A new concept for a wave-propelled autonomous surface vehicle: an experimental investigation

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ABSTRACT

This study focuses on the hydrodynamic testing of a novel wave-propelled Autonomous and Surface Vehicle (ASV) called Demeter. The main objective of the study is to understand the vehicle performance in different wave conditions and its wave propulsion capability.

Experiments were conducted in the towing tank facility at the Kelvin Hydrodynamics Laboratory (KHL) at the University of Strathclyde. Qualisys system is used to capture the vehicle motion in waves. Both time domain and frequency domain analyses have been conducted. The results have shown that the vehicle velocity and response in waves are highly related to their natural frequency. The data collected in the study will also be used for further numerical simulations and design optimization.

KEYWORDS: Wave propulsion; Autonomous Surface Vehicle; Hydrodynamic test; Response Amplitude Operator.

INTRODUCTION

Wave gliders or wave-propelled vehicles are a new type of autonomous surface vehicle (ASV) which harness wave energy to move the vehicle through the water. Its enduring appearance at sea serves as a long-standing platform for ocean research, surveillance, defence and etc. purposes. The renowned products include the wave glider by, AutoNaut and the “Black Pearl” (Sun et al., 2022) wave glider. The vehicle is made up of two primary parts: a surface float that floats on top of the water and houses the propulsion, navigation, and sensor systems, and a subsurface glider that is tethered to the surface float and uses wave motion to propel itself forward.

The wave glider transforms the vertical motion of the waves into horizontal propulsion through a process known as "heaving." While the surface float is largely immobile, the subsurface glider travels up and down with the waves. Following that, a series of mechanical or hydraulic linkages turn this motion into thrust.

Wave gliders are commonly used for extended oceanographic missions that involve monitoring ocean conditions, such as temperature, salinity, and pH levels, tracking marine life, and measuring ocean currents. They are also utilized in search and rescue operations, coastal surveillance, and oil spill monitoring. Their ability to run for extended periods without refuelling, thanks to their wave energy propulsion, makes them ideal for long-term missions. However, it's worth noting that traditional wave gliders are limited in speed. The general cruise speed is around 1 knot; some high-performing vehicles can reach 3kn. This limits its capability and operational efficiency for missions. Its core issue relates to a technology called wave propulsion, which was originally developed to propel large ships only by waves. But now wave-assisted propulsion is more used for energy saving and reducing ship motions at sea. To improve the performance of wave propulsion for gliders, Yang et. al first built a fully-coupled CFD model and attempted to use a torsional spring for tandem foils to enhance the propulsion force (Yang et al., 2019; Yang et al., 2018). However, traditional wave gliders normally have the surface body and the underwater body distanced to use the orbital velocity difference in different water depths. This creates a large drag body as it travels through a larger area of water. How to develop a wave glider with low drag and high propulsion is the research focus.

Recently, proposed by Autonomous Devices Ltd., a new concept of wave glider, Demeter, is introduced. Demeter uses energy-harvesting, intelligent, uncrewed vehicles to provide a persistent, infrastructure-independent subsea sensor data retrieval and analysis service. A novel energy harvesting Unmanned Underwater and Surface Vehicle, which bridges the gap between long endurance surface vehicles and short endurance underwater vehicles. Understanding the energy harvesting mechanism of the vehicle and developing new concepts are the main objectives of this study. To understand its dynamics and behaviour in different sea conditions a series of experiments are conducted at the Kelvin Hydrodynamics Laboratory (KHL) at the University of Strathclyde. The experimental dataset will also be used as a validation case for the numerical studies.

EXPERIMENTAL METHOD AND MEASUREMENTS

Testing facility and equipment

The experiments for this study are performed in the towing tank in the Kelvin Hydrodynamics Laboratory (KHL) at the University of Strathclyde. The principal dimension of the towing tank is 76 m x 4.6 m x 2.5 m, shown in Fig. 1. The facility is equipped with a computer-controlled digital drive carriage with a max speed of 5 m/s, a variable-water-depth computer-controlled four-flap absorbing wavemaker generating regular/irregular waves over 0.5 m height, and high-quality variable-water-depth sloping.

