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Investigating Wave Energy Effects on Swimmer Dynamics: An Analytical and Experimental Approach

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Abstract:
Swimming in open water has unique biomechanical challenges due to the effects of various waves and environmental factors on the swimmer's pattern, stability, and performance. This study examined how wave energy parameters affected a swimmer's biomechanical response in a water environment. In this study, a theoretical and experimental approach investigated wave energy through parameters such as amplitude, frequency, and power using standard fluid dynamic equations. A wave generation system utilizing two MG996R motors was de- signed to control a flap mechanism, which simulates wave motion. The system is controlled via a microcontroller to create waves, and a swimmer model fitted with an MPU6050 triaxial accelerometer and gyroscope was used to collect precise motion capture data that was as detailed as possible. Controlled experiments were conducted under multiple wave conditions. Data acquisitions took place and were analyzed in the time and frequency domains. Data was analyzed in the frequency domain using Fast Fourier Transform (FFT) to determine dominant frequency components in the swimmer's movements. Power Spectral Density (PSD) provided an estimate of the energy distribution in the swimmer's movements. The results showed that as the wave energy increased, the swimmer's body displacements increased, the swimmer's in- stability increased, and the average corrective movement frequency also increased. The results illustrate that environmental wave dynamics had a significant effect on swimmer biomechanics and provide implications for training opportunities for open water swimmers, safety for athletes, and human-aquatic body interactions.

Keywords: *Wave energy Parameters, Flap Mechanism, Swimmer Motion pattern, Motion analysis, Fast Fourier Transform (FFT), Power Spectral Density (PSD).*

Introduction

The study of wave power and its interaction with the human body is an important juncture for fluid dynamics, biomechanics, and energy transduction. Waves, defined by their velocity, energy, and power, are pivotal to determining swimming athlete dynamics. These interactions are critical not only in optimizing athletic ability but also in designing novel solutions that capture wave energy for everyday use. This study is most applicable in that it goes beyond theoretical investigation, providing practical advantage to both sport participants aiming to improve performance and engineers concerned with renewable energy systems [1].
Regarding alternative solutions, wave energy offers a clean and sustainable power source for energy production, especially via methods such as wave energy converters. Nonetheless, this method has its own strengths and weaknesses. The benefits of tapping wave energy are many. Firstly, it is a renewable form of energy, which emits much less carbon dioxide compared to conventional fossil fuel sources. Furthermore, wave energy is a form of energy that has high density, i.e., it will be able to produce large quantities of power for relatively small sets of installations. This makes the energy an appropriate choice for the coastal towns willing to utilize regional resources for supplying energy[2].
Nevertheless, the integration of wave energy technology is far from easy. Among the important shortcomings is that the patterns in waves are imponderable because of weather factors and seasonal changes. This ambiguity raises concerns for calculating energy production and transferring the energy to conventional power systems. In addition, technical innovation in extracting and converting the energy stored in waves into useful power remains a formidable challenge. These are central to the solution if the maximum potential of wave power as a source of clean energy is to be achieved[3].
The research methodology used in this case is a scientific study of wave behavior and its inter- action with

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swimmers. The following equations will be utilized to quantify the energy transfer between swimmers and waves: wave number $k = \frac{2\pi}{}$, angular frequency $\omega = 2\pi f$, and group velocity $vg = \frac{d\omega}{}$. By measuring these parameters, this study seeks to develop a solid theoretical and empirical basis which can be implemented in real life. The long-term vision is to bridge the gap between theoretical physics and application, ultimately benefiting sports science and sustainable energy technology[1].

This research has wide applications to the general public because it provides information that makes life easier. To swimmers, wave kinematics can lead to improved training techniques that maximize performance in competitive competitions and even recreational swimming. Training techniques can be formed by coaches using this information, maximizing better techniques for maximum performance in the water[4]. Moreover, improvements in wave energy technologies may lead to more sustainable energy options, which will benefit communities through less de- pendence on non-renewable resources. With society increasingly looking for cleaner sources of energy, the results of this research could lead to new innovative uses that ensure environmental sustainability while also contributing to economic development. In the end, this research seeks not only to develop academic knowledge but also to lead to practical applications that improve the daily lives of people and communities[5].

