AN ABSTRACT OF THE THESIS OF

Adam C Brown for the degree of Master of Science in Mechanical Engineering presented on June 9, 2009.

Title: Towards Reliable and Survivable Ocean Wave Energy Converters.

Abstract approved:

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Ocean wave energy is a new and developing field of renewable energy with great potential. The energy contained in one meter of an average wave off the coast of Newport Oregon could supply dozens of homes with electricity. However, ocean waves are usually quite irregular which leads to large bursts and lulls in the power available for extraction. These bursts and lulls generate large cyclic system stresses that will invariably work over time to damage an ocean wave energy converter.

Due to the generally remote and extreme conditions of deployment, the reliability and survivability of an Ocean Wave Energy Converter (OWEC) are expected to greatly impact the cost of generated power passed to the consumer. For this reason, it is imperative that OWECs are both highly reliable during operation, and highly survivable through extreme conditions.

This thesis is a compilation of three papers relating to the reliability and survivability of OWECs. The first paper broadly addresses the probabilistic design of ocean wave energy converters for real ocean waves. The analysis conducted in this paper
used 13 years of data from the Stonewall Banks data buoy off the coast of Newport Oregon (NDBC buoy 46050) to extrapolate probabilistic information that could be used throughout the design process to improve system reliability. The second paper provides a definition and metric for the widely used term survivability. Survivability is often confused with the similar concept of reliability. The paper seeks to highlight differences between the two terms with the intention of clarifying their relation to system design.

The final paper presents a method for concept evaluation in the earliest stages of design. A comparative function based failure analysis is conducted during the concept stage to aid in design selection. Selecting concepts that show promising failure traits early in the design process will improve the reliability and survivability of the final system.
Towards Reliable and Survivable Ocean Wave Energy Converters

by

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A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented June 9, 2009
Commencement June 2010

APPROVED:

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Adam C. Brown, Author
ACKNOWLEDGEMENTS

My Parents are amazing! Mom sat beside me for years, helping me through algebra and geometry, history and literature. My Dad instilled in me a great respect for the natural world that is largely responsible for my interest in sustainable energy. Both have been supportive of my every endeavor, idiotic or not, and for this I owe them almost everything. The rest I owe to Duck Dog whose velveteen ears helped me through many long nights.

I’d also like to thank my brother Daniel, who has shared my time at Oregon State. Your advice on a wide range of subjects is sometimes wrong, but always welcome. Who would’ve thought you’d become my best friend.

I met my girlfriend Robyn and her/my dog Sunny in Oregon, and it was perhaps the best thing I did while I was here. Robyn, your vocal renditions of “Sunny Pie” and “Sunny Dog” are the best I’ve ever heard! I love you and just so you know, I’m planning on keeping you around.

Outside of family and loved ones I have many other individuals to whom I owe a great debt of gratitude. I’d like to thank my advisor, Dr. Robert Paasch, for his patience and guidance. I am extremely grateful to both Dr. Annette von Jouanne and Dr. Ted Brekken for providing me with the opportunity to explore the field of ocean wave energy. A massive thank you is also extended to Dr. Irem Tumer for being a great advocate, teacher, and co-author!

Finally, I’d like to thank all of my friends and peers in WESRF for making my first year at Oregon State one of the most fun and interesting I’ve ever had. And to both Justin and Pukha, my NNMREC compatriots (and friends), your thoughtful revisions, criticisms, and recommendations made this thesis a heck of a lot better.

“We need men who can dream of things that never were.”

John F. Kennedy, June 28, 1963

Robyn, I’m sure he meant to say women too.
CONTRIBUTION OF AUTHORS

Dr. Robert Paasch, Justin Hovland, and Pukha Lenee-Bluhm contributed to the ideas behind and revisions for all three papers. Dr. Irem Tumer contributed ideas and revisions for the papers, “Early Stage Failure Modeling and Analysis Applied to a Wave Energy Converter,” and, “Towards a Definition and Metric for the Survivability of Ocean Wave Energy Converters.”
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1) Introduction

1.1) Introduction to Wave Energy Conversion

In the Earth’s atmosphere radiation emitted from the Sun is stored as heat. Thermal gradients in the atmosphere create the planet’s winds, and the winds in turn create waves as they cross the oceans. With each conversion the density of the stored energy increases. Everyday waves crash against our beaches and shores, violently dissipating their energy in the form of heat. The power dissipated is truly immense. For example, along the coast of Oregon, waves average nearly 30kW/m of crest length. The promise and potential of this power source has long lured inventors and scientists to design devices that harvest the energy of the waves.

The investigation into ocean waves as a modern energy source began in the 1970’s during the oil crisis. Pioneering research was performed by Budal, Evans, Falnes, and Salter (Budal, 1977; Evans, 1976; Falnes, 2002; Salter, 1974). A huge number of designs have appeared over the previous decades, beginning most notably with Salter’s Duck and the Limpet Power Station. Recently, designs have been proposed by Pelamis Wave Power, Archimedes Wave Swing, Wave Dragon, Ocean Power Technologies, Finavera Renewables, and Columbia Power Technologies. Many additional designs have been proposed by individual inventors. Some of the numerous of designs show potential, but a clearly superior device has yet to be demonstrated. The number of unsuccessful attempts demonstrates the difficulty associated with ocean wave energy. Commercialism has further complicated the task. Not only does the technology have to work, it must enter the energy market at a cost of power that is financially competitive.

1.2) Previous Research at Oregon State University

Interest in wave energy at Oregon State University dates to the spring of 1975 when Dr. Larry Slotta, of the Ocean Engineering department, submitted a proposal to the National Science Foundation to study, “The Potential of Oceanic Water Waves for Recoverable Power,” (Slotta, 1975). In 1998 Dr. Annette von Jouanne and Dr. Alan Wallace of the Electrical Engineering department began writing white papers and giving presentations on the subject of ocean wave energy; successfully securing funding for
future research. By 2000, the Motor Systems Research Facility headed by Dr. Wallace began investigating direct drive power take-off systems for use in wave energy converters.

In 1997 the SeaBeav1 was deployed off the coast of Newport Oregon (Elwood, 2008; Joseph H Prudell, 2007). The device used a large linear permanent magnet generator driven by a cylindrical float to generate power. Due to problems during the construction phase of the buoy, the SeaBeav1 did not successfully generate power during ocean deployment. However, valuable experience was gained.

In the fall of 2007 a partnership was developed with Columbia Power Technologies, a venture wave energy company, which culminated in the ocean deployment of the Blue Ray device during the summer of 2008. The Blue Ray incorporated the generator designed for the SeaBeav1 into a new and redesigned buoy system. The design and manufacture of the buoy and reaction plate system drew heavily from the lessons learned during the deployment of the SeaBeav1. The Blue Ray wave energy converter was the first device to successfully generate electricity from Oregon waves (Elwood, 2008). In the Fall of 2008 the Northwest National Marine Renewable Energy Center was founded by Oregon State University and the University of Washington with matching funds from the US Department of Energy to aid in the development of Ocean Marine Energy. One part of the NNMREC’s mission is to
investigate and develop the understanding of reliability and survivability in the context of ocean marine energy (“NNMREC OSU,” 2009). This thesis is aimed at that goal.

1.3 The Need for Reliability and Survivability in Ocean Wave Energy

The field of ocean wave energy seeks to harvest this clean and renewable energy and put it to use powering homes, offices, and industries. However, in ocean wave energy, the energy source is also the operating environment. The same waves that are used by a device to generate electricity continuously impart huge cyclic stresses on that device. Over time these stresses are likely to induce fatigue failures of critical components. Due to the typically remote nature of ocean wave energy, servicing the device during a midwinter storm is likely to be impossible. Instead, maintenance crews will need to be placed on standby waiting for a weather window to access the device. In ocean wave energy the cost of accessing the device for service is likely to dominate the cost of repair. This may be expected even if a failure occurs during calm weather, as a vessel and its crew, wave energy technicians, and possibly divers will all be needed to service the failed device. For this reason, the reliability and survivability of ocean wave energy converters is absolutely critical to the cost of power they produce, and therefore their ultimate viability.

This thesis seeks to improve the reliability and survivability of ocean wave energy converters in three ways. First, the two terms must be adequately defined, providing scientists and engineers with a clear goal upon which to focus their design. Second, designs must be based upon an accurate and thorough understanding of the ocean environment. Finally, the reliability and survivability of conceptual designs must be objectively compared in order to select the most promising designs for further research and development. These are the individual focuses of the three papers presented in this thesis. The infancy of ocean wave energy demands that these papers are simply a sentence in a developing discussion on system reliability and survivability.
2) Towards a Definition and Metric for the Survivability of Ocean Wave Energy Converters

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Manuscript will be submitted to: Proceedings of the ASME 2010 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2010

http://www.asmeconferences.org/idetc10/
Towards a Definition and Metric for the Survivability of Ocean Wave Energy Converters

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ABSTRACT
Survivability is a term that has found its way into the business of Ocean Wave Power. The word itself seems to have an intrinsic meaning that people understand. But, the term has never been defined in the context of Ocean Wave Energy. This fact often leads to the term’s misuse and its confusion with reliability.

The ocean is anything but consistent, and probabilistic design practices must be used. In the field of ocean energy, the use of survivability is necessary to account for the failures of a device that occur outside of its typical operating conditions, while reliability focuses on failures that occur while the device is operational.

The purpose of this paper is to provide an initial and amendable definition for survivability with the intent of opening a dialog on this extremely important topic. This paper introduces a simple metric that provides a relatively objective comparison of the survivability of varying wave energy converter technologies, and allows for a more accurate prediction of each system’s risk related expenditures.

1) INTRODUCTION
1.1) Wave Power
The ocean contains an immense amount of energy. Waves may climb to over thirty meters, while hurricane force winds shear the surface. Even in relatively calm conditions the ocean is a formidable environment. Salt water is highly corrosive and waves, wind, and current all produce significant loading on any device that calls the ocean home [1,2].

It is possible with wave energy converters to tap into some of the ocean’s nearly limitless energy, using it to heat our homes and power our factories. The difficulty lies in the details. Ocean waves are anything but the simple sinusoids that are often used as their representation. Rather, they are the product of the continuous superposition of smaller waves that vary in period, amplitude, and direction of propagation. The result is highly variable bursts of power as potential energy is converted to kinetic and kinetic is converted back to potential. The energy of the ocean can only be extracted during these bursts of power, but it is also these bursts that make surviving the ocean extremely difficult. Figure 1 shows a typical confused wave displacement time history developed by the author from actual buoy measurements off the coast of Newport, Oregon.

![Figure 1: Time history of vertical wave position reconstructed from data recorded by NDBC Buoy 46050 on Nov 29, 2007 at 7am [3].](image-url)
1.2) Research at Oregon State University

Although concepts for wave energy devices have been around for much longer, modern investigation into the use of ocean waves as a form of renewable energy began in the 1970s during the oil crisis [4]. Since that time many designs have been proposed, but a clearly superior machine has yet to be developed. Ocean wave power is still a very immature technology with many interesting questions waiting to be answered.

Most past research conducted by Oregon State University has focused on technology development [5,6]. In a recent project the Wallace Energy Systems and Renewables Facility (WESRF) evaluated various technologies which could be used for ocean wave energy conversion. The “best” design was chosen for construction and testing during the summer of 2008. The developed converter was comprised of a fully enclosed linear generator that was driven using a two body float and spar buoy combination [7,8].

