Simulation of a Small Scale Wave-Powered Rotary Pump for Seawater Desalination

1 ABSTRACT

As a part of the larger Waves to Water Project, the purpose of this project was to investigate the amount of high pressure water a rotary pump could be expected to produce when powered from a wave energy source. The simulator took numbers for absorber characteristics from previous studies, and pump characteristics from a low-cost commercial pump intended for submerged operation. The simulator exposed a major issue with rotary pumps: to remain lubricated, rotary pumps have minimum rpm ratings. Waves inherently do not provide the kind of motion that can be used to keep a pump spinning at a consistent rpm efficiently.

2 INTRODUCTION

The Waves to Water competition challenges teams to make small-scale wave-powered desalination systems. Reverse Osmosis is one of the most efficient methods of desalination. Desalination using reverse osmosis requires extremely high pressures (600-800 psi). The team debated between using a linear and rotary pump to create such pressures. Rotary pumps have numerous advantages, as the absorber can be allowed to move with the tides without being limited by the stroke length of a linear pump. The system devised to convert the sinusoidal, linear motion of waves into continuous rotary motion was to use a spool, connected to the floating absorber by a cable, and coupled to the pump using a one way clutch. In this system, only the upward motion of waves is captured, and the pump is allowed to continue rotating as the absorber descends.

3 SYSTEM GEOMETRY

While several geometries are in consideration for the wave absorber motion, they are sufficiently similar that only one was used for this study. An absorber, with the dimensions of an inflatable queen mattress, floats on the water surface, rising and falling with the heave motion of the waves. It is tethered to a spool driving the rotary pump, which is rotated every time the absorber rises. A one way clutch only allows torque to be applied when pulley rpm exceeds pump rpm (positive torque). This allows the pump to continue rotating in the positive direction while the absorber descends.

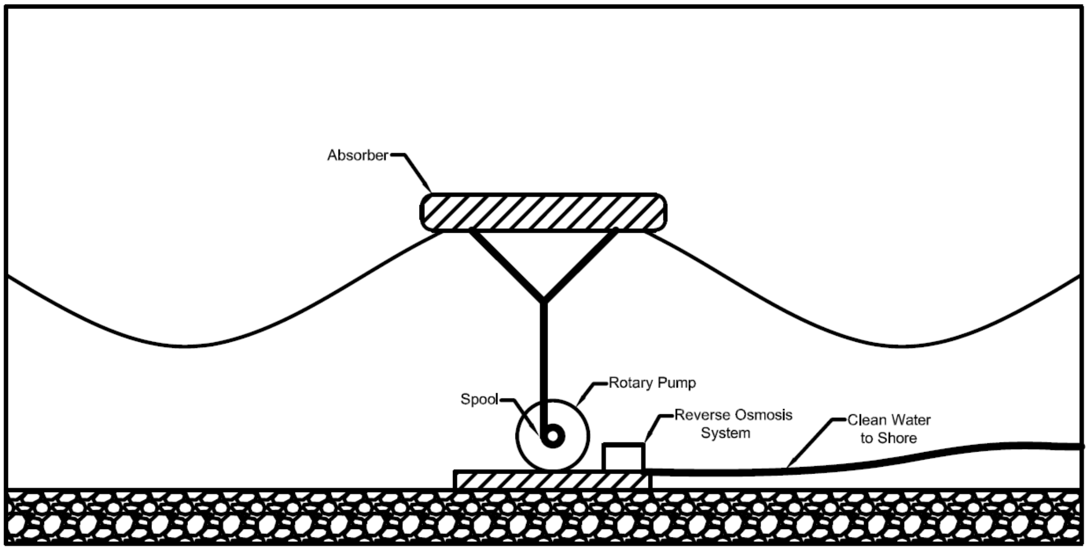

Figure 1. Diagram showing design of desalination system being simulated

4 SIMULATOR METHODOLOGY

In creating the simulator, all forces are modeled as torques on a flywheel, which accounts for the effective moment of inertia of the moving parts of the pump, as well as a physical flywheel that smooths the angular velocity of the pump in between wave periods. Water height is modeled as a simple sinusoid, with constant amplitude A_{wave}, and constant period T_{wave}:

$$x_{water} = A_{wave} \cdot sin(\frac{t \cdot \pi}{T_{wave}})$$

The tension force exerted by the absorber on the vertical cable tethering it to the submerged spool is calculated using a coefficient, $K_{elasticity}$, that combines both the compliance of the cable and the force required to submerge the absorber a given distance. This coefficient is taken from CFD simulations done by another member of the Waves to Water team.

