In situ results from a new energy scavenging system for an autonomous underwater vehicle

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***Abstract*—This paper presents initial results from the first in-situ trials of a new gyroscopic energy scavenging system for an autonomous underwater vehicle.**

I. Introduction

A. Motivation

Autonomous Underwater Vehicles (AUVs) are finding increasing use for a wide range of scientific, commercial and military applications [1]. However, AUVs are limited by their finite energy reserves [2]. With typical AUV endurance measured in hours or days [3] (as shown in Table I), batteries accounting for approximately 20% of the vehicle mass [4] and the need for periodical recharging (and redeployment) from a dedicated (and often expensive) host platform or support vessel. New in-situ battery charging and/or alternative power systems are required to improve AUV endurance and autonomy. Especially given the demand for longer term deployments, e.g., for environmental monitoring and surveillance [5], [6].

Renewable energy represents a potential viable source to power many maritime systems and robots. With an average solar energy power density at the surface of approximately $168W/m^2$ (and approximately $1.27kW/m^2$ at the limits of the atmosphere) [8], an average (ocean) wind power density of greater than $50W/m^2$ for more than 80% of the year (with a maximum of $1.6kW/m^2$) [9] and average global wave energy densities greater than $2kW/m$ for 90% of the year (and wave energy densities are greater than $20kW/m$ in mid-latitudes) [10], the available power is comparable to many systems and sensors.

To date several commercial AUVs and Autonomous Surface Vehicles (ASVs) utilise solar panels to augment the on-board supplies, for example SAUV-II [11], Autonaut [12], WaveGlider [13] and C-Enduro [14]. While solar potentially offers unlimited mission durations, as found by the SAUV II it is limited to night-time missions and daylight recharging strategies and is susceptible to bio fouling [11].

Various wind based concepts, e.g. C-enduro [14] and the Submaran [15], are being developed. The C-enduro uses a deck mounted wind turbine to generate power (similar to the small wind turbines available for sailing yachts) and the Submaran uses a fixed wing (sail) for propulsion. Various sail based (propulsion) systems have also been developed for the Microtransat Challenge [16] a fully autonomous sailing boat transatlantic race.

Wave propelled systems, e.g. the Autonaut [12], Wave Glider [13] and FLEUR [17] have also been developed,

TABLE I
Typical torpedo style AUV durations (sourced from [7])

AUV Name	**Typical Duration [hrs]**
Taipan 300	1
Taipan 2	2
Sea Wolf A	3
Gavia Off Shore Surveyor	4.5
ARCS	4.85
Bluefin 9	5
MUN Explorer, Folaga Configuration, Blue Star	6
Gavia Defence/Scientific	7
Maya	7.2
Tunnel Sea Lion TSL	8
MBARI AUV (Seafloor Mapping AUV)	8.5
OKPO300/600/6000/SQX 1 (500)/ CR-01	10
Ocean Explorer OEX	12
BPAUV	18
Explorer IFRMER AsterX	18.5
Bluefin 12 (MANO configuration)	19.5
R-One/Caribou/ALISTER Daurade/MBARI Upper Water Column AUV	20
Nessie VT configuration/Explorer 5000/Remus 6000/100	22
Hugin 1000	24
Hugin 1000 (3000 metre variant)	25
Bluefin 12D	30
Tiphlonus	35
Explorer EagleRay	36
Hugin 3000/4500/LMRS	60
Remus 600	70
Theseus	100
AutoSub 3	166
AutoSub 6000	206.4

however, only the FLEUR system [17] generates power. Ideas of recharging AUV power supplies using wave-energy absorbers and sea current generators have also been proposed in [18], [19], however, no practical demonstrations were made.

In addition a prototype thermal energy harvesting underwater vehicle, the SOLO-TREC, has also been developed, which uses a phase-change material (a waxy fluid) that melts and expands in warm water (at the surface) and solidifies in cooler (deeper) water to drive a hydraulic generator and provide power [20]. The SOLO-TREC is reported to provide over 7000J per dive, sufficient to power GPS, iridium and conductivity-temperature-depth (CTD) sensors [20]. Fuel cells have also been trialled, e.g. on the AUV URASHIMA [21] and IDEF Ifremer [22], however, these systems are expensive and complex [22].