Literature Review

The study examined by Eyal Setter et al.[6] explored the role of body undulations in butterfly swimming, focusing on two potential benefits: minimizing vertical displacement of the center of mass (CM) to conserve energy and using body wave motion to enhance propulsion. The CM and key body landmarks (head, shoulders, hips, knees, and ankles) were tracked, and Fourier analysis was used to study oscillation amplitudes, wave velocities, and phase relationships dur- ing the stroke cycle. The findings revealed that vertical CM movement was small (0.106 m for males, 0.089 m for females), but reducing CM oscillation did not correlate with better per- formance. Instead, simultaneous peak movements of the shoulders, hips, knees, and ankles suggested that elite swimmers do not prioritize minimizing CM displacement. Fourier analysis showed that most energy in vertical oscillations of the vertex and shoulders was at the funda- mental frequency (H1), while the two-beat dolphin kick (H2) dominated in the hips, knees, and ankles. However, the only limitation of the research was not explicitly stated.

The study by C. J. Fulton et al.[7] measured wave-induced water motion across different reef habitats using Lagrangian and Euler flow measurements and found significant spatial variation in water velocity and flow direction with depth and exposure. They categorised 5230 reef fish from 117 species into three swimming modes: pectoral (labriform), pectoral-caudal (chaetodontiform), and caudal (subcarangiform). Experimental trials measured critical swim- ming speeds and found that labriform swimmers, which use lift-based thrust with high aspect ratio (AR) pectoral fins, were the fastest and dominated high wave energy habitats. The study found a strong correlation between pectoral fin AR and swimming speed, an ecomorphological adaptation of labriform fishes to wave-swept environments. The results show that wave energy has a significant evolutionary and ecological impact on reef fish distribution and locomotor abilities. But a limitation of the study is the reduced diversity of temperate reef fish assemblages compared to tropical ones, which may have impacted the generalisability of fin-shape-related results.

The study by J. H. Long Jr et al.[8] addresses whether American eel myomeric muscles can actively change body stiffness while bending, thereby influencing the eel's swimming kinematics. The methodology involved dynamically bending mid-caudal sections of freshly killed eels using the whole-body workloop technique at 3 Hz. Muscles were alternately activated at supra- maximal voltages during eight different stages of the cyclic strain cycle. Results showed that muscle stimulation increased the body's flexural stiffness by up to threefold and reduced the external work required for bending by up to sevenfold, with both effects varying sinusoidally based on stimulus phase. Results indicate that live eels can simultaneously increase stiffness and mechanical useful work when swimming, and that elastic strain energy can power movement. Nevertheless, owing to the use of frozen specimens, this study has a potential limitation in that muscle coordination and behavior in live eels during complex swimming patterns may differ significantly.

The study by Z. M. Yuan et al.[9] examines hydrodynamic interactions between human swimmers, focusing on how the presence of adjacent competitors influences wave drag and performance. Using a steady potential flow solver, the researchers calculated wave drag on a single swimmer in an open pool and a drafter swimming in the wake of one or two leaders, incorporating the free-surface effect in all calculations. Results demonstrated that drafters in optimal wave-riding positions could reduce wave drag by up to 63% behind a single leader, with drag reduction doubling when drafting behind two side-by-side leaders. The study concluded that hydrodynamic interactions significantly enhance a drafter's performance by leveraging wave interference and cancellation effects. However, the study's limitation lies in its reliance on simulations, which may not fully capture the complexities of real-world swimming dynamics.

The investigation by David R. Bellwood et al.[10] examines how wave energy affects swim- ming performance and distributions of reef fish assemblages in tropical and temperate regions, focusing on morphological adaptations such as pectoral fin shape and body size. Researchers conducted field surveys at 33 sites to quantify wave exposure and fish assemblage structures. Swimming performance (critical speed, U_{crit}) and morphological characteristics (pectoral fin aspect ratio; body size) were recorded for 56 species. Tropical species had very high pectoral fin aspect ratios associated with abundance in high-energy habitats, while temperate species re- lied mainly on larger body sizes to swim in wave-swept areas. Labriform swimmers dominate high-energy zones worldwide. Wave energy results in parallel ecomorphological adaptations in reef fishes, but biogeographical differences exist—tropical systems select for fin shape spe- cialization, while temperate systems show greater reliance on body size specialization.

