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## Harnessing the Power of Wave Energy Converters

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*The ocean wave energy industry is faced with immense challenges. In particular, there are uncertainties and negative perceptions surrounding the performance and survivability of wave energy conversion technologies. Building on classic mathematical models of wave energy converters, advanced simulations now offer the opportunity to assess these traits in a low risk and technically relevant manner.*

### Introduction

Humankind has long speculated at the origins of ocean winds, waves and tides, and the creatures sheltered beneath the ocean surface. Human creativity, rather than logical reasoning, has often filled gaps in knowledge of these subjects, and imaginations reflected the power, mystery and danger the ocean presented. Non-fictional accounts of ocean processes and biology now outnumber fictional writings on these subjects and humankind invests, heavily, in research focused on local and global

ocean processes. Many of the tools applied in these scientific pursuits resulted from ocean engineering achievements made in the hunt for oil and gas reserves beneath the seabed. “A Critical Review of the Nature of Vortex-Induced Vibrations” published in 2004 by T. Sarpkaya presents a relationship summarizing the increasing depths to which humankind now reaches in search of raw resources.

Sarpkaya’s relation suggests that ocean depths of 3700 m will be reached by 2013. Ironically, these ocean engineering tools are now used to gather data that supports climate change concerns that is motivating a move away from oil and gas and toward sustainable energy sources, including wave energy.

The scale and conceptual design of most wave energy converters (WECs) tend to evoke comparison to fictional sea monsters. Both current and past device names such as *Wave*

*Dragon, Pelamis, and Mighty Whale* seem to support the comparison. Nevertheless, if WECs and their mooring systems are not carefully designed to survive in extreme seas, violent failures (such as device overturning) can be expected. The engineers charged with taming the WEC in these conditions must draw on ocean and structural dynamics fundamentals to accurately predict the WEC response.

The goal of this article is to highlight advances in numerical simulation tools that recreate the ocean's interaction with this emerging class of ocean technology. While a great deal of WEC invention, model based design, and optimization has been completed to date, the simplified form of the dynamics models that are typically used leaves room for skeptics to question WEC performance claims. Of particular interest are the mooring lines, which must act as the figurative reins on these steel sea creatures. For floating WEC systems, the mooring systems must perform a difficult task: safely restrict the undesirable modes of motion while allowing the desirable, power producing modes of motion. Despite their importance, mooring systems are rarely discussed in conventional WEC dynamics analysis.

## Wave Energy Converter Development

*"Anything one man can imagine, other men can make real."* Jules Verne (1828-1905)

Unlike other renewable energy technologies like solar, wind, and tidal current, wave energy conversion is not well understood outside of the WEC engineering community. This is partly due to the lack of widespread implementation of WEC technology, but is also due to the plethora of WEC concepts currently under development. As a result, the term "wave energy converter" has no single specific connotation.

Most wave energy conversion concepts are not new. The first WEC patent was filed by a French engineer, Francois Girard, in 1799 for an invention inspired by the ability of ocean waves to lift large ships. Inventions to

capture wave energy using various operating principles proliferated between the mid 1800s and early 1900s. This was an age with far less sophisticated control over materials and construction and a much smaller market for the energy derived from waves.

For devices that employ surface floats to drive the energy conversion process (see Figures 1 and 2), a mooring is needed which allows the useful heaving motions of the float, restricts the unwanted motions, and delivers the kinetic energy of the float to the power-take-off system (mechanical, hydraulic or electrical). Despite this integral role, the text of these historic patents disregards mooring line design and dynamics.

The floats in the conceptions of Dempsey and Johansen shown in Figures 1 and 2 are ancestors of the modern point absorber, a

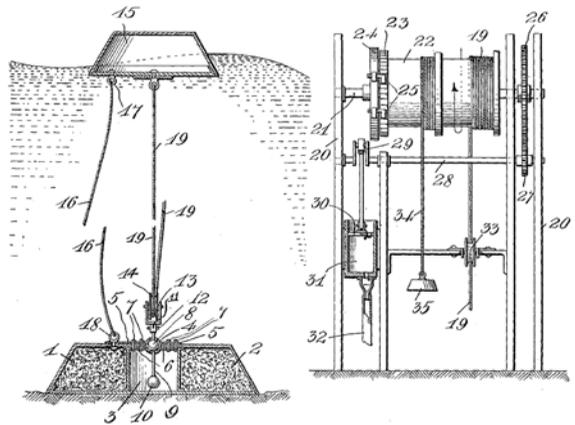


Figure 1: Images from F.M. Dempsey's "Wave Motor," U.S. Patent No. 819006, April 24, 1906.

