WAVE module for hybrid oceanographic Autonomous Underwater Vehicle – prototype experimental validation and characterisation

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Synopsis

WAVE (Wave-powered Autonomous Vehicle for marine Exploration) is an Italian National Research Projects of Military interest (PNRM) concluded in October 2017. The final goal of the project was the enhancement of the endurance of a typical marine mission with Autonomous Underwater Vehicles (AUVs). To this aim, a system to provide a generic carrier AUV for both energy harvesting from the wave motion and low energy propulsion capabilities was developed. A first prototype of the WAVE module was realised and installed on a commercial AUV platform. After a preliminary assessment of the integrated system at sea, a systematic experimental characterisation of the module capabilities was carried out in a controlled environment at the CNR-INSEAN test tank facility in Rome, Italy. During the three days experimentation, a considerable quantity of data related to different recreated sea conditions and WAVE module configurations was collected. This work details the energetic characterisation of the proposed system, presenting a comparison of the performance of the different WAVE module layouts in terms of average generated power. The main result emerged from the previous analysis is the identification of the most effective configuration of the WAVE module for the battery charging. A deeper processing of data will allow to critically tune the available dynamical model of the system. This way, it will be possible to evaluate, through simulations, the expected performance of the WAVE AUV under typical wave profiles of the Mediterranean sea.

Keywords: Long Endurance AUV; Energy Harvesting; Hybrid Oceanographic AUV; Underwater Wave Glider

1 Introduction

Long endurance in marine applications with Autonomous Underwater Vehicles (AUVs) represents one of the emerging trends in the marine robotics research. Reducing the energetic consumption of the vehicles by improving the efficiency of the power supply and the propulsion systems Griffiths et al. (2004); Bellingham et al. (2010); Wang et al. (2012) is instrumental in extending the duration of a mission from hours to days, or even months in the case of the underwater gliders Eriksen et al. (2001); Sherman et al. (2001); Webb et al. (2001); Willcox et al. (2009). A complementary approach consists in recharging the internal batteries of the vehicle during a mission in dedicated off-shore docking stations Kawasaki et al. (2003); Hagerman (2002); Singh et al. (2001); Hobson et al. (2007). This solution presents the major drawbacks of requiring a cable-link either to a ground station or to a support vessel and, most important, the suspension of the main mission of the vehicle in order to reach the installation and charge the batteries. A more flexible, almost unexplored idea would be to equip the vehicle with a portable device capable of harvesting energy from the surrounding environment. To this aim, the wave motion is particularly appealing because it is theoretically not restricted by time and place. Nevertheless, the difficulties in

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Authors' Biographies

Andrea Caiti is Full Professor of Automatic Control at the University of Pisa, Italy, since 2007. He has held position as Staff Scientist at the NATO SACLANT Undersea Research Center, La Spezia, and as assistant and associate professor at the Universities of Genova, Siena and Pisa. He has been Director of ISME, the Italian Interuniversity Res. Ct. on Integrates Systems for the Marine Environment (2001-2008) and of the Research Ctr. "E. Piaggio" of the University of Pisa (2015 - 2017).

Riccardo Costanzi is Assistant Professor of Automatic Control at the School of Engineering of the University of Pisa, Italy. His research activity is focused on underwater robotics with particular interest to navigation and control systems for Autonomous Underwater Vehicles.

Davide Fenucci received the M.Sc. degree in automation engineering and the Ph.D. degree in ICT, robotics and automation engineering from the University of Pisa, Italy, in 2012 and 2017, respectively. His research interests are in the field of underwater robotics, in particular distributed control and cooperative navigation for swarms of AUVs.

Vincenzo Manzari received the M.Sc. degree in Telecommunications Engineering in 2013 from Pisa University. Since 2015, he has been an engineer officer at the Naval Experimentation and Support Centre of the Italian Navy in the Autonomous Systems branch. He is currently a Ph.D. student in the underwater acoustics and robotics group of the University of Pisa.

Andrea Caffaz, after the Ph.D. in robotics from the University of Genova, was a cofounder in 1999 of the university spin-off GraalTech, specialised in research applications in the field of underwater robotics and mechatronics and manufacturer of the eFolaga AUV.

Mirko Stifani received the M.sc. degree in ICT and 2nd Level Master Degree on Underwater Electro-Acoustics and its applications from the University of Pisa in 2000 and 2005, respectively. Currently he is Head of Underwater Warfare Office at the Naval Experimentation and Support Centre of the Italian Navy, La Spezia.