S. G. Posveh et al.[11] studied the wave dynamics and phase coordinates of free-swimming flagellar apparatus removed from a wall-less strain of *Chlamydomonas*. It was established that there was insufficient coupling between the two flagella through their basal bodies, either mechanically or through hydrodynamic interactions, to synchronize them when the frequency difference was large. This indicates that the phasic frequency must be regulated intracellularly through signaling processes. High-speed videography and computational modeling were used to analyse phase lag similarities. Further investigation was conducted on the role of dynein motor proteins in flagellar coordination, proposing intracellular signaling mechanisms as the regulating factor.

H. Kurtuldu et al.[12] investigated time-dependent flagellated waveform propagation patterns of biflagellate algae and their influence on forward motion. Researchers quantitatively ana- lyzed flagellar movement using resistive force theory and singularity methods. High-resolution microscopy and computational fluid dynamics simulations identified net forward displacement generated mainly during the recovery stroke due to hydrodynamic interactions between flagella and the cell body. The study also evaluated propulsive efficiency over varying Reynolds num- bers to determine optimal propulsion strategies. However, extrapolating these findings to other microorganisms is limited due to diversity in flagellar structures.

Allison P. Berke et al.[13] examined hydrodynamic interactions impacting microorganism motil- ity through observational studies and fluid-structure interaction modeling of microorganisms swimming in closed containers. The models provided insight into collective behavior in biofilms and microbial mats. Findings confirmed that hydrodynamic coupling can enhance swimming performance and synchronize bacterial movement. A limitation is that laboratory conditions may not fully represent natural environments where factors such as fluid viscosity, turbulence, or complex habitats influence microbial behavior.

The study by Yu Pan et al.[14] demonstrates hydrodynamic interaction within schooling fish. Researchers combined controlled experiments with mathematical modeling and tracked indi- vidual fish movements to quantify vortex-induced effects on swimming. High-speed flow vi- sualization confirmed that fish adjust positions relative to neighbors to optimize hydrodynamic efficiency. Long-bodied species with high aspect ratio fins benefited most from collective mo- tion, especially against drag. However, the artificial environment used in the study limits gener- alizability to natural schooling behavior where predation and habitat complexity also influence coordination.

Peter J. Baddoo et al.[15] developed advanced fluid dynamic theories based on Theodorsen, von Ka´ rma´ n, and Wu to expand understanding from single swimmers to multi-body hydrody- namic interactions. Using multiply connected complex analyses and the Schottky–Klein prime function, the authors formulated conformal maps and leading-edge suction functions to solve generalized Schwarz and Wu's waving-plate problems. A numerical model of two interacting swimmers enabled fast force calculations and accurately predicted flow-mediated equilibria, validated against experimental results. The limitations include assumptions of two-dimensional inviscid flow, which restrict applicability to real three-dimensional, viscous environments.

The study by Banks, Joseph et al.[16] highlights challenges in quantifying swimmer wave re- sistance due to difficulties in direct measurement and inconsistencies in previous research. This work integrates experimental measurements with Computational Fluid Dynamics (CFD) using OpenFOAM. A generic human model was morphed to reflect swimmer posture and depth, and URANS simulations with Volume of Fluid (VOF) captured the air–water interface. CFD results matched experimental data well, verifying the numerical approach. Limitations arise from the generic human geometry and single swimming speed tested.

Research by Per Ludvik et al.[17] explored how swimming performance in calm water trans- lates to dynamic open-water conditions. The study assessed performance decrements across four swimming strokes (front crawl, head-up crawl, back crawl, breaststroke) at three wave heights (flat, medium, large). (1) Thirty-three participants swam 25 m sprints in a specialized wave-generating pool. Results showed significant reductions in velocity under wave condi- tions, but stroke ranking remained consistent. Although informative, the study is limited to short-distance sprints and controlled wave patterns.

Thomas et al.[18] examined swimmer wave resistance at varying depths to optimize glide- phase strategies. Using a mannequin representing a female swimmer, drag and wave patterns were measured at depths between 0.05 m and 1.00 m while moving at 2.50 m/s. Numerical simulations validated thin-ship theory and assessed the effects of pool confinement and body truncation. Results showed wave resistance was highest above 0.40 m depth and highlighted the importance of shoulder proximity to the surface. Limitations include the inability of man- nequins to replicate human motion and fixed-speed testing conditions.

