PRINCIPLES OF WIND WAVE ENERGY EXTRACTION

V.V. Volshanik
Professor, Department of water power utilization, Moscow State University of Civil Engineering, Russia

Keywords: Wind waves, Wave processes, Wave phenomena, Energy conversion, Energy extraction, working tool, Wave power device (WPD)

Contents

Summary

The principle of wind wave energy extraction is defined by wave processes, described by equations of water motion in the wave. The following wave effects can be used to extract the wave's energy:

- Recurrent water level change relative to a stabilized body;
- Difference of hydrostatic pressure fluctuations in spatially spread spots;
- Difference of total water pressure fluctuation in spatially spread spots;
- The slope of water surface in the wave;
- Concentration of water energy by front and depth;
- Combination of above mentioned effects.

Wave power devices usually consist of three parts: primary wave energy converter, secondary (power) converter and a stabilizing system.

1. General Equations

Principles of wave energy extraction are defined by wave processes, described by fluid motion equations. In special cases, such as eddy-free wave movement of a non viscous fluid, these equations can be integrated. Particularly for external perturbation the Lagrange-Koshi integral is valid. It sets a direct correlation between velocities and pressure:

$$p - p_a = -\rho \frac{\partial \varphi}{\partial t} - \frac{1}{2}\rho \left[\left(\frac{\partial \varphi}{\partial x}\right)^2 + \left(\frac{\partial \varphi}{\partial y}\right)^2 + \left(\frac{\partial \varphi}{\partial z}\right)^2 \right] - \rho g z \,, \qquad (1)$$

where p and p_a are respectively the pressure in the wave and the atmospheric pressure; φ is the velocity potential; ρ is the water density; x, y, z, t are respectively Cartesian and time coordinates.

The velocity components are:

$$u = \frac{\partial \varphi}{\partial x};\ \ v = \frac{\partial \varphi}{\partial y};\ \ w = \frac{\partial \varphi}{\partial z}. \qquad (2)$$

Equation (1) describes a wave profile $z=\eta$, on the surface, where $p\text{-}p_a=0$, when $z=0$

$$\eta \Big|_{z=0} = -\frac{1}{\rho}\frac{\partial \varphi}{\partial t} - \frac{1}{2g}\left[\left(\frac{\partial \varphi}{\partial x}\right)^2 + \left(\frac{\partial \varphi}{\partial y}\right)^2 + \left(\frac{\partial \varphi}{\partial z}\right)^2 \right]. \qquad (3)$$

The potential φ, in equations (1-3), in the plane of progressive waves of small amplitude H and finite depth h is equal:

$$\varphi = \frac{Hg}{\omega}\frac{\operatorname{ch} k(z+h)}{\operatorname{ch} kh}\sin(kx - \omega t)\,, \qquad (4)$$

and on deep water:

$$\varphi = \frac{Hg}{\omega} e^{-kz} \sin(kx - \omega t)\,, \qquad (5)$$

where $k = 2\pi/\lambda$ is the wave number; λ is the wave length.

Expressions (4, 5) and also (1-3) allow us to describe a general correlation, which indicate, that in every fixed space point (x, y, z) in earth conditions (ρ, g), a set of variable time- dependent processes exist:

$$V(H, T, t,);\ p(H, T, t);\ \eta(H, T, t)\,, \qquad (6)$$

where V is the total velocity; T is the wave period; η is the wave profile.

These processes are defined by wave parameters H, T. Hence to extract mechanical energy from the wave one can use time-dependent alterations of fluid velocity, elevation of free level and increase of pressure that has hydrostatic and hydrodynamic components.

Besides the mechanical processes in the fluid, there are a number of processes originated by earth conditions. The most important are gravity and magnetic field, electrical conductivity and ionization of water.