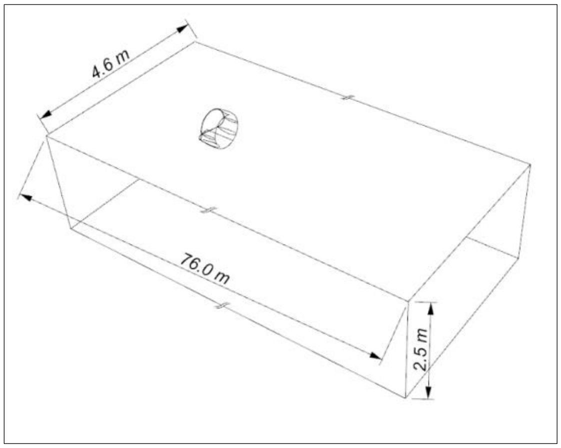


Fig. 1 A sketch of the towing tank

Methodology

The methodology for this study involved conducting a series of experiments to track the 6 DOF (degrees of freedom) motion of Demeter, in a towing tank. The vehicle, D080 shown in Fig. 2, has a diameter of 0.80m. The experiments were conducted in both head sea and following sea conditions. All tests were conducted by using reflective balls to track the vehicle's motion using Qualisys motion tracking cameras and Qualisys software. Reflective balls were attached to the Demeter by using a stainless steel M6 bolt. Four reflective balls were used for the Qualisys cameras to capture the motion of the vehicle in 6 Degree of freedom (DOF). The wave height was measured using an electrical resistance-based wave sensor. In the towing tank, we used four cameras to capture the motion of the D080, as shown in the below Fig. 3.

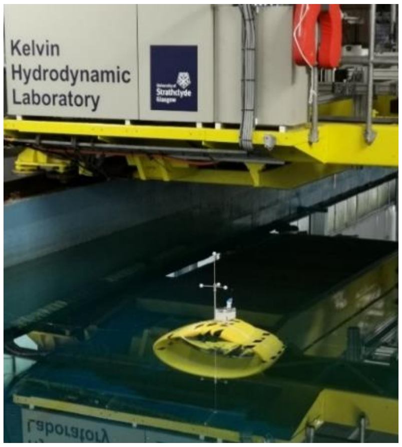


Fig. 2 A photo of the D080 in the towing tank

Using the above setup, we were able to observe Demeter's behaviour in a contained environment and collect comprehensive data on the vehicle's behaviour under various wave conditions. Prior to the investigations, we also performed free decay tests to find the natural frequencies of the vehicle's roll, pitch, and heave motions. These experiments comprised releasing the vessel in a still water environment and monitoring the motion decay over time. These tests' outcomes were crucial in determining the heave, pitch, and roll motions of the vehicle's natural frequencies, which were then used to create the test matrix in the studies. Based on this, the below testing matrix in Table 1 is used.

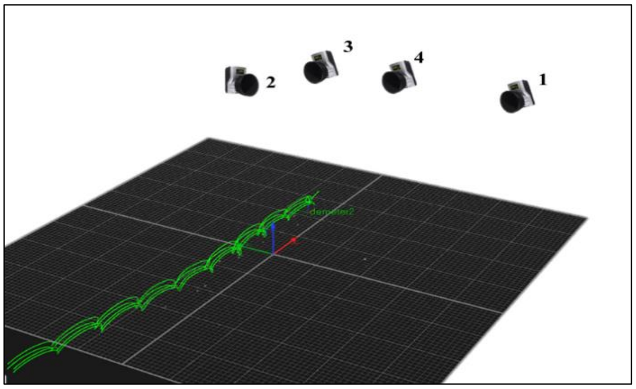


Fig. 3 Qualisys cameras and tracked motion trajectory

Table 1 Wave frequencies and wave heights which are covered during the experiment

Model Code	Wave Frequency	Wave Height
D080	0.3 – 0.9 Hz	0.075 – 0.15 m

RESULTS AND DISCUSSIONS

Free Decay tests

As stated previously, free decay tests are first conducted to find natural frequencies in heave, pitch and roll. During the free decay tests, the initial motion was given at only the relevant degree of freedom, i.e. pure heave, pure pitch, or pure roll. The time series results for heave and pitch are given as examples shown in Fig. 4 and Fig. 5. As shown in Fig. 4 for the heave free-decay test, it is evident that the pitch motion is highly coupled with the heave motion. Conversely, Fig. 5 displays that pitch free-decay motion is less influenced by the heave motion.

