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AN EVALUATION METHOD FOR ARTIFICIAL SEA STATE TIME TRACES AND HIGH LEVEL DESIGN OF POWER-TAKE-OFF IN MARINE WAVE ENERGY APPLICATIONS

Dominic DIEßEL[1], Hubertus MURRENHOFF[2]

[1] RWTH Aachen University, Germany, Institute for Fluid Power Drives and Controls (IFAS), Dominic.Diessel@ifas.rwth-aachen.de

[2] RWTH Aachen University, Germany, Institute for Fluid Power Drives and Controls (IFAS), post@ifas.rwth-aachen.de

Abstract: *The design of Power-Take-Offs for marine Wave Energy Converters is carried out using reference sea state time traces as load cycles for simulation. These are used for the high level design at the beginning of the design process and for detailed design at its end. However, two problems arise in this approach. First, the sea state time traces are often generated using superimposed sine waves with amplitudes defined by wave spectra being prone to statistical deviations. Second, especially for the high level design this approach is time consuming due to many simulations needed. Within this paper these two problems are tackled with help of a characteristic time trace diagram, which is proposed in this paper and enables the evaluation of the average power of a sea state time trace and its distribution. Additionally, this diagram is used for a high level design of the hydraulic system in a Power-Take-Off including the cylinder size, accumulator size, motor size and pressure levels.*
The background of the proposed approaches lies in the marine wave energy applications; however, the method might be used for any irregular load cycles and any hydraulic system containing accumulators for power storage.

Keywords: *Marine Wave Energy, Sea state, statistical analysis, average power, power distribution, Power-Take-Off, Design*

1. Introduction

Marine waves contain energy, which is usually dissipated while hitting the shore [1]. Extracting the energy of the marine waves before its dissipation can be done with a so called Wave Energy Converter (WEC). There are several types of WECs, of which one contains at least one body, which oscillates with the waves. Damping this motion extracts energy from it. This is done with a so called Power Take-Off (PTO) [2].
A PTO usually features a hydraulic cylinder, which is installed between the oscillating body and a fixed foundation, transforming the motion into a volume flow impressed by a pressure. This flow subsequently is treated by rectification, a certain amount of smoothing and transformation into a rotational motion in order to power an electric generator. Thus, usable electric power, which can be fed into the main grid, is generated [2]. The PTO type considered here generates the flow with at least one cylinder, rectifies it with help of check valves, then smoothes it with accumulators and transforms it into mechanical motion with at least one hydraulic motor.
The main component parameters enabling a cost effective electric power output to the electric grid within the PTO are the cylinder size, the accumulator capacity and the hydraulic motor size. Furthermore the PTO`s operation needs to be confirmed in every occurring sea state, which is done by testing it in artificially generated sea state time traces. Accordingly, following design steps are usually carried out:

- High level design of the **general dimensions** for a cost effective operation

- Design of control algorithm for every degree of freedom

- Detailed design and proof of operation in **artificial sea state time traces**

While the first step is either heuristic or related to an excessive amount of simulations in an iterative process, the last step relies on the artificial sea state time traces (SSTT). The second design step is not relevant for this paper.

Various methods are known to generate SSTT, while the most easy and common one, is prone to errors as generating wrong spectra and wrong wave distributions, called groupiness [3], [4], [5]. Since other methods are seldom used and difficult in implementation, the focus of this paper is put on the method mentioned above. In this method sine waves of different frequencies are superimposed, while each sine wave features an amplitude derived from an energy spectrum [6]. Therefore, this paper focuses on a fast screening method for identifying suitable general dimensions for a high-level design considering the wave conditions expected and an evaluation method for the artificial SSTT for comparison against real waves in all frequency domains.

To achieve the above explained aims, the paper is divided into the following parts. First, marine waves and their sea states are presented in chapter 2. Next, a measure for comparing the power provided in a sea state is identified and visualized in chapter 3. With this measure methods for the sea state evaluation and PTO design screening are presented in chapter 4. The paper is summarized in chapter 5 and an outlook is given.

2. Marine waves

Marine waves result from the wind accelerating the top layer of calm water. Since this process is irregular, small ripples occur. These are amplified by the wind over time forming larger and larger waves. Once build up, the energy of a wave is dissipated only in a negligible extent, as long as the wave is in open and deep water. Thus, marine waves can travel over long distances and can become decoupled from the wind [1].

The generation of waves takes place whenever wind blows, the direction of the wave propagation is the same as the direction of the generating wind and different wave frequencies travel with different speeds. Accordingly, at each position there will always be a superimposing of waves from different directions and speeds [1]. Thus, the water elevation becomes highly irregular.

2.1 Measuring sea states

The wave measurement is carried out with help of buoys measuring the water elevation over time at a specific geographic point. The resulting elevation trace can be examined with the Fourier transformation, returning intensities of various frequencies. These frequency dependent intensities can be displayed in a diagram as the spectrum of the water elevation trace, shown in fig.1. In the spectrum the wave peak period T_P correlates with the frequency of highest intensity, while the specific wave height H_S is related to the highest intensity.