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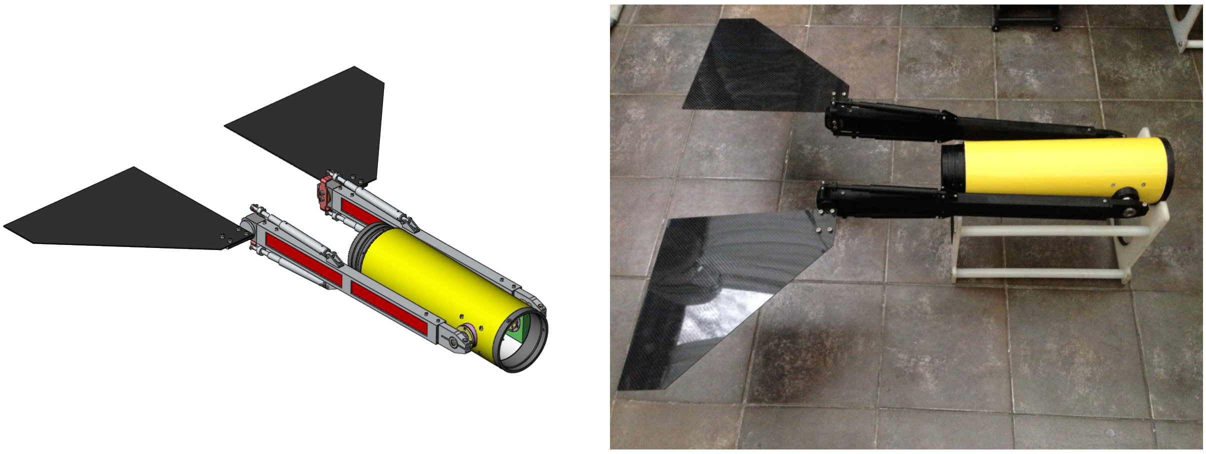

(a) (b)

Figure 1: The WAVE module: (a) CAD design and (b) prototypal realisation.

storing the wave generated power and the low efficiency of the energy conversion process has left the progresses in this direction confined to few, very recent prototypes Bowker et al. (2015); Townsend (2016).

This line of research includes the project "Wave-powered Autonomous Vehicle for marine Exploration" (WAVE), an Italian National Research Projects of Military interest (PNRM) concluded in October 2017. The project was conducted by a team composed of University of Pisa (node of ISME, the Italian Interuniversity Center of Integrated Systems for the Marine Environment) and GraalTech company, under the supervision, steering and control of the Naval Experimentation and Support Centre of Italian Navy (CSSN). The final goal of the project WAVE is to study, develop and test a novel system for both energy harvesting from the wave motion and low energy propulsion, to be integrated on a generic, modular, torpedo-shaped AUV. The envisioned recovery system, namely the ”WAVE module“, is composed of two robotic, wing-terminated arms, free of moving about a unique rotational joint transversal to the hull (Figure 1a). The motion of the two arms due to the interaction of the waves with the wings surface is exploited for battery charging through a brushless motor, acting as a generator, mounted on the rotational axis. When necessary, the two arms can be locked along the hull so that the two wings can act as active surfaces, jointly working with the internal variable buoyancy device, allowing the AUV to advance in a gliding fashion. A first prototype of the WAVE module was built (Figure 1b) and installed on a hybrid AUV/underwater glider eFlaga, commercialised by GraalTech Caffaz et al. (2010). A preliminary assessment of the integrated system was performed at sea in April 2016, showing the practical feasibility of the proposed system Fenucci et al. (2016). A systematic experimental characterisation of the module capabilities was thus carried out in a controlled environment at the National Institute for Studies and Experiences of Naval Architecture (CNR-INSEAN) test tank facility in Rome, Italy. During the three days experimentation (7-9 February 2017), a considerable quantity of data related to different recreated sea conditions and WAVE module configurations was collected. In this work the energetic characterisation of the proposed system through a comparison of the performance of the different WAVE module layouts in terms of average generated power is detailed. The main result emerged from the previous analysis is the identification of the most effective configuration of the WAVE module for the battery charging. A deeper processing of data will allow to critically tune the available dynamical model of the system Fenucci et al. (2016). This way, it will be possible to evaluate, through simulations, the expected performance of the WAVE AUV under typical wave profiles of the Mediterranean sea.

In Section 2, the experimental setup is described with particular emphasis on the various configurations of the WAVE module. In Section 3, the experimental data analysis is reported along with extensive energy recovery performance comparison and discussion on generated electric power. Finally, in Section 4, conclusions and further related research topics are outlined.

2 Experimental setup

In order to characterise and assess the performance of the WAVE module, the tests of energy recovery and wave-induced propulsion systems were held from 7 to 9 February 2017 at the facilities of the CNR-INSEAN. CNR-INSEAN is a Research Institute active in the field of naval architecture and marine engineering within the frame of the National Research Council of Italy. Established in 1927, and known since then as ”The Italian Ship Model Basin”, it is located in the south-west suburb of Rome (Figure 2).

CNR-INSEAN has two towing tanks. Tank no. 1 is today one of the largest worldwide. It is 470 m long,

Figure 2: Overview of CNR-INSEAN test facilities. The Towing Tank no.2 (in red) was used for testing the WAVE module (`http://www.insean.cnr.it/`).

(a) (b)

Figure 3: Tank no. 2 facilities. (a) The carriage system. (b) View of the tank while the wave generator is in motion.

13.5 m wide and has a depth of 6.5 m. It is equipped with a towing carriage that can achieve a maximum speed of 15 m/s. Tank no. 2, used for the WAVE module experimentation, is of smaller size, with a slower carriage (Figure 3a). It is equipped with a 9 m wide single-flap wave generator, that provides regular as well as irregular waves for the investigation of sea-keeping characteristics and ride comfort (Figure 3b). The wave generator is electro-hydraulically powered with 3 pumps of 38.5 kW total power, controlled by a 100 harmonic components electronic programming device. Each harmonic may be modulated both in amplitude and frequency. Table 1 summarises the main characteristics of the Tank no. 2 and related wave generator and carriage structure.