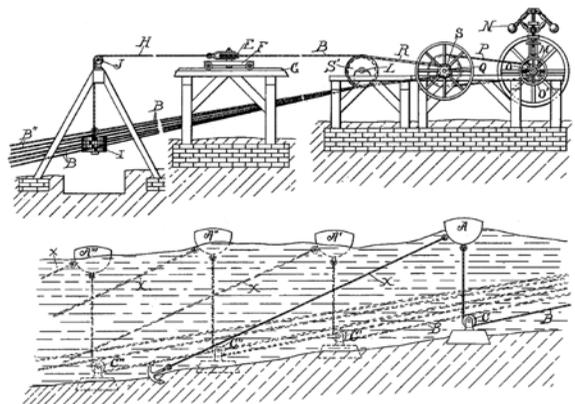


Figure 2: Images from R.L. Johansen's "Ocean Power" Invention, U.S. Patent No. 508320, November 7, 1893.

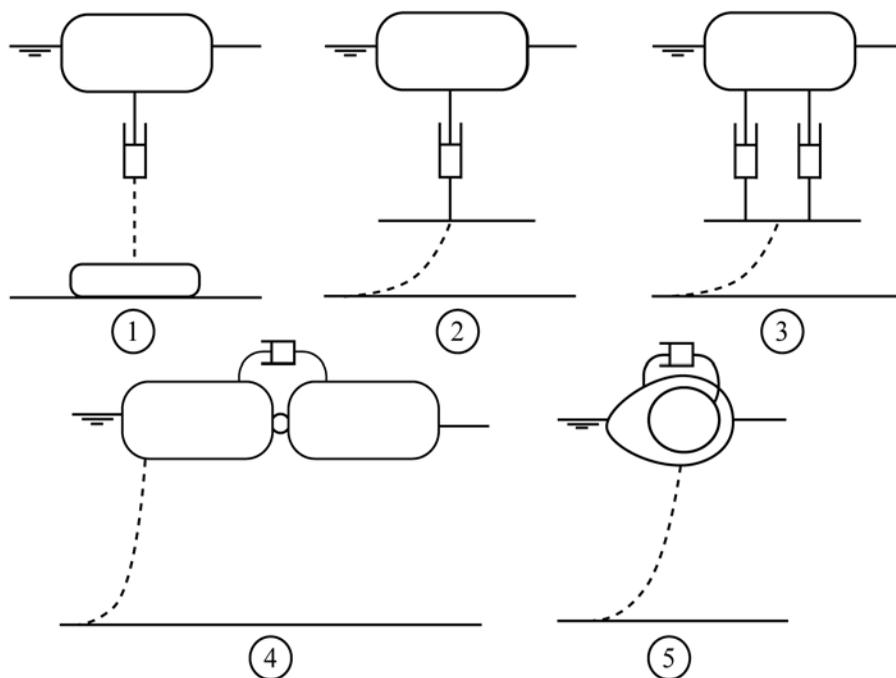


Figure 3: Generic classes of modern floating wave energy converters.

WEC that occupies a small surface area that is considered insignificant compared to the wavelengths of the waves from which it extracts power. To order the discussion of WEC technology, Figure 3 shows several generic classes of floating WECs. The key aspect of Figure 3 is the necessity of mooring most of the designs using a taut or slack mooring design.

Despite wave energy's rich history of thought from early inventions to modern research, the widespread use of wave energy technology in the portfolio of fossil fuel alternatives has yet to occur. In addition to meeting the challenges common to all sustainable energy technologies (i.e. managing intermittency and satisfying economic and environmental constraints), problems faced by WEC engineers are exacerbated by the ferocity of the resource they try to harvest. Unfortunately for the engineers who are driving WEC technology forward, development derived from trial and error is, in most cases, not a viable option.

An extensive body of dynamics modeling and optimization work has been completed for the concepts shown in Figure 3. That work has determined optimal configurations and geometries of the converter hulls and the power take-off systems. Most often, however, these models are idealized such that only the power producing motions of the converter are considered. The non-linear contributions to the remaining dynamics, such as mooring forces and frictional forces, are linearized or entirely removed. For optimization studies, these simplifications are necessary to increase the speed of the computations, which must be repeated millions of times in automated searches to find WEC geometries having acceptable performance across a range of prevailing sea states. While necessary, the simplified linear modeling techniques are not sufficient. An accurate assessment of the complete device dynamics must be made for specific sea conditions where non-linearities dominate the device behaviour, such as storm conditions.

Non-linear behaviour is best validated through tank testing of small-scale physical models. However, while low risk to the general population and the environment, wave tank testing is an expensive way for engineers to learn lessons in hindsight that are obfuscated by the complexity of the moored WEC system. A great deal of effort and expense goes into crafting a physically representative scale model. Additional challenges are confronted because the physical laws that govern the scaling of the hydrodynamic and structural stiffness effects of moorings are inherently in conflict.

As a device developer's first step, simplified dynamics modeling and optimization analyses are appropriate for early stage evaluation of WEC design concepts. As a second step, dynamic simulations are an inexpensive means to evaluate performance and risk of catastrophic failure modes while including the previously neglected but extremely important mooring systems and non-linear forces. Provided that the simulation software includes numerical representations of all the relevant physical processes, it can be used to evaluate detailed control strategies and survivability. The response of the moored WEC system in any sea state of interest, not just those available in the test tank, can be examined in detail before investing in physical models.