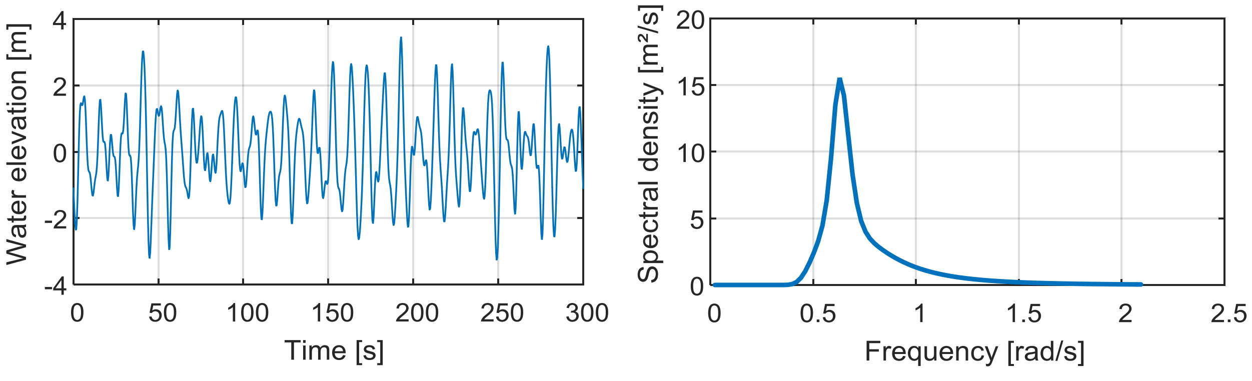
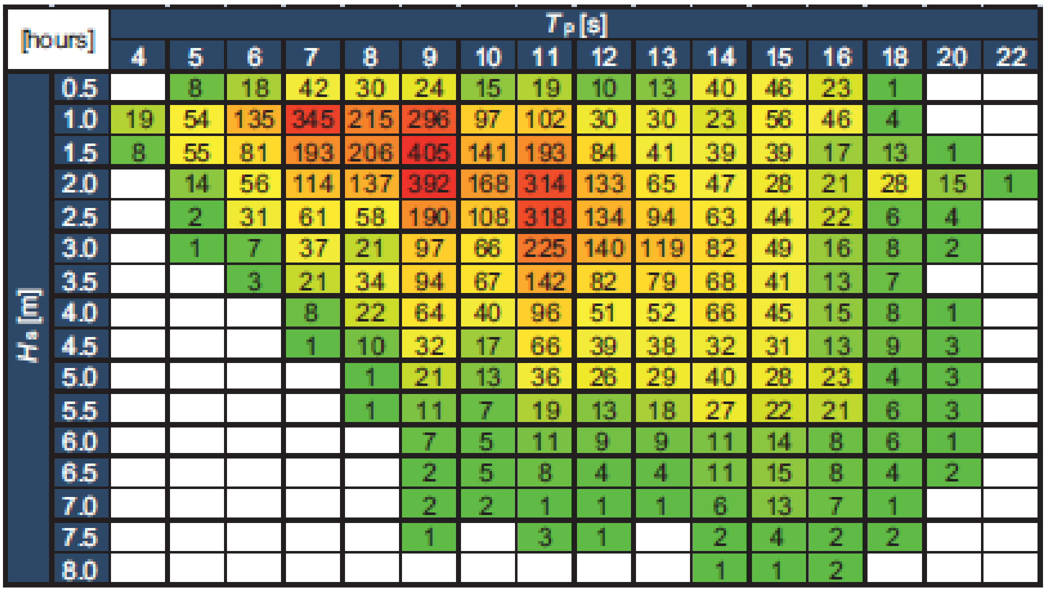


Fig. 1. Exemplar water elevation trace (SSTT 1) and its spectrum diagram for H_S = 5 m, T_P = 10 s

The wave spectrums measured are not only dependent on the weather, but on the location as well. Thus, typical spectrums for waves were found for the North Sea, the Atlantic Ocean and others. Furthermore, they are dependent on the water depth and distance of wind penetration [1].

2.2 Artificial sea state time trace generation

Sea state time traces (SSTT) of the water elevation are required for simulation of various wave heights and periods in order to evaluate the annual energy performance or the proof of operation. These sea states are commonly selected from location dependent scatter diagrams with the aim to obtain a reference set modelling the annual water elevation for a specific position, see fig 2 or [7]. However, for each of these sea states either only a limited measured wave trace can be used or an artificial SSTT needs to be generated. Accordingly, both options only model the reality and possible modelling errors need to be known. Since this is one focus of this paper, the artificial generation of sea states is explained in detail.



