

Article

A Novel Structure of Electromagnetic Lead Screw for Wave Energy Converter

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Abstract: A magnetic lead screw (MLS) is a device that can help a wave energy converter (WEC) to transform the low-speed linear wave motion into high-speed rotary motion with no frictional contact. However, the dynamic performance of the MLS is insufficient because only the permanent magnet (PM) is used to couple the magnetic field between the rotor and mover. To improve the dynamic performance of the MLS, a novel structure of an electromagnetic lead screw (EMLS) for the application of a WEC is proposed in this paper. In the proposed EMLS, a helical-shaped PM is mounted on the inner side of the rotor, which is as same as the traditional MLS. However, helical-shaped slots are grooved on the surface of the mover, and two-phase helical-shaped AC winding is placed in these slots to generate the controlled helical-shaped magnetic field. In this paper, the topology and the operating theory are introduced firstly. Then, the three- and its corresponding two-dimensional axis-symmetric finite element analysis model is developed to analyze the performance of the proposed EMLS. Moreover, the design aspects are presented for the realization of the proposed EMLS. Then, the performance of the proposed EMLS is compared with that of the traditional EMLS. From the results, the proposed EMLS shows larger maximum thrust force than the traditional one. Finally, the potential use value and applications in WECs of the proposed EMLS are mentioned.

Keywords: magnetic lead screw; helical magnetic field; permanent magnet; wave energy converter



Citation: Zhu, L.; Ma, C.; Li, W. A Novel Structure of Electromagnetic Lead Screw for Wave Energy Converter. *Energies* **2022**, *15*, 2876. <https://doi.org/10.3390/en15082876>

Academic Editors: Eugen Rusu, Nunzio Salerno and Ryszard Palka

Received: 18 February 2022

Accepted: 12 April 2022

Published: 14 April 2022

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1. Introduction

Compared with conventional tidal power, wave power has no time limit for generating electricity, and it covers a wide range of generation cycles. Among many existing wave energy converter (WEC) systems [1–6], the point-absorber-type WEC is known as one of the most promising solutions [2]. There are many direct-drive point absorber systems that use a linear generator [2]. To decrease the size of the generator and to improve the reliability of the WEC system, the motion velocity of the point absorber needs to be significantly increased and the linear motion needs to be transferred to rotational motion.

A mechanical lead screw is a device that can transfer slow-speed linear motion to high-speed rotational motion. By replacing the slots with magnets that can create a helical magnetic field, the magnetic lead screw (MLS) is proposed to not only avoid the disadvantages of the mechanical lead screw, such as mechanical friction and jam, but also maintain its function [7]. The structure of an MLS contains a rotor and translator, similar to the mechanical one. Each part strikes two helical magnets with different poles to create a helical magnetic field. By pushing the translator to axial motion, the wave can rotate the rotor via magnetic coupling. Thus, the captured wave energy can be converted into electrical power by the high-speed rotating generator [8,9].

Recently, many researchers have focused on the permanent magnet (PM)-type MLS due to its good reliability [10–14]. The substitution of the MLS to the power take-off (PTO)

system of the Wavestar[®] WEC system, which is one of the actual point-absorber-type WEC systems, is discussed in [15]. It includes a huge float connected to the generation platform with a mechanical arm and the power take-off (PTO) device with an MLS as the core. Thus, when the float is driven by the wave, the mover of the MLS and the mechanical arm can fluctuate up and down with the float, as shown in Figure 1. Then, the generator in the PTO system, which connects to the rotor of the MLS, can generate the electric power. Each float can generate an average power of 20–30 KW with 200–300 KW of peak, according to the statistics in [8].

However, the pure MLS displays some problems that are challenging to solve. The first is the uncontrollability of the screw magnetic fields. This results in excessive axial resistance when the device starts [16]. In addition, the installation of MLS becomes difficult because the magnetic attraction between the mover and the rotor is enormous. The second problem is the difficulty in assembling the magnets of the required helical shape. Although a simplified manufacturing method is proposed in [11], this can result in too many remaining permanent magnets being wasted, while the PMs are very expensive and rare. Moreover, utilizing a great number of small magnets makes the manufacturing very difficult and time-consuming. Finally, the magnetic field of the airgap cannot be adjusted with the wave fluctuation.

To improve the disadvantages of the PM-MLS and simplify its structure, the electromagnetic lead screw (EMLS) is proposed [16]. It replaces magnets on the MLS mover with two sets of windings with opposite DC current, and the windings are fixed in helical-shaped slots to generate helical magnetic fields. A helical-shaped magnetic field is formed with an adjustable current so that the installation and manufacturing are no longer difficult. However, the EMLS cannot generate a satisfactory maximum thrust force, and only the magnitude of the generated magnetic field can be adjusted.

In this paper, a novel structure of the EMLS with a helical-shaped slot, winding, and pole-shoe is proposed to improve the maximum thrust force, and an AC current can be applied on the winding to control not only the magnitude but also the phase of the generated magnetic field. The topology and its operation theory are introduced, and it is analyzed through finite element analysis (FEA) to test its performance. The design aspects of the proposed EMLS are also studied. Then, the performance of the proposed EMLS is compared with that of the traditional one to verify the effectiveness of the proposed structure.