For the purposes of the described experimentation, the vehicle equipped with the WAVE module was deployed in the tank from the tank-side and secured to the carriage through two ropes. The vehicle was tied such that it was completely free to move under the action of the generated waves (Figure 4). Starting from the rest condition of the

Table 1: Tank no. 2 main characteristics.

Towing tank			Wave generator			Carriage
length (m)	breadth (m)	depth (m)	wave length (m)	wave height (m)	slope (deg)	maximum speed (m/s)
220	9	3.5	1 to 10	0.1 to 0.45	1 to 9	10

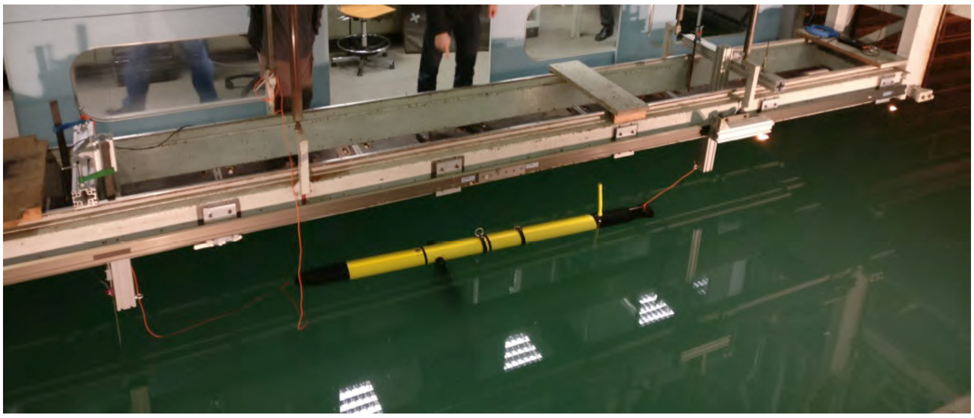

Figure 4: eFlaga vehicle with WAVE prototype during tank tests.

water in the tank, the wave generator was activated for about 5 minutes, with the vehicle having the bow directed in the opposite sense with respect to the wave propagation. During this period, the output voltage and current of the recharging circuit, as well as the vehicle pitch and the relative angle between the hull and the arms were measured and logged. After the end of each test, the wave generator was stopped for the time needed by the water in the tank to return in the rest condition (about 30 minutes in average). The period between one test and the next one was also exploited to change the configuration of the WAVE module. To recap, each test is organised into the following main phases:

WAVE module setup (30 minutes max) was made according to Section 2.1 while the water in the tank return in its rest condition.

Vehicle deployment (5 minutes max).

Wave generator activated (5 minutes) in line with the parameters described in Section 2.2.

2.1 WAVE module configurations

The functioning of the wave energy recovery system was investigated for different configurations of the WAVE module, in order to derive a comparative analysis among the several different possible configurations in terms of developed average power. Throughout the experimentation, the vehicle was maintained slightly buoyant with the center of mass and the center of buoyancy vertically aligned. The calibration procedure was carried out, if needed, after the configuration changes of the WAVE module. The calibration tuning parameters are the quantity of water inside the bow buoyancy chamber and the position of the rear battery pack; further details about the eFlaga architecture can be found in Caffaz et al. (2010). Moreover, the output of the internal recharging circuit was not directly connected to the battery of the vehicle, but on the measurement circuit used to evaluate the capability of electrical power generation. The circuit was composed of a constant load of $10\,\Omega$ in addition to both a current sensor and a voltage sensor. Separate dry tests were performed to evaluate the generated electrical power as the resistive load changes.

The WAVE module configuration was changed according to the following parameters.

Wing shape The impact of both wing dimensions and materials on system performance has been experimentally verified. The tests were done with four different profiles (Figure 5), whose characteristics are briefly reported in the following table:

Type	Material	Max. length (mm)	Max. width (mm)
1	Carbon fiber	400	400
1-bis	Aluminium	400	400
2	Aluminium	800	400
3	Aluminium	400	800

Wing mounting position The wing shapes type 2 and 3 are provided with fixing holes at three positions (Figure 5), corresponding to different possible mounting points of the arm. In the following, the labels *High*, *Middle* and *Low* will be used for those positions as indicated in the figure.