[hours]	T_p [s]															
H_s [m]	4	5	6	7	8	9	10	11	12	13	14	15	16	18	20	22
0.5		8	18	42	30	24	15	19	10	13	40	46	23	1		
1.0	19	54	135	345	215	296	97	102	30	30	23	56	46	4		
1.5	8	55	81	193	206	405	141	193	84	41	39	39	17	13	1	
2.0		14	56	114	137	392	168	314	133	65	47	28	21	28	15	1
2.5		2	31	61	58	190	108	318	134	94	63	44	22	6	4	
3.0		1	7	37	21	97	66	225	140	119	82	49	16	8	2	
3.5			3	21	34	94	67	142	82	79	68	41	13	7		
4.0				8	22	64	40	96	51	52	66	45	15	8	1	
4.5				1	10	32	17	66	39	38	32	31	13	9	3	
5.0					1	21	13	36	26	29	40	28	23	4	3	
5.5					1	11	7	19	13	18	27	22	21	6	3	
6.0						7	5	11	9	9	11	14	8	6	1	
6.5						2	5	8	4	4	11	15	8	4	2	
7.0						2	2	1	1	1	6	13	7	1		
7.5						1		3	1		2	4	2	2		
8.0											1	1	2			

Fig. 2. Sample scatter diagram with sea state occurrence [7]

The artificial SSTT is commonly generated with a reverse Fourier transformation. Accordingly, sine waves in discretized frequency steps are superimposed. In the most common approach (method 1), despite being prone to errors [3], [4], [5], the sine waves are generated with an amplitude x_A according to eq. 1 for each frequency ω [6]. Other methods include different definitions of the amplitudes (method 2), deterministic approaches (method 3) or filtering white noise to get the desired spectrum (method 4) [3], [4], [5]. These methods 2 to 4 are seldom used. Thus, the focus of this paper is put one method 1. However, the evaluation of SSTT, proposed in this paper, works for SSTT generated with one of the methods 2 to 4 as well.

Eq 1: $x_{\mathrm{A}} = \sqrt{2S(\omega)\Delta\omega}$

Examples for method 1 SSTT generations are shown in fig. 3. Frequencies are selected from a spectrum and the according sine waves are superimposed with a constant zero (left, SSTT 0) and with a random (right, SSTT2) phase delay. After a time range, according to the least common multiple of the frequencies, the SSTT repeats itself. For this paper, each sea state has been generated with 100 superimposed sine waves at frequencies being a multiple of the basic frequency of 1/300 Hz.

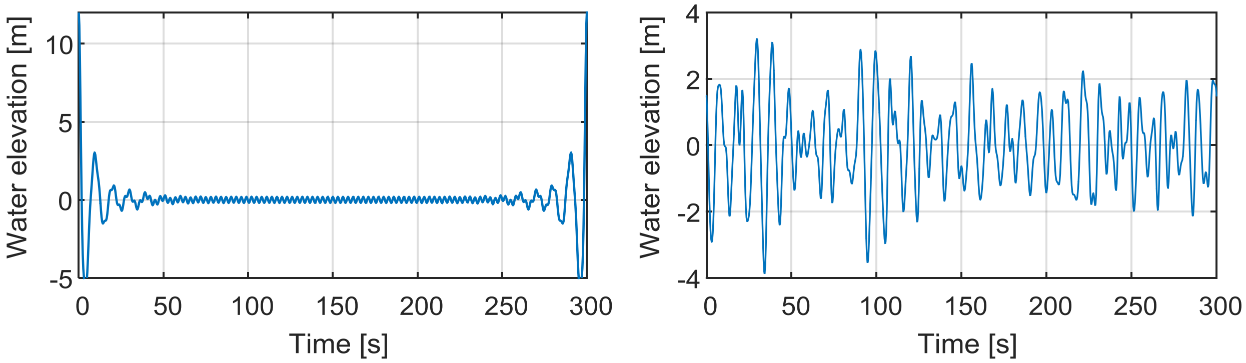


Fig. 3. SSTT 0 without (left) and SSTT2 with (right) phase delays for H_S = 5 m, T_P = 10 s

Analysing the sample SSTT following conclusions can be drawn: First, the full SSTT needs to be considered, because different parts of the sea state provide completely different power, correlating with wave height. Second, the phase delays have a major influence on the sea state behaviour in terms of power distribution and peak power. Whether the average power is affected by the phase delays cannot be told from the diagrams so far. However, it needs to be ensured that a selected SSTT provides an average power and neither too large waves overestimating the output power nor too small waves underestimating the wave loads. Accordingly a measure needs to be available for comparing artificially generated SSTT with real ones. Additionally, with this the error made by using the inverse Fourier Transform with defined wave height amplitudes (method 1) against other methods [5] can be visualised.

3. Measure for the power provided in a sea state

For comparing sea states and for screening various dimensions concerning their effect on the total output energy, a measure of the expected waves is required. This measure needs to incorporate the expected average energy and its time-dependent distribution. Furthermore, it either needs to be related only to the wave condition or to the WEC`s behaviour within the waves. Thereby it needs to be generic, i.e. independent from PTO parameters as cylinder area, accumulator capacity, motor volume flow and pressure. Furthermore it needs to be usable. Accordingly, this chapter is divided in the identification of the measure and its visualization.

