American Recovery and Reinvestment Act of 2009
Advanced Water Power Technology Development: Wave and Current Energy Technologies
DOE SBIR (DE-SC0003571)
Development of Wave Energy-Responsive Self-Actuated Blade Articulation Mechanism for an OWC Turbine

Phase I: Performance Period: 02/2010 to 06/2010 (Completed)

1 Company and Project Information

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Phase II. Project Title: Development of Wave Energy-Responsive Self-Actuated Blade Articulation Mechanism for an OWC Turbine- Prototype Fabrication and Wind Tunnel Lab Test

Topic Number: 6. Advanced Water Power Technology Development
Subtopic Letter: C. Wave and Current Energy Technologies

Water wave energy has 15 to 20 times more energy per square meter than wind or solar. (Ref: "Electric Power from Ocean Waves," *Wavemill Energy Corp.*), and an oscillating water column (OWC) wave energy conversion system has the highest potential of all of the conceived energy converters to provide this renewable energy in the form of electric power. It is also well known by researchers that the efficiency of the air turbine used in OWC systems can be improved by adjusting the pitch or the blade angle of attack to best match the air and blade surface velocities, thus increasing the aerodynamic blade lift and rotor torque. All existing variable pitch control systems rely on electric/pneumatic/hydraulic feedback control systems to actuate the blade pitch. However, this approach is mechanically complex, unreliable, and costly. For this Phase I SBIR, Concepts NREC proposed a wave energy-responsive, self-actuating blade articulation system design that can use the aerodynamic forces derived from the incident air streams to provide the motive force that can instantaneously rotate the blade to its optimum position, providing maximum rotational rotor torque without additional feedback controls.

1.1 Phase I Results

The Phase I SBIR effort completed the feasibility design, fabrication, and wind tunnel testing of a self-actuated blade articulation mechanism that uses a torsion bar and a lightweight airfoil to affect the articulation of the Wells airfoil. The articulation is affected only by the air stream incident on the airfoil. The self-actuating blade eliminates the complex and costly linkage mechanism that is now needed to perform this function on either a variable pitch Wells-type or Dennis-Auld air turbine. Using the results reported by independent researchers, the projected improvement in the Wells-type turbine efficiency is 20-40%, in addition to an increase in the operating air flow range by 50-100%, therefore enabling a smaller or slower single turbine to be used.

1.2 Phase II Plans

The Concepts NREC (*CN*) project team will detail design and fabricate a prototype Wells-type turbine using the self-actuating, blade articulation design identified in Phase I. The prototype turbine will be tested in MIT's Wright Brothers wind tunnel after its design is optimized by continued testing in *CN*'s wind tunnel on a single blade mechanism.

1.3 Commercial Applications and Other Benefits

The end result of this research will be the demonstration of the first self-actuated blade articulation mechanism that can improve the efficiency and operating range of a Wells turbine for OWC applications.

1.4 Technical, Economic, and Social Benefits of the Project

The purpose of the proposed research is to increase the energy recovery from a wider range of incident wave energies by optimizing the performance of the OWC system. The increase in power generation is estimated to be as high as 40%, i.e., equivalent to the improvement in the energy efficiency of the turbine due to the self-actuated blade articulation mechanism. This increase in energy recovery is, in effect, a reduction in the cost per kW for an OWC system. This cost reduction improves the economics of the OWC application, and thus makes the system more attractive to entrepreneurial commercial developers and/or governmental or institutional funding agencies. The net benefit to the world is to make available another economically attractive and viable alternative, renewable energy resource that can be used to recover the projected 17.5×10^{12} kW-hr energy that is available from the world's oceans (Ref. 44). Assuming even a 0.1% utilization factor of the world's ocean energy, this is enough energy to power an additional 70 million households throughout the world.

1.5 Federal and Commercial Benefactors of Technology

The US Department of Energy, major energy companies, and local power utilities will gain important benefits towards the advancement of this technology. This renewable technology has the potential to provide at least as much affordable clean energy as present wind turbines, with negligible environmental impact. As explained in Section 2.1, OWC systems are considered to be the most viable means of recovering the world's wave energy resources, and many have been prototyped and are under testing, either on the coastlines where wave energy content is high or as floating vessels. An improvement of up to 30% in the energy recovery would effectively reduce the cost per kW for the systems and make the economics of their application much more viable.

1.6 Proposed Final Product and Market Potential

A large number of Oscillating Water Column (OWC) water wave energy recovery systems have been constructed over the past 30 years either on the shoreline, near the shoreline, or in the breakwater in a number of countries (Ref. 40). There are over 60 companies currently engaged in the development of ocean wave energy devices (Ref. 42). These systems include subsurface hydroturbines, oscillating buoys, OWCs, and many other devices. In general, near-shore OWCs have an overall efficiency of wave energy to electric power of 10 to 25% (Ref. 40), consisting of: 42% of the wave energy converted to pneumatic power, 65% of the pneumatic power converted to mechanical power, and 91% of the mechanical power converted to electric power. In the 1980s, relatively small demonstration systems, with ratings under 100 kW (Ref. 40) were conducted by several companies, but most were installed on coastlines, and thus, stationary with respect to the wave vertical velocity. However, in the early 2000s, interest in OWC technology significantly increased, with Oceanlinx Ltd., a world-renowned developer of OWC systems located in Sydney, Australia, taking a leading role and moving aggressively toward the development of

Figure 1. Oceanlinx Ltd.'s first 300 kW unit

multi-megawatt wave farms. Their first 300 kW unit (Figure 1) is shown operating in Port Kembla, Australia, in 2000, followed by its most recent demonstration OWC (the Mark3 Prototype Component or Mk3PC), shown in Figure 2. Both of these systems are no longer in operation, but they do provide evidence of the entrepreneurship and advances that Oceanlinx has made in order to foster the commercial success of the OWC-style wave energy conversion system.

Figure 2. Oceanlinx Ltd.'s Mark3 prototype component

The final product from this development effort will be an advanced, unique variable pitch Wells-type air turbine using a self-actuated, blade articulation non-electrical mechanism. This self-actuated system is ideal for matching the transient behavior of air volume flow rate and pressures exhibited in OWC systems. However, the same self-actuating mechanism design is thought to be adaptable to all variable pitch air turbines that otherwise use an electric/pneumatic/hydraulic feedback control system to affect blade articulation. In an OWC application, the self-actuated, blade articulation system enables a "next-generation, advanced adaptive OWC" method to recover more energy from incident waves that have a wider range of incident wave amplitudes and periods interacting with the OWC. The net result is more energy to recover, and thus a more economic OWC on a per kWe and per annual kWh basis than existing systems. The market opportunity for this technology is very significant, given the increased interest in the use of large-scale, renewable energy in the face of depleting fossil fuel supplies. It has been estimated by the World Energy Council that the world's oceans can provide an annual energy equivalent of 17,500 TeraW-hrs. The 40% projected increase in recoverable energy per kWe rating for an OWC, if the proposed subsystem redesigns are implemented, translates directly into a 40% decrease in the cost per kWe for the system. This should enable the Return on Investment for an OWC system to be even more attractive for the entrepreneurial investor, governmental world body, or private funding agency. Wave energy is much more predictable (using advanced weather warnings) and more continuously available over 24 hours, even when compared to wind energy. The low-profile OWC design is also very friendly to the panorama even when installed close to shore. Based on a 0.1% utilization of the available ocean energy and a marketable 1% with nominal 10 MWe OWC modules, a market of 150 OWC systems per year can be substantiated and projected.

A relevant excerpt from Oceanlinx's addendum to Concepts NREC's Commercialization Plan is given here as witness to Oceanlinx's interest in the development and commercialization of the self-actuated, blade articulated Wells turbine.

"Because of the varying conditions at the proposed sites and the subsequent available wave power energy patterns, the design of the turbine needs to have a wide operational range. This is important in terms of the logistics of manufacture where the goal is to build one turbine for all site applications. The Self-Actuated Blade turbine has the widest operation range for this application thereby enabling the economics of scale for a return on investment as well as providing an earlier adoption of renewable

energy production. The cost per unit as well as maintenance and robustness of the turbine are all critical elements of the total system performance. Improving these design parameters means not only the large scale adoption of wave energy generation but an accelerated adoption based on the reduced cost of electrical generation which will attract further investment from commercial parties.

Commercial arrangements with MECO (Maui Electric Company) are underway to install a Mark3 2.7MW OWC in Maui. This system would use the Concepts NREC turbine but only if the performance of the turbine is improved and the cost per unit decreased in comparison to other current technology turbines."

2. SIGNIFICANCE, BACKGROUND INFORMATION, AND TECHNICAL APPROACH TO IMPROVING WAVE ENERGY RECOVERY EFFICIENCY

2.1 Identification and Significance of Initial Problem and Technical Approach

2.1.1 SBIR Background

An oscillating water-air column (OWC) is one of the most technically viable and efficient options for converting wave energy into useful electric power. Referring to Concepts NREC's (*CN*) illustration of an OWC in Figure 3, the conversion of the wave energy into electric power entails four interrelated energy conversion stages: 1. conversion of the wave energy into the OWC water column motion, 2. conversion of the water column energy into pneumatic energy by compressing the entrapped air to pressures that are slightly above atmospheric pressure, 3. conversion of pneumatic power into mechanical rotating shaft power as the air flows through an inlet diffuser to the turbine-generator system, and 4. conversion of mechanical power into electrical power typically done using a bi-directional turbine such as a Wells turbine, an impulse turbine, or a Dennis-Auld turbine (such as invented by Oceanlinx Ltd. shown in Figure 4). Since the early 1980s, the Wells-type air turbine with fixed blades has been used almost as a standard turbine of choice for OWC applications due to its simplicity and robustness. A Dennis-Auld wind turbine was introduced by Oceanlinx Ltd. at the turn of the century as a more efficient turbine because of its use of articulating turbine blades. The electro-mechanical articulation was controlled by a control feedback system that responded to changes in the OWC chamber pressure due to the ascending and descending wave. In 2007, *CN* was commissioned by Oceanlinx Ltd. with private funding to develop a more robust and economical Dennis-Auld turbine for its OWC systems. *CN* and Oceanlinx Ltd. have since collaborated on other turbine developments for OWC applications.

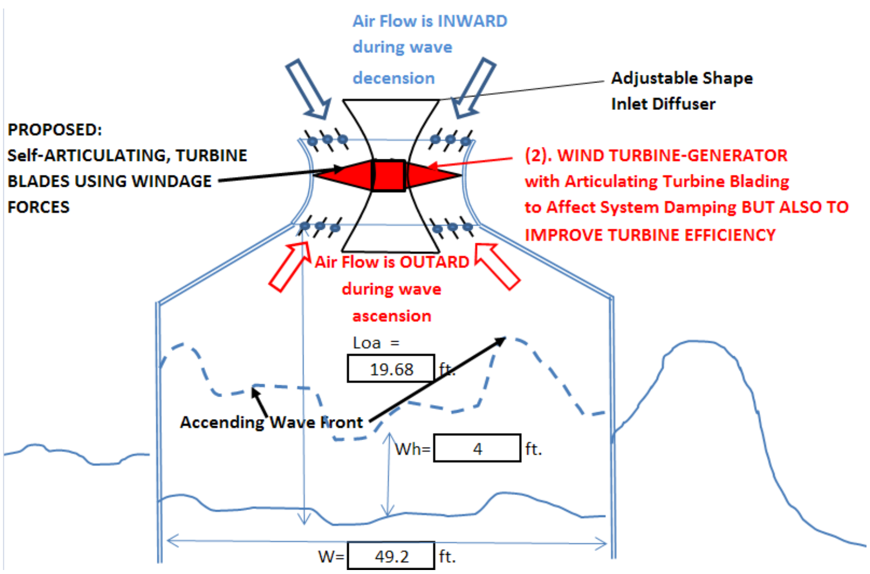


Figure 3. An illustration from a *CN* computer model of changes to a turbine subsystem that can be used to "tune" an OWC system for improved power recovery across a range of incident wave energy

The collaboration with Oceanlinx Ltd. emphasized the need by Concepts NREC to develop its own numerical model of an OWC system, one that could be used to help identify other potential wave energy improvement opportunities. The development of this engineering numerical model has since been aided by another STTR grant from DOE. In a very early phase of its research that was first publicly identified in its Phase I proposal, Concepts NREC identified an important parameter, a system Time Constant, T_c (units: seconds) that analytically can be shown to characterize the optimum design point for an OWC as a function of wave period. Stated simply, the optimum energy recovery opportunity is when the OWC system is designed to have a Time Constant, T_c equal to $1/6^{th}$ the wave period, T_{wave}. The flow characteristics of the turbine along with other parameters of the OWC that define a Time Constant (T_c) are given in Equation 1. The Time Constant is a characteristic time parameter, which represents the pneumatic pressure decay within the OWC chamber. Using several simplifying assumptions that enable a "closed-form" classic, analytical solution, the percent (%) recoverable wave energy pneumatic power was presented for the first time by Concepts NREC, as graphically displayed in Figure 5.

Figure 4. Blade actuation system used on a Dennis-Auld turbine to rotate the blades in response to air velocity

$T_c = \Delta P/P_o \times V/Q$ or: $T_c = \sqrt{(\Delta P)} \times V/(P \times C_v)$ Eq. 1

where: $Q = C_v \times \sqrt{\Delta P}$

and: for the first time, C_v was identified as the flow coefficient for the OWC air chamber-turbine as an integrated system.

A similar relationship for the dependency of the OWC flow rate on the OWC chamber pressure may also be used that considers the more familiar turbine operating characteristics. This is given in Equation 2.

$\varphi = K \times \Psi$ Eq. 2

where: ϕ, Flow Coef. = Q,cfs/(ND^3); Load Coef. $\Psi = \Delta P/\rho/(ND)^2$

and: in the formula K is a proportionality constant that depends on the type of turbine in use.

In order to better catalogue other analytical revelations concerning various mechanical and electrical subsystems that could provide improvements in wave energy recovery for Oceanlinx's OWC systems, Concepts NREC classified two categories of improvements to OWC systems: MICRO Wave Energy Dynamics and MACRO Wave Energy Dynamics.

MACRO Wave Energy Dynamics (pertaining to magnitude of wave period and amplitude):

1. "Tuning" the OWC turbine system so that the system operates at the theoretical maximum power recovery with respect to the OWC system's Time Constant, T_c.; the design of a diffuser at the inlet and discharge of the bi-directional turbine that can have a variable aspect ratio so as to

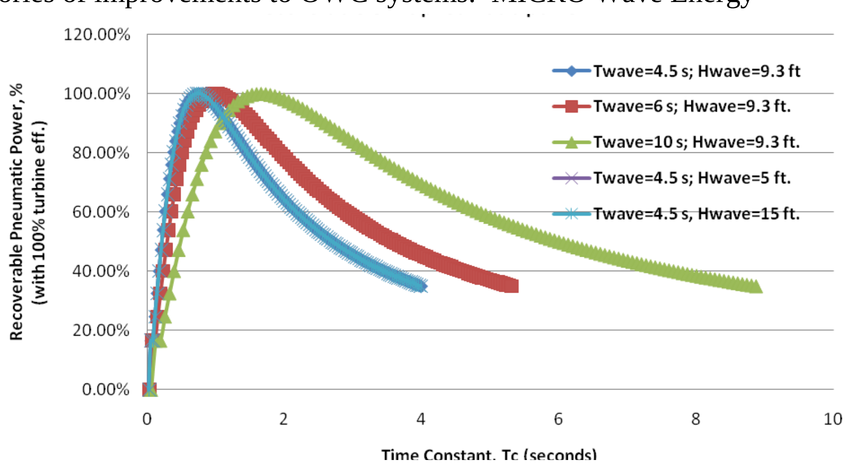


Figure 5. Effect of wave period (Twave) and wave height (Hwave) on percent recoverable OWC pneumatic power

optimize the diffuser's pressure recovery efficiency through the range of changing air flow rate and chamber pressure profiles. Once again, this will effect a change in the C_v for the composite turbine-generator system.

2. Adjusting the oscillation of the OWC structure so that it is 180 degrees out of phase, with the incident wave using adaptive controls. This can be effected by damping the OWC via, for example, varying the projected area of the stabilizer-heave plates by adjusting the orientation of the plates; this is an interesting area for future research, but not part of the turbine-generator composite system options.

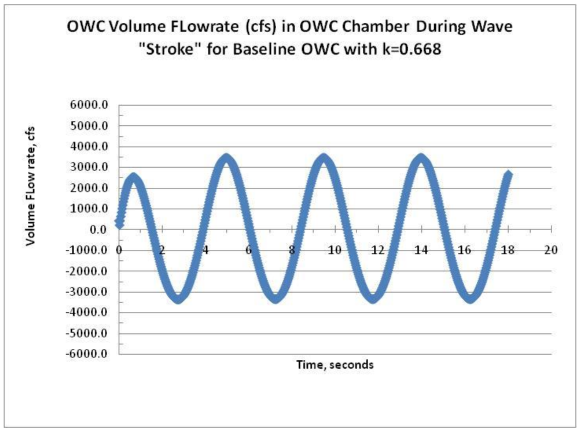
MICRO Wave Energy Dynamics (pertaining to effects of wave cycles in OWC chamber)

1. The design of a variable aperture that works similar to the iris in the human eye to open and close the flow through the turbine and thus affect the velocity through the turbine blades, which would then affect the overall flow coefficient, C_v for the turbine system. The aperture would be installed at the hub of the turbine and open from the outer radius to admit flow into the turbine, thus controlling the chamber pressure by maintaining flow control of the air though the turbine, which would then effect a variable flow coefficient for the turbine system.
2. The design of flexible blade profiles (along blade axis) that self-adapt to the instantaneous pressure in the OWC chamber, and thus, to the pressure at the leading edge of the turbine blade.
3. The design of an effective means of articulating the blade in order to continually optimize the aerodynamics of the turbine blade during each intake and discharge "stroke" of the wave. This is currently being explored via DOE funding.

MICRO Wave Energy Dynamics (WED) system improvements are closely associated with how the ascending and descending wave fronts affect the chamber pressure and air volume flow rates. The MACRO WED system improvements are closely associated with how the amplitude and periods of the wave energy affect the dynamics of the OWC structure. An example of one such MICRO modification is the design of the Dennis-Auld turbine by Oceanlinx, along with the re-engineering contributions made by Concepts NREC. The Dennis-Auld turbine, shown in Figure 4, was considered a significant innovation when it was first introduced early in the decade as a replacement for the Wells-type turbine for OWC applications. It utilizes a mechanical torsion device to vary the pitch of the blades through a feedback control loop that measures the velocity, direction of the airflow, and inlet pressure. The variable pitch blades effect an increase in the efficiency of the turbine, particularly when the air flow rate through the turbine varies. Another MICRO modification is the adaptation of a Turbine Shutter Valve that can boost the pressure and air flow rate through the turbine, and thus increase its weighted (cycle) efficiency. This modification is the subject of another proposal.

In order to quantify the improvements that can be achieved in each of these areas within each MACRO or MICRO category, it was necessary for Concepts NREC to development an "engineering-friendly" numerical model of an OWC wave energy conversion system that could be used as an effective engineering tool to affect the design of the OWC subsystems and predict the integrated performance as a complete system. Concepts NREC developed a novel means of modeling OWC performance that was heretofore unknown, or at least unreported in the technical literature, but that has been validated as accurate. Details of this model are provided in Section 2.3 of this report. The basis for this numerical model is as straightforward as its ability to provide greater physical insight into the behavior of an OWC system as it is acted upon by incident waves of fluctuating wave amplitudes and frequency. This improved insight leads to practical engineering solutions on how to increase wave energy capture. The algorithms used in the numerical model are based on the Conservation of Energy principle applied to the potential energy content of waves. Of particular importance to the use of this algorithm is the ability to use only the energy content of the wave as defined by kW/meter or energy per area, without the need to stochastically account for the variation of the wave frequency and amplitude as a function of time.

There has also been considerable research performed by Concepts NREC, Oceanlinx Ltd., and other independent researchers to develop a more efficient air turbine that can be used with an OWC-type wave energy conversion system. This effort is necessary in order to improve the capture efficiency from the wave after it has first transferred its potential and kinetic energy to the air column in the form of a very transient air chamber pressure and volume flow rate. These two operating parameters, flow rate and pressure, are the ones that all turbine devices require to be kept constant for maximum efficiency. The inherent nature of the OWC system is to have a cyclic profile of pressure, and consequently, volume flow rate, as may be observed in Figures 6a and 6b.



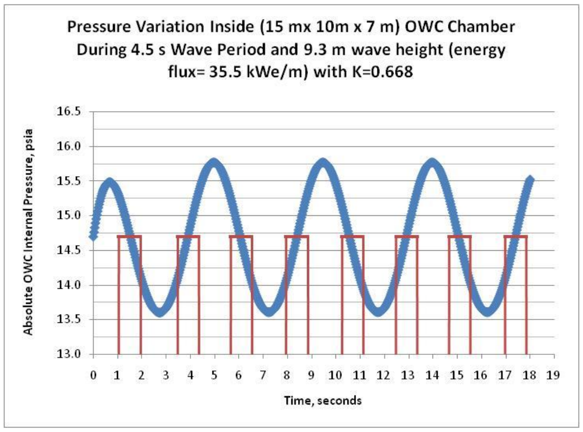


Figure 6a and 6b. Cyclic profile of pressure and volume flow rate

The consequence of the time variant pressure and flow rate is that the efficiency of the turbine changes. Most importantly, particularly for a Wells turbine, the air flow rates may be too high or too low, causing the turbine to stall at high air flow rates or have very poor efficiency at low flow rates, as may be seen in Figure 7.

There has been considerable research into ways of improving the two serious drawbacks of a Wells turbine that otherwise is considered very robust and relatively inexpensive (and thus, suitable for OWC applications), efficiency and limited flow rate operating range of the Wells-turbine. Concepts NREC's survey of the technical literature as summarized in Table I clearly reveals the salient points made by a consensus of researchers that a variable-pitched Wells-type turbine cannot only improve the efficiency of the turbine, but also increase its operating range of air flow rate. The latter effect has the consequence of enabling a single turbine taking the place of two smaller and faster Wells turbines. As may be seen from Table I, turbine efficiency improvements from 20 to 40% (and as high as 50%) were noted by these independent researchers. Similarly, the technical literature identifies an increase in the operating range of as much as 300%, although a more reasonable and conservative increase of 50 to 100% is suggested in this proposal as the goal of the Phase II SBIR effort.

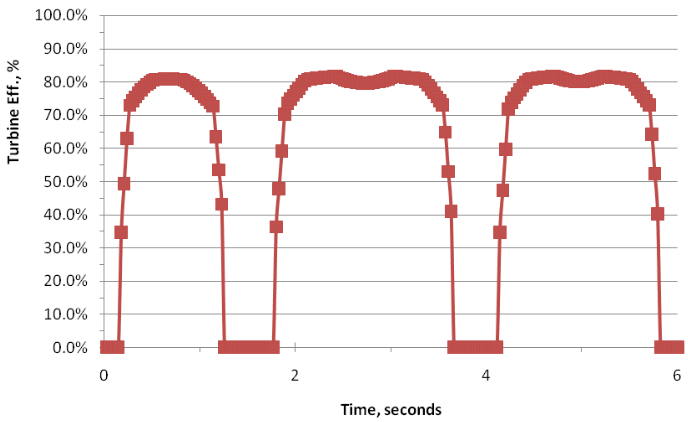


Figure 7. Turbine efficiency during pressure and temperature transients during wave ascension and dissension

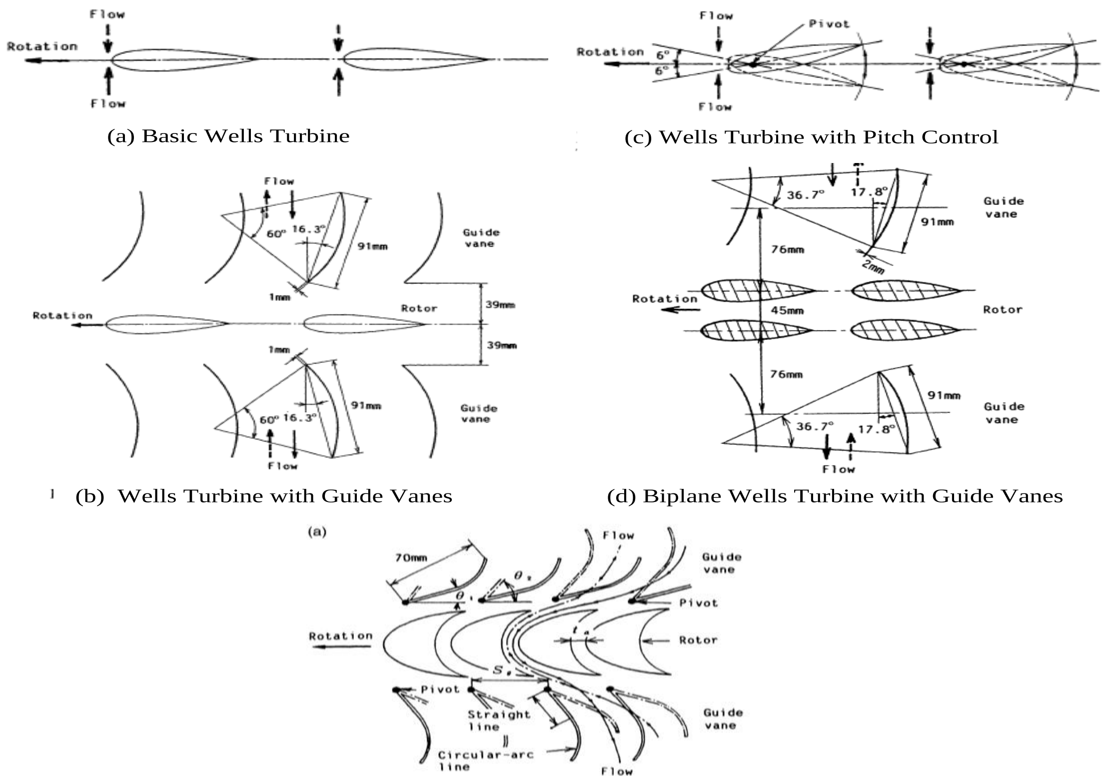
TABLE I. EFFECT OF USING VARIABLE PITCH AS CITED IN TECHNICAL LITERATURE

CN's Sited Ref #	Page No., Fig. Or Table No.	Cited Increase in Range	Cited Increase in Turbine Eff.	Noteable & Relevant Quote
35	Fig.2	60%	44%	
25	page 145	40%	12%	
34	Fig. 7	61%	23%	
2	Fig. 14 (0 to 24 degs)	100%	42%	
2	Fig. 14 (0 to 11 degs)	287%	50%	
30	Fig. 15	150%		Experimental results with powered variable Pitch blades
32	Fig. 2 (0 to 5 deg.s)	33%		
32	Fig. 4 (0 to 15 deg.s)	135%		Variable pitch found to be a means of improving phase control
32	Fig. 5 (0 to 10 deg.s)	87%		
36				Energy recovery increases from 28 to 82% due to phase control
33				Blade offset improves Range of Operation
40				Pitch control may accompany Bypass Valve to improve operating rar
26	page 266			Inlet guide vanes and proper profile can improve eff by 17%
42	pg. 151 & 190			substantial improvement in time-weighted avg. of turbines but cost increases with varia ble pitch blades on Wells turbines

The increase in operating range before airfoil stall is encountered has been verified by Concepts NREC's numerical modeling of a NACA0015 airfoil in the Phase I SBIR effort. In addition, based on Concepts NREC's numerical OWC model, variable pitch blades not only can increase the efficiency of the turbine as the air flow rate varies through the turbine, but also control of the pitch can change the system's Time Constant, T_c. The development of a self-actuating blade articulation system that uses the aerodynamic forces of the air stream that is driving the turbine has been completed by Concepts NREC during turbine research conducted in the Phase I SBIR.

The variety of air turbines and the use of inlet guide vanes or variable pitch control are summarized in Figure 9 (Ref. 17). Shown in Figure 8 are five wave power turbine configurations capable of operating with bi-directional air flows. While other design concepts have been proposed that provide unidirectional flows through the use of switching valves, only bi-directional designs were examined. These configurations are: 1. conventional Wells turbine, 2. Wells turbine with guide vanes, 3. Wells turbine with pitch-controlled blades, 4. biplane Wells turbine with guide vanes, 5. impulse turbine with pitch-controlled guide vanes, and 6. Oceanlinx Ltd. reversible pitch blade.

One of the MICRO Wave Energy Conversion options that has been studied by Concepts NREC and Oceanlinx is the use of a blade articulation linkage design that would improve the manufacturing cost of a Dennis-Auld turbine for OWC applications. The performance of various turbine concepts is best examined in terms of the velocity flow coefficient ($\emptyset$), defined as the maximum (or sometimes actual) axial velocity of the air divided by the mean (or sometimes maximum tip) circumferential velocity of the turbine blade. Given the recognized benefits of a variable pitch control as summarized in Table I, Oceanlinx Ltd. (formerly Energetech) embarked on further improvements in blade design using non-standard airfoils with the capability to provide high torque levels over a wide range in flow. Concepts NREC collaborated with Oceanlinx Ltd. in a privately funded engineering effort in 2007. The intention of the design was to maximize the energy conversion efficiency over the complete cycle. The DOE provided assistance to Concepts NREC and Oceanlinx to successfully test the mechanical integrity of the blade articulation linkage, as well as the blade bearings and seals that are contained in a closed cartridge, for ease of replacement while in service and later repair. However, the system still needed an expensive linkage system to accomplish the improvement in turbine efficiency over the less-expensive Wells turbine.



(a) Basic Wells Turbine (c) Wells Turbine with Pitch Control

(b) Wells Turbine with Guide Vanes (d) Biplane Wells Turbine with Guide Vanes

(e) Impulse Turbine with Pitch-Controlled Guide Vanes

Figure 8. Five different turbines considered for use with OWC systems

In an attempt to eliminate the linkage system, and thus to reduce the cost and increase the reliability of the turbine, Concepts NREC began to research how a similar blade articulation device might be designed for a Wells-type turbine, in order to provide the increased efficiency, but without the complicated linkage system. However, the general consensus of researchers is that the simple Wells-type turbines are prone to low weighted efficiency (due to the high variations in air flow rate and narrow operating regime) and poor starting ability unless a variable blade pitch design is adopted. Unfortunately, an inexpensive way of providing the variable pitch option without compromising the cost of the Wells turbine, and that could be used outside the laboratory and in an actual OWC application, has not been provided. A 2003 wave energy study (Ref. 41) indicated that "If the rotor blade pitch angle is adequately controlled, a substantial improvement in time-weighted average turbine efficiency can be achieved. Of course, on the downside, it is a more complex and more expensive machine compared to the mechanically simple and robust conventional Wells turbine".

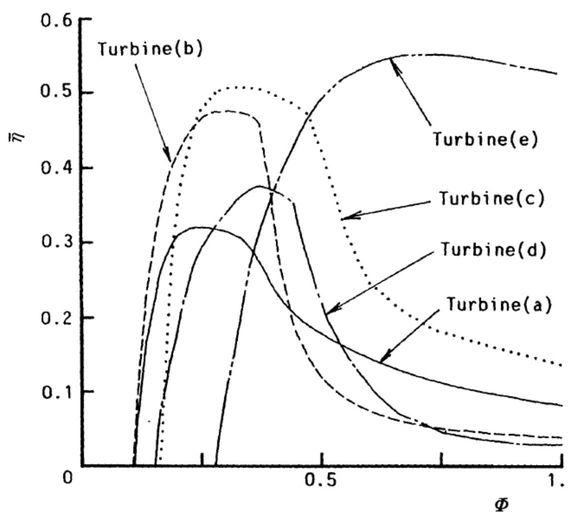


Figure 9. A comparison of turbine efficiencies

To emphasize this point, WaveGen, Ltd (Ref. 29, c/o Dr. W. K. Tease) did develop a laboratory scale system of a Wells-type turbine that uses a variable pitch blade with a feedback control system. Figure 10 illustrates their design. Their conclusions cited the improvement in the weighted efficiency of the turbine and an increase in the range of air flow that the turbine could handle before a phenomenon called "turbine stall" prevents power recovery from the turbine. They concluded their laboratory testing with the intent of reducing the cost of the electric actuation and feedback control system, as well as to detail a design that could be practically implemented in actual OWC application.

Figure 10. WaveGen Ltd.'s Wells-type turbine

Therefore, the objective of the Phase I SBIR effort by Concepts NREC was to develop a means of providing a cost-effective, variable pitch control of a Wells-type turbine in order to increase its efficiency and operating air flow rate range in OWC applications. The Concepts NREC design team has succeeded in providing a feasible design. In fact, the *CN* self-actuated, blade articulation system conceived in Phase I of the SBIR, and as identified in this Phase II SBIR proposal, accomplishes the goals as identified in the WaveGen technical paper (Ref. 29). It is also important to note that the *CN* design for a self-actuating, blade articulation system is an advance over any that can be found in this field of study.