This project led to many fundamental questions that required a base knowledge of the operational conditions, environment and their effect on design considerations that was ultimately lacking. For instance, some of the questions which arose were; how often will the converter exceed its maximum travel, what capacity factor is the converter likely to achieve, what velocities and accelerations are likely to occur? These are only a few of the questions that recent work at Oregon State has been forced to address [8,9].

1.3) Survivability?

Comparison of the varying technologies called for an estimate of the “survivability” of each device. This term was used because of its intrinsic meaning relating to how well a device will survive the ocean. But this implied definition was vague and cumbersome and allowed for a great deal of subjectivity throughout the comparison process. Upon further investigation, it was found that even though survivability is commonly used in the marine renewable energy industry, it has yet to be adequately defined, and its relation to system reliability is extremely ambiguous [10,3]. For this reason any proposed definition must make a clear distinction between survivability and reliability.

1.4) The Development of the NNMREC

In the fall of 2008 the Northwest National Marine Renewable Energy Center (NNMREC) was established at Oregon State University and the University of Washington with matching support from the Department of Energy [11]. The center is now envisioned as a store house of knowledge and resources with a streamlined regulatory process that should help companies develop their marine renewable energy systems better and faster. As a small part of its overall mandate the center was tasked with research into the survivability of marine energy converters. As with any project the opening task must be to define and bound the scope. In particular, it is imperative that the meaning of survivability is established and its specific use is constrained to be useful and appropriate. This clarification of an already used word will allow future research to be built on a standard view of what survivability is, and help define how it is different than other parameters such as reliability and dependability, and how it can be influenced by manufacturability and maintainability.

2) BACKGROUND

2.1) Survivability in the Literature

The only definition for survivability in the context of ocean wave energy was recently published by the European Marine Renewable Energy Centre (EMEC) [10]. Survivability is broken into safety survivability and functional survivability. Safety survivability is defined as,

“the probability that the converter will stay on station over the stated operational life.”

Whereas, functional survivability is defined as,

“the probability that the converter will produce its rated energy (or an allowed degraded energy rating) without damage leading to the need for major unplanned removal or repair over the stated operational life.”

In this set of definitions, safety survivability seems to apply to primarily to the device mooring
system, while functional survivability applies to the converter itself. The drawback of these definitions is that they appear nearly identical to the EMEC’s definition of reliability, which is,

“the probability that an item can perform a required function under given conditions for a given time interval.”

The differences appear to lie in the magnitude of the repair, which remains ambiguous, and the time duration considered, which is left undefined for reliability, but set at the life of the system for survivability. This definition of survivability is inadequate, as it does not provide a clear distinction between survivability and reliability. Without a clear distinction between the parameters, a metric for survivability cannot be developed.

Survivability has been discussed in several fields prior to its use in marine energy. Possibly the most apparent use of survivability in the past decades has come from the military. A relatively comprehensive list of military publications relating to survivability can be found inside the Aerospace Systems Survivability Handbook Series. Survivability in that context is defined as [12],

“the capability of a system and crew to avoid or withstand a man-made hostile environment without suffering an abortive impairment of its ability to accomplish its designated mission. Survivability consists of susceptibility, vulnerability, and recoverability.”

This definition also requires the definition of susceptibility and vulnerability. Susceptibility is defined as,

“the degree to which a weapon system is open to effective attack because of one or more inherent weakness. Susceptibility is a function of operational tactics, countermeasures, probability of enemy fielding a threat, etc. Susceptibility is considered a subset of survivability.”

Vulnerability is defined as,

“the characteristic of a system that causes it to suffer a definite degradation (loss or reduction of capability to perform its designated mission) as a result of having been subjected to a certain (defined) level of effects in an unnatural (manmade) hostile environment. Vulnerability is considered a subset of survivability.”

Recoverability is left undefined although it can be understood as the ability of a system to recover from a deterioration of function after encountering an unnatural hostile environment. This definition of survivability is partially applicable to wave power, but its focus is on the lethality of a manmade event to individuals and missions. It should also be noted that the military standards dealing with survivability demonstrate no metric for its determination. Survivability is therefore simply a concept that should be designed for using best engineering practice.

Survivability has also been considered in detail by the information systems community. Information systems drive our society. Without computers and information networks many modern industries would simply collapse. For instance modern paperless banks, hospitals, and businesses require the uninterrupted flow of information to operate. For this reason the survivability of an information system can be critical. Despite this community’s wide spread research into the concept of survivability, definitions and metrics still vary between sources. In general survivability is defined as [13],

“the ability of a given system with a given intended usage to provide a pre-specified minimum level of service in the event of one or more pre-specified threats.”

This definition requires the specification of the systems intended usage, level of service, and the considered threats. This makes the definition somewhat vague and only useful in that it is a similar concept to survivability’s use in marine energy. It could apply to an ocean wave energy converter encountering a rogue wave, extreme gust, or tsunami. However, as described later these encounters lie somewhere between reliability and survivability according to the way in which they are defined.

A description of recent research as well as an exhaustive list of the definitions of survivability in
the information systems community can be found in Westmark [13], and Knight et. al. [14]. According to Westmark, the most referenced definition of survivability appears to be,

“the capability of a system to fulfill its mission in a timely manner in the presence of attacks, failures, or accidents.”

Once again, this is a rather vague definition in that it makes no specification of the meaning of a “timely manner”, and provides no means of quantifying the survivability of a system.

Yet another general definition of the concept of survivability is provided by the Institute for Telecommunications Services which is part of the Department of Commerce [15]. Survivability is defined as,

“a property of a system, subsystem, equipment, process, or procedure that provides a defined degree of assurance that the named entity will continue to function during and after a natural or man-made disturbance; e.g., nuclear burst.”

It is noted that this definition requires the determination of the parameters upon which this definition is built, such as the defined degree of assurance and the time period and type of disturbance.

The field of software engineering produced another similar definition that states that survivability is [16]

“the degree to which essential functions are still available even though some part of the system is down.”

Once again this definition does a nice job of relating the meaning of the concept, but does not provide the audience with a concrete measurement method. The questions of what are “essential functions,” and what is meant by “the degree to which essential functions are still available,” are still present.

Survivability of fiber optic networks was first discussed in the late 80’s and has seen continued interest throughout the last two decades [17]. In this case survivability of the fiber optic network implies the continuous, uninterrupted flow of a signal pulse through the fiber optic cable to its destination. System failures relating to non-hardware failures are also considered as they still have the potential to cause a signal interruption. However a strict definition has not been developed, the focus is instead placed on passive and dynamic survivability mechanisms. These mechanisms range from simple fiber grid layout and backup to protective cable enclosures. This is not an appropriate view of survivability in the context of marine renewable energy where maintenance costs and structural fatigue drive design [2].

Most of the systems discussed here cannot predict when an extreme condition will occur, and therefore their definitions of survivability must be valid while the system is still operating. However, in ocean wave energy extreme storms and heavy sustained seas pose the greatest risk to a converter, yet with modern technology they can be accurately forecast and the system can be shut down, alleviating stresses, when conditions grow too extreme. For this reason, the systems’ recommended operating conditions become a natural separating point for the definitions of reliability and survivability. This key separation also allows for a simple metric for survivability in the context of ocean wave energy which is proposed in section 3.4.

2.2) Reliability in Engineering Design

Reliability in engineering design has been well researched and published over the last decades. The concept of reliability is important in that it seeks to reduce the number, frequency, and severity of system failures. Reliability in engineering design is a vast subject spanning many disciplines and explained in depth in many publications [18-20].

As with survivability, reliability has been given a plethora of definitions over the years. Dhillon [21] defines reliability as,

“the probability that an item will carry out its assigned mission satisfactorily for the stated time period when used under the specified conditions.”

Reliability is typically equated as, \( \text{Rel(system)} = 1 - \text{prob(failure)} \), or measured as the Mean Time Between Failure (MTBF).
This definition of reliability as with many includes the clause “under the specified conditions.” For most machinery operating conditions are relatively stable, and situations that push the system outside of standard operating conditions are rare.

But, how do we judge the likelihood of failure if our system is pushed beyond its stated operating conditions? To adequately consider these occurrences the concept of system survivability is necessary.

2.3) The Marine Renewable Energy System

In order to adequately define survivability for marine renewable energy systems it is first important to establish the context and important factors related to marine energy. In particular, four important questions are here addressed.

What portions of the marine renewable energy field does this paper address? The research in this paper is specifically applicable to survivability in the field of ocean wave energy. However, in general the topic being discussed could be broadly applicable to any of the marine renewable energy technologies.

What will an ocean wave energy system look like? At this point, the proposed designs for ocean energy systems are extremely diverse, so for every generalization, there is likely an exception. However, in general most wave parks are envisioned as an array of individual wave energy converters spaced over several square kilometers of ocean. A power take-off cable (PTO) is then routed along one of the converter’s mooring lines to the ocean floor. Individual PTO cables are then routed to one or more central junction boxes containing power electronics to combine and condition the individual wave converter’s power output into a regular grid ready source. Another potential option for the implementation of marine energy is the production of hydrogen through electrolysis. This method offers a benefit in that it eliminates the costly cable networks associated with grid electricity allowing for wave parks to be sited further from shore; however, using electrolysis for energy storage is significantly less efficient than direct grid connection. As mentioned previously, individual converters can be realized in many different forms. Proposed designs for converters include wave attenuators like the Pelamis, Oscillating Water Columns like those created by Wavegen, and point-absorber buoys like those pursued by Ocean Power Technologies, Finavera Renewables, Columbia Power Technologies, and Oregon State University [22-27].

In what environment will a wave energy converter operate? Most wave energy parks will be located off the west coasts of the various continents. This is due to the normal path of the jet stream which builds energy into the waves as it blows to the east. Initial permitting suggests that most wave parks will be sited one to eight miles offshore in water depths of 30 to 60 meters [28]. Wave conditions are expected to average around 2 meters in significant wave height. However, fourteen meter significant wave heights have been recorded off the Oregon coast in the last 10 years [29]. The continuous operation of marine energy converters in a salt water environment requires the use of anti-corrosive materials and design techniques. During the winter months (December through March) prevailing wave conditions are strong averaging around 3 meters in height. During this time the wave park could only be accessed during short, “weather windows,” that present themselves sporadically throughout the season when wave heights drop back to around two meters. Wave energy converters will likely be expected to operate without a major overhaul for over 10 years.

In what stage of development is ocean wave energy? Marine energy in general is still in the concept to prototype stages of development. Many different and drastically varying designs have been proposed, but a clearly superior design has yet to appear. Due to the large capital investment that is required to develop, design, build, permit, and deploy a marine energy converter, survivability is critical. Without a clear and measurable definition of survivability designers and venture capitalists are left with the use of completely subjective statements with no support. By establishing a definition for survivability that can be demonstrated, start-up companies will be capable of proving their claims, therefore reducing the capital
ventures’ risk. It is highly likely that a reduction in risk will increase the total capital investment in a well founded technology [30].

2.4) The Relation of Reliability, Maintainability, and Survivability

If we assume that extreme events can happen any time during system operation, then the definition of survivability becomes very similar to that of reliability. However the concepts of reliability and survivability should be distinctly separate. Many of the previous definitions highlight that survivability relates to an “extreme event” that in some way deteriorates the function of the system. The notion of extreme events represents the major difference between survivability and reliability.