The authors use the ProteusDS simulation software environment. Complete systems, with multiple floating or submerged components including moorings, can be modeled and the dynamic response to any desired sea conditions can be fully realized through the time domain. Simulation-based design does have a cost: the user must understand the intricacies and limitations of the numerical methods to properly interpret the results. Other commercial simulation packages are available and are being applied to ocean engineering projects worldwide.

## **Dynamics Simulation of Moored Technologies**

A qualitative description of the fundamental components of dynamics simulation tools and how these effects are computed in ProteusDS

is given here. Case studies in which Dynamics Systems Analysis and University of Victoria researchers have applied dynamics simulation techniques to solve relevant ocean engineering challenges are given.

### ***Fluid interaction with floating bodies***

In ProteusDS, as with most simulation tools, buoyant "rigid bodies" are discretized into panels. Figure 4 shows how the geometry of an environmental monitoring buoy, a new WatchMate buoy developed by AXYS Technologies in 2009, was geometrically represented by a collection of flat panels for dynamic simulation. During simulation, the buoyant, drag, and inertial loads for each panel are considered independently, and subsequently integrated, leading to estimates of the forces applied by the fluid on the buoy.

The forces and moments due to buoyancy are calculated by analyzing the number and distribution of panels on the rigid body surface that are submerged. The relative velocity between each surface panel and the adjacent sea-water flow field is established, and drag forces are calculated by applying empirical or experimentally determined drag force coefficients to both the normal and tangential directions of each panel. Similar to the drag force estimation, the fluid inertial loading and added mass effects are modeled using either empirical or experimentally derived coefficients on a panel-by-panel basis. The distribution of forces is replaced by an equivalent force couple system at the buoy mass centre, and Newton's and Euler's equations of motion are evaluated for the buoy accelerations. This brute force numerical process is carried forward through time using standard numerical integration techniques such as an explicit adaptive time step Runge-Kutta method or an implicit integration technique such as the Generalized- $\alpha$  method. If the applied hydrodynamic coefficients of the model are accurate, the process yields an accurate depiction of the floating body's motion.

### ***Cable dynamics***

Since 2006, Dynamic Systems Analysis Limited (DSA) has partnered with the



Figure 4(a): WatchMate Wave monitoring buoy alongside.

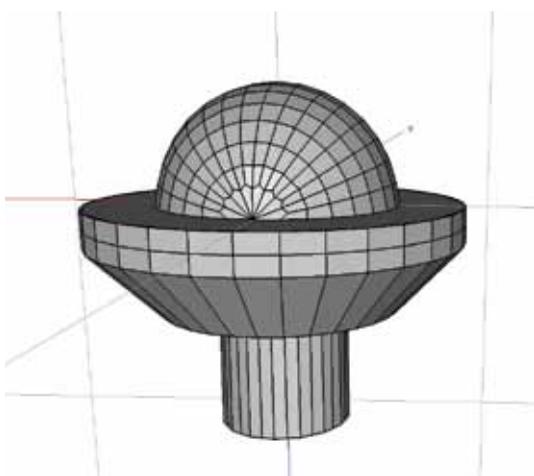


Figure 4(b): The mesh used to model it in simulation.

University of Victoria in the continuing development of a cable dynamics model that is accurate in both taut and low-tension situations. A cable is segmented into a serial arrangement of cubic spline segments with a characteristic axial, bending and torsional stiffness. A classic Morison's approximation is applied for the hydrodynamic loads and the mass of the cable is lumped at the node points of the model to afford fast evaluation of the cable dynamics equations using Newton's Second law. An advantage of the model is that it is expressed directly in terms of the cable node positions and so connections of a cable to a float, another cable, an anchor, etc. are guaranteed through all time. Figure 5 shows an instant of an aquaculture raft simulation, which shows three pontoon rafts (two rigid surface piercing floats each) anchored by bridled moorings with rigid subsurface shellfish