Concepts NREC's computational modeling of an OWC system has shown that the OWC chamber air velocity and volume flow rates through the turbine constantly change due to the inherent nature of the OWC energy conversion system. The proposed innovation takes advantage of this transient air flow rate by having the blade articulation mechanism use the same aerodynamic forces, derived from the blade's *in situ*, albeit changing, air velocity to instantaneously provide the motive force to uniquely articulate each blade as an active "real-time" feedback control. The blade articulation action is now directly coupled with the actual cyclic changes in the air velocity that is passing each individual blade, and does so without the use of an intermediate, electrical feedback control system. In summary, *CN*'s evolution in blade articulation uses the *in situ* aerodynamic forces on each blade to solve the problem of having a means of instantaneously and precisely synchronizing the articulation of the turbine blade to the cyclic changes in the OWC air flow rate. When developed, the wave energy-responsive, self-actuating blade will eliminate the current complex mechanical linkage mechanism that is now needed to perform this function on the Dennis-Auld air turbine. The consequence of a self-articulating turbine blade is two-fold: first, a reduction in the complexity of the blade articulation mechanism that reduces the cost of the OWC turbine by as much as 50% compared to the Dennis-Auld type turbine, and second, an increase in the turbine's efficiency and operating range for the Wells-type turbine due to an optimum angle of attack between the blade and the air velocity vector. The efficiency and range improve by 20 to 40% and 100-150%, respectively. The elimination of the blade articulation linkage and the feedback control system to regulate the variable pitch blades is thought to decrease the cost per kW ($/kW) of the electro-mechanical systems by as much as 40%, i.e., equivalent to the increase in the projected efficiency of the variable pitch Wells-type air turbine.

2.1.2 Executive Summary of SBIR Results: A cost-effective, self-actuated blade articulation mechanism for a Wells-type turbine in OWC Applications

The primary objective of Phase I was to prepare a preliminary design of a wave-responsive, self-actuating turbine blade articulation mechanism utilizing the aerodynamically induced pressure distribution across the blade to create a self-stabilizing blade profile that results in maximizing the turbine performance under varying flow conditions. This was achieved through an iterative integrated systems analysis of the nonlinear OWC system and the self-adaptive turbine. Based on this analysis, the detailed design specifications were established, and a preliminary design was prepared. The specific questions to be answered focused on defining the coupled relationship between the blade pitch and blade pressure distribution that results in maximizing the turbine efficiency at each flow condition. Listed below are the specific questions (taken directly from the original proposal) and answered in the Phase I SBIR:

a. What are the critical design parameters of each subsystem that impact the overall system performance?

b. What is the desired blade profile and pressure distribution at each flow condition that will result in peak performance?

c. What are the primary design issues that must be overcome to translate the pressure distribution into an associated blade pitch and contour?

d. Can the blade design be made self-stabilizing over its operating range?

The Phase I work plan focused on the mechanical design satisfying Design for Manufacturing and Assembly criteria, testing to verify aerodynamic forces, and estimating costs for the self-actuating turbine blade articulation mechanism. The blade-articulation conceptual rotor design with self-actuating blades is shown in Figure 11. The prototype, full-scale single blade for a 250-300 kWe Wells air turbine is shown in Figure 12. Both are the results of the Phase I SBIR effort. The mechanical mechanism that affects self-actuation of the blade articulation is based on the use of a long torsion bar that twists to change the angle of attack to the optimum position to maximize the aerodynamic force on the airfoil. The articulation is +/- 15 degrees for the mechanism shown in Figure 12. The articulation system uses an elastomeric sleeve seal that safely retains the lubricant that is used with the sliding contact pivot-axle bushing. The lubrication also provides torsion damping of the airfoil to prevent flutter during the continuous changes in the air flow rate that is incident on the airfoil. The airfoil is designed as a composite system using a thin steel skin covering a hard foam core. The nose of the airfoil consists of a heavy core that maintains the center-of-gravity of the airfoil over the pivot-axle in order to reduce bending moments caused by the centrifugal forces. Additional details of the design are provided in Section 3.3 of the report.

This design enables the turbine to operate efficiently over a wide range of air flow conditions caused by varying wave energy intensities, and more reliably, to achieve the net effect of reducing the cost per kW for the OWC system. The preliminary design and manufacturing specifications for this design have been defined.

The conclusions from Concepts NREC's Phase I SBIR modeling studies of a Wells turbine as they apply to Wave Energy Conversion systems of the OWC type are summarized as follows:

1. A variable pitch Wells turbine allows for a much larger range of relative flow angles, defined as atan(Cm/U), than that of a fixed-blade Wells turbine. This could mean two things for the variable pitch turbine: that the speed of the turbine can be much slower (lower U) for a given flow, or that the flow can be greatly increased (higher Cm) for a given rotational speed.

2. One could also look at a benefit from the perspective of the flow coefficient, φ. The variable pitch turbine could dramatically extend the range of flow coefficient for which a fixed-blade Wells-type turbine could operate efficiently.

3. Two fixed bladed Wells turbines would be needed to perform that same as the single, variable pitch Wells rotor. If a larger and faster Wells turbine is used to operate in the same flow range, the power output of the variable pitch Wells turbine is greater than the fixed blade turbine by 6% for the Case Study shown in Table II.

The proposed SBIR Phase II effort will further demonstrate the feasibility with the fabrication and demonstration of a prototype turbine and its testing in a full-admission wind tunnel test using MIT's Wright Brothers wind tunnel test facility.

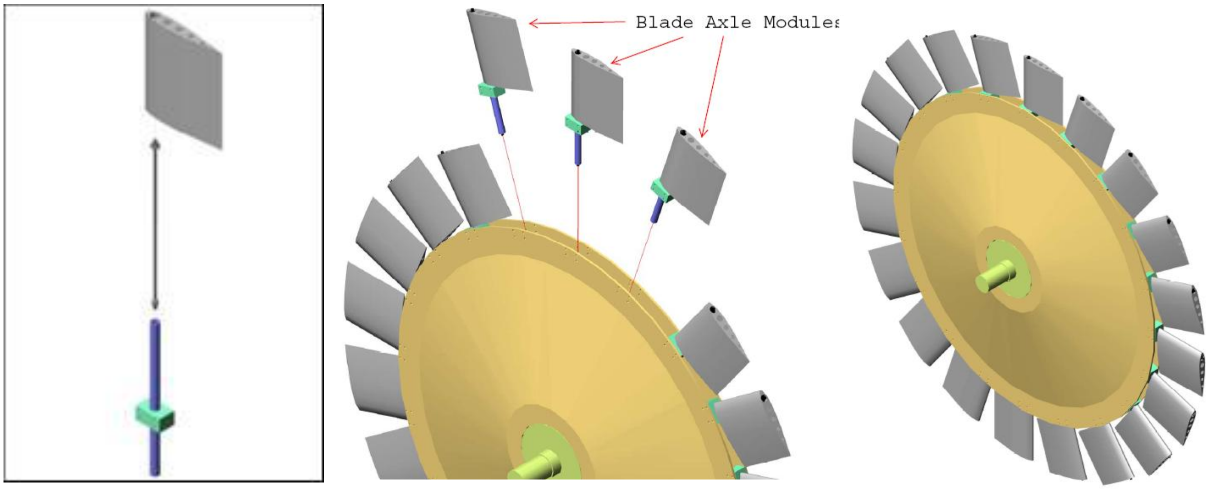


Figure 11. Blade-articulation conceptual rotor design with self-actuating blades

Figure 12 shows a disassembled, full-scale blade (one of 15 required for a 300 kW Wells turbine (7 ft. tip-to-tip diameter), and each approximately 24 inches long when assembled) that was fabricated according to the design displayed in Figures 13. The system was tested in the *CN* wind tunnel and determined to function as expected, with the airfoil articulating 15 degrees in response to a high-speed air stream.

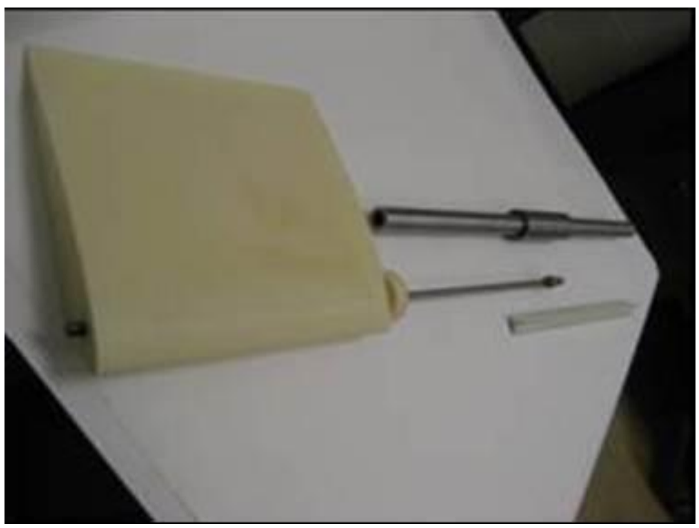


Figure 12. Prototype, full-scale single blade (disassembled)

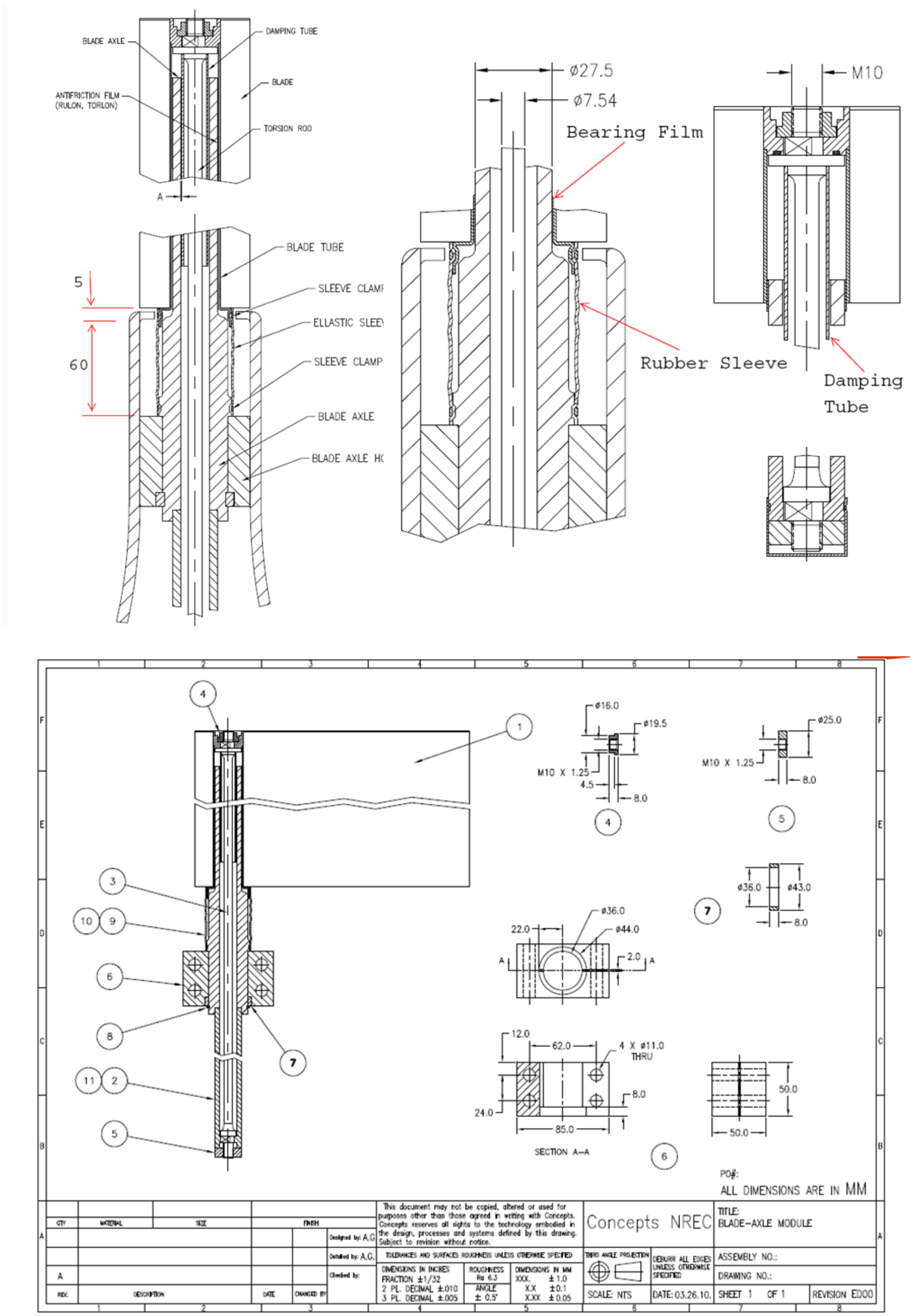


Figure 13. Concepts NREC's blade design

2.1.3 Simple Payback Analysis for the OWC Improvement

The reduction in the first-time cost $/kWe is essential if the economics of a wave energy conversion device using the oscillating water column principle is to be high enough for its adaptation. The overall wave-to-electric efficiencies of conventional OWC systems are often less than 25% (Ref. 40), which results in an increase in the effective cost per kW ($/kWe) for the OWC system. The cost of prototype-level OWC systems is relatively high, at $6,000 to $8,000 per kW, while future economy of scale units rated up to 23 MW are estimated to have a projected capital cost of $4,000 per kW (Ref. 40). Increasing the capture efficiency by improvements in the OWC air turbine, as well as *CN*'s suggestions for the better "tuning" of the OWC, has the largest impact on decreasing the cost per kW ($/kWe) for the OWC system. A 2003 study by The Carbon Trust, entitled: "Oscillating Water Column Wave Energy Converter Evaluation Report" (Ref. 40), suggested that the goal of reaching a competitive price for the generated electric power from an OWC system would require "…a combination of capture efficiency being increased by 10% to a (net) of 52%" after considering the electric power turbine-generator efficiency. Concepts NREC's proposed innovations to the basic Wells-type air turbine as outlined above (and detailed in this report, Section 3.2) are seen as important contributions to the efforts to reduce the first time and operational costs of an OWC system. The net consequence is a reduction in the cost per kW ($/kW) of the system by as much as 23%, as summarized in Table II. Table II was developed by Concepts NREC to correctly account for the energy savings that can be attributed to an OWC subsystem, but it then also accounts for any costs (or savings) for additional (or fewer) OWC components needed to affect these savings.

TABLE II. SIMPLE PAYBACK ANALYSIS FOR OWC SYSTEM MODIFICATIONS AND ENERGY IMPROVEMENTS COMPARING FIXED BLADE (BASELINE) WELLS TURBINE WITH SELF-ACTUATED ARTICULATED BLADE WELLS TURBINE

(Ref.: Carbon Trust Marine Energy Report, page 283, averages from 3 OWC systems)

			Component Costs			$cost adder for Additional Component(s)	% Improvement Energy Recovery
			Baseline $ Cost	+ or - % change	$ Final Cost		
System Availability, %	85%						
OWC Base Cost , $/kWe	6000						
Kwe=	350						
OWC Cost	$ 2,100,000						
Mechanical & Electric Systems, %	20.0%		$ 420,000				
Generator & Switchgear		2.5%	$ 52,500	0.00%	$ 52,500	$ -	1.0%
Turbine		4.7%	$ 98,356	8.7%	$ 106,932	$ 8,576	25.0%
Diffuser & Inlet Guide Vanes		1.5%	$ 31,500	0.00%	$ 31,500	$ -	0.0%
Structural Framework		5.0%	$ 105,000	0.00%	$ 105,000	$ -	0.0%
Controls		6.3%	$ 132,644	0.00%	$ 132,644	$ -	0.0%
Installation, %	15.0%		$ 315,000				
Mechanical		10.0%	$ 210,000	0.0%	$ 210,000	$ -	0.0%
Electrical		5.0%	$ 105,000	0.0%	$ 105,000	$ -	0.0%
Vessel Construction, %	25.0%		$ 525,000	0.0%	$ 525,000	$ -	
Electrical Trans., %	15.0%		$ 315,000	10.0%	$ 283,500	$ -	0.0%
Contingencies, %	10.0%		$ 210,000	0.0%	$ 210,000	$ -	
Transportation, %	15.0%		$ 315,000	0.0%	$ 315,000	$ -	0.0%
	100.0%		$ 2,100,000		$ 2,077,076	$ 8,576	

NET OWC Cost Savings,%	1.09%	Energy Improv.=	26.0%
NET Effective $/kWe=	4,710		
Net Improvement, $/kWe %=	21.5%		
$O&M=	0.02	$/kwH	
$finance=	0.06	$/kwH	
$/kWh)income=	0.15	$/kWh	
Yearly Income=	$ 225,660		
Incremental Simple Payback=	0.15	years	

It is also important to note that this economic Simple Payback does not account for the benefit of having a larger operational flow range. The wider flow rate range can reduce the cost by allowing one larger, slower rpm Wells-turbine with variable pitch to be used instead of two smaller and faster, fixed-blade Wells turbines.

The costs associated with the OWC turbine were determined by Concepts NREC during Phase I of the SBIR. These costs reflect manufacturers' quotes for the self-actuated blade articulation system that was developed in Phase I, coupled with a consistent comparison of turbine-related costs determined by Concepts NREC's analysis of a Dennis-Auld turbine and the air turbine costs reported in the available technical literature. A side-by-side comparison of these turbine costs is shown in Table III. The cost analysis indicates that there is a 3-sigma confidence level (i.e., greater than 99%) that the proposed Wells turbine with self-actuating blades will have a cost between $98,000 and $110,000 when the turbine is produced in mass production quantities and uses a stamped or forged rotor body. This is compared to the fixed-blade Wells turbine with a cost of approximately $98,000 and typically using a more solid machined rotor body. The per unit cost of single prototypes is estimated to be $145,000, assuming a 30% margin on the manufacturing costs.

TABLE III. MANUFACTURING COSTS FOR SELF-ACTUATING BLADE ARTICULATION ROTOR

OWC Cost/kw 6000

Fraction of Total $ OWC for Turbine= 4.7%

		Conventional, fixed Blade Wells Turbine	Concepts NREC Self-Articulating Wells Turbine				Dennis-Auld Turbine	
		Middle Est.	Low Est.	Middle Est.	High Est.	Variance σ^2	Power Rating , kW 750	350
10%	Brake System	$ 10,303	$ 10,303	$ 10,303	$ 10,303	$ -	$ 12,000	$ 10,303
17%	Drive Shaft Bearings	$ 17,185	$ 17,185	$ 17,185	$ 17,185	$ -	$ 21,600	$ 17,185
15%	Rotor Body	$ 14,753	$ 11,803	$ 11,065	$ 14,753	$ 241,848	$ 7,500	$ 6,440
20%	Rotor Body Mach.ing	$ 14,718	$ 3,311	$ 3,679	$ 7,359	$ 455,022	$ 16,500	$ 14,718
10%	Blades	$ 9,579	$ 9,579	$ 14,368	$ 19,158	$ 2,548,805	$ 21,000	$ 18,031
0%	Blade Articulat. Sys.	$ -	$ 15,491.25	$ 18,225	$ 21,870	$ 1,130,235	$ 60,000	$ 40,988
17%	Shaft (Matl. &Mach.)	$ 16,679	$ 16,679	$ 16,679	$ 16,679	$ -	$ 18,000	$ 16,679
0%	Articulation Control	$ -	$ -		$ -	$ -	$ 54,000	$ 54,000
10%	Misc.	$ 9,836		$ 9,151		$ -	$ 20,000	$ 15,000
			$ 84,352	$ 100,656	$ 107,308	$ 4,375,910		
100%	Turbine System Cost=	$ 98,356	Low		High		$ 230,600	$193,344
	(without Generator)		$ 98,564	1-sigma(σ)	$ 102,748			
			$ 96,473	2-sigma(σ)	$ 104,840			
			$ 94,381	3-sigma(σ)	$ 106,932			

2.2 A Summary of Phase I SBIR Demonstrated Technical Feasibility of Proposed Innovations

The Phase I SBIR work plan has focused on developing a mechanical design of a self-actuating articulation blade mechanism that satisfies Design for Manufacturing criteria, and then determining the production cost of the self-actuating turbine blade articulation mechanism. The SBIR will conclude with a wind tunnel test of the articulation mechanism to verify that aerodynamic forces will actuate the blade according to the torque-angular displacement schedule that has been predicted for the device.

The following report provides a summary of the engineering effort that is in progress to support the SBIR: Design and Analysis of a Self-Articulating Blade for OWC Applications. Most of this summary is based on excerpts from a PowerPoint presentation that continues to be updated as the progress of the analysis and design proceeds.

The design and analysis specifications for a self-activated blade are based on the specifications of a turbine rotor that can be used with an OWC system to theoretically generate 300 to 350 kWe. This size system is now considered to be the base system chosen by Oceanlinx Ltd. for its future OWC applications and will be first deployed at their Maui test site. It has been dubbed by Oceanlinx as their Mark 3 (Mk3) System. The actual values used in <u>*CN*</u>'s analysis and design for a self-actuated blade are based on a computer model of Oceanlinx's Mk3, 350 kWe system and assume a turbine efficiency of 55%. Thus, the design of a self-actuated blade for this size system has immediate applications which are an important consideration in the Phase II follow-on for the SBIR. The output from this computer model is shown in Figure 14.

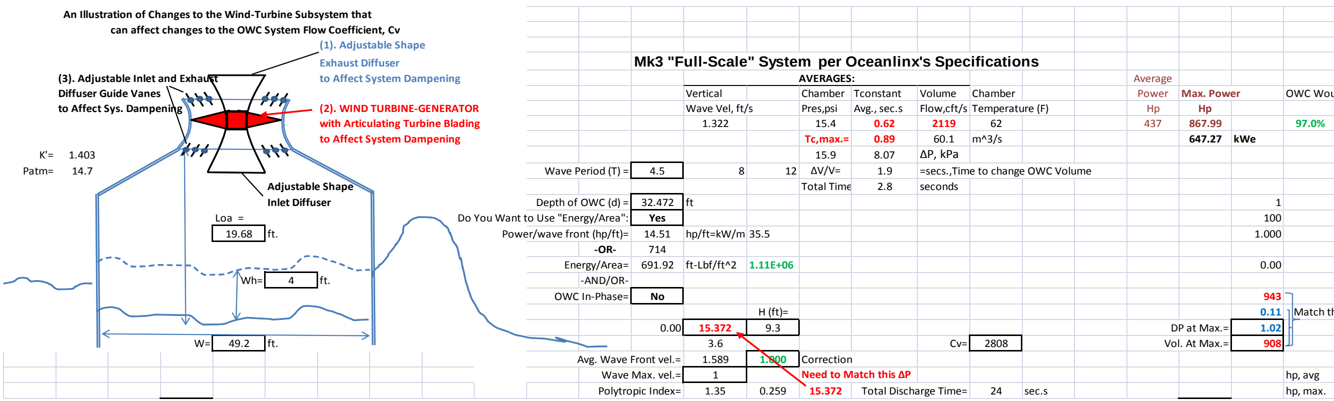


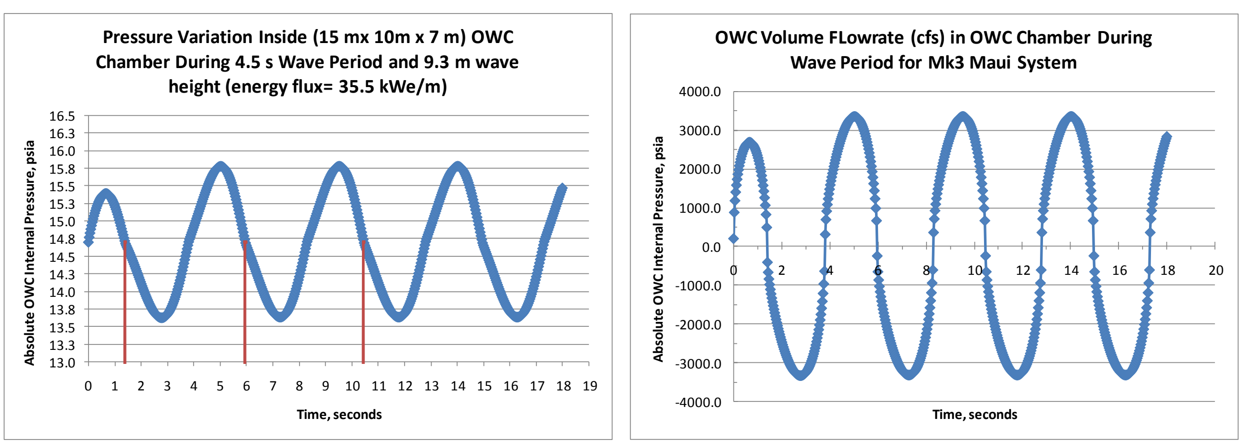
Figure 14. Output page from numerical model that established the design point conditions for the project's turbine performance

The pertinent aero data for designing the airfoil and for determining the forces and moments on the blades are summarized in Table IV.

TABLE IV. AIR FLOW RATE AND CHAMBER PRESSURE DESIGN POINTS FOR THE PROJECT'S TURBINE DESIGN

Mk3 "Full-Scale" System per Oceanlinx's Specifications							
	AVERAGES:						
	Vertical		Chamber	Tconstant	Volume	Chamber	
	Wave Vel, ft/s		Pres,psi	Avg., sec.s	Flow,cft/s	Temperature (°F)	
	1.322		15.4	0.62	2119	62	
			Tc,max.=	0.89	60.1	m^3/s	
			15.9	8.07	ΔP, kPa		

A more detailed presentation of the transient chamber pressure and flow rate as a function of time is shown in Figures 15a & b.



Figures 15a & b. OWC chamber pressure and air flow rate transients during wave "stroke"

Table V indicates the methodology used in Phase I of the SBIR feasibility analysis. The feasibility analysis uses XFOIL airfoil code via a simpler-to-use spreadsheet platform that was prepared by Concepts

NREC to calculate the aerodynamic performance of the NACA0015 airfoil. The air flow rate generated by the wave energy is shown in the left-hand figure (which is the same as Figure 14) and is input into the left-hand column of the NACA0015 XFOIL-based spreadsheet. The cycle time is the moment in time that the OWC air chamber generated the air flow rate shown. The values for the Angle of Attack (AOA) column are manually changed until the maximum amount of power, shown in the right-hand column, is generated aerodynamically from the 7.5 ft.-diameter rotor (at the tip) that is operating at 750 rpm. The loci of points shown in the figure located at the lower right-hand column are thus the optimum pitch (or stagger angle) for the variable pitch blades used with a Wells turbine. This figure is the basis for the torque-angle relationship that must be maintained by the mechanism that is to self-actuate the turbine blades using only the aerodynamic forces.

TABLE V. METHODOLOGY FOR FEASIBILITY ANALYSIS

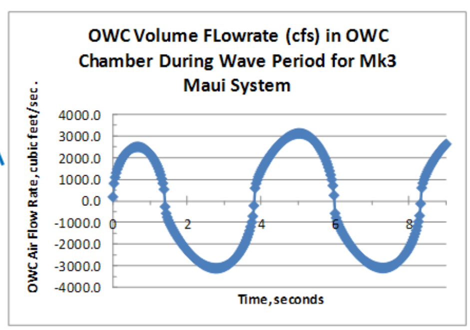
NACA 0015 XFOIL Software is Used to Determine Aerodynamic Blade Forces as a function of Angle of Attack (AOA) for a 350 kWe OWC System

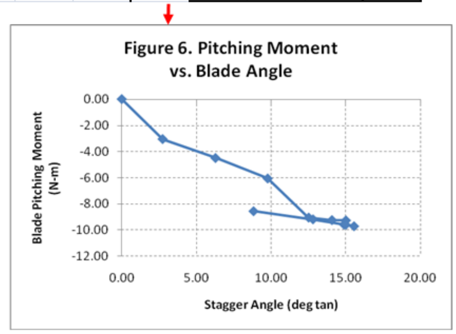
b	m	0.2794
c	m	0.254
rh	m	0.8636
rt	m	1.143
N	rpm	750
pivot Location	% chord	15%
Blade Count	-	15.00
air density	kg/m^3	1.225

Area_ann	m^2	1.76
r_m	m^2	1.01
U	m/s	79.56
Losses		0.1
Tip clearance		0.02
EndWall		0.02
Diskfriction		0.01
2nd Flow		0.05

NACA 0015

flow Rate	Cycle Time	AOA	C_m	W_m	flow Coeff	Rel Flow Angle	Q	Mom. Coef.	Lift Coef.	Drag Coef.	Mom. Coef. @ pivot	Driving Force Coef.	Stagger	Pitching Moment	Total Torque	Blade Power	Power
m^3/sec	sec	deg	m/s	m/s	-	deg tan	Pa	-					deg tan	N-m	N-m	kW	kW
0.000	0.000	0	0.00	0	0.00	0.00	0.00	0.000	0.000	0.006	0.000	-0.006	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
16.539	0.206	4	9.39	80.11145	0.12	6.73	3930.93	0.003	0.460	0.007	-0.043	0.047	**2.73**	**-3.06**	**197.50**	**15.51**	**13.96**
30.460	0.395	6	17.29	81.41711	0.22	12.26	4060.11	0.006	0.682	0.008	-0.061	0.137	**6.26**	**-4.50**	**592.86**	**46.56**	**41.91**
44.875	0.601	8	25.48	83.53922	0.32	17.76	4274.52	0.011	0.902	0.010	-0.079	0.265	**9.76**	**-6.07**	**1210.50**	**95.07**	**85.57**
58.022	0.807	10	32.94	86.10961	0.41	22.49	4541.61	0.005	1.168	0.013	-0.111	0.435	**12.49**	**-9.05**	**2109.46**	**165.68**	**149.11**
68.496	0.996	12	38.89	88.5552	0.49	26.05	4803.24	0.022	1.314	0.016	-0.107	0.562	**14.05**	**-9.25**	**2885.60**	**226.63**	**203.97**
77.627	1.202	14	44.07	90.95112	0.55	28.98	5066.67	0.038	1.432	0.022	-0.102	0.674	**14.98**	**-9.27**	**3647.83**	**286.50**	**257.85**
83.700	1.408	16	47.52	92.67108	0.60	30.85	5260.11	0.044	1.501	0.036	-0.101	0.739	**14.85**	**-9.58**	**4151.38**	**326.05**	**293.44**
85.962	1.597	16	48.81	93.33618	0.61	31.53	5335.88	0.044	1.501	0.036	-0.101	0.754	**15.53**	**-9.72**	**4298.90**	**337.63**	**303.87**
84.122	1.803	16	47.76	92.79413	0.60	30.98	5274.08	0.044	1.501	0.036	-0.101	0.742	**14.98**	**-9.60**	**4178.72**	**328.20**	**295.38**
76.980	2.010	16	43.71	90.77385	0.55	28.78	5046.93	0.044	1.501	0.036	-0.101	0.691	**12.78**	**-9.19**	**3726.28**	**292.66**	**263.40**
64.780	2.198	16	36.78	87.64911	0.46	24.81	4705.45	0.044	1.501	0.036	-0.101	0.597	**8.81**	**-8.57**	**3001.73**	**235.76**	**212.18**



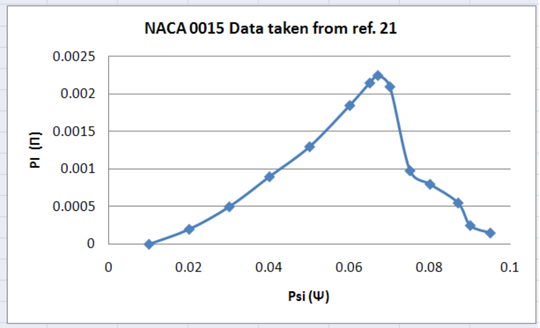


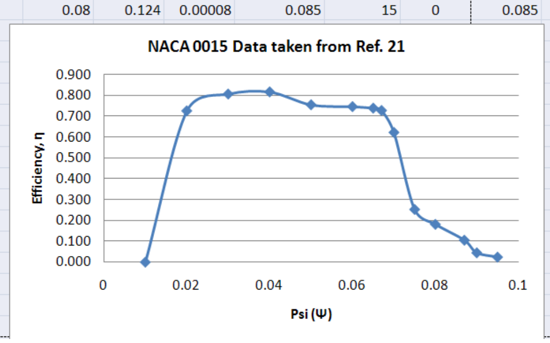
2.2.1 Some General Background on Efficiency and Overall Performance for Typical Wells-type Turbines as It Applies to this SBIR

A Wells turbine is a bidirectional turbine that is ideal for use in water wave energy conversion (WEC) systems that require a turbine to operate in air flows that can change direction by 180 degrees. The Oscillating Water Column WEC is the most common of the WEC systems that utilize a Wells turbine. It is well-known from work done by Oceanlinx Ltd. and other independent researchers (Refs. 17, 24, 26, 29, 31, 32, 33; see also Table I) that the efficiency of the turbine can be improved by adjusting the blade angle of attack to best match the air and blade surface velocities, which ultimately affects the aerodynamic blade lift and rotor torque. Independent researchers have demonstrated that the Wells turbine operates in a very narrow range of phi ($\varphi = U/U_{tip}$ or $Q/RPM/D^3$), typically between 0.01 and 0.15, but that a variable pitch Wells turbine can increase this range of operation to 0.4, an increase in operating range by more than 2 times. However, all such studies are always done with an electro-mechanical, pneumatic, or hydraulic system coupled with a closed feedback control system that actuates the blade articulation. The consensus from these studies has been that a self-actuating blade articulation (pitch) system would improve the operating range and efficiency of the rotor, and thus make such a rotor particularly effective in OWC water wave energy conversion systems. At this time, there are no self-actuated blade designs available that mechanically adjust to the aero forces acting on the blade, adjusting the blades to the optimum positions. The objective of this SBIR was to determine the feasibility of designing a self-actuating blade articulation system that can use the aerodynamic forces derived from the constantly changing air velocity and volume flow rates to provide the motive force that can rotate the blade to its optimum position, providing maximum rotational torque.

The table and figures reproduced below in Figure 16 are taken directly from a technical paper prepared by Falcao and Justino (Ref. 20) and clearly illustrate the design parameters (flow and load coefficients) and the typical relationships and values of these design parameters.