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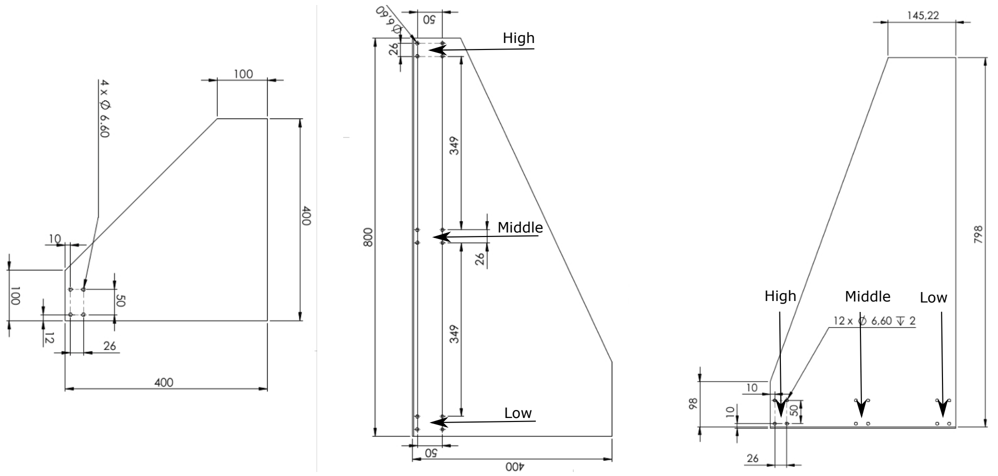
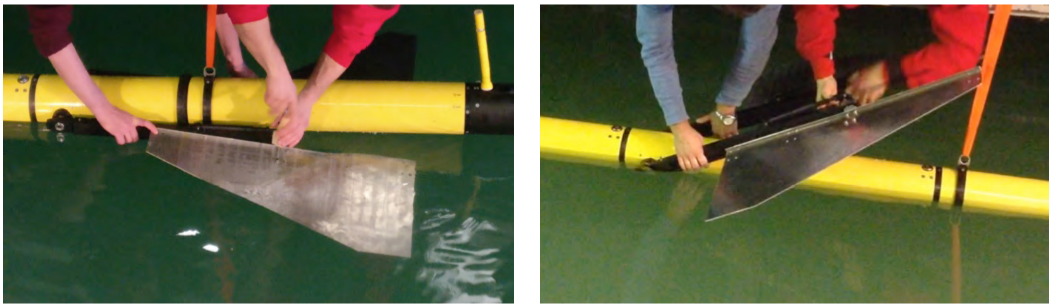


(a) (b) (c)

Figure 5: Drawings of the wing sections used in the tank tests. (a) Type 1 and 1-bis. (b) Type 2. (c) Type 3.



(a) (b)

Figure 6: Wing sections in the two mounting directions. (a) Right Side Up mounting direction. (b) Upside Down mounting direction.

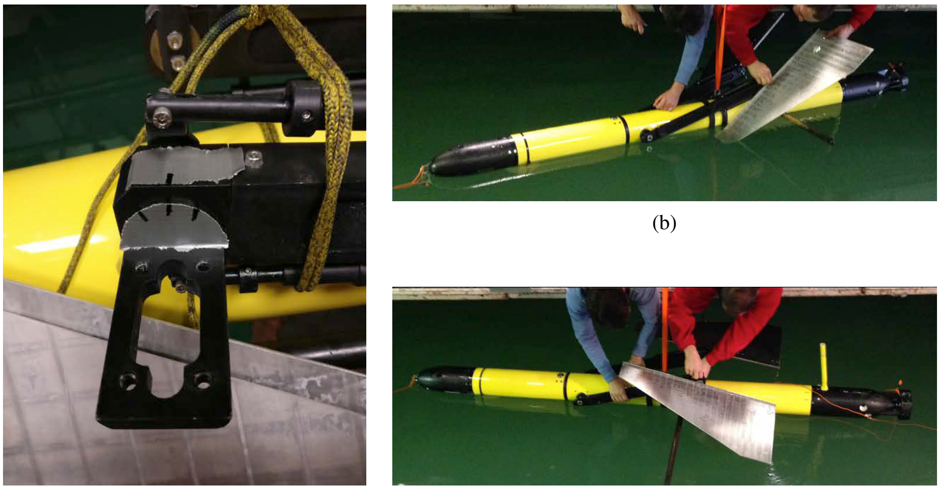
Wing mounting direction Each wing type was mounted according to the two possible mounting directions depicted in Figure 6. In the following, the configuration corresponding to the narrow part of the wing profile closer to the joint will be referred as *Right Side Up* (RSU, Figure 6a), whereas the opposite one will be labelled as *Upside Down* (UD, Figure 6b).

Wing mounting angle Each of the two joints connecting the arms of the WAVE module to the wings can be rotated manually acting on two sliders connected to the arm (Figure 7a). Depending on the locking position of the sliders, the joint may be fixed with a desired angle or free to rotate between two angular positions located at about $\pm 30°$ from the position in which the wings are perfectly aligned with the arms (*i.e.* 0°). During the energy recovery system tests the wings inclination was set at the two final angles, bringing the WAVE module in the configurations called *Knee* (-30° end of stroke) and *Foot* (+30° end of stroke), shown in Figure 7b and Figure 7c, respectively. Finally, the configuration in which the joint is free to move between two positions was also tested and it will be indicated as $[a,b]$, where a and b are the selected limits of the movement.

Wing buoyancy The buoyancy of the wings was modified by attaching additional weights or floats as shown in Figure 8. In the following, an increase in the buoyancy of the wing profiles will be indicated with the sign "$+$"; vice versa a weight addition will be indicated with the sign "$-$".

WAVE module position The modularity of the WAVE prototype allowed to move the energy recovery system towards the stern or the bow by assembling on the vehicle an additional neutral-buoyant module as shown in Figure 9.