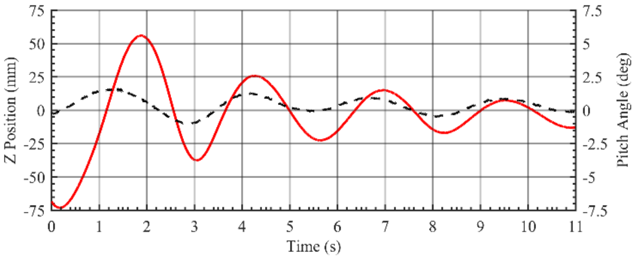


Fig. 4 Heave free decay test result for D080, red: heave motion, black dashed: pitch motion.

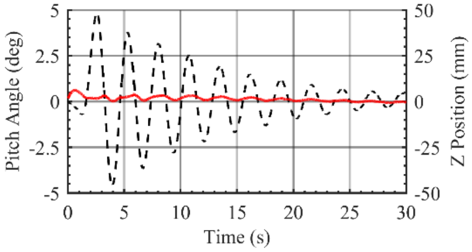


Fig. 5 Pitch free decay test result for D080, black: pitch motion, red dashed: heave motion.

Based on the above test, the damped natural frequencies can be obtained by measuring the time between peaks and they are summarised as shown in Table 2. The damping has not been corrected to its highly coupled nature of heave and pitch motions.

Table 2 Damped natural frequencies of the vehicle

	Motion	$f_n\ (Hz)$
D080	Pitch	0.375
	Heave	0.364
	Roll	0.396

Furthermore, during the test, it can be observed that the heave and pitch motions are also coupled with the surge motion as the motion in surge has not been constrained. Fig. 6 portrays that the heave motion excited the surge motion.

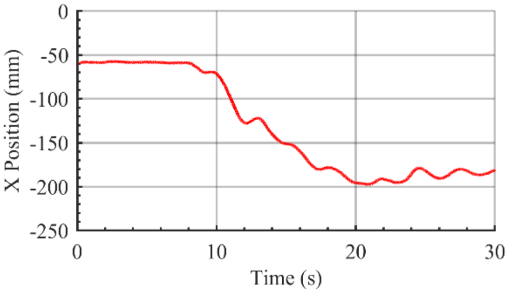


Fig. 6 Change in the X position of the vehicle during the heave free decay test.

Free running tests

Time domain responses and analysis

With the vehicle motion captured through the Qualisys system, the vehicle's position, velocity and acceleration information can be obtained. A screenshot has been captured in the Qualisys system, shown in Fig. 7. It can be observed that the vehicle tends to be vertically climbing up and then slowly gliding down and forward. This kind of motion is a combined effect with waves generating the heave motion and the foil underwater propelling the vehicle forward, which forms the fundamental principle of wave propulsion.

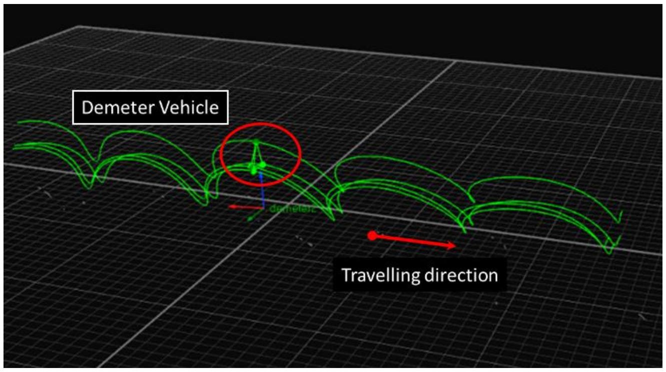


Fig. 7 Motion of Demeter vehicle captured by Qualisys system

Further information has been extracted from the Qualisys system to analyse the motion characteristics of the vehicle. As shown in Fig. 8, the time history of heave motion shows a sinusoidal type of motion with distinct amplitude and frequency, while surge motion in X is showing an oscillating increase indicating the vehicle's forward motion. The motion in sway is minimum showing a small drift. In order to analyse the motion amplitude and frequency information which is critical to understanding the vehicle behaviour, a detailed frequency domain analysis has been conducted and elaborated in the following session.