		K=	0.6882			
Corrected FActors=	0.314		0.408			
	Ψ	Π	Φ		η	
0	0.01	0	0.006882	1	0.000	0.006882
0.2	0.02	0.0002	0.013764	2	0.727	0.013764
0.5	0.03	0.0005	0.020646	3	0.807	0.020646
0.9	0.04	0.0009	0.027528	4	0.817	0.027528
1.3	0.05	0.0013	0.03441	5	0.756	0.03441
1.85	0.06	0.00185	0.041292	6	0.747	0.041292
2.15	0.065	0.00215	0.044733	7	0.739	0.044733
2.25	0.067	0.00225	0.0461094	8	0.728	0.046109
2.1	0.07	0.0021	0.048174	9	0.62274	0.048174
0.98	0.075	0.00098	0.051615	10	0.253	0.051615
0.8	0.08	0.0008	0.055056	11	0.182	0.055056
0.55	0.087	0.00055	0.0598734	12	0.106	0.059873
0.25	0.09	0.00025	0.061938	13	0.045	0.061938
0.15	0.095	0.00015	0.065379	14	0.024	0.065379
0.08	0.124	0.00008	0.085	15	0	0.085





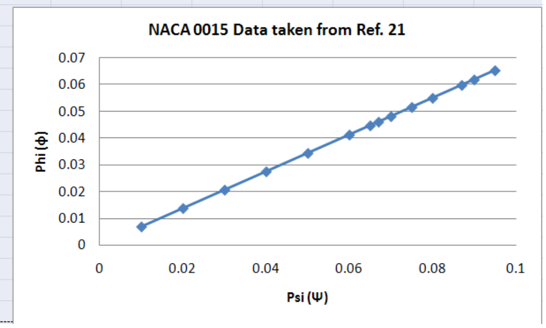


Figure 16. Reproduced from Technical Paper (Ref. 20) by Falcao and Justino.

These are offered here to illustrate a set of performance curves for a NACA0015 airfoil that has a given speed and diameter. Note the drastic decrease in turbine efficiency over the relatively short air flow rate range (φ). Attention is also focused on the linear proportionality constant, K, from the equation that is used to analytically model the turbine:

$$\varphi = K \times \Psi, \text{ where } K = 0.688$$

The flow coef. (φ) is defined as $(m/\rho)/(ND^3)$.

The load coef. (Ψ) is defined by: $\Delta P\, g_c/(\rho\, N^2 D^2)$.

The power coef. (Π) is defined by: Power $g_c/(\rho\, N^3 D^5)$

The rotor efficiency (η) can be shown to be equal to: $\varphi \times \Psi/\Pi$

It is desirable to have these same parameters for a variable pitch Wells turbine rotor. In particular, it is of interest to determine the proportionality constant, K (from the equation: φ= K x Ψ), as a function of incident angle or angle of attack (AOA). The proportionality constant, K, can be useful in the OWC system modeling. For this reason, Concepts NREC calculated the proportionality constant for a variable pitch blade Wells turbine using its own Pushbutton CFD®[1] software for a range of air flow rates. The results are shown in Figure 17 below with a new calculation of Phi vs. Psi using the definitions provided above.

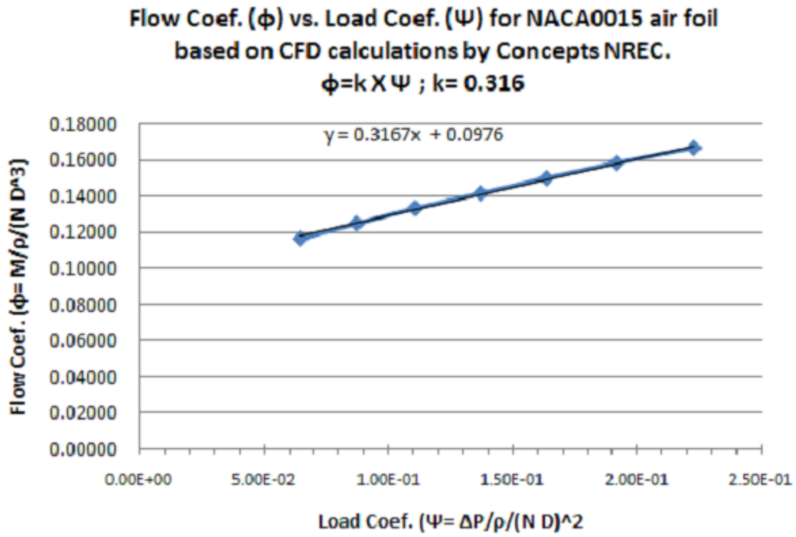


Figure 17. Results of a CFD analysis using Concepts NREC's software, Pushbutton CFD for a variable pitch Wells turbine

Clearly, this curve is representative of a Wells turbine with the characteristic linearity of the flow coefficient and the load coefficient as evidenced by the linear proportionality constant, K. Of particular interest is the obvious (almost 100%) increase in the range of the Wells turbine with variable pitch blades, confirming the results that have been presented by other researchers (see Table I). These were calculated with the assumptions of a wheel diameter of 6 ft. and speed of 750 rpm to achieve an OWC system with a rating of 300 kWe. These results were then used to model the Wells turbine during all of the subsequent Phase I SBIR analyses to design a viable self-actuating, blade articulation system.

2.2.2 Determining Torque vs. Angle or Attack for NACA0015 Airfoil

The three tables shown below identify the effect of a variable pitch blade and a fixed-pitch blade. These tables come from the NACA0015 XFOIL analysis that was developed for use in this SBIR. Table VI shows the variation in the flow rate for the 300 kWe-rated (Base-Line) OWC system, the system specification that we have been using since the start of the SBIR project. Particular attention is focused on the input changes to the AOA (0 to 16 degrees) and the output or calculated result for the Stagger angle (0 to 15 degrees). It is also noted that the stall angle for this NACA0015 airfoil is approximately 16 degrees, as may be observed from Figure 18. A theoretical maximum power generated (i.e., turbine efficiency is 100%) is 304 kW, with a weighted average of 227 kWe. The diameter of the rotor is approximately 6 ft. and the rotor speed is 750 rpm. The solidity of the rotor is 60%.

The NACA 0015 airfoil was chosen to be used for this project. The onset of stall occurs at an angle of attack (AOA) of approximately 16 degrees. The table was generated for a variable stagger Wells-type turbine and calculates a blade stagger angle for a given volume flow rate and angle of attack. The data for the calculation of lift, drag, and moment coefficients come from potential airfoil flow generators that include friction losses. The peak power generated is 304 kW, and a weighted average of 227 kWe (not shown) assuming the additional losses shown in the losses dialog box.

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[1] Pushbutton CFD is a registered trademark of Concepts ETI, Inc.

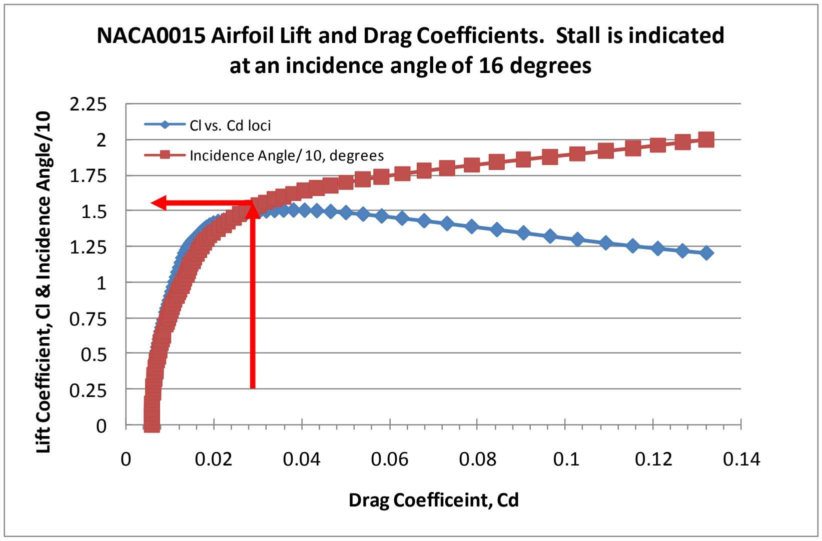


Figure 18. Stall angle shown to be approximately 16 degrees for NACA0015 Airfoil

TABLE VI. PRINTOUT FROM NACA0015 XFOIL ANALYSIS PREPARED BY CONCEPTS NREC FOR VARIABLE PITCH WELLS TURBINE TO DETERMINE PROPER TORQUE-ANGLE RELATIONSHIP FOR ARTICULATION MECHANISM

b	m	0.2794
c	m	0.254
rh	m	0.8636
rt	m	1.143
N	rpm	750
pivot Location	% chord	15%
Blade Count	-	15.00
air density	kg/m^3	1.225

Area_ann	m^2	1.76
r_m	m^2	1.01
U	m/s	79.56
Losses		0.1
Tip clearance		0.02
EndWall		0.02
Diskfriction		0.01
2nd Flow		0.05

228

NACA 0015

These valu
about 10%

flow Rate	Cycle Time	AOA	C_m	W_m	flow Coeff	Rel Flow Angle	Q	Mom. Coef.	Lift Coef.	Drag Coef.	Mom. Coef. @ pivot	Driving Force Coef.	**Stagger**	**Pitching Moment**	**Total Torque**	**Blade Power**	**Power**	**ΔP s-s**
m^3/sec	sec	deg	m/s	m/s	-	deg tan	Pa	-					**deg tan**	**N-m**	**N-m**	**kW**	**kW**	**Pa**
0.000	0.000	0	0.00	0	0.00	0.00	0.00	0.000	0.000	0.006	0.000	-0.006	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
16.539	0.206	4	9.39	80.111	0.12	6.73	3930.93	0.003	0.460	0.007	-0.043	0.047	**2.73**	**-3.06**	**197.50**	**15.51**	**13.96**	**937.88**
30.460	0.395	6	17.29	81.417	0.22	12.26	4060.11	0.006	0.682	0.008	-0.061	0.137	**6.26**	**-4.50**	**592.86**	**46.56**	**41.91**	**1528.67**
44.875	0.601	8	25.48	83.539	0.32	17.76	4274.52	0.011	0.902	0.010	-0.079	0.265	**9.76**	**-6.07**	**1210.50**	**95.07**	**85.57**	**2118.61**
58.022	0.807	10	32.94	86.11	0.41	22.49	4541.61	0.005	1.168	0.013	-0.111	0.435	**12.49**	**-9.05**	**2109.46**	**165.68**	**149.11**	**2855.42**
68.496	0.996	12	38.89	88.555	0.49	26.05	4803.24	0.022	1.314	0.016	-0.107	0.562	**14.05**	**-9.25**	**2885.60**	**226.63**	**203.97**	**3308.73**
77.627	1.202	14	44.07	90.951	0.55	28.98	5066.67	0.038	1.432	0.022	-0.102	0.674	**14.98**	**-9.27**	**3647.83**	**286.50**	**257.85**	**3690.74**
83.700	1.408	16	47.52	92.671	0.60	30.85	5260.11	0.044	1.501	0.036	-0.101	0.739	**14.85**	**-9.58**	**4151.38**	**326.05**	**293.44**	**3895.45**
85.962	1.597	16	48.81	93.336	0.61	31.53	5335.88	0.044	1.501	0.036	-0.101	0.754	**15.53**	**-9.72**	**4298.90**	**337.63**	**303.87**	**3927.73**
84.122	1.803	16	47.76	92.794	0.60	30.98	5274.08	0.044	1.501	0.036	-0.101	0.742	**14.98**	**-9.60**	**4178.72**	**328.20**	**295.38**	**3901.45**
76.980	2.010	16	43.71	90.774	0.55	28.78	5046.93	0.044	1.501	0.036	-0.101	0.691	**12.78**	**-9.19**	**3726.28**	**292.66**	**263.40**	**3801.77**
64.780	2.198	16	36.78	87.649	0.46	24.81	4705.45	0.044	1.501	0.036	-0.101	0.597	**8.81**	**-8.57**	**3001.73**	**235.76**	**212.18**	**3639.35**

An “overall” proportionality constant, K, for an airfoil that has a continuously varying blade pitch is shown below. This was calculated using the spreadsheet labeled: JAMIN_KerryJan15_10300Naca0015Blade Torque in the project files. The proportionality constant was calculated by first determining the flow and load coefficients (as defined above) for the varying flow rate through the turbine as originally determined by Concepts NREC using its OWC model. The spreadsheet was used to determine the torque-angle displacement relationship, and thus, the required torsion stiffness, $k_{torsion}$, for the torsion bar that was to be used in the Self-Actuated Blade Articulation Mechanism. However, the proportionality constant, K, is only for a thermodynamically ideal Wells turbine. The linearity of the relationship is to be noted. Most important is the pressure drop across the turbine which is shown to be 3930 Pa at 86 m^3/s.

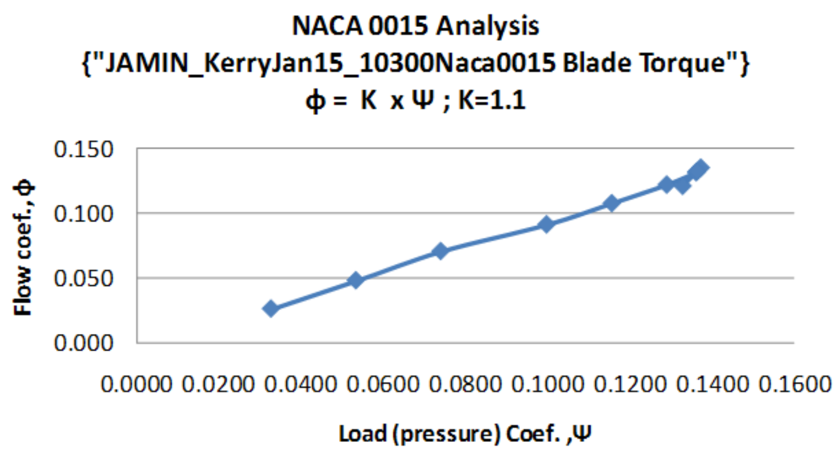


Figure 19. Linear relationship for variable pitch Wells turbine

Table VII reveals a similar summary table that uses the same range of flow rates, but using an AOA that results in a Stagger Angle of zero (0) degrees. However, in order to be able to be effective throughout the operational flow rate range, the diameter of the rotor had to be increased by 17.5%, the speed increased to 950 rpm, and the number of blades increased to 16, in order to have the same 60% solidity. The max power is now 509 kW, with a weighted average of 401 kW. However, adjusting for the maximum pressure available from the OWC system (3930 Pa), the de-rated power available from the turbine is 213 kW, or 6.5% less than that available from the self-actuated turbine rotor. The peak power also occurs at a slightly less volume flow rate: 83 m^3/s compared to 86 m^3/s.

Table VIII reveals a similar summary calculated to approximate the results one would expect for a Wells-type turbine with a fixed stagger angle of 0 degrees. If the AOA goes beyond the Cl-Cd data (maximum AOA is 20), it means that the rotational speed has to be increased or that the size of the turbine needs to decrease in order change the relative flow angle to stay in the airfoil data range. Alternatively, the range of the airfoil data could be increased, but it would still not be able to adequately cover the range needed by the OWC that was chosen as the Baseline System for the Phase I SBIR study.

TABLE VII. CONCEPTS NREC ANALYSIS OF A FIXED-BLADE WELLS TURBINE USING NACA0015 ROTOR

	b		m	0.2794		Area_ann	m^2	2.43											
	c		m	0.254		r_m	m^2	1.19											
	rh		m	1.0147		U	m/s	118.41											
	rt		m	1.343		**Losses**		0.1											
	N		rpm	950		Tip clearance		0.02											
	pivot Location		% chord	15%		EndWall		0.02											
	Blade Count		-	16.00		Diskfriction		0.01									**401**	**kWe**	
	air density		kg/m^3	1.225		2nd Flow		0.05						**NACA 0015**				These values will be	
			Solidity=	0.549														about 10% low	
flow Rate	Cycle Time	AOA	C_m	W_m	flow Coeff	Rel Flow Angle	Q	Mom. Coef.	Lift Coef.	Drag Coef.	Mom. Coef. @ pivot	Driving Force Coef.	**Stagger**	**Pitching Moment**	**Total Torque**	**Blade Power**	**Power**	**ΔP s-s**	**ΔP t-s**
m^3/sec	sec	deg	m/s	m/s	-	deg tan	Pa	-					**deg tan**	**N-m**	**N-m**	**kW**	**kW**	**Pa**	**Pa**
0.000	0.000	0	0.00	0	0.00	0.00	0.00	0.000	0.000	0.006	0.000	-0.006	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
16.539	0.206	3.29	6.80	118.61	0.06	3.29	8616.24	0.002	0.375	0.007	-0.035	0.015	**0.00**	**-5.51**	**202.52**	**20.15**	**18.13**	**1218.15**	**1246.48**
30.460	0.395	6.04	12.53	119.07	0.11	6.04	8684.01	0.006	0.682	0.008	-0.061	0.063	**0.00**	**-9.63**	**867.05**	**86.26**	**77.63**	**2831.84**	**2927.95**
44.875	0.601	8.86	18.45	119.84	0.16	8.86	8796.50	0.009	1.000	0.011	-0.090	0.143	**0.00**	**-14.30**	**1977.21**	**196.70**	**177.03**	**4383.31**	**4591.89**
58.022	0.807	11.39	23.86	120.79	0.20	11.39	8936.62	0.014	1.270	0.015	-0.111	0.236	**0.00**	**-17.86**	**3321.60**	**330.44**	**297.40**	**5695.18**	**6043.89**
68.496	0.996	13.38	28.17	121.71	0.24	13.38	9073.88	0.032	1.397	0.019	-0.104	0.305	**0.00**	**-17.04**	**4348.75**	**432.63**	**389.37**	**6316.16**	**6802.13**
77.627	1.202	15.09	31.92	122.64	0.27	15.09	9212.08	0.043	1.479	0.027	-0.101	0.358	**0.00**	**-16.75**	**5193.03**	**516.62**	**464.96**	**6655.21**	**7279.38**
83.700	1.408	16.21	34.42	123.31	0.29	16.21	9313.56	0.044	1.502	0.038	-0.101	0.382	**0.00**	**-16.99**	**5603.10**	**557.42**	**501.68**	**6659.72**	**7385.37**
85.962	1.597	16.62	35.35	123.57	0.30	16.62	9353.31	0.043	1.498	0.044	-0.102	0.387	**0.00**	**-17.14**	**5688.43**	**565.91**	**509.32**	**6583.23**	**7348.63**
84.122	1.803	16.29	34.59	123.36	0.29	16.29	9320.89	0.044	1.502	0.038	-0.101	0.384	**0.00**	**-16.99**	**5636.27**	**560.72**	**504.65**	**6665.55**	**7398.54**
76.980	2.010	14.97	31.66	122.57	0.27	14.97	9201.73	0.042	1.469	0.026	-0.101	0.354	**0.00**	**-16.75**	**5128.45**	**510.20**	**459.18**	**6627.64**	**7241.46**
64.780	2.198	12.68	26.64	121.37	0.22	12.68	9022.57	0.026	1.349	0.017	-0.106	0.279	**0.00**	**-17.19**	**3963.14**	**394.27**	**354.84**	**6086.31**	**6520.97**

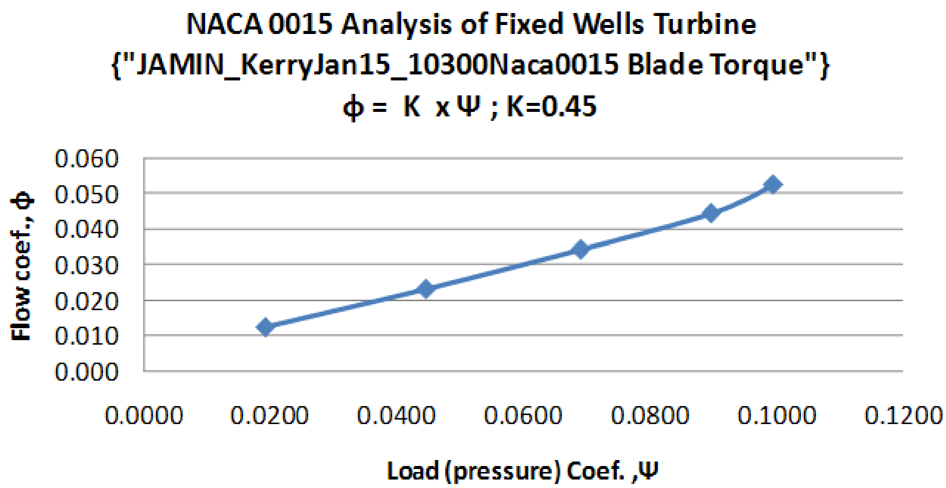


Figure 20. Flow coefficient vs. load coefficient relationship for fixed-pitch rotor using NASA0015 XFOIL software

Table VIII shown below is almost identical to Table VI except that the speed and diameter of the Wells turbine is kept the same as that originally proposed for the self-actuated articulated bladed Wells turbine. For this rotor, the AOA input cannot be adjusted until the stagger angle is zero (0) degrees for the entire flow rate range, as evidenced by the AOA that exceeds 16 degrees (i.e., exceeds the stall angle of the rotor). Thus, the Wells turbine with fixed blades cannot operate through the entire range of flow rates that is available from the OWC system. The result of the calculation is a maximum power of 122kW and a weighted average of 100 kW. <u>Thus, two fixed-blade Wells turbines would be needed to perform equal to the single variable pitch Wells rotor</u>.

TABLE VIII. COMPUTER OUTPUT SHOWING LIMITED RANGE OF A WELLS TURBINE USING FIXED BLADES

	b		m	0.2794		Area_ann	m^2	1.76										
	c		m	0.254		r_m	m^2	1.01										
	rh		m	0.8636		U	m/s	79.56										
	rt		m	1.143		Losses		0.1										
	N		rpm	750		Tip clearance		0.02										
	pivot Location		% chord	15%		EndWall		0.02									228.7	
	Blade Count		-	15.00		Diskfriction		0.01										
	air density		kg/m^3	1.225		2nd Flow		0.05							NACA 0015			These valu
																		about 10%
flow Rate	Cycle Time	AOA	C_m	W_m	flow Coeff	Rel Flow Angle	Q	Mom. Coef.	Lift Coef.	Drag Coef.	Mom. Coef. @ pivot	Driving Force Coef.	Stagger	Pitching Moment	Total Torque	Blade Power	Power	ΔP s-s
m^3/sec	sec	deg	m/s	m/s	-	deg tan	Pa	-					deg tan	N-m	N-m	kW	kW	Pa
0.000	0.000	0	0.00	0	0.00	0.00	0.00	0.000	0.000	0.006	0.000	-0.006	0.00	0.00	0.00	0.00	0.00	0.00
16.539	0.206	6.73	9.39	80.11145	0.12	6.73	3930.93	0.008	0.736	0.009	-0.065	0.078	0.00	-4.64	325.69	25.58	23.02	1546.63
30.460	0.395	12.26	17.29	81.41711	0.22	12.26	4060.11	0.024	1.332	0.017	-0.106	0.266	0.00	-7.77	1155.57	90.76	81.68	2979.58
44.875	0.601	17.76	25.48	83.53922	0.32	17.76	4274.52	0.036	1.445	0.063	-0.103	0.381	0.00	-7.95	1737.94	136.50	122.85	3041.72
58.022	0.807	22.49	32.94	86.10961	0.41	22.49	4541.61	0.002	1.202	0.132	-0.114	0.338	0.00	-9.33	1637.49	128.61	115.75	2216.54
68.496	0.996	13.73	38.89	88.5552	0.49	26.05	4803.24	0.034	1.411	0.020	-0.104	0.602	12.32	-8.97	3086.89	242.44	218.20	3539.54
77.627	1.202	15.48	44.07	90.95112	0.55	28.98	5066.67	0.044	1.491	0.030	-0.101	0.696	13.50	-9.21	3766.98	295.86	266.27	3811.30
83.700	1.408	16.63	47.52	92.67108	0.60	30.85	5260.11	0.043	1.498	0.044	-0.102	0.731	14.22	-9.64	4104.40	322.36	290.12	3851.37
85.962	1.597	17.05	48.81	93.33618	0.61	31.53	5335.88	0.041	1.484	0.050	-0.102	0.733	14.48	-9.83	4179.46	328.25	295.43	3818.61
84.122	1.803	16.71	47.76	92.79413	0.60	30.98	5274.08	0.043	1.498	0.044	-0.102	0.733	14.27	-9.66	4131.63	324.50	292.05	3857.48
76.980	2.010	15.36	43.71	90.77385	0.55	28.78	5046.93	0.043	1.486	0.029	-0.101	0.690	13.42	-9.17	3719.31	292.11	262.90	3794.66
64.780	2.198	13.01	36.78	87.64911	0.46	24.81	4705.45	0.030	1.382	0.018	-0.105	0.563	11.80	-8.89	2830.25	222.29	200.06	3431.45

A variable pitch Wells turbine allows for a much larger range of relative flow angles, defined as atan(Cm/U), than that of a fixed-blade Wells turbine. This could mean two things for the variable pitch turbine: either the speed of the turbine can be much slower (lower U) for a given flow, or the flow can be greatly increased (higher Cm) for a given rotational speed. One could also look at it in terms of the flow coefficient. The variable pitch turbine could dramatically extend the range of flow coefficients for which a fixed-blade Wells type turbine could operate efficiently.

It would appear that the larger AOA allows for an increase in the air velocity (and hence, volume flow rate) before stall occurs. Thus, a major benefit for a Wells turbine with a variable pitch blade is the ability to extend the operating range and also perhaps provide a smaller turbine or fewer turbines to operate with the larger flow. This is a major advantage over a fixed-blade Wells turbine, particularly if the blades need to be fixed with zero (0) incidence angle for a bidirectional turbine application, such as is required for an OWC.

2.2.3 Summary of Major Advantages of Variable Pitch Wells Turbine Applied to OWC System

The constantly changing air velocity and volume flow rate has been shown by Concepts NREC's computational modeling to be an inherent nature of the OWC energy conversion system as different wave energy intensities are incident to the OWC system. When developed, the wave energy-responsive, self-actuating blade will eliminate the current linkage mechanism that is now needed to perform this function on the Dennis-Auld air turbine. The consequence is two-fold: a reduction in the complexity of the blade articulation mechanism that reduces the cost of the OWC turbine by 10 to 15%, and an increase in the turbine's efficiency due to the constant adjusting of the angle of attack between the blade and the air velocity vector which improves the aerodynamic lift on the blade and increases the turbine's overall efficiency by as much as 15 to 20%. It is interesting to note that the efficiencies that are often cited for Wells turbines can be as high as 65^{+}% if the air flow rate is kept in the "sweet spot".

Thus, the conclusion from these modeling studies of a Wells turbine as they apply to Wave Energy Conversion systems of the OWC type may be summarized as follows:

1. A variable pitch Wells turbine allows for a much larger range of relative flow angles, defined as atan(Cm/U), than that of a fixed-blade Wells turbine. This could mean two things for the variable pitch turbine: either that the speed of the turbine can be much slower (lower U) for a given flow or that the flow can be greatly increased (higher Cm) for a given rotational speed.

2. One could also look at a benefit from the perspective of the flow coefficient, φ. The variable pitch turbine could dramatically extend the range of flow coefficients for which a fixed-blade Wells type turbine could operate efficiently.

3. Two fixed-blade Wells turbines would be needed to perform that same as the single, variable pitch Wells rotor. If a larger and faster Wells turbine is used to operate in the same flow range, the power output of the variable pitch Wells turbine is greater than the fixed-blade turbine by 6% for the Case Study shown in Table II.

2.3 Detailed Feasibility Analysis of Self-Actuated Blade Articulation Mechanism

The extreme transients in the pressure and air flow rate, as shown in Figures 15a & b, clearly reveal the major issue involved with the design of an efficient airfoil, and hence, turbine rotor that is applied to OWC applications. That is, the continuous changes in the pressure and air flow rate through the turbine are not desirable for maintaining an efficient turbine. The efficiency can be improved by articulating the blade in such a manner as to maintain the highest airfoil pressure for a given air flow rate across the blade. The higher airfoil pressure results in an increase in the rotor torque. This articulation is presently accomplished with a complicated set of linkages and feedback controls that monitor the chamber pressure and mechanically articulate the blade. The proposed concept considers using the aero forces caused by the air flow rate across the blade to articulate the blade and precisely match the necessary articulating forces and thus eliminate the complicated, mechanical linkage design. As shown in Figure 21, the articulation can be accomplished by inserting a pivot axle along the chord of the blade in such a position as to maintain a twisting torque that can be provided by the aerodynamic (lift and drag) forces exerted on the blades. Since these forces are dependent upon the transient air pressure and flow rate that are produced by the OWC chamber (Ref. Figures 15a & b), they are also constantly changing. Thus, theoretically and in practice, there is an optimum blade Angle of Attack that provides the highest value of aerodynamic lift on the blade, and hence, highest value of rotor torque. Several airfoil shapes have been studied including the NACA 0015, NACA 0020, and NACA 0025.[2] The most aerodynamically efficient blade is the NACA 0015, and this blade has been revealed to be a viable candidate for the self-articulating blade concept.

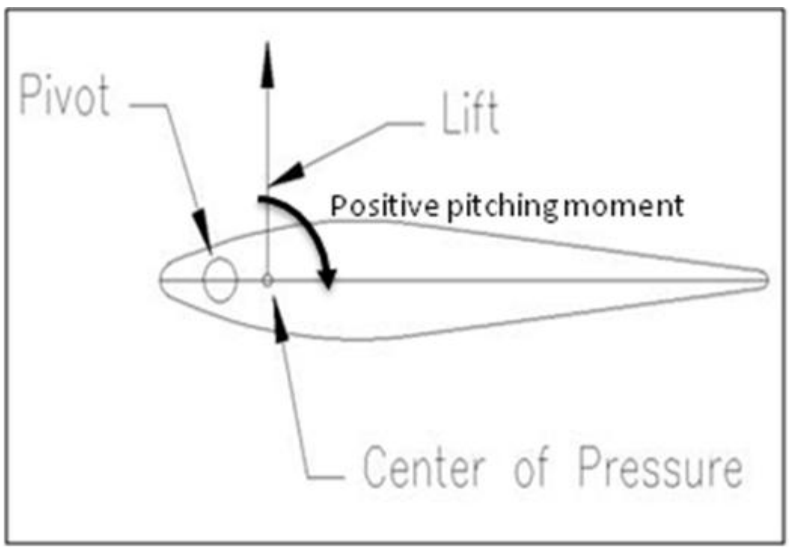


Figure 21. Diagram of pivot axle location offset from center of blade aero force to produce blade twisting torque

Using this blade profile and the air flow rate and available chamber pressure (and hence pressure drop across the rotor) as presented in Figures 15a & b, a turbine rotor size specification was determined. The physical design of the rotor is given in Tables IX a & b.

[2] The numerical designation refers to the thickness of the airfoil at its thickest point along the chord as a percent of the chord length.

TABLE IX A & B. PHYSICAL DESIGN OF ROTOR

b	m	0.2794
c	m	0.254
rh	m	0.8636
rt	m	1.143
N	rpm	750
Pivot Location	% chord	15%
Blade Count	-	15.00
Air Density	kg/m^3	1.225

Area_ann	m^2	1.76
r_m	m^2	1.01
U	m/s	79.56
Losses		0.1
Tip Clearance		0.02
End Wall		0.02
Disk Friction		0.01
2nd Flow		0.05

The NACA airfoil computation was used to determine the optimum Angle of Attack (AOA) for the airfoil to achieve the maximum useful forces on the blade, and thus the maximum rotor torque. The results of this iteration are shown in Table V or in Table X for a close-up of the relevant columns. It must be noted that the NACA computations do not calculate the efficiency of the blade in converting the air stream energy into useful rotor power. Thus, the columns shown in Table X reflect the 100% conversion of the air energy.

It is noted that an independent research paper by Gato, Eca, and Falcao (Ref. 24, "Performance of the Wells Turbine with Variable Pitch Rotor Blades", Vol. 113, Sept. 1991, p. 141) reported a measured improvement in the turbine efficiency of 23% and the doubling of the operating range of the air flow rate before airfoil stall is encountered. The blade pitch was adjusted manually for the experiments and did not include a means of accomplishing the variable blade pitch automatically. The means of mechanically enabling the self-actuating of the blade was also not considered or even suggested in the research. This independent research provides additional incentive for developing the self-actuating blade design.

A graphical presentation of the pitching torque as a function of the stagger angle is provided in Figure 22 for a pivot placed at 15% of the chord position.

Table X and Figure 22 provide the necessary engineering specifications for the twisting moment to initiate the mechanical design of a self-articulating blade.