Most land based systems are operated within a standard operating range. For instance, within a natural gas turbine the combustion process is strictly controlled to maintain operation within a relatively limited band of speeds. For these systems, reliability has been an adequate metric of system failures. However, modern renewable energy systems cannot exercise the same level of control over their environment, and more frequently encounter conditions that necessitate the immediate termination of operation to prevent system failure. Wind turbines have been operating for years with variable pitch blades that rotate into the wind when the average wind speed exceeds the operating conditions of the turbine greatly alleviating loads on the turbine. These periods lie outside the normal operating conditions of the turbines, forcing them into survival mode. The reliability of wind turbines is determined by failures that occur while the system is operating in standard conditions. The survivability of a wind turbine is affected by those failures that occur while the systems are shut down. By the proposed definition of survivability, wind turbines are therefore highly survivable even though they may be unreliable; pitching the blades into the wind is a highly effective survival mode that prevents most damage due to extreme events, yet gearbox failures during routine operation are still common which greatly reduces overall system reliability.

The typical wave energy converter would be designed to operate in the likely wave conditions of a site (from one to four meter mean wave heights). However, ocean conditions may rise to an average wave height of over 8 meters on a yearly basis. The energy of ocean waves is proportional to the square of wave height; therefore, in extreme conditions, the ocean wave energy converter will be exposed to four to 8 times the amount of energy as it is during its operating conditions. For this reason, marine energy converters are expected to have a point similar to wind turbines at which they can no longer harvest power safely, and must be shut down to prevent damage. It is during these periods where the system is simply trying to endure the current conditions that survivability becomes a necessary and distinct concept. The definition of survivability in the context of marine energy is therefore intricately connected to the operating conditions of the system.

Survivability and reliability also differ in their relation to system costs. Reliability is typically calculated as the mean time between failure, and it is assumed that during the time between failures the system is operational. Therefore the system fails as a direct result of its operation, and these failures are typically placed in the realm of operational expenditures. However, in most systems where survivability is considered a failure may occur even when the system is not operational. The cost of these failures is unrelated to system operation and is purely risk based. The strong dependence of risk related expenditures (RISKEX) on the concept and definition of survivability demonstrates the need for a consistent definition and metric of survivability.

It has previously been mentioned that the maintainability of marine energy converters is likely to impact their survivability. Yet, maintainability and survivability should be viewed as distinctly separate but necessary design goals. The goal of improved maintainability focuses on the post failure and preventative maintenance aspects of design. Obviously, these tasks should be streamlined to the greatest extent possible. However, survivability focuses entirely on failure avoidance. Of course if the system is not maintained properly it will be more likely to fail,
but even if the system is well maintained, ocean survivability is still of absolute importance.

3) SURVIVABILITY DEFINED IN THE CONTEXT OF WAVE ENERGY

3.1) The Definition

Taking full account of the background and previous literature on the topic of survivability it is now possible to propose a definition of survivability that should be considered open for debate and revision.

In the context of marine renewable and specifically ocean wave energy, survivability is defined as:

The ability of a marine energy system to avoid damage, during sea states that are outside of intended operating conditions, that results in extended downtime and the need for service.

As a given part of this definition, system based operating conditions must be defined which satisfy the balance of revenue and reliability. Operating conditions in a stochastic ocean environment can be exceeded when the average operating conditions (sea state) become too large for an extended period of time for the device to continue operating safely. This type of event is usually predictable, and steps can be taken to mitigate the risk of damage to the device. This mitigation is typically termed survival mode, and it is expected that, due to extreme environmental conditions, most devices will need to cease generation and enter some form of survival mode at some point in their life.

3.2) Failures Affecting Survivability

In general, due to the remote nature of ocean renewable energy, the cost of any repair or service will in large part be driven by the cost of accessing the device. For instance, suppose a key fails on the main drive shaft. If it were more readily accessible, this failure would be relatively insignificant to repair in comparison to a gearbox. However, in the ocean environment this failure may necessitate the use of special equipment to access and repair the device. During the winter months, access to the system is likely to be delayed while vessels are placed on standby waiting for a weather window. The base cost of accessing the converter will have the effect of leveling repair costs for the key and gearbox. Although it is unlikely, depending on the urgency of repair, the cost of the key replacement could actually exceed that of the gearbox. For this reason any failure that occurs when the system is beyond its operating conditions must be considered as pertinent to system survivability.

3.3) Developing a Metric for Survivability

The dominant and independent design parameters that affect the cost of energy of a marine energy converter are the site’s conditions and the device’s operating conditions, efficiency, capacity factor, capture width, reliability, maintainability, and survivability. Reliability is critical to maximize the amount of time that a converter is producing electricity and profit within the system’s designed operating conditions. Maintainability reduces expenditures by reducing system downtime. Maintenance costs and system profit are both directly impacted by maintainability. Survivability is clearly pertinent to the success of any proposed marine energy converter, as a large capital investment must be risked to develop the resource. If a technology cannot successfully weather a midwinter storm, than the technology is simply not viable.

The previous discussion of survivability is vitally important for the success of marine renewable energy, but subtleties exist within the concept of survivability that make simple statements such as, “our device is highly survivable,” completely arbitrary and meaningless. The device developer must prove that their system is survivable, but a consistent metric must be accepted that allows them to prove it.

A consistent method requires that survivability must be in some way measurable; otherwise it is simply an abstract concept that will easily be confused with other design parameters such as reliability. It is thus also important that any proposed metric should clearly recognize the difference between survivability, reliability, and maintainability.
3.4) A Survivability Metric

The proposed metric is built off the probability of failure during seas of a certain height outside the operating conditions of the system. For instance, a probability curve can be developed for a system relating the chances of suffering a failure in a one hour period of waves of a certain height outside the standard operating conditions of the device (Figure 2). This curve is the metric that should be used to complete a comparative analysis of different technologies. An added benefit of this metric is that it can easily be used by any device design to provide a location specific survivability cost estimate assuming an average cost of access and repair.

For this example we will apply the proposed survivability metric to the design of two different imaginary wave energy converters. Actual failure probability data is not currently available for any actual system due to the proprietary nature of the information. Therefore, supposed failure probabilities will be used for the example and are shown in Table 1. Failure probability curves will typically grow at a faster than linear rate with the significant wave height as can be seen in Figure 2. This is due to the fact that the amount of energy that our device will encounter grows at a faster than linear rate with wave height [31].

For Ocean Energy Converter A, power generation is ceased and the system enters survival mode at a five meter significant wave height. Ocean Energy Converter B is designed to continue harvesting power up to a seven meter significant wave height before the system enters survival mode. Failure probabilities for both converters are only shown, in Figure 2 and Table 1, out to a 12 meter significant wave height for the sake of brevity. In reality data should extend further. For reference, a significant wave height of six meters would have a mean wave height of approximately four meters and one in a hundred waves would top 10 meters. A 12 meter significant wave height would have a mean wave height of seven meters with one in a hundred waves topping 19 meters [32]. Needless to say, even wave conditions with a six meter significant wave height could do serious damage to a poorly designed marine energy converter.

Useful information is already apparent from Figure 2 and Table 1. First we can see that Converter A enters survival mode earlier than Converter B. This gives Converter B an obvious advantage in that it is still capable of generating power when Converter A is already shut down. However, it is also apparent that the failure rates of Converter B are higher than Converter A in the smaller more common significant wave heights giving Converter A a slight advantage. The two failure curves intersect at a significant wave height of 10 meters, beyond which it appears converter B has the advantage.

In order to clearly compare and contrast the survivability based benefits of the two designs, additional information is required. Site specific data relating the frequency of wave height conditions must be used to determine an overall probability of failure of a device over some specific period of time.

Binomial distributions are used in systems where results are classified in black and white as success or failure. By making the assumption that any failure no matter the magnitude will have roughly the same impact on risk expenditures (see section 3.3), we are able to make this simplification. The average hours per year of a given wave condition shown in Table 2 were developed from data recorded by NDBC buoy 46050 off the coast of Newport Oregon. Let us suppose that the site chosen for the example is located near this buoy, and thus this data is applicable. Assuming a binomial distribution as the model of system failures, we can then combine the probability of failures in one hour of operation at a certain wave height with the number of hours operated at those conditions to determine the probability of failure over the course of a year.

In order to determine the probability of survival, we must first find the complements of the probabilities shown in Figure 2. The complements represent the probability of success, or more clearly, they are the probability of the converter surviving one hour in the specified conditions without failing. The complements or probabilities
of success \( (P_{\text{success}} = 1 - P_{\text{failure}}) \) are shown in Table 2 for each Converter A and Converter B.

Using the binomial distribution we can calculate the individual probabilities of surviving 235 hours of five meter significant wave height, 70 hours of six meter significant wave height, and so on \( (P_{\text{survival}}) \). The binomial distribution equation is:

\[
P_{\text{survival}}(Y) = \frac{n!}{t!(n-t)!} p^t q^{(n-t)}
\]

In this equation, \( n \) is the number of hours per year of a certain wave height, \( t \) is the number of hours that the system operated without failing. Therefore, to calculate the probability of going an entire year without failing \( n \) and \( y \) should be equal. Lowercase \( p \) is the probability of a failure free hour given as shown in Table 2, and \( q \) is the complement of that probability.

These probabilities must be calculated for each combination of wave height and converter. The calculation below is for Converter A surviving a full year’s worth of six meter wave height conditions.

\[
P_{\text{success}}(70) = \frac{70!}{70!(70-70)!} 0.997^{70} (1 - 0.997)^{(70-70)} = 0.81
\]

Therefore, there is an 81% chance that Converter A will survive one year’s worth of six meter wave conditions (70 hrs). There is also an 85.4% chance that it will survive a full year’s worth of 7 meter waves (21 hrs). Results for both converters and all wave heights are given in Table 3.

The total probability of surviving a whole year of survival conditions is therefore the product of the individual probabilities of success. The cumulative probability of one year survival, shown in Table 3, is an estimate of the probability that the two converters will last a full year’s worth of survival conditions without failure.

By this analysis, Converter A is more likely to suffer a yearly failure than Converter B. This is due to the fact that Converter A enters survival mode in smaller, but more frequently observed seas. However, this also means that Converter B is likely to have poor reliability in its upper operating region, and thus an economic tradeoff is present for each individual converter. By entering survival mode earlier, risk related expenditures are increased but operational expenditures will be decreased.

Determination of the conditions at which a device should transition from operational mode to survival mode is critical to the ultimate reduction of the cost of power, reliability, and survivability of marine energy converters. If the goal of the analysis is to simply determine which device will be more survivable in a general sense and the conditions at which the device enters survival mode have yet to be determined, then the analysis should be conducted assuming the varying converters will enter survival mode at the same conditions.
4) DISCUSSION AND FUTURE WORK

A comparison of marine energy converter technologies cannot be made relying solely on one metric. Reliability, survivability, maintainability, and efficiency all affect the ultimate cost of power, and in the end the cost of power produced by a device will determine its success. Survivability is just one part of the whole picture, but developing the concept will lead to more accurate early predictions of the risk related expenses associated with producing electricity from the ocean. The proposed definition and metric for survivability hopefully helps the wave energy community move beyond rhetoric, and open a dialogue on the subject of survivability, by providing a useful starting point.

Ocean wave energy poses some unique challenges to the field of marine engineering. To date most designs that interact with the ocean have a natural frequency substantially larger or smaller than the frequency of the wave [10]. However, for optimum power capture wave energy converters must operate at or near resonance. This introduces many difficult fatigue based design considerations that effect reliability. As mentioned previously, system reliability has a strong impact on operational expenses. For this reason design techniques for reliability in the ocean wave energy field must be developed and adapted from current engineering practices.

