Institution: University of Surrey

Unit of Assessment: UOA 10 Mathematical Sciences

Title of case study: Modelling and analysis of ocean wave energy extraction devices

1. Summary of the impact (indicative maximum 100 words)

Extraction of energy from ocean waves is a high-priority sustainable-energy initiative in the UK. The OWEL wave-energy convertor involves a floating rectangular box which captures waves and extracts their energy. This configuration dovetails with research at the University of Surrey on fluid sloshing in rotating-translating rectangular containers.

The Surrey team is providing underpinning mathematics for the modelling and has led to the development of a suite of algorithms that are being tailored for use to optimise system parameters. The outcome is direct impact on the wave energy industry and indirect impact on the environment and the economy.

2. Underpinning research (indicative maximum 500 words)

The device under development at OWEL (Offshore Wave Energy Ltd) is rectangular in shape, floats on the surface secured by mooring cables, and it traps waves inside. A novel power take off (PTO) system extracts the energy from the waves. Hence the interior fluid motion is similar to shallow water sloshing, with oscillatory mass input and output at the ends, in an almost rectangular vessel undergoing fully three-dimensional rotation and translation. At Surrey, research in the area of shallow water sloshing in moving vessels has been on-going since 2008. The Surrey theory, although developed independently, is a perfect match for the required underpinning theory for OWEL, and an alternative to CFD.

The research team at Surrey consists of Tom Bridges (Professor), Matt Turner (Lecturer) and Hamid Alemi Ardakani (former PhD student, now Postdoc). This project discovered a new set of shallow water equations for sloshing in a vessel undergoing fully three-dimensional motion. In addition, the project has produced

(a) A numerical method for shallow-water sloshing in 3D rectangular vessels with prescribed motion of the vessel (e.g. from ocean wave forcing). The numerical method is implicit, robust and fast (compared with fully 3D simulations). Results on a number of configurations and forcing have been published in [4].

(b) A theory and numerical framework for dynamic coupling between the vessel motion and the fluid motion. Coupled simulations are difficult because a proper energy partition needs to be maintained. Using a Lagrangian formulation, an approach was developed at Surrey for maintaining accurate energy partition for long times. Initial results are published in [5].

(c) The linear and nonlinear implications of resonance between the fluid and vessel motion. Resonances can create physical transfer of energy between the vessel and fluid motion. This energy transfer can be positive (used to control vessel motion) or negative (transfer of energy from the wave to vessel motion, rather than PTO). The Surrey project shows how to identify these resonances and analyse the nonlinear implications. Recent linear results are reported in [3] and nonlinear results on (positive and negative) energy transfer are published in [2].

(d) The effect of baffles on resonance structure and control of sloshing motion, including coupling with vessel motion, recently published in [1].

(e) Motivated by the OWEL configuration, development of a two-layer two-layer shallow-water model with variable bottom and cross section, which includes a model for the escape of the upper fluid into the PTO.

(f) The OWEL team have provided the Surrey team with a vast amount of (confidential) data, including measurements and videos, obtained from experiments at HMRC (UCC, Ireland), University of Southampton wave basin, and the Plymouth University wave basin, and this data is being used for comparison with the modelling.

3. References to the research (indicative maximum of six references)

The principal underpinning research is reported in the following five papers.

1. M.R. Turner, T.J. Bridges & H. Alemi Ardakani. *Dynamic coupling in Cooker's sloshing experiment with baffles,* Phys Fluids **25** 112102 (2013b). http://dx.doi.org/10.1063/1.4827203
2. M.R. Turner & T.J. Bridges. *Nonlinear energy transfer between fluid sloshing and vessel motion,* J Fluid Mech **719** 606-636 (2013a). http://dx.doi.org/10.1017/jfm.2013.29
3. H. Alemi Ardakani, T.J. Bridges & M.R. Turner. *Resonance in a model for Cooker's sloshing experiment,* Euro J Mech B/Fluids **36** 25-38 (2012). http://dx.doi.org/10.1016/j.euromechflu.2012.04.007
4. H. Alemi Ardakani & T.J. Bridges. *Shallow-water sloshing in vessels undergoing prescribed rigid-body motion in three dimensions,* J Fluid Mech **667** 474-519 (2011). http://dx.doi.org/10.1017/S0022112010004477
5. H. Alemi Ardakani & T.J. Bridges. *Dynamic coupling between shallow-water sloshing and horizontal vehicle motion,* Euro J Appl Math **41** 479-517 (2010). http://dx.doi.org/10.1017/S0956792510000197

The project has also been supported by four grants.

- Leverhulme Trust Fellowship, "*Three-dimensional shallow-water sloshing in rotating vessels*", 2009-10, £ 42K; PI: Bridges
- ORS award for PhD studies of H. Alemi Ardakani, 2007-10 (the last ORS award made to Maths at Surrey by Universities UK before the scheme was discontinued); approx £30K; PI: Bridges
- Internal grant from the department for a one-month postdoc in Spring 2013.
- EPSRC grant EP/K008188/1: "*Dynamics of floating water-wave energy extraction devices*," PI: Bridges, Co-I: Turner, 2013-2016, £291K, http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/K008188/1

There is also a wide range of internal reports and preprints and they can be found on the website: http://personal.maths.surrey.ac.uk/st/T.Bridges/SLOSH/

A Non-disclosure agreement has been signed between the University of Surrey and OWEL and ITPower Ltd (ITPower Ltd is the largest shareholder and parent company of OWEL). This covers the exchange of information and data between OWEL/ITPower and the Surrey team. The content of this impact case study is general enough that it is not affected by the NDA; concomitantly discussion of the detailed data is not needed for this impact case study.