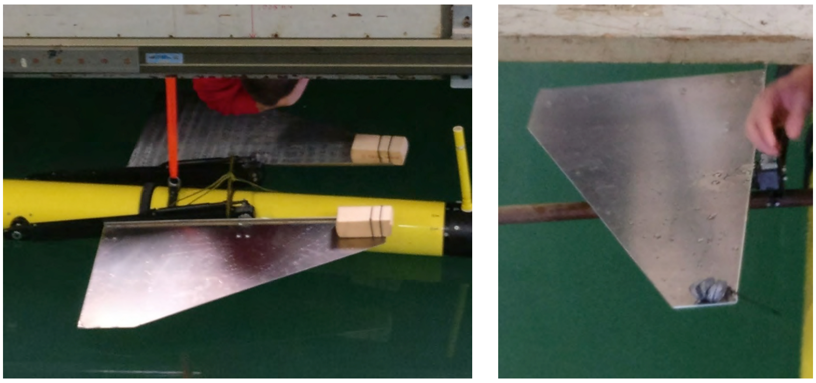
The setup of the WAVE module during the trials conducted with the energy recovery system is reported in Table 2 along with the experimental results. It is possible to notice that the configurations used in tests 2, 14 and 23



(b)

(a) (c)

Figure 7: Possible angular positions of the wings: (a) Joint end of stroke. (b) Knee configuration. (c) Foot configuration.



(a) (b)

Figure 8: (a) Floats and (b) weights were added or removed to modify the buoyancy of the wings.

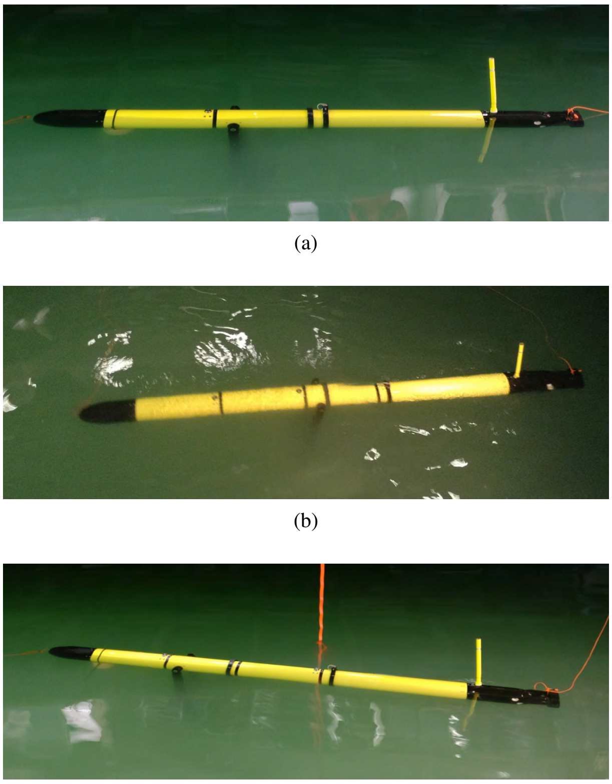
are the same of tests number 1, 6 and 15, respectively. This happened because the latter were affected by some experimentation anomalies that invalidate the mentioned tests, requiring a repetition of the runs.

2.2 Wave parameters configuration

The parameters describing the generated wave profiles were kept constant at 0.45 m of height and 0.33 Hz of frequency for most of the tests, except for the numbers 25 and 26 which were performed using a wave profile with continuous spectrum and variable heights. The choice of the frequency and the amplitude of the generated waves needs a specific comment. The CNR-INSEAN wave generator is typically used for the testing of scale models of marine vessels. Hence, the parameters of the wave profile are in turn scaled with respect to those of the real sea state where the system under test would work. In the experimentation of the project WAVE the vehicle is a *full scale* model. The wave characteristics chosen for the most of the tests corresponds to the highest *full scale* sea state that could be replicated by the plant. According to the CNR-INSEAN engineers, the best trade-off configuration for the highest sea state corresponds to the lowest frequency at which the wave generator is able to produce the maximum wave height of 0.45 m, namely 0.33 Hz. The configuration, on the basis of the World Meteorological Organization sea state code (based on the *wind sea* definition of the Douglas Sea Scale), corresponds to a sea state 2, denominated *smooth (wavelets)*. A calmer configuration condition, according to the previous simulative analysis, would not have provide an effective energy recovery Fenucci et al. (2016).

3 Data analysis and discussion

Table 2 summarises the average values of voltage, current and power generated by the WAVE recharging system for the different trials configurations described in Section 2.


(a)

(b)

(c)

Figure 9: The vehicle with three different relative positions of the WAVE module: (a) no additional module, (b) additional module at the bow and (c) at the stern of the energy recovery system.