More information still needs to be included in the metric of survivability. For instance, sea wave conditions vary both in amplitude and frequency, yet the previous analysis was conducted assuming that only wave amplitude affects the survivability of the device. However, variations in wave frequency are also likely to have an impact, and for this reason future work will include this consideration. The probabilistic nature of the ocean leads to other necessary areas of research and development.

The education of most engineers does not include a strong emphasis on probabilistic design. But the fact is that the oceans are anything but consistent, and can only be completely understood and designed for through the practical application of statistical methods. Research has also begun on the development of design recommendations for marine energy converters that are based on a statistical analysis of the wave climate off the Oregon Coast.

The definition of survivability proposed in this paper does not cover extreme conditions that may occur while the ocean wave energy converter is operational. Some examples of these extreme events would be rogue waves, tsunamis, and boat impacts, and shark bites. The likelihood of encountering these events is in general very small, lying outside what would typically be considered in probabilistic system design. The chance of boat impacts and shark bites may be higher, but these issues can be addressed through preventative measures such as cable shrouding and a compliant shock absorbent buoy bodies. If we include them in the definition of survivability they muddle the separation that has been developed with reliability. Tsunamis and rogue waves should be addressed separately from the standard probabilistic design for reliability and survivability, as it is unlikely than an appropriately sized device could encounter these events without some failure. Therefore future work should address the appropriate sizing and specification of damage limiting weakest link mechanisms designed specifically for these extreme singular events.

5) CONCLUSIONS

As energy demand increases at the same time production peaks and begins to fail, it becomes imperative that new alternative energy sources become available. The oceans are one alternative source of clean renewable energy. The oceans continuously receive and store an immense quantity of solar energy in the form of waves. Harvesting this energy has great potential, but also great risk. The same energy which is being harvested has the potential of destroying the harvester. This risk is the essence of the term “survivability”. In order to reduce the risk associated with ocean energy, the concept of survivability must be clearly defined, developed and understood.

This paper proposed a standard definition and metric for survivability in the context of marine
renewable energy. Their potential use and value was then explored in a brief example. The definition is by no means perfect, and the metric should be further developed, but the intent of this paper is to provide a starting point for future discussion on the topic of survivability and marine renewable energy.

Ocean wave energy is a budding renewable energy field with new ideas continuously being proposed. It is therefore necessary for investors and developers to have a clear picture of the survivability, and therefore the risk of their system. Without clearly developing the concept of survivability and its affect on the viability of marine renewable energy investments will frequently fail, and time and money will be wasted on the development of inferior technology.

REFERENCES


3) Design Through Understanding for the Reliability and Survivability of Wave Energy Converters

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Manuscript will be submitted to: Renewable Energy an International Journal Published by Elsevier:

http://www.elsevier.com/wps/find/journaldescription.cws_home/969 description
Design Through Understanding for the Reliability and Survivability of Wave Energy Converters

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ABSTRACT

The potential of ocean wave energy is truly extraordinary. This potential has driven the development of many concepts for wave energy converters. In most cases these conceptual designs are simply not feasible. They are developed on a very limited knowledge base that does not adequately consider the intricacies of the ocean environment. Many designs assume that reliability and survivability may be built in as the design progresses. This is likely a flawed philosophy that will lead to systems being grossly overdesigned just so they can endure the ocean. A system that does not adequately consider the true environmental and operational conditions early in the design process will not be a cost competitive option for energy generation.

Ocean waves are not the simple sinusoids that many designers use as their representation. They are complex and confused, and an adequate representation of their behavior can only be shown through statistics. Design methods using regular waves are simply not adequate to ensure the long-term reliability and survivability of a wave energy converter concept. For this reason, probabilistic design must be employed throughout system development.

This paper presents some of the necessary information that any ocean wave energy engineer must possess.

1) INTRODUCTION

Ocean wave energy is becoming more widely recognized as a potential source for the nation’s power [1,2]. Yet, the ocean is a difficult working environment, and ocean waves are not an ideal energy source. Ocean waves of different amplitudes and frequencies combine to form wave sets that travel at varying velocities and directions (Figure 1). The wind and currents developed during storms are capable of destroying any wave energy converter. Even arbitrary events such as a fish biting the mooring line can lead to a lost wave energy converter [3,4]. Yet, the waves themselves pose the greatest threat to a wave energy converter. The constantly varying wave induced cyclic loading will likely lead to the fatigue failure of system components. Individual waves may be encountered that are much larger than the average leading to an instantaneous catastrophic failure. Perhaps the most likely failure mode is a combination of fatigue and an extreme load.

Figure 1: Time history of the vertical displacement of a water particle near the ocean surface. The plot was constructed, by the superposition of random phase wave components, from data recorded by NDBC buoy 46050 on Nov 29, 2007 at 7am.
A wave energy converter cannot be built specifically for a certain wave height, or a certain sea state. Instead, a reliable and survivable wave energy converter will be designed to withstand all of the individual wave heights, accelerations, velocities, and subsequent loads that will occur during operation. If the designer fails to adequately consider the conditions under which their system will be deployed, then the reliability and survivability of that device will likely be impaired. Therefore, this paper seeks to improve the reliability and survivability of ocean wave energy converters by providing the reader with a baseline understanding of the ocean as a design environment.

This paper begins with an investigation and description of real ocean conditions off the coast of Newport, Oregon. A discussion of fatigue and reliability in ocean wave energy is then presented. The paper concludes with a discussion of the effect of wave irregularity on the reliability, survivability, and efficiency of ocean wave energy converters.

2) BACKGROUND

The reliability and survivability of an ocean wave energy converter depend on the environmental conditions of its deployment. For this reason, it is essential to examine the climate and conditions of an area that will likely support a wave energy park in the future. The Oregon Coast has a strong wave energy flux (20-30 kW/m), the people and politics of the area are extremely accepting of wave energy, and much of the necessary infrastructure is already in place and available [5,6]. The National Data Buoy Center (NDBC) has 10 buoys off the Oregon Coast [7]. One of those buoys, 46050 (Stonewall Banks), is located approximately 22 miles off the coast of Newport in deep water (123 meters). Newport’s strong interest in ocean wave energy, excellent wave climate, and its proximity to Oregon State University make the Stonewall Banks buoy an ideal candidate for analysis. Spectral wave data is publicly available from 1996 to the present. An analysis of extreme wave conditions has also been conducted on the site [8].

Ocean waves are comprised of many smaller waves that propagate at different speeds and oscillate at different frequencies. Data buoys convert their measurements in the time domain to the frequency domain using a fast fourier transform, creating an energy spectrum. To clarify, spectral data records the energy in a wave that is associated with a certain frequency of oscillation. Recording data in the time domain is simply impractical due to the storage space required; the data is significantly compressed by converting it to the frequency domain. All analyses presented in this paper were conducted on the spectral data recorded by buoy 46050. Techniques for spectral analysis are presented in [9-11].

From the spectral data (spectral energy distributions), time histories of the wave parameters were developed. The raw significant wave height time history is shown in Figure 2, and an averaged yearly history is shown in Figure 3. The significant wave height (Hs or H 1/3) is defined as the average height of the largest 1/3 of waves. It can be seen in Figure 2 that several large gaps exist in the data. These gaps are due to system failures, and are a simple reminder of how difficult it is to reliably operate in the ocean environment.

By averaging the significant wave height data, the seasonal variation in wave height becomes clear (Figure 3). Off the coast of Newport, the wave climate changes from an average significant wave

![Figure 2: 13 year significant wave height history of NDBC buoy 46050, 22 mi off the coast of Newport, OR.](image-url)
height of around a meter and a half over the summer months to 3 meters during the winter. This variation implies that the winter wave climate is nearly 4 times more energetic than that of the summer. This is due to the fact that the energy contained in a wave is proportional to the square of its height according to the equation 1 [12]:

\[ E = \rho g H^2 \frac{c_g b}{8} \]  

(1)

In this equation \( \rho \) is the density of sea water, \( g \) is the acceleration of gravity, \( H \) is the peak to trough wave height, \( c_g \) is the group velocity, and \( b \) is the considered crest length of the wave. In deep water \( c_g \) can be approximated as half the phase velocity, \( c \); where the phase velocity is the velocity of the wave crests. The considered crest length is usually one meter, resulting in the wave energy flux, more commonly termed the wave power (kW/m).

Figure 4 shows a plot of the yearly average wave period. The mean wave period is defined by the center of area of the spectral energy distribution. Once again it can be seen that wave period is longest during the winter, around 9 seconds, and falls to around 6 seconds during the summer months. The inverse of wave period is the wave frequency (\( f = 1/T_m \)). Wave energy converters will respond more vigorously to certain wave frequencies. For this reason, a location’s seasonal variation of mean period is critical to the efficiency of a wave energy converter.

Probability distributions can and should be developed for the main wave parameters such as significant wave height (\( H_s \)), mean period (\( T_m \)), crest to crest period (\( T_p \)), zero up-crossing period (\( T_z \)), and wavelength (\( \lambda \)). The crest to crest period is the average time between crests, irrespective of their vertical elevation. The zero crossing period is the average time between points where the surface elevation is equal to the still water level.

A probability distribution can also be developed relating to the number of hours spent per year at a given significant wave height (Figure 6). This plot provides useful information while selecting operating conditions for the device. For instance, if the device must be operational for a certain number of hours per year to turn a profit, then we can identify the significant wave height that marks the upper limit of our operating region. It may also be known that a certain number of MW-hrs of energy must be sold to the grid per year to be profitable. The information in Figure 6, along with estimates of device efficiency and power output can...
be used to establish the upper bounds of the device’s operating region.

Three dimensional probability distributions can also be developed relating wave parameters. Figure 7 shows the probability distribution of significant wave height and wavelength combinations. The most probable combination of significant wave height and wavelength occurs at approximately $H_s=1.5\text{m}$ and $\lambda=50\text{m}$. Certain wave energy converters like the Pelamis are designed to operate most efficiently at a certain combination of wavelength and amplitude [12,13]. The information in Figure 7 would likely be used to optimize the device to operate most efficiently at or close to the most probable combination of wave amplitude and wavelength. Doing so would maximize the amount of time that the device is operating at its highest efficiency.

Figure 8 is a probability distribution of significant wave height and mean wave period. This figure provides useful information for the design of quasi-resonant point absorber buoys. These devices such as Ocean Power Technologies’ PowerBuoy or the WaveGen are designed to operate in quasi-resonance with the waves to increase their extraction efficiency [12,14-18]. It is therefore important that the natural frequency of the device is close to the most probable frequency of the waves.

Figure 5: Monthly probability distributions for significant wave height derived from 13 years of data.

Figure 6: An estimate of the number of hours per year off the coast of Newport Oregon that will be spent at a certain significant wave height.

Figure 7: Contour plot of the probability of the combination of significant wave height and wavelength. The cyan line along the upper edge of the distribution marks the wave breaking condition.

