ISSN 1454 - 8003
Proceedings of 2024 International Conference on Hydraulics and Pneumatics - HERVEX
November 13-15, Băile Govora, Romania

FLUID-MECHATRONIC SYSTEMS IN SEA AND OCEAN WAVE POWER-TAKE-OFF PROCESSES

Alexander SKVORCHEVSKY[1,*]

[1] Research Centre of Robotics, Mechatronics and Production Informatization, Kharkiv, Ukraine

* sircrmpi@gmail.com

Abstract: *The study aimed to identify problems in the development of fluid-mechatronic systems for wave energy converters and to propose solutions to these problems. The problem was solved by heuristic methods using the theory of automatic control, technical hydraulics and fluid mechatronics. The proposed study is based on the hypothesis that power capture can be increased through the use of wave energy converters` power take-off systems with variable parameters and structures. Using the specified hypothesis and methods were proposed power flow diagram of the fluid-mechatronic system of power-take-off of wave energy converters, as well as a float arm with hydraulic drive. The directions of proposed fluid-mechatronic systems of sea and ocean wave power-take-off future development were discussed.*

Keywords: *Fluid-mechatronics, wave energy converter, power-take-off process, float arm, buoy*

1. Introduction

Ocean and sea waves are the world's largest untapped energy source [1]. The Intergovernmental Panel on Climate Change (IPCC) puts the potential annual global electricity production from ocean and sea waves at 29,500 TWh. This is almost ten times Europe’s annual electricity consumption of 3,000 TWh. It is also a clean, effective alternative to polluting and expensive diesel for remote islands and offshore industries, such as fish farms or oil & gas platforms [1]. The article [2] shows that in some regions, for example in the Mediterranean, the wave energy potential correlates with the wind energy potential. In general, wave energy can be considered as concentrated wind energy, which in turn is a derivative of solar radiation energy. The high density of wave energy necessitates the usage of engineering systems capable of creating high power density for taking it off. Today, such systems are hydraulic devices. Despite the enormous potential of renewable wave energy, wave power capture technologies are still emerging. Economically efficient power take-off can be achieved by wave energy converters' adaptive control according to the maximum power capture criteria. The application of hydraulic systems with their adaptive control involves the usage of fluid-mechatronics [3] methods. Fluid mechatronics is an integrative engineering and scientific field that combines hydraulics, fluid mechanics, control theory, mechanics, electrical engineering, electronics and other disciplines.

2. Literature review and problem statement

Hydraulic power take-off (PTO) systems for wave energy usually fall into two broad categories. These are, firstly, variable pressure systems where control of the primary force/torque is achieved by pressure modulation, and secondly, constant pressure systems where control of the primary force/torque is achieved by valve transitions that select between discrete effort levels determined by the approximately constant accumulator pressure and alternative piston areas. Energy storage is integral to the constant pressure category while, in the purest form of the variable pressure category, it is not provided. Hybrid systems which combine elements of both categories are also possible. The paper [4] reports an analysis of the most elementary of systems from each of these categories. The analysis uses a coupled hydrodynamic-hydraulic time domain model. The model is used to assess the effectiveness of the hydrodynamic power absorption and the efficiency of the hydraulic power transmission. The results show that, in each case, the hydraulic motor performance is a critical consideration and the optimal configuration of any one system is dependent on motor selection. In the best instances of both categories of PTO, the indicated performance is sufficiently high to facilitate the commercial viability of such systems [4].

From the analysis, the next conclusion was made: of the combinations of system concept and motor technology presented in [4], notwithstanding the spread in efficiencies, all possibilities are worthy of further investigation and development. However, the results are calculated for a single short-term sea state rather than for a complete year [4].

In the PhD dissertation [5] shown that despite 40 years of research activities within wave energy, the PTO is still a hindrance. No matured designs exist. The lack of advances in PTO research a contributing factor to wave energy remaining in a pre-commercialisation phase - a phase where electrical power production has been demonstrated but needs to find a road to larger power scales and effective production. One of the difficulties in PTO design is performing the trade-off between contradicting PTO characteristics, e.g. controllability, efficiency and peak power capacity. A PTO system for wave energy converters (WEC) is a classic example of a mechatronic design problem, where all aspects of the design couples.

