the wave number, the channel slope and the wave frequencies

$$\omega^2 = gk \sin\alpha \tag{3}$$

which is analogous to the usual dispersion relation.

Plots of various orders of solutions for Ursell's wave trapped modes are shown in Fig. 12. These are standing waves between the channel walls, that decay exponentially with channel depth.

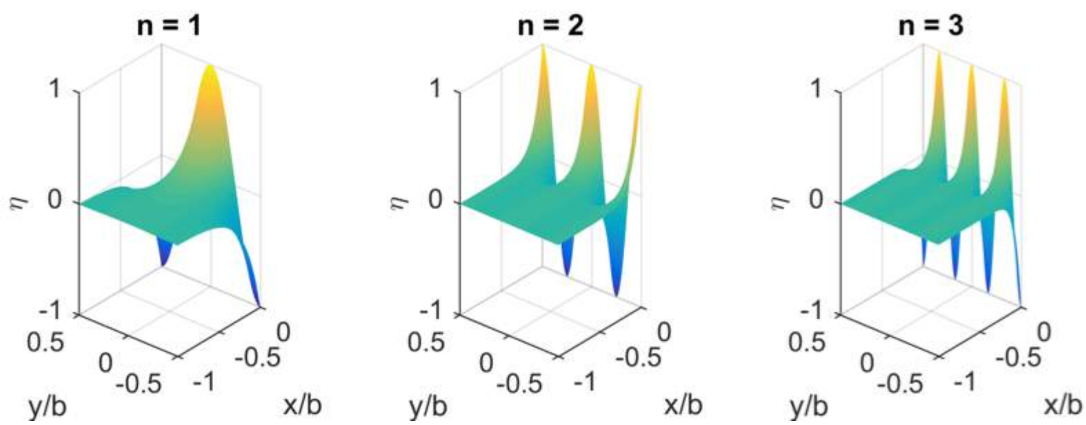


Figure 12: Wave trapped modes as solved by Ursell (1951).

The similarities between the wave trapped modes as described by Ursell and the fluid resonance that we observed on the channel are:

1. Both occur in a geometry characterized by a sloped bottom and side walls.
2. Both describe extreme fluid behaviours, i.e. large fluid motions that decrease with distance down the channel.

The differences are that:

1. Ursell's geometry is infinitely long, while the Mocean channel is finite length, within an infinite wave domain.
2. Ursell's waves are not forced by other waves (it is a mathematical situation), while the Mocean channel waves are excited by incident waves (or body motions).

3. Ursell's waves propagate back and forth between the side walls, while the Mocean resonant flow is more in-and-out of the channel. However, it may be that the Mocean wave forces could be described by a Fourier sum of Ursell waves, but more work is needed to show this.
4. The frequencies of Ursell's waves are higher than those at which the Mocean channel is excited. For example, the first order wave as predicted by Ursell for a channel of the same width at our model at α = 30°, would occur at f =2.03 Hz, while we see the peak in the Mocean channel at f = 0.83 Hz. However, the dispersion relation put forward by Ursell is not related (yet) to the more familiar flat-bottom dispersion relation. It may be that wave shoaling in the channel shortens wave sufficiently to create the Ursell resonance effect.