Figure 8: Contour plot of the probability of the combination of significant wave height and mean wave period. The cyan line along the upper edge of the distribution marks the wave breaking condition.
3) DESIGN INFORMATION

Ocean waves often become confused and irregular as various waves of different frequencies and amplitudes progressing at different speeds and in different directions combine to form the wave set. An example of the vertical displacement of a buoy or particle riding the waves can was presented in Figure 1. There is often no consistent underlying dominant wave structure. However, if a statistical analysis is completed on the displacement of the peaks and troughs from the mean water level, it can be shown that the probability distribution of a certain wave height often closely follows a Rayleigh distribution:

\[ P(h) = \frac{h}{\sigma^2} e^{-\frac{h^2}{2\sigma^2}} \]  

(3)

In this equation \( \sigma \) is the standard deviation of the desired Rayleigh distribution, and \( h \) is the peak to trough wave height. It is also simple to show, through differentiation, that for a Rayleigh distribution, the standard deviation is equal to the most probable wave height in the data (mode). By integrating and differentiating the Rayleigh distribution, it is possible to determine the relevant statistical wave heights such as the significant wave height, the average wave height, and the most probable wave height. Further, if it is assumed that the Rayleigh distribution approximates the distribution of wave heights regardless of the modal wave height, then it is possible to generalize the distribution and calculate ratios that relate the modal or mean wave height to the other statistical wave heights. This is done by setting the independent variable of the distribution to the ratio of wave height over modal wave height or mean wave height. In equation 3, \( h \) would be replaced with the ratio of wave height over mean wave height (\( h = H / H_{\text{mean}} \)), and \( \sigma \) would be replaced with the ratio of modal wave height over mean wave height (\( \sigma = H_{\text{mode}} / H_{\text{mean}} \)). The resulting distribution is shown in Figure 9. Integration of the distribution allows the various ratios relating the probabilistic wave heights to be found (Table 1) [19,20]. These ratios have previously been calculated, but have not often been visualized.

The inclusion of the commonly used sea states, in Figure 10, shows just how meaningless it is to say that a device was designed for a certain sea state. Exactly what wave sizes were considered; those at the upper boundary, the lower boundary, or somewhere in the middle of the range?

<table>
<thead>
<tr>
<th>Table 1: Factors Relating Statistical Wave Heights</th>
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<td>( H_X = C \cdot H_S )</td>
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Figure 9: Rayleigh distribution of individual wave heights relative to the mean wave height. This distribution may be used in the estimation of design wave heights.

Figure 10: Various statistical wave heights relation to the widely reported significant wave height. The sea states have also been marked for reference. Ratios determined by integrating the Rayleigh distribution.
It is much more meaningful to indicate the maximum significant wave height that the system was designed for. It should be noted that the Rayleigh distribution is not the most accurate distribution for predicting small probability wave heights. As the probability of occurrence becomes smaller, both Lognormal and Weibull distributions provide more accurate estimates of wave height [10]. However, both the Lognormal and Weibull distributions require site specific parameters, and if these parameters are estimated or generalized their added benefit will be reduced. However, regional estimates of the parameters can be found in the appendices of DNV-RP-C205 [11]. In the concept and early stages of the design process, site specific parameters are not typically available, and thus the Rayleigh distribution provides the best balance of simplicity and value.

Figure 10 demonstrates the numerical relation of the various statistical wave heights, as shown in Table 1, to the significant wave height. $H_{\text{mean}}$ is the height that 50% of the waves will reach; $H_{\text{1/10}}$ is the mean height of the highest 10% of waves; $H_{\text{1/100}}$ is the mean height of the highest 1% of waves; and so on. $H_{\text{1/10000}}$ corresponds to about the number of waves that would be seen in 24 hours of a certain significant wave height.

As mentioned previously, estimate error increases with decreasing probability of occurrence while using the Rayleigh distribution. For this reason, it should not be used for long term (100-year wave) prediction. However, estimating the maximum height of a wave during a 24 hour midwinter storm with a certain sustained significant wave height may be beneficial even if error is as much as 10% [10]. For instance, this may aid in the design of the maximum travel of the power take-off system or in the design of the mooring system.

4) DESIGN FOR RELIABILITY AND SURVIVABILITY

The average design life of an ocean wave energy converter will likely increase in order to maximize profitability, from a low of around 10 years to 30 or more years as the technology matures [13,21]. Ten years of service off the coast of Oregon would subject the device to over 40 million waves according to the analysis performed for this paper (Figure 11). If it is assumed that each of these waves places an individual load on the converter, then the wave energy converter must be designed to withstand over 40 million loading cycles of varying amplitude. In this scenario the mitigation of fatigue failure becomes critical to the reliability and survivability of the device.

It is widely accepted that a wave energy converter will only be viable if it can endure a minimum of 10 years of ocean deployment. Through modeling, stress response curves may be developed for individual devices. A hypothetical stress curve is shown in Figure 12. Combining this information with the real estimate of the number of waves of a certain height encountered during 10 years of operation (derived from NDBC buoy 46050) will lead to an estimate of the number and amplitudes of loading cycles that the device will be subjected to throughout its design life.

In order to maximize the power captured from ocean waves, wave energy converters are also likely to be operated in a quasi-resonant state with the average frequencies of the most energetic waves [12,14-18]. This fact complicates the design of ocean wave energy converters for reliability and survivability.

![Figure 11: An estimate of the number of waves of a certain height encountered in the course of a 10 year design life. Estimate was developed from 13 years of data from NDBC buoy 46050.](image)
Figure 12: Imaginary Stress Response curve for the mooring system of an ocean wave energy converter.

The process of estimating loading cycles can and should be expanded and improved by including the frequency response of the device as a separate independent variable resulting in a response surface.

After the estimate of loading cycles has been established, it should be applied to a fatigue analysis. The linear cumulative damage theorem is used widely in industry; however crack-propagation theory may also be used for a more accurate but time consuming analysis. Many sources are available in the field of fatigue reliability [22-27].

5) RELIABLE WAVE ENERGY EXTRACTION

The simple principle of ocean wave energy is that by resisting the motion induced by the waves a reactionary force is developed. That force can then be used to move any combination of gears, pulleys, pistons, turbines. These mechanical power take-off systems (PTOs) ultimately move generators that convert that initial resistance of the ocean’s natural motion into electricity [12]. The key to ocean wave energy is the motion of the waves themselves. It is therefore useful to quantify that motion beyond the standard yet somewhat ambiguous parameters of significant wave height, mean period, and wavelength.

Particles of water in simple sinusoidal waves move in an orbital within a vertical plane defined by the direction of wave propagation. It can be shown that in monochromatic waves the magnitude of particle velocity and acceleration is constant. However, as the ocean waves become more confused and less regular, the orbitals become irregular (Figure 13). In this scenario, the magnitudes of water particle velocity and acceleration at the water surface are not constant (Figure 14). In Figure 14 the magnitude of water particle velocity for a spectral wave state is compared to the constant velocity of an equivalent sinusoid. It can be seen that in a real sea state the magnitude of water particle velocity is

Figure 13: This figure shows 20 seconds of a water particle’s position for a wave recreated from spectral data and a sinusoidal equivalent wave.

Figure 14: A spectral recreation of the seas on 1/1/99 at 1am and that seas equivalent power sinusoid. A comparison of the magnitudes of water particle velocity for the spectral seas and the equivalent sinusoid shows bursts and lulls in motion.
usually less than that of the sinusoid with short bursts of speed that exceed that of the sinusoidal waves.

This reality has important implications for the reliability and survivability of ocean wave energy converters. Let us consider a wave energy converter that can harvest energy in both surge and heave. Such a converter in perfectly sinusoidal waves would be able to generate power 100% of the time. However, as the waves become less consistent the converter will start to experience lulls and bursts of motion that will reduce the consistency of power generation. The lull and burst scenario will affect the efficiency and capacity factor of the device. With every burst of energy, large amounts of energy are available to be harvested. However, harvesting these large bursts will invariably lead to large cyclic system loads. For this reason system reliability is greatly influenced by the irregularity of the ocean waves.

In an attempt to characterize the effect of wave irregularity on the magnitudes of water particle velocity and acceleration, a time domain Monte Carlo simulation was performed using Matlab. The simulation began by sorting 13 years of hourly wave spectra based on their resulting significant wave height. The spectra were placed in bins with a one meter wave height differential. The spectra were then averaged within each bin. The result was an average three meter wave spectrum, an average four meter wave spectrum, and so on. Superposed sinusoids were then developed for each average spectrum, according to equations 5, 6, 7, and 8 [10].

\[
x(t) = \sum_{i=1}^{n} A_i \cos(-\omega_i t + \varepsilon_i) \\
y(t) = \sum_{i=1}^{n} A_i \sin(-\omega_i t + \varepsilon_i)
\]

\[
A_i = \sqrt{2} S(\omega_i) \Delta \omega
\]

\[
\varepsilon_i = 2\pi \text{ rand}(n)
\]

In these equations, \(A_i\) is the wave amplitude, \(\omega\) is the angular frequency, \(S(\omega)\) is the spectral energy density at \(\omega\), and \(\varepsilon_i\) is the phase offset of the wave component.

Wave particle position was then calculated every quarter second for 3000 seconds. Magnitudes of particle velocity and acceleration were then calculated according to equations 8 and 9.

\[
V = \sqrt{(dx/dt)^2 + (dy/dt)^2}
\]

\[
A = \sqrt{(d^2x/dt^2)^2 + (d^2y/dt^2)^2}
\]

Probability distributions for both the magnitude of velocity and acceleration were developed and are shown in Figures 14 and 15 respectively. It can be seen that both the acceleration and velocity distributions are similar in shape to a Rayleigh distribution. This implies that the majority of the time the magnitude of water particle velocity and acceleration will be less than the mean. However, the shape also implies that instantaneous particle velocities and accelerations will likely reach between three to four times the

![Figure 15: Probability distributions for the magnitude of water particle velocity at three significant wave heights. (Monte Carlo Sim, 13yrs data, buoy 46050).](image)

![Figure 16: Probability distributions for the magnitude of water particle acceleration at three significant wave heights. (Monte Carlo Sim, 13yrs data, buoy 46050).](image)
mean. In order to harvest the same amount of energy as a converter operating in sinusoidal waves, these bursts of motion must be captured. If the energy is not captured, the efficiency of the device will be reduced ultimately increasing the cost of power produced by the device.

6 FUTURE WORK

A method was outlined in this paper that provided a means of estimating the number of waves of a certain height encountered in ten years, and thus the number of loading cycles that must be designed for. However, ocean waves are always to some extent irregular. The extent to which this irregularity influences system loading must be better understood.

System reliability and survivability is dependent on many traits of the specific device, for instance is the system maintainable, allowing for easy repair in rough weather, is the mooring system compliant allowing for large system displacements over a short period of time. Is the system built with redundancies? The benefit of these principles and the extent to which they should be included in the design must be further researched.

Estimation of loading and fatigue is in many respects a design dependent topic; however a great deal of research on passive load reduction is still possible. Following the logic of wind turbines feathering their blades to reduce system loading, a wave energy converter that could become partially transparent to extreme conditions would possess an obvious advantage. But it is still questionable if this type of passive survivability is even possible.

The standardization of many of these design considerations and methods is an ongoing area of interest and research. Standards for ocean wave energy were recently published [28,29]. However, these standards do not include comprehensive coverage of the early stages of design. In a field that is still very much in the early stages, it is important to develop the standards to include this period of the design process. Providing developers with a road map through the concept, modeling, and prototype phases of design would greatly reduce the time to final deployment.