This paper presents initial in-situ results from a prototype gyroscopic based wave energy scavenging system installed in a 2m cylindrical AUV platform. A theoretical description of the system and advantages and disadvantages are presented next. This is followed by a description of the experimental platform in Section 2.

B. Theoretical Description

The system, based on control moment gyroscope (CMG) principals, utilises the gyroscopic response of a gimballed flywheel mounted within the AUV body to generate energy from the wave induced rotational motions of the platform, Figure 5. That is, the wave induced roll and pitch motions of the AUV cause an internally housed gimballed flywheel to precess - resulting in a relative motion and torque - enabling energy to be generated internally within the vehicle and in-situ. A detailed theoretical description of the system can be found in [23].

The system has several potential advantages. As the system is housed internally it is not exposed to the harsh underwater environment, it is not susceptible to bio-fouling and does not add any hydrodynamic drag. In addition, as the system responses to rotational motion, assuming a rigid AUV body the system can positioned anywhere within the AUV body without performance degradation. Furthermore, the technology has the potential to be developed into an integrated energy harvesting, storage and motion control system; whereby the wave induced gyroscopic precession of the flywheel can be used to generate energy, the flywheel kinetic energy (spin) can be utilised for energy storage (similar to Kinetic Energy Recovery Systems or KERS) and motion control can be provided by precession control of the flywheel (providing improved monitoring/recording capabilities). However, in practice as the effect of surface waves and swell diminishes with depth [24], similar to solar-based AUVs (e.g. SAUV II), the AUV system would need to surface to recharge exposing

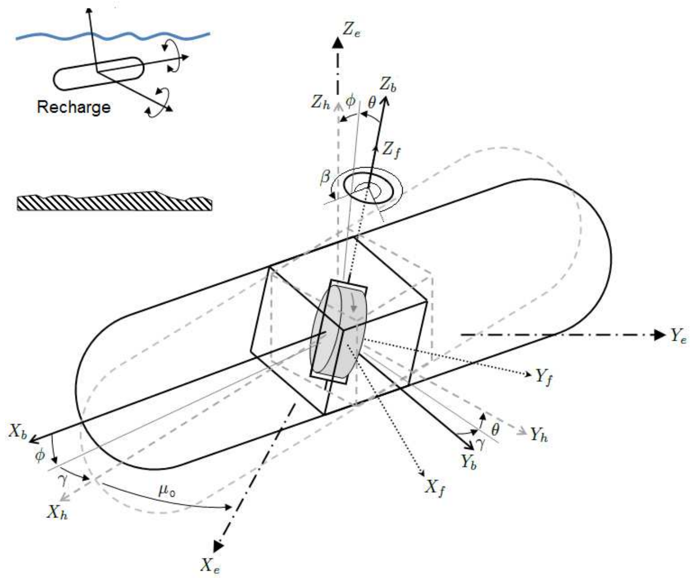

Fig. 1. System Schematic

TABLE II
AUV AND GYROSCOPIC SYSTEM PARAMETERS

Parameter	Value
Vehicle Diameter	$0.3m$
Vehicle Length	$2m$
Vehicle Displacement	$\approx 80kg$
Flywheel Diameter	$0.1m$
Flywheel Mass	$3.5kg$
Flywheel Inertia (about spin axis)	$0.00482kgm^2$
Flywheel Spin rate	$5000rpm$

the AUV to the potentially hazardous wave environment.

C. Paper Contribution

Building on previous work, including theoretical studies of the system [23], [25] and initial results from laboratory (towing tank) based experiments [26], this paper presents initial results from the first in-situ trials of the system. The paper is structured as follows; Section 2 describes the experimental platform, Section 3 details the experimental trials conducted and Section 4 presents the results. This is followed by a discussion and conclusion of the results, in Sections 5 and 6 respectively.