The study by Hochstein Stefan et al.[19] investigated complex flow dynamics associated with human underwater undulation. Time-resolved 2D particle image velocimetry (TR-2D-PIV) was combined with CFD simulations to analyze flow variables. Findings showed that swimmers generate undulatory body waves similar in amplitude distribution to fish but at significantly higher Strouhal numbers. CFD highlighted 3D flow structures, vortex formation, and recapture. Limitations include the 2D nature of PIV compared to fully 3D flow.

Methodology

1. Wave Theory

This study aims to determine the wave energy produced by swimmers, specifically the wave resistance aspect of the total drag.

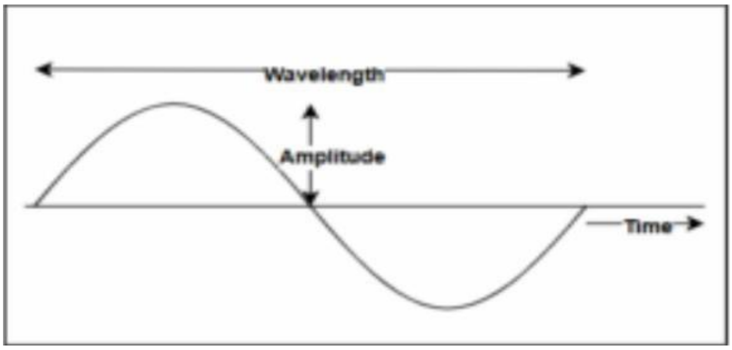

Figure 1: Sinusoidal waveform

Figure 1 depicts a sinusoidal wave; amplitude, wavelength, and period define the motion and energy transfer characteristics of water waves. Amplitude is the maximum distance from equilibrium, wavelength is the distance from one crest to the next, and period is the time required for one complete cycle. Frequency is defined as the reciprocal of the period, expressed as:

$$f = \frac{1}{T}$$

where f is frequency (Hz) and T is the period (s).

Wave speed is given by:

$$v = f\lambda \tag{2}$$

where v is wave speed (m/s), λ is wavelength (m), and f is frequency (Hz) or T is the period.

The total energy of the wave is:

$$E = \frac{1}{2}\rho g A^2 \tag{3}$$

where ρ is water density (1000 kg/m^3), g is gravitational acceleration (9.8 m/s^2), and A is amplitude. The power of the wave is:

$$P = \frac{1}{2}\rho g^2 T A^2 \tag{4}$$

Equations (1)–(4) form the basis of artificial wave creation. From these equations, various components for wave generation were selected and discussed later in this section.

2. Swimmer Force and Energy Consumption

The energy consumption of the swimmer was calculated using motion data obtained from the MPU6050 sensor placed inside the swimmer model. The MPU records triaxial accelerometer data (a_x, a_y, a_z) and gyroscope data (g_x, g_y, g_z) at a fixed sampling interval.
The resultant acceleration is:

$$a_r = \sqrt{a_x^2 + a_y^2 + a_z^2} \tag{5}$$

Force exerted by the swimmer:

$$F = m \cdot a \tag{6}$$

To approximate displacement per wave cycle, the IMU captured acceleration every 0.5 seconds. Assuming constant acceleration during each interval, displacement was calculated using:

$$D = \frac{1}{2} a_r t^2 \tag{7}$$

with $t = 0.5$ seconds. Mechanical energy consumption:

$$E = F \cdot D \tag{8}$$

$$F_{motor} = \frac{\tau}{r} \tag{9}$$

where $\tau = K_t I$.
Mechanical energy from motor force:

$$E_{motor} = F_{motor} \cdot D \tag{10}$$

Acceleration data was also analyzed in the frequency domain using the Discrete Fourier Trans- form (DFT):

$$X(k) = \sum_{n=0}^{N-1} x(n) e^{-i \frac{2\pi}{N} kn} \tag{11}$$

FFT representation in terms of physical frequency f:

$$X(f) = \sum_{n=0}^{N-1} x(n) e^{-i \frac{2\pi f n}{N}} \tag{12}$$

Power at each frequency bin:

$$P(f_k) = |X(f_k)|^2 \tag{13}$$

Power Spectral Density:

$$PSD(f_k) = \frac{|X(f_k)|^2}{N \Delta f} \tag{14}$$

3. Assumptions for Experimental Analysis

- Scale model accuracy: the tank and action figure represent swimmer dynamics at scale.
- Sensor accuracy: MPU6050 readings are assumed reliable.
- Wave generation: servo motors create consistent, periodic waves.
- Negligible boundary effects: reflections and distortions are minimal.
- Linear motion: pulley system approximates forward–backward swimmer motion without slippage.