Gravity defines first, existing of waves *per se*, and second, defines the direction of the vertical axis *0z* in every space point (*x*, *y*, *z*). The presence of this axis allows mentioning one more wave process that can be used for energy extraction. This is the alteration of angle α between the normal to the wave profile and vertical axis *0z* (or between the horizon and the tangent to the wave profile):

$$\alpha = \frac{\partial \eta}{\partial \mathrm{t}} = -\frac{1}{\rho}\frac{\partial^2 \varphi}{\partial \mathrm{t} \partial \mathrm{x}} - \frac{1}{\mathrm{g}}\left[\frac{\partial \varphi}{\partial \mathrm{x}}\frac{\partial^2 \varphi}{\partial \mathrm{x}^2} + \frac{\partial \varphi}{\partial \mathrm{y}}\frac{\partial^2 \varphi}{\partial \mathrm{x} \partial \mathrm{y}} + \frac{\partial \varphi}{\partial \mathrm{z}}\frac{\partial^2 \varphi}{\partial \mathrm{x} \partial \mathrm{z}}\right]. \qquad (7)$$

Taking into account equation (5), it gives correlation for another type of wave process - the alteration of a angle phases.

Hence, fluid' wave movement is characterized by the following set of effects:

- Periodic alterations of free water level in a certain point;
- Spatial alteration of the free water surface shape;
- Periodic variations of particles velocities, spatial and in a certain point;
- Periodic variation of pressure, spatial and in a certain point;
- Exponentially decreasing of velocity and pressure with increase of depth.

2. Principles of Wave Energy Extraction

The following wave effects can be used to extract the wave' energy:

- Periodic water level alterations in a certain point relatively to a stabilized body;
- Difference of hydrostatic pressure fluctuation phases in spatially spread points;
- Difference of total water pressure fluctuation phases in spatially spread points;
- The slope of water surface in the wave;
- Concentration of water energy by front and depth;
- Combination of above mentioned effects.

A substantial number of devices that utilize these effects operate using a half-period cycle, with its return to the initial position by gravity.

The choice of a certain type of wave energy extraction scheme depends on the type of mechanical energy of the wave, which is used by the wave power device (WPD). Most of WPD of known types use mechanical energy of waves, which do not depend on other types of energy of water masses (thermal, chemical etc.).

Physical properties of water such as ionization and electric conductivity together with water movement in the wave produce electric currents that can be converted to useful energy by appropriate methods. For example interaction of electric current with magnetic field of the Earth makes it possible to use magneto-hydrodynamic method of wave energy extraction.

3. Principles of Design for Wave Energy Extraction

The principles of mechanical wave energy extraction are described by general equations (6). The main idea of wave energy extraction is to convert the wave energy flow into internal energy of some intermediate device - a working tool that transmits it to a generator producing useful energy. That is why WPD of any kind consist of three main parts: a working tool, power converter and a mooring system. The working tool has a direct contact with the wave. It either performs some motion initiated by the wave or alters by some way conditions of wave propagation. The working tool can be designed as various floats and their systems, water wheels, breakwaters, embankments and others. In most cases (except some water wheels), they convert wave energy into other type that is more suitable for further conversion.

The power converter is designed for conversion of energy, accumulated by the working tool (mechanical energy, water head energy in reservoirs, liquid or air pressure) into energy which is either locally consumed, or transmitted. A mooring system is included for the WPD stabilization.

To harness wave energy, a movement of solid, fluid or gas working bodies which move relative to a somehow stabilized frame is used. This movement is further used by various secondary converters, which convert it into more suitable energy types. The transmission and effective conversion of the working tool (body) movement to the secondary converter of the WPD is rather important, however the first stage has to be considered as the main link in the chain of wave energy extraction. Here, the interaction between the working tool and the wave takes place, which defines the character of working tool movement.

In those designs which use oscillations of water relative to a stabilized frame, the necessary stabilization is provided either by usage of deep, not perturbed water layers, or by usage of a frame having large dimension in the wave propagation direction, or finally by using supports fastened to the coast or to the bottom. In some cases stabilization is secured using difference of oscillation phases on a frame, which has a size about a half of the wave's length.

There are differences between wave' kinetic or potential energy extraction. Kinetic energy is the energy of the mass movement. Accordingly, appropriate wave processes, contain types of energy that are shown in Table 1.