TABLE X. ENGINEERING SPECIFICATIONS

	NACA 0015				These values will be about 10% low	
Stagger	Pitching Moment	Total Torque	Blade Power	Power	ΔP s-s	ΔP t-s
deg tan	N-m	N-m	kW	kW	Pa	Pa
0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.73	-3.06	197.50	15.51	13.96	937.88	991.89
6.26	-4.50	592.86	46.56	41.91	1528.67	1711.86
9.76	-6.07	1210.50	95.07	85.57	2118.61	2516.20
12.49	-9.05	2109.46	165.68	149.11	2855.42	3520.11
14.05	-9.25	2885.60	226.63	203.97	3308.73	4235.05
14.98	-9.27	3647.83	286.50	257.85	3690.74	4880.48
14.85	-9.58	4151.38	326.05	293.44	3895.45	5278.64
15.53	-9.72	4298.90	337.63	303.87	3927.73	5386.69
14.98	-9.60	4178.72	328.20	295.38	3901.45	5298.61
12.78	-9.19	3726.28	292.66	263.40	3801.77	4971.79
8.81	-8.57	3001.73	235.76	212.18	3639.35	4467.88

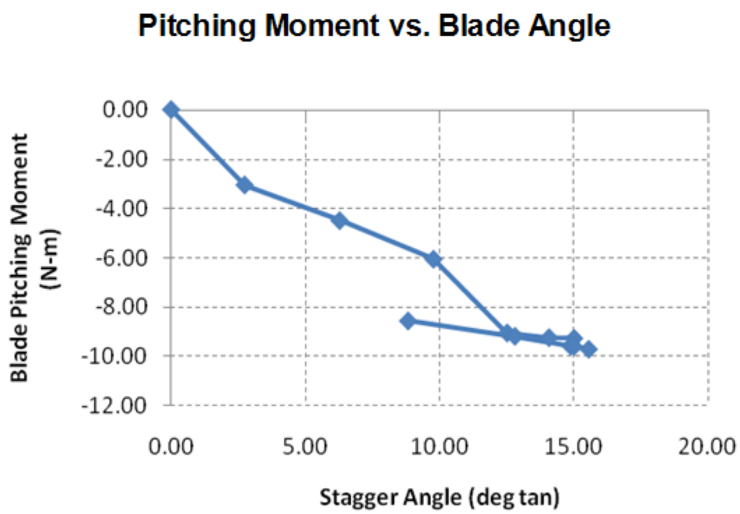


Figure 22. Pitching torque as a function of the stagger angle

Figure 23 reveals the first of many mechanical designs that were considered for the self-articulating blade design. However, while these designs were viable, these initial designs were not considered for more detailed development due to the need for roller element radial or thrust bearings. A significant requirement of a successful design is to eliminate the need for radial or axial (thrust) roller bearings in the design in an effort to reduce the mechanical complexity of the self-articulating blade design, and thus, to reduce its manufacturing costs. It is also necessary to design a self-articulating blade that can be fabricated as a module or cartridge and be installed around the hub of a turbine rotor, effectively eliminating the large and expensive rotor mass, along with the mechanical complexity of an articulating linkage and actuator. It is also necessary to consider the use of a damping system for eliminating the aero-induced blade flutter or vibrations that result during the changes in the operating pressure and flow rate.

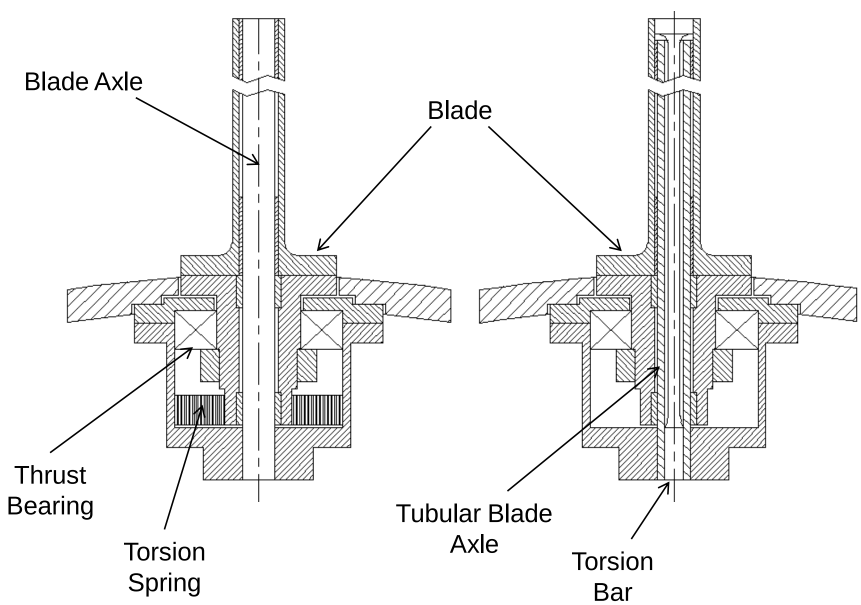


Figure 23. Cartridge-blade design

Figure 24 illustrates an alternative concept for self-articulating the rotor blade. This concept uses the pressure differential between the front and the back faces of the turbine to move a linkage system that directly articulates the blade.

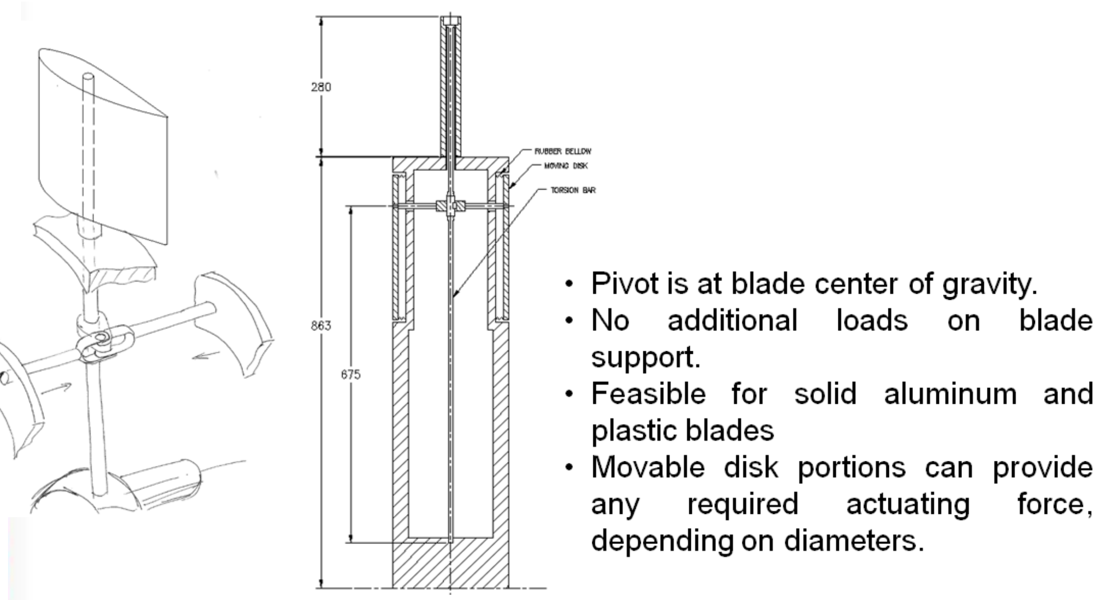


Figure 24. An alternative concept for articulating the blade using aerodynamic pressure differential across the front and back of the rotor

After much consideration of the pros and cons of these designs, another basic mechanical design that satisfies the requirement of eliminating roller bearings while providing a simple mechanical device, using a torsion bar concept, is shown in Figure 25. This design utilizes a long, slender torsion rod that is fixed near the rotor hub's axis of rotation. In order for 15 or more blades to be part of the assembly, the torsion bar length cannot be equal to the radius of the rotor, approximately 38 inches. The top end of the torsion bar is fixed to the airfoil. The airfoil is designed with a collar that is inserted at the pivot point along the blade chord. The collar provides the contact surface that is supported by a cylindrical post attached (fixed) to the rotor. This design provides the necessary structural support to withstand the three major forces that are exerted on the airfoil during operation. These three loads are illustrated in Figure 26, and the basic equations are also given in Figure 26. The loads include: 1. the airfoil distributed force due to the aerodynamic loading on the blade which results in a bending moment on the structural post, in addition to the twisting torque on the torsion bar, 2. the radial centrifugal force due to the rotation of the rotor that causes a tension in the torsion bar, and 3. a second bending moment on the structural post (i.e., the blade axle) caused by the centrifugal force on the center of mass of the blade (assuming that the center of mass is not on the pivot axis). A viable design would be one that would have the pivot axle support the

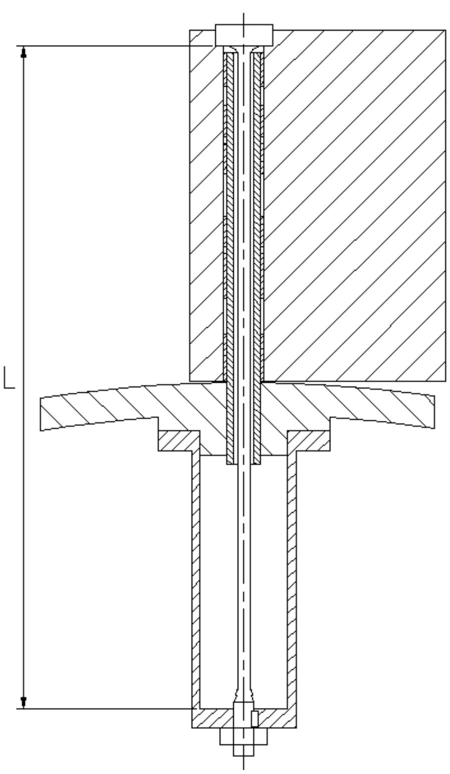
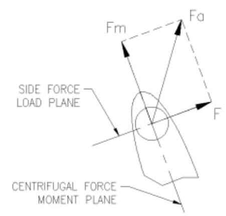


Figure 25. Conceptual design used as the basis for continuing feasibility analysis

tensile and torsion stress, while also providing the necessary torsion spring constant to enable the blade articulation through the range of air flow rates as given in Figure 7. It was necessary that the pivot axle be large enough to provide a contact bearing surface for the structural post that needed to counter the bending stresses caused by the airfoil.



$$Fside = Mpitch / ARM$$

$$Fcentr = m * \omega^2 * R$$

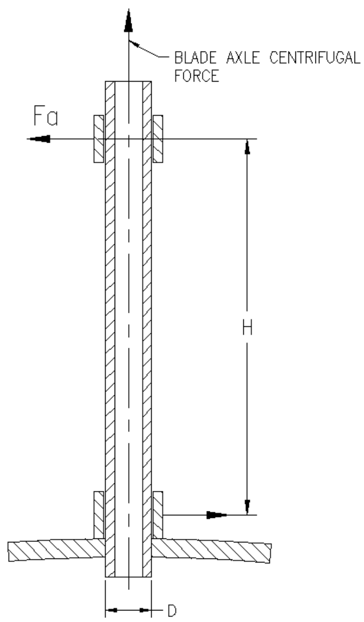
$$\omega = \frac{\pi * RPM}{30}$$

$$Mcentr = Fcentr * L$$

$$F = F_{Side} / 2$$

$$F_M = M_{centr} / H$$

$$F_{axle} = \sqrt{F^2 + F_M^2}$$



Maximal Stress

$$\sigma_{\max} = \frac{F_a * H}{Z} + \frac{F}{A}$$

$Z - Section\_Modulus$

$A - Section\_Area$

Deflection at upper bearing

$$y = \frac{F_a * H^3}{3 * E * I}$$

$E - Modulus\_of\_elastisity$

$I - Section\_moment\_of\_inertia$

Safety

$$S = \frac{[\sigma]}{\sigma_{\max}}$$

$S - Safety$

$[\sigma] - allowable\_bending\_stress$

Figure 26. Torsion mechanism feasibility, blade axle stress, and deflection

With the acceptable basic mechanical design concept as shown in Figure 25 and the specifications for the aero forces exerted on the NACA airfoils, a feasibility analysis was initiated to determine if the NACA airfoils[3] could be integrated with a pivot axle that could serve as a torsion bar to counter the twisting and tension stresses, and a structural post that could provide the necessary bending strength. For this feasibility analysis, the airfoil blade was properly drawn in CAD in order that its mass and center of gravity could be readily determined each time the location of the pivot axle was changed. With the equations shown in Figure 26, a suitable diameter for the pivot axle (torsion bar) was determined that could accommodate the twisting torque and bending loads. The analysis was first performed for a solid aluminum blade and subsequently progressed to a hollow and foam-filled blade. These are illustrated in Figures 27, 28, & 29. Also illustrated inside the blade profiles is the use of either a "solid nose" or a rod insert. These masses provide a means of shifting the center-of-gravity towards the pivot point (shown in Figure 27), thus reducing the moments exerted on the blade shaft due to centrifugal forces generated by the spinning rotor.

[3] Throughout most of the initial feasibility analysis, the NACA 0015, 0020, and 0025 airfoils were all studied to determine their feasibility to accommodate the forces and moments caused by the aero forces. This report will summarize only the results on the NACA 0015 airfoil, since it was determined that the NACA 0015 airfoil can be used with a viable self-articulating blade mechanical design.

1. Solid blade and positioning pivot and diameter for best torque-angle
2. Hollow blade with dense solid nose to move CG over or close to pivot,
3. Foam filled blade with dense, rod insert to reduce mfg.ing cost and move CG

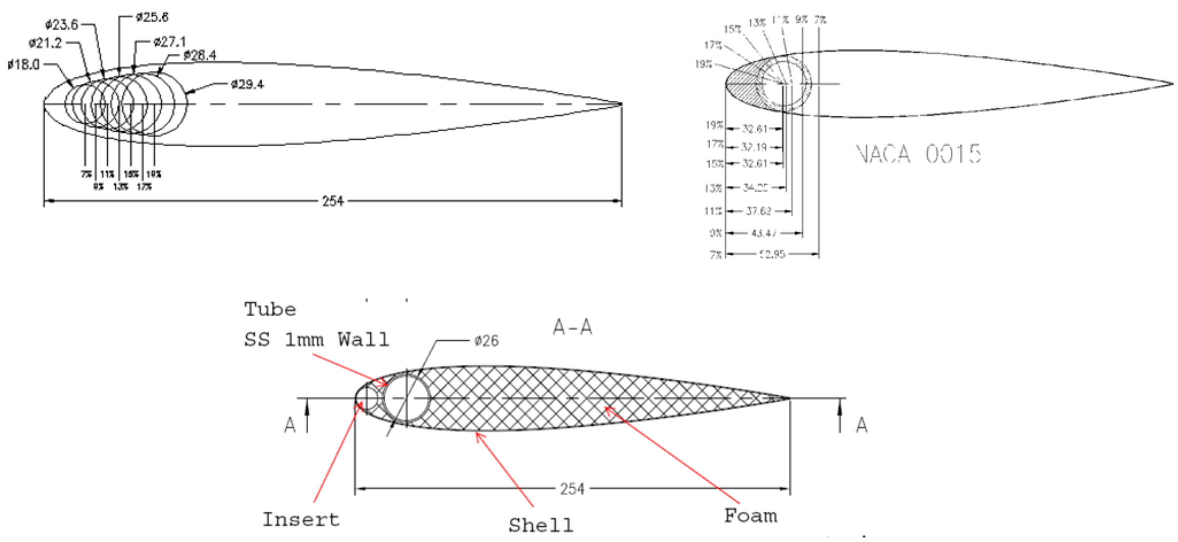
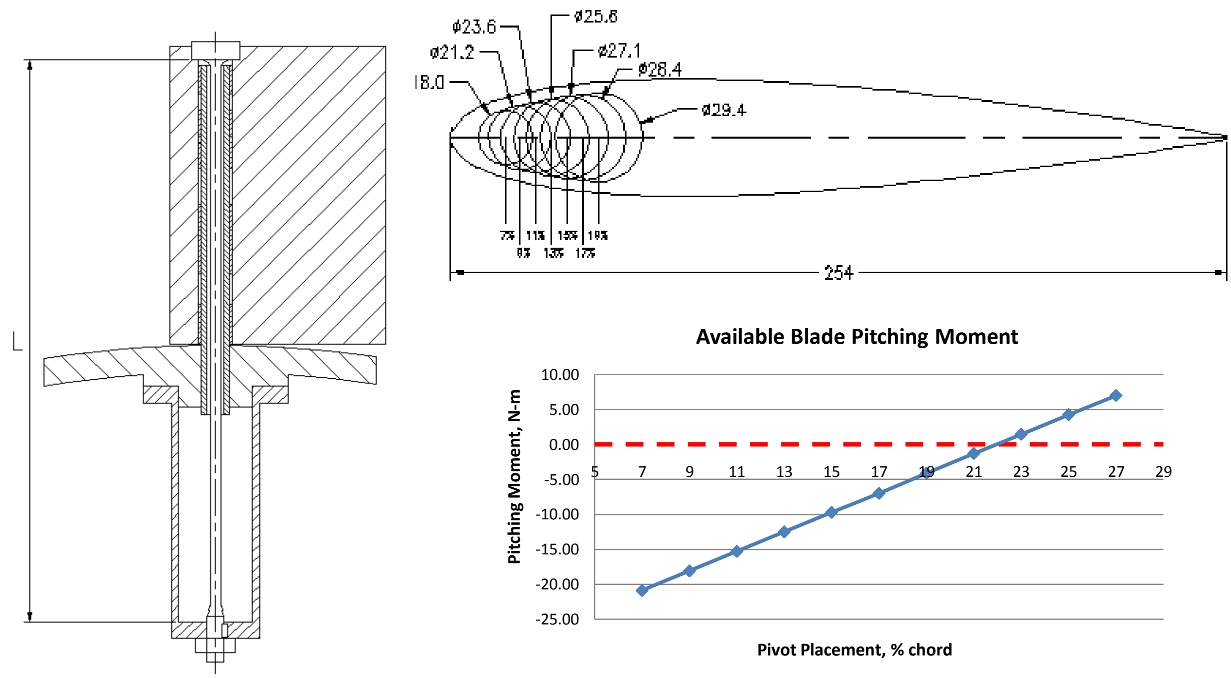


Figure 27. Three blade cross-section options considered during feasibility study



Figures 28 & 29. Torsion mechanism feasibility

Figure 30 illustrates samples of the feasibility study that was conducted to determine the correct placement of the axle pivot with respect to the chord length. The chord length of the blade is 10 inches, and a pivot designation of 15% indicates that the pivot is placed at 15% of 10 inches, or 1.5 inches from the front, i.e., the blunt edge of the airfoil. It must also be noted that the calculations shown are only samples of the many feasibility analyses that were conducted in order to determine the proper location of the pivot, as well as the size and material of the blade axle and torsion bar.

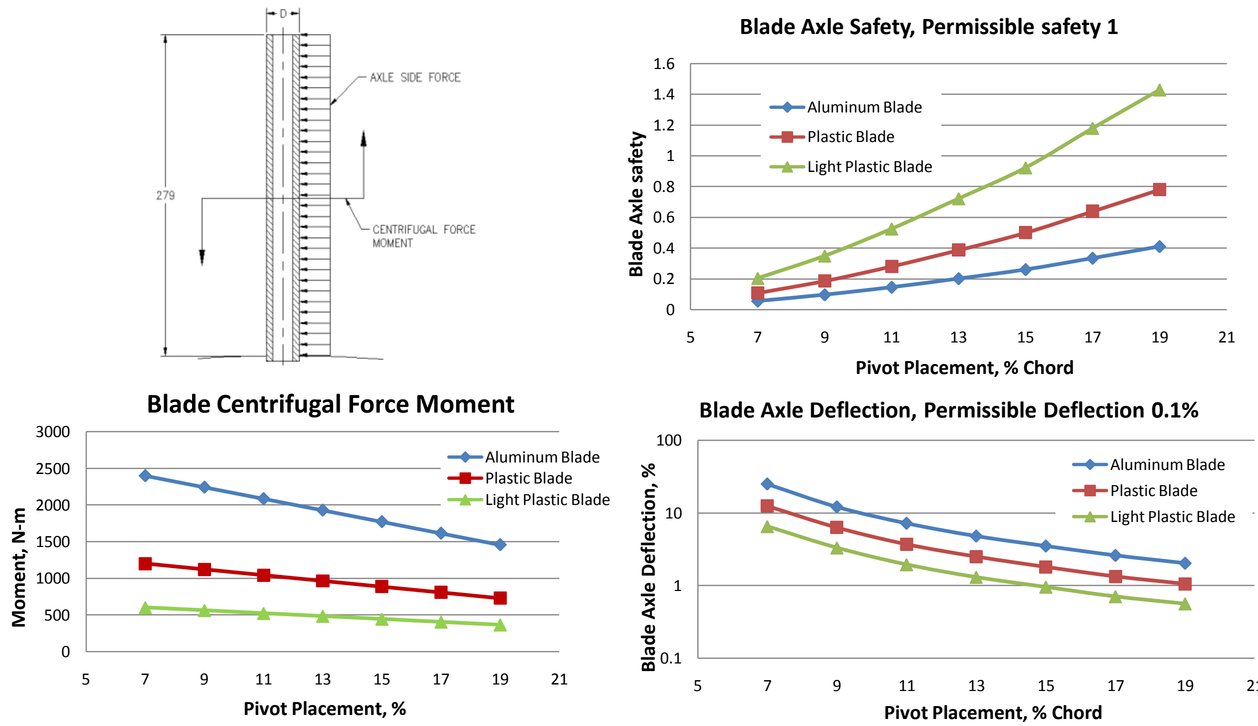


Figure 30. Torsion mechanism feasibility, NACA 0015 profile

A study of these results concluded that the analysis needed to be modified to include a hollow or lighter blade when it was found that the bending moments caused by the solid blade's center of mass would result in an unacceptably large support post and/or a low safety factor for the complete mechanical design. The lighter or hollow blade did result in improvements in the safety factor of the torsion bar (pivot axle) design as shown in Figure 31.

Similarly, the blade axle (i.e., the structural support post) which provides the majority of the support for the bending loads also provided the reasonable safety factor for the mechanical design as shown in Figures 32a & b.

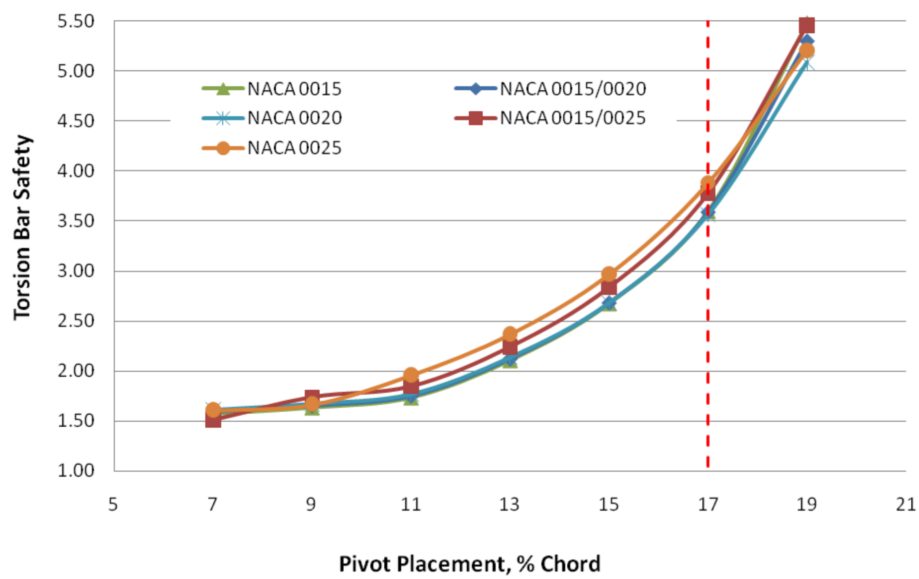


Figure 31. Torsion bar feasibility
DIA min 7.0 mm, length range 300-1050 mm

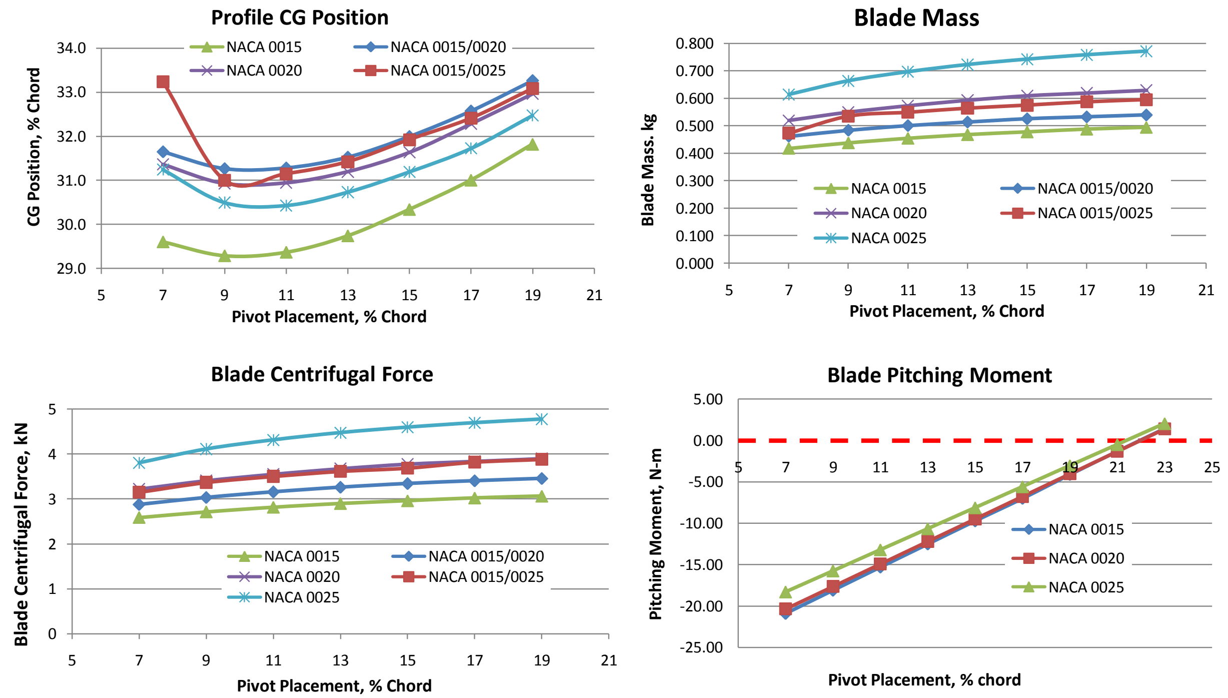
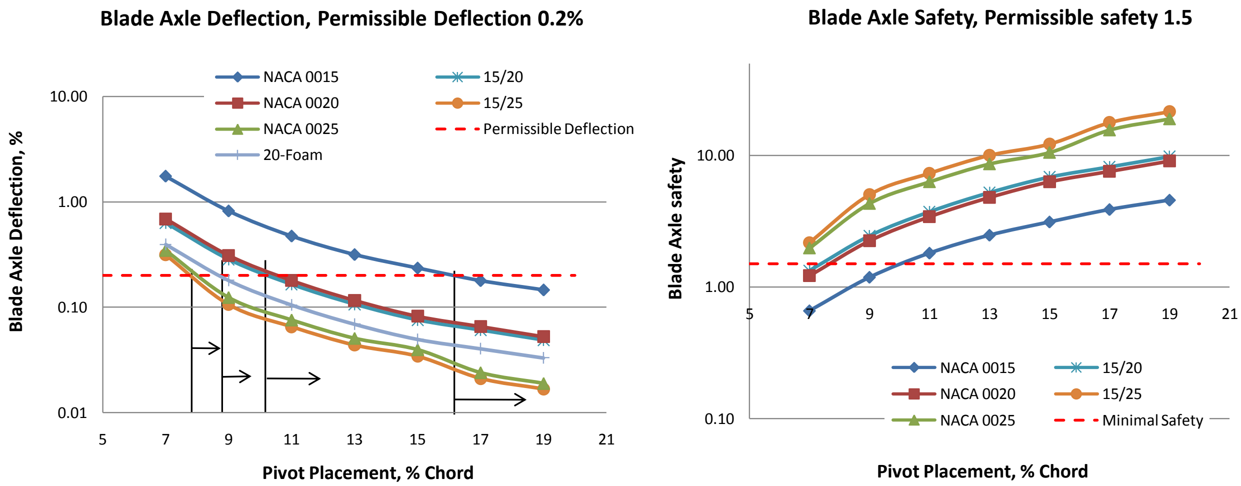


Figure 32a. Torsion mechanism feasibility, hollow blades characteristics



- NACA 0015 Profile is working from pivot placement at 16 % cord (Permissible deflection higher than 0.2%)
- NACA 0020 and 0015/0020 profiles are working starting from pivot placement at about 10.5% cord
- NACA 0025 and 0015/0025 profile are working starting from pivot placement at 8% cord
- NACA 0020 made from rigid foam is working from 8.5% chord

Figure 32b. Torsion mechanism feasibility, blade axle safety and deflection

However, the lighter blade still had a center of mass that was not coincident with the pivot axis, and therefore, the aero forces still resulted in higher than necessary bending moments and thus high bending stresses.

As a result, the analysis considered the use of a "heavy nose" section of the airfoil and a hollow blade body filled with hard foam material. Figure 33 illustrates the basic design. An aluminum alloy of the 5xxx series was considered a material of choice for the blade skin and blade tube load surface. However, further analysis indicated that a stainless steel blade skin was necessary for strength purposes, and that stainless steel should be used for the pivot or blade axle.

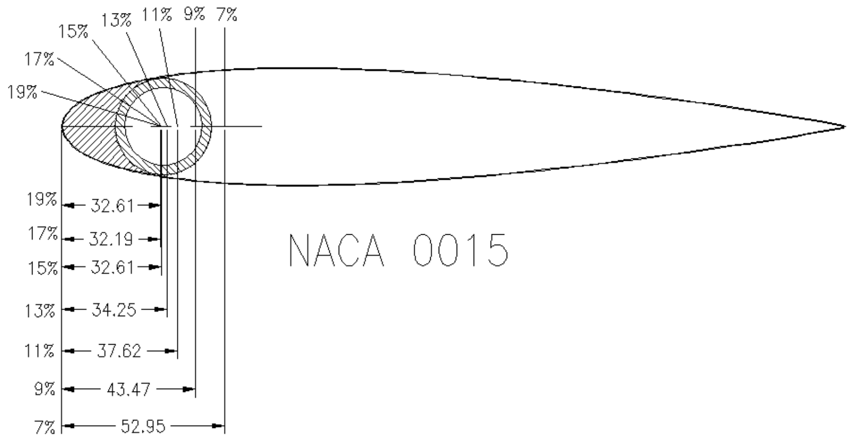


Figure 33. Basic design

The analysis was also extended to consider the effects of friction between the blade sleeve-tube and the (bushing) bearing surfaces of the blade axle which provide support against the bending moments. The contact surfaces can be limited to the top and bottom bushings as shown in Figure 34. The tensile stresses supported by the torsion (i.e., the pivot axle) must also consider the centrifugal forces on the torsion bar in order to determine a more accurate safety factor for the mechanical design. The result of this feasibility analysis is shown in Figures 35a & b, where it may be observed that the safety factors for the blade axle (i.e., the support post) are generally above 1.5, with a blade deflection less than 0.2 % for all pivot axle locations greater than 13% of chord length for the NACA 0015 airfoil. These results are more acceptable than for the NACA 0020 airfoil, which is the rationale for focusing on the NACA 0015 airfoil in all future design analyses. Similarly, the safety factor for the torsion bar (i.e., the pivot axle) is above 1.5 for all pivot axle placements above 7%, as may be observed from Figures 35a & b. Ultimately, a pivot location of 13% was chosen.