4. Experimental Setup and Testing

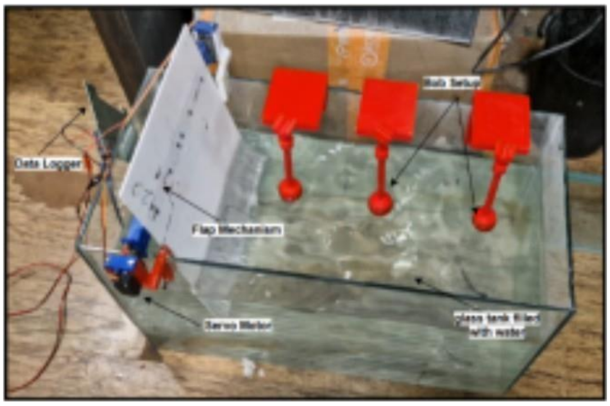

Figure 2: Experimental setup of servo-controlled wave tank

Figure 3: Model used to mimic the swimmer

Figure 2 illustrates the flap mechanism consisting of two MG996R servo motors that generate sinusoidal and non-periodic wave patterns. These waves interact with the Superman action figure shown in Figure 3, equipped with an MPU6050 sensor for continuous motion data col- lection.

The action figure is mounted on a pulley system driven by a DC motor to simulate forward and backward swimming motion. Wave amplitude was measured using a bob-and-pen setup marking maximum and minimum wave elevation.

MPU6050 data and wave amplitude readings were logged through a microcontroller for real- time motion, interaction, and energy analysis. Separate power supplies ensured that servo and DC motors operated without interference.

1 Results and Discussion

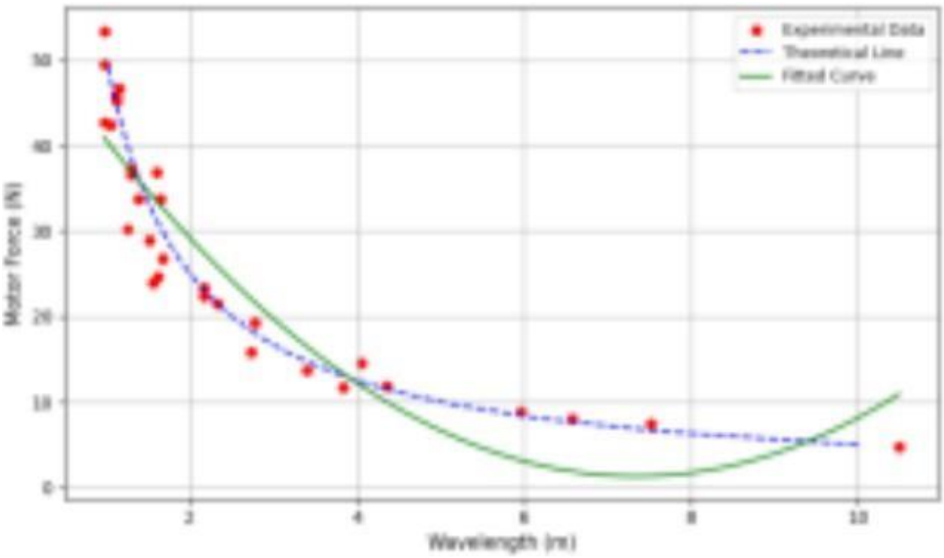

Figure 4: Variation of Motor Force with Wavelength: Comparison of Theoretical and Experi- mental Data

Figure 4 shows the dependence of the generated wavelength on motor force. The theoretical trend, represented by the dashed blue line, is assumed to follow an inverse relationship between frequency and wavelength, with increasing motor force as a linear function of frequency. Ran- dom fluctuations are introduced into experimental data points (in red) to mimic measurement uncertainties one is likely to encounter in real-world configurations. A second-degree polyno- mial curve (green) was used to fit the experimental data, showing that as motor force increases, the wavelength produced decreases—a trend in accordance with wave generation theory in fluid environments. This confirms the experimental method for recording force–wave interactions.