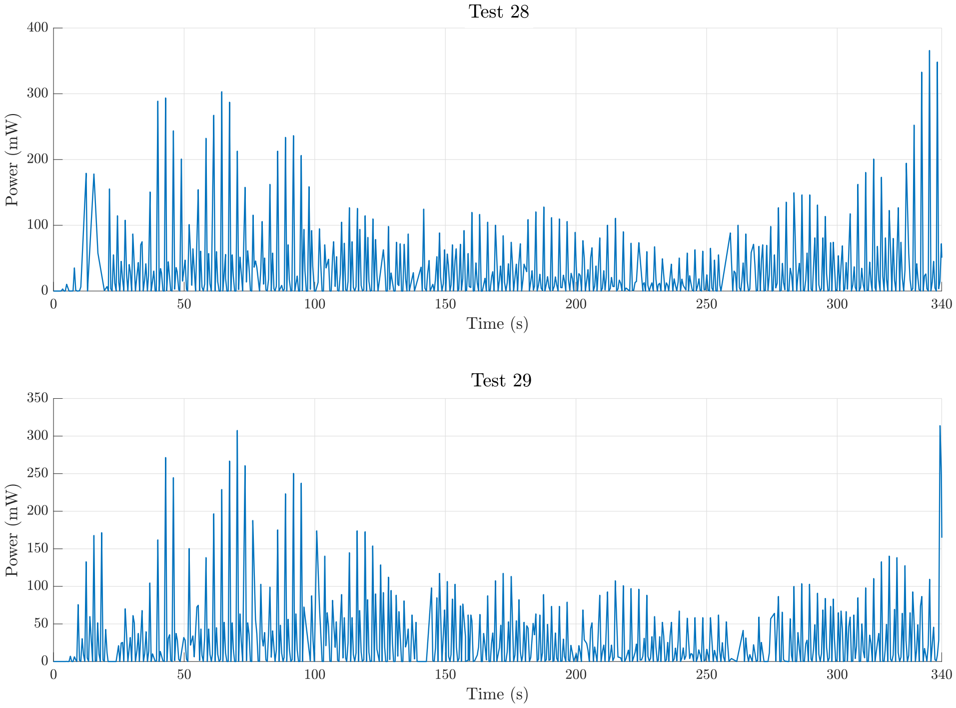


Figure 10: Power generated by the WAVE harvesting system for test no. 28 and no. 29.

Comparing the tests from 2 to 11, it is possible to notice that when the wing mounting angle is 0°, the best results in terms of developed power are obtained with the wing profile type 2, illustrated in Figure 5b. Looking at the test pairs 14-23, 4-18, 10-24, an evident improvement in system performance is achieved by tilting the wings in the so-called *Foot* configuration shown in Figure 7c. A further increase in the recovered average power is given by the displacement of the WAVE module towards the bow thanks to the insertion of an additional module as in Figure 9c, as demonstrated by the direct comparison between the test pairs 23-28 and 18-29. As expected, the tests 25 and 26 did not result in a significant outcome due to the under-sized parameters of the generated waves compared to those considered for the real scenario.

Figure 10 shows the power generated by the WAVE module in the two tests exhibiting the best performance, 28 and 29 respectively. The wave action causes an oscillatory motion of the arm of the WAVE module within a range of about 20° with respect to the rest position as highlighted in Figure 11 that reports the relative angle between the arm and the vehicle body. This continuous motion triggers the energy recovery mechanism, which repeatedly generates voltage and current peaks as shown in Figure 12.

3.1 Bench-tests

In this section the analysis of the generated electric power with respect to the electric load and the WAVE arms angular velocity is presented.

Table 2: Experimental test configurations and results. Average values of voltage, current and power obtained in the campaign are reported. The tests marked with the asterisks were performed by generating a wave profile with continuous spectrum and variable heights.

Test	WAVE configuration parameters						Experimental outputs		
	Wing profile	Wing mounting position	Wing mounting direction	Wing mounting angle (°)	Additional weight per wing (g)	Additional module position	Voltage (mV)	Current (mA)	Power (mW)
1	1	-	RSU	0	0	None	152.18	13.69	6.30
2	1	-	RSU	0	0	None	137.34	12.29	5.04
3	1-bis	-	RSU	0	0	None	187.07	16.77	8.05
4	2	Middle	RSU	0	0	None	269.70	24.16	14.49
5	2	Low	RSU	0	0	None	253.19	22.83	15.01
6	2	Middle	UD	0	0	None	307.06	27.55	18.77
7	2	High	UD	0	0	None	198.83	17.81	10.17
8	3	High	RSU	0	0	None	256.63	23.14	14.63
9	3	Low	RSU	0	0	None	279.46	25.14	16.23
10	2	High	RSU	0	0	None	273.78	24.61	16.54
11	1-bis	-	UD	0	0	None	199.35	17.88	9.41
12	2	Middle	UD	0	+380	None	282.28	25.13	18.04
13	2	Middle	UD	0	−400	None	271.52	24.27	14.97
14	2	Middle	UD	0	0	None	304.34	27.27	18.70
15	2	Middle	UD	+30	0	None	345.85	31.03	26.93
16	2	Middle	UD	−30	0	None	302.93	27.20	18.04
17	2	Middle	RSU	−30	0	None	305.06	27.33	17.51
18	2	Middle	RSU	+30	0	None	386.35	34.42	28.56
19	3	Low	RSU	+30	0	None	321.78	28.82	20.43
20	3	Low	RSU	−30	0	None	294.33	26.55	17.33
21	3	High	RSU	−30	0	None	265.98	24.00	13.26
22	3	High	RSU	+30	0	None	338.96	29.99	23.06
23	2	Middle	UD	+30	0	None	391.66	34.99	30.70
24	2	High	RSU	+30	0	None	340.83	30.37	23.74
25*	2	Middle	UD	+30	0	None	8.16	0	0
26*	2	Middle	UD	+30	0	None	13.89	1.21	0.16
27	2	Middle	UD	+30	0	Bow	75.66	6.73	2.05
28	2	Middle	UD	+30	0	Stern	436.46	39.24	34.77
29	2	Middle	RSU	+30	0	Stern	409.72	36.76	30.75
30	2	Middle	UD	−30	0	Stern	243.90	22.05	10.50
31	2	Middle	UD	[−30, +30]	0	Stern	348.79	31.50	20.85
32	2	High	RSU	[−30, +30]	0	Stern	283.82	25.69	15.75
33	2	High	RSU	[0, +30]	0	Stern	266.32	24.10	13.78

