A hybrid drivetrain for low-speed, linear WEC applications

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ABSTRACT

This paper presents a hybrid drivetrain concept developed specifically for wave energy applications. The drivetrain comprises a hydrostatic hydraulic front end coupled to Vernier linear generator in such a fashion as to provide the advantages of both a hydraulic drivetrain and a direct-drive electrical system, while improving on the efficiency of both. In addition to the concept and functionality, work will be presented on the development of numerical models and the coupling of these models with the OPI Triton™ WEC. Further, recent validation of the numerical work on a 1:10 scale physical drivetrain prototype will also be presented.

1. INTRODUCTION

The most significant challenges for any WEC power take-out (PTO) are the low velocities and the very high peak-to-average nature of the input power waveform, both inherent to the resource. The use of conventional direct-drive or hydraulic solutions tends to result in low efficiencies and low capacity factors, as generators must be rated to many times their mean output power. Furthermore, power capture enhancement through active controls can put substantial demands [1] upon the generator and subsystems. The drivetrain presented here aims to address these challenges primarily through its novel and hybrid nature. While designed primarily for the Triton WEC [2], the architecture is applicable for any WEC that can use a linear hydraulic actuator as an input, and has been specifically developed with attenuator and point absorber concepts in mind.

1.1 Linear Hydraulic 'Gearbox'

The hydrostatic hydraulic front end, at the simplest level, acts like a hydraulic press (see figure 1), whereby the force and displacement provided by the marine system to the 'input' hydraulic cylinder is transferred to a smaller diameter 'output' hydraulic cylinder that drives a linear generator. A return spring functionality in the drivetrain is particularly important for two-body, compliantly connected WEC concepts, such as the Triton.

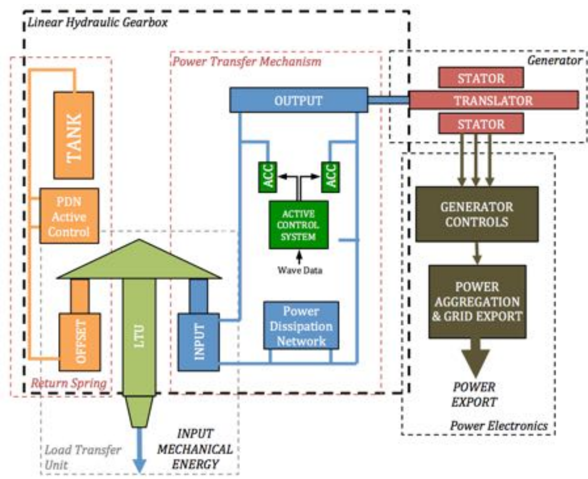

Figure 1: Block diagram of the drivetrain indicating different subsystems. Power dissipation is not shown.

In these systems a restoring force is required to balance the mean load offset on the system. This functionality is provided by a hydraulic cylinder connected mechanically in tandem with the drivetrain input cylinder and hydrostatically connected to an accumulator, the air volume of which can be varied by valving to different sized reservoirs. The incorporation of this hydraulic system has important benefits in terms of overall efficiency and functionality, namely:

1. *Enhanced generator efficiency*: Depending upon the ratio of the input and output piston areas, the hydraulic system provides an amplification of the applied velocity, in effect acting as a gearbox, allowing the linear generator to be smaller, provide lower force and operate at a higher efficiency.

2. *Sea-state specific tuning*: Through appropriate valving the system can also switch between different input cylinders, allowing different gear ratios to be used for different sea conditions. The primary advantage of this variable gear ratio is to provide additional velocity amplification in

smaller sea conditions where conventional generators would suffer from extremely low efficiency as a result of small displacements.

3. *WEC displacement control*: With respect to the return spring, by changing the accumulator air volume while keeping pressure constant, the spring constant can be varied while ensuring the offset mean load remains constant. This functionality can be valuable for managing WEC displacement in larger seas and preventing end stop events (through use of a small air volume), while also allowing more travel in smaller seas (through use of a larger air volume).