II. Experimental Platform

The experimental platform is illustrated in Figure 2 (and Figure 5). The AUV and gyroscopic system parameters are summarised in Table II.

III. Experimental Trials

Two trials were conducted. One in Mudeford harbour, on the south Coast of England (see Figure 3(a)) on the 11th

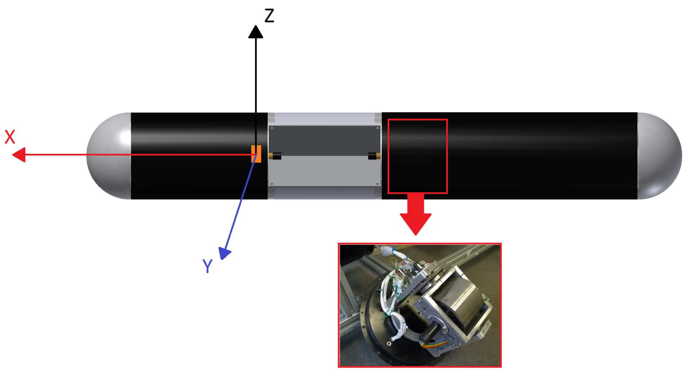

Fig. 2. AUV Platform and Gyroscopic system showing coordinate system

TABLE III
SUMMARY OF WEATHER CONDITIONS

Parameter	**Trial 1** (Mudeford)	**Trial 2** (Southampton Water)
Date of Trial	11/07/2016	13/07/2016
Time of Trial	$\approx$ 8pm	$\approx$ 7pm
Wind Speed	$7.63m/s$ [27]	$4.6m/s$ [28]
Wind Direction	239 SW [27]	319 NW [28]
Wave Height	$\approx 0.1 - 0.15m$	$\approx 0.1m$

July 2016. and one on the 13th July 2016 on Southampton water (Figure 3(b)). The first trial in Mudeford harbour was conducted after high water with the tide going out. This lead to wind over tide and the moored AUV going beam on to the waves. The second trial, on Southampton water, was conducted at approximately high tide (slack water), with the moored AUV aligning with the dominant wave direction i.e. head on (see Figure 5). Table III and Figure 4 detail the weather conditions during the trials.

A. Experimental Setup

The experimental setup is outlined in Figure 5. The data was logged, at $100Hz$, using a National instruments compactRIO and NI9205, NI8790, NI9401 modules. The gyroscopic precession angle was measured using a Maxon ENX16 EASY encoder, the flywheel spin rate was acquired via the spin motor hall sensors and the AUV motions (in 6DOF) were measured with a xSENS MTi-100 inertial measurement unit.

IV. Results

A. AUV Motions

As shown in Figures 6 and 7 the AUV angular velocities were found to be greatest in roll, exhibiting varying amplitudes and a larger range of frequencies than the measured pitch and yaw angular velocities, which primarily occurred at the dominant wave frequencies. This finding suggests that the gyroscopic system had the greatest influence on the roll motion. However, Figure 7 shows that the pitch and yaw angular velocities also exhibit a secondary frequency component, below the dominant wave frequency which could be the due to the gyroscopic system. The AUV accelerations were also found to occur at the dominant wave frequencies.