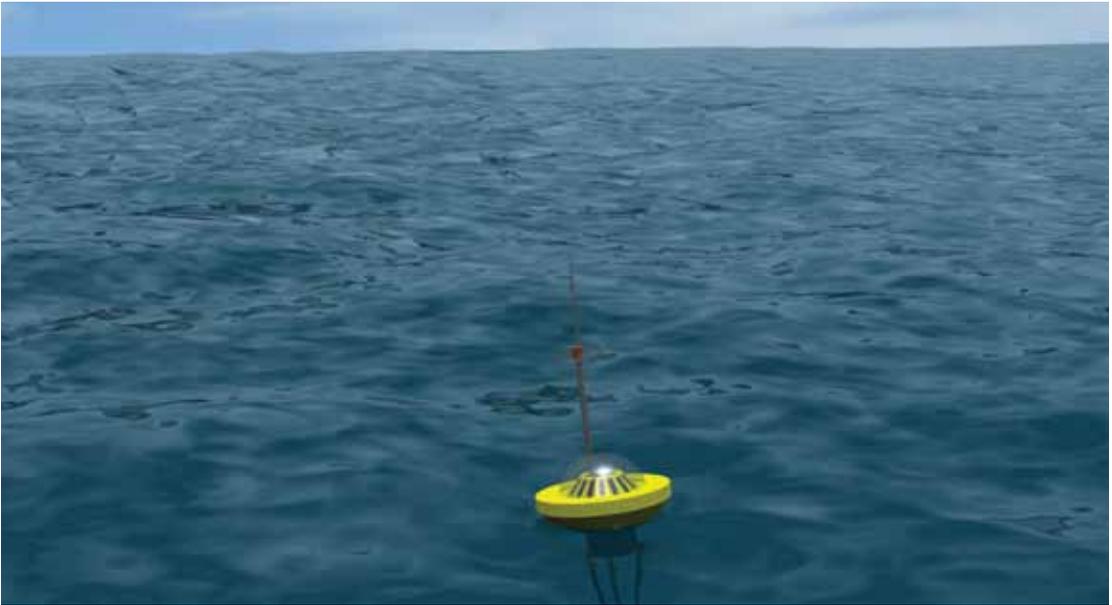


Figure 4(c): A rendered view of the WatchMate in simulation.

cultivation tray stacks. Each raft supports about 100 shellfish cages, weighing 80 lbs each, which are connected by independent cables. For the aquaculture application (as is obvious from Figure 5), various mooring configurations are possible and simulation is necessary for an engineering team to minimize risk of failure and ensure safe moorings to be physically implemented.

On the east coast of Vancouver Island, BC, Canada, wooden rafts intended for shellfish cultivation have been failing catastrophically and require engineering analysis and design to improve their survivability and longevity. A series of simulations were used to deduce the cause and to address it through structure configuration and material changes. When exposed to the design sea-state that included short period, high steepness, wind-waves, the oscillating tray-stacks tend to submit the raft's cross beams to high dynamic loads. Finding the complete loads on each beam of the raft using ProteusDS enabled the design team to investigate safety factor sensitivities to various beam cross sections, materials, raft geometries, and mooring geometries. Extremely high tension values in mooring lines can arise due

to mooring shocks and these can be seen in simulation and effectively mitigated through system reconfiguration that is not possible post-deployment.

### **Contact dynamics**

Figure 5 highlights the complexity of modern mooring systems and a problem surrounding the operation of such systems – the possibility of entanglement of the mooring cables. For some WEC concepts, this is a concern since several cables, or reins, are needed to constrain the WEC, yet the WEC must move to generate power. This opens the door to entanglement of the improperly conceived WEC and its mooring.

In 2007, DSA, University of Victoria, and University of New Brunswick researchers initiated development of a cable contact dynamics model. The current implementation uses a visco-elastic mode to the contact force that depends on locating points on the cable(s) that are in contact, calculating the volume of the intersection and the time rate of change of this volume, and specifying a restitutional force on the cable segments in proportion to these values. To use the

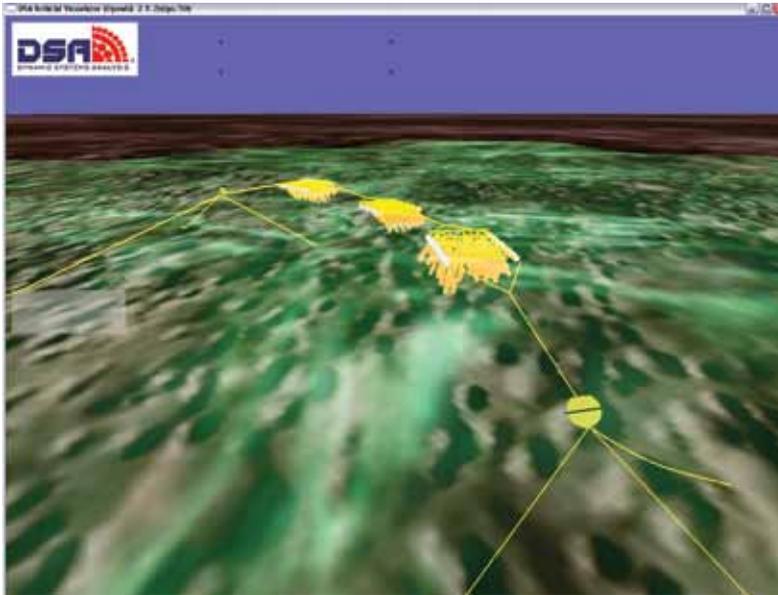


Figure 5(a): Dynamic simulation results (shown in visualization) of moored shellfish rafts in extreme sea conditions. Also shown are rendered simulation snapshots viewed from above water in (b) and below water in (c).

technique, global optimization routines developed at the University of New Brunswick are used to quickly locate the contacting points. This is aided by tracking minimum separation distances to focus the search for contacting locations and to ensure that the numerical integration does not allow cables to “tunnel” or pass through each other on a step of the simulation. Cable contact is a formidable challenge and is a continuing area of development. The first use of the technique was in a preliminary study of a trawl-proof buoy developed by Kintama Research.