4. *Power dissipation in large seas*: Furthermore, the fluid power flow from the input cylinder, which is driven by the WEC, to the output cylinder, which drives the generator, is a hydrostatic connection and can be manipulated to provide additional power dissipation. By diverting the flow through a set of controlled valves and heat exchangers, the drivetrain can provide a much higher apparent damping coefficient to the WEC, dissipating excess energy and transferring a fraction of input power to the generator. This functionality would be implemented in larger waves to allow the generator to continue to operate at rated power in sea states larger than otherwise possible, enabling a smaller generator to operate with a better capacity factor. This can also be enhanced dynamically during large wave crests, allowing high instantaneous power to be dissipated, improving the peak to average power ratio, and improving power quality.

5. *Active control and power storage*: Implementation of active control in WEC relies upon the ability to apply control forces to the prime mover as determined by an algorithm. Typically, a reactive control system can thus require the generator to 'motor' at times. In the presented hydraulic arrangement, this effect can be implemented through an accumulator and appropriate valving, releasing energy back to the prime mover as determined by the control algorithm. Such approaches can have the benefit of providing significant net power increase in WEC performance [3]. Furthermore, this controlled store and release can be used to limit the maximum generator loads enabling a larger system capacity factor.

1.2 Linear Generator

For the mechanical-to-electrical conversion, a double sided, dual-airgap Vernier Permanent Magnet (PM) linear generator architecture was chosen and has been developed and optimized for this application. The Vernier topology is known to provide exceptional low velocity performance through a modulated stator/translator pole spacing that provides a frequency amplification of the magnetic flux, resulting in a high electrical frequency and increased back-EMF for low linear velocities [4] (Figure 2). A double sided design is used as this provides the highest theoretical power density and reactive force,

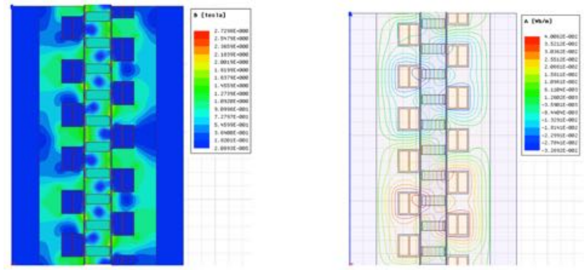

Figure 2: Vernier PM magnetic Flux density (L) and Lines (R)

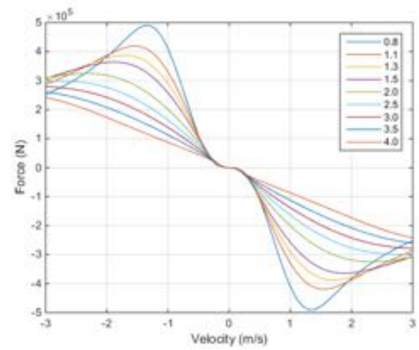

Figure 3: Force/Velocity characteristic curves for the Vernier generator at different load resistances(Ω)

however this design requires a robust translator support and bearing solution and work is needed to characterize long term performance.

2. DRIVETRAIN MODELLING

To quantify the performance of each component, the drivetrain was initially modeled as separate subsystems. The hydraulic systems were represented using Matlab and Simscape fluids, with SimulationX also used to provide a comparative validation. The models for the hydraulic systems incorporated the primary loss terms in the cylinders including friction due to seal compression, friction proportional to pressure, and friction proportional to velocity due to viscous effects. A representative force/displacement profile from a Triton WEC numerical model (OrcaFlex) was provided for initial evaluation in both software packages. They were found to provide consistent results, although SimulationX proved to be faster and slightly more stable with the added complexity of cylinder seal friction.

The generator was modeled using ANSYS Maxwell FE. In order to exploit symmetry and reduce computation time, the analysis consisted of a single pole pair. Given that we are most interested in the primary electromagnetic characteristics of the airgap stator/translator interaction, a 2D model rather than a 3D model was used in to further reduce computation time. FEA simulation output of the Vernier topology can be seen in figure 2.