3.1 Identification

The main reason for building a WEC is to produce electric energy. Accordingly, the energy produced should be considered when evaluating the PTO in various sea states. However, the total PTO efficiency is unknown at this point of the design process. This is why the input energy should be considered instead of the output energy, see fig. 4. Furthermore, to incorporate time variant effects, the power should be analysed instead of the energy, which is its integration over time. Thus, the WEC power is considered, which can be described as the product of the PTO force and WEC velocity. Here it is assumed that the PTO force always acts against the direction of WEC motion. When furthermore assuming a constant PTO force independent from the direction of motion, the power can be written as the product of the constant force and the absolute value of the velocity.

No PTO parameter should have an effect on the measure evaluating the sea states. Thus, the PTO force, as the product of cylinder area and pressure, should not be taken into account and the actual water elevation velocity should be considered. Later, for screening the high level PTO design, the PTO parameters should be used as variables and their estimated effect on the WEC motion should be considered, too. However, by removing all PTO related parameters from the input power only the absolute velocity of either the WEC or the water elevation remains. This absolute velocity is used for the measure. It represents a power normalised by the PTO force of cylinder area times pressure.

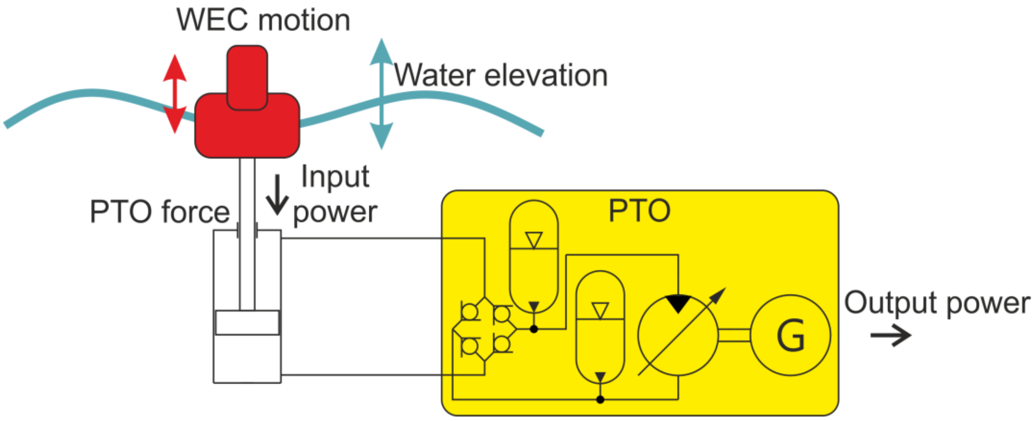


Fig. 4. Power transfer in a simplified wave-WEC-PTO-system

3.2 Visualization of the measure

The absolute velocity of the water elevation is as irregular, as the water elevation. Thus, it cannot directly be evaluated. Its distribution over time including high or low speed and power regimes or peaks, and thus volatility, needs to be considered. Since finally a smooth electric power output would be ideal for the use of the motors and generators, the average power over various time ranges is relevant according to the accumulator capacity. Therefore, the absolute velocity is smoothed with moving averages of different time ranges, see fig. 5.