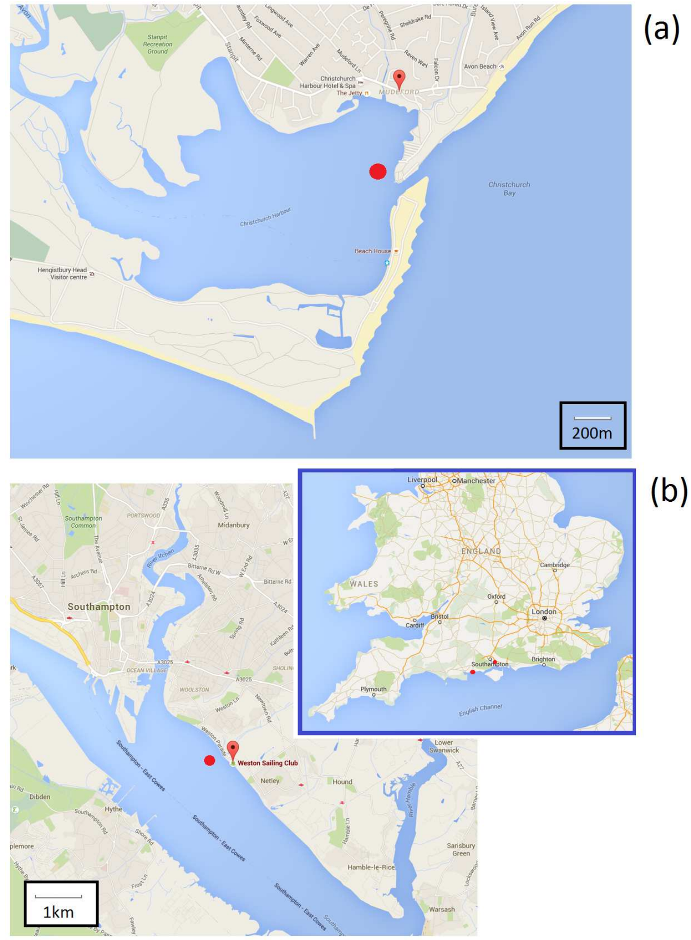

Fig. 3. Locations of trials ((a) Trial 1: Mudeford Harbour (b) Trial 2: Southampton Water) (Images from Google maps)

Integrating the angular velocity signals (assuming the signal starts from zero and applying a high pass 2nd order Butterworth filter at $0.01Hz$) estimates of the angular displacements were made. These estimates, presented in Table IV, show that the AUV roll angles were similar between the two trials and that the pitch and yaw angles were greater during trial 1. That is, in beam waves in Mudeford Harbour (attributed to the greater wave height).

B. Gyroscopic Response

Figure 8 shows that the gyroscopic precession responses during the trials are similar, displaying non-linear oscillatory and rotational motion responses, comparable to those predicted in [25]. As the system responds to rotational motion and can continuously rotate (precess) the system has no