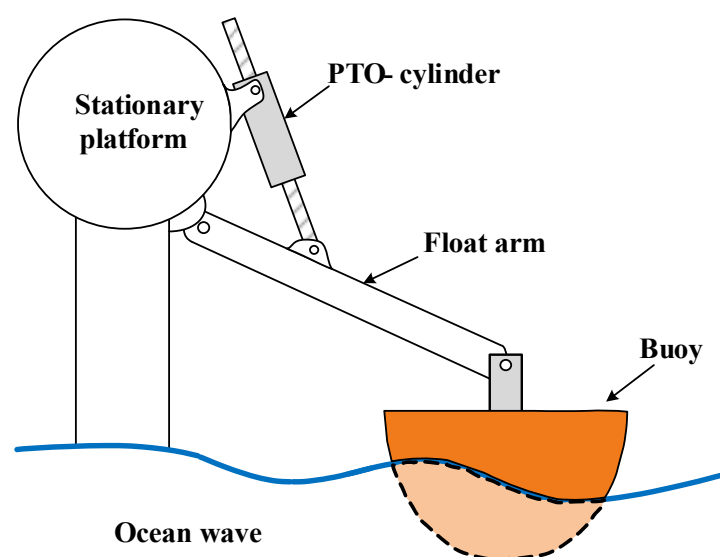


Figure 1. The wave generation system.

2. Topology and Basis Theory of the Novel EMLS

In order to improve the dynamic performance of the MLS and reduce the PM consumption, a novel structure of the EMLS is proposed in this paper; the three-dimensional (3D) and side view of the proposed topology are illustrated in Figure 2a,b, respectively. It can be observed that the proposed EMLS consists of two parts, which are also called the rotor and mover, corresponding to the normal MLS. The helical-type PMs are mounted on the inside surface of the rotor, and two-phase helical-type windings, which are shown in Figure 2c, are mounted in the helical-type slots, which are grooved on the surface of the mover. Thus, the helical-shaped magnetic fields can be generated from the rotor and mover, and they can couple through the airgap. Moreover, the pole-shoes can help to improve the magnetic flux distribution.

To easily understand the operational principle, the corresponding two-dimensional (2D) model from the main view is shown in Figure 2d. As illustrated in Figure 2c, each helical-shaped winding is wrapped around the teeth of the slot. After the current of the opposite direction is applied on the two phases, A and B, the helical-shaped magnetic field can be generated, and it can be adjusted by changing the amplitude of any phase-winding current. Because the PM is only mounted on the mover, the consumption of the EMLS is much lower than that of the traditional MLS.

If the same amplitude and opposite current is applied on the A and B phase winding, the thrust force is 0 N when the positions of the pole-shoe and the magnet are completely opposite to each other, as shown in Figure 2d. As the position of the mover moves forward along the axial direction, the relative displacement between the mover and rotor magnetic poles rises and the thrust force increases to a peak until $\tau_p/2$, as shown in Figure 2e.

With the help of the helical magnetic field, when the mover is moved back and forth, the rotor will rotate around the same axis synchronously, and vice versa. As the mover moves along the z-axis by one lead (denoted as τ), which also refers to 2 poles pitch, the rotor will rotate 2π rad. Following this relationship, the mover's linear speed v (m/s) is linked to the rotor angular velocity ω (rad/s) by

$$v = \frac{\tau}{2\pi} \omega \quad (1)$$

Moreover, a gear ratio $G = \omega / v$ is used to describe the above relationship. Neglecting the losses, the power related to the rotor rotation is equal to the power associated with the linear motion of the mover. Hence, the relationship of the magnetic thrust force F_n and torque T_n can be expressed as:

$$T_n = \frac{v}{\omega} F_n = \frac{\tau}{2\pi} F_n \quad (2)$$

Through adjusting the quantity and the direction between the A and B phase winding, the thrust can be controlled. This means that even if an irregular wave is applied to the mover of the EMLS, the torque of the rotor can be kept constant by controlling the exciting current of the windings.