PTO solution is based on the discrete control of a hydraulic cylinder and is assessed in [5] to be the most promising solution. It is therefore analysed in depth. The solution is named a Discrete Displacement Cylinder (DDC). The developed DDC allows discrete force control of a multi-chambered cylinder driven by the absorber, while efficiently transferring the generated power directly into a battery of high-pressure accumulators. The concept allows DDCs of multiple absorbers to supply the same accumulator battery, where a hydraulic motor may use the stored energy to drive a generator at a near-constant load.

In addition, dissertation 5 substantiates the following statements:

- Mechanical solution as for example ball screws may show the required force density and efficiencies, but are viewed as not having the durability.

- A hydraulic cylinder around Ø 25 cm and 1600 kg may give 420 kN. The problem is to control the force of the cylinder while efficiently converting the produced flow into electricity.

- Hydraulic accumulators are viewed as best suited storage technology for wave energy. It may cover both wave-to-wave and wavegroup-to-wavegroup power smoothing. It has a high-power density and low cost, combined with a round trip efficiency of about 94%.

- Discrete control of a hydraulic cylinder by pressure shifting seems to give the required efficiency while providing force control.

- Efficient and durable hydraulic PTOs with constant force control exist, but have a poor extraction.

The dissertation [5] is a fundamental work in the field of WECs` PTO and certainly deserves recognition. However, it should be noted that many of the statements made in [5] are still valid even at the time of its publication in 2013.

Multi-chamber cylinders, studied in detail in [5], do not look like a promising part of the fluid-mechatronic system of the PTO. This is due to their increased complexity, increased dimensions, the impossibility of converting standard, serially produced products (like conventional hydraulic cylinders), and a complex hydraulic control system with many valves. Hydraulic accumulators are considered the most promising storage of captured wave energy. However, the dissertation mainly considers hydro-gas accumulators. In [5], it was not possible to identify studies on the applicability of weight-loaded hydraulic accumulators, while gravity energy storage is considered one of the most promising in recent years [6, 7].

Discrete control of a hydraulic cylinder by pressure shifting can array the next problems:

1. The power flow carried by the sea wave is smooth, although it has peaks. Any attempts at discrete control of a smooth power flow will lead to significant power losses due to the need for modulation.

2. Discrete pressure control will lead to pressure surges in the hydraulic system, which in turn will increase the risk of pipeline rupture, damage to the membrane of the hydro-gas accumulator, damage to the seals of the hydraulic cylinders and generally reduce the reliability of the system. In addition, the presence of two elastic elements in the system - hydraulic fluid and compressed gas in the hydro-gas accumulator can lead to the system entering a self-oscillating mode during a discrete transition from one pressure level to another. In the dissertation [5], many WECs are considered. They have different kinematic diagrams. However, not a single WEC scheme was found in which the hydrokinematic diagram could change and adapt to the wave parameters - frequency, amplitude, and wavelength. This could be achieved, for example, by changing the length of the float arm. In this way, the pressure and speed of the piston of the hydraulic cylinder of the PTO could be changed adaptively.

Analysis of recent scientific publications [6-11] and practical examples of WEC [12, 13] did not show significant progress in the development of hydrokinematic and electrohydraulic (fluid-mechatronic) schemes of WECs` PTO. Mainly wave energy converters are built on the same principle, namely, there is a buoy that makes reciprocating movements under the action of waves. The buoy is mechanically connected by a constant-length float arm to hydraulic cylinders, which convert mechanical energy into hydraulic energy accumulated in hydro-gas accumulators. The flow of fluid rotates the shaft of the hydraulic motor, which rotates the shaft of the electric generator. McCabe Wave Pump (MWP), Pelamis Wave Energy Converter [12] and Eco Wave Power Company`s Converters [13] are built on this principle. The stagnation in the mass application of WEC, despite the enormous potential of sea and ocean waves as a source of renewable energy, is apparently caused by the use of typical hydrokinematic and electrohydraulic (fluid-mechatronic) diagrams for WECs` PTO. Using similar principal fluid-mechatronic PTO systems limits the potential for wave power captures and reduces the fault tolerance of WECs. This is because waves can vary greatly in frequency, amplitude, and length, with a significant random component.

3. The aim of the study

The study's aim is scientific foundation development for the structural and parametric synthesis of hydro-cinematic and fluid-mechatronic systems of WECs` PTO according to the maximum power capture and fault-tolerance criteria.