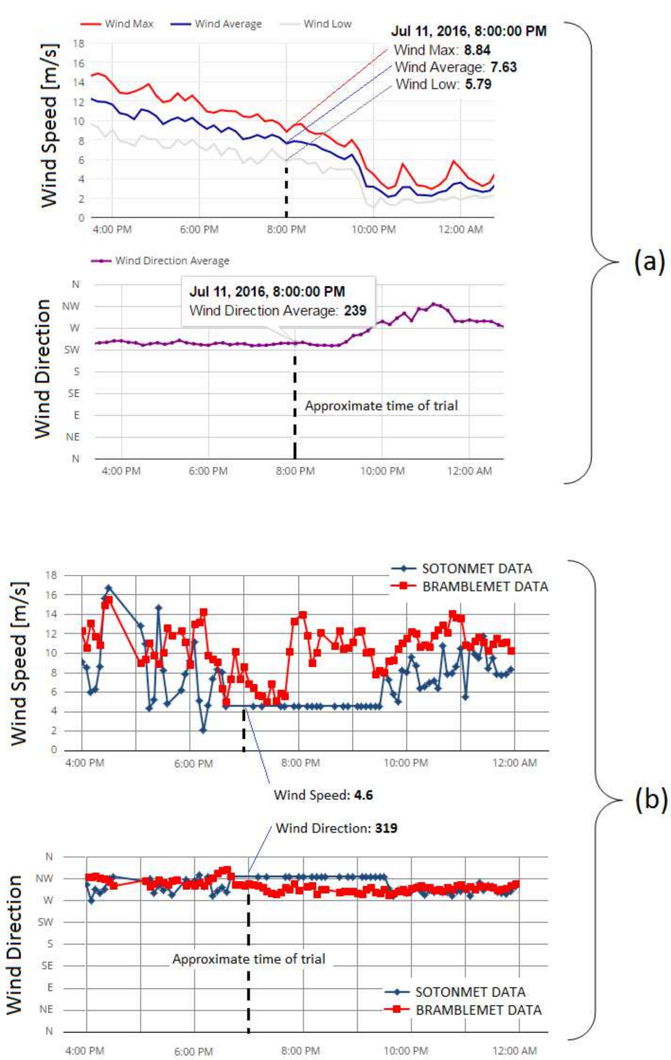

Fig. 4. Wind speeds and directions ((a) Trial 1: Mudeford Harbour (adapted from [27]) (b) Trial 2: Southampton Water (adapted from [28]))

TABLE IV
ESTIMATED ANGULAR DISPLACEMENTS (IN DEGREES) OF AUV PLATFORM DURING SEA TRIALS

	rms	min	max
Roll (Beam waves)	4.06	-12.27	14.39
Pitch (Beam waves)	3.63	-8.82	16.06
Yaw (Beam waves)	6.25	-14.27	24.08
Roll (Head waves)	3.46	-11.56	14.39
Pitch (Head waves)	1.68	-4.69	7.18
Yaw (Head waves)	3.21	-6.65	9.87

physical ends stops.

C. Generated Power

Figure 9 shows the frequency components of the generated power take off (PTO) voltage (the measured voltage across a 15ohm resistor). While the precession was found to exhibit oscillatory and rotational motions, the induced voltage was generated at the dominant wave frequencies (or rather at the frequency of the wave excited angular velocity of the AUV).

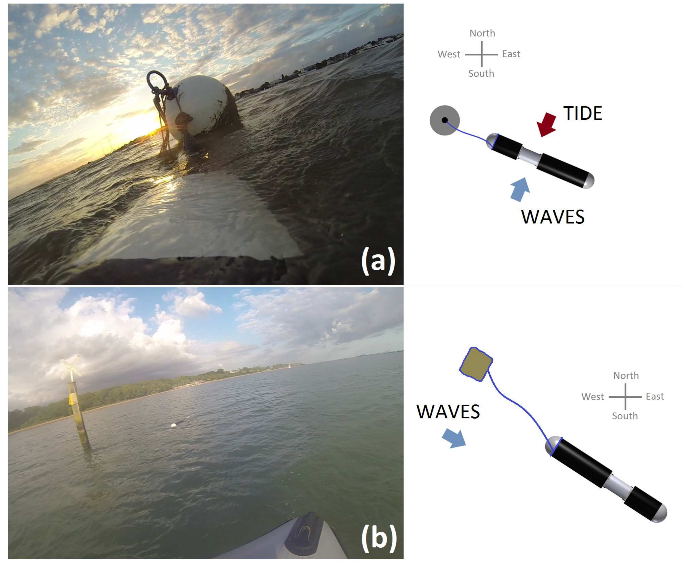

Fig. 5. Schematic and image of AUV Willie in-situ ((a) Trial 1: Mudeford Harbour (b) Trial 2: Southampton Water)

Figure 10 shows the power generated by the system. To summarise the;

- Maximum instantaneous power during trial 1 (beam waves) was 3.58W (0.17W rms), and the
- Maximum instantaneous power during trial 2 (head waves) was 2.86W (0.10W rms)

V. DISCUSSION

While the average generated powers are low, the maximum powers are encouraging. Although there are wave induced motions, Figure 10 shows that there are periods of no gyroscopic precession and no power generation. This finding suggests that the gyroscopic precession needs to be aligned to the dominant motion - as otherwise there is no induced gyroscopic precession and no power generated. That is, control of the PTO and precession angle may be needed to maximise the generated power.