A full drivetrain simulation was achieved with these packages using a simple coupled approach whereby a

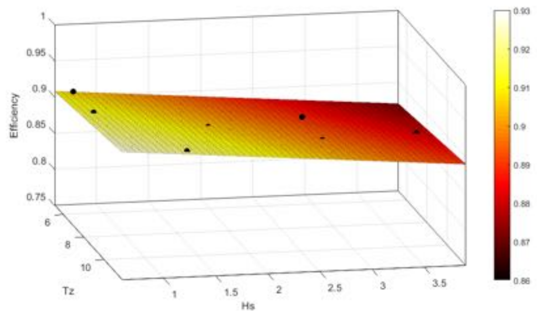

Figure 4: Contours of system efficiency for different sea states obtained from numerical models

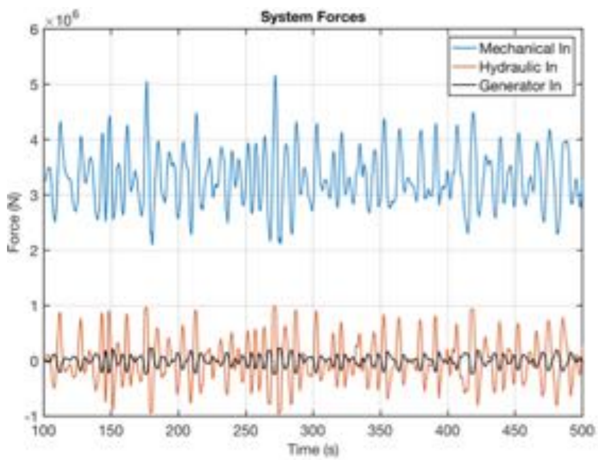

Figure 5: Forces on the system in a large wave condition. The three traces represent the input mechanical force, the reduced hydraulic force and the output generator force (2x velocity multiplier)

series of reactive force to velocity curves for the generator across a variety of load cases was generated in ANSYS (figure 3). These were represented in Matlab as simple look-up tables, allowing the correct electromechanical reactive force to be applied for a given output/generator velocity, for a given load setting. The coupled hydraulic/generator system was evaluated in a variety of waves and mechanical-to-electrical efficiencies of greater than 90% were observed in all conditions with higher efficiency seen in larger sea states, shown in figure 4. The output in a large irregular condition (with some power dissipation) is shown in figure 5.

A scheme for storage and re-injection is shown in figure 6. These traces show how the combined use of storage and valving can be used to significantly improve the peak to average ratio of the output. This effect is also somewhat analogous to the use of controlled power dissipation. The control signal shown here can be generated straightforwardly in a causal manner from the input displacement, although by combining this with knowledge of the input wave would be first step to enabling a reactive control algorithm.

3. COUPLED WEC-PTO MODELLING

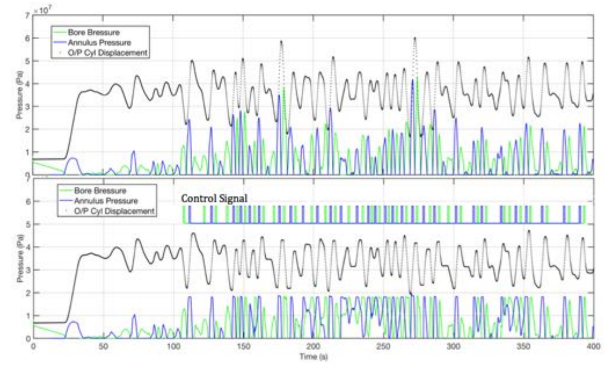

Figure 6: Output from gearbox with and without power control. Nominal output (top) with accumulators and controlled re-injection (bottom), the indicated trace indicates the valve control signal

To further understand the power performance of the drivetrain as part of a complete WEC system, the coupled system response was investigated. To obtain an accurate model, it is important to dynamically couple the numerical simulations of the drivetrain and WEC. Ideally this is completed across a common time domain solution, however the use of different incompatible numerical modelling softwares requires either a simplistic linear or non-coupled PTO representation in the WEC software, or a simpler WEC representation in the PTO software. Instead, we developed a simple yet robust iterative approach in order to approximate the impact of the realistic drivetrain on the WEC performance.