4. The study materials and methods

Heuristic methods were used for the structural synthesis of the WECs` PTO. Simplified block models of hydraulic and electro-hydraulic components were used during the concept and system-level design stages. The proposed study is based on the hypothesis that power capture can be increased through the use of WECs` PTO with variable parameters and structures. For example, an adaptive change of the float arm length can control the pressure in the hydraulic PTO. PTO`s fluid-mechatronic systems will be equipped with pressure and flow sensors included in feedback loops using proportional valves. Such PTO`s fluid-mechatronic systems will be controlled using PID regulations and other advanced control methods depending on changes in the frequency and amplitude of waves, taking into account random wave processes. In addition, this approach will increase the fault tolerance of wave energy converters due to the use of disturbance feedback loops. The next research hypothesis is that applying weight-loaded accumulators instead of hydro-gas accumulators will lead to a more stable pressure regime in the fluid-mechatronic system of PTOs and the ability to store more energy than in the case of a hydro-gas accumulator. This is because the weight-loaded accumulator produces constant pressure, and not pressure associated with gas expansion processes. The research materials were ideas, innovations, hydraulic and hydro kinematic diagrams of power-take-off systems of wave energy converters. The author's publications in fluid mechatronics [14-18] were used for the conducting of this project.

5. Results of the structural synthesis of fluid-mechatronic systems of sea and ocean wave power-take-off

The creation of cost-effective WECs rests on three core questions:

1. How to capture wave energy?

2. How to store the captured energy?

3. How to transfer energy to the electric grid? Moreover, doing this in the right amount and at the right time is desirable.

To solve these three problems, the author proposes some approaches, which are illustrated in Fig. 1.

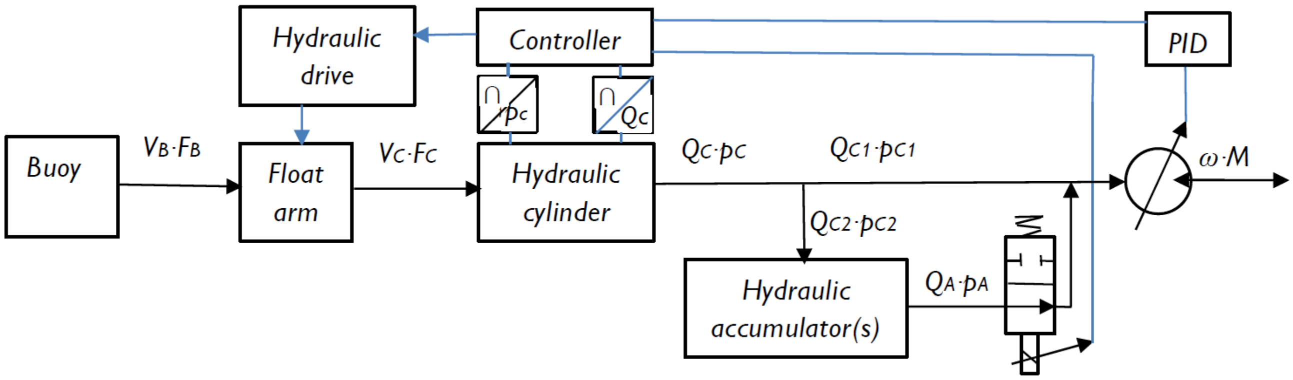

Fig. 1. Power flow fluid-mechatronic PTO of WECs

The parameters in Fig. 1 are variables of the "flow" type and the "potential" type, the product of which gives the power (Table 1). It is necessary to accept that all these values are constantly changing over time and to generate electricity of a given voltage and current, the power flow must be controlled in real time. A PID controller is well suited for this.

Table 1: The parameters in Fig. 1

"Flow" type variables	"Potential" type variables
V_B– buoy velocity	F_B – force on the buoy
V_C·– cylinder velocity	F_C – cylinder force
Q_C·– cylinder flow	p_C – cylinder pressure
Q_{C1}·– flow cylinder-motor	p_{C1} – pressure in line cylinder-motor
Q_{C2} – flow cylinder-accumulator	p_{C2} – pressure cylinder-accumulator
Q_A – flow accumulator-motor	p_A – pressure accumulator-motor
ω – motor`s frequency	M – motor`s torque

Fig. 2 illustrates how the parameters of the hydrokinematic diagram of the WEC can be controlled. Changing the float arm length makes it possible to stabilize the force on the hydraulic cylinder, and therefore the pressure. The basis of Fig. 2 is taken from the dissertation [5], and then modified by the author according to his proposals for improving the WEC.