Wave process	Type of mechanical energy that is changing in time	Source of energy and conversion steps
$\eta(t)$	Potential	$\eta(t)$ is transformed into linear velocity $V(t)$
$\alpha(t)$	Kinetic	
$\alpha(t)$	Potential	$\alpha(t)$ is transformed into linear velocity $V(t)$
$V(t)$	Kinetic	
$V(t)$	Kinetic	$\alpha(t)$ is transformed into level

$p(t)$ $p(t)$	Potential Potential	difference Δz Orbital movement of particles Wave flow Hydrostatic pressure Hydrodynamic pressure

Table 1. Types of mechanical energy in wave processes

-
-
-

Bibliography

Budal K. and Falnes J. (1979). *Interacting Point Absorbers with Controlled Motion*. Proceedings, Power from Sea Waves Conference, University of Edinburgh, Scotland, June 1979. [Results of research are depicted for the 'point float' transducer of wind waves. The transducer is equipped with a system of phase control].

Evans D.V. (1976) *A Theory for Wave-Power Absorption by Oscillating Bodies*, pp.1-25. Journal of Fluid Mechanics, Vol 77. [Theoretical analysis of working process in wave power devices using oscillating vertical floats is presented].

Hiramoto A.(1978). *The theoretical Analysis of an Air Turbine Generation System*. Proceedings. Wave and Tidal Energy Symposium, Canterbure, England, Paper B5. [Theoretical analysis of the working process of an air turbine is given used as a secondary energy converter in an 'oscillating water pillar' WPD].

McCormick M.E.(1974). *A parametric Study of a Wave-Energy Conversion Buoy*. Proceedings, Offshore Technology Conference. May, Paper No. OTC 2125. [Results of working process research are shown for the float converter of wave energy that uses the horizontal alterations of water in a vertical oscillating tube].

Mehlum E and Stamnes J.(1979). *On the Focusing of Ocean Swells and its Significance in Power Production*. Proceedings, Symposium on Wave Energy Utilization, Chalmers University, Gothenburg, Sweden. [Possibilities of a WPD working process improvement are discussed. The improvements are achieved by fitting the construction to the wind wave parameters].

Moody G.W. (1979). *Reprint, Symposium on Wave Energy Utilization*. Chalmers University, Gothenburg, Sweden. [Research results and ways of improvement are shown for the 'oscillating water pillar' wave power device].

Salter S.H. (1974). *Wave Power*. Nature. Vol. 249, No 5459. [Analysis of practical ocean wave usage possibilities is given and description of a 'Solter's duck' wave power device is presented].

Sichkarev V.I. (1987). *The basics of research and development of wave power plants*. Vladivostok, DVNTS AN USSR. (in Russian). [Results of theoretical research are given for power characteristics of ocean waves, principles of conversion, principles for wave power devices design are presented].

Sichkarev V.I., Shpak A.V. (1984). *Classification and analysis of technical methods of wave energy extraction*. pp. 34-40. In a digest: The usage of tidal and wind waves in oceans. Vladivostok, TOI DVNTS AN USSR. (in Russian). [Wave power devices are examined, depending on the number of steps in energy conversion].

Taylor G.W. (1979). *Piezoelectric Power Generation from Ocean Waves.* Princeton Resources, Princeton, N.J., report, March. [Research results are presented for a wave device that uses the alteration the WPD internal units to produce piezoelectricity].

Volshanik V.V., Matushevsky G.V.(1985). *The energy of sea wind waves and principles of it's conversion*. Hydraulic Engineering Construction #4, pp. 41-45. (in Russian) [Correlation for estimation of wave power resources is presented depending on the static characteristics of wave].

Biographical Sketch

Valeri V. Volshanik, Professor, Department of water power utilization, Moscow State University of Civil Engineering, Russia

Born 14 November 1939, Moscow

1962 Graduated from the Moscow State University of Civil Engineering

1972 Ph.D.

1997 Full professor

1962 up to now collaborator of the Moscow State University of Civil Engineering, starting from 1997 Professor at the Chair «Utilization of hydraulic energy»

Author of 150 scientific papers (in particular 17 concerned with wave energy) and 20 patents

Main field of activity - hydraulic engineering including wave energy installations

Member of the Russian Engineering Academy