**Scientific Journals**
**of the Maritime University of Szczecin**

**Zeszyty Naukowe**
**Akademii Morskiej w Szczecinie**

**2015, 41 (113), 30–34**
**ISSN 1733-8670 (Printed)**
**ISSN 2392-0378 (Online)**

# Energy retrieval from sea waves

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**Key words:** sea waves, wave parameters, wave energy, converters wave parameters, solid wave power plant, floating wave power plant

**Abstract**
Seas and oceans occupy approx. 71% of the Earth. On their surface wave action of stronger or weaker magnitude can be observed throughout a major part of the year. Wind-generated wave action contains energy, which can be retrieved and used for electrical current production. The paper shows what energy is contained in wind-generated waves on various ocean areas, presents dynamics of water movement in a wave as well as several examples of calculation results of the velocity of water particles and hydrodynamic pressures occurring in a wave.

## Introduction

Two basic elements of sea environment: air and water are in constant motion throughout a major part of the year. Air travels over the sea surface in the form of wind, and water in the form of sea currents and tides as well as waves (however the movement of water particles is here totally different than in sea currents or wind). The area covered by seas and oceans constitutes approx. 71% of the surface of the Earth, one can therefore easily think of the immense energy resources of wind, sea currents and waves. However, there is mainly a technical problem of obtaining such energy, as well as the effectiveness and efficiency of this process. Research into energy retrieval from sea environment has been carried out for a number of years.

The paper presents value units of energy contained in waves, wave parameters decisive for energy value as well as possible ways of energy retrieval (together with their efficiency) and a few examples of technical devices used for converting wave energy into electric current.

## Sea waves

The deformation of free, undisturbed surface of sea water is called sea waves. Such deformation can be due to several causes, which influence the type of resulting waves (variability of basic parameters [1].

**Wind waves** (**irregular**, **random**) are the most common type of waves across oceans and seas. Wind waves alone are a highly random phenomenon, i.e. they can be characterized by large irregularity both in space and time [2]. Wind waves occur directly on a sea area over which the wind blows. The waves travel slightly deflected from the direction of the wind. Wind-generated wave parameters depend on: speed, direction and time of wind action and fetch length and individual features of the sea area over which the wind blows, including the depth. It means, that wind-generated waves of different statistical parameters occur in various regions of the same ocean or sea at the same wind speed. Three types of wind-generated waves can be distinguished as: storm wave, swell and surf breaker. Storm wave is a fully irregular (random) wave, while swell is similar to a regular, periodic wave (these two kinds of irregular wave emerge when wind-generated waves arise or die out.

Due to significant irregularity, randomness and complexity of storm waves, probabilistic models based on random processes are used for their (storm waves) description.

Two models are used mainly due to the variation of mean statistic wave parameters in time (e.g. wave height $H_w$, length $L_w$, time $T_w$):

- short-term waves – it is a model of a fully-developed storm wave being a random process (instantaneous wave parameters are random quantities), homogenous, stationary and ergodic, in which statistical wave parameters including variance of this process $D_{\varsigma\varsigma}$ are constant and independent from time;
- long-term waves – statistical wave parameters including variance depend on time (mean statistical wave parameters are random quantities).

#### Short-term waves

In short-term wave prognosis, e.g. the probability distribution of a wave height occurrence is the Rayleigh distribution:

$$f(H_w) = \frac{H_w}{4D_{\zeta\zeta}} \exp\left(-\frac{H_w^2}{8D_{\zeta\zeta}}\right) \tag{1}$$

where:
$H_w$ – instantaneous value of wave height;
$D_{\varsigma\varsigma}$ – wave variance.

From this distribution mean statistical wave height (at constant variance) can be calculated with an estimated probability of excess it, e.g. a significant wave height $H_S$ equals:

$$H_S = 4.0\sqrt{D_{\zeta\zeta}} \tag{2}$$

#### Long-term waves

In long periods of time, sea waves are not a stationary process, i.e. mean statistical value of wave height and variance change in time: $H_S(t)$, $D_{\varsigma\varsigma}(t)$ (they are random quantities). The Weibull [3] probability distribution is used for statistical calculations of a long-term wave, e.g. its height (when there is no measurement of wave parameters), whose form for wave heights or periods is as follows:

$$f(x) = \left(\frac{\gamma}{b}\right)\left(\frac{x-a}{b}\right)^{\gamma-1} \exp\left[-\left(\frac{x-a}{b}\right)^{\gamma}\right] \tag{3}$$

where:
$x$ – height or period of a long-term wave;
$a$, $b$, $\gamma$ – parameters of the Weibull probability distribution.