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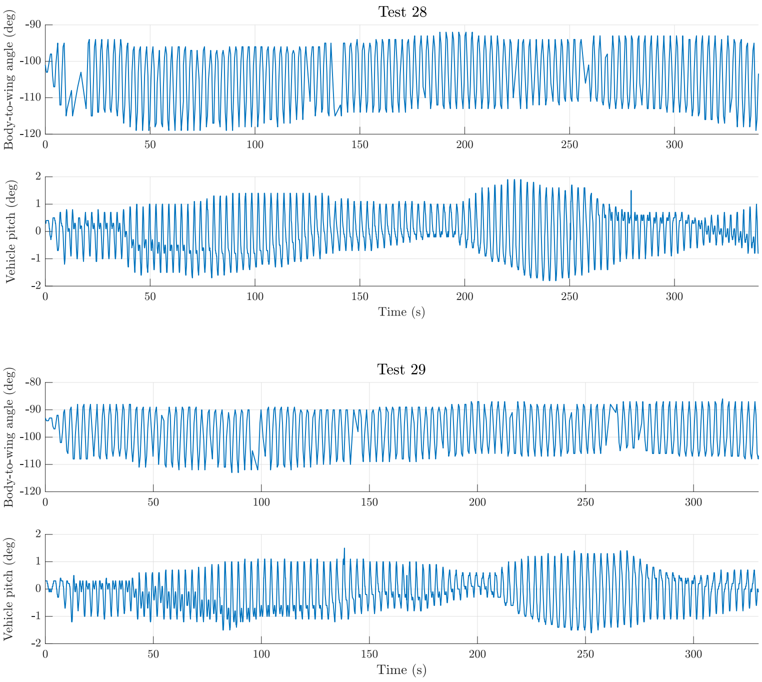

Figure 11: The relative angle between WAVE arms and vehicle body and the vehicle pitch for test no. 28 and no. 29.

In the experimental activity described in Section 2, the resistive load was constant and equal to 10 Ω. In order to characterise the variation of the WAVE generated electric power with respect to the resistive load, bench tests have been carried out at the GraalTech facilities.

The voltage and current generated were measured while a single arm (without wings or additional weights) fell from the horizontal position (*i.e.* aligned to the vehicle body) until reaching the equilibrium position. For various resistance values between 1 and 51.7 Ω, the procedure was repeated 10 times. All the dry tests showed a clear repeatability, as illustrated in Figure 13 where the data collected with resistive load equal to 10 Ω are reported. The maximum power value for each corresponding resistance was therefore chosen as the index according to which characterise the effect of the load variation on the performance of the energy recovery system. Figure 14 shows the trend of this index. The maximum electric power was obtained in a range of resistance values between 4.7 and 14.7 Ω, which includes the value of the load used in the tank experimentation.

4 Conclusions and further research

A comparative analysis of the experimental performance of energy recovery obtainable from several different configurations of the WAVE module is described in this paper. WAVE is a module designed and developed for the AUVs with the aim of extending their energy autonomy. The comparison is based on the data collected through an extensive experimental campaign carried out in a controlled environment, the CNR-INSEAN tank equipped with a wave generator. During three days of activity the configuration of the module, mounted on a eFlaga as testing vehicle, was modified while maintaining the same generated wave characteristics corresponding to sea state 2. For the 33 performed tests, generated electric power was indirectly computed from measurements of current and voltage. This procedure allowed to qualitatively understand the effect on the generated electric power due to wing shape, mounting position, the mounting direction, the mounting angle the module buoyancy and its position.The manuscript proposes the details of this analysis.

From a preliminary analysis of the data shown, it is clear that for the considered configurations the WAVE system is not sufficient to fully guarantee the necessary energy supply for long-endurance missions. Indeed, the collected experimental results constitute a solid reference database for a critical tuning of the dynamic model of the system characterised during the first phase of the project. This way, it will be possible to carry out further simulations that can reliably predict the performance of the system even in conditions not tested yet due to the physical limits of the tank facility. Performance related to different wing shapes and mounting configurations may be inferred by means of the model without the necessity of additional experiments with considerable advantages in terms of time and costs.

The combination of the experimental and calibrated simulative results will allow to draw further analysis on the achievable performance in terms of both expected wave energy harvesting capability and also wave-gliding navigation skills with respect to the vehicle consumption.