The website for OWEL is http://www.owel.co.uk

4. Details of the impact (indicative maximum 750 words)

The interaction between OWEL and Surrey began in August 2011, when a member of the research and team at OWEL contacted Surrey. They had seen the sloshing website, with its published papers and reports on shallow water sloshing in three-dimensional rotating and translating vessels. It was exactly what was needed for their project.

At the time, OWEL was using CFD (Computational Fluid Dynamics) for fully 3D simulations.

However CFD is very time consuming. The Chief Technical Officer at OWEL writes "*It takes between 3 and 9 days to get a simple CFD model to run and, as we have 60 odd load cases, it is too long by far. CFD is also a bit of an unknown in terms of quality, and validating it against physical models has been tricky and is on-going*." The principal CFD researcher at OWEL adds "... *and we need to increase the real time in simulations by a factor of 10! This is clearly impractical*."

"*The interaction with Surrey has changed our research programme into the modelling of the OWEL WEC. This new approach to modelling is being used to (a) optimise the power conversion performance by simulating various naval architectural layouts and control strategies …; (b) cross-validate the CFD models; (c) provide direction for new experiments …. These tasks … are essential to the commercial success of the machine*."

OWEL was interested in a more refined mathematical model built around the shallow water equations (SWEs) for the interior flow. By comparison the Surrey shallow water code has run times of the order of minutes. The OWEL CFD researcher writes "*With the speedup obtained using the SWEs, it will become the basis of an optimisation tool, which is needed to identify optimal physical geometry, mooring characteristics, and implementing control systems*."

Initially the Surrey team sent the SWE codes to OWEL and advised them on shallow water hydrodynamics. This interaction was low key for the first year. When one of the main research engineers departed from the OWEL project, a plan was set in motion to obtain funding for a large-scale Surrey input into the project. An EPSRC grant, awarded in Spring 2013, has provided the infrastructure to make this happen. The department also provided bridging funds, and the post-doc (Alemi Ardakani) starting working on the project in March 2013.

The principal impact, going back to the initial interaction, has been that the Surrey team has changed the way OWEL/ITPower approach the problem of using theory and simulation to understand the problem. CFD has enormous value, but is insufficient as a design tool. The approach based on the shallow water equations is now a firm part of the OWEL R&D strategy. The inventor of the original OWEL WEC configuration and founder member of the company OWEL remarked: "*This is just the kind of underpinning research that I wish we had when we started the project ten years ago*!"

"*I believe development of the OWEL WEC would have progressed at a much faster rate if the modelling capabilities of the Surrey team had been available ten years ago. However, their study is still timely in that it is complementary to the extensive tank-testing result already collected by the OWEL team." And "In my view, the improvement in efficiency that I expect to follow from the Surrey study is likely to lead to the design of the first wave energy device that is commercially viable*."

The research interaction is now fully developed. In addition to the shallow water approach, the project has expanded in two other directions: linear and nonlinear implications of resonance in the OWEL WEC coupled system, the stabilisation and control (the more stable the OWEL WEC is when at sea, the higher the efficiency in the PTO).

The Surrey-OWEL interaction is planned for the long term. The EPSRC grant runs to 2016, the Surrey team has secured funding for a 3.5 year PhD studentship starting in October 2013, and OWEL has a 20 year plan for implementing successively more refined wave energy extraction devices, so the Surrey team is impacting R&D at an early stage of the project. A test prototype (called the "Marine Demonstrator") has been designed and, subject to construction scheduling, is expected to be deployed at "WaveHub" in summer 2014. The current OWEL WEC has deficiencies, and it is the analysis and optimisation to remove these deficiencies that is the principal aim of the Surrey and OWEL teams, in preparation for the next generation prototype.

The impact on the environment and economy is expected to be significant. Approximately 35% of the wave energy available to Europe is directed at the UK, which is therefore well-positioned to lead wave energy extraction research in the region. A strong combined industry-governmentacademia initiative is underway and gathering momentum. As of March 2011 the UK has 3.4MW of installed marine energy capacity, with an additional 23MW in planning: potentially 2.17GW of marine energy projects can be in place by 2020. Indeed, it is predicted that marine energy could ultimately provide 20% of UK electricity consumption. In preparation the government has supported the design and construction of “WaveHub” which is an offshore test bed which WECs can plug into and feed generated electricity into the grid.

On-going impact on the ocean industry includes a “Water Waves in Industry Day” organised by Bridges which will be part of the Newton Institute programme on “Theory of Water Waves” in July 2014, where a range of speakers from the ocean industry are invited to speak about the role of the theory of water waves in their industry. The principal speakers are from the ocean wave energy industry.

5. Sources to corroborate the impact (indicative maximum of 10 references)

The various aspects of the impact are corroborated by letters and emails from

1. The Chief Technical Officer on the OWEL project. Provided statement.
2. Marine Engineer and principal CFD researcher on the OWEL project. Contact details provided.
3. The inventor (and original patent holder) of the OWEL WEC prototype and founder member of the company OWEL. Provided statement.