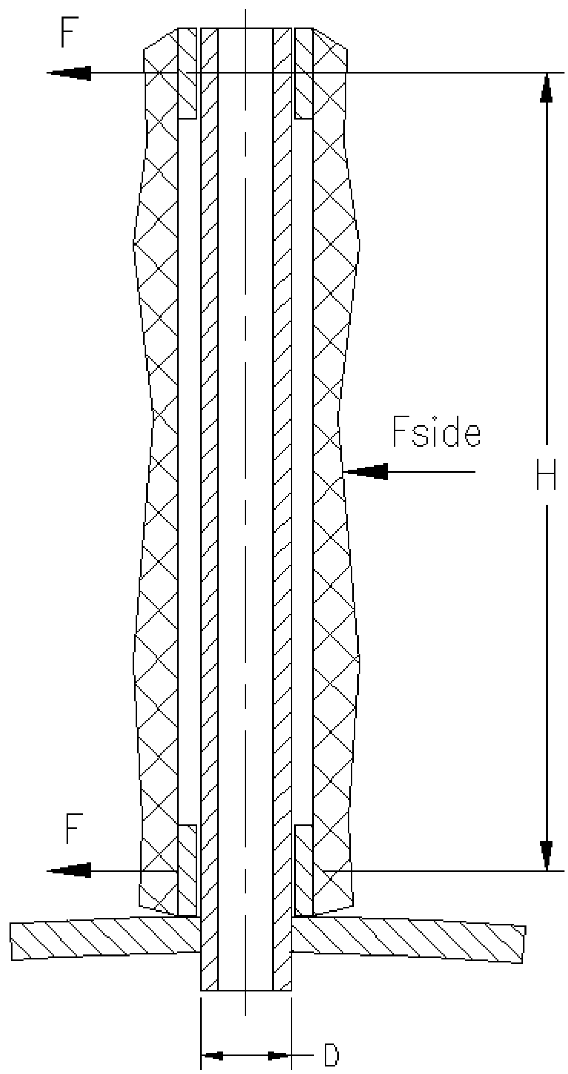


Figure 34. Contact surfaces on top and bottom bushings

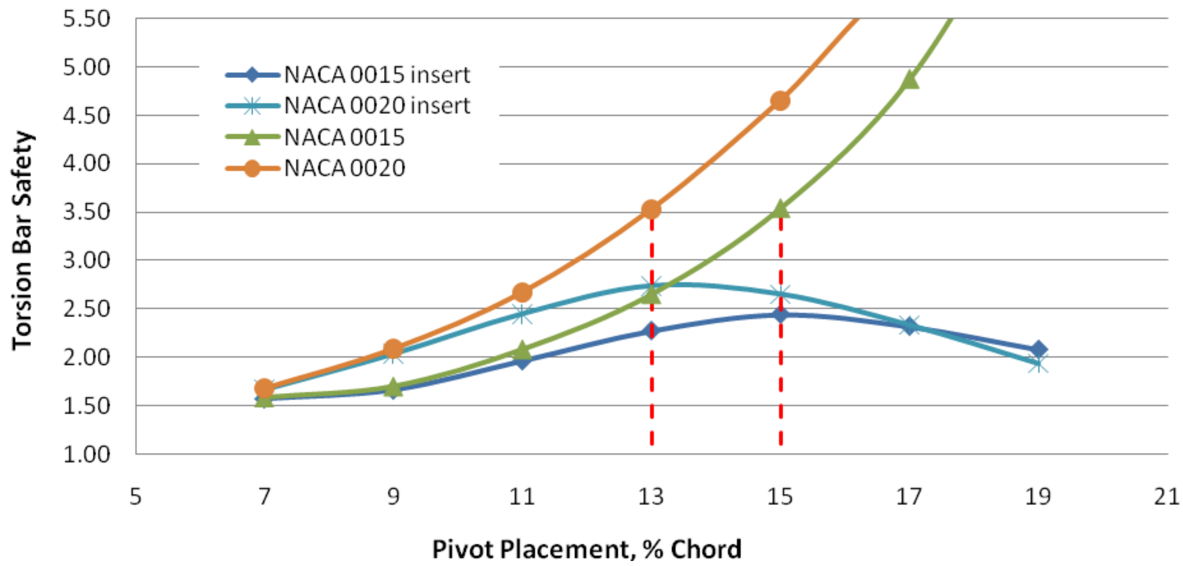
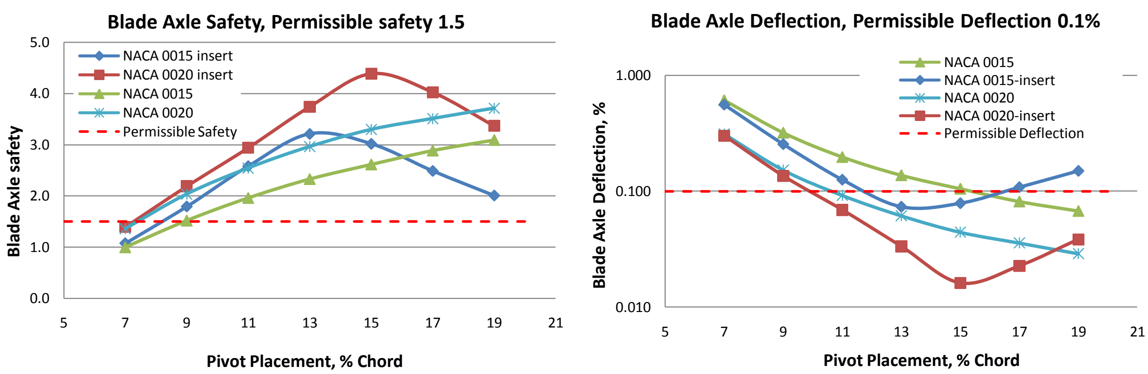


Figure 35a. Torsion bar feasibility
DIA min 7.0 mm, length range 300-1050 mm



- Heavy nose NACA 0015 Profile is working at pivot placement in the range 13%-16% of chord (deflection is lower than 0.1%)
- Heavy nose NACA 0020 profile is working starting from pivot placement at about 10% of cord (deflection is lower than 0.1%)
- Hollow NACA 0015 profile is working starting from pivot placement at about 15% of cord (deflection is lower than 0.1%)
- Hollow NACA 0020 profile is working starting from pivot placement at about 11% of cord (deflection is lower than 0.1%)

Figure 35b. Torsion mechanism feasibility
heavy nose and hollow blades comparison

An analysis was done to determine the blade materials that would enable the center of gravity for the blade to be positioned as close to if not directly on the pivot axle for the blade. The analysis shown in Table XI is a summary of that analysis. The results indicate that the pivot placement at 13% of the chord length could be achieved if the nose of the airfoil could be filled with steel or tungsten.

TABLE XI. SUMMARY OF ANALYSIS TO DETERMINE BLADE MATERIAL

Torsion Mechanism with Heavy Nose Blade

	Pivot Placement	%	11	12	13
	Torsion Rod DIA	mm	7.54	7.54	7.54
	Axle DIA	mm	26.5	27.5	28.0
	Blade Mass	kg	0.333	0.340	0.343
Tungsten Insert	Insert DIA	mm	12.0	12.7	12.0
	Insert Mass	kg	0.534	0.595	0.534
	Blade Assy CG	%	12.6	12.1	13.0
	Axle Deflection	%	0.084	0.086	0.061
	Torsion Rod LG	mm	510	545	625
Lead Insert	Insert DIA	mm	12.7	14.5	16.0
	Insert Mass	kg	0.400	0.522	0.590
	Blade Assy CG	%	14.5	13.2	13.0
	Axle Deflection	%	0.095	0.069	0.061
	Torsion Rod LG	mm	507	555	625
SS Insert	Insert DIA	mm	12.7	14.5	16.0
	Insert Mass	kg	0.283	0.368	0.478
	Blade Assy CG	%	16.81	15.48	14.3
	Axle Deflection	%	0.1	0.079	0.064
	Torsion Rod LG	mm	515	567	630

Subsequent analysis determined that a steel or lead rod insert could also be used if the airfoil hollow blade could be manufactured using injected liquid foam that hardens when cured, as illustrated in Figure 36. The hard foam would be mechanically reinforced with very thin steel ribs. The ribs would be evenly spaced along the interior of the hollow blade before the liquid foam is injected into the hollow blade core and allowed to solidify. Although this design is considered feasible using current state-of-the-art materials and manufacturing techniques, the final design and manufacturing of a prototype airfoil using this composite assembly is a goal of the Phase II SBIR. Several versions of the composite airfoil will be constructed and individually tested in Concepts NREC's wind tunnel test facility to measure their mechanical integrity when exposed to high air forces.

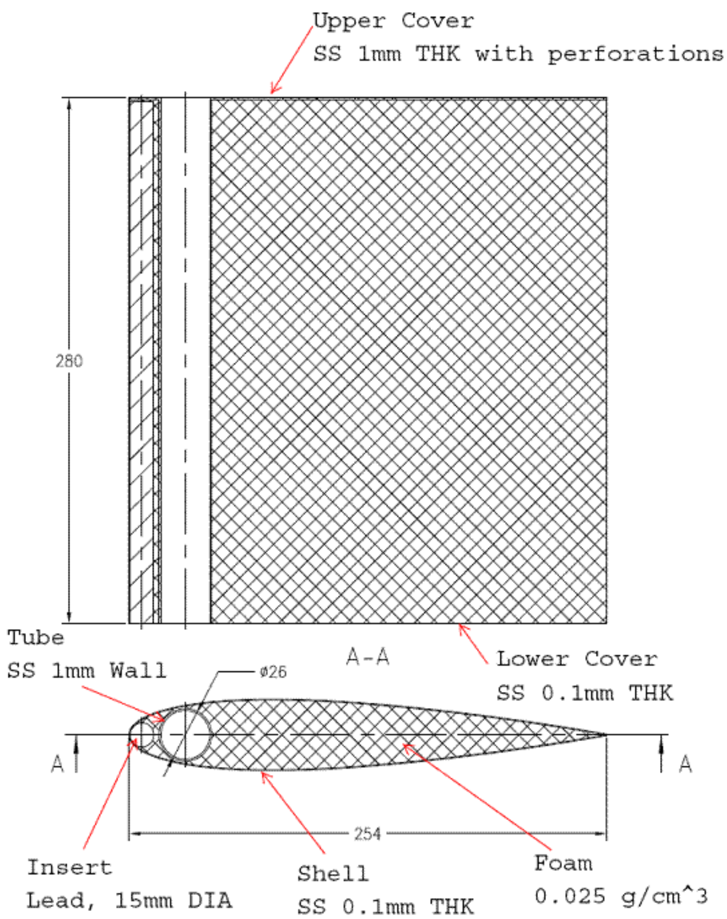


Figure 36. Steel or lead rod insert used with an airfoil hollow blade injected with liquid foam that hardens when cured

Conclusions from Feasibility Analysis

The conclusions from these feasibility studies of the mechanical design for the self-articulating blades using hollow and "heavy nose" airfoils is presented in Figures 37a & b.

- Round section Torsion Bar is feasible at pivot placements in the range of 7%-15% of chord for NACA 0015 and 7%-13% for NACA 0020
- Torsion mechanism is feasible for light hollow aluminum blades (wall thickness 0.25 mm) with soft foam filling. Blade weight is about 500-700 gram.
- Hollow NACA 0015 blade is working only at pivot placement 15% of chord (axle deflection lower than 0.1%)
- Hollow NACA 0020 blade is working at pivot placement in the range of 11% -13% of cord (axle deflection lower than 0.1%)
- Combined section hollow blades don't show significant advantages from mechanical point of view comparing base blades. (0015/0020 vs. 0020 and 0015/0025 vs. 0025)
- Blades made from rigid foam (density 0.15-0.3 g/cubic cm) are working as hollow blades
- Using heavy nose blades makes torsion mechanism feasible for heavier blades. (1.1kg-1.75 kg for NACA 0015 and 0.95kg-2.35kg for NACA 0020

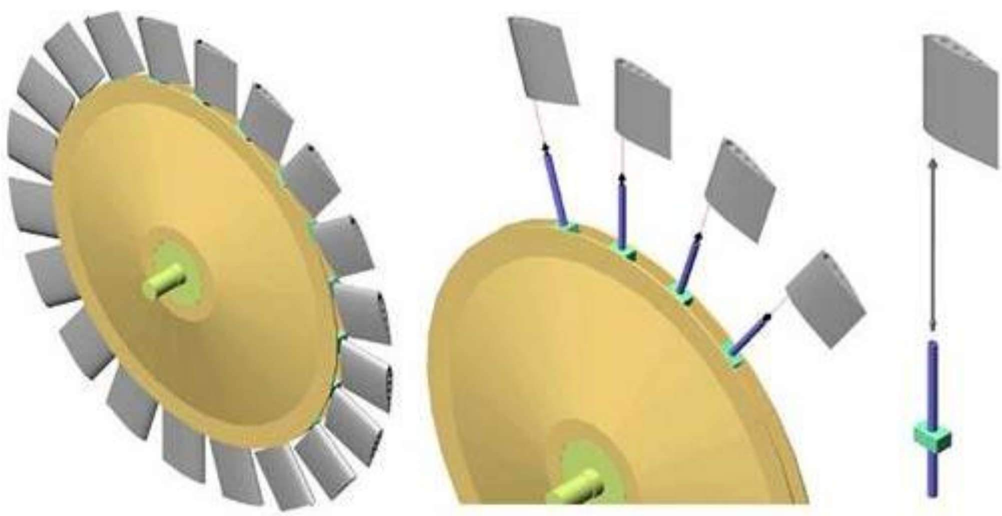
Figure 37a. Torsion mechanism feasibility, conclusions 1

- NACA 0015 heavy nose blade is working at pivot placement in the range of 12%-15% of chord (axle deflection is lower than 0.1%)
- NACA 0020 heavy nose blade is working at pivot placement in the range of 10%-13% of chord (axle deflection lower than 0.1%)
- NACA 0020 light hollow blade is working at pivot placement in the range of 11%-13% of chord (axle deflection lower than 0.1%)
- NACA 0020 light hollow blade may be a candidate for prototype.
  - complicated design
- NACA 0020 light blade, made from skinned rigid foam or using fiber glass technology with metal tubular insert or without it may be candidate for prototype design.
  - more simple design
  - mature technology
- NACA 0015 and NACA 0020 metal, shelled heavy nose blade are also candidates for prototype.
  - more ridged, reliable design
  - but more complicated (involve welding, brazing, inside support structures)
- NACA 0015 or NACA 0020 blade made from skinned rigid foam with heavy nose insert may be the best candidate for prototype.

Figure 37b. Torsion mechanism feasibility, conclusions 2

2.4 Conceptual Rotor Design and Single-Blade Prototype for Proof-of-Principle Phase I Lab Test

Based on the feasibility analysis performed to date and summarized here, several blade modules have been conceptualized that can be manufactured inexpensively. These are shown in their various degrees of development in Attachment No. 1. A down-select was performed on the blade module and integrated with a rotor design. This is shown in Figures 38a, b, and c, respectively, and Figure 39.



Figures 38a, b, & c. Results of down-select on blade module integrated with a rotor design

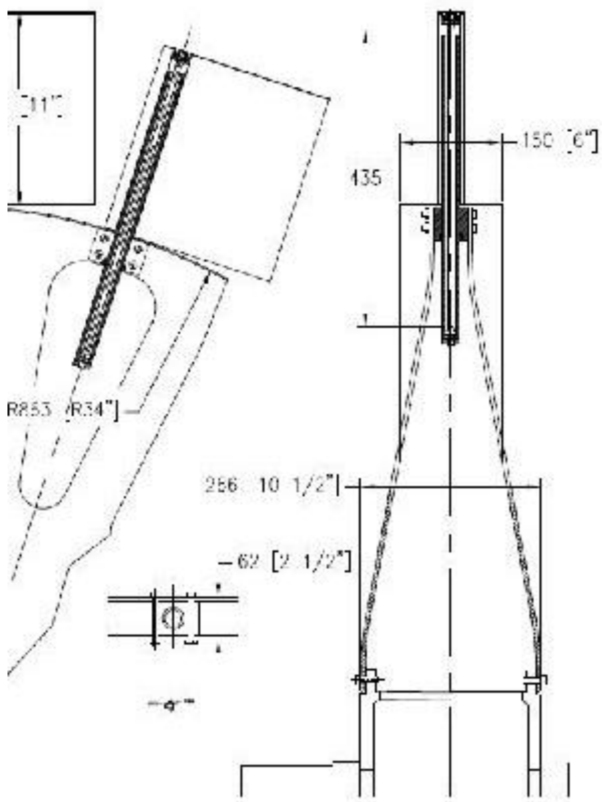


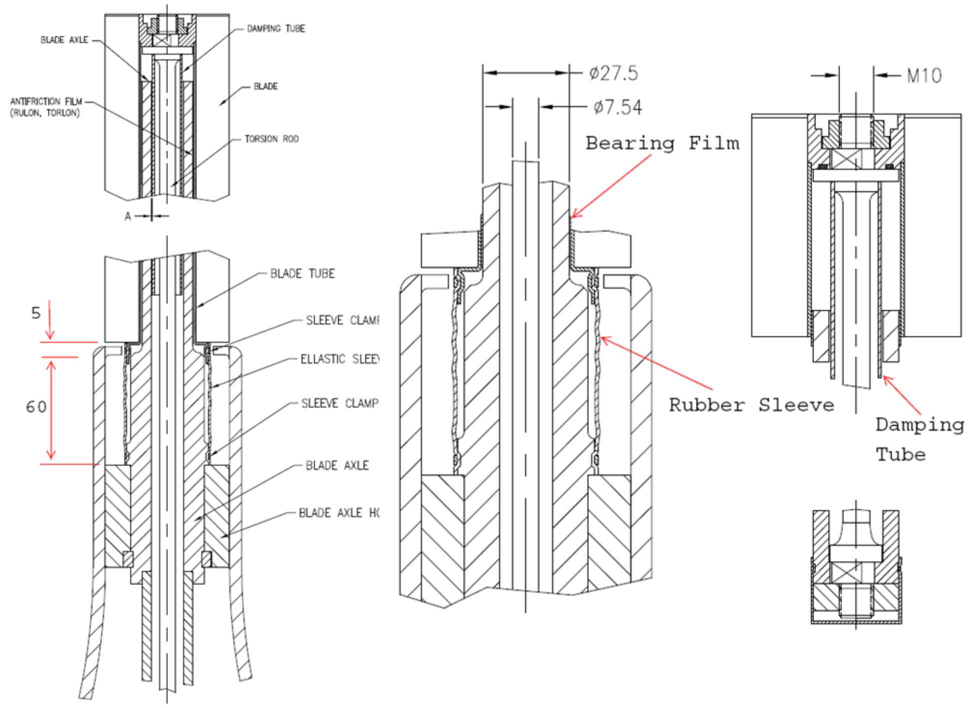
Figure 39. Illustration of self-actuated blade articulation system installed into Wells Rotor using steel stampings instead of castings to reduce cost

The 1.25-kg blade assembly shown in Figure 36 is fitted with a torsion rod and two clamps that enable it to be assembled into a complete self-actuated articulating blade assembly, as shown in Figure 39. This assembly is then ready to be inserted as a complete fabricated module into the OWC rotor as shown in Figure 38.

The blade module is composed of an elastomeric sleeve seal that completely isolates the internal passages from the external environment. A close-up of this seal assembly is shown in Figures 40a, b & c. The sleeve seal is clamped to the bottom stationary body of the blade module that is, in turn, fixed to the rotor rim. The seal need only articulate by +/- 15 degrees, and thus, can easily flex in response to the constant articulation while maintaining the sealing integrity required to prevent internal lubrication from leaking from the module. A damping tube has been added to the top of the blade which will use the constrained grease to provide some damping of the blade vibration.

As illustrated in Figure 40a, the blade articulation mechanism is secured to the rotor body which is, in turn, secured via a hub that holds the drive shaft. The rotor body will be manufactured using a metal stamping process in order to reduce the cost of the rotor. A complete Bill of Materials and dimensioned drawings for a self-actuating mechanism that is suitable for a 300 kWe-rated turbine is given in Attachment No. 2 of this final report.

The detailed design includes a flexible elastomeric sleeve seal, shown in Figures 40a & b, that prevents the leakage of any sliding surface grease from escaping from the inside of the sealed system. The sleeve seal enables lubrication to be used not only to provide low friction between the contact bushing surfaces, but also to enable the grease to serve as a damping fluid. The damping will prevent the unwanted high frequency movement or induced vibration of the blades that could be caused by the sudden changes in the air flow rate through the turbine. The elastomeric seal is ideal for this application given that the blade axle articulation is only +/- 15 degrees and never a complete revolution.



Figures 40a, b, & c. Detailed design of blade articulation mechanism

Based on the feasibility studies, a detailed design of the self-actuated blade articulation system was prepared in order to assemble a laboratory prototype. The complete assembly is shown in Figure 41. A Bill of Materials (B.O.M.) and a complete set of dimension parts that make-up the entire assembly was prepared and issued to vendors for their costs to produce these items. The lowest manufacturing cost for the laboratory prototype axle and torsion rod assembly was $1,215 for an order of one set. A rapid prototype production of the NACA0015 solid blade was $250 and was used in lieu of manufacturing a composite airfoil. One manufacturer did quote $365 a partial order for Items 1, 2, and 3 of the Blade Assembly (see Attachment No. 1 of this report).

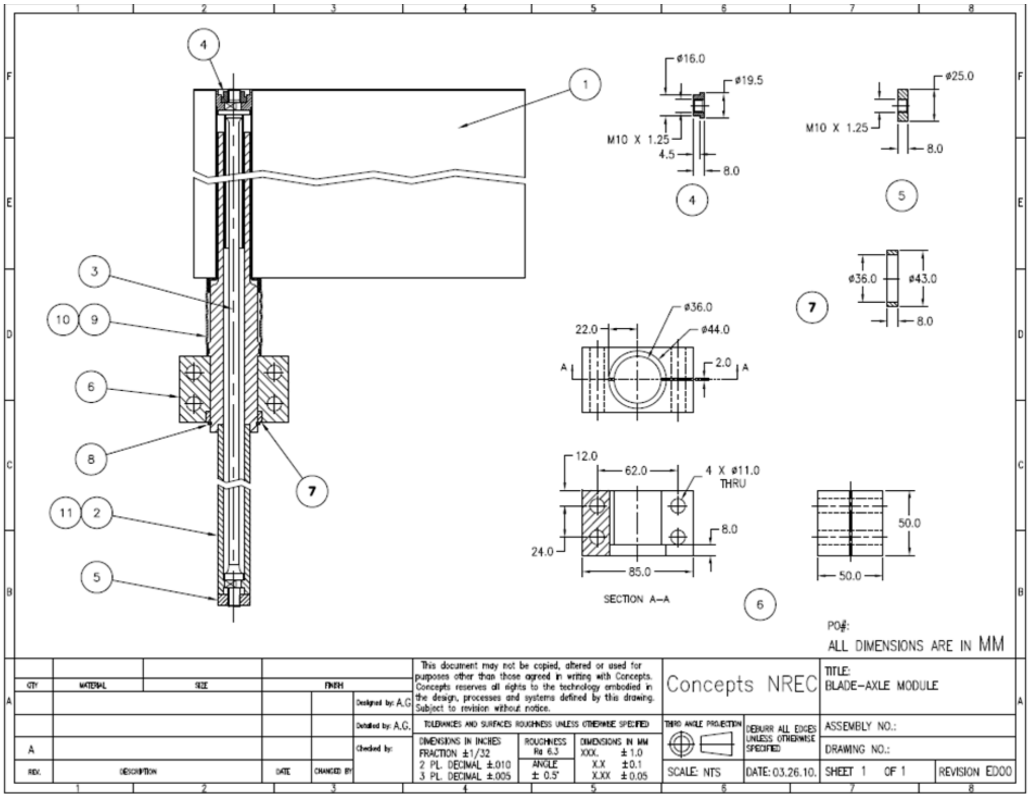


Figure 41. Detailed design planned for prototype test in Woburn or Wilder

The laboratory prototype self-actuating assembly mechanism prepared for the Phase I SBIR wind tunnel tests is shown in Figure 43 along with the *CN* wind tunnel shown in Figure 42. The single blade self-actuating mechanism shown in Figure 43 is a full-size prototype for a 300 kW turbine and would be one of 15 blades required to complete the rotor. The wind tunnel testing continues as of this writing. The measured torque vs. angular displacement for the prototype (torsion bar-based) blade articulation mechanism is given in Figure 44. The results indicate that the torsion stiffness is too high for the extreme angular displacements (angle of attack) of the airfoil. This can be solved by using either a tapered or different size diameter for a fraction of the total length of the torsion rod or an internal mechanical stop that allows two different torsion stiffnesses to be incorporated into the mechanism.

Figure 42 & Figure 43. Concepts NREC's wind tunnel (left), Laboratory prototype self-actuating assembly mechanism (right)

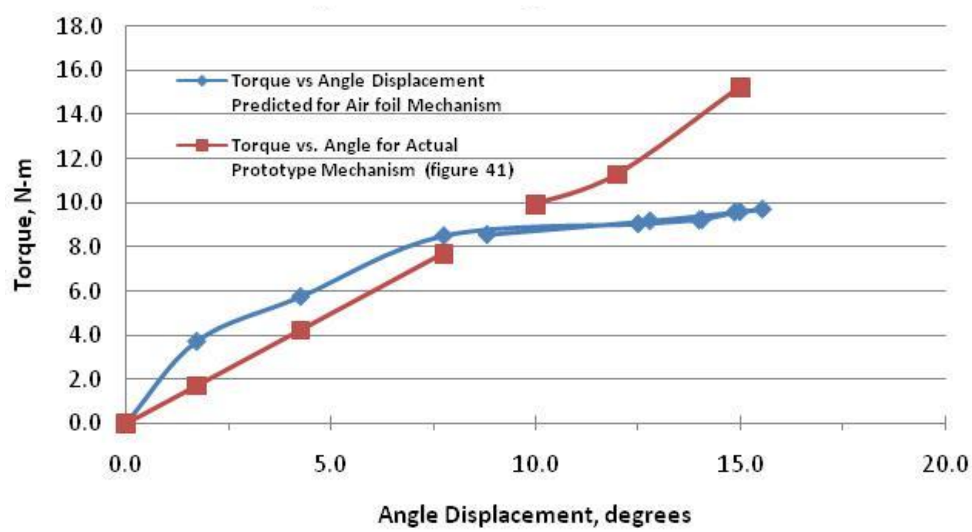


Figure 44. Torque-angular displacement required for airfoil vs. actual torque-displacement as measured for fabricated lab prototype self-actuating blade mechanism

Some design issues to consider in Phase II SBIR effort are:

1. Can the SST skin of the blade be increased to make it easier to handle during assembly without adversely affecting the pivot location?
2. “Shape” the torsion-angular displacement to better match the airfoil torsional-angular displacement that is needed.
3. The blade cap should be able to fasten on the entire blade profile in order to help reduce the shearing load on the interface between the foam core and the blade tube, and the foam core must be able to “wet” and/or secure itself to the blade tube via serrated or roughened surface, for example.
4. The elastomeric sleeve seal is a good idea, but does it need to be 60-mm long, given that the articulation is only 15°?
5. The metal insert is better/less expensive than the full-blade nose insert. However, the material of choice could be inexpensive but still very dense tungsten power-fused into a hard nose to be viable from the standpoint of the necessary pivot location.
6. Is there any advantage to the “blade weight issue” if the torsion rod and the blade skin material are made of carbon-reinforced material? This material is strong and light.

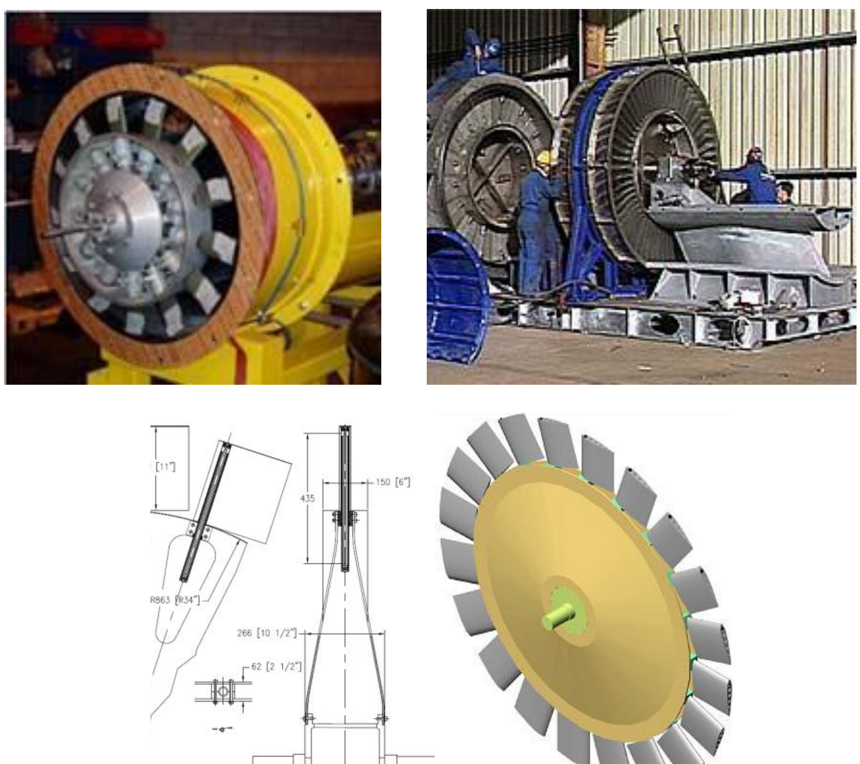
2.5 Incremental Simple Payback Economics for Component Modifications

Concepts NREC has researched the cost for producing many types of air turbines used in renewable energy recovery. The three types of air turbines used in OWC water energy conversion include the basic Wells turbine, the Dennis-Auld turbine, and impulse-type turbines. The Wells and Dennis-Auld turbines represent the extremes in the available efficiency, cost, and mechanical reliability. The fixed-blade Wells turbine is generally considered to be robust while relatively inexpensive compared to the Dennis-Auld turbine. However, as indicated in this proposal, based on *CN*’s experience and confirmed in the technical literature by independent researchers, the Wells turbine can be relatively inefficient in OWC applications if it has a fixed blade and if the air flow rate (hence, air velocity) is fluctuating. As shown in Figure 9, the operating air flow rate range of the Wells turbine is relatively small compared to an impulse or Dennis-Auld type. As has been demonstrated in this proposal, it is for this reason that the proposed self-actuated blade articulation modification to a basic design of a Wells turbine is beneficial from a performance point of view. Similarly, it is shown in this section that the incremental simple payback for these mechanical modifications also improves the first time cost ($/kW) of the OWC by 24%. This is due to the large efficiency improvement expected of the modified Wells turbine which can be shown to exceed the increase in the cost of the mechanical self-actuated blade articulation mechanism that must be added to the turbine.

To demonstrate this cost benefit, two tables are presented that together provide a consistent summary of the cost modifications of the turbine and then their combined effects on the overall cost of the OWC system in terms of cost per kW delivered or $/kW.

Table XII presents a side-by-side comparison of the subsystem costs that constitute the baseline Wells turbine, the self-actuated blade articulation Wells turbine, and the Dennis-Auld turbine. These costs were derived from the cost estimates that have been inventoried by *CN* for the Dennis-Auld turbine and the recent costs obtained from the manufacturers of the prototype self-actuated blade articulation mechanism developed in Phase I of this SBIR. Where possible, the costs for the modified Wells turbine subsystems have also been given a low, medium, and high cost estimate based on the multiple vendors that responded to *CN*'s request for budgetary estimates.

It is somewhat helpful to show the relative complexity of these three types of turbines in order to help assess the accuracy of these cost estimates. For this purpose, Figures 45a, b, & c are offered as representative designs that reveal their relative manufacturing complexity.



Figures 45a, b, & c. Images of Wells-type Air Turbines: electro-mechanical hydraulic powered variable pitch (top left), b. fixed-blade (top right, and Concepts NREC's proposed self-actuating blade articulation with stamped/forged rotor body (bottom). (NOTE: Dennis-Auld turbine is shown in Figure 4)

The high cost estimate to manufacture the composite airfoil blade, as described in the previous section, was assumed to be twice the cost of producing a solid aluminum, symmetric profiled, Wells turbine blade.

Using these high and low estimates, a standard deviation (σ) and variance (σ^2) was determined for each constituent turbine subsystem. The variances were totaled, and an overall standard deviation for the modified Wells turbine was determined. This resulted in a 99+% confidence that a Wells turbine that is modified to use a self-actuated blade articulation system would have a cost between $94,000 and $107,000, as shown in Table XII.

TABLE XII. MANUFACTURING COSTS FOR SELF-ACTUATING BLADE ARTICULATION ROTOR

OWC Cost/kw 6000
Fraction of Total $ OWC for Turbine= 4.7%

		Conventional, fixed Blade Wells Turbine	Concepts NREC Self-Articulating Wells Turbine				Dennis-Auld Turbine	
		Middle Est.	Low Est.	Middle Est.	High Est.	Variance σ^2	Power Rating , kW 750	350
10%	Brake System	$ 10,303	$ 10,303	$ 10,303	$ 10,303	$ -	$ 12,000	$ 10,303
17%	Drive Shaft Bearings	$ 17,185	$ 17,185	$ 17,185	$ 17,185	$ -	$ 21,600	$ 17,185
15%	Rotor Body	$ 14,753	$ 11,803	$ 11,065	$ 14,753	$ 241,848	$ 7,500	$ 6,440
20%	Rotor Body Mach.ing	$ 14,718	$ 3,311	$ 3,679	$ 7,359	$ 455,022	$ 16,500	$ 14,718
10%	Blades	$ 9,579	$ 9,579	$ 14,368	$ 19,158	$ 2,548,805	$ 21,000	$ 18,031
0%	Blade Articulat. Sys.	$ -	$ 15,491.25	$ 18,225	$ 21,870	$ 1,130,235	$ 60,000	$ 40,988
17%	Shaft (Matl. &Mach.)	$ 16,679	$ 16,679	$ 16,679	$ 16,679	$ -	$ 18,000	$ 16,679
0%	Articulation Control	$ -	$ -		$ -	$ -	$ 54,000	$ 54,000
10%	Misc.	$ 9,836		$ 9,151		$ -	$ 20,000	$ 15,000
			$ 84,352	$ 100,656	$ 107,308	$ 4,375,910		
100%	Turbine System Cost=	$ 98,356	Low		High		$ 230,600	$193,344
	(without Generator)		$ 98,564	1-sigma(σ)	$ 102,748			
			$ 96,473	2-sigma(σ)	$ 104,840			
			$ 94,381	3-sigma(σ)	$ 106,932			

Table XIII was derived using published data (Ref. 40) on the average cost of the subsystems that constitute a complete off-shore OWC system. Using the incremental cost of $10,000 (9%) for a self-actuated blade articulation system added to the Wells turbine, an incremental simple payback of only 0.15 year is calculated, as shown in Table XIII. More important, however, is the significant reduction in the first-time cost or $/kW for the OWC system of 22% using a conservative turbine efficiency of only 25% (and not the high 40% as projected by some independent researchers). This is more significant, because it reduces the overall Simple Payback for the system by an equivalent amount, thus making the OWC system more attractive to the entrepreneurial user of wave energy renewable energy systems.

