

A rotating wing for the generation of energy from waves

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Introduction

This contribution deals with a concept for a wave energy conversion device which converts wave energy directly into rotational energy. This ‘rotating wing’ device was conceived based on the kinematics of a regular, long-crested wave. See Figure 1. In this figure the velocity vector in a point in the vertical plane is shown. In all such points, in deep water, the vector is constant in amplitude and rotates with the angular frequency of the wave. Consider a fixed horizontal shaft perpendicular to the plane of the figure with a lifting foil attached as shown in Figure 2. Given proper dimensions etc, the foil will experience a lift force perpendicular to the fluid velocity vector giving rise to a lift force which is perpendicular to the connection between the shaft and the foil. This lift force results in a moment around the shaft inducing rotation in the same direction as the rotating velocity vector. If the foil lags behind the rotating velocity vector, the angle of attack will increase thus increasing the lift force on the foil and the torque on the shaft. This constitutes a stable rotating system which locks on to the rotation frequency of the velocity vector and hence to the regular wave. In effect we have a synchronous wave energy device. The energy is transmitted by a generator fixed directly to the shaft.

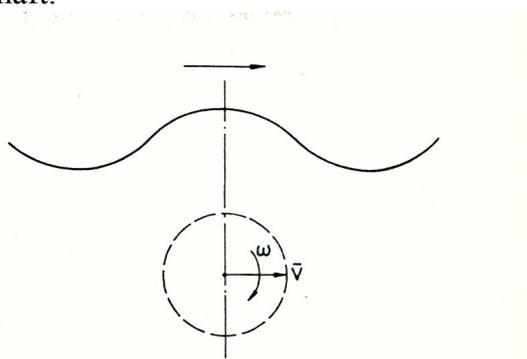


Figure 1 : Kinematics in a regular wave

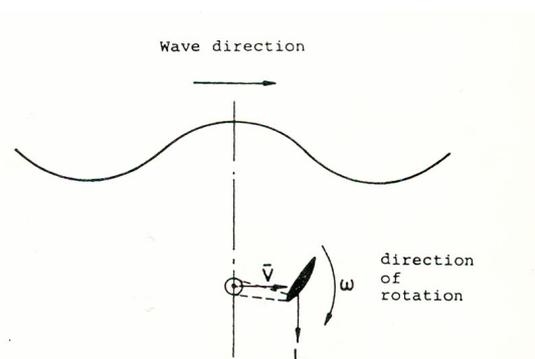


Figure 2 : Principle of the Rotating foil

Initial model tests carried out at MARIN with a simple model of the foil showed that in regular waves a weight could be lifted by a thin wire wound around the shaft and running over and overhead pulley. Based on these initial tests, a comprehensive analysis and detailed model tests were carried out by two MSc students, van Sabben and C. Marburg (see ref 1 and ref 3). This contribution briefly summarises their work which to date has not been published. Finally a novel application of the rotating foil is introduced along with relevant model test results.

Theoretical analysis

The flow in a regular, long-crested wave around a foil moving along a circular path around a point in the vertical plane can be approximated from knowledge of the flow around a foil rotating with constant angular motion around the shaft in still water combined with the kinematics of the undisturbed regular wave. See also ref. 2.

Use is made of linearized potential flow described by a potential (ϕ) satisfying the Laplace equation and the linearized free-surface boundary condition. The foil is modelled as a line vortex and the waves are perpendicular to an infinitely long foil. The problem is thereby reduced to two dimensions. Due to the assumed linearity, the total potential is the superposition of the potential of the regular wave and the rotating foil. The complex potential

$f(z, t) = \phi(x, y, t) + i\psi(x, y, t)$ of a vortex with position $c(t)$ moving under a free surface in two dimensions is given by Wehausen & Laitone (ref. 4)

$$f(z, t) = \frac{\Gamma}{2\pi i} \log \frac{z - c(t)}{z - \bar{c}(t)} + \frac{g\Gamma}{\pi i} \int_0^t \int_0^\infty \left\{ \frac{1}{\sqrt{gk}} e^{-ik(z - \bar{c}(\tau))} \sin[\sqrt{gk}(t - \tau)] \right\} dk dt$$

The first part is the potential of a vortex and of an additional vortex required to satisfy the kinematic free surface condition. The second part describes the radiated waves related to the pressure condition at the free-surface. The integral is evaluated for the following situations :

1. Foil of small dimensions rotating in deep water on a circular path of small radius R with respect to the wave length (kR small)
2. The disturbance of the foil is considered to be small so that the shed vorticity is conveyed with the undisturbed flow of the incident waves.

Using the above assumptions the following results are obtained :

1. The foil does not create waves up-wave. Waves from the foil are only created in the down-wave direction
2. The energy absorbed by the device leads to a decrease in the incident wave amplitude ζ_{ali} and higher harmonics of the fundamental wave frequency with amplitude ζ_{an} are generated. As shown in ref (1) , the difference in energy flux is :

$$F = \frac{1}{2} \rho g \left[-2\zeta_{ali}\zeta_{an} \cos \gamma + \sum_{n=1}^{\infty} \zeta_{an}^2 \right]$$

where γ is the phase difference between the incident and radiated first harmonic component. The amplitudes ζ_{an} are :

$$\zeta_{an} = 2\Gamma \frac{n\omega}{g} \frac{(\omega^2 n^2 R / g)^n}{n!} e^{\frac{\omega^2 n^2}{g} y_c}$$

3. The moment (torque) exerted on the shaft is equal to the lift force times the moment arm. The force depends on the circulation around the foil :

$$\vec{L} = \rho \vec{V} \times \Gamma$$

Experiments

Model tests were carried out in the High Speed Basin of MARIN (200 m x 4 m x 3.6 m) with a foil with a span of 1.5 m and a chord length of 0.10 m with a camber of 0.022 m. The thickness distribution was according to NACA 0015 . See Figure 3.