Apart from the Weibull distribution, statistical wave parameters on seas and oceans based on measurements of ocean areas have been collected and studied for many years to be published in print [4] or electronically (atlases of wave parameters across seas and oceans).

The atlases contain the amount of waves of height $H_w$, period $T_w$ and geographical direction $\mu$ or occurrence probability of waves with such parameters as registered on specific ocean areas. Some atlases also contain more detailed information of measured wave parameters depending on seasons.

## Wave energy

Wave energy unit (per unit of wavy sea surface) for a two-dimensional short-term wave model can be presented as follows:

$$\overline{E}_w = \rho_w \cdot g \int_0^\infty S_{\zeta\zeta}(\omega)\,\mathrm{d}\omega \tag{4}$$

where:
$\rho_w$ – density of sea water;
$g$ – the gravitational acceleration;
$S_{\zeta\zeta}(\omega)$ – spectral energy density function for two-dimensional wave action;
$\omega$ – frequency component of a harmonic wave.

The most popular function $S_{\zeta\zeta}(\omega)$ is the ITTC function [3] describing wave fully developed on the open sea:

- **ITTC** (International Towing Tank Conference):

$$S_{\varsigma\varsigma}(\omega) = A\omega^{-5} \exp\left(-B\omega^{-4}\right) \tag{5}$$

where:
$A$, $B$ – spectral function constants,

$$A = 173\overline{H}_S^2 / \overline{T'}^4 \qquad B = 691 / \overline{T'}^4 \tag{6}$$

$\overline{H}_S$ – significant wave height, [cm];
$\overline{T}$ – mean statistical characteristic wave period, [s].

Another function, more universal and often used is the JONSWAP spectrum [5]:

- **JONSWAP** (Joint North Sea Wave Project):

$$S_{\varsigma\varsigma}(\omega) = \alpha g^2 \omega^{-5} \exp\left[-1.25\left(\frac{\omega_m}{\omega}\right)^4\right]\gamma^a \qquad a = \exp\left[-(\omega-\omega_m)^2 / 2(\delta\omega_m)^2\right] \tag{7}$$

where:
$\alpha$, $\omega_m$, $f_m$, $\delta$, $\gamma$ – parameters function of the JONSWAP:

$$\alpha = 0.076\overline{x}^{-0.22}; \qquad \omega_m = 2\pi f_m$$
$$f_m = 3.5\left(\frac{g}{\overline{V}_A}\right)\overline{x}^{-0.33}; \qquad L_A = gx / \overline{V}_A^2 \tag{8}$$
$$\delta = 0.07 \text{ for } \omega \le \omega_m \text{ and}$$
$$\delta = 0.09 \text{ for } \omega > \omega_m$$

$x$ – dimensionless fetch;
$L_A$ – the fetch length of sea area in the direction of wind action, [m];
$\overline{V}_A$ – average wind velocity, [m·s$^{-1}$].

Examples of calculations of a wave energy unit $\overline{E}_w$ for various sea areas have been given in table 1.

Table 1. Wave energy unit $\overline{E}_w$ on various sea areas

| Wind force [°B] | The Baltic | | The North Sea | | The North Atlantic | |
|---|---|---|---|---|---|---|
| | $H_S$ [m] | $\overline{E}_w$ [kWh/km$^2$] | $H_S$ [m] | $\overline{E}_w$ [kWh/km$^2$] | $H_S$ [m] | $\overline{E}_w$ [kWh/km$^2$] |
| 6 | 1.20 | 246 | 3.00 | 1,533 | 3.10 | 1,637 |
| 8 | 1.95 | 646 | 5.10 | 4,430 | 5.25 | 4,694 |
| 10 | 3.15 | 1,690 | 7.20 | 8,829 | 7.45 | 9,453 |
| 12 | 4.30 | 3,160 | 7.70 | 10,098 | 9.20 | 14,415 |

As can be seen, energy of wavy water per unit is not too big, and additionally dispersed over a large surface.