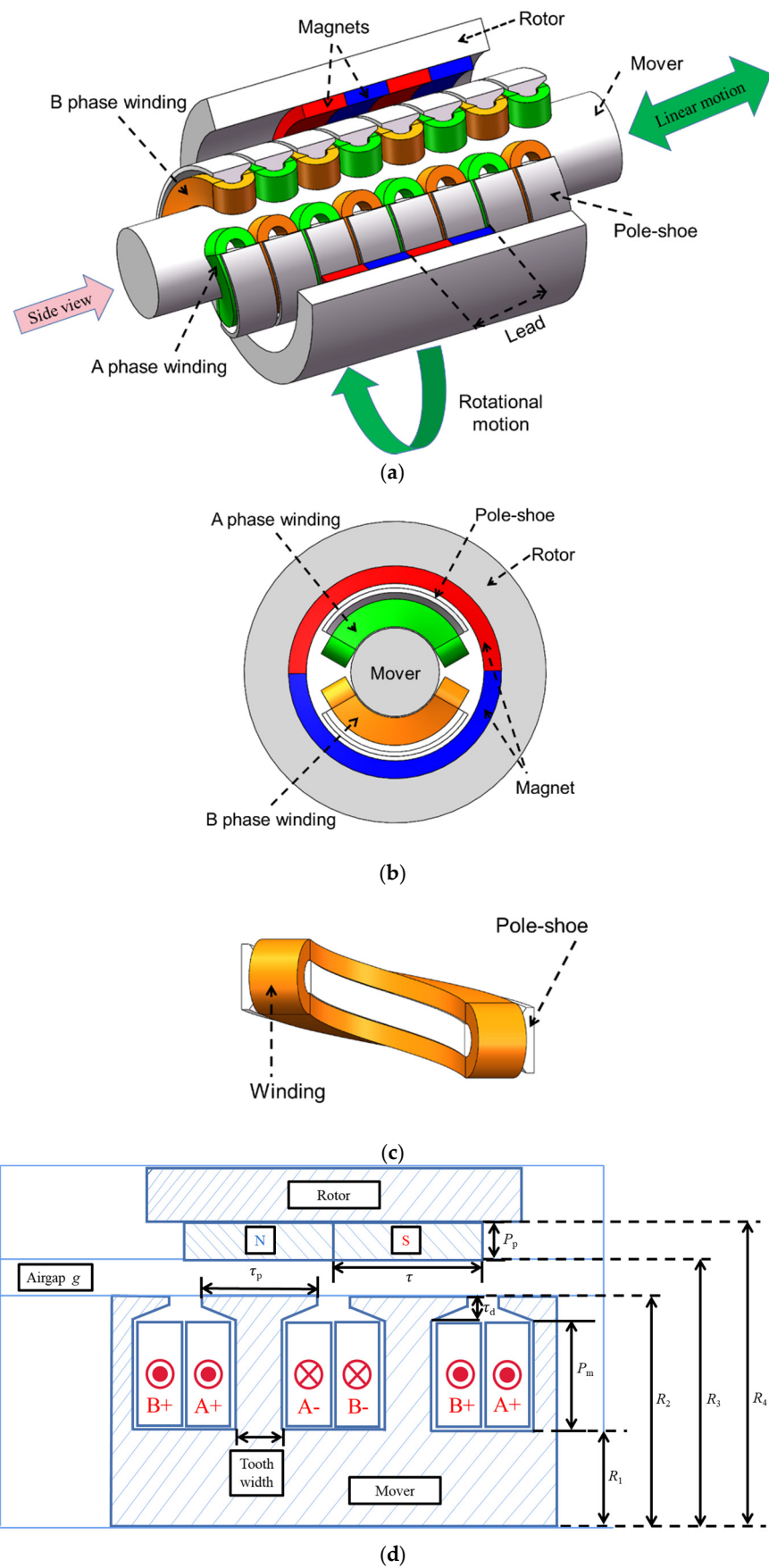


Figure 2. Cont.

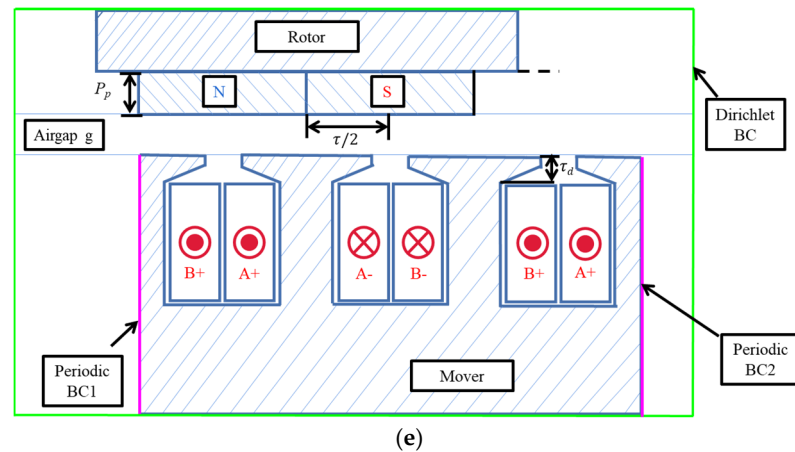


Figure 2. The topology structure of the proposed EMLS. (a) The 3D view of the proposed EMLS. (b) The side view of the proposed EMLS. (c) The helical-shaped winding. (d) The corresponding 2D model from main view of the 3D model when the thrust force is zero. (e) The 2D axially symmetric FEA model when the thrust force is maximum.

3. Numerical Model of the Proposed EMLS

The magnetic field distribution in the proposed EMLS is a 3D helical shape (Figure 3), which means that it requires a 3D FE model to analyze the performance of the magnetic field. The vector magnetic potential $\mathbf{A}$ is selected to formulate the magnetic field distribution of the EMLS. The governing equations are

$$\begin{cases} \nabla^2 \mathbf{A} = \frac{1}{\mu_r} \nabla \cdot \mathbf{M} \text{ (in PM)} \\ \nabla^2 \mathbf{A} = 0 \text{ (in iron and air)} \end{cases} \quad (3)$$

where μ_r and $\mathbf{M}$ denote the relative recoil permeability and remanent magnetization vector of the PMs. The magnetic field intensity $\mathbf{H}$ can be obtained by

$$\mathbf{H} = -\nabla \mathbf{A} \quad (4)$$

In this paper, a 3D FEA model of the proposed model is developed by using the commercial FEA software Ansys Maxwell. To verify the model and compare it with the traditional EMLS, the specification of the traditional EMLS, which is mentioned in [16] and shown in Table 1, is applied to the proposed 3D FEA model. The 3D vector magnetic field distribution of the proposed EMLS is shown in Figure 3. The corresponding thrust curve is shown in Figure 4. Moreover, to verify the model of the proposed EMLS, a 3D model of the traditional EMLS was also developed. In Figure 4, the thrust force curve of the traditional EMLS is compared with the published one in [16]. From the figure, the calculated result of the traditional EMLS is in line with the published one, and this verifies the effectiveness of the 3D FEA model developed in this paper.