7 CONCLUSION

The most powerful tool for an engineer is knowledge. The engineering process begins with the recognition of a problem. Information is then gathered to help classify the nature and context of the problem. Only then, after all of the necessary information has been gathered and understanding has been gained, can solutions be proposed. This paper sought to provide the reader with a baseline understanding of the ocean as an operating environment, with the intent of improving design through understanding.

A method for estimating the number of waves of a certain height that will be seen in a typical design life was then presented. This allowed for an approximation of the number and amplitude of fatigue cycles encountered by a device which is critical for design reliability.

Ocean waves contain an immense amount of energy. But it was shown, using a Monte Carlo simulation, that the energy that is contained in a wave cannot be extracted freely; it is given by the waves in bursts of motion that must be efficiently and reliably absorbed. Capturing these bursts of energy will impart large cyclic system loads that must be appropriately designed for.

The reliability and survivability of an ocean wave energy converter is in large part decided early in the design process. A strong understanding of the operating conditions associated with ocean deployment of a wave energy converter is critical to the long term success of the device. The ocean behaves randomly, and it can only be reliably designed for with a probabilistic approach.

REFERENCES


4) Early Stage Failure Modeling and Analysis Applied to a Wave Energy Converter

Adam Brown, Irem Tumer, Robert Paasch


Paper number: DETC2008-49360

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ABSTRACT

Ocean wave power is still in its infancy. New systems are conceptualized on nearly a daily basis. The systems vary wildly in complexity and scope, but share one common trait; they have never been built. This scenario is ripe with massive financial risk and of course the possibility of reward. Providing an early stage failure and safety analysis could greatly improve the design process by identifying potential weak points in the system prior to the costly build and testing stages of product development. More broadly, determining potentially successful conceptual designs which should be pursued becomes critical. However, there is currently no tool readily available for such a task. In this paper, we adapt and simplify function-based modeling and analysis to fill this void.

Completing a function based failure analysis allows engineers to evaluate the dependencies and fault tolerance of their system early in the design stage. This process aids in catching design problems when they are still relatively cheap to address. This paper proposes the System Functionality Method for conceptual design stage analysis. This proposed method places systems and subsystems in a flow (mass, energy, and signal) based on their location, and assigns functionality numbers to help describe their contribution to the system. Component or sub-system faults are then used to determine the effect on other components and the system as a whole. The process is unique in its simplicity and adaptability to the conceptual stage of designing wave energy technologies.

1) INTRODUCTION

1.1) Wave Power

The ocean collects and channels the power of the wind to the coast in the form of waves. The energy that is in these waves is more dense than that in either solar or wind. The power in ocean waves could become one weapon in the fight to end global warming. The search for new sources of clean and renewable energy becomes ever more important as the world’s temperatures continue to rise.

Investigation into the use of Ocean waves as a form of renewable energy began in the 1970s during the oil crisis [1]. Since that time many designs have been proposed, but a clearly superior machine has yet to be developed. Ocean wave power is still a very immature technology with many interesting questions waiting to be answered.

Researchers at Oregon State University have been working to develop an ocean wave energy converter that could potentially provide power to the grid at a competitive price [2, 3]. In a recent project the research group evaluated the various
technologies which could be used for ocean wave energy conversion. The “best” design was chosen for construction and testing during the summer of 2008. Initially, each design was roughed out as a series of sketches that included the major functions and components needed, and a simplistic layout. The selection process then became difficult as there was no tool available to aid in the process. As it was, the various engineers estimated these traits in different ways, and thus subjectivity in the conceptual design phase was difficult to overcome. A consistent method for arriving at traits such as efficiency, maintainability, and failure modes would have been extremely helpful.

In a field of engineering where new designs are being proposed on a consistent basis, it can be difficult to determine which concepts are most likely to work without a consistent method for comparative evaluation. Due to the conceptual nature of the proposed designs, simple functional modeling and function based failure analysis techniques can be used effectively as a tool to help evaluate the likelihood of success for varying designs even before all of the components have been finalized. This paper uses one such energy converter design currently being investigated at Oregon State University as a case study for analysis.

A rough diagram of the wave energy converter concept can be seen in Figure 1. The design used for the case study is a point absorber; a buoy located off shore, generating power from one point on the ocean’s surface. As the buoy climbs to the crest of a wave its kinetic energy is transmitted through the mooring system to the main drive spindle. The drive spindle unwinds rotating the drive shaft. The angular velocity of the shaft is relatively slow and is increased in the gearbox. This rotational kinetic energy is then used by the generator to create electricity. Simultaneously, the rewind spindle is winding up, stretching the extension springs. The potential energy that is stored in the springs is used to rewind the main drive spindle as the buoy falls into the trough of the next wave. Any spring energy that isn’t needed to rewind the drive spindle is harvested by the generator.

1.2) Conceptual Stage Failure and Safety Analysis

In the field of ocean wave energy, one clearly superior technology has not yet been introduced. This opens the field to a myriad of possible ideas. This fact demonstrates the need for an analysis technique that will allow potential concepts and designs to be evaluated for safety, and reliability at an early stage. There are several failure and safety analysis techniques currently being employed in system design, such as FMEA (Failure Modes and Effects Analysis), FTA (Fault Tree Analysis), ETA (Event Tree Analysis), FFDM (Function Failure Design Method), and FFIP (the Functional Failure Identification and Propagation framework). The aforementioned analysis techniques all have strengths and weaknesses. Automation of a method that simplifies and links them could help solve many of the problems associated with their implementation. However, in order to provide
accurate results, current automation techniques typically use advanced models to describe the behavior of the system based on components. The drawback is that if the main system designer is not an expert in system modeling, errors could be made in the description of the system leading to wasted time and inaccurate results. This is also a problem because it requires the design to be nearly complete prior to modeling, thus preventing use in the conceptual design stage. For this reason it is highly desirable to make the modeling process based on function, and as simple as possible. 

It is also desirable to reduce the number of components and subsystems analyzed. Most designs include many standard components, everything from motors and pumps to nuts and bolts. It is suspected that for these common components there are common failure modes across applications. A huge time savings could be achieved by reusing the results of previous failure analyses completed specifically on these devices, and linking them to the overall system.

Modeling of systems in the conceptual stage of design can be difficult. A vague list of customer needs has potentially been developed, and possible solutions have come to life on the back of napkins, but little concrete information is available. To proceed past the napkin stage of design, necessary system functions are outlined. At this stage simple analysis can begin to aid in the selection of a promising concept. In order to do this, the analysis technique itself needs to be simple, providing useful information to the engineer.

In the area of novel system design there is a strong need for an analysis technique that is simple and abstract; that can be used in the conceptual stage, prior to specific component selection. The technique cannot rely on information gathered from similar past experiences, as this information does not always exist. The method does not need to be as thorough as the other techniques mentioned; it simply needs to provide engineers with useful information that can be used to help identify problematic design choices and evaluate the likelihood of success for different designs early in the process prior to major financial investment.

1.3) The System Functionality Method (SFM)

This paper introduces the System Functionality Method (SFM) for failure analysis of such systems, shown schematically in Figure 2. SFM includes a functional decomposition of the design which allows the engineer to determine the necessary sub-systems and sub-functions required. A functional flow path is then generated which aids in the determination of fault propagation. Each component or sub-system is given a “Functionality Number” (FN), a function, and if necessary, a sub-function. The FN maps to efficiency, representing the component or functional sub-system’s ability to support the flow. Faults relating to the FN or function of components can then be introduced to the system. The fault propagation paths are then determined and followed.

SFM is particularly suited for the earliest stages of design; however it could be used throughout the design process to provide the engineer with valuable information as designs become more complex.

The overall goal of this research is to provide a tool that will help all engineers focus on safety and quality. The analysis method is applied to the design of a wave energy converter being developed at Oregon State University. The technique is unique in its simplicity and adaptability and is well suited to use in the conceptual design stage.

Figure 2: Basic flowchart for the System Functionality Method
This trait helps identify potential problem areas early, and could be used in the future to help select promising designs.

This paper first provides some background information on failure analysis, automation, and functional modeling techniques. The proposed System Functionality Method is then described in detail and applied to the wave energy converter previously described. The paper concludes with a discussion of future work, and some thoughts on the value of SFM.

2) BACKGROUND

2.1) Failure Analysis

Failure Analysis is truly a crucial aspect of the design process. Techniques such as FMEA, FTA, ETA, FFDM, FFIP provide a broad view of the system being designed [17, 18, 19, 20, 30]. This view helps to identify potentially hazardous problems before they actually occur [21]. These techniques were originally developed to improve product safety, but they also have the potential to greatly improve product quality.

FMEA is one widely accepted method of safety and failure analysis that identifies individual failure modes of system components and identifies the effects of their failure on the overall system and user [7, 8, 9, 10, 12]. This procedure is very labor intensive and subjective. Failure Mode, Effects, and Criticality Analysis (FMECA) simply expands on FMEA by attempting to quantify the results [6, 15]. This quantification of the process may in some instances actually increase the subjectivity of the analysis. The wave buoy seen in Figure 1 has been conceptualized, and a small prototype has been built, but full scale designs are yet incomplete. This poses a problem for both FMEA and FMECA as they are thorough component-based analysis techniques that would be difficult to implement early before any final design decisions have been made.

Fault Tree Analysis (FTA) tracks a system level fault to the subsystems or components that were responsible [4, 11, 13, 14]. This process is also labor intensive due to the sheer number of possible system faults and combinations of component and subsystem failures that may lead to such a system fault. Automating the safety analysis processes could greatly improve repeatability while reducing the inherent subjectivity. It also allows for the analysis of multiple concurrent failures that lead to system faults; a task that is extremely difficult when done manually. However, this method is not appropriate for the conceptual stage of design due to its thorough component centric analysis.

Event Tree Analysis (ETA) is an analysis technique that begins with an initiating event and follows the effects of the initial event through logical scenarios to determine its potential consequences. This technique is broadly applicable to the characterization of possible fault propagation paths. However, the method does not provide an easy way of dealing with partial failures.

The performance of a failure and safety analysis is widely accepted as a means of improving the quality of a product. However, these analyses are usually performed late in the development process, when fundamental design changes are costly. A few methods developed in recent years have attempted to incorporate failure and safety analysis into the conceptual stage of design.

The Function-Failure Design Method is a relatively new technique for failure analysis [5, 16] that links function to component and component to failure in matrices. FFDM was later expanded on by the Risk in Early Design (RED) Method, which developed a ranking system for the functional-failures [31]. The major benefit of FFDM is that it allows failure analysis to be conducted very early in the design stage. However, FFDM is a knowledge based system, relying on databases of previous component failures. The quality of the analysis therefore depends on the quality of the database. In the case of the wave energy group, some of the systems which were evaluated relied on brand new technology with unique failure modes being applied in a harsh environment; therefore little information can be drawn from past experience.
The Functional Failure Identification and Propagation (FFIP) framework has also been developed in recent years [19]. The intent of the system is to estimate potential faults and their propagation paths under critical event scenarios using behavioral simulation [19, 30, 36]. The technique is aimed at the early stages of conceptual design, but can be used throughout the design process. FFIP uses three major components to assess functional failures and their propagation paths. The components of the technique are the graphical system model, the behavioral simulation, and the reasoning scheme which is called function failure-logic (FFL). This is a very promising system for early failure analysis that solves many of the problems inherent to the other techniques discussed. However, FFIP can best reason through failure scenarios that have already been modeled. This may prove to be a problem for novel system design in which new and unexpected failure modes can be present.