Estimating the power to maintain the flywheel spin rate, overcoming friction, as

$$P = \frac{1}{2} I_{yy} \omega_f^2 / t \tag{1}$$

where $\frac{1}{2} I_{yy} \omega_f^2$ represents the stored kinetic energy in the flywheel and t the time for the flywheel to slow from $5000rpm$ to rest (measured to be 710 seconds from a laboratory test following the trials). Then assuming a constant energy loss, the power loss due to friction (to maintain the flywheel rpm) was estimated as; $P = (0.5 \times 0.00482 \times (5000 \times 2\pi/60)^2)/710 \approx 0.9W$. That is,

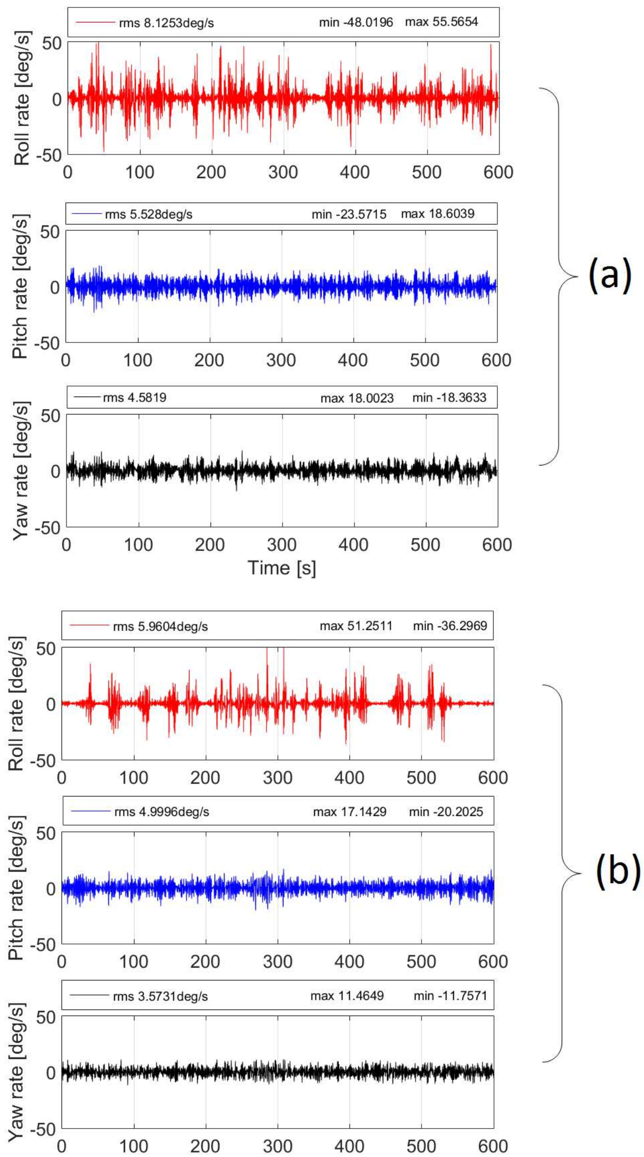

Fig. 6. AUV angular velocity time histories ((a) Beam seas (Trial 1: Mudeford Harbour) (b) Head Seas (Trial 2: Southampton Water))

a net gain energy gain was only achieved instantaneously, and not achieved on average. While the system is not optimised, requiring a reduction in friction, operation at greater rpm and PTO control, the results demonstrate the concept. However, further research and development is required.

VI. Conclusion

This paper presented the results from two in situ trials, conducted off the south coast of the United Kingdom, of a new gyroscopic energy scavenging system for an autonomous underwater vehicle. The system was found to generate a maximum instantaneous power during trial 1 (beam waves) of 3.58W (0.17W rms), and a maximum instantaneous power during trial 2 (head waves) of 2.86W (0.10W rms), in relatively small waves. While the average generated powers are low, the maximum powers are encouraging and further research and development is required to control the PTO, reduce friction and optimise the system operation.