TABLE XIII. SIMPLE PAYBACK ANALYSIS FOR OWC SYSTEM MODIFICATIONS AND ENERGY IMPROVEMENTS COMPARING FIXED BLADE (BASELINE) WELLS TURBINE WITH SELF-ACTUATED BLADE ARTICULATED WELLS TURBINE

(Ref: Carbon Trust Marine Energy Report, page 283, averages from 3 OWC systems)

			Component Costs			$cost adder for Additional Component(s)	% Improvement Energy Recovery
			Baseline $ Cost	+ or - % change	$ Final Cost		
System Availability, %	85%						
OWC Base Cost , $/kWe	6000						
Kwe=	350						
OWC Cost	$ 2,100,000						
Mechanical & Electric Systems, %	20.0%		$ 420,000				
Generator & Switchgear		2.5%	$ 52,500	0.00%	$ 52,500	$ -	1.0%
Turbine		4.7%	$ 98,356	8.7%	$ 106,932	$ 8,576	25.0%
Diffuser & Inlet Guide Vanes		1.5%	$ 31,500	0.00%	$ 31,500	$ -	0.0%
Structural Framework		5.0%	$ 105,000	0.00%	$ 105,000	$ -	0.0%
Controls		6.3%	$ 132,644	0.00%	$ 132,644	$ -	0.0%
Installation, %	15.0%		$ 315,000				
Mechanical		10.0%	$ 210,000	0.0%	$ 210,000	$ -	0.0%
Electrical		5.0%	$ 105,000	0.0%	$ 105,000	$ -	0.0%
Vessel Construction, %	25.0%		$ 525,000	0.0%	$ 525,000	$ -	
Electrical Trans., %	15.0%		$ 315,000	10.0%	$ 283,500	$ -	0.0%
Contingencies, %	10.0%		$ 210,000	0.0%	$ 210,000	$ -	
Transportation, %	15.0%		$ 315,000	0.0%	$ 315,000	$ -	0.0%
	100.0%		$ 2,100,000		$ 2,077,076	$ 8,576	

NET OWC Cost Savings,%	1.09%	Energy Improv.=	26.0%
NET Effective $/kWe=	4,710		
Net Improvement, $/kWe %=	21.5%		
$O&M=	0.02	$/kwH	
$finance=	0.06	$/kwH	
$/kWh)income=	0.15	$/kWh	
Yearly Income=	$ 225,660		
Incremental Simple Payback=	0.15	years	

3.0 Phase II Work Plan

Project Title: Development of Wave Energy-Responsive Self-Actuated Blade Articulation Mechanism for an OWC Turbine-Prototype Fabrication and Wind Tunnel Lab Test

3.1 Project Objectives and Concept Description

An oscillating water-air column (OWC) is one of the most technically viable and efficient options for converting wave energy into useful electric power. However, there is a need to increase the overall energy conversion efficiency of the OWC system from its current 25% efficiency to improve the economics necessary for an OWC to compete effectively with other alternative forms of renewable energy. A potential improvement of as high as 30% in wave energy recovery has been determined by Concepts NREC based on its thermo-fluids computational model of an OWC system. The exact amount of improvement is dependent on the off-design operation of the OWC as it attempts to recover energy from a wide range of wave energy that is incident on the OWC system. Concepts NREC has worked with Oceanlinx Ltd., a world renowned developer of OWC wave energy converter systems, under private contracts to advance the design of Oceanlinx's unique turbine for its OWC systems in order to achieve this improvement. Concepts NREC has complemented this contracted engineering study with its own research to determine options for increasing the power conversion efficiency of an OWC over a wider range of water wave energy intensities while exploring options for new turbine designs. The proposed work for this SBIR Phase II effort is a result of Concepts NREC's research in Phase I of the SBIR.

The primary objective of Phase II is to design, fabricate, and test a 15 kWe prototype rotor design that utilizes the wave-responsive, self-actuating turbine blade articulation mechanism that was conceptually designed during Phase I based on an engineering feasibility analysis. An illustration of the rotor design using an easily installed, and hence, interchangeable Self-Actuated Blade Articulation Mechanism is shown in Figure 46 below. The self-actuating aspect of the blade articulation is caused by the aerodynamically induced pressure distribution across the blade to create a self-stabilizing blade profile that results in maximizing the turbine performance under varying flow conditions. Specific issues that were addressed in Phase I included: a. What are the critical design parameters of each subsystem that impact the overall system performance? b. What is the desired blade profile and pressure distribution at each flow condition that will result in peak performance? c. What are the primary design issues that must be overcome to translate the pressure distribution into an associated blade pitch and contour? and d. Can the blade design be made self-stabilizing over the operating range of air flow rate generated in a 350 kWe Oscillating Water Column wave energy conversion system?

The Phase I feasibility analysis and detailed engineering design was successful in demonstrating the viability and effectiveness of a bi-directional turbine rotor to withstand the aero forces and rotor torque that are prevalent in a 350 kWe water wave energy conversion system. A detail of the blade articulation mechanism that was built for the Phase I SBIR for proof-of-concept testing and costing is shown in Figure 47. The Phase I work also included satisfying Design for Manufacturing and Assembly criteria, wind tunnel testing to verify aerodynamic forces, and cost estimates for the self-actuating turbine blade articulation mechanism.

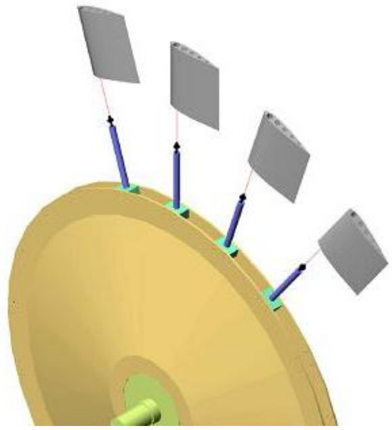


Figure 46. Rotor design with interchangeable self-actuated blade articulation mechanism

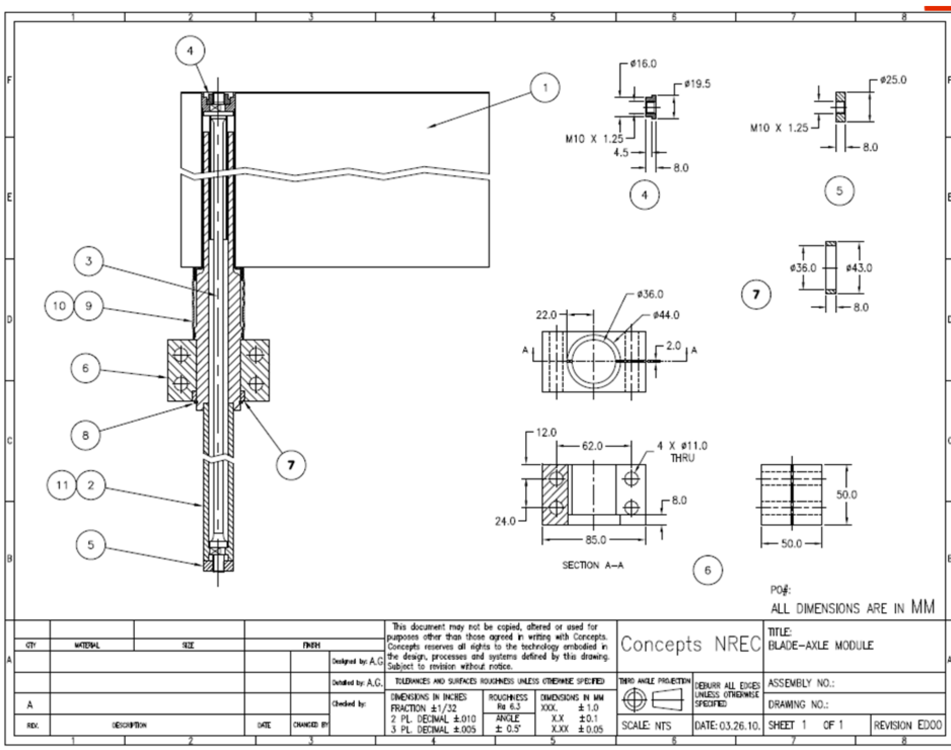


Figure 47. Detailed design of the blade articulation mechanism

During the first year of Phase II of the project, Concepts NREC is proposing to design, fabricate, and instrument for laboratory testing a complete 15 kWe prototype turbine rotor-generator that uses the Self-Actuated Blade Articulation Mechanism that was conceived during the Phase I SBIR. During the design effort, *CN* will use its small wind tunnel test facility to continue the testing of the single, self-actuating blade articulation unit that it began testing during the SBIR Phase I. The 15 kWe rotor will be approximately 3 ft. in diameter and will operate at 700 rpm. A major focus of the engineering effort will be the determination of the best mechanically robust airfoil composite design that will be an integral part of the Self-Actuated Blade Articulation Mechanism. During the second year of the Phase II project, the prototype turbine will be tested in the MIT Wright Brother's wind tunnel in a series of well-defined tests, in order to determine the turbine's aerodynamic performance and mechanical integrity. Based on these test results, a redesign of the blade actuation mechanism will be performed to eliminate any weak points of the turbine design. A full report of the test results will be prepared, and a technical research paper will be authored to disseminate the results. During the second half of Year 2 of Phase II, a full-scale 350 kWe turbine rotor will be designed that can be used in Phase III of the project. The fabrication of the turbine rotor will be completed in Phase III of the project, and assuming that Oceanlinx's Maui facility is operational and that the testing can be fit into Oceanlinx's schedule, Oceanlinx is agreeable to testing the turbine. Concepts NREC will also contact other possible users of advanced Wells turbines to determine whether Concepts NREC's innovative turbine design can be tested with established OWC on-shore testing facilities such as the Limpet in Scotland or the Pico system in the Azores. Certainly, this can only be done in coordination with DOE's interest and the support of these facilities.

3.2 Commercial Plan

Summary of Commercialization Plan for Self-Actuating Blade Articulation Rotor System

Since its inception in 1980, thousands of advanced turbomachinery products have been successfully developed and integrated into products brought to the marketplace by both *CN* and our customers, whose designs were developed by *CN* through private business contracts. This must also include the worldwide marketing and sales of the CFD turbomachinery software that is almost universally accepted as the leading turbomachinery design and analysis software on the market. Based on its marketing efforts for its software sales, the company has also prospered as a product engineering and development organization, as software customers recognize the strength of the company's experience with a wide variety of energy utilization applications. As a result, the company is exposed to new and relevant technology opportunities and is well-positioned to capitalize on new business opportunities. In this regard, Concepts NREC is already teamed with Oceanlinx Ltd. and several confidential entrepreneurs to develop OWC and hydrokinetic energy systems to not only develop the engineering and testing of the renewable energy technology, but also bring it to the market in a well-orchestrated fashion.

Concepts NREC has collaborated with Oceanlinx Ltd. for several years in their development of a viable water wave energy conversion system. Oceanlinx Ltd. is a world-renowned developer of an Oscillating Water Column-type water wave energy system. Oceanlinx is proceeding to deploy their Mark 3 (Mk3) OWC system (2.5 MWe net) off the coast of Maui, Hawaii, in 2011. Concepts NREC's proposed innovation of using the aerodynamically induced forces produced by the variable air flow across the blades during each wave cycle to articulate a turbine rotor blade will reduce the complexity, and hence, the cost of the OWC turbine rotor while also increasing the turbine efficiency. The result is expected to be a per kW cost ($/kW) reduction of the OWC system by as much as 40%. This cost reduction is significant for the OWC WEC renewable energy system, typically $5,000 to $6,000/kWe for each of the first production systems.

The work in progress with Oceanlinx is an example of the first phase of successful commercialization of an OWC system. This prior privately funded effort is the strongest evidence of Concepts NREC's intent to commercialize this and similar renewable energy systems. The Phase I effort has succeeded in identifying a very viable advanced Wave Energy Conversion opportunity: a self-actuated blade articulation system for a Wells turbine that can improve the OWC system economics by increasing the turbine's weighted efficiency by as much as 40%. This has the net effect of reducing the OWC first-time capital costs, while confirming the robustness of the system.

Through the work completed in the Phase I effort, the proposed design of a turbine shutter prototype and validation testing of this technology in Phase II, Concepts NREC will have a well-documented and established technical foundation from which to incorporate this adaptive turbine technology into the next generation OWC systems, starting with the Oceanlinx Mk3 2.5 MWe OWC system, which is planned and permitted for in-water testing in Maui, Hawaii. After completing the Phase II SBIR study, the self-actuated blade articulation system will be manufactured by Concepts NREC and made available for use with Oceanlinx's Mk3 (350 kW) OWC modular wave energy recovery systems, as well as other on or off-shore OWC facilities.

With the success of **Phase I: The mechanical design and partial testing of a Self-Actuated Blade Articulation Mechanism**, followed by the successful implementation of **Phase II: The construction and wind tunnel testing of a scaled turbine rotor that will confirm the efficiency and wider operating range of the Wells turbine**, the self-actuating mechanism will have been validated as a viable blade articulation mechanism for a less-expensive Wells-type turbine.

The next step would be to manufacture a full-scale, 350 kWe rated rotor for its use in the Oceanlinx Mark 3 OWC system. The Mark 3 OWC system, as it currently stands, consists of six identical 300 kWe OWC modules. One of these 350 kWe modules can potentially be outfitted with the full-scale rotor for its Beta-test in full operation. This is expected to occur after Phases I and II have been completed and capital can be obtained to construct the new rotor. This is likely to occur in or about 2012. The IP for this innovation in blade articulation and control is retained exclusively by Concepts NREC, but will be licensed to Oceanlinx as an active and early collaborative partner in its developmental testing. Thus, once demonstrated as a viable system for water wave energy OWC systems, it is anticipated that the use of the innovation via licensing rights to the patent will garner interest from other OWC developers.

The principal concept of using the aerodynamic forces to help articulate the rotor blade into an optimum position for rotor torque production is thought to also be applicable to slower, larger wind turbines. Thus, the success of this DOE development program will also encourage interest with developers of the more traditional land-based wind turbines.

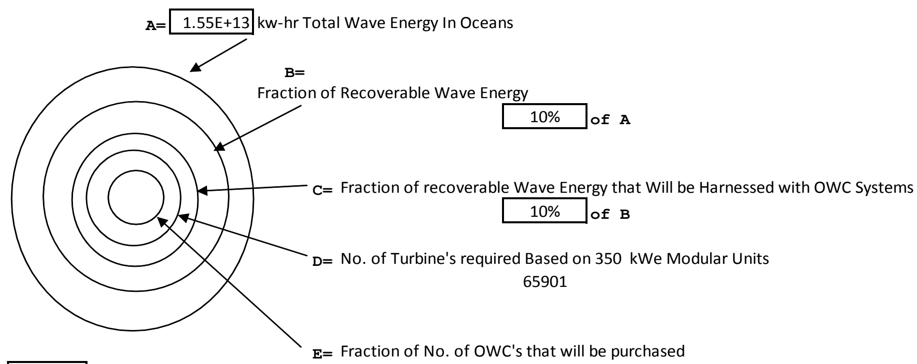
4. Market Opportunity

4.1 Addressing Market Opportunities with Concepts NREC's Technology Innovations

A 2003 study by The Carbon Trust entitled: "Oscillating Water Column (OWC) Wave Energy Converter (WEC) Evaluation Report" (Ref. 40) suggested that the goal of reaching a competitive price for the generated electric power from an OWC system would require "…a combination of capture efficiency being increased by 10% to a (net) of 52%" after considering the electric power turbine-generator efficiency into the net calculation of wave energy to useful electric power. The cost of a first (prototype level) OWC system is relatively high at $6,000 to $8,000 per kW, while future economy of scale units rated up to 23 MW are estimate to have a projected capital cost of $4,000 per kW (Ref. Carbon Trust Report). Increasing the capture efficiency has the largest impact on decreasing the cost per kW ($/kWe) for the OWC system. The self-actuated blade articulation modification to a basic Wells turbine is thought to enable as much as a 40% increase in efficiency, and thus a reduction in the cost per kWe ($/kW) of 20 to 22%. This reduction is over twice what was identified by the Carbon Trust Report as necessary to achieve commercial success for a OWC-type water energy conversion system.

The reduction in the first-time-cost $/kWe is essential if the economics of a wave energy conversion device that uses the oscillating water column (OWC) principle is to be high enough for its adaptation. The overall wave-to-electric efficiencies of conventional OWC systems are often less than 25%, which results in an increase in the effective cost per kW ($/kWe) for the OWC system. A 20+% cost per kW reduction improves the economics of the OWC application, and thus makes the system more attractive to entrepreneurial commercial developers and/or governmental or institutional funding agencies. The net benefit to the world is to make available another economically attractive and viable alternative, renewable energy resource that can be used to recover the projected 17.5×10^{12} kW-hr energy that is available from the world's oceans (Ref. 43). Assuming even a 0.15% utilization factor of the world's ocean energy, this is enough energy to power an additional 70 million households throughout the world. Concepts NREC has used this renewable energy to determine the size of the OWC market to be approximately 9,900 OWC turbines, each rated at 350 kW. The assumptions used for this determination are shown in Figure 48. The manufacturing cost for a 350 kW rated, self-actuated, blade articulated (variable pitch) Wells turbine is approximately $110,000, and with a margin of 30%, the cost to the OWC developer would be $147,000.

Table XIV shown below has been constructed by Concepts NREC as an engineering cost improvement and market study analysis to correctly account for the energy savings proposed for any innovations made to OWC subsystems, and also to fairly charge the cost of these system improvements to the net cost of the OWC system on a cost per kWe ($/kWe) basis. It has been assumed that a 30% margin over the manufacturer's price would be charged for the innovative Wells turbine. The results from this Simple Payback analysis indicates a Cost per kWe ($/kW) improvement of 23% and an incremental Simple Payback of 0.75 years (9 months). This is considered the most conservative estimate for the cost of producing small numbers of turbines, i.e., not a mass-produced turbine. In fact, if as expected the innovations to the Wells turbine positively affect the market for variable pitch Wells in OWC applications, then the manufacturer's price for multiple units ordered at the same time should reduce the cost. At best, an incremental Simple Payback of 0.15 years is considered possible for a sales price of $110,000 per turbine unit.



Engineering Mfg. Cost ($)=	14,700	2% Materials Escalation/year	
Margin 1=	0.4	3% Price Escalation /year	15% of D
Margin 2=	0.0		
Sale Price=	24098		Total No. of Anticipated Units= 9,885
% YRLY. Budget for further Eng.g. Develp.=	5%		Product Sales Period= 11 years

			YEAR	1	2	3	4	5	6	7	8	9	10
Frac. of Market sold			0.02	0.08	0.15	0.20	0.25	0.15	0.06	0.04	0.03	0.01	0.01
YEAR FROM LAUNCH	-2	-1	0	1	2	3	4	5	6	7	8	9	10
Income ($1000) or Expense (fee & NREC)	$ -	$ (375)	$ (375)	$ 1,858	$ 7,961	$ 16,005	$ 22,905	$ 30,765	$ 19,859	$ 8,557	$ 6,155	$ 4,987	$ 1,799
Products Sold=	**0**	**0**	**0**	**198**	**791**	**1,483**	**1,977**	**2,471**	**1,483**	**593**	**395**	**297**	**99**

Figure 48. Assumptions for determination of OWC market

TABLE XIV. ENGINEERING COST IMPROVEMENT AND MARKET STUDY ANALYSIS

Ref: Carbon Trust Marine Energy Report ; page 283 averages from 3 OWC systems

SIMPLE PAYBACK ANALYSIS FOR OWC SYSTEM MODIFICATIONS AND ENERGY IMRPOVEMENTS

COMPARING: Fixed Blade (Baseline) WELLS turbine with Self-Actuated Blade Articulated WELLS turbine

			Baseline $ Cost	+ or - % change	$ Final Cost	$cost adder for Additional Component(s)	% Improvement Energy Recovery
System Availability, %	85%		Mfg. margins=	30%			
OWC Base Cost , $/kWe	6000		Component Costs				
Kwe=	350						
OWC Cost	$ 2,100,000						
Mechanical & Electric Systems, %	20.0%		$ 420,000				
Generator & Switchgear		**2.5%**	$ 52,500	0.00%	$ 52,500	$ -	1.0%
Turbine		**4.7%**	$ 98,356	55.3%	$ 152,760	$ 54,404	30.0%
Diffuser & Inlet Guide Vanes		**1.5%**	$ 31,500	0.00%	$ 31,500	$ -	0.0%
Structural Framework		**5.0%**	$ 105,000	0.00%	$ 105,000	$ -	0.0%
Controls		**6.3%**	$ 132,644	0.00%	$ 132,644	$ -	0.0%
Installation, %	15.0%		$ 315,000				
Mechanical		**10.0%**	**$ 210,000**	0.0%	$ 210,000	$ -	0.0%
Electrical		**5.0%**	**$ 105,000**	0.0%	$ 105,000	$ -	0.0%
Vessel Construction, %	25.0%		$ 525,000	0.0%	$ 525,000	$ -	
Electrical Trans., %	15.0%		$ 315,000	10.0%	$ 283,500	$ -	0.0%
Contingencies, %	10.0%		$ 210,000	0.0%	$ 210,000	$ -	
Transportation, %	15.0%		$ 315,000	0.0%	$ 315,000	$ -	0.0%
	100.0%		$ 2,100,000		$ 2,122,904	$ 54,404	

NET OWC Cost Savings,% -1.09% Energy Improv.= 31.0%

NET Effective $/kWe= 4,630
Net Improvement, $/kWe %= 22.8%

$O&M= 0.02 $/kwH
$finance= 0.06 $/kwH
$/kWh)income= 0.15 $/kWh
Yearly Income= $ 234,614
Incremental Simple Payback= 0.75 years

4.2 Description of Concepts NREC's Technology Innovation

Concepts NREC's computational modeling of an OWC system has shown that the OWC chamber air velocity and volume flow rates through the turbine constantly change due to the inherent nature of the OWC energy conversion system. The proposed innovation overcomes the disadvantage of a transient air flow rate by using the air velocity to provide the motive force that articulates the airfoil. The motive force is instantaneously applied and its magnitude increased as the air stream velocity increases. Thus, feedback control is eliminated and replaced by an *in situ* "real-time" feedback control. In summary, *CN*'s evolution in blade articulation uses the *in situ* aerodynamic forces on each blade to solve the problem of having a means of instantaneously and precisely synchronizing the articulation of the turbine blade to the cyclic changes in the OWC air flow rate. When developed, the wave energy-responsive, self-actuating blade will eliminate the current complex mechanical linkage mechanism that is now needed to perform this function on the Dennis-Auld air turbine. The consequence of a self-articulating turbine blade is two-fold: 1. a reduction in the complexity of the blade articulation mechanism that reduces the cost of the OWC turbine by as much as 50% compared to the Dennis-Auld-type turbine, and 2. an increase in the Wells turbine's efficiency and operating range compared to the basic Wells-type turbine, due to an optimum angle of attack between the blade and the air velocity

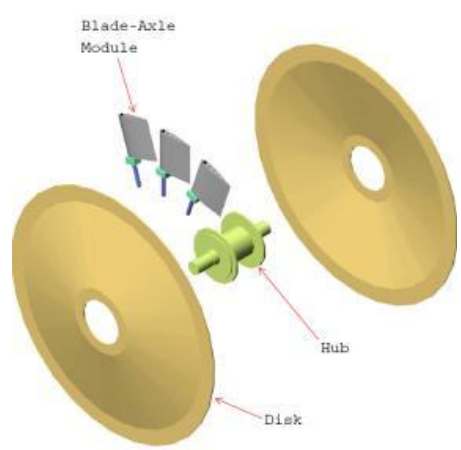


Figure 49. Basic construction of proposed turbine

vector. The efficiency and range improve by 20 to 40% and 100-150%, respectively, according to independently published reports as summarized in Table XV below. The elimination of the blade articulation linkage and the feedback control system to regulate the variable pitch blades is thought to decrease the cost per Kw ($/kW) for the OWC system by as much as 20^{+} %, i.e., equivalent to the increase in the projected efficiency of the variable pitch Wells-type air turbine.

TABLE XV. EFFECT OF USING VARIABLE PITCH AS CITED IN TECHNICAL LITERATURE

CN's Sited Ref #	Page No., Fig. Or Table No.	Sited Increase in Range	Sited Increase in Turbine Eff.	Noteable & Relevant Quote
35	Fig.2	60%	44%	
25	page 145	40%	12%	
34	Fig. 7	61%	23%	
2	Fig. 14 (0 to 24 degs)	100%	42%	
2	Fig. 14 (0 to 11 degs)	287%	50%	
30	Fig. 15	150%		Experimental results with powered variable Pitch blades
32	Fig. 2 (0 to 5 deg.s)	33%		
32	Fig. 4 (0 to 15 deg.s)	135%		Variable pitch found to be a means of improving phase control
32	Fig. 5 (0 to 10 deg.s)	87%		
36				Energy recovery increases from 28 to 82% due to phase control
33				Blade offset improves Range of Operation
40				Pitch control may accompany Bypass Valve to improve operating range
26	page 266			Inlet guide vanes and proper profile can improve eff by 17%
42	pg. 151 & 190			substantial improvement in time-weighted avg. of turbines but cost increases with varia ble pitch blades on Wells turbines

Figure 49 describes the basic construction of the proposed modified Wells turbine with Self-Actuated Blade Articulation Mechanisms. As illustrated in Figure 50 below, the turbine is easily assembled and remains a robust air turbine for the OWC applications.

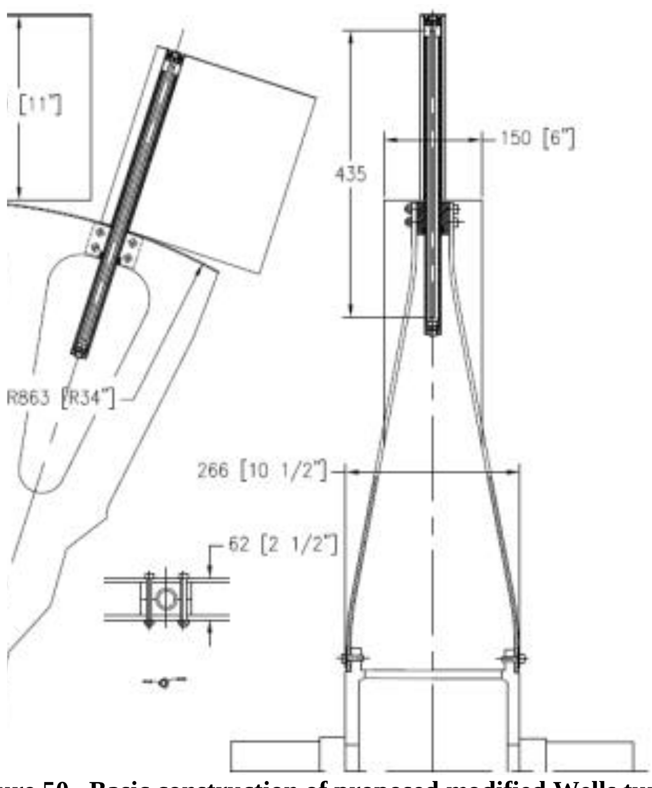


Figure 50. Basic construction of proposed modified Wells turbine

Concept NREC's most immediate customer for these innovations is Oceanlinx Ltd., an engineering collaborator and existing customer for Concepts NREC's analytical and engineering services. Based on their collaboration with *CN* and willingness to use their OWC Mk3 demonstration system as a testing platform, Oceanlinx will be offered a preferred licensing arrangement by Concepts NREC for the variable pitch Wells turbine with self-actuating blade articulation system.

A prototype single airfoil with the Self-Actuated Blade Articulation Mechanism was designed, fabricated, and tested by *CN* during Phase I of the SBIR effort. This prototype is shown in Figure 51. The detailed internal design of the self-articulating torsion rod, coupling, and sleeve seal is shown on the right. The single blade wind tunnel testing will continue with alternative airfoil composite assemblies to determine the best airfoil design to use in assembling a complete prototype turbine rotor for testing in the MIT Wright Brothers wind tunnel test facility.

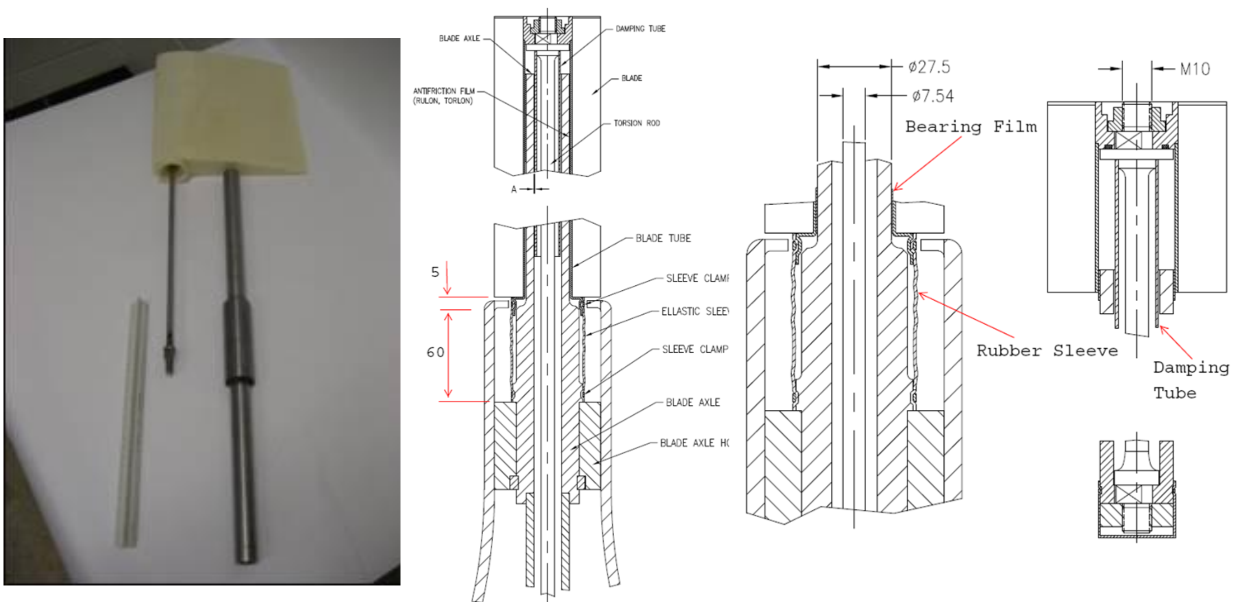


Figure 51. Prototype single airfoil with Self-Actuated Blade Articulation Mechanism

4.3 Channels to Reach Targeted Customers

Concepts NREC has worldwide sales representatives for its existing product line of thermo machinery analysis and design engineering services. The sale of the modified Wells turbine will be offered via these existing channels. More details of Concepts NREC's corporate structure and industrial experience are provided in Section 3 of this Commercialization Plan. The exposure through the successful development and proof-in-testing of the advanced variable pitch Wells turbine innovation under the auspices of the Department of Energy is expected to provide worldwide exposure. Concepts NREC continues to participate in the major turbomachinery conferences and expositions, as well as in renewable energy conferences throughout the United States. Concepts NREC also offers educational courses in turbomachinery design, manufacturing, and renewable energy applications. All of these channels will continue to be used to promote the proposed innovation. Certainly all of this is conditional on the successful implementation of the proposed project plan and the tested effectiveness of the innovation.

4.4 Business Model

Oceanlinx Ltd., Concepts NREC's primary OWC industrial entrepreneurial engineering collaborator (and customer) on several OWC projects, is currently negotiating the installation of over 30 OWC units each consisting of eight, 350 kWe OWC turbines throughout the world, including 15-20 megawatts of capacity off the coast of Rhode Island and 2.7 MW off an island in Hawaii. Concepts NREC is already working with Oceanlinx Ltd. (Australia) in a DOE-funded project that involves the redesign of their OWC turbine.

In the early 2000s, interest significantly increased in OWC technology, with Oceanlinx Ltd., Sydney, Australia, taking a leading role and moving aggressively towards the development of multi-megawatt wave farms. Their first 300 kW unit, Figure 52a, is shown operating in Port Kembla, Australia, in 2000, followed by its most recent demonstration OWC (the Mark3 Prototype Component or Mk3PC), Figure 52b. The Mk3PC was designed to accommodate multiple turbines, each with its own OWC air chamber. This system was designed and installed by Oceanlinx to be an in-water test platform for testing any proposed innovations that Oceanlinx considered viable. These two systems are no longer available for testing, but provide evidence of Oceanlinx's success in engineering, fabricating, and testing a series of prototype OWC systems which will eventually lead to the deployment of the Mk3 system in Maui, Hawaii.

Figures 52a & 52b. Oceanlinx's first 300 kW unit (left); the OWC Mark3 Prototype Component (right)

Testing plans for several of Concepts NREC OWC innovations have had to be cancelled due to irreparable damage from a storm in May, 2010. However, Oceanlinx Ltd., is still planning to use as many as six of the full-scale Mk3 modules in a single-wave climate location, as shown in Figure 53, to produce as much as 10 to 15 MW per climate wave site. The earliest first test of the self-actuated blade articulation Wells-type turbine will likely be with the prototype Mk3 system that Oceanlinx is designing for its Maui, Hawaii site.

Figure 53. Six 2.5 MWe WEC systems, each with eight (8) individual OWC chambers each utilizing a single 350 kWe OWC turbine. Each module is identified as the Mark 3 (Mk3) System (signifying the third in a series of OWC systems) with the first scaled prototype dubbed Mk3PC (200 kWe from 8 turbines).

While the project collaborator will be offered a special licensing arrangement, the Turbine Shutter Valve and Controls strategy will be offered through direct sale to mechanical and electrical contractors and engineers of OWC systems.

4.5 Addressing Societal Benefits

Given the importance in utilizing more of the Earth's natural and renewable energy resources, as evidenced by the US Department of Energy's commitment to supporting this research, Concepts NREC's customer base is expected to include major energy companies and local power utilities once the OWC-type waste energy conversion system has been demonstrated as being economically viable. The 20^{+}% improvement in the first time cost of the OWC system is expected to increase interest from energy and utility companies. *CN* expects that this renewable technology has the potential to provide at least as much affordable clean energy as present wind turbines, with negligible environmental impact. Thus, a Wells turbine with *CN*'s self-actuated blade articulation system will be offered for direct sale to the mechanical and electrical contractors who are constructing OWC systems as integral parts of turbine-generator subsystems. This product is seen as a good match with Concepts NREC's main line of interest which continues to be the analysis, design, and manufacturer of turbomachinery components and systems. A complete description of these business interests is given in Section 3 of this Commercialization Plan.