## Wave parameters, which can be used in electrical energy converters

Velocity, pressure or difference in levels are basic parameters characteristic of the flow of air (wind) or water (a current). In case of wave action, the movement of water particles is different from the movement of air or water in a sea current. Real sea wave action (Fig. 1) can be replaced by a sum of regular, harmonic waves (9).

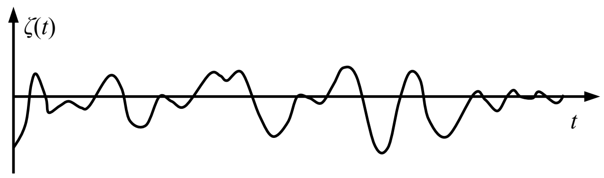



Fig. 1. The course of random wave ordinate $\zeta(t)$ in time and its approximation by regular waves

Approximation of the real sea wave will be:

$$\zeta(t) \approx \sum_{n=1}^{N} \zeta_{An} \cos(\omega_n t - \varepsilon_n) \qquad (9)$$

$\zeta_A$ – regular wave amplitude;
$\omega$ – frequency of a regular wave;
$t$ – time;
$\varepsilon$ – angle of phase displacement between component regular waves.

A singular regular wave (harmonic) has the profile shown in figure 2. Water particles in wave movement in deep water flow along circular orbits (Fig. 2).

For example a regular wave as in figure 2, equation (9), parameters:

- wave amplitude $\zeta_A = 1$ m;
- wave length $\lambda = 171$ m;
- wave period $T = 10.5$ s,

the calculated velocities and pressures are as follows:

- phase velocity $C_W = 16.3$ m/s,
- velocity of water particles in orbital movement:
  - – on wave surface $V_{z=0\,\mathrm{m}} = 0.6$ m/s
  - – at the depth of 5 m $V_{z=-5\,\mathrm{m}} = 0.5$ m/s
- fluctuation of hydrodynamic pressures at the depth of 5 m

$$P_{DZ=5\,\mathrm{m}} = (34 \div 65)\ \mathrm{hPa} \approx (0.34 \div 0.65)\ \mathrm{at}.$$

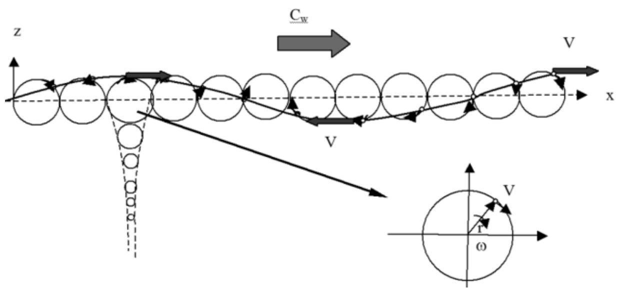



Fig. 2. Movement of water particles in a regular wave, deep sea

It results from the performed calculations, that velocity of water particles and hydrodynamic pressure in wave movement are very small, while phase velocity $C_W$ quite big indeed, is not connected to the flow of water mass, but only to the rate of shape change of the wavy ocean surface.

On the basis of the above analyses, the wave energy can be retrieved using:

- water particles velocity in wave movement (such velocity is oscillatory changeable with wave frequency, and it quickly decreases with depth);
- changes in water surface inclination in wave motion;
- water level fluctuation in wave motion (fluctuation on the water surface equal the wave in height);
- dynamic pressures in wave (these are small and oscillatory-changeable, they disappear quickly with depth);
- breaking of waves in shallow water and washing over the shore (such movement is oscillatory-changeable, with wave frequency in shallow water).

Wave energy can be transformed into electrical energy using converters of the following types:

- mechanical;
- pneumatic;

– hydraulic;
– induction.

## Converting water wave energy into electrical current – examples of technical solutions

### Pneumatic converter for vertical water movement in a wave

Diaphragm compressors (Fig. 3) or telescopic compressors (Fig. 4) are used in such devices. Vertical water movement in a wave forces air between cylinder chambers. The pressurized air sets in propels a turbine connected to an electric generator.

There are also converters designed, in which:

– vertical water movement in a wave is converted using a mechanical device (through a mechanism similar to the slider-crank mechanism) into rotational velocity;
– or induction device (vertical movement of magnets against each other), electrical current is induced in the coil of the converter.