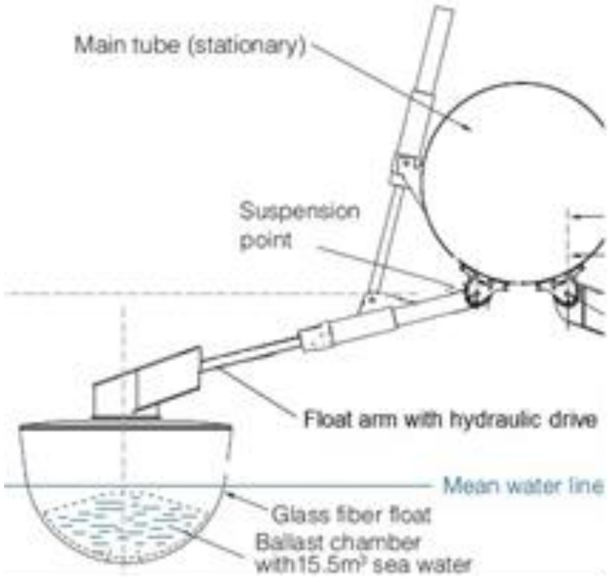

Fig. 2. Float arm with hydraulic drive

6. Discussion of the directions of fluid-mechatronic systems of sea and ocean wave power-take-off future development

The future direction of proposed fluid-mechatronic systems of sea and ocean wave power-take-off development should be the next:

1. Adaptive control of the pressure and flow rate of the fluid-mechatronic system of WECs` PTO to maximize the capture of wave power depending on the frequency, amplitude and length of sea waves;
2. Creation of WECs` PTO with the geometry of their moving parts, which will adaptively change depending on the frequency, amplitude and length of sea waves, thus ensuring more efficient capture of wave power;
3. Usage of the methods of machine learning and artificial intelligence for WECs control depending on changes in the frequency, amplitude and length of waves, taking into account random wave processes.
4. Usage of fluid-mechatronic systems not only as an intermediate link for converting wave power into electrical power but also as a drive for bringing the WECs into a more compact state (possibly submerging them under water) to counteract the destruction of converters during storms and hurricanes;
5. Detection of foreign objects getting between the moving parts of WECs to increase their fault tolerance, as well as reduce the risks of harm to marine mammals and birds by convectors;
6. Wider application of more environmentally friendly liquids (for example, rapeseed oil, polyethylene glycol and aqueous emulsions of these substances) in WECs` PTO.
7. Evaluation of using technologies for gravitational storing of sea wave energy by applying weight-loaded accumulators instead of hydro-gas accumulators.

5. Conclusions

Despite many decades of research, the development of WEC is at the stage of emerging technologies for many reasons. One of the most important, in the author's opinion, is that similar hydraulic circuits are used in various WECs. Further development of the concepts of fluid-mechatronic systems of WECs proposed in the paper will contribute to a more complete power take-off and more reliable operation of wave energy converters.