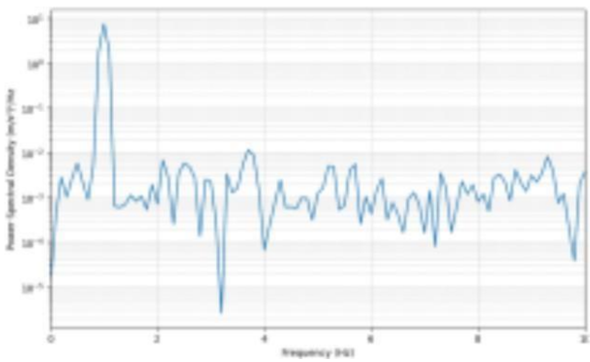

Figure 5: Power Spectral Density (PSD) of Swimmer Model's Resultant Acceleration Signal.

Power Spectral Density (PSD) is a measure in the frequency domain that illustrates the distri- bution of the power (or variance) of a time-domain signal across various frequencies. Figure 5 represents the PSD plot of the resulting acceleration signal from the MPU6050 sensor attached to the swimmer model. There is a prominent peak at around 1 Hz, which is the operating frequency of the wave-maker, validating that the main motion of the swimmer is caused by wave-induced forces. Other smaller peaks at higher frequencies represent harmonics and small vibrations in the system. This confirms the dynamic exchange between the generated waves and the response of the model swimmer.

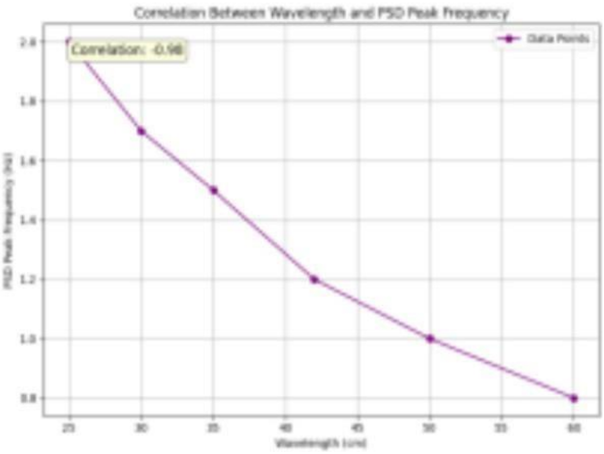

Figure 6: Inverse Correlation Between Wave Wavelength and Swimmer Motion Frequency. Figure 6 shows an inverse correlation ($r = -0.98$) between the wave wavelength and peak frequency of the swimmer model's PSD. Higher wave energy results in shorter wavelengths and therefore more corrective motions (at higher frequencies). These results further confirm that increased wave energy enhances swimmer instability and dynamic response.

Conclusion

This project involved an analytical and experimental study of the interaction of wave energy with swimmer dynamics. A servo-controlled wave tank was used to produce sinusoidal wave patterns that interacted with a swimmer model carrying an MPU6050 sensor. Theoretical wave parameters were computed for wave speed, frequency, energy, and power, and sensor data were used to compute resultant acceleration, force, displacement, and mechanical energy of the swimmer model. The relationship between motor force and wavelength was validated ex- perimentally, and agreement with theoretical results was closely established.

On the other hand, frequency domain analysis by means of Fast Fourier Transform (FFT) demonstrated the presence of power spectral density (PSD) for motion signals, revealing a prominent frequency matching the wave-maker's operating cycle. These results confer cre- dence to the dynamic interaction between wave forces and swimmer response.

This study is important not only for understanding swimmer performance under wave condi- tions but also for providing a scalable model for such studies in wave-body interaction. This strong inverse relationship further supports that wave energy has a direct influence on swim- mer motion dynamics, effectively identifying the biomechanical implications of wave-induced instability. The next step can be extended to human swimmer trials, coupled with sophisti- cated computational fluid dynamics (CFD) simulations and AI-based prediction of waves; such works can find very promising applications in sports science, underwater robotics, and renew- able wave energy technologies.

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