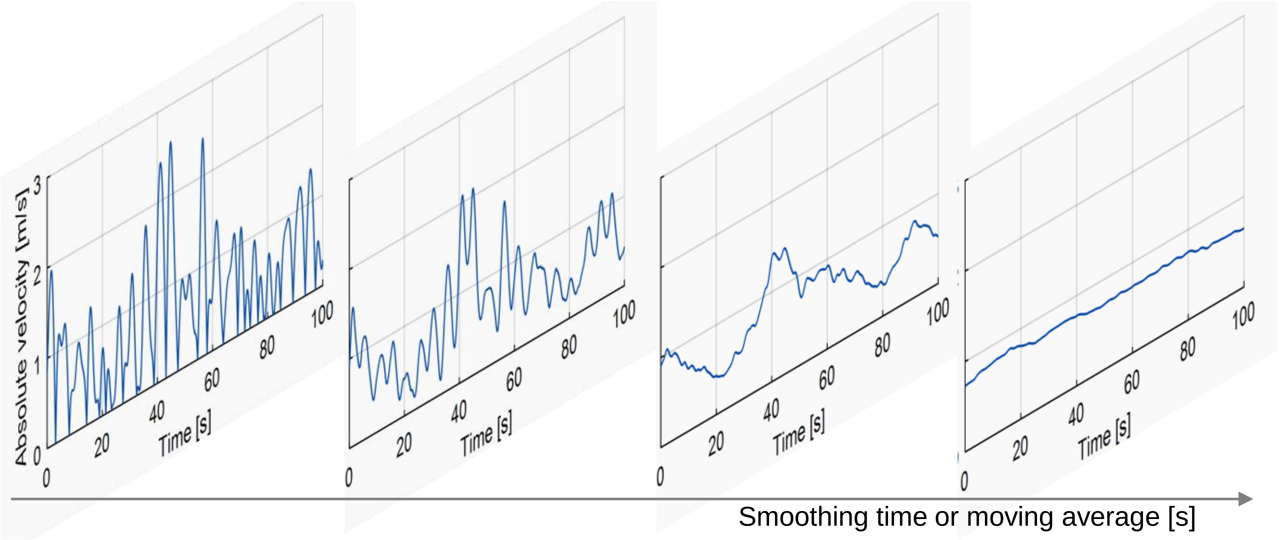


Fig. 5. Moving averages of the absolute velocity

With the absolute velocity displayed in various smoothing steps, information about the volatility is included twice, once in the original SSTT and second in the various smoothing steps. Accordingly, the volatility information of the traces can be reduced without losing information on the volatility in general. Thus, the traces in all smoothing steps are analysed in terms of which absolute velocity covers which share of the total distance travelled. This relates to the question which installed input power is required for collecting a certain share of the total power. An example is shown in fig. 6 on the left side. The first 20% of the distance correlating with the transferred energy can be covered with velocities below 0.2 m/s, while peaks between 1.2 m/s and 2.8 m/s need to be tapped for the last 20%.

The procedure of generating horizontal lines for collectable shares of the available power can be repeated for every smoothing range. Then the three dimensional chart with the axes time, absolute velocity and smoothing range can be looked at from the side, so that a two dimensional chart forms, which does not contain the time anymore. In this chart the percentages of collectable power appear as points for each smoothing range and can be connected to lines. This gives a characteristic diagram of a sea state time trace, see fig.6 on the right side, with a line for every 10% step of the collectable power.

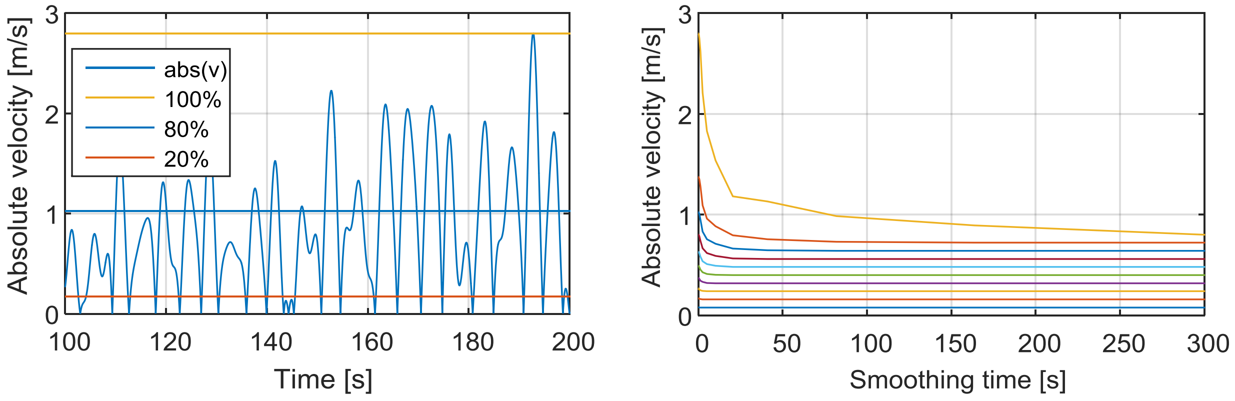


Fig. 6. Power percentages in a time trace (left) and characteristic sea state diagram (right)

For further use and easier comparison the characteristic sea state diagram is modified. First, a logarithmic scale is applied to both axes. Then, the smoothing time range is substituted by a radial frequency according to eq. 2. This relationship is similar to the common correlation between period and radial frequency, when considering the smoothing period to be half of a full rotation period. Finally, the diagram is mirrored, so that the frequency increases from left to right, see fig. 7. This diagram can either be set up for single sea states or for a full year's sea state set. The reason for these cosmetic changes will get clearer when being used for SSTT comparison and for high level design.