However, the process of 3D FEA is time-consuming. If the length of the airgap g is much smaller than the pole pitch τ , the magnetic field distribution can be approximated as 2D axially symmetric [16]. Thus, ignoring the loss of generality, an axially symmetric model, as shown in Figure 2e, which corresponds to the 3D FEA model, can be used for analyzing the performance of the proposed EMLS. In addition, the thrust force of the 2D model is shown and compared with the 3D model in Figure 4. From Figure 4, the thrust force of the 2D and 3D models shows good agreement, and the error of the maximum thrust force is 4.2%. Hence, the 2D axis-symmetrical model is proven to be a reasonable alternative to the 3D model for force prediction. Moreover, the magnetic flux distribution of the 2D model is given in Figure 5.

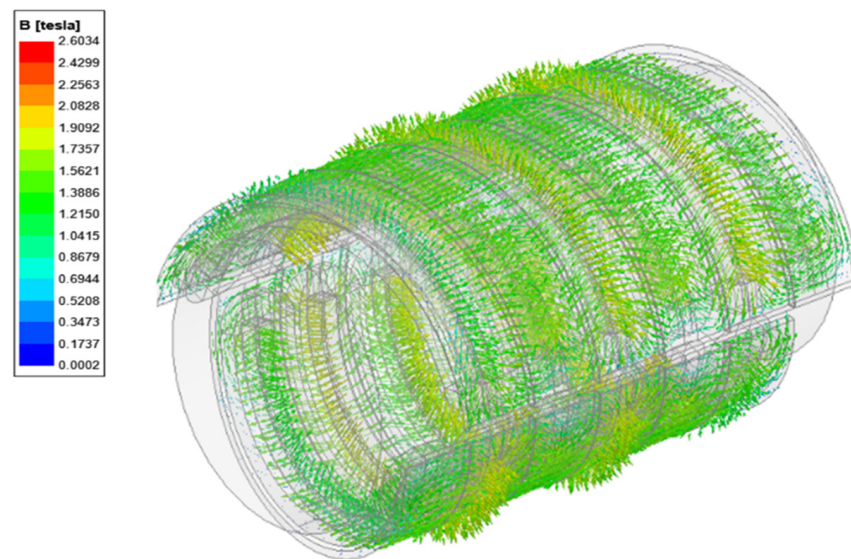


Figure 3. The 3D vector magnetic field distribution of the proposed EMLS.

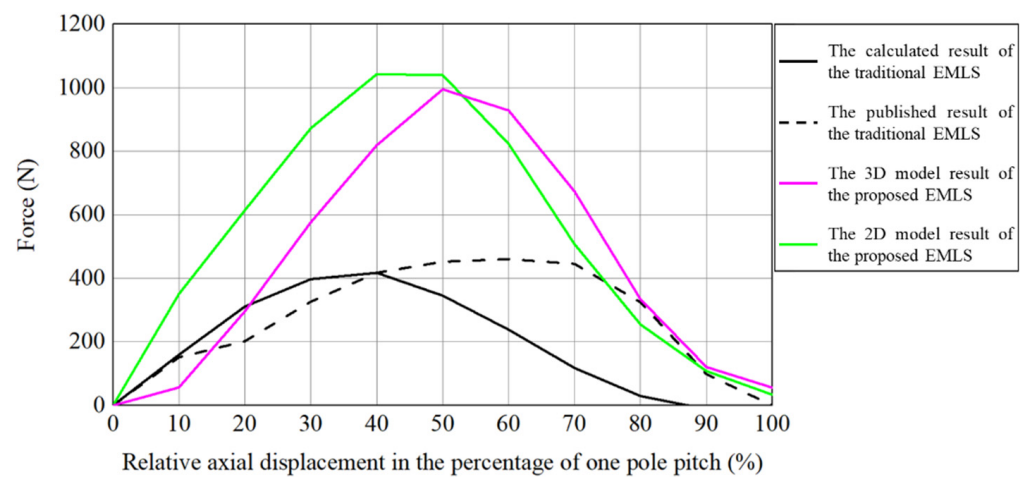


Figure 4. The thrust force curve of the FE models.

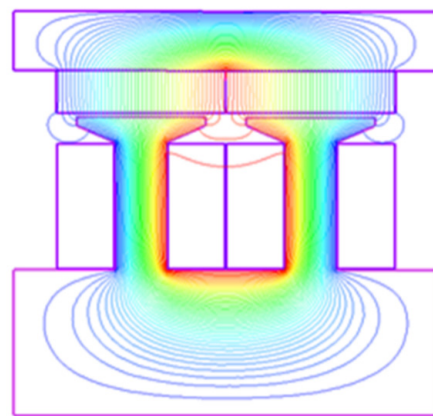


Figure 5. The 2D magnetic flux distribution of the proposed EMLS.