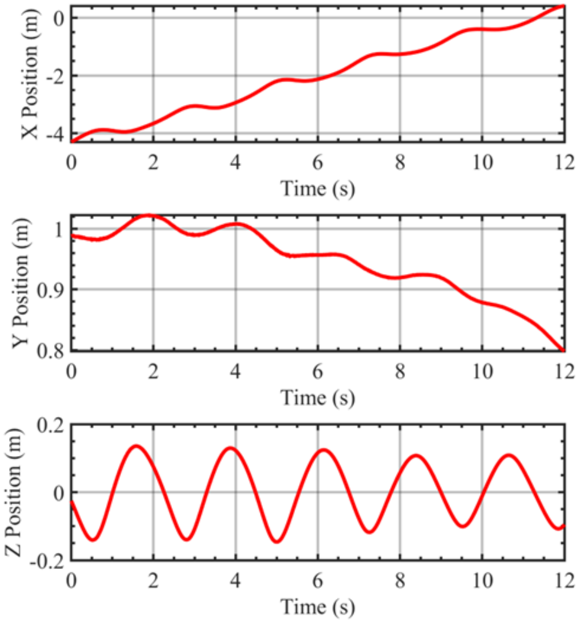
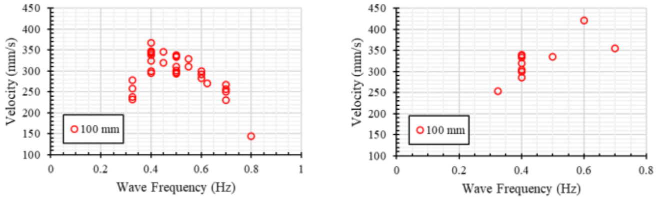


Fig. 8 Time history of motions recorded in Qualisys

Time-averaged vehicle velocity has been first investigated regarding the change in the wave frequency. In the tests, the wave amplitude has been maintained at 100 mm. The results have been plotted in Fig. 9. In the head sea condition, the maximum velocity was observed to be reached around the natural frequency of the vehicle around 0.4 Hz. In the following sea condition, the result peaks at 0.6 Hz. And comparing the results between the head and following seas, the vehicle in the following seas generally has a higher velocity, which is believed to be due to the wave drift velocity. But it is important to find that the vehicle's performance is highly related to the wave frequency.



Head seas　　Following seas

Fig. 9 Average velocity against wave frequency for D080 in head and following sea conditions

Following this investigation, the time average velocity has been analysed to understand the vehicle performance in different wave amplitudes. In Fig. 10 and Fig. 11, the average velocities in head seas and following seas are presented against wave amplitude at two different wave frequencies, 0.4 Hz close to the natural frequency and 0.6 Hz away from the natural frequency but has the highest velocity in following sea. In both head and following seas, it was observed that the velocity tends to increase with the wave amplitude when the wave frequency (0.4 Hz) is close to the natural frequency of the vehicle. For the following sea condition, the velocity seems to plateau after certain wave amplitudes, whereas the velocity tends to continuously increase in the head sea conditions. On the other hand, when the wave frequency is away from the natural frequency (0.6 Hz), the vehicle velocity doesn't have a clear trend to increase with the wave amplitude. This highlights the ability of the vehicle to effectively use the wave energy to propel itself when it is close to its natural frequency. But this increase in velocity will be reduced or stopped after reaching a certain threshold. This threshold is not clear in the current tests due to the limitation of the testing capability.