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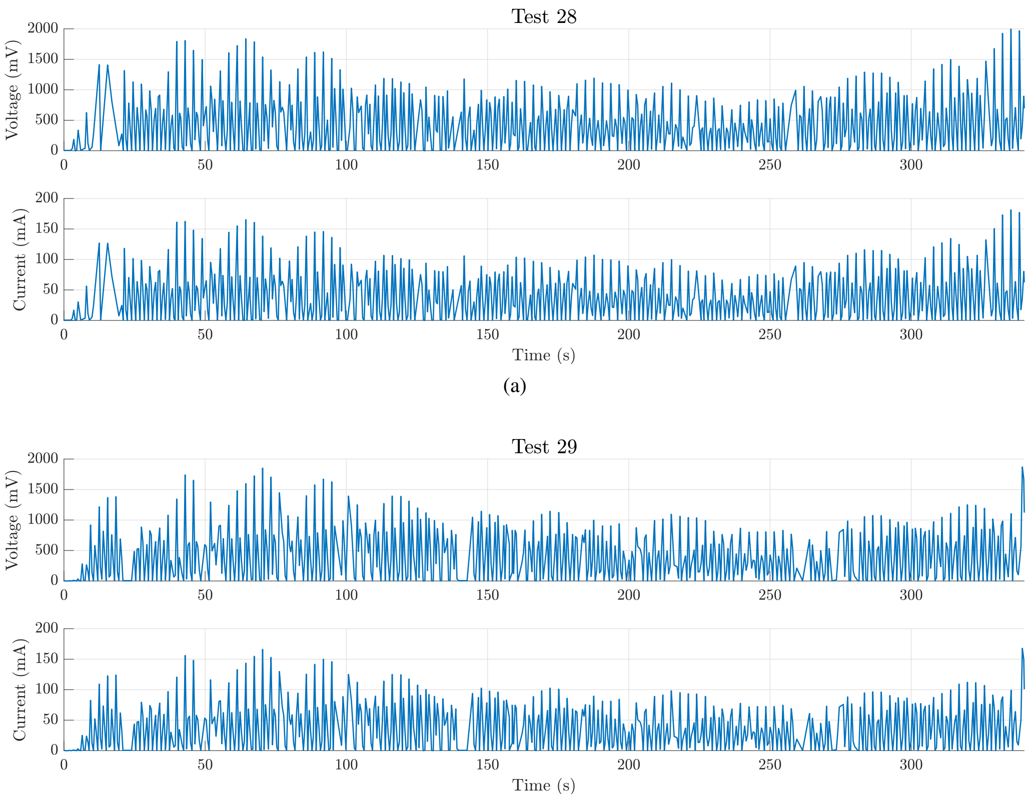

(a)

(b)

Figure 12: Generated voltage and current by the WAVE harvesting system for test no. 28 (a) and no. 29 (b).

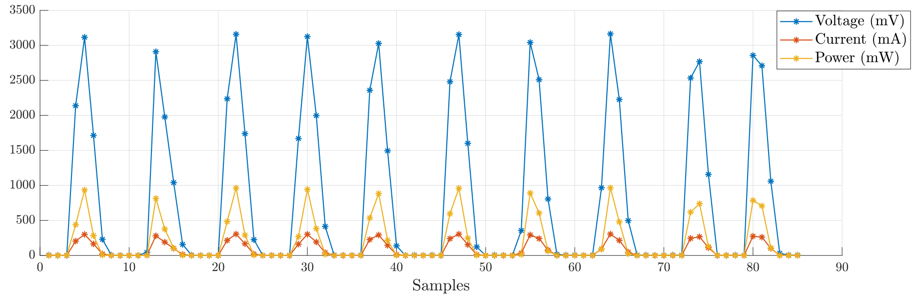

Figure 13: Voltages (blue), currents (red) and corresponding electrical power (orange) measured during the 10 lab tests performed with resistance equal to 10 Ω.

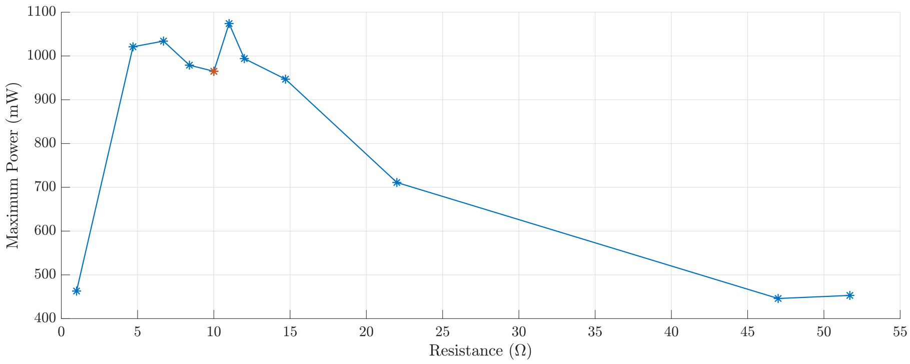

Figure 14: Maximum power measured in the bench test with various resistive loads connected to the motor. In red, the value used in the experimental activity.

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