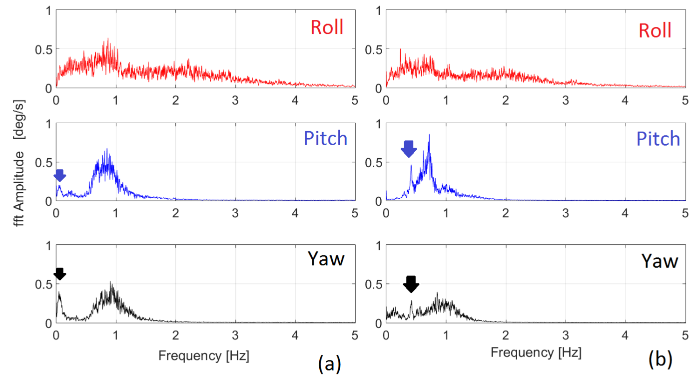

Fig. 7. AUV angular velocity fast Fourier transforms (fft) ((a) Beam seas (Trial 1: Mudeford Harbour) (b) Head Seas (Trial 2: Southampton Water))

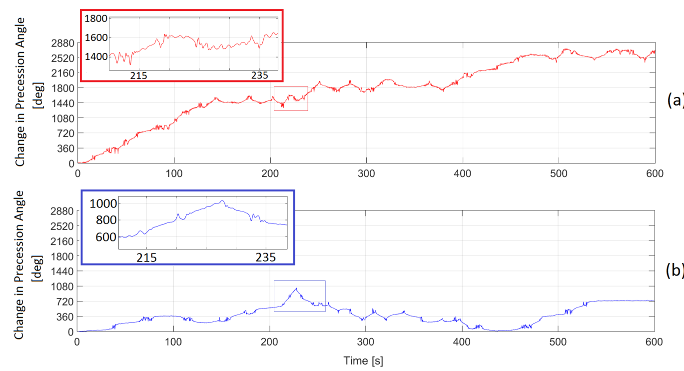

Fig. 8. Precession Angle ((a) Beam seas (Trial 1: Mudeford Harbour) (b) Head Seas (Trial 2: Southampton Water))

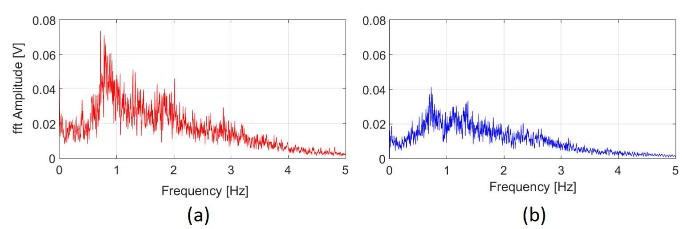

Fig. 9. Fast Fourier transforms of measured PTO voltage ((a) Beam seas (Trial 1: Mudeford Harbour) (b) Head Seas (Trial 2: Southampton Water))

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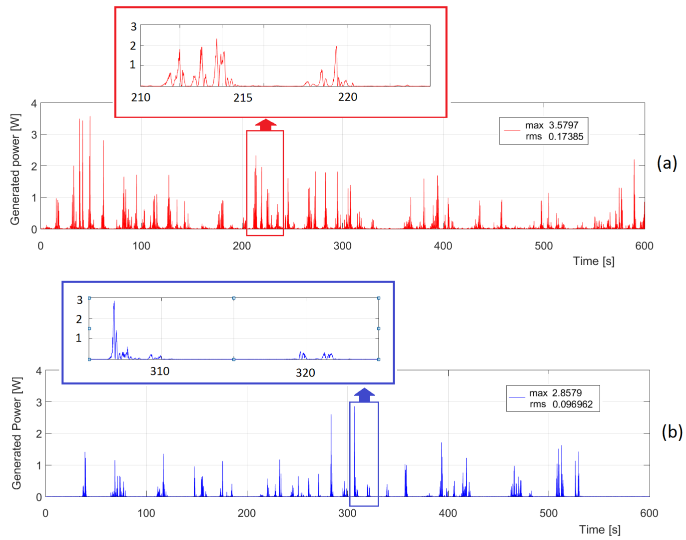

Fig. 10. Generated Power ((a) Beam seas (Trial 1: Mudeford Harbour) (b) Head Seas (Trial 2: Southampton Water))

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