### ***Bottom interaction***

Habitat destruction is a danger posed by large massive WEC concepts that leave a large footprint on the seafloor’s ecosystem. While minimizing the anchor masses reduces environment impact and facilitates handling for installation and maintenance, the anchor must be large enough to prevent the WEC from drifting in nominal or storm conditions. Similar concerns exist for other applications and to capture anchor performance in simulation one must treat the anchor as a rigid body or lumped mass that interacts with the surface of the seabed rather than an

idealized pin that sustains any mooring tension. In ProteusDS, this is currently accomplished by modeling the seafloor as a bed of springs. In direction normal to the ocean floor, the springs provide a restoring force; in the direction tangent to the floor, static and dynamic friction coefficients are applied so that the frictional resistance is proportional to the product of normal force and the frictional coefficient. However, anchors are typically modeled as spheres; to capture the effects of anchor “digging,”

anchors could be modeled as geometrically accurate rigid bodies that interact with the seafloor interface in a similar manner that floating bodies currently interact with the sea-air interface in the modeling framework.

In support of the West Coast Wave Collaboration Program (WCWCP), AXYS Technologies supplied a redesigned WatchMate buoy, shown earlier in Figure 4, to better withstand the fierce wave conditions at the WCWCP site on Amphitrite Bank near Ucluelet, British Columbia. ProteusDS was used to evaluate various mooring configurations. Figure 6 shows a snapshot of the simulation study DSA performed of the system and the anchor movement that occurred with a variety of anchor masses in a worst case storm condition. Sensitivities of the mooring performance were investigated to parameters such as anchor clump mass, chain size, chain materials, chain lengths, total mooring lengths and the placement of clump weights and subsurface floats. The final mooring configuration was chosen with the help of the simulation results, resulting in a hybrid chain with synthetic rope design that employs both subsurface floats and clump weights.



Figure 5(b)

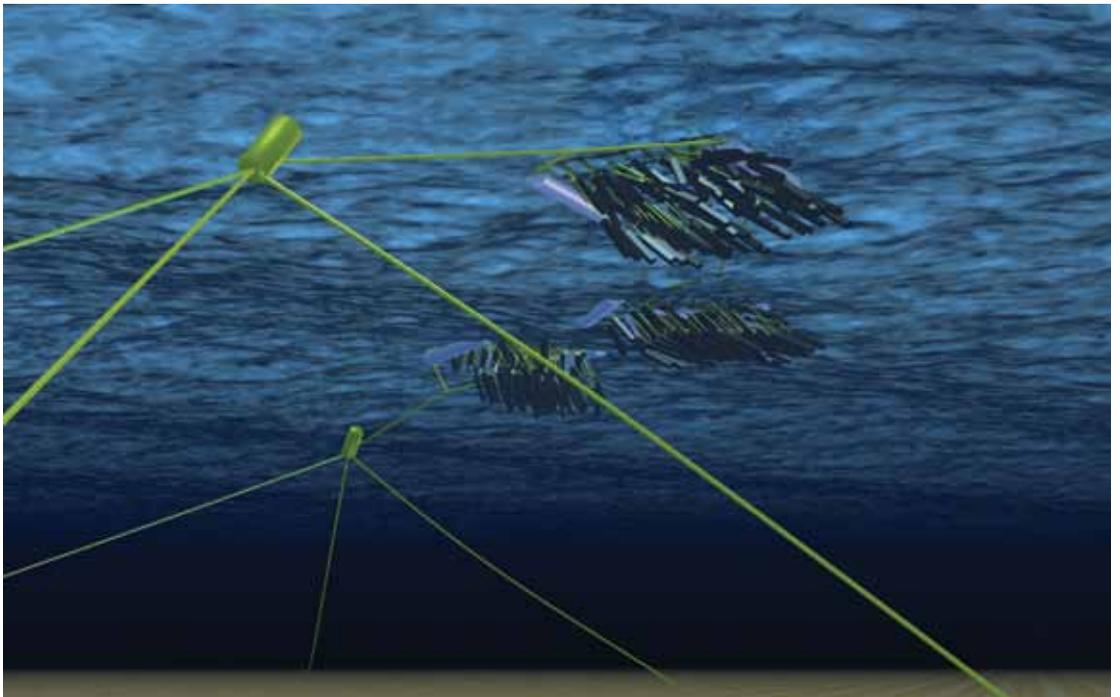


Figure 5(c)