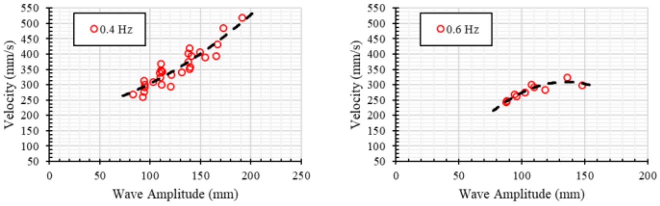


Fig. 10 Average velocity against wave amplitude for D080 in head sea condition at wave different frequencies.

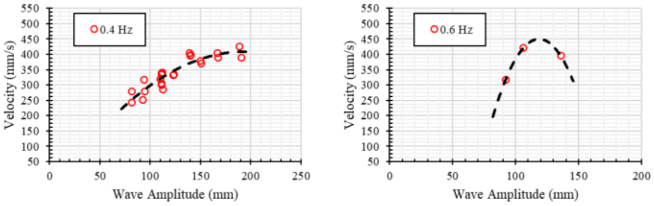


Fig. 11 Average velocity against wave amplitude for D080 in following sea conditions at wave different frequencies.

With the above investigation, the vehicle will favour operating in the waves close to its natural frequency. Further research will be necessary to determine the optimal operating conditions and the optimal design for the vehicle to operate in different sea conditions.

Frequency domain analysis

Following the above time domain analysis, it can be seen that the waves exert vertical motion, flap the underwater foil and hence propel the vehicle forward. Therefore, to understand the vehicle performance, the oscillation motion needs to be analysed. Hence a frequency domain analysis has been conducted with the Fast Fourier Transform (FFT). And as the heave presented a distinct sinusoidal oscillation, the analysis has been focused on the heave motion.

Three different wave conditions have been presented here with the same wave amplitude of 0.125 m and three different wave frequencies $(0.4, 0.6, 0.65\ Hz)$. The vehicle's time-based heave reaction is provided, along with an FFT analysis of that response. The results are presented in figures Fig. 12 - Fig. 14.

In Fig. 12, the wave frequency is around the natural frequency of the vehicle. The FFT analysis showed that the heave motion of the vehicle has a dominant peak of around *0.44 Hz*. Considering the vehicle is travelling against the wave with an average velocity of 0.37 m/s, the wave encounter frequency is needed which can be calculated using the equation (1).

$$f_e = f - \frac{2\pi f^2 U cos\mu}{g} \qquad (1)$$

where f_e is wave encountering frequency in Hz, and f is wave frequency in Hz, U is the average speed in m/s, μ heading angle in rad, and g is the acceleration of gravity in m/s^2.

It can be seen that the peak frequency captured in FFT analysis is the same as the calculated wave encounter frequency 0.44 Hz. And also the heave amplitude is around 120 mm which is close to the wave amplitude. For this case, the energy of oscillation is most around the wave encounter frequency with some small components centred around two times the peak frequency (close to the second harmonic).

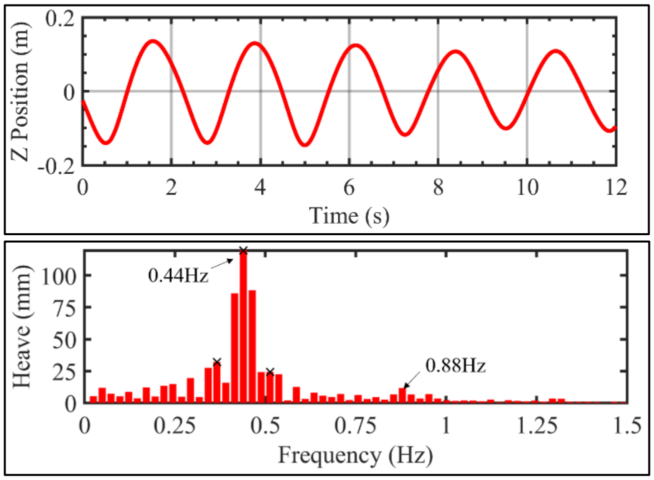


Fig. 12 An example of the measured heave response of the vehicle in time domain (top), FFT analysis (bottom), $f = 0.40\ Hz,\ H = 0.25\ m,\ V \cong 0.37\ m/s$.