The safety analysis process has the potential to bring together designers from all of the individual subsystems; increasing the number of individuals familiar with the design as a whole [22]. This type of knowledge sharing can help find many problems that would have otherwise been missed. For instance the electrical team might want to run some power lines along a machine’s frame, while the engine team might want to put their fuel tank in nearly the same area. This orientation of the system could be hazardous, and without the designers from varying groups coming together to perform a safety analysis this hazard may be missed. It is also important to note that if an automated safety analysis technique was relied on, it is likely that the hazard would be missed. This oversight is due to the fact that only direct functional dependencies between components are included in these analyses; the components’ location and orientation are typically omitted. It should be noted that in certain cases, FFIP might catch such a hazard, as it includes information pertaining to configuration, but not location and orientation [19]. This fact demonstrates that even as automation techniques advance in their abilities to accurately perform safety analysis, a team of engineers from the varying design groups must still oversee and contribute to the process.

2.2) Failure Analysis Automation

It is widely recognized that great improvements could be made through automation of failure analysis techniques. Several techniques have already been developed to automate the process. These methods can be generalized as using three different analysis techniques: 1) Knowledge Based (Expert) Reasoning, 2) Numerical Simulation, and 3) Causal Reasoning [7].

To date, knowledge based systems have enjoyed the most success [6, 9, 15, 20, 35]. By focusing on the individual components and using data mining for their individual failure modes, it is possible to reduce the necessary amount of system modeling and analysis. However, by relying on previously observed failures, these systems may miss new, unique, and design specific failure modes. The Flame System, which was eventually commercialized as AutoSteve [6, 15] focuses on circuit analysis and has been adopted by several automotive companies. However, knowledge based systems are not appropriate for wave power devices as they rely on information collected from failures of previous similar designs. This information is simply not available for some novel wave energy converters as there are no previous similar designs.

Numerical simulators attempt to quantify the level of component failure and then using mathematical equations, link component failures to system failures [8, 13]. These systems are usually very thorough and accurate. However, they are also very modeling intensive, requiring in-depth and accurate functional models and state models. They also usually include the time domain. After it has been developed, the model is simulated for every possible fault to determine the system level effects. Grunske et al. proposed an analysis method that uses behavior trees to simulate a system at or near the functional level. However, the modeling and simulation time necessary for most numerical
simulations can be huge. This fact is a problem for the wave power project, as many conceptual designs need to be analyzed quickly at a fairly high level of abstraction.

Causal Reasoning was proposed as a method for safety analysis in a paper by Bell et al [7], and has been adopted in varying degrees by many of the methods already discussed. The system uses natural language to describe component and system function as cause and effect. This natural language then becomes the “value” used for logical operators which extrapolate the effects of component failures on the system. The natural language operators are then easily combined to form an FMEA report. The main problem with this system occurs when a positive term and a negative term must be combined. The result is ambiguous because no degree of positive or negative can be assigned to the natural language which is used as the “value”. There are some ways around this problem, and as stated, many of the systems previously discussed use this construct to some degree.

The systems currently proposed all have benefits and limitations. Some techniques work well for the functional stage of design while others are only intended for analysis in the latest stages. The main weakness of these systems when applied to the wave power project is their level of complexity. In a field of engineering where designs need to be evaluated quickly at a high level of abstraction, the analysis technique should be simple and functional.

2.3) Functional Modeling

Functional Modeling is a way of representing the intended purpose of a device by describing the role of its individual functional sub-systems and/or components. Functional modeling is not concerned with the specifics of the component, but merely its purpose. For that reason, functional models of a system can be developed prior to component selection. This trait lends functional modeling to the conceptual stages of design [23]. Part function can be used in the conceptual stage for design by analogy as well as for failure analysis [24].

Many different functional modeling-based techniques have been developed including Bond Graphs, Function Structures, Goal Tree Success Tree, Behavior Trees, Graph Grammars, Exemplars, Function Converters, and FFIP [10, 19, 23, 27, 28, 32, 37].

Functional modeling has great potential for use in early stage failure analysis. However, functional models are often complex, and if the designer is not proficient, mistakes may easily be made in the functional description of the design. Once again this complexity poses a problem for the wave power project due to the number of devices which would need to be modeled in a limited amount of time. Furthermore, functional modeling has often been criticized in that different engineers may arrive at completely different functional models of an identical system. It has been shown that this problem is partially tied to the language of function, which can be fairly ambiguous [24, 33, 34]. This problem has led to the creation of functional taxonomies intended to help standardize the way in which function is described [27, 29].

In order to become widely used by a majority of engineers, any proposed early stage analysis technique should be repeatable and simple, with as few steps and processes leading up to the actual analysis as possible. The functional flow needs to be simple and direct so that it may be established in yet un-finalized systems. Finally, the technique must be able to handle a mix of actual components and simple functional descriptions when components have not yet been selected.

3) SYSTEM FUNCTIONALITY METHOD (SFM)

3.1) Overview

In this paper the System Functionality Method for safety and failure analysis is introduced (Figure 2). This method is a tool for use in the earliest stages of design. It is simple, yet adaptable and can be used throughout the design process to provide useful information to the engineer.

The method begins with a functional decomposition of the conceptual system (Section
This decomposition allows the engineer to determine the level of abstraction possible for the analysis, and aids in the brainstorming process. Components and sub-systems from the functional decomposition are then given a “functionality” number (FN), and placed in a flow of energy, material, or signal (Section 3.3 and Figure 5). The FN is a numerical representation of the component or sub-system’s ability to support the flow; a fraction of the input flow that reaches the output of the component or sub-system. Function is defined to be the main purpose of the sub-system or component. Faults are then introduced to the FN (Section 3.4) or the component/function (Section 3.5), and propagation paths and effects are determined.

3.2) Functional Decomposition

The SFM method begins by assigning a system its functions and sub-functions, as introduced by Papadopoulos et al. [13, 14]. The components and assemblies of the system are then handled in a like manner. This system can be visualized as a functional tree that starts at the main function of the entire system and then branches directly to the necessary sub-functions that directly support the main system function. These sub-functions are then also decomposed as far as possible with the information that is known (Figure 3). The individual sub-assembly or component branches of the tree can then be removed or altered without affecting the overall function of the system as long as the necessary sub-assemblies still remain (Figure 4). This demonstrates the ability of functional modeling to analyze the system at varying levels of abstraction, even when individual components which contribute to a system’s function are yet unknown. This is important to the wave power project because it allows varying design choices to be substituted quickly and analyzed at a high level of abstraction. For instance the extension springs which are used to rewind the main drive spindle could be replaced with a hanging mass or flywheel, and the system could be re-analyzed.

3.3) System Flow

The system assemblies and components are also related to one of the three standard flows (energy, material, or signal) [27, 37]. The flow paths are then developed using the known functions and if possible components. Flow paths are used to describe functionality in terms of inputs and outputs, and relate to the system layout. An example of a flow path for the wave energy converter can be seen in Figure 5.

In this case the main flow of the system is energy. All components that relate to the main flow must be included in the flow stream. Other functional blocks or components that only absorb small amounts of energy from the system (e.g., bearings) can be included as inputs to the function or component that they affect. In this scheme specific components are unnecessary because the larger functional sub-assembly block that they belong to can be given a functionality number, and substituted in the components’ place (Figure 5). Of course this substitution should be done in the reverse order replacing functional blocks with components as they become known. The increase in system detail will lead to an increase in the fidelity of the final analysis. This fact is incredibly important to the wave power field as it allows conceptual systems to be analyzed prior and evaluated prior to serious financial investment. Another benefit comes from the systems’ adaptability in the conceptual design stage. Ideas for functional sub-assemblies can be quickly altered or modified allowing different designs to be analyzed. For example the simple tension mooring system described in the flow model could be quickly altered allowing different variations of the mooring system to be analyzed quickly.

3.4) Flow Characterization and Failure

The ability of any modeling technique to handle partial failures is necessary, as the overall function of the system may depend on a certain percentage of the total flow being carried through until the end. If enough “leaks” are present, the system might fail, even if none of the components have completely failed. To handle this situation,
SFM gives all components and assemblies a “functionality number”. This number represents a percent of functionality from the nominal (designed value). Failures or efficiency degradation relating to the flow can be modeled by altering the functionality number of that component. For instance, if the gearbox has a bad internal bearing that’s absorbing 25% of its input energy, then the FN of the gearbox would be 0.75 because only 75% of the input energy was delivered to the generator. Pure efficiency can also be modeled using the functionality number if that efficiency is known. For instance, if the nominal efficiency of the gearbox is known to be 95%, then gearbox is simply given a FN of 0.95 to reflect that efficiency. The functionality number is then lowered from this nominal value of efficiency if a fault or failure is present. If the efficiency of a functional block isn’t directly known, it can either be estimated or a functionality number of 1 can be assumed to represent nominal operation. Functionality numbers may range from 0 to ∞, with “1” representing nominal operation, “0” representing a failure that eliminates the flow, and any value greater than “1” representing a failure that generates more flow than desired.

Components, such as shafts or tubes, which are only capable of carrying through what they are given, have functionality numbers scaled from 0 to 1, as they cannot possibly generate excess flow. As described above, fractional numbers are used to describe partial loss of the flow resulting from either component failure or efficiency degradation. All functional flow diagrams used in SFM should have at least one block which initiates the flow. In the wave energy converter flow diagram this block is “Hydrodynamic Wave Power” (Figure 5). For an electrical system, it could be a battery, or, for a communication flow system, a human speaking. Blocks of this type have the capability to overload the system, and their function is therefore scaled from 0 to ∞.

The flow number attached to the initiating block is then multiplied by the functionality number of the first component, which results in an output flow number from the first component. This procedure is then continued as the flow passes downstream. The result is a percent of initial flow that arrives at its destination. The case of parallel generation or extraction from a flow complicates the procedure slightly. The actual flow values coming into the junction are summed and compared to the sum of the desired nominal values in a ratio. This ratio is the output flow value from the junction. Flows that work against the main input flow are given a negative value. This situation can be observed in the wave power example at the driveshaft (Figure 5). The main flow of energy from the wave splits; some of the energy is directly passed through the gearbox to the generator, while the rest of the energy is stored in the extension springs. Torque from the extension springs is applied concurrently with the positive drive torque; however the spring torque is applied opposite to the drive torque; therefore its flow value is negative. The sum of the two actual flows is then divided by the sum of their nominal values. The resulting flow value is then applied to the downstream generator.

The extension springs in this case represent an energy storage block. The functionality number of storage blocks should be placed on a scale from 0 to ∞, as they also have the ability to overload the flow of a system.

One interesting characteristic of storage blocks is that they almost always indicate an additional state of the system that needs to be analyzed. Applied to the Wave Energy Converter, this extra state is the rewind stroke of the buoy. As the buoy falls into a trough, the tension of the mooring line fails to provide sufficient torque to overcome that of the springs, and the energy stored in the springs is used to rewind the drive spindle. In this state the springs dominate the flow. This situation could lead to different failure modes than would be encountered in the drive stroke. The system should therefore be analyzed twice to account for the two different system states. An example of the previously described calculations is shown in Section 3.6 for both states of the wave energy converter.
Inputs will be attached to some components of the flow. Inputs are simply any artifacts that contact or influence the component, but do not carry through the overall flow. For instance an encoder might be attached to a shaft, but the encoder absorbs a negligible amount of energy from the shaft, and therefore does not support the main flow of energy through the system. However, failure of an input artifact may affect the system flow. If the encoder head begins grinding on the encoder wheel it may apply drag to the driveshaft reducing its FN, therefore affecting the flow of the system.