5 Competition/Intellectual Opportunity (IP)

A large number of Oscillating Water Column (OWC) water wave energy recovery systems have been constructed over the past 30 years, either on the shoreline, near the shoreline or in the breakwater in a number of countries (Ref. 40: The Carbon Trust, Marine Energy Report). There are over 60 companies currently engaged in the development of ocean wave energy devices, whether with complete systems or subsystem components, that serve the water wave energy recovery market. (http:/peswiki.com/energy/directory:ocean_wave_energy). These systems include subsurface hydro turbines, oscillating buoys, OWCs, and many other devices. In general, near-shore OWCs have an overall efficiency of wave energy to electric power from 10 to 25% (Carbon Trust, Marine Energy Report) consisting of: 42% of the wave energy converted to pneumatic power, 65% of the pneumatic power converted to mechanical power, and 91% of the mechanical power converted to electric power. Therefore, a 30 to 40% improvement in the efficiency of the turbine and thus an equivalent decrease in the cost per kW ($/kW) for the first-time cost of the OWC should be extremely attractive to the entrepreneurial developers of oscillating water column-type wave energy conversion systems; including government supporters.

TABLE XVI. EFFECT OF USING VARIABLE PITCH AS CITED IN TECHNICAL LITERATURE

CN's Sited Ref #	Page No., Fig. Or Table No.	Sited Increase in Range	Sited Increase in Turbine Eff.	Noteable & Relevant Quote
35	Fig.2	60%	44%	
25	page 145	40%	12%	
34	Fig. 7	61%	23%	
2	Fig. 14 (0 to 24 degs)	100%	42%	
2	Fig. 14 (0 to 11 degs)	287%	50%	
30	Fig. 15	150%		Experimental results with powered variable Pitch blades
32	Fig. 2 (0 to 5 deg.s)	33%		
32	Fig. 4 (0 to 15 deg.s)	135%		Variable pitch found to be a means of improving phase control
32	Fig. 5 (0 to 10 deg.s)	87%		
36				Energy recovery increases from 28 to 82% due to phase control
33				Blade offset improves Range of Operation
40				Pitch control may accompany Bypass Valve to improve operating range
26	page 266			Inlet guide vanes and proper profile can improve eff by 17%
42	pg. 151 & 190			substantial improvement in time-weighted avg. of turbines but cost increases with varia ble pitch blades on Wells turbines

There has been considerable research into ways of improving the efficiency for the very robust and relatively inexpensive Wells turbine-type, as well as the operating range of the Wells turbine. These are the two characteristics that are considered negatives for their wider use in OWC applications. Concepts

NREC's survey of the technical literature as summarized in Table XVI clearly reveals the salient points made by a consensus of researchers that a variable-pitched Wells-type turbine cannot only improve the efficiency of the turbine, but also increase its operating range of air flow rate. The latter effect has the consequence of enabling a single turbine taking the place of two smaller and faster Wells turbines. As may be seen from Table XVI, turbine efficiency improvements from 20 to 40% (and as high as 50%) were noted by these independent researchers. Similarly, the technical literature identifies an increase in the operating range of as much as 300%, although a more reasonable and conservative increase of 100-150% is suggested in this proposal as the goal of the Phase II SBIR effort.

There is also considerable technical literature concerning the mathematical analysis and numerical modeling of an OWC system that is subject to incident water wave energy. The modeling has led to theoretical suggestions but few if any practical and applied "outside-the-laboratory" implementations of means of controlling an OWC motion in order to affect optimum wave energy recovery. A short list of some of the more relevant technical papers that can provide the quickest introduction to the relevant mathematical models of OWC is given in Attachment No. 1 of this proposal. Dominating this list of technical research is the work by A. F. de O. Falcao, J. Falnes, and T. Setoguchi. However, most of the research remains theoretical or documenting the development and testing of only laboratory scale systems.

5.1 Intellectual Property Based on Proposed Innovations

Concepts NREC has filed a Provisional Patent for the self-actuated blade articulation mechanism. The patents also disclose the wider claim that the mechanism can be used in any and all air turbines where air velocity may be constantly changing and where otherwise an electro-mechanical, pneumatic/hydraulic drive with a direct feedback control system must be used to affect control over the blade articulation. The patent disclosure also considers the ability of the seal to contain the bushing lubricant which can also serve as a damping system for the blade flutter during operation.

5.2 Closest IP Competitor

A 2003 wave energy study (Ref. 41) indicated that: "If the rotor blade pitch angle is adequately controlled, a substantial improvement in time-weighted average turbine efficiency can be achieved. On the downside, it is a more complex and more expensive machine compared to the mechanically simple and robust conventional Wells turbine." Parts of this report was contributed by WaveGen, Ltd.

To emphasize this point, WaveGen Ltd. (Ref. 29, c/o Dr. W.K. Tease) did develop a laboratory scale system of a Wells-type turbine that uses a variable pitch blade with a feedback control system that electro-mechanically articulated the blades. Figure 54 illustrates their design. Their conclusions cited the improvement in the weighted efficiency of the turbine and an increase in the range of air flow that the turbine could handle before a phenomenon called "turbine stall" prevents power recovery from the turbine. They concluded their laboratory testing with the intent of reducing the cost of the electric actuation and feedback control system, as well as to detail a design that could be practically implemented in actual OWC applications. Concepts NREC's self-actuating blade articulation system for a Wells turbine is thought to be an advance over the WaveGen electro-mechanical pitch control system.

Figure 54. WaveGen Ltd.'s Design

5.3 Other Relevant IP

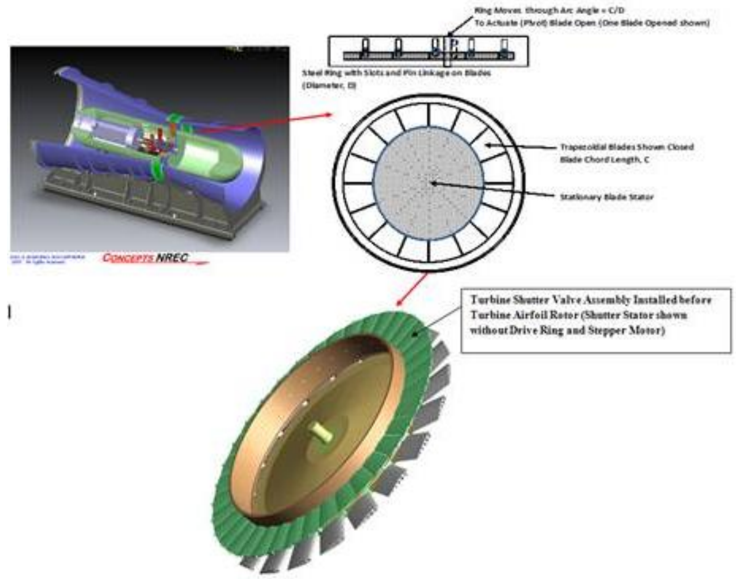


Figure 55. *CN*'s Proposed Turbine Shutter Valve

There has also been considerable research performed by Concepts NREC, Oceanlinx, and other independent researchers to develop a more efficient air turbine that can be used with an OWC-type wave energy conversion system. This effort is necessary in order to improve the capture efficiency from the wave after it has first transferred its potential and kinetic energies to the air column in the form of very transient air chamber pressure and volume flow rate, which are the two operating parameters (flow rate and pressure) that all turbine devices require to be kept constant for maximum efficiency. The inherent nature of the OWC system is to have a cyclic profile of pressure, and consequently, volume flow rate as may be observed in Figure 15 of the technical proposal.

A different Phase I STTR award (Aug., 2009; DE-FEC-0001692) afforded Concepts NREC an opportunity to not only analyze the feasibility of improving the energy recovery efficiency by as much as 30% depending on the initial design point selection, but also to identify the mechanical mechanism and the control methodology to effect this improvement. The analysis is based on Concepts NREC's numerical model for an OWC system; a numerical model that has been validated by wave tank experiments conducted by the Maine Maritime Academy under the supervision of Prof. Patrick Lorenz during this Phase I effort. The simplicity of the proposed mechanical shutter is as important as the control methodology identified by the numerical model is to the achievement of the expected energy improvement. The mechanism is henceforth identified as a "Turbine Shutter Valve" (shown schematically in Figure 55), and the control methodology of when and for what time duration that the Turbine Shutter Valve is used is an essential part of the delivered product. The turbine shutter is a mechanical subsystem designed to quickly shut off the air flow to the turbine during the initial ascension (or "upstroke) of the wave into the OWC chamber and during the last moments of its dissension (or "downstroke"). The turbine shutter can also affect the control of the relative phasing of the OWC with the incident wave, causing the OWC to be 180 degrees out-of-phase with the incident wave. The phasing of the OWC causes the OWC to descend as the wave ascends, thus increasing the relative speed of the wave and the OWC device, and in turn, enabling higher operating pressures within the air chamber. The shutters on the stator wheel are simply actuated using a slotted ring drive wheel that articulate approximately 20 degrees to move the shutters to an 80-90% closed position. The slots drive the blades through a floating pin linkage system that will use non-lubricated bushings to simultaneously articulate the 18 shutters.

Concepts NREC researchers have also discovered the advantage of lifting and/or lowering of the OWC Chamber with respect to the water line as a function of the incident wave's frequency and amplitude, i.e., energy content and the necessary controls methodology as a function of the wave amplitude and frequency. This adjustment of the OWC system enables energy from a wider range of water wave energies to be recovered. The control algorithms derived from the computer modeling for the Shutter Valve along with controlling the OWC's height by integrating the new control algorithms with the existing buoyancy control system is considered an essential and commercially viable product for sale along with the Turbine Shutter Valve hardware.

The combination of this variable pitch design will enhance the Turbine Shutter Valve improvements. In fact, it may be possible to design the self-actuating valve with a mechanical system that enables the opening of the blades to slowly open upon starting and then accelerate after a momentary time delay. This is a subject of an additional project.

6 Proposed Final Product and Market Potential

The final product from this development effort will be a Wells-type turbine with self-actuating blade articulation system that enables a "next-generation, advanced adaptive OWC" method to recover more of the energy from incident waves by increasing the turbine efficiency, as well as enabling a single turbine to be used instead of two smaller and faster (rpm) fixed-blade Wells turbines. The net result is more energy to be recovered, and thus, a more economic OWC on a per kWe and per annual kWh basis than existing systems. The market opportunity for this technology is very significant given the increased interest in the use of large scale, renewable energy in the face of depleting fossil fuel supplies. It has been estimated by the World Energy Council that the world's oceans can provide an annual energy equivalent to 17,500 TW-hrs. The potential of a 40% increase in recoverable energy per kWe rating for an OWC if the proposed subsystem redesigns are implemented translates directly into a 40% decrease in the cost per kWe for the system. This should enable the Return on Investment for an OWC system to be even more attractive for the entrepreneurial investor, governmental world body, or private funding agency. Wave energy is much more predictable using advanced weather warnings and more continuously available over 24 hours, even when compared to wind energy. The low profile OWC design is also very friendly to the panorama even when used close to shore. Based on a 0.15% utilization of the available ocean energy and a marketable 1% with nominal 10 MWe OWC modules, a market of 150 OWC systems per year, three years after product launch, can be substantiated and projected, as may be observed in Table XIII.

7 Company/Team: Concepts NREC and Oceanlinx Ltd. (Project Collaborator And Primary Customer)

Concepts NREC provides a "One-Stop-Shop" for the complete design and development of radial, mixed-flow, and axial blowers, for fans, compressors, turbines, and pumps…plus extensive experience in energy systems modeling, analysis, prototype development and testing. Based on this professional experience and background, the design and manufacturing of the Turbine Shutter Valve is well within Concepts NREC's capabilities and is consistent with its present line of products and services. The company was formed in the early 1980s to provide analysis and instruction in turbomachinery design. It has grown to over 90 engineering, technical, software, and clerical staff. It markets its turbomachinery software integrated with its CAD/CAM manufacturing software. Its founder and still Chairman of the Board, Dr. David Japikse is world-renowned for his expertise in turbomachinery analysis and testing. Concepts NREC remains a privately owned small business with software and manufactured products sales around the world.

Concepts NREC is headquartered in a 28,000 sqft facility in Wilder, VT, and has a 45,000 sqft product manufacturing center in Woburn, MA. As a leading designer in turbomachinery, Concept NREC's facilities are designed to satisfy the needs of its world-class engineering and product development projects. The facilities are organized for the development and testing of turbomachinery and are typically required to support design concepts and products involving advanced fluid mechanics, heat transfer, combustion, applied mechanics, system controls, and manufacture.

Engineering services include:

1. Rotordynamics, bearing and seal analysis
2. Full-scale and scaled rig testing and evaluation

3. Cycle & performance studies for trade-off evaluations of new designs and technologies
4. Design audits by component, stage, machine, or train
5. CFD analysis and design optimization
6. Collaborative design projects for technology transfer

Figure 56. Centrifugal compressor designed by *CN*

Concepts NREC is an independent leader in full-service turbomachinery design, development, and manufacturing.
CN also offers manufacturing services to support research engineering staff in the prototyping of turbomachinery components, as well as undertaking full production runs for over 150 of the world's most recognized users of turbomachinery components.

Figure 57. Centrifugal compressor designed by *CN*

Our turbomachinery expertise includes:
1. CAE/CAM Software
2. Engineering Services
3. Manufacturing
4. Testing Services
5. Educational Services

CN is also developing a pipeline compressor (DOE DE-FG36-08GO18059) for the hydrogen fuel delivery to forecourt stations as part of DOE's Hydrogen Economy Plan. The system uses current technology (bearings, seals, materials, intercoolers) to meet the near-term solution for the development of the necessary infrastructure to provide hydrogen as an alternative fuel.

7.1 Software

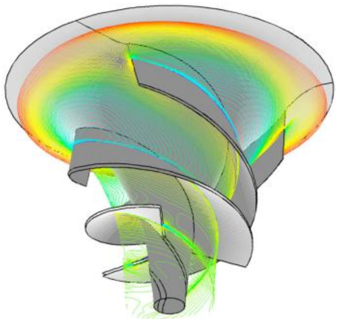


Figure 58. Fish Friendly Turbine Prototype developed by Concepts NREC

Concepts NREC uses several software packages for the design and development of axial and radial turbomachinery. First and foremost is Concepts NREC's own Agile Engineering Design System®[4]. The Agile System encompasses the complete turbomachinery design process from modeling and analyzing fluid flow through to the 5-axis manufacture of sculpted turbomachinery components. The Agile software utilizes analysis tools consisting of computational fluid dynamics (CFD), finite element analysis (FEA), and rotordynamics analysis. The software allows design teams to balance issues of performance, reliability, operating life, and low-cost manufacturability. The Agile software integrates well with other commercially available programs for Computer-Aided Engineering (CAE) and Computer-Aided Design (CAD). Concepts NREC partners with software developers to offer state-of-the-art tools for cycle performance, stress analysis, rotordynamics analysis, Design for Manufacture and Assembly (DFMA®[5]) analysis, and seamless interaction with CAD packages. To support the design and development process, Concepts NREC has multiple licenses of popular CAD packages including Pro/ENGINEER®[6], SolidWorks®[7], and AutoCAD®[8]. Engineering analysis such as FEA is performed using ANSYS®[9] or COSMOS®[10] and CFD is

Figure 59. Miniature centrifugal pump designed by *CN*

[4] Agile Engineering Design System is a registered trademark of Concept ETI, Inc.
[5] DFMA is a registered trademark of Boothroyd Dewhurst, Inc.
[6] Pro/ENGINEER is a registered trademark of Parametric Technology Corporation (PTC).
[7] SolidWorks is a registered trademark of Dassault Systèmes.
[8] AutoCAD is a registered trademark of Autodesk, Inc.
[9] ANSYS is a registered trademark of Ansys, Inc.

commonly performed with FLUENT®[11]. Bearing design and rotordynamics analysis are performed using commercial software called DyRoBeS™[12] or the ROMAC software suite from the University of Virginia.

7.2 Manufacturing

Concepts NREC maintains state-of-the-art temperature-controlled manufacturing facilities to support complex prototype designs and produce sophisticated parts for the commercial market. The manufacturing facilities commonly machine the sculpted and high-tolerance geometry associated with turbomachinery, including shrouded and non-shrouded impellers for compressors, turbines, pumps, propellers, fans, and blowers. Full-service capabilities include turning centers and three 5-axis CNC mills capable of milling turbomachinery up to 32 inches in diameter. Secondary processes include surface finishing, heat treating, welding, brazing, and coatings. Secondary processes include surface finishing, heat treating, welding, brazing, and coatings. To ensure accuracy and design fidelity, inspection capabilities include computerized coordinate measuring and dynamic balancing of turbomachinery ranging from less than 1 pound to 2,200 pounds. Shown below in Figure 60 is a mobile air brake dynamometer that is used by the US Military for testing repaired engines for flight certification.

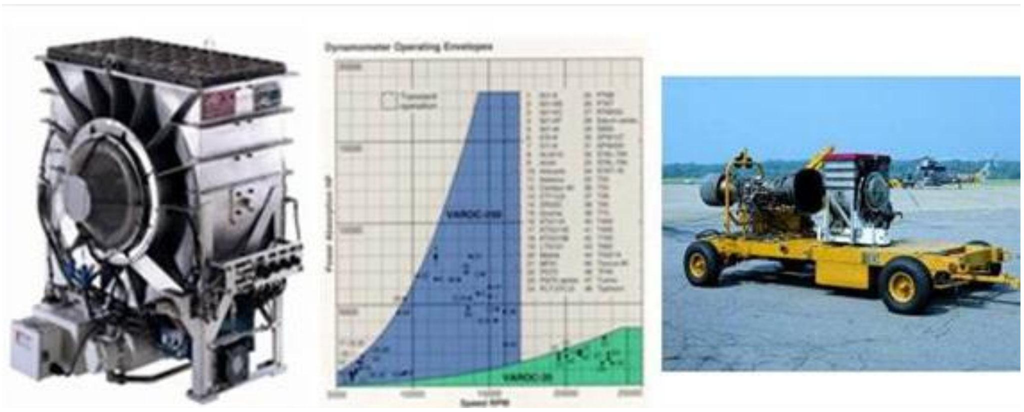


Figure 60. Concepts NREC's mobile air brake dynamometer

7.3 Testing Facilities and Instrumentation

<u>*CN*</u> has a reputation for acquiring quality data and has a battery of data acquisition and processing equipment. <u>*CN*</u> maintains extensive test facilities to validate designs of pumps, compressors, and turbines. Possible test specimens include airfoil swirl generators, vaneless diffuser units, and non-rotating diffuser elements (including conical, annular, and channel diffusers). Test facilities in Vermont and Massachusetts allow for flow visualization and contain instrumentation ranging from pneumatic and thermal probes to hot-film anemometers, lasers velocimeters, high-frequency pressure transducers, strain gauge telemetry, and proximity probes. <u>*CN*</u> can accommodate a range of test specimens from scale-model prototypes to full-dimension turbomachinery. A summary of typical test abilities includes: high power drives up to 1300 hp for high-speed power testing, components from 2" to 24" in diameter, and over-speed spin pits capable of spinning 34" diameter discs

7.4 Demonstrable Manufacturing History

Since its inception in 1980, thousands of advanced turbomachinery products have been successfully developed and integrated into products brought to the market by both <u>*CN*</u> and its customers whose design was developed by <u>*CN*</u> in private business arrangements. This must also include the world-wide marketing

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[10] COSMOS is a registered trademark of Dassault Systèmes.
[11] FLUENT is a registered trademark of Ansys, Inc.
[12] DyRoBeS is a trademark of Eigen Technologies, Inc.

and sales of the CFD turbomachinery software that is almost universally accepted as the leading turbomachinery design and analysis software on the market

Based on its marketing efforts for software sales, the company has also prospered as a product engineering and development organization, as our software customers recognize the strengths of the company and its experience in a wide variety of energy utilization applications. As a result, the company is exposed to new and relevant technology opportunities and is well-positioned to capitalize on new business opportunities. In this regard, Concepts NREC is already teamed with Oceanlinx Ltd. and several confidential entrepreneurs to develop OWC and fluid kinetic energy systems to not only develop the engineering and testing of the renewable energy technology, but also bring it to market in a well-orchestrated fashion.

The work in progress with Oceanlinx Ltd. is an example of not only their commercial success but also the first phase for such successful commercialization of an OWC system using private and only recently DOE funding, and this is the strongest evidence of the intent of Concepts NREC to commercialize this and similar renewable energy systems. Through the work completed in the Phase I effort and the proposed effort for Phases II and III, Concepts NREC will have a well-documented and established technical foundation from which to incorporate this adaptive turbine technology into the next generation OWC systems, starting with the Oceanlinx Mk3 (2.5 MWe) OWC system which is planned and permitted for in-water testing in Maui, Hawaii. At the conclusion of the SBIR, the modified Wells turbine system will be manufactured by Concepts NREC and offered for use with Oceanlinx's Mk3 (350 kW) OWC modular wave energy recovery systems, as well as other on-shore OWC systems such as the Limpet system in Scotland, the Pico Island system (Azores, Portugal), the Trivandrum (India), and Sakata (Japan).

7.5 Oceanlinx Qualifications as Industrial Entrepreneurial Developer and Primary Component Customer

The overall objective of the two-year effort planned for Phase II will be to test the self-actuating blade articulation Wells turbine in the laboratory to determine its efficiency and mechanical integrity. In Phase III of the program, Oceanlinx may be in a position to test one of the full-scale 350 kW self-actuating Wells turbines in its Mk3 OWC facility which should be under test in Maui, Hawaii. Concepts NREC is also considering the coordination of the modified Wells turbine in one of the OWC demonstration systems such as the Limpet or Pico on-shore OWC system facilities. The DOE may support this coordinating activity as a means of fostering international cooperation in the development of OWC systems. Oceanlinx, Ltd. has filed and received permits for testing full-scale (350 kWe) OWC systems in Maui, Hawaii. It is logical therefore that Oceanlinx Ltd. would participate in the third phase of this SBIR project by making their Mk3 demonstration system available for the first test of a Wells turbine with a self-actuated blade articulation system.

Oceanlinx has finalized their Water Wave Energy Conversion system concept to consist of six (6) identical oscillating water column-based modules, each with its own air turbine, harnessed in a 3 x 2 array of modules as shown in Figure 53. This configuration has been labeled the Mark 3 (Mk3) system and is much like an "egg-package" container with the advantage that each module can be prefabricated and towed to the ocean site at a lower transportation cost. The full-size system has been designed to utilize one 350 kWe (nominal) rated wind turbine per OWC module, for a total power of approximately 2.5 MWe. This system is planned for in-water testing at their permitted site in Maui, Hawaii.

8 Finance and Revenue Model

Concepts NREC has prepared an estimate for the manufacturing cost to produce a prototype modified Wells turbine system and the cost to produce systems that are designed for manufacture. These estimates are based on *CN*'s previous cost analysis of Dennis-Auld turbine subsystems, the published data on Wells turbines, and the manufacturing costs received for the prototype self-actuation blade articulation mechanism that was fabricated for its initial testing during Phase I of this SBIR. This cost summary is shown in Table XVII below.

TABLE XVII. COST SUMMARY FOR MANUFACTURE OF PROTOTYPE MODIFIED WELLS TURBINE SYSTEM

MANUFACTURING COST FOR SELF-ACTUATING , BLADE ARTICULATION ROTOR

OWC Cost/kw 6000

Fraction of Total $ OWC for Turbine= 4.7%

		Conventional, fixed Blade Wells Turbine	Concepts NREC Self-Articulating Wells Turbine				Dennis-Auld Turbine	
		Middle Est.	Low Est.	Middle Est.	High Est.	Variance σ^2	Power Rating , kW 750	350
10%	Brake System	$ 10,303	$ 10,303	$ 10,303	$ 10,303	$ -	$ 12,000	$ 10,303
17%	Drive Shaft Bearings	$ 17,185	$ 17,185	$ 17,185	$ 17,185	$ -	$ 21,600	$ 17,185
15%	Rotor Body	$ 14,753	$ 11,803	$ 11,065	$ 14,753	$ 241,848	$ 7,500	$ 6,440
20%	Rotor Body Mach.ing	$ 14,718	$ 3,311	$ 3,679	$ 7,359	$ 455,022	$ 16,500	$ 14,718
10%	Blades	$ 9,579	$ 9,579	$ 14,368	$ 19,158	$ 2,548,805	$ 21,000	$ 18,031
0%	Blade Articulat. Sys.	$ -	$ 15,491.25	$ 18,225	$ 21,870	$ 1,130,235	$ 60,000	$ 40,988
17%	Shaft (Matl. &Mach.)	$ 16,679	$ 16,679	$ 16,679	$ 16,679	$ -	$ 18,000	$ 16,679
0%	Articulation Control	$ -	$ -		$ -	$ -	$ 54,000	$ 54,000
10%	Misc.	$ 9,836		$ 9,151		$ -	$ 20,000	$ 15,000
			$ 84,352	$ 100,656	$ 107,308	$ 4,375,910		
100%	Turbine System Cost=	$ 98,356	Low		High		$ 230,600	$193,344
	(without Generator)		$ 98,564	1-sigma(σ)	$ 102,748			
			$ 96,473	2-sigma(σ)	$ 104,840			
			$ 94,381	3-sigma(σ)	$ 106,932			

Based on this manufacturing cost, a simple Return on Investment (ROI) analysis has been conducted, and the results are summarized in Tables XVIII and XIX. The two tables identify ROI for 2 Case Studies. The first assumes that the Non-recurring Engineering Costs (NREC) to develop the self-actuating blade articulation Wells turbine as identified by Concepts NREC in the budget for this proposal were not assisted by DOE's grant. The second Case Study assumes that only the typical 7% fee for the proposed work was not charged to the Phase II STTR project by Concepts NREC. This is a value of approximately $66,000 and is thus correctly considered a project cost contribution to the development project. The number of sales distributed over the 10-year product life is also shown and was determined by the assumptions shown for the percent of total energies available from the applicable world's oceans. Also included was a continuous cost to Concepts NREC of 5% of sales for each year to account for non-recurring engineering charges for design improvement, marketing for the Turbine Shutter Valve and Controls product. The price increase (3%) to cover materials cost increases, and higher product demand after the in-water development tests have been successfully demonstrated was also factored into the ROI calculation.

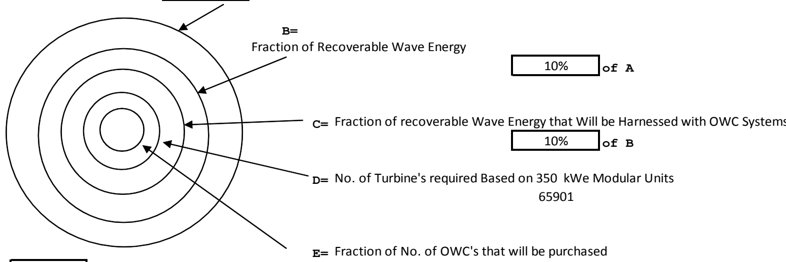
The result (shown in Table XIX) indicates that the ROI with DOE's financial assistance and promotion of this technology would result in a 15% ROI. Without DOE's financial assistance the ROI would be only 4% (Ref. Table XVIII). This ROI is generally not considered to be high enough to qualify as a business opportunity, despite the 30 to 40% improvement that this technology has in improving the Cost per kW, and hence the cost of the electricity to the consumer. The ROI shortfall for the investment of private capital to develop the product would likely not encourage the product development to proceed beyond the analysis phase unless capital investment, such as available from DOE's Grants Program, could be obtained. However, as shown in Table XIX, with this capital investment, the revenue from the sale of the first 1000 units during the first 3 years of the product's introduction after Phase II and Phase III are successfully completed is comparable to the revenues from several of the company's existing divisions.

TABLE XVIII. ROI ANALYSIS WITHOUT ASSISTANCE FROM DOE'S GRANT

"FERMI"-STYLE MARKETING ANALYSIS and INTERNAL RATE OF RETURN CALCULATION (WITHOUT DOE SUPPORT)

for Wells Turbine with self-actuated, blade articulation system

A= 1.55E+13 kw-hr Total Wave Energy In Oceans



Engineering Mfg. Cost ($)=	110,000
Margin 1=	0.3
Margin 2=	0.0
Sale Price=	146667
% YRLY. Budget for further Eng.g. Develp.=	5%

2% Materials Escalation/year

3% Price Escalation /year

Total No. of Anticipated Units= 9,885

Product Sales Period= 10 years

													TOTALS
			YEAR	1	2	3	4	5	6	7	8	9	10
		Frac. of Market sold	0.02	0.08	0.15	0.20	0.25	0.15	0.06	0.04	0.03	0.01	0.01
YEAR FROM LAUNCH	-2	-1	0	1	2	3	4	5	6	7	8	9	10
Income or Expense (fee & NREC)	$ -	$ (500,000)	$ (500,000)	$7,249,150	$ 30,771,542	$61,253,374	$ 86,743,051	$115,214,446	$ 73,489,828	$31,266,148	$22,181,992	$ 17,714,242	$6,290,998
Products Sold=	0	0	0	198	791	1,483	1,977	2,471	1,483	593	395	297	99
Net Income per unit=	0	0	0	$ 36,667	$ 38,911	$ 41,310	$ 43,875	$ 46,621	$ 49,562	$ 52,715	$ 56,099	$ 59,733	$ 63,641

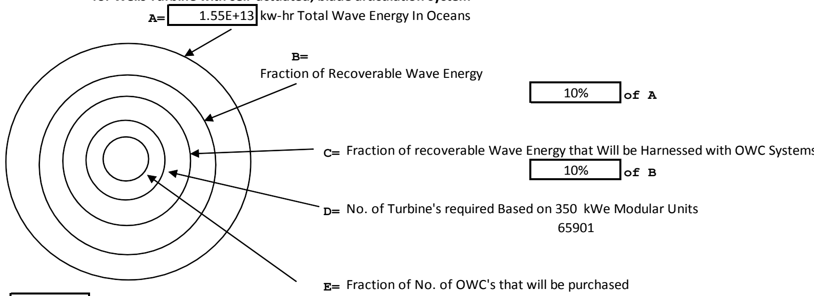
Internal Rate of Return= 4

TABLE XIX. ROI ANALYSIS WITH ASSISTANCE FROM DOE'S GRANT

"FERMI"-STYLE MARKETING ANALYSIS and INTERNAL RATE OF RETURN CALCULATION (WITH DOE SUPPORT and CN Fee Cost Shared)

for Wells Turbine with self-actuated, blade articulation system

A= 1.55E+13 kw-hr Total Wave Energy In Oceans



Engineering Mfg. Cost ($)=	110,000
Margin 1=	0.3
Margin 2=	0.0
Sale Price=	146667
% YRLY. Budget for further Eng.g. Develp.=	5%

2% Materials Escalation/year

3% Price Escalation /year

Total No. of Anticipated Units= 9,885

Product Sales Period= 10 years

													TOTALS
			YEAR	1	2	3	4	5	6	7	8	9	10
		Frac. of Market sold	0.02	0.08	0.15	0.20	0.25	0.15	0.06	0.04	0.03	0.01	0.01
YEAR FROM LAUNCH	-2	-1	0	1	2	3	4	5	6	7	8	9	10
Income or Expense (fee & NREC)	$ -	$ (33,000)	$ (33,000)	$7,249,150	$ 30,771,542	$61,253,374	$ 86,743,051	$115,214,446	$ 73,489,828	$31,266,148	$22,181,992	$ 17,714,242	$6,290,998
Products Sold=	0	0	0	198	791	1,483	1,977	2,471	1,483	593	395	297	99
Net Income per unit=	0	0	0	$ 36,667	$ 38,911	$ 41,310	$ 43,875	$ 46,621	$ 49,562	$ 52,715	$ 56,099	$ 59,733	$ 63,641

Internal Rate of Return= 15

Phase III's next step would be to manufacture a full-scale 350 kWe-rated rotor for its possible use in the Oceanlinx Mark 3 OWC system. The Mark 3 OWC systems consist of six identical 350 kWe OWC modules. One of these 350 kWe modules can be outfitted with the full-scale rotor for its Beta-test in full operation. This is expected to occur after Phases I and II are completed and capital can be obtained to construct the new rotor. This is likely to occur in 2012.

9 Phase II Proposed Technical Objectives and Work Tasks

9.1 Principal Investigator and Key Personnel

Mr. Francis Di Bella, PE, will be the Principal Investigator for the STTR. Mr. Di Bella is the Program Manager for several large renewable energy projects at Concepts NREC, including the development of a high capacity, centrifugal hydrogen compressor for pipeline applications that can serve the DOE's Strategy for the Hydrogen Economy. Mr. Di Bella has spent over 25 years developing large scale power generation systems, including cogeneration and waste heat recovery Organic Rankine Cycle Systems. Working with Mr. Di Bella will be Mr. Alexander Gofer, a Mechanical Engineer who worked on the Phase I SBIR effort, and Dr. Louis Larosiliere, the Director of the Aero engineering group at Concepts NREC. Dr. Larosiliere has worked on the turbines for the previous Oceanlinx project that developed a mechanical articulating turbine blade system for Oceanlinx's OWC. For more information on the team participants, see the included biographical sketches.

9.2 Task Descriptions and Discussion

Task 1. Initial Performance Specification for 15 kW Prototype and 350 kW OWC Turbine for Oceanlinx's Demonstration and Full-scale System

In order to provide demonstrable evidence of the viable application and benefit of the self-actuated blade articulation system in Task 2, a 15 kW prototype rotor for OWC application will be designed, installed, and tested in MIT's Wright Brothers wind tunnel research facility. This demonstration will be followed by a full-scale rotor development in Phase III of the SBIR project. For this purpose, a design specification will be prepared in this Task that clearly and accurately identifies the engineering design parameters required for the 15 kW rotor, including rotational speed, air flow rate, etc. Similarly, the design specification will be prepared for a full-scale, 350 kWe-rated turbine rotor with self-actuated blades for the specific requirements for integrating the full-scale rotor into Oceanlinx's OWC WEC system that is planned for in-water testing in Maui, Hawaii. The design will enable a detailed cost estimate to be made for the entire turbine, thus supporting the commercialization of the turbine after the DOE program.