Table 1. Specification of the verified model.

Symbols	Description	Value
τ	Lead	10 mm
τ_p	Pole-shoe width	8 mm
τ_d	Pole-shoe thickness	3 mm
J_m	Current density	2.8 A/mm ²
R_2	Outer diameter of mover	45 mm
R_4	Outer diameter of rotor	52 mm
R_1	Mover thickness	25 mm
p_p	PM thickness	6 mm
g	Airgap length	1 mm
B_r	Magnet remanence	1.2 T

4. Design and Analysis

Some parameters, such as the current density of wires J_m , width of shells τ_p , thickness of pole-shoe τ_d , the ratio of tooth width to the lead n_d , and thickness of the winding p_m , which are illustrated in Figure 2d, can significantly affect the performance of the proposed EMLS. To study the impacts of the parameters on the performance of the proposed EMLS, parametric analysis using the above axis-symmetrical 2D FEA was carried out.

The thrust force variation with the pole-shoe width τ_p is shown in Figure 6. It may be observed from Figure 6 that τ_p slightly influences the maximum thrust force. However, it changes the rise rate of the curves. Wider pole-shoes provide a faster rise in the thrust force, which means that the EMLS can enter working mode with less displacement. For example, suppose that the WEC requires 300 N as the minimum drive force to keep the generation device in working condition; a 16 mm width pole-shoe of the proposed EMLS with only approximately 2 mm of moving displacement can help the WEC to cope with frequently changing sea conditions. Under the premise of ensuring the installation space of wires, increasing τ_p as much as possible within lead can increase the timeliness of the WEC response.

At the same time, Figure 7 shows the variation in the maximum thrust force with the thickness of the pole-shoe τ_d . From the figure, the τ_d enhances the thrust force in a rate of decay. However, the τ_d has no effect on the shape of the thrust force waveform. Therefore, with a reasonable choice of τ_d and τ_p , one can help the EMLS to increase its drive force without slowing down the EMLS' startup.

The effect of p_m and n_d is illustrated in Figures 8 and 9; it seems to be simpler because these two variables only affect the maximum value while keeping the waveform. The effect of p_m on the force is gradually diminishing due to the saturation, as shown in Figure 10. When p_m rises to 17.5 mm, there is almost no increase in thrust force compared to the last comparative level. Moreover, the influence of n_d on the maximum thrust force is weak first, and then strong, and finally weakened again. However, an excessive increase in n_d will lead to a decrease in the energy density of the EMLS. Therefore, choosing an appropriate p_m and n_d according to the required torque of the generator will help the EMLS to achieve the best energy utilization efficiency.

With the analysis of the above variables, the designed EMLS with parameters shown in Table 2 is compared to a traditional MLS with the same PM thickness p_p under the same moving speed condition. The compared result is shown in Figure 11. As the comparison shows, the maximum value of the proposed EMLS is roughly one third lower than that of the traditional MLS. However, the designed EMLS reaches the peak speed value faster than the traditional one. With the same hypothetical required force, the minimum displacement of the novel EMLS d_1 is approximately half that of MLS d_2 , as shown in Figure 11. For the rotating linear conversion device, taking less displacement than the MLS requires to reach the same drive value means higher motion performance and timeliness, especially in changeable wave conditions. It should also be noted that the quality of this kind of EMLS's helical magnetic field is much better than that of an MLS. In [14], 4000 pieces of magnets

were mounted on a 400 mm stroke length MLS one by one. However, due to the gaps between magnets, 40% of the stall force was lost. In [6], though the segmented installation provided 90% of the analysis force, the glue between the magnet and rotor caused the outer surface not to be perfectly round. This resulted in a large airgap to ensure relative motion between the mover and rotor. Thus, it can be concluded that with its optimal design, the novel EMLS can produce better performance than a traditional MLS.

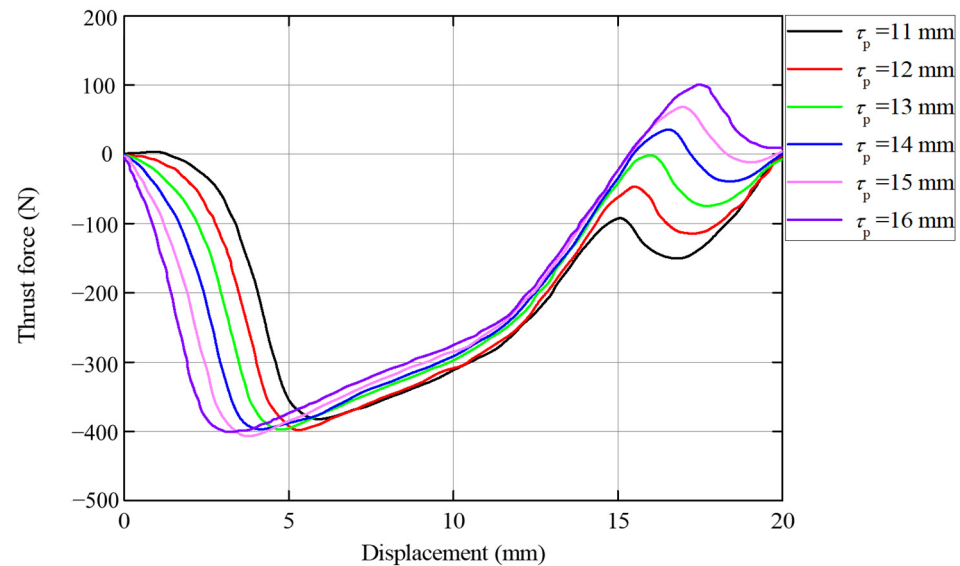


Figure 6. The thrust force waveform variation with the pole-shoe width τ_p .