References

[1] Ocean Energy Europe. "Wave Energy." Accessed October 22, 2024. https://www.oceanenergy-europe.eu/ocean-energy/wave-energy/.
[2] Ponce de León, Sonia, João Horta Bettencourt, John V. Ringwood, and Jérôme Benveniste. "Review of Assessment of Combined Wind and Wave Energy in European Coastal Waters Using Satellite Altimetry." *Applied Ocean Research* 152 (2024): 104184. https://doi.org/10.1016/j.apor.2024.104184.
[3] Chair of Fluid-Mechatronic Systems (Fluidtronic), TU Dresden. Start page. Accessed October 22, 2024.. https://tu-dresden.de/ing/maschinenwesen/imd/fms.
[4] Costello, Ronan, John Ringwood, and Jochem Weber. "Comparison of two alternative hydraulic PTO concepts for wave energy conversion." Paper presented at the 9th European Wave and Tidal Energy Conference (EWTEC), Southampton, United Kingdom, September 5-9, 2011.
[5] Hansen, Rico Hjerm. *Design and control of the powertake-off system for a wave energy converter with multiple absorbers*. PhD thesis. Department of Energy Technology, Aalborg University, Denmark, 2013.
[6] Emrani, Anisa, and Asmae Berrada. "A comprehensive review on techno-economic assessment of hybrid energy storage systems integrated with renewable energy." *Journal of Energy Storage* 84 (2024): 111010.
[7] Li, Fang-Fang, Jia-Zhe Xie, Yu-Fan Fan, and Jun Qiu. "Potential of different forms of gravity energy storage." *Sustainable Energy Technologies and Assessments* 64 (2024): 103728.
[8] Barone, Piofrancesco, Teresa Castiglione, and Sergio Bova. "Wave Energy Converters and Hydraulic Power Take-off: analysis of a possible control strategy." *Journal of Physics: Conference Series* 2648, (2023): 012006.
[9] Soares, C.G., and T.A. Santos (eds.). *Advances in Maritime Technology and Engineering*, vol. 2, 1st Edition. London, CRC Press, 2024. Gaspar, J.F., C. Zeng, H.T. Xu, T.S. Hallak, C. Guedes Soares, and M.J.G.C. Mendes. "Wave energy converter power take-off with active oil-hydraulic accumulator", pp. 427-433.
[10] Wang, Hao, J. Sun, Z. Xi, S. Dai, F. Xing, and M. Xu. "Recent Progress on Built-in Wave Energy Converters: A Review." *Journal of Marine Science and Engineering* 12, no. 7 (2024): 1176.
[11] Jusoh, Mohd Afifi, Zulkifli Mohd Yusop, Aliashim Albani, Muhamad Zalani Daud, and Mohd Zamri Ibrahim. "An innovative dry-lab test rig for mechanical-hydraulic power take-off of wave energy conversion system." *International Journal of Power Electronics and Drive Systems* 15, no. 2 (2024): 715-724.
[12] EMEC - European Marine Energy Centre. "Pelamis Wave Power." Accessed October 23, 2024. www.emec.org.uk/about-us/wave-clients/pelamis-wave-power/.
[13] Eco Wave Power. "How It Works." Accessed October 23, 2024. www.ecowavepower.com/our-technology/how-it-works/.
[14] Skvorchevsky, Alexander. "Comparative Analysis of Current Approaches to Digital Twins of Electro-Hydraulic Mechatronic Systems Creations." Paper presented at the 27th International Conference on Hydraulics and Pneumatics – HERVEX 2023, Baile Govora, Romania, November 8-10, 2023.
[15] Skvorchevsky, Alexander. "The Possibilities Evaluation of Replacing Electro-Hydraulic Actuators with Planetary Roller Screws Linear Actuators." Paper presented at the 5th International Scientific Conference (KTM) KhNADU, Kharkiv, Ukraine, May 24, 2023. *Computer Technologies and Mechatronics* (2023): 89–93.
[16] Skvorchevsky, Alexander. "Electronic Load Sensing for Integrating Electro-Hydraulic Mechatronic Actuators with Industry 4.0 and 5.0 Components." Paper presented at the International Conference on Reliable Systems Engineering (ICoRSE), Bucharest, Romania, September 7-8, 2023. *Lecture Notes in Networks and Systems* 762 (2023): 440–455. https://doi.org/10.1007/978-3-031-40628-7_37.
[17] Skvorchevsky, A. "Identification of the Directions of Self-contained Linear Electrohydraulic Actuators' Development in the Context of Smart-Hydraulics Concept Emerging." Paper presented at the International Conference on Reliable Systems Engineering (ICoRSE), Bucharest, Romania, September 5-6, 2024. *Lecture Notes in Networks and Systems* 1129 (2024): 328–338. https://doi.org/10.1007/978-3-031-70670-7_28.
[18] Volontsevich, D., and A. Skvorchevsky. "Restoration and transformation of high-tech machine building industry by implementing the principles of the CALS-concept in the context of Industry 4.0 development." *Східно-Європейський журнал передових технологій / Eastern-European Journal of Enterprise Technologies* 3, no. 1 (117) (2022): 15-24. https://doi.org/10.15587/1729-4061.2022.260045.