A manually iterative method was used which relied upon generating non-linear spring-damper representations of the drivetrain, when subject to the typical forces and velocities that would be generated by the WEC in a particular sea-state. These representations are provided as lookup tables and imported to validated Orcaflex models of the Triton WEC and used to generate a new time-series of forces and velocities. These are then fed back into the drivetrain model to produce improved lookup tables, plus power and efficiency metrics. The process is repeated until the forces and displacements produced by the Triton numerical model did not change between iterations of the drivetrain lookup table. While the process was not particularly well suited to automation, it was able to produce a good representation of the coupled system after a couple iterations.

1. OrcaFlex run with linear PTO coefficients
2. Provide forces/velocities to the drivetrain model.
3. Simulate drivetrain with WEC forces/velocities.
4. Determine non-linear spring and damper tables.
5. OrcaFlex run with non-linear PTO coefficients.
6. Provide forces/velocities to the drivetrain model.
7. Simulate drivetrain with WEC forces/velocities.
8. Compare to previous, iterate 4→7 to convergence.

Linear vs Non-Linear PTO Power Delta *(negative values indicate non-linear power is lower than linear approximation)*

Hs(m)\Te(s)	5.3	6.4	7.6	8.8	10.0	11.2	12.4	13.6
0.25	5%	-1%	-3%	-10%	-12%	-12%	-5%	3%
0.75	8%	1%	-4%	-9%	-12%	-11%	-6%	4%
1.25	8%	3%	-3%	-8%	-10%	-10%	-4%	5%
1.75	10%	4%	-2%	-6%	-9%	-8%	-3%	6%
2.25		5%	0%	-5%	-8%	-7%	-2%	8%
2.75		7%	1%	-3%	-6%	-5%	0%	9%
3.25		8%	3%	-2%	-4%	-4%	1%	10%
3.75			4%	0%	-3%	-2%	3%	12%
4.25			6%	2%	-1%	0%	5%	13%
4.75				4%	1%	2%	7%	15%
5.25				6%	4%	5%	9%	17%

Figure 7: Power performance difference between a linear and non-linear (realistic) PTO.

The wave-to-wire model was evaluated in a selection of irregular waves across the power matrix. For each wave, the gearbox configuration was selected to provide the optimal system damping that would be applied in the WEC. The power matrix shown in figure 7 identifies the performance delta between a system with an idealized linear PTO (commonly assumed in WEC modeling) and the non-linear results obtained through this method for a realistic PTO. It can be seen that the variation is in the order of a few percent on a cell by cell basis which shows that the drivetrain provides a good linear approximation. As expected, a general trend is that the impact is slightly higher around the system natural periods, although in some cases the non-linearity can generate an increase in power. It should be noted that the limitations in this approach restricted the simulation to only include the fundamental functionality; in that it is only able to represent components whose state is constant over the course of the simulation and thus it is unable to represent accumulators or other such dynamic discrete time components. In this case this limitation meant that the power storage and other advanced functionality was not represented but will be investigated in future work.

4. LABORATORY VALIDATION

The drivetrain presented here has been constructed at 1:10 scale at the OPI laboratory in Seattle, as shown in figure 8. The prototype includes a linear hydraulic gearbox, return spring system and Vernier PM generator. It is currently undergoing evaluation and testing with the aim of validating the numerical simulations. More detailed results of this testing will be presented.

5. ONGOING WORK

In terms of numerical modeling, ongoing efforts are aimed at developing a time-synchronized fully coupled model where the WEC dynamics (simulated in ProteusDS) and drivetrain dynamics (simulated in Matlab as described above) are passed between these models at each time-step. This will enable an automated and more accurate evaluation of the impact of different drivetrain configurations upon both the WEC and the output power for a particular sea state.

Hydrostatic hydraulic systems such as the system described here have the ability to transfer power with high efficiencies. The primary losses are dependent upon the performance of the cylinder seals, with typical efficiencies being well above 90%[5]. However, a known challenge is achieving suitable seal longevity, with PTFE bearing materials providing the current state of the art solution. Further work with the laboratory prototype will be used to characterize seal performance and evaluate alternatives.

Figure 8: Laboratory test setup of the Vernier generator (left) coupled to the linear hydraulic gearbox (right). The air tanks at the top left are for the return spring

Finally, while this paper discusses a Vernier PM linear generator, the system can equally integrate other linear electrical machines or alternative generator technologies.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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