Eq. 2: $\omega = \dfrac{1}{4\pi\, t_{\text{Smoothing}}}$

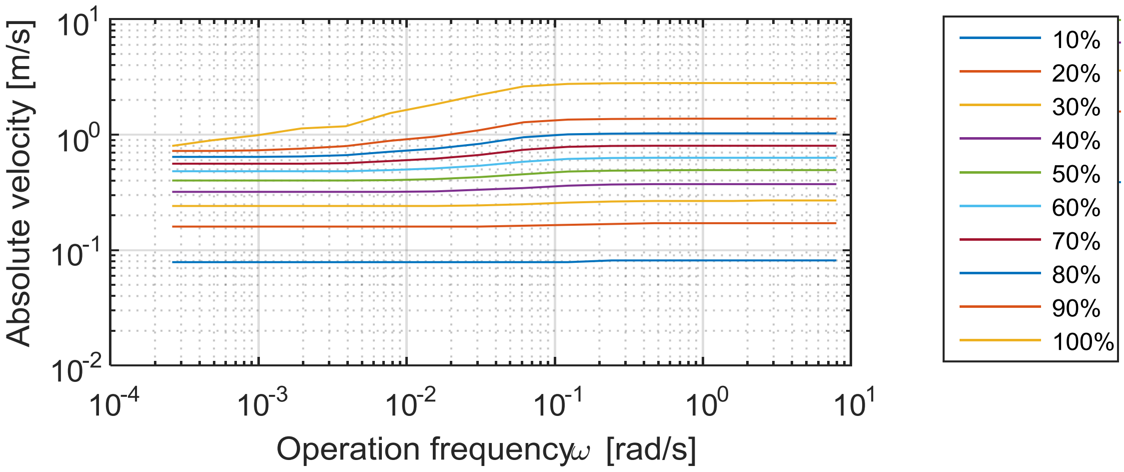


Fig. 7. Final characteristic sea state diagram (SSTT 1)

4. Methods

4.1 Evaluation of sea states

For evaluating a SSTT it needs to be compared with other SSTT. Thus, it can be ensured that the analysed one provides a common power distribution at a common power level. Accordingly, the characteristic sea state diagram is created for several SSTT featuring the same wave height and period, only differing in either the random phase delays of the single sine waves when using the method 1 or differing in the method of SSTT generation (method 2 to 4, not focused on in this paper) respectively measurement. The values of the characteristic sea state diagrams of these SSTT are then averaged resulting in a mean characteristic sea state diagram. By dividing the analysed characteristic sea state diagram of the SSTT by this mean characteristic sea state diagram, differences in average power and in power distribution become apparent.

As an example for this method three SSTT (0 to 2), which have been generated with method 1 are compared. The SSTT 0 was created with all phase delays being zero, while the other two have random phase delays, see fig. 1 and fig. 3. By looking at these three SSTT it can be said that the one with zero phase delays (SSTT 0, fig. 3 left) has a completely different power distribution, while the other two are similar. However, no statement on average power provided can be made.

In fig. 8 the comparison of the characteristic sea state diagrams are shown. For this the characteristic diagrams of the SSTT 0 and 2 are shown at the top. At the bottom left, the SSTT 0 with zero phase delays has been divided by the SSTT 2, including non-zero phase delays. On the right, the SSTT 1 and SSTT 2 are compared. As can be seen, the SSTT 0 shows an average velocity about six times higher than the SSTT 2, see left for small operation frequencies. However, this does not result from the huge wave at the beginning of the time trace, because this wave provides only approx. 10% of the sea state power. This can be deduced from the 100% collectable power curve being 18 times higher for high operation frequencies than for the SSTT 2. Otherwise, all power curves are approximately five to six times higher for the SSTT 0 than the SSTT 2 even for high operation frequencies. This indicates that the velocities occurring for the SSTT 0 are evenly distributed over the sea state time range and always are higher than for the SSTT 2. Analysing the SSTT 0 motion in detail (fig.3), it shows many short waves resulting in high, fast alternating, velocities, while the SSTT 2 includes longer waves with in average smaller velocities.

On the right side of fig. 8 SSTT 1 and SSTT 2, both with random phase delays, are compared by dividing SSTT 1 by SSTT 2. Three main results can be taken from this. First, despite being created for the same wave height and period, the collectable power differs strongly by 20 to 25% in average. Second, the stronger SSTT 2 has disproportionately high velocity peaks, which can be seen by the 100% collectable power curve being at 0.75 for high frequencies and thus, without smoothing. Finally, the ratio differs with the frequency considered, see frequencies of approx. 10^{-2} rad/s. Accordingly, these SSTT are very different and will provoke a completely different PTO behaviour and output energy.

As the explanation above shows, SSTTs generated with the simple and erroneous method 1 strongly depend on the random phase delays used, influencing both the average power and the power distribution. Accordingly, special care is required when selecting representative sea states. However, the same method as applied here can be used to compare any SSTT either measured or artificially generated for ensuring representative SSTTs.