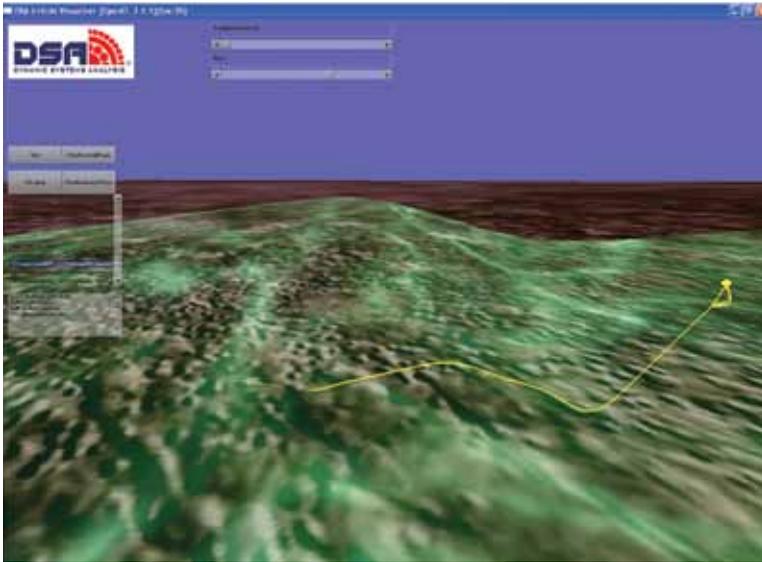


Figure 6(a): Dynamic simulation results (shown in visualization) of a WatchMate buoy and mooring in extreme sea conditions.

## Wave Energy Converter Simulations

The capabilities described in this essay have been applied to the design of a demonstration ocean wave energy converter pioneered by SyncWave Systems Inc. and involving research at the University of Victoria, Marinus Power of Houston, Texas, and Dynamic Systems Analysis. The device is a point absorber similar to others of its class: it extracts energy through the relative motion of two axis-symmetric

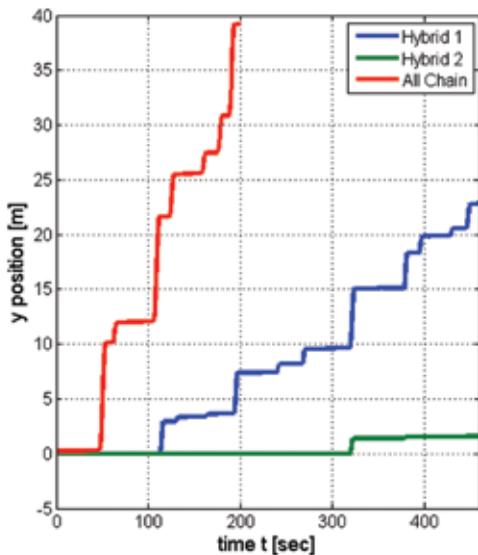


Figure 6(b): Anchor positions over time for various mooring designs. Improvements in station keeping performance due to mooring design changes are notable.

surface piercing floats. The differentiating characteristic is its method of frequency response tuning. An internally housed mechanical system with an adjustable rotational inertia is employed. Nonlinear dynamics simulations are now being applied to this device to consider the tuning system design, mooring configuration, device stability, and power capture performance in typical and heavy seas.

For articulated WECs like the SyncWave device, ProteusDS uses an

implementation of Roy Featherstone's articulated body algorithm to properly constrain the two floats and the internal reaction mass. The method is ideally suited to marine systems as it affords a direct incorporation of the added mass forces that are important in wave driven systems.

Time series of the relative position between the heaving bodies were used to reveal at what sea conditions "end-stop" impacts due to stroke limitations of hydraulic machinery were probable. Further, the evaluation of power take-off control and the effects of the mooring system on the performance of the WEC were quantified.

## Conclusions

Wave energy is attractive because it is globally abundant, less site-limited than tidal energy resources, predictable in magnitude over a 36 to 72 hour period, and is available at many remote locations where other energy sources are not feasible. Despite these positive traits, wave energy has yet to gain acceptance in the world-wide portfolio of alternative energy technologies. Lessons learned through hindsight of the importance of sustainable development on land are instilling a passion in many to ensure human progression into the ocean environment is executed in a sensible manner. Investors and engineers in pursuit of