![Diagram of Wave Energy Converter]

**Figure 3:** Component Tree Developed for an Ocean Wave Energy Converter

![Diagram of Wave Energy Converter with components removed]

**Figure 4:** Component Tree developed for an Ocean Wave Energy Converter that has had several components removed from the tree, without degrading the functionality of the model.
Figure 5: This is an energy flow model of an Ocean Wave Energy Converter with the mooring and driveshaft assemblies shown independently. Their components could be replaced by their assemblies and the system could still be analyzed.

3.5) Function Based Failure

Failures of component functions and sub-functions may or may not affect the main functional flow, and are therefore handled separately. For example, a closed failure of a filtration system (clogged filter) will have the effect of reducing fluid flow. However, if a filtration system is simply not filtering the fluid passing through it, the flow is not necessarily reduced. However, in this case, a downstream pump is going to wear out faster than usual if it is pumping unfiltered fluid, but it might not completely fail or fail immediately [19]. This system effect still needs to be documented in the final report. For this reason, a system of failure warnings needs to be developed. These warnings are called flags in SFM, and are developed any time a function or sub-function fails. They are applied to the component that failed and all other components that could be affected. A flag is also developed any time the system is overloaded, as this scenario can cause damage to the system.

Failures can propagate either downstream, upstream, or in both directions. For instance, in the wave power example, if the gear box suddenly seize, a flag would be developed for the failure and applied to the gearbox itself. This failure obviously affects the downstream generator; at least cutting off the flow and in an extreme case it could cause severe damage. However, a gearbox failure could also damage the upstream driveshaft or mooring line. For this reason the flag that was developed should be passed to both upstream and downstream components and assemblies. These components would then be compared to the flag to determine any effects. During these comparisons, other flags could be developed and passed along.

The possible component faults used for analysis can be designated by the engineer, or all possible combinations of failure modes for a given
3.6) Example Calculations

This section presents the calculations that would be performed by an automated system, and are shown simply to illustrate how SFM would work. Figure 6 presents the tabulated values for a nominal operation and a failure case.

Case 1 illustrates a scenario during nominal operation, where with the given component efficiencies, the wave energy converter is able to convert 73% of the initial wave’s usable energy to electricity. Case 2, on the other hand, illustrates the event of a large wave anomaly that is double the size of the nominal wave, in which case, the initiating flow number, HP, becomes “2”. This generates a flag, as it will overload the system. The flow and flag are then passed through the system. The individual components have their failure modes compared to the input flow and flag, to check for potential problems. For instance if the mooring system is receiving a sustained input that is twice what it is designed for, it may fail, leading to a stray buoy. In the event of a system overload, there could also be a failure of the rewind springs, or a failure of the generator. These possible problems are then placed in a failure report; any additional flags generated would likewise be passed on, and analyzed.

<table>
<thead>
<tr>
<th>Assembly / Component</th>
<th>Abbrev</th>
<th>Func Number</th>
<th>Reasoning</th>
<th>Assembly / Component</th>
<th>Abbrev</th>
<th>Func Number</th>
<th>Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro Power</td>
<td>HP</td>
<td>1</td>
<td>Average sized wave</td>
<td>Hydro Power</td>
<td>HP</td>
<td>2</td>
<td>Large wave anomaly</td>
</tr>
<tr>
<td>Buoy Float</td>
<td>BF</td>
<td>1</td>
<td>Nominal</td>
<td>Buoy Float</td>
<td>BF</td>
<td>1</td>
<td>Nominal</td>
</tr>
<tr>
<td>Anchor</td>
<td>AN</td>
<td>1</td>
<td>Nominal</td>
<td>Anchor</td>
<td>AN</td>
<td>1</td>
<td>Nominal</td>
</tr>
<tr>
<td>Sackle</td>
<td>SH</td>
<td>1</td>
<td>Nominal</td>
<td>Sackle</td>
<td>SH</td>
<td>1</td>
<td>Nominal</td>
</tr>
<tr>
<td>Mooring Line</td>
<td>ML</td>
<td>0.9</td>
<td>Reduced efficiency from stretch in the mooring line</td>
<td>Mooring Line</td>
<td>ML</td>
<td>0.9</td>
<td>Reduced efficiency from stretch in the mooring line</td>
</tr>
<tr>
<td>Drive Spindle</td>
<td>DSP</td>
<td>1</td>
<td>Nominal</td>
<td>Drive Spindle</td>
<td>DSP</td>
<td>1</td>
<td>Nominal</td>
</tr>
<tr>
<td>Rewind Spindle</td>
<td>RSP</td>
<td>-1</td>
<td>Nominal torque capability in opposite direction as main Drive Spindle</td>
<td>Rewind Spindle</td>
<td>RSP</td>
<td>-1</td>
<td>Nominal torque capability in opposite direction as main Drive Spindle</td>
</tr>
<tr>
<td>Extension Spring</td>
<td>ES</td>
<td>0.5 x actIFDSP</td>
<td>Stores and provides 50% of the power delivered to the Drive Spindle</td>
<td>Extension Spring</td>
<td>ES</td>
<td>0.5 x actIFDSP</td>
<td>Stores and provides 50% of the power delivered to the Drive Spindle</td>
</tr>
<tr>
<td>Driveshaft</td>
<td>DSH</td>
<td>1</td>
<td>Nominal</td>
<td>Driveshaft</td>
<td>DSH</td>
<td>1</td>
<td>Nominal</td>
</tr>
<tr>
<td>Transmission</td>
<td>TR</td>
<td>0.9 90% efficiency</td>
<td></td>
<td>Transmission</td>
<td>TR</td>
<td>0.9 90% efficiency</td>
<td></td>
</tr>
<tr>
<td>Generator</td>
<td>GN</td>
<td>0.9 95% efficiency</td>
<td></td>
<td>Generator</td>
<td>GN</td>
<td>0.9 95% efficiency</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 6:** Tabulated values for a nominal operation case and a failure case.

**Nomenclature:**

Actual Inlet Flow to Drive Spindle

\[ \text{actIFDSP} \]

Nominal Inlet Flow to Drive Spindle

\[ \text{nomIFDSP} \]

**Case 1: Nominal Operation with Efficiency Losses**

\[
\begin{align*}
\text{actIFDSP} &= \text{HP} \times \text{BF} \times \text{AN} \times \text{SH} \times \text{ML} \times \text{DSP} \\
\text{actIFDSP} &= 1 \times 1 \times 1 \times 0.9 \times 1 = 0.9 \\
\text{nomIFDSP} &= 1.0 \\
\text{Net Flow Passed Driveshaft} &= \frac{\text{actIFDSP} + \text{actIFRSP}}{\text{actIFDSP} + \text{actIFRSP}} = \frac{0.9 + (-0.45)}{1.0 + (-0.5)} = 0.9 \\
\text{Power Generated} &= \text{Net Flow Passed Driveshaft} \times \text{TR} \times \text{GN} = 0.9 \times 0.9 \times 0.9 = 0.73
\end{align*}
\]

Actual Inlet Flow to Rewind Spindle

\[ \text{actIFDSP} \]

Nominal Inlet Flow to Rewind Spindle

\[ \text{nomIFDSP} \]
Case 2: Possible Large Wave Failure

4) DISCUSSION AND FUTURE WORK

This paper developed the theory behind the System Functionality Method (SFM) for failure analysis, and applied it to the early design of a wave energy converter. SFM allowed variations of a wave energy converter design to be analyzed quickly and simply; providing information that could be used to help identify weak spots in the design. The proposed method can track and report possible functional failures, as well as flow degradation from efficiency losses. SFM can be employed in the earliest stages of conceptual design. The method needs to be further developed and tested on multiple systems of varying designs. The initial implementation of this technique on the wave energy converter showed great potential. SFM could be greatly improved by research and development in a few key areas.

First, the functional definition process within SFM could be improved by providing flow specific templates. These templates would require the necessary information for analysis, yet allow the engineer to add any other available information. The functional blocks developed from these templates could then be inserted into the system flow model and used for analysis. The internal functional description could be developed by the engineer according to a simple flow specific template.

SFM will be tested on larger more intricate systems to better determine its effectiveness on designs of varying complexity. It is expected that the information provided by the analysis method will become more useful as system complexity increases. This is due to the fact that as complexity increases, it becomes more difficult for the engineer to consider all potential failure modes independently.

5) CONCLUSIONS

This paper begins by outlining some of the current techniques used to perform and automate failure analysis. Though many of these systems are very powerful, they are limited by computational time, the complexity of the necessary system modeling, and their dependence on components for analysis. Automated systems still need to be expanded to include the full breadth of mechatronics. Though many of the systems appear extremely useful, they do not seem suited to the field of novel system design, in which many possible designs need to be analyzed quickly at a functional level.

The System Functionality Method (SFM) provides a technique for engineers to evaluate systems in the earliest stages of design. Its simplicity is its strength, allowing it to be extremely adaptable. SFM will not and should not replace any of the thorough failure and safety analysis techniques that currently exist in literature and in practice. However, the technique’s relative simplicity lends itself to the initial stages of design. Due to its functional base, the method can analyze systems at varying levels of abstraction, while its ability to quickly model design changes appears well suited for use in the earliest stages of system design.

SFM was demonstrated using a wave energy converter design that is currently being developed at Oregon State University. The methodology,
though still being developed, shows great potential, and will be applied to a more complex system. The ultimate goal of SFM is to bring failure and safety analysis into the earliest stages of design. In this way money can be saved and product quality can be improved.

REFERENCES


[22] D. Stamatis, Failure Mode and Effect Analysis, FMEA from Theory to Execution, ASQ Quality Press, 1995, Milwaukee, WI.


5) Conclusions

It is imperative that reliability and survivability are considered early in the design phase when design modifications and changes are still relatively cheap. Three papers are presented within this thesis, with three specific goals to improve the long-term reliability and survivability of wave energy converters.

The first paper clearly defines the goals of reliability and survivability in the context of ocean wave energy. Conceptual designs are frequently proposed, and the terms reliable and survivable are often found in their descriptions, but without establishing the use and measurement of these goals, it is all but impossible to assess the extent to which they have been achieved by any design.

An engineer’s greatest tool is knowledge. In order to design a system that will endure the seas, the conditions in which an ocean wave energy converter will operate must be clearly understood. This is the purpose of the second paper; to provide the engineer with an imperative base understanding of the design conditions.

The final paper provides a method for completing a comparative analysis of the likely reliability and survivability of multiple wave energy converter concepts. By providing a method for the comparison of novel technologies at the earliest stages of design, it is possible to reduce the financial risk associated with capital investment in a specific technology. Hopefully, this method will help clarify the most promising technologies for ocean wave energy extraction.

Ocean wave energy has huge potential, but the success of this budding technology is heavily dependent on its long-term reliability and survivability. It should be the goal of every engineer at the earliest stages of design to ensure that their machine is capable of enduring the ocean environment.
6) Bibliography


Finavera Renewables WaveTech Home Page. (n.d.).


Moritz, H. P., & Moritz, H. R. (2004). Regional Analysis of Extremal Wave Height Variability Oregon Coast, USA. Oahu, HI.


Standard Meteorological Data for 1999: Recorded by NDBC Buoy 46050 off the Coast of Newport Oregon. (n.d.).