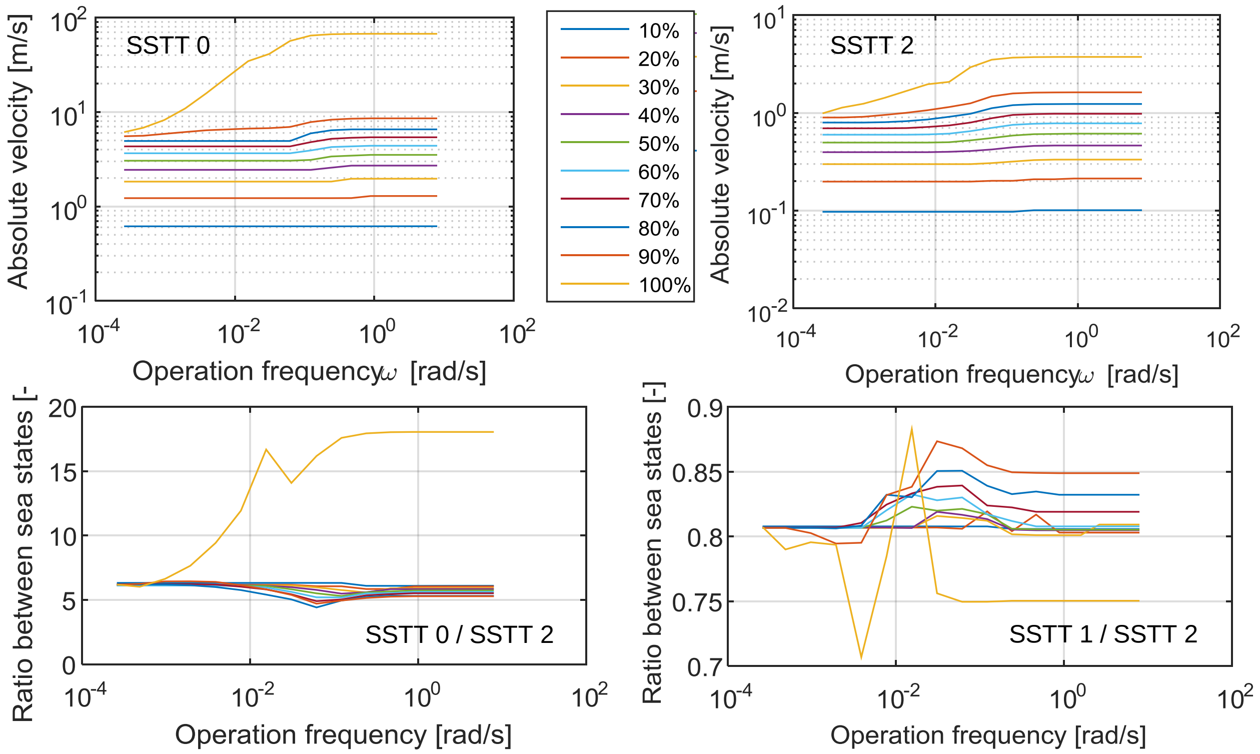


Fig. 8. Comparison of the characteristic sea state diagrams, top: characteristic diagrams of SSTT 0 and SSTT 2, bottom left: comparison of SSTT 0 divided by SSTT 2, bottom right: comparison of SSTT 1 divided by SSTT 2

4.2 PTO high level design screening

Designing a hydraulic system including accumulators for energy storage of irregular load cycles requires detailed knowledge about the load cycle and the design goals. For wave power applications the design goal usually is to generate as much electric power as possible in a cost efficient way. Accordingly, the hydraulic transmission will not be designed for peak power, but for a power providing a large amount of full load hours. Since the hydraulic motor and the adjacent generator are rather expensive when compared to accumulator costs, including accumulators in the design can be cost efficient. This enables a larger amount of full load hours by averaging the input power peaks and provides a higher output power average with only slightly increased costs. However, especially during the early design process a selection of the sizes for installed power and accumulators are related to an iterative process, because for each sea state a time based simulation is required in order to roughly estimate the accumulator effect. With help of the characteristic sea state diagram a more straight forward approach is proposed here.

As mentioned before, the characteristic sea state diagram can be used for single sea states as well as for a full year's sea state representation. Accordingly, using the diagram of a five minute period instead of a full year representative does not restrict the explanation, but only the validity when designing the system. Therefore a five minute period is used for the following example, being the SSTT 2, with random phase delays, see fig. 3.

As shown in fig. 9, the installed power, correlating with the motor-generator-set size (horizontal line) can be included in the characteristic sea state diagram by normalising it with the PTO force consisting of the system pressure and the average cylinder area, see eq. 3. This relationship requires the y-axis of the characteristic diagram to be the WEC velocity instead of the water elevation velocity. However, the WEC velocity can be simulated for several possible PTO forces in advance without excessive simulation effort. Even for a system with a slightly variable system pressure in the accumulators, this velocity trace will provide a good approximation.

Eq. 3: $v_{Inst} = \dfrac{P_{Inst,Motor-Generator-Set}}{p_{System} A_{Cylinder}}$

The accumulator characteristic can be drawn in the characteristic sea state diagram. The volume flow an accumulator can take in, in relation to its volume capacity for an accepted pressure variation and the period of time loading during the load cycle and normalised by its average cylinder area, see eq. 4, gives a diagonal straight in the characteristic sea state diagram. It shows the power, which can be absorbed by the accumulators for later use in dependency of the frequency.

Eq. 4: $v_{Acc} = \dfrac{\Delta V_{Acc}}{2 A_{Cylinder} t_{Smoothing}} = 4\pi\omega \dfrac{\Delta V_{Acc}}{2 A_{Cylinder}}$

Adding the normalised installed power of the motor-generator-set to the one of the accumulator gives a characteristic of the power, which can be absorbed by the accumulator and the motor-generator-set and which can be used for generating electric power (curved line). The lowest line of the collectable power percentages hit by this power characteristic gives the share of the available power, which can be used by the motor-generator set, i.e. a statement on the total energy output. In the example 70% of the maximal available energy can be used for transformation to electric energy. This can be deduced from the fact that the power characteristic curve hits the 70%-line at 10^{-1} rad/s. This means that the sum of the normalised motor power and the normalised accumulator capacity cannot cover input power peaks when considering a smoothing over several waves equivalent to 10^{-1} rad/s operation frequency. If the accumulators would be larger, i.e. the diagonal line further to the top left, the usable energy might increase by up to 10%-points. Finally, the share of the available power, which cannot be used for generating electric power, will be dissipated in the hydraulic system, requiring cooling.