While for most of the test cases the response is similar to what has been observed in Fig. 12, some strange phenomena shown in Fig. 13 & Fig. 14 have been observed when the wave frequency is close to the second harmonic and the vehicle speed drops significantly in these conditions.

It can be seen that in both cases the vehicle's heave motion has significant energy distributed in the frequencies around half of wave encounter frequencies.

In Fig. 13, the vehicle displayed a non-sinusoidal motion. The FFT analysis revealed that the maximum response is around $0.67\ Hz$, which is equal to the wave encountering frequency, but the second peak is around $0.33\ Hz$ which is close but lower than the natural frequency of the vehicle. A similar non-sinusoidal behaviour was observed in Fig. 14. But the maximum response is around $0.34\ Hz$ which is half of the wave encounter frequency $0.68\ Hz$. And in this condition, the vehicle speed dropped significantly to $0.13\ m/s$. Based on this observation it can be seen that the vehicle is experiencing a parametric resonance phenomenon, which results in a significant speed drop for the vehicle.

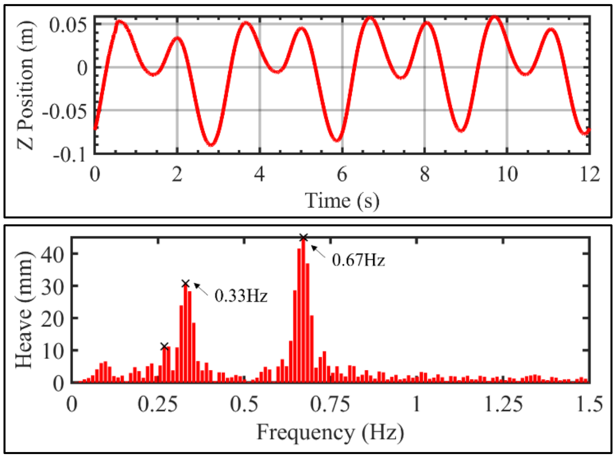


Fig. 13 An example of the measured heave response of the vehicle, $f = 0.60\ Hz, H = 0.25\ m, V \cong 0.29\ m/s$.

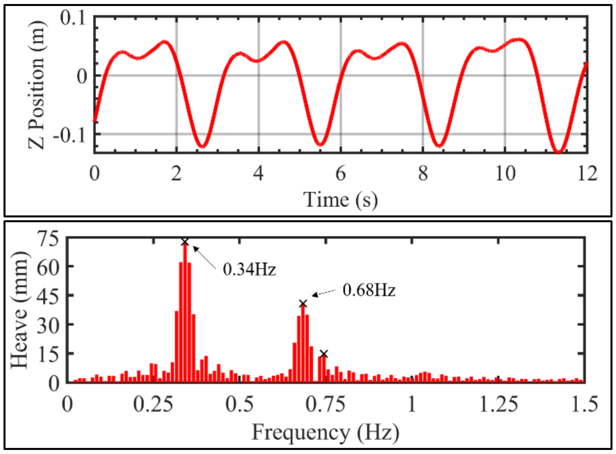


Fig. 14 An example of the measured heave response of the vehicle, $f = 0.65\ Hz, H = 0.25\ m\ V \cong 0.13\ m/s$.

Overall, the FFT analysis's findings offer insightful information about the Demeter's behaviour in the frequency domain. The vehicle responses to the wave encountering frequency and influenced by the vehicle's natural frequency. Significant energy dissipation away from the encounter frequency which is also the excitation frequency will adversely affect the vehicle performance.

RAO analysis

Based on the above frequency domain analysis, it can be seen that, apart from the rare phenomenon observed around the second harmonic, the vehicle responds to the wave excitation with a dominant response in the encounter frequencies. To understand the vehicle behaviour in different wave heights and to predict the response in different wave height, the concept of Response Amplitude Operator (RAO) defined in Equation 2 is adopted.

$$RAO(f) = \frac{R(f)}{A(f)} \tag{2}$$

where RAO(f) is the response amplitude operators regarding to different frequencies, f; R(f) is the response amplitude of the vehicle; A(f) here is the wave amplitude.