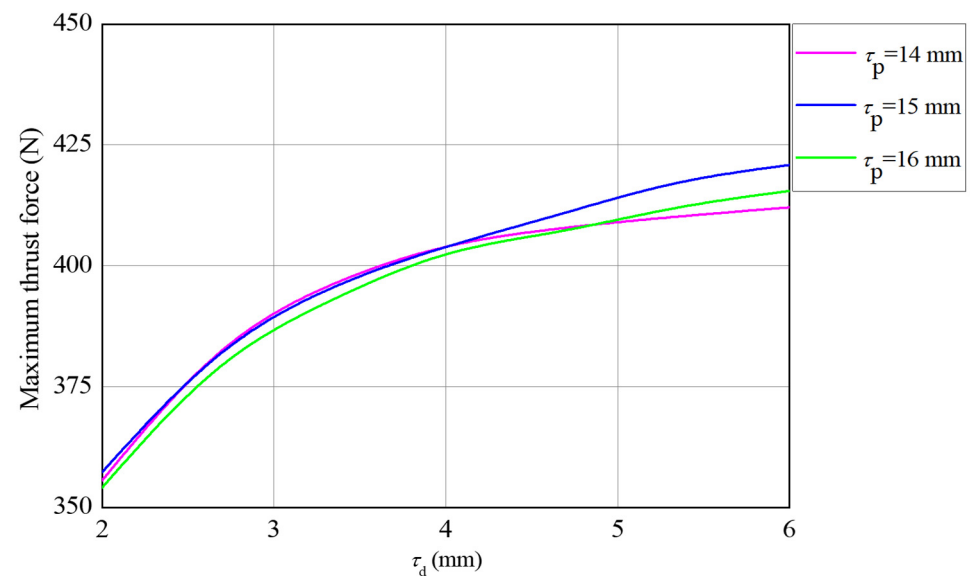


Figure 7. Variation in the maximum thrust force with thickness of the pole-shoe τ_d .

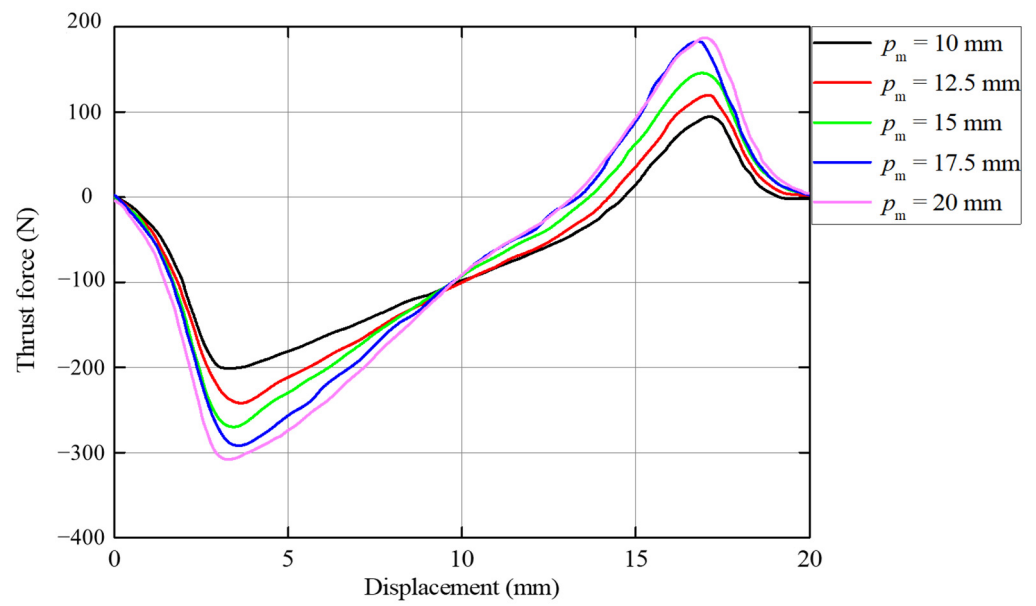


Figure 8. Variation in thrust force with thickness of windings p_m .