Figure 61. Assembled full-scale blade

Task 2. Detailed Design of the 15 kWe Prototype System Using *CN*'s Self-actuating Blade Articulation Design

The specification development in Task 1 for turbine speed, air flow rate, and rotor pressure drop will be used to design a 15 kWe prototype turbine rotor with the basic wave energy-responsive self-actuating blade mechanism that was conceived in Phase I of the SBIR project, and fabricated for proof-of-principle testing as shown in Figure 61 and 62. Using real fluid properties as appropriate, Concepts NREC will perform the design of the 15 kWe turbine rotor using *CN*'s AXIAL™[13] (CFD) software code. The detailed design of the rotor will begin with the design of the blade articulation device that was conceived in Phase I of the SBIR and will utilize accepted engineering practice design considerations to extend beyond that preliminary design to produce a complete Wells-type turbine rotor system, including the use of an induction generator. This design effort will focus not only on the mechanical torsion mechanism, but also on the mechanical design of the blade structure so as to enable the cost-effective mass production of the self-actuating blade assembly, while maintaining the

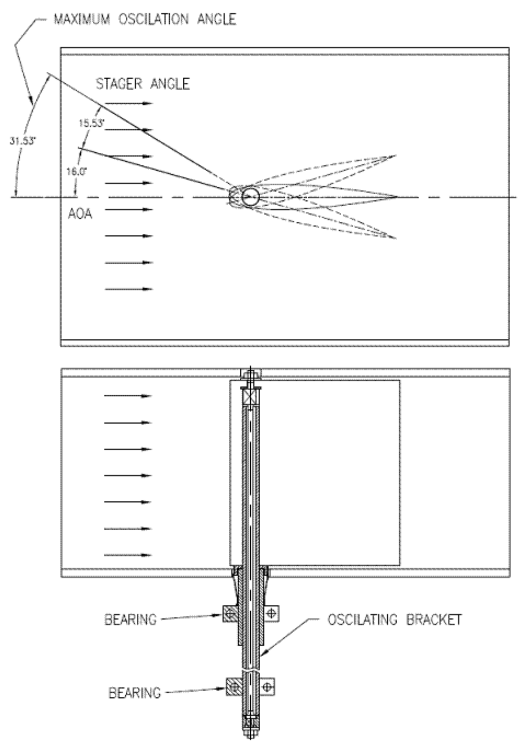


Figure 62. Airfoil module developed in Phase I

[13] AXIAL is a trademark of Concepts ETI, Inc.

necessary center-of-gravity, low weight, and structural integrity. For this purpose, an objective of this task will be to consider a composite structure for the airfoil but constrained with the need to be manufactured most easily and inexpensively while still providing a robust structure. Several versions of the composite airfoil may need to be constructed and tested in Concepts NREC's wind tunnel test facility to measure its mechanical integrity when exposed to high air forces.

The rotor system will be designed with the necessary instrumentation to measure the aerodynamic performance of the rotor during the laboratory and actual field site testing. This instrumentation will measure air velocity and/or mass flow, and pressure drop across the blade. The pitch of the blades will be measured simply using marking son the blade and the blade shaft via strobe lighting.

Task 3. Continued Wind Tunnel Testing at *CN* using the Single Self-Articulating Blade Mechanism from Phase I of the Project

CN proposes to continue its testing of a single self-actuating articulating blade using *CN*'s wind tunnel (shown in Figure 63) and a single airfoil that is constructed similar to the airfoil module that was developed during Phase I of the SBIR and shown in Figure 62. The testing will reveal more accurately the torsion-angular displacement relationship, as well as provide a test platform for demonstrating the mechanical design integrity of the composite airfoil designs that will be detailed in this task, along with the fatigue properties of the torsion bar and the attached elastomeric sleeve seal that are selected for use in Task 2. In order to determine the fatigue integrity of the self-actuating blade, it will be necessary to replicate the reversal of air stream that passes over the airfoil. The reversing of the air stream is a unique characteristic of the OWC system caused by the ascending and descending wave front and its pushing and inducing air out of and into the OWC chamber. The reversal of the air stream will be replicated by actually adjusting the angle of attack of the blade by using a stepping motor that is attached to the blade shaft and cyclically rotates the airfoil so as to have the airfoil have a positive and negative angle of attack corresponding to each wave cycle, or approximately every 5 to 10 seconds. Figure 62 illustrates the concept of affecting the blade's angle of attack using a stepper motor on the blade axle (the outer covering of the torsion rod). As the air is flowing over the blade, the stepper motor articulates the blade to its extreme angle (plus or minus 15 degrees) and maintains this position by providing the torque that counters the torque exerted on the blade by the air stream. This is thought to be the simplest method for simulating air reversal, but others will be studied as necessary to more accurately simulate the air reversal effects on the air foil. The method chosen will be automated as necessary to cycle the air reversal effects.

Figure 63. Concepts NREC's wind tunnel

Another major goal of the single-blade wind tunnel test will be the testing of one or more composite airfoil designs to ensure ease of manufacture and functionality of the design. The *CN* wind tunnel test will also allow an opportunity to perfect any instrumentation that will be installed in the complete turbine assembly, assuring its operational integrity, and thus maximizing the usefulness of the time spent in the MIT wind tunnel facility.

Task 4. Construction of 15 kWe Turbine Rotor for MIT Wright Brothers Wind Tunnel Testing

Concepts NREC will construct the 15 kWe prototype rotor based on the detailed design prepared in Tasks 2 and 3. The rotor will be balanced and instrumented as appropriate for output torque, and measurements of the self-actuating articulated blade torque vs. angular displacement, and otherwise prepared to be tested in the MIT Wright Brothers wind tunnel research facility. The turbine will be coupled to a 15 kWe induction generator in order to enable power to be generated and also to easily change the rotor speed through an electronic speed control that uses a commercially available pulse width modulation (PWM) to effect the frequency of the electric power to the motor and thus the turbine's rotational speed. The power thus generated will be returned to the grid or dispensed through a resistor load bank.

Task 5. Lab Testing and Measurements of Aerodynamic Performance using Wind Tunnel Testing

A Test Protocol will be prepared based on the efforts performed in Tasks 2 and 3. The Test Protocol will include a series of tests with the turbine's airfoils locked in a fixed position so as to compare the aerodynamic turbine efficiencies and thus to confirm the benefit of a variable pitch design, along with the evaluation of the mechanical integrity of the self-actuating blade articulation module. The system will be installed in MIT's Wright Brother's wind tunnel test facility for a full-admission wind tunnel test. The proximity of the MIT test facility in Cambridge, MA, to the *CN* laboratories in Woburn, MA, facilitates the ability to coordinate the necessary testing at each of these facilities, so as to cost-effectively complete the validation of the aerodynamic and mechanical integrity of the Wells-type turbine. The functional integrity of the pressure, air flow rate, and blade displacement instruments will have been checked prior to the full admission testing at *CN*'s wind tunnel facility in Task 3. A comparison of the performance of the installed turbines will be made at the conclusion of the testing. A comparison of the thermodynamic efficiency as well as net power generation performance of the installed turbine with the fixed blade or the self-actuating blade articulation system will be made at the conclusion of the testing.

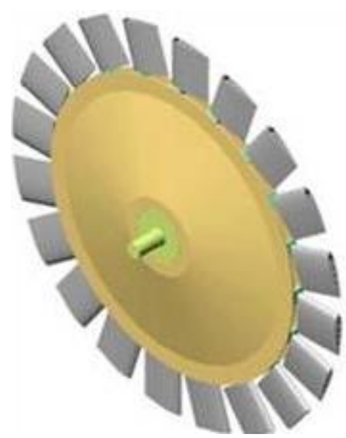


Figure 64. Conceptual rotor design with self-actuating blades

Task 6. Design of 350 kWe Wells-Turbine with Self-Actuating Blades and Cost Analysis of a Manufactured System

A complete Bill of Materials will be developed for the 350 kWe detailed design based on a dimensional analysis of the 15 kW prototype turbine and any modifications that need to be made to the design based on the MIT wind tunnel testing. The cost of the 350 kW turbine will be determined by *CN* and its subcontractors in order to identify an accurate cost of the manufactured unit, and thus to start the commercialization of the turbine.

Task 7. Preparation of Phase III Demonstration Test Plan and Overall Program Management and Reporting

CN will develop a detailed design, fabrication, and test plan for the Phase III full-scale 350 kWe wave-responsive self-actuating blade articulation cartridge based on a 350 kWe OWC turbine rating from the information learned in Tasks 1 through 5. The plan will also identify the timetable for manufacturing a full-scale turbine and its use in the 350 kWe OWC system that would be under test by Oceanlinx Ltd. in Maui, Hawaii, or with other prototype OWC systems that are already developed.

During the course of this program, progress reports will be submitted to the DOE program monitor. The reports will document the status of each task, problem areas, and proposed courses of action. A final report will be prepared at the end of the program documenting the results and the Phase III plan.

10 References Used in Phase I STTR Study

The following references have been selected as "the place to start" from among the many references that have been reviewed in researching the analytical work that has been conducted by others, particularly in completing the objectives as stated at the conclusion of this report. These are in the order in which it would seem to be most useful to review and use in completing these STTR project objectives.

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11 Related R&D on OWC Systems by ***CN*** and Others

11.1 Recent Research for Other Methods for Optimizing OWC Performance

There is considerable technical literature concerning the mathematical analysis and numerical modeling of an OWC system that is subject to incident water wave energy which has led to positive suggestions as to how to improve OWC performance. A short list of some of the more relevant technical papers that can provide the quickest introduction to the relevant mathematical models of OWC is given in the previous reference section. Predominant in this list of technical research is the work by A. F. de O. Falcao, J. Falnes, and T. Setoguchi to name only a few, but not intended to minimize the contributions of others. Important papers, summaries on the status of OWC systems modeling, control, and energy capture improvements are Ref. 19: "Principles for Capture of Energy from Ocean Waves. Phase Control and Optimum Oscillation", by J, Falnes, and Ref 22: "Control of an Oscillating-water-column wave power plant for maximum energy production", by A.F. de O. Falcao. These two papers, like many of the others, utilize a more mathematical approach to model the fluid dynamic behavior of the water as it interacts with an obstruction. The obstruction is typically a reflecting barrier that is placed in the path of the incident wave. The fluidic modeling of the wave-obstacle interaction typically provides an expression for the fraction of incident wave energy that is reflected into the wave energy conversion device or diffracted away from the device.

It has been well-established mathematically by the University researchers (such as Falnes, Evans & Porter, Suzuki & Arakawa, Sarmento & Falcao, Justino, and Lee to name the most prolific researchers in the field) that an OWC without a refracting wall will be able to recover only 50% of the wave's potential and kinetic energies; and this is before considering the efficiency of the power turbine. The use of a reflecting wall will increase the potential recovery efficiency to 100%. The precise maximum theoretical recovery efficiency of the OWC depends on several factors. Chief among these are length of the wall into the water, the width of the chamber with respect to the incident water wave length, and the water wave frequency. It has also been established that these physical parameters for the OWC can be combined with the linear or non-linear relationship between the volume flow rate (cfm)-pressure differential (ΔP) of the air turbine to determine an effective damping coefficient. Whether the damping coefficient is represented by C, D, or Beta (β) by different authors or with different system variables, all of the various forms for the damping coefficient can be reduced to:

$$(\Delta P_{avg} \ A_{owc}^{2} / Q_{avg})$$

Where: ΔP_{avg} is the turbine pressure differential (i.e., chamber pressure minus ambient pressure)
A_{owc} is footprint area
Qavg is the volume flow rate through the turbine

Research into the modeling of OWC systems continues, and researchers have agreed that the damping coefficient is a key parameter in optimizing the power output of the OWC for a given wave energy source, and that the energy absorbed by the damping of the radiated fraction of the incident wave energy is equivalent to what potentially may be recovered by the pneumatic oscillating column, and then by an efficient, well-engineered power recovery subsystem.

The reference to this technical literature and its collaboration with Oceanlinx Ltd. on several private and public (DOE) projects afforded Concepts NREC an opportunity to begin its development of a unique OWC computer numerical model that Concepts NREC has found to correctly characterize the OWC system. During a Phase I STTR effort (Sept. 2009 to May 2010; Project DE-SC0001692), Concepts NREC presented a unique method, based on an Energy Conservation Methodology algorithm, for solving how the refracted energy that is input to the OWC air chamber can be better understood for purposes of improving the wave energy recovery if a more practical design parameter, the system's Time Constant, T_c= (units: seconds) is used to determine the optimum operation of the OWC system. By knowing the physical size (length, width, and height) of the OWC and the relationship between the turbine's volume flow rate and chamber pressure, _*CN*_'s thermo-fluids models can calculate the optimum power output from the OWC for a given size water wave energy; an energy which is a function of the water wave's amplitude and frequency.

Concepts NREC's modeling was found to concur with several very relevant results by these named researchers. For example, de O. Falcao analytically identifies a 37% increase in the power output from an OWC system if a bypass valve is used in the OWC chamber. The bypass valve provides this improvement by simply eliminating the stalling of the turbine and thus allowing the turbine to continue to generate power at a higher overall efficiency. However, what is not clear is how much more power could have been achieved if the air flow that is forced to bypass the turbine could drive the turbine while also having the turbine operate at higher efficiency.

This technical prior art was seen as supporting Concepts NREC's innovation and is the subject of another Phase I STTR: the feasibility analysis of a Turbine Shutter Valve®[14]. The Turbine Shutter Valve momentarily impedes air flow into or out of the OWC chamber, trapping the air volume in the OWC chamber. When this trapped air is released, the turbine operates with a higher pressure and a larger air flow rate in a performance zone that is more efficient for the turbine. If the Turbine Shutter Valve is closed for longer periods of time, it may be used to effectively increase the spring constant for the chamber and thus cause the OWC to be raised or lowered with the wave front, literally having the wave energy content stored in the mass of the OWC in the form of potential energy. Some or all of this

[14] Patent pending by Concepts ETI, Inc.

potential energy can then be restored to the water when the OWC "rides" the wave downward. Whether some or all of the wave energy is dissipated in this manner is dependent on when the Turbine Shutter Valve is closed or opened in the wave cycle. The timing of the Turbine Shutter Valve operation would be guided by keeping the OWC 180 degrees out-of-phase with the incident water wave.

An interesting conclusion from J. Falnes' technical paper was the suggestion that "…to obtain the optimum oscillatory motion for maximizing the absorbed energy or the converted useful energy, it may be necessary to return some of the energy back to the sea". Falnes proposed (but like de O. Falcao did not implement the proposals) that mechanical power be input into the OWC system in the form of pneumatic or hydraulic energy "…during some small fractions of each oscillation cycle and profit from this during the remaining part of the cycle".

11.2 Concepts NREC's Numerical Spreadsheet Thermo-Fluid Model

The key to the development of this numerical model is the adaptation of a physical analogy between the ascending and descending wave in the OWC chamber to a piston moving up and down in a cylinder, except that the cylinder has an aperture at its top in which is placed a power turbine. Thus, as the piston (wave) ascends into the cylinder (OWC chamber), it compresses the air and also pushes some of the air out of the cylinder through the turbine. The amount of air that can be pushed out of the turbine is dependent upon whether the aperture can be considered a simple orifice, or if it must be more correctly represented by a spinning obstruction or turbine. For a simple aperture, the flow coefficient, C_v, is typically used in fluid dynamics as the ratio of the volume flow rate (Q, cft/s) to the square of the pressure drop through the aperture. The turbine flow rate-pressure drop relationship is most adequately and conventionally represented by the aerodynamic terms: ϕ, Flow Coef. = $Q,cfs/(ND^3)$ and Load Coef. $\Psi = \Delta P/\rho/(ND)^2$ in the formula: $\varphi = K \times \Psi$, where K is a proportionality constant that depends on the type of turbine in use. For this study, both methods were used and determined to give the same wave energy recovery improvement results. The wave power density (kW/meter) or wave energy flux (E/ft^2) is the primary wave characterization that is needed for this numerical model. Certainly, the energy flux and power density are determined from the classical wave energy derivations that consider the wave height and period as given in Equation 1. For this reason, the *CN* numerical model developed in the Phase I STTR is identified as the Energy Conservation Methodology to discern it from the analytical classical solution presented in the previous section. The major link between the wave energy content and the piston-cylinder analogy is the calculation of an average piston velocity. The piston average velocity is determined from knowing the energy content of the water wave and iterating on the weighted average of the piston-cylinder (i.e., OWC chamber) pressure using the relationship:

Avg. velocity (V_{avg}) = (Wave Energy per A_{owc})/ Avg. chamber pressure ($\Delta P_{avg.}$)/T

or: Avg. Velocity(Vavg)=(Power per wave front)/ $\Delta P_{avg.}$)/(λ/2)

Where the energy content of the wave is equivalently expressed as either:

Energy per area (E/Aowc) = $\rho \times g_g/g_c \times a^2/8$ **Eq. 1**

or: Power/wave front length (Power/L) = $\rho \times g^2{}_g/g_c \times a^2 \times T^2/(32 \times \pi)$

λ is the (deep sea) wave length and is determined from (Ref. 7) : $T^2 \times g_g/(2\pi)$

These are classical expressions for water wave energy derived in any good text (Refs. 6, 7, 8) on ocean wave energy by integrating the potential and kinetic energy of the water particles assuming a sinusoidal wave shape in three dimensions.

The velocity of the free-surface wave front (similar to DL/Dt) is then determined to be a function of time according to the following equation:

$V(t)= \pi\ (Vavg)/2 \sin(2\pi/T \times t)$; where T is the wave period **Eq. 2**

With the velocity of the free-surface wave front known, and assuming a relationship between the volume flow rate through the turbine as a function of chamber pressure (i.e., $Q= C_v \times \sqrt{\Delta P}$), it is possible to model the transient behavior of the chamber pressure and volume flow rate during the ascension (or dissension) of the wave. The transient power of the wind turbine can then be determined from the conventional turbine power calculations or:

$$\textbf{Power(t)} = \Sigma \{\Delta P(t) \times Q(t) \times \eta_{turbine} \times \text{Constant (for unit conversions)}\} \qquad \textbf{Eq. 3}$$

An example of the comparison of the theoretical analytical solution and this numerical solution is shown in Figure 65a using the C_v relationship between flow rate and pressure, and in Figure 65b when the turbine relationship: $\varphi = K \times \Psi$ is used. This virtually identical result is even more remarkable due to the fact that the expressions used for the vertical, free surface velocity in both models are different, although both are ultimately dependent on the energy content of the wave. That is, the numerical model uses the classical expression for wave energy (Eq. 1) to determine the vertical velocity of the free surface of the water, whereas the theoretical solution uses only the entire wave height and wave period in its derivation.

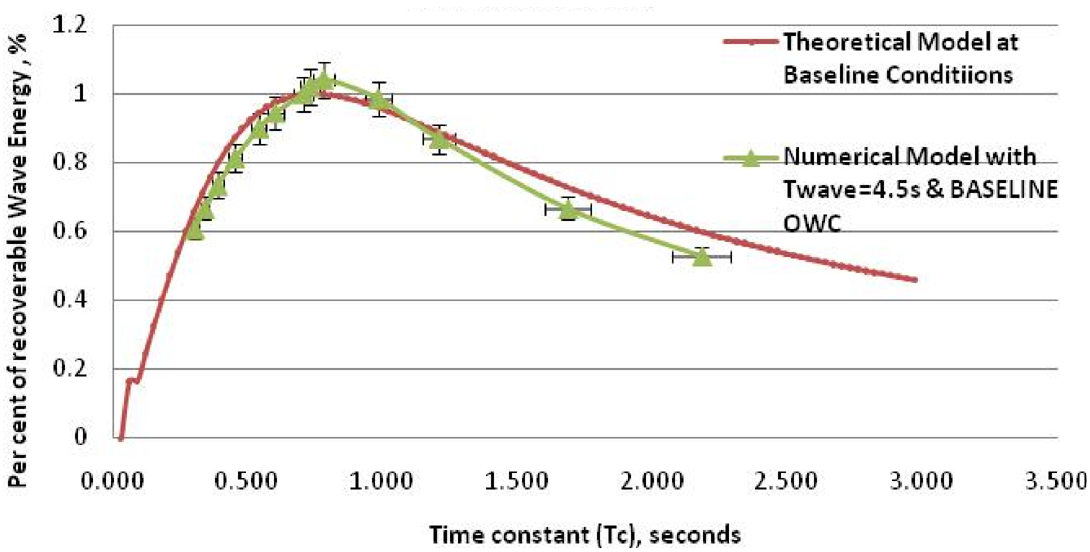


Figure 65a. Comparison of Theoretical Analysis and Numerical Model using K(α) as proportionality constant {Twave=4.5 s; Howc-=7 m, W=16 m, L=10 m; Hwave=9.3 ft; Energy=35 kW/m; 5% error bars shown}

11.3 Numerical Model Validation

The simplicity of this Energy Conservation Methodology and its ability to provide time variant, numerical solutions was extremely welcome, as it easily enabled the changes to several critical OWC design parameters in order to calculate any energy recovery improvements as a result of these changes.

The most definitive validation of *CN*'s numerical model was only recently determined from testing conducted by the Maine Maritime Academy (MMA) engineering professors and students as part of their collaboration in Phase I of the STTR. A small-scale OWC chamber was used, fabricated, and tested in the MMA wave tank. The MMA OWC chamber is shown in Figures 66a & b as it is readied for a test. The dimensions of the chamber are 12" x 12" x 14" tall, and it is instrumented with a pressure transducer to record the chamber pressure changes as the water wave ascends and descends in the OWC chamber. This OWC prototype was built without a reflector wall, and thus only half of the available wave energy could be potentially recovered.

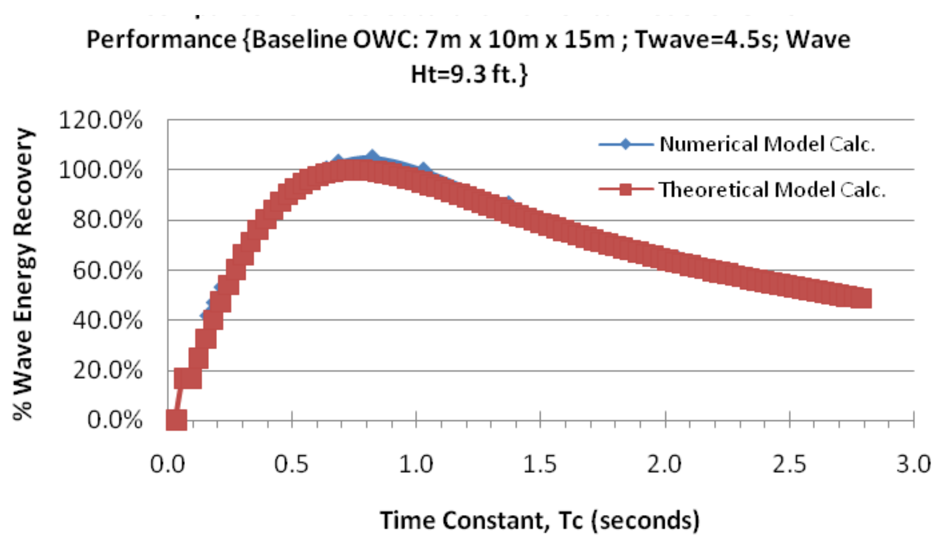


Figure 65b. Numerical solution using turbine relationship: $\varphi = K \times \Psi$

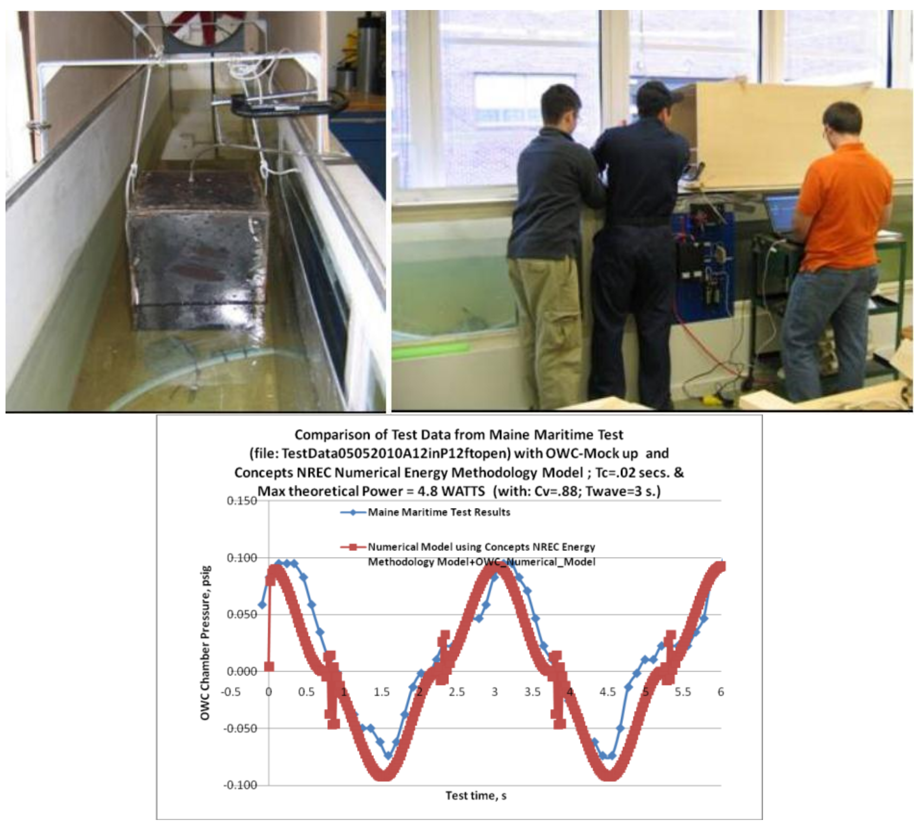
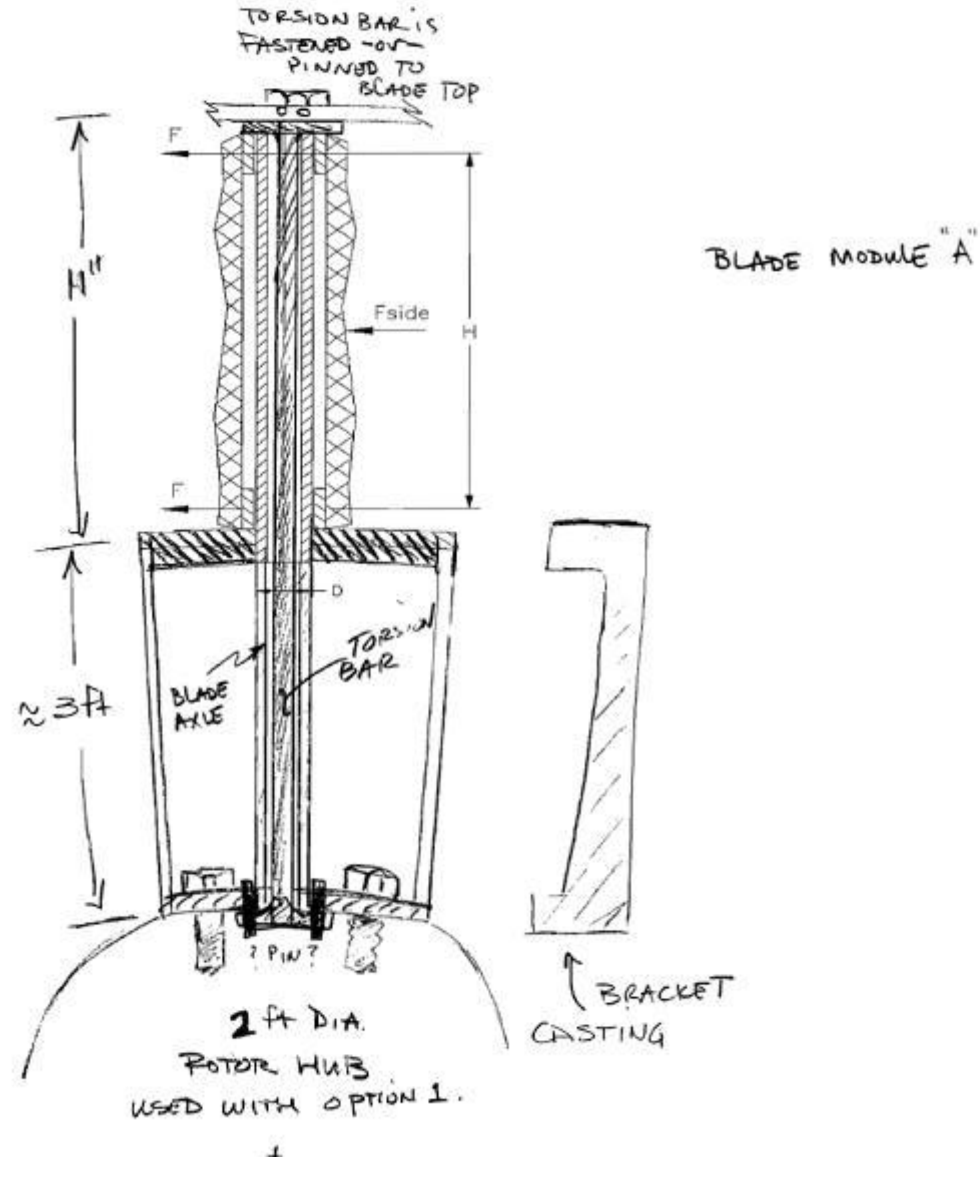


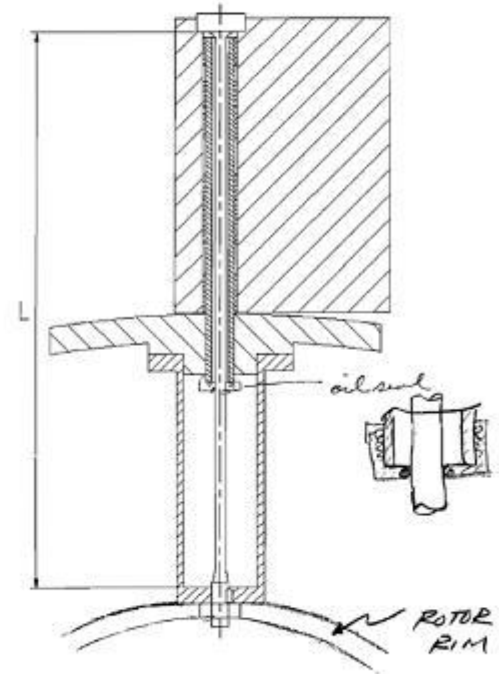
Figure 66a, b, c, & d. Maine Maritime Academy's OWC Chamber

A series of tests were performed using 6-inch and 12-inch tall waves with a wave period of 3 seconds. The output from this test is shown in Figure 66c, compared to the predicted performance according to the Energy Conservation Methodology Numerical Model. The match between predicted and actual test measurements is particularly strong in the model's ability to display an inflection of the pressure as it changes sign. These inflections are noticeable when modeling a very small OWC chamber and not as apparent, or perhaps not existing in larger systems, as may be witnessed from the comparison shown in Figure 53.

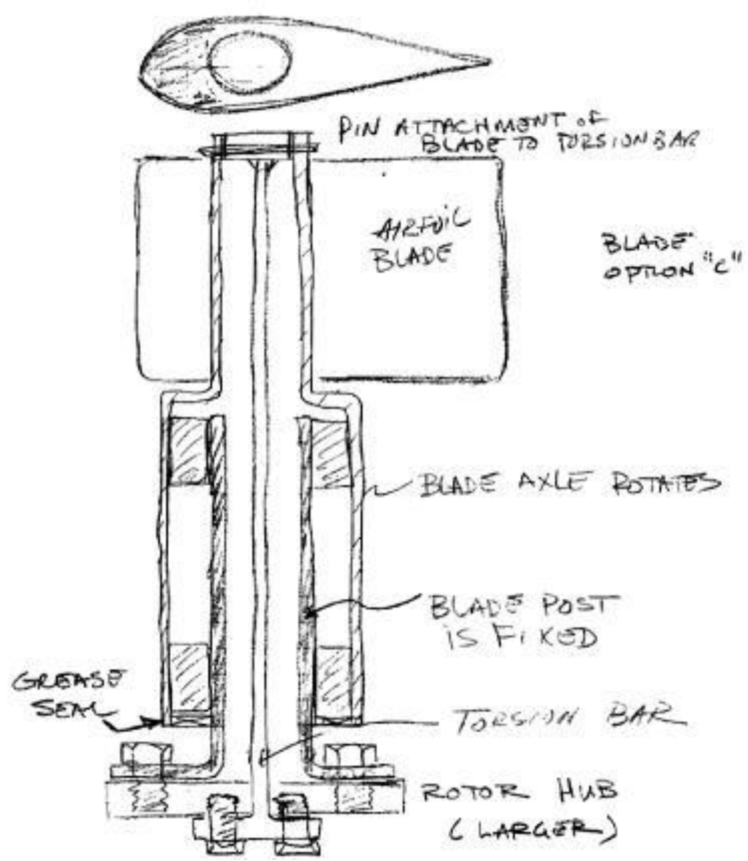
Attachment 1: Conceptual Rotor Designs for Securing the Articulation Blade



BLADE MODULE "B"



BLADE MODULE
USED WITH ROTOR OPTION 2



BLADE OPTION "C"