The RAOs for the heave and pitch motions of the vehicle against the wave encounter frequency were calculated. Three different wave amplitudes (85, 100, and 125mm) have been tested with a range of wave frequencies. Fig. 15 and Fig. 16 show the heave and pitch motion responses against the wave encountering frequency in the head and following sea conditions. It can be seen that the vehicle responds linearly to the wave amplitude as the RAOs obtained in three different wave amplitudes coincide with each other.

In the head sea condition, both the heave and pitch motions showed a decreasing trend with the increasing wave frequency for three different wave amplitudes. In the following sea condition, the heave motion response showed a similar trend. For the pitch motion, it is very scattered compared to other tests. And it is also interesting to notice that, combined with the result shown in Fig. 9 and Fig. 10, the maximum RAO doesn't correspond to the maximum velocity.

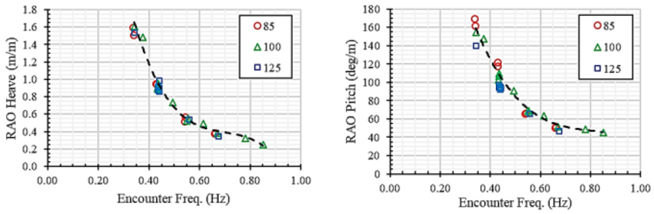


Fig. 15 Heave and pitch response amplitude operator in the head sea condition for D080.

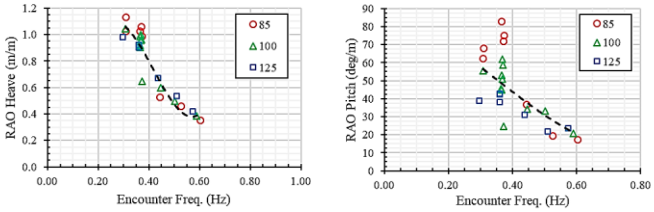


Fig. 16 Heave and pitch response amplitude operator in the following sea condition for D080.

CONCLUSIONS

In conclusion, the results of the experiments conducted at the Kelvin Hydrodynamics Laboratory provide a comprehensive understanding of the wave propulsion performance of the vehicle and the vehicle's behaviour under different sea conditions. The following key conclusions can be obtained,

1. Based on the Qualisys measurement and time domain analysis, the vehicle tends to have a sudden climb-up and slowly gliding-down behaviour. Based on this principle, the vehicle can sail against waves using waves to provide propulsion power.
2. The average vehicle velocity in the head seas peaks when the wave frequency is around the natural frequency of the vehicle. In the following sea condition, it peaks around two times the natural frequency.
3. The average velocity increases with the increasing wave amplitude. It has a trend to plateau in following sea conditions but in head seas, it shows a continuous increase with no signs to slow or drop. Further investigation is needed as it might be because of the limitation of the testing capability.
4. FFT analysis has been conducted to understand the behaviour in the frequency domain. In most of the conditions, the dominant response is in the wave encounter frequency. But when the wave frequency increases to match the second harmonic, a significant response can be observed around the natural frequency and the speed of the vehicle drops significantly.
5. The study identified the presence of parametric resonance, evident in non-sinusoidal motions and significant speed drops at half the wave encounter frequency. This highlights the need for further investigation and potential mitigation strategies to address this effect.
6. RAO analysis has been performed. The vehicle responds linearly to the wave excitation. With RAO results, vehicle response at different wave heights can be predicted.
7. Combining the vehicle response and the vehicle velocity results, it can be seen that the maximum response doesn't correspond to the maximum vehicle velocity.

The findings of the study can be used to further improve the design and performance of the vehicle and bridge the gap between long-endurance surface vehicles and short-endurance underwater vehicles. This can lead to the development of more efficient and effective energy harvesting systems for underwater and surface vehicles and enable new applications in the field of subsea sensor data retrieval and analysis.

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