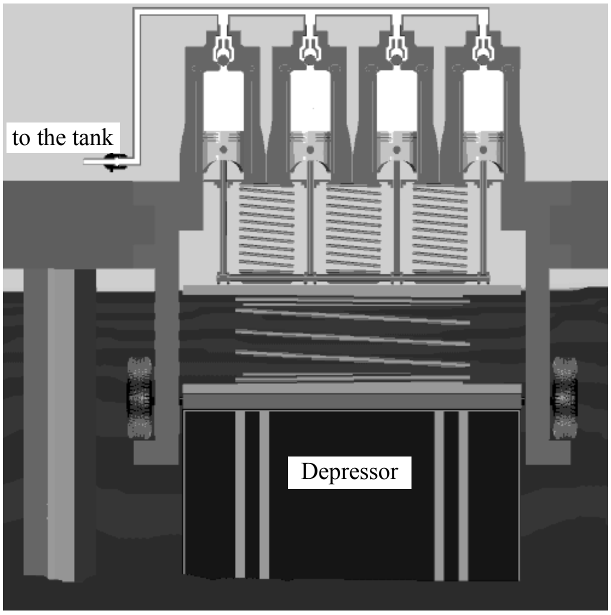



Fig. 3. A diagram of diaphragm compressors using sea wave energy [6]

Apart from compressing solutions, using vertical water movement in a wave, mechanical and induction converters are used as well.

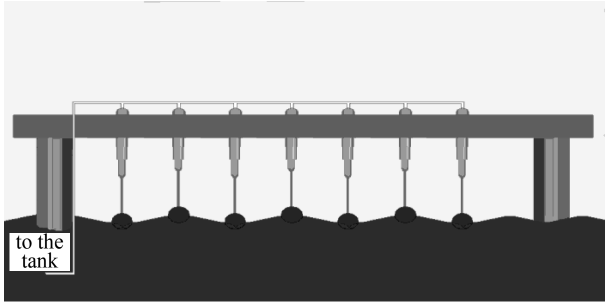



Fig. 4. A diagram of telescopic compressors using sea wave energy [6]

### Fixed wave power plant

Fixed wave power plant (Fig. 5 and 6 ) can be built on offshore or inshore. In such technical solutions water accumulated as a result of a wave breaking against the shore enters a horizontal or inflected column (pipe) to enforce airflow, the air travels in an oscillatory way in both directions and propels the Wells turbine.

In other solutions (Fig. 6) a wave enters a offshore tank through a feedthrough rising the water level, and then leaves the tank propelling the water turbine. The device works cyclically as the wave enters the container.

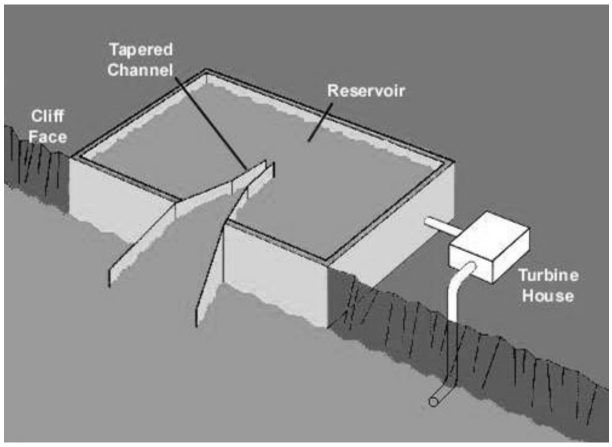



Fig. 6. Wave-refillable tank – of the TAPCHAN type [8]

### Floating wave power plant

In these devices, the main element of a converter – "a duck" (Fig. 7) floats on a sea surface and makes an angular oscillatory movement (sway) with the wave action.