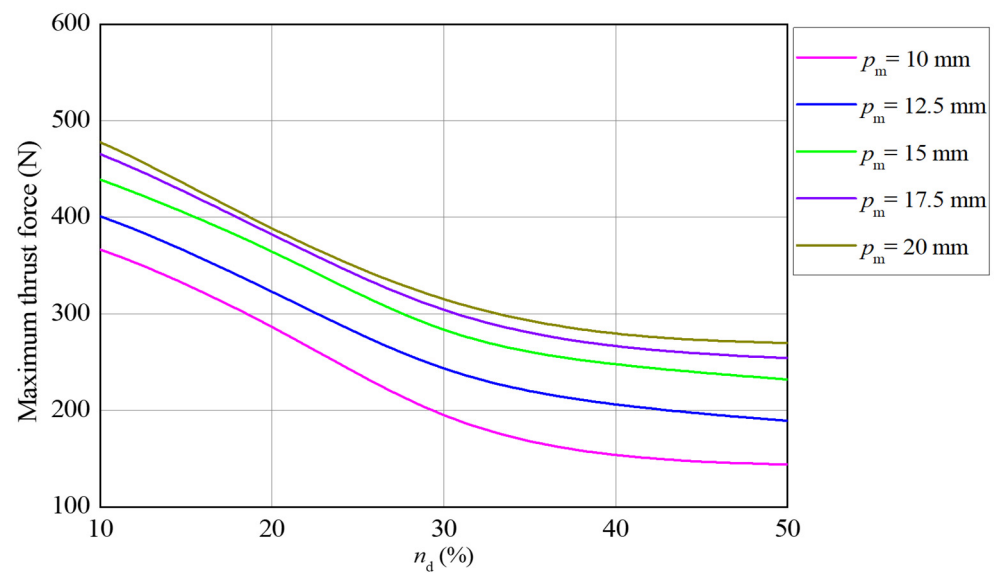


Figure 9. Variation in thrust force with slot ratio n_d .

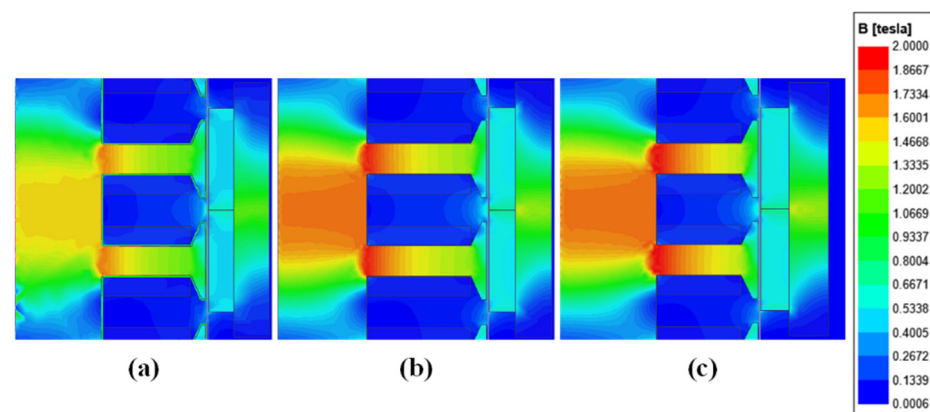


Figure 10. The 2D magnetic flux distribution of the proposed EMLS. (a) $p_m = 15$ mm; (b) $p_m = 17.5$ mm; (c) $p_m = 20$ mm.

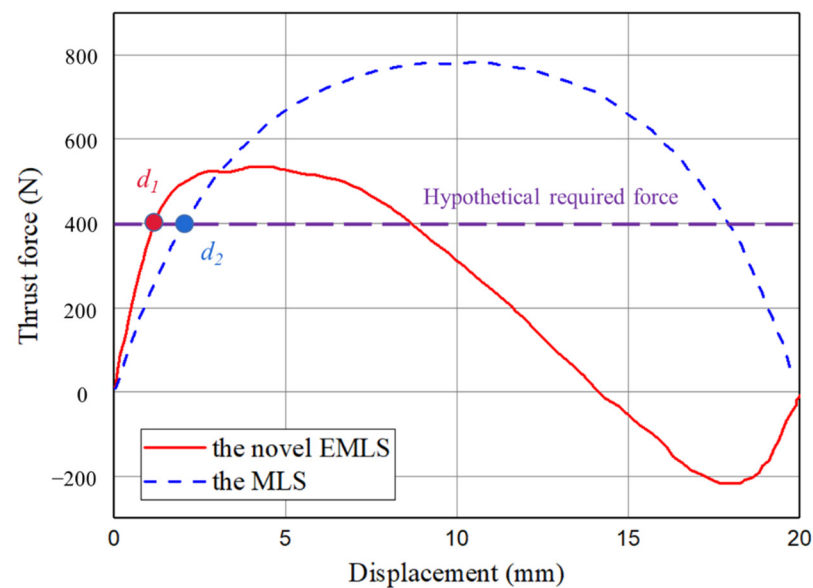


Figure 11. The thrust force comparison between the novel EMLS and normal MLS.

Table 2. Designed parameters.

Symbols	Description	Value
τ	Lead	20 mm
τ_p	Pole-shoe width	16 mm
τ_d	Pole-shoe thickness	4 mm
n_d	Ratio of the tooth width to the lead	20%
p_m	Winding thickness	17 mm
J_m	Current density	8 A/mm ²

5. Applications of Proposed EMLS in WECs

With the exception of the quick start, the main feature of the proposed EMLS is the adjustable parameters. Unlike a pure MLS with a permanent magnet, the EMLS can change the strength of the magnetic field by changing the current through it; thus, the thrust force can be changed too [7]. According to the overview of energy conversion shown in Figure 12, the PTO system with the proposed EMLS can receive a signal from the sensor, which collects current information from the generator. The AC source stores some electricity to ensure that the EMLS has enough power to provide the minimum force capable of actuating the PTO. When the wave comes to push the PTO, the EMLS starts to operate and the AC signal of generation rises from 0. The AC source will provide an increasing current at the same frequency as the generator's signal. The increasing current must be limited to a predefined maximum value to ensure that the EMLS is always able to provide suitable thrust, instead of being affected by overlarge torque. Thus, the EMLS will be quick and easy to start, and it will have a satisfactory thrust force during operation at the same time. The electricity from the generator will be converted into DC for transmission, and then converted to qualified AC collected by the AC source. Then, the accumulated energy will be divided into two parts; a small fraction is used to provide the power needed by the EMLS, and the rest will be exported to the grid.