SyncWave Systems

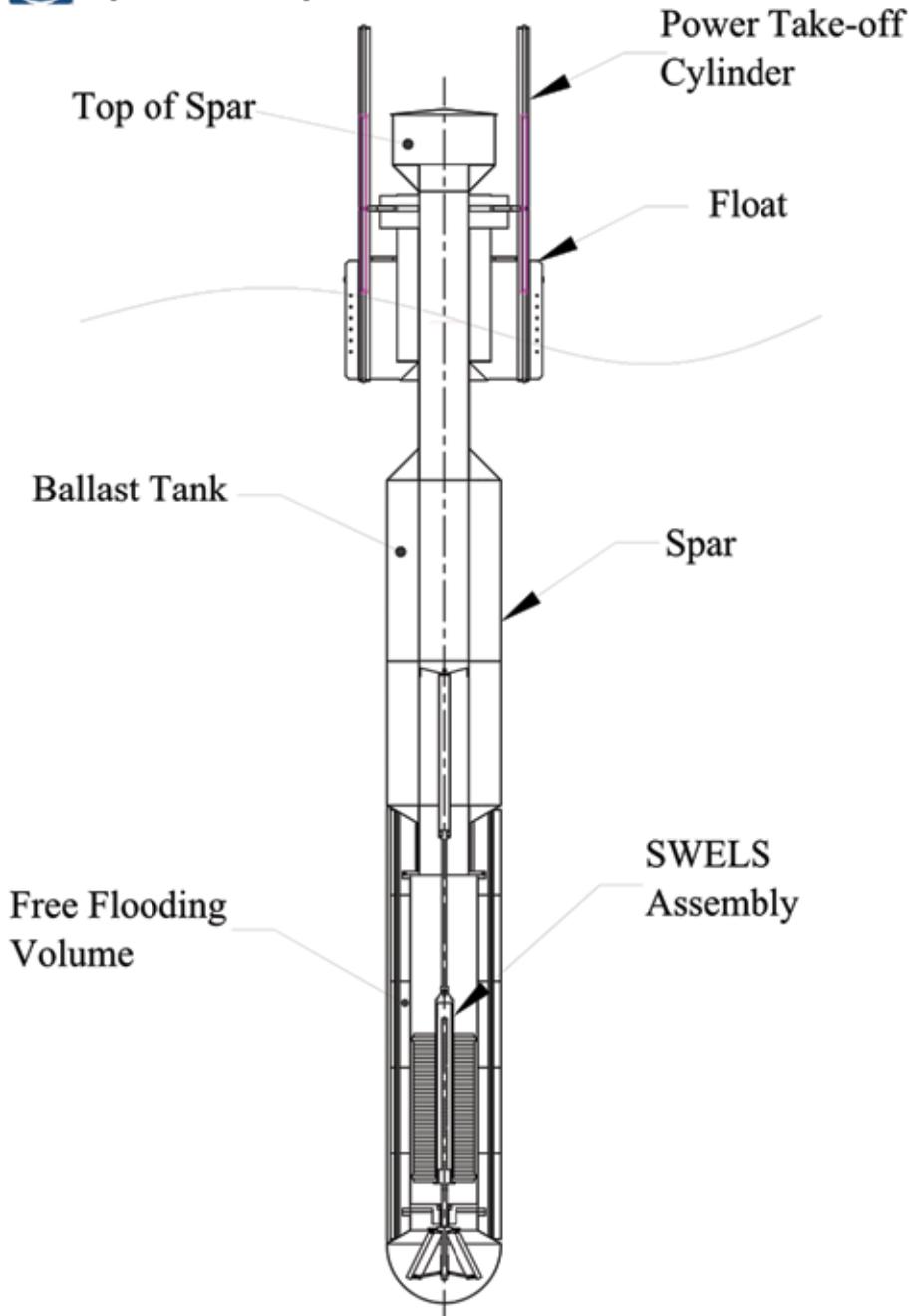


Figure 7(a): Mechanical schematic of the SyncWave point absorber WEC.