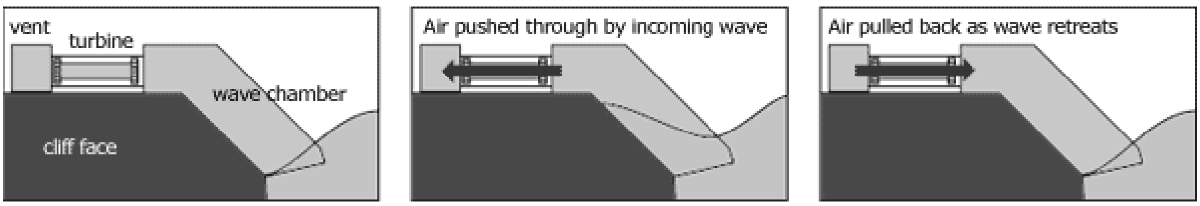



Fig. 5. Airflow in an oscillating water column – an outline [7]

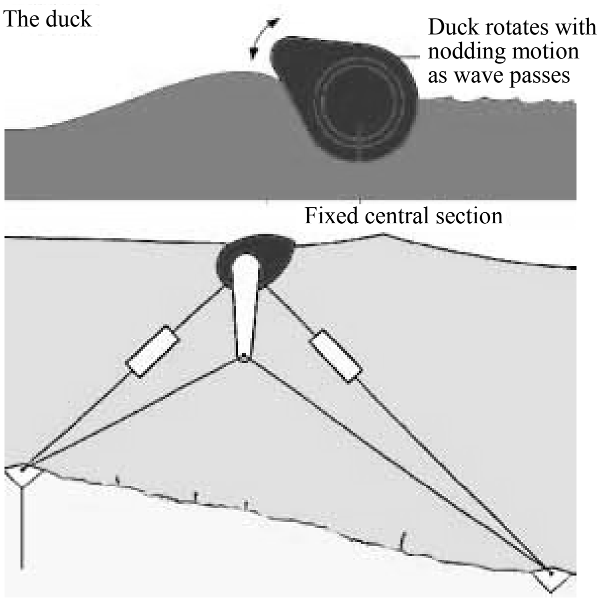
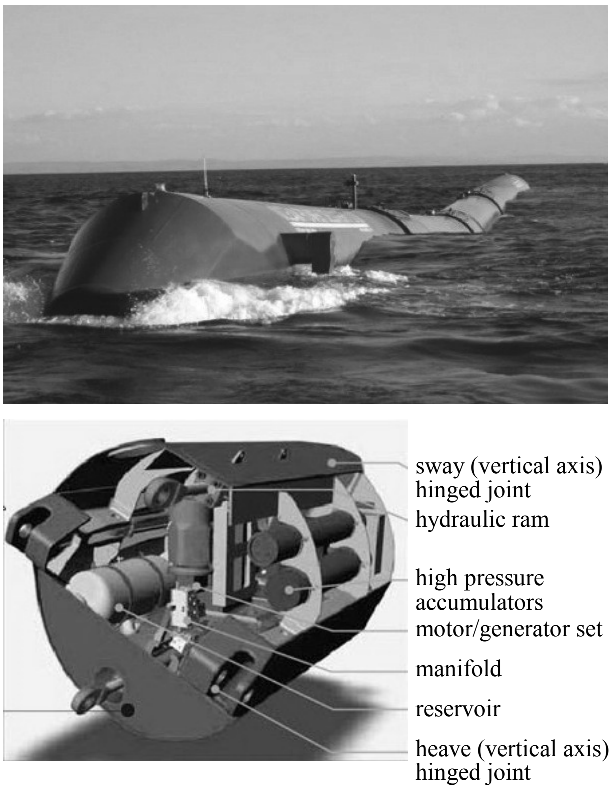



Fig. 7. Floating wave power station Salter Duck [7]




Palemis 750 hydraulic modlule cross-section

Fig. 8. Palemis machine floating on the sea surface [9]

Yet another technical solution using changes in sea surface in wave motion are the so called "sea snake" (Fig. 8). They are made up of a number of universal joints allowing flexing in two directions. As the waves pass down the tube and the sections bend in water, the movement is converted into electricity.

## Conclusions

- Energy of wavy water is small and dispersed across large sea areas.
- Velocities of water particles in wave motion are of small values, are oscillatory changeable and rapidly change with the increase of water depth.
- Hydrodynamic pressures in wavy water are small and decrease rapidly with the water depth.
- Wave energy retrieval is not very effective (therefore devices used are of small efficiency).
- There are a number of ways and types of converters which make it possible to convert wave parameters into electric energy.
- Numerous possibilities in this field encourage further research work into effective wave farms.

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