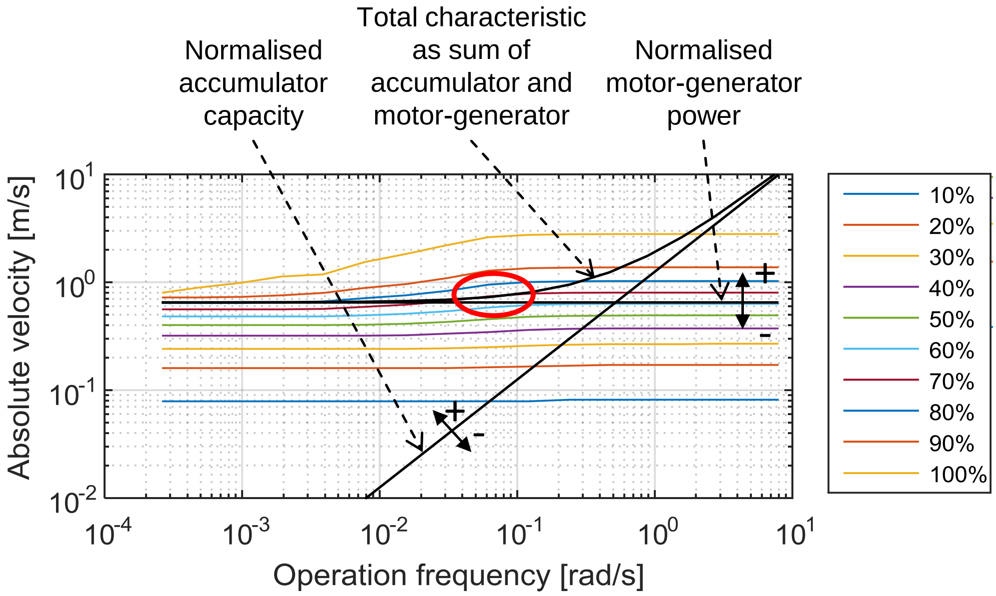


Fig. 9. Use of the characteristic sea state diagram for the high level PTO design process

The approach explained above can either be carried out for a full year characteristic diagram or separately for reference sea states. The latter enables the use of different operation pressures used in the sea states, varying the forces on the WEC and thus its motion and changing accumulator capacities. However, in either case a baseline with suitable PTO parameter values can be drawn for later optimisation with high-end simulations.

5. Conclusions and outlook

For wave energy applications SSTT are used for both high level design of roughly optimised PTO parameters and for detailed design of the final operation. However, by using the common and simple, but erroneous, generation method with applying random phase delays and defined wave heights for superimposed sine waves in order to create SSTT, a certain variance in the sea state power as well as in its distribution is created. Within this paper a method for comparing SSTT was proposed, featuring the absolute velocity of the water particles as a measure for the collectable power and using moving averages in various frequency domains for evaluating its time distribution visualised in a characteristic sea state diagram. First investigations with this method show that the average collectable power can differ by up to 25% for randomly generated sea states depending on the random numbers used.

So far simulations in various sea states are carried out for a high level design of the hydraulic transmission of Wave Energy Converters. Since the duration of the sea states needs to be in the range of multiple minutes for proper modelling and single aspects of the hydraulic transmission require a high resolution in time, these simulations are time consuming. With the help of the aforementioned characteristic sea state diagram a method is proposed in this paper for a fast screening of high level design parameter options. Thus, a parameter set roughly optimised for cost efficiency can be found, including cylinder sizes, accumulator sizes, motor sizes and pressure levels.

The results of this paper can be used for further research in various domains. First, the method for evaluating various SSTT can be used for a statistical analysis. This statistical analysis can comprise the variance of various SSTT related values, influences of the discretisation of the spectrum on this variance, required SSTT length for a reliable model and different SSTT generation methods.

Second, the high level design with the characteristic sea state diagram can be improved by considering efficiencies of the various components as well as various control strategies. Furthermore, the results of detailed simulations can be compared with the results of the high level design for analysing its accuracy. Additionally, the comparison of different characteristic time traces of e.g. the input power and the output power provides a tool for evaluating the function of the transmission analysed similar to a Bode-diagram.

Third, the method using the characteristic time trace diagram might be transferred to other applications, such as mobile machinery in terms of load cycle analysis and required accumulator volume estimation. Furthermore, the method could be used for automatic process cycle monitoring in industrial applications enabling the detection of deviations and identifying potential for improvement.

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