$$F_{tension} = K_{elasticity} \cdot (x_{water} - x_{absorber})$$

In steady state operation, the absorber should not be submerged fully during any of the cycle, meaning that the assumption that the force scales linearly with distance is valid. The torque exerted onto the pump-flywheel system by the absorber is piece-wise, as a result of the one way clutch, which only allows torque to be applied when pulley rpm exceeds pump rpm:

$$\tau_{absorber} = \begin{cases} (r_{spool} \cdot F_{tension}) & if \ \omega_{spool} \geq \omega_{pump} \\ 0 & if \ \omega_{spool} < \omega_{pump} \end{cases}$$

The simulator assumes that in the case where the angular velocity of the pump exceeds the angular velocity of the spool, no downward force is exerted on the absorber, and it floats fully on top of the surface of the water. This happens both on the down-stroke of the absorber, where the spool is rotating in reverse, and when the upward wave stroke is beginning, and ending. Also important to simulation is the resistive torque exerted by the pump itself. The pump's resistive torque, as a function of rpm, is modeled by the equation:

$$\tau_{pump} = \tau_0 \cdot \frac{{\omega_{pump}}^2}{{\omega_0}^2}$$

where τ_0 is the pump resistive torque at its minimum operating angular velocity, Ω_0, numbers taken from manufacturer data sheets. Resistive torque is assumed to scale with the square of angular velocity, as most of the resistance will come from fluid effects, though this exact relationship does not significantly affect simulator results. This is because, after a sufficient amount of time, the pump should be rotating at almost exactly Ω_0 $rad\ s^{-1}$.

5 PULLEY RADIUS AND FLYWHEEL MASS OPTIMIZATION

Water output is proportional to pump RPM, so maximizing pump RPM is a good proxy of maximizing water output. Matlab's built in nonlinear optimizer was used, with the objective (minimization) function set to the steady state $-\omega_{pump}$. Ideal pulley radius is well below one inch for all reasonable wave characteristics. Intuitively, it is positively related to wave amplitude, and inversely related to wave period.