Because of its dynamic performance, the PTO of the point absorber with the proposed EMLS can be improved as shown in Figure 13. Two stators are fixed inside the float, and support structures are connected between them to hold up the center. The rotor is mounted inside the center, and the mover is fixed between two stators to remain completely still. Different from a normal WEC device, which is powered directly by waves, the device relies on gravitational potential energy from the buoy as it is pushed by waves. The central part will slide back and forth linearly with the float. Then, the linear motion can be transferred

to rotational motion by the proposed EMLS. With the very small initial magnetic resistance, the variable magnetic resistance enables the device to start working at a small incline angle and to have sufficient torque and thrust when it reaches the normal working state. The device can also ignore high and low tides, which render normal PTO devices difficult to operate due to their structure, which moves with the sea level. In addition, this proposed EMLS also can be introduced in floating wind turbine energy conversion, as mentioned in [17,18].

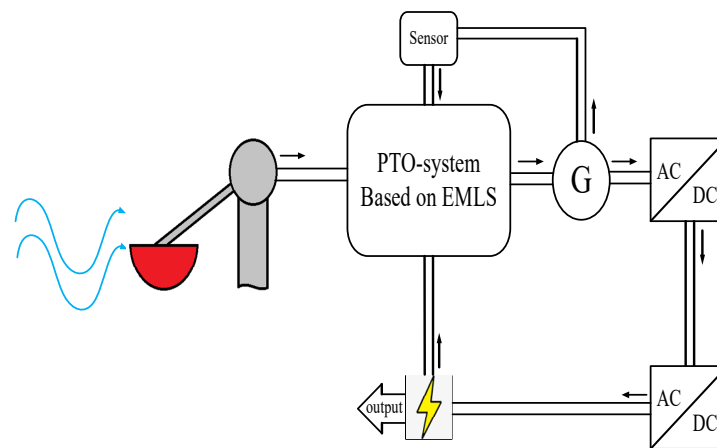


Figure 12. Overview of energy conversion with proposed EMLS.

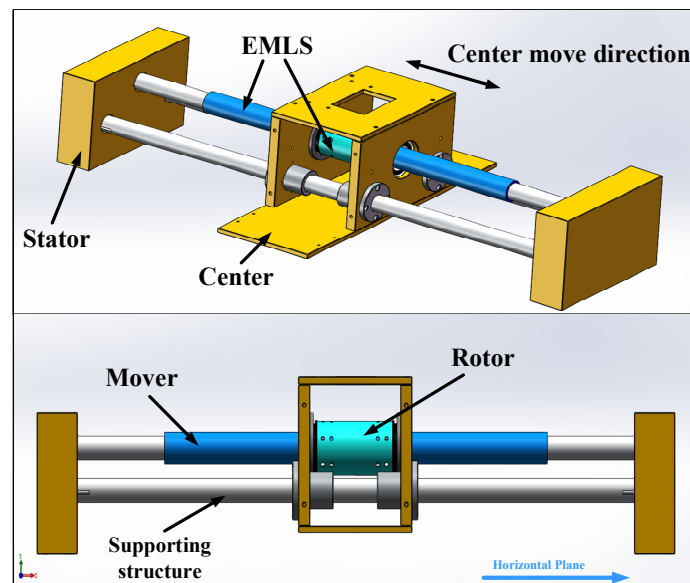


Figure 13. Structure of the improved PTO device.

6. Conclusions

In this paper, a novel structure of an electromagnetic lead screw (EMLS) for the application of WECs is proposed. The helical PM is mounted on the inner side of the rotor. However, the helical-shaped slots are grooved on the surface of the mover, and two-phase helical-shaped AC windings are placed in these slots to generate the controlled, helical-shaped magnetic field. The proposed EMLS is analyzed with its FEA model, and the design aspects are presented. The performance of the proposed EMLS is compared with that of the traditional MLS. Though the maximum thrust force of the proposed EMLS is smaller than that of an MLS, it shows some particular advantages, such as a fast force rise rate, lower PM consumption, and better dynamic performance. This design will help

the WEC system to enhance its power density and controllability when dealing with the complicated wave generation demands.

Author Contributions: Conceptualization, L.Z.; Investigation, C.M.; Methodology, C.M.; Software, C.M.; Supervision, L.Z. and W.L.; Writing—original draft, C.M.; Writing—review and editing, L.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was sponsored by the National Natural Science Foundation of China under grant 52007113 and 51777139, the SHANGHAI SAILING PROGRAM under grant number 20YF1416300, and the Shanghai Frontiers Science Center of “Full Penetration” Far-Reaching Offshore Ocean Energy and Power.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest: The authors declare no conflict of interest.

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