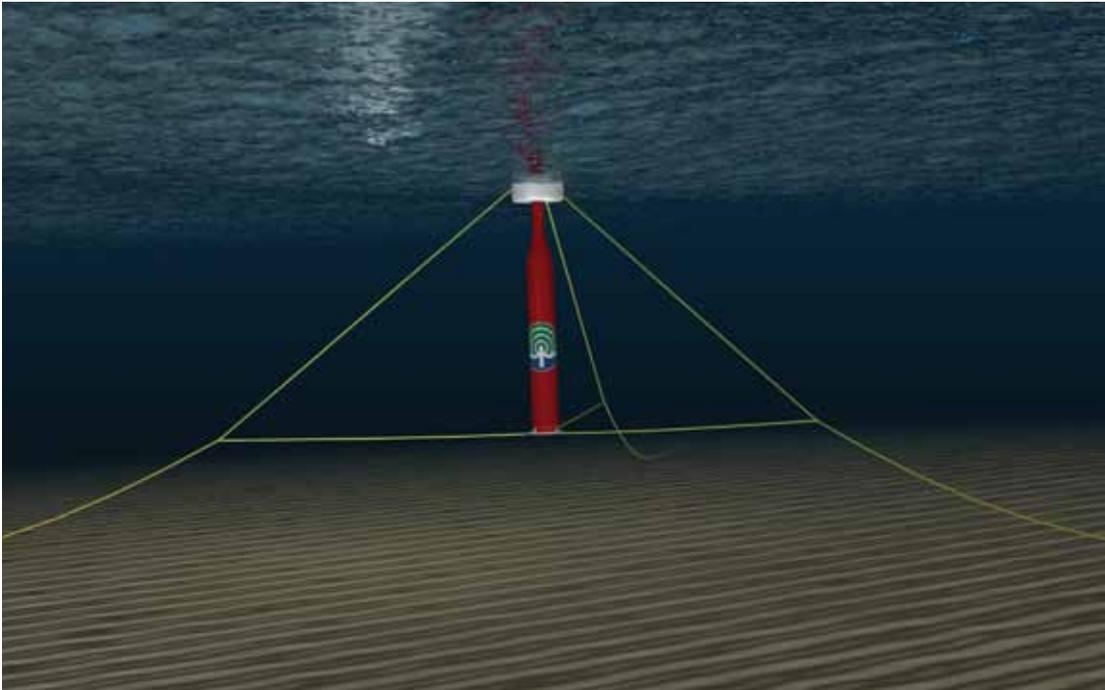


Figure 7(b): An undersea view of an early simulation of a SyncWave WEC mooring option.

viable WEC designs have to employ low-risk predictive assessment in the development of their technology to avoid costly environmental, social and economic repercussions. Accurate computational dynamics tools are a means for such assessment.

A powerful feature of the dynamics simulation technique is that time-series data describing force, position, velocity or acceleration for any of the system components can be extracted from the results. This provides valuable feedback including general conceptual feedback, specific load data that establishes the design of key mechanical components, and evaluation of proposed control strategies as the operational stage of development nears. Further, numerical simulation allows the design team to design and select machinery for power take-off systems and evaluate the power take-off dynamics in shutdown or power maximization procedures.

There is room to improve dynamic simulations for WEC studies. ProteusDS execution time suffers during pressure spikes in the hydraulic

power take-off, during end-stop collisions of the float WEC, or when cable elements are made small as required; for example, to accurately capture chain link behaviour or cable to cable contact. To understand ocean energy systems from an electrical system operator point of view, the system scope must be expanded to allow simulation of farms of deployed ocean energy devices, and this would necessitate improving execution speed. For farm-scale studies, the dynamics simulation could be coupled to numerical models of the local electrical system, which would facilitate the evaluation of candidate ocean energy devices when integrated into the electrical network: a true “wave to wire” simulation. ≈



Scott Beatty graduated from the University of British Columbia in May 2003 with Bachelor's degree in Mechanical Engineering. In September 2006, he joined the Institute for Integrated Energy Systems at the University of Victoria to pursue a Master's in Mechanical Engineering

with a research focus on the analysis, design, and development of offshore point-absorber wave energy converters in collaboration with SyncWave Energy Inc. After completing his Master's degree in May 2009, Mr. Beatty joined Dynamic Systems Analysis Limited as a research engineer and is now continuing wave energy research through the PhD program at the University of Victoria. Mr. Beatty has recently joined the Canadian delegation of the IEC Standards Technical Committee 114, which is an effort to develop international standards for ocean renewable energy systems.



Bradley Buckham obtained his PhD from the University of Victoria in 2003 and is currently an Associate Professor in the UVic Department of Mechanical Engineering. His interests lie in the dynamics and control of surface piercing wave energy converters (WECs) and undersea remotely operated vehicle-

manipulators (ROVMs). For both technologies, Dr. Buckham is interested in applying numerical simulations to guide the design and the development of control strategies. An important part of these simulation studies is a cable dynamics model developed between 2003 and present day. Dr. Buckham's WEC research is focused on methods for actively tuning a point absorbing technology using adjustable internal reaction masses. His WEC dynamics modeling makes use of articulated body dynamics codes he first applied in the simulation of ROVM systems. Dr. Buckham's ROVM research aims to improve the efficiency of ROVM operations such that they can effectively service WECs and other offshore equipment.



Ryan Nicoll received his Bachelor of Engineering degree in Mechanical Engineering in 2004 and his Master of Applied Science degree in the spring of 2007 from the University of Victoria. With a specialization in simulation of nonlinear mechanical systems, including riser and cable dynamics, Mr. Nicoll and

a fellow graduate student, Mr. Dean Steinke, formed the consulting company Dynamic Systems Analysis Limited to provide advanced simulation services to marine sectors such as ocean and tidal renewable energy, aquaculture, and oil and gas systems.



Peter Wild is a Professional Engineer and Professor of Mechanical Engineering at the University of Victoria. He is the Executive Director of the Institute for Integrated Energy Systems at UVic and holds the Natural Sciences and Engineering Research Council Chair in Sustainable Energy Systems Design.

Dr. Wild earned a Bachelor's degree in Mechanical Engineering from University of British Columbia in 1983 and then worked for six years in industry before earning his PhD from UVic in 1994. His first academic appointment was at Queen's University in Kingston, Ontario, in 1996 and, in 2003, Dr. Wild returned to British Columbia to take up a position at UVic. Dr. Wild's areas of research include impacts of integrating renewable energy generation into the grid; renewable energy generation technologies; and sensors for industrial and biomedical applications.