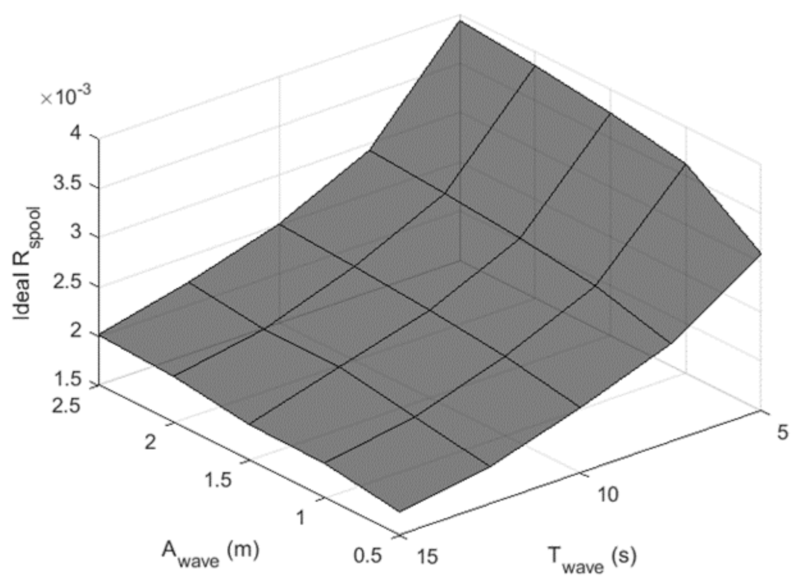

Figure 2. Ideal Spool Radius for Given Wave Characteristics

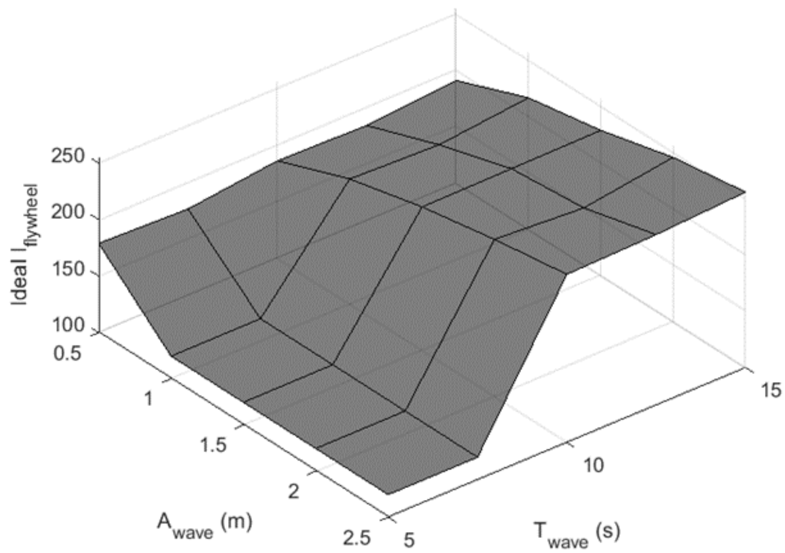

Figure 3. Ideal Flywheel Moment of Inertia for Given Wave Characteristics

6 SIMULATOR RESULTS

Based on earlier calculations, even small waves were expected to have more than enough power to drive the pump at the required RPMs. However, results indicated that this was not at all the case. The pump failed to reach the RPM required for it to remain lubricated, even on relatively large waves. The only remedy was to decrease flywheel moment of inertia, which increased the amplitude of fluctuations between maximum rpm and minimum rpm, at the crest and trough of waves, respectively.

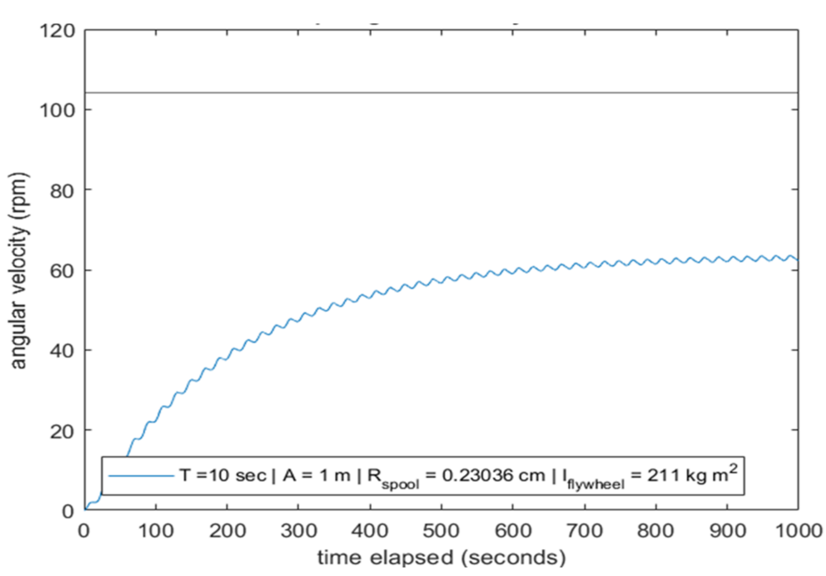

Figure 4. Example Graph of Angular Velocity vs Time

As it can be seen above, at even relatively high energy conditions, the pump struggles to reach half of the required angular velocity. The problem soon became clear: the rpm of the spool is a sinusoid (derivative of water surface height). With each successive stroke of the absorber, the pump rpm rises. Eventually, it begins to approach the max rpm of the pulley, reached at $x_{water} = 0$. However, at this point, the system loses the ability to capture power at other positions on the stroke, where $\omega_{pump} > \omega_{spool}$. This meant that the pump can only capture energy from under half of the wave stroke. For some wave amplitudes and frequencies, efficiency is well below 50%.

Because of this issue, unless some other method of transferring torque from the wave to the pump is devised, it seems that it will be advisable to use another method to absorb wave power, less limited by rpm. Perhaps a low moment-of-inertia electric generator will be a better alternative.