The first tests that were carried out were tests in still water. The purpose of these tests was to verify the theoretical prediction that waves are only generated in one direction i.e. the

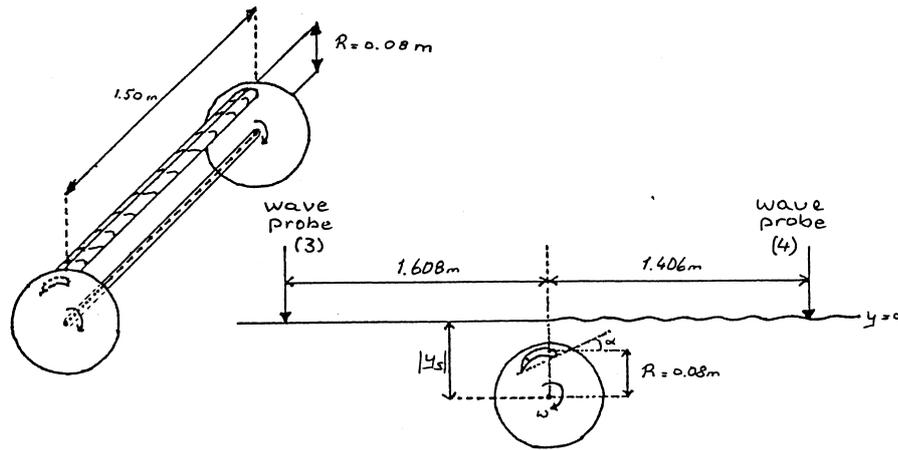


Figure 3 : Foil with end disks attached to a rotating shaft

direction corresponding with the direction of motion of the foil when in the highest point. See above. The following figure shows the wave elevation records in location 3 and 4 shown in Figure 3 for the foil rotating with constant frequency in still water. Higher harmonics can be seen in wave 4. Results for different frequencies are shown in Figure 5.

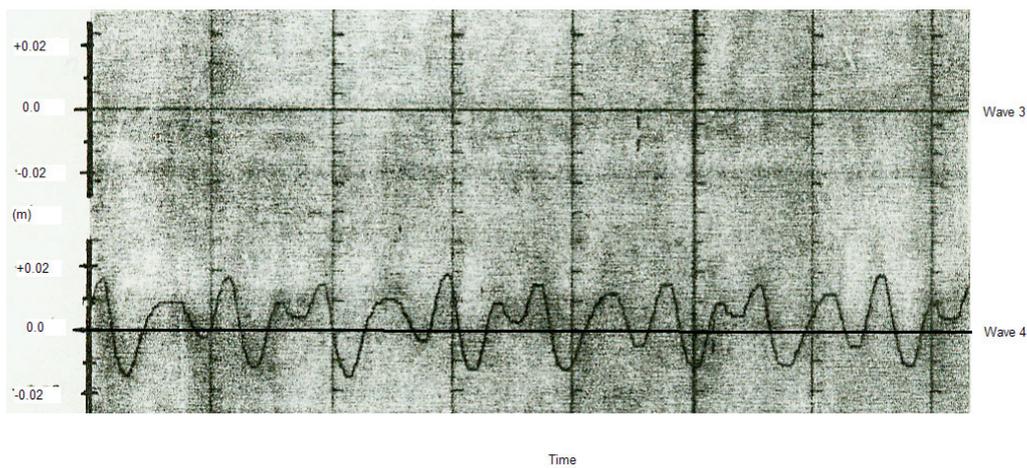


Figure 4 : Wave elevation records to either side of the foil rotating at 3.45 r/s

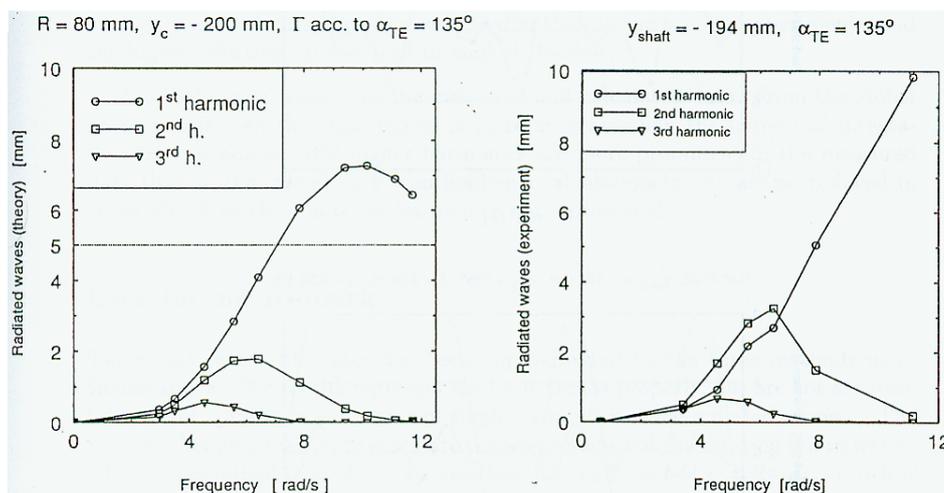


Figure 5 : Computed and measured harmonics of the foil rotating in still water

During tests in regular waves the torque exerted on the shaft was measured as well as the

rotation angle and the wave elevations up- and down-wave. Some results are shown in Fig.6.

Run 1698, $y_{shaft} = -235$ mm, $\alpha_{TE} = 110^\circ$, $\lambda = 5$ m, $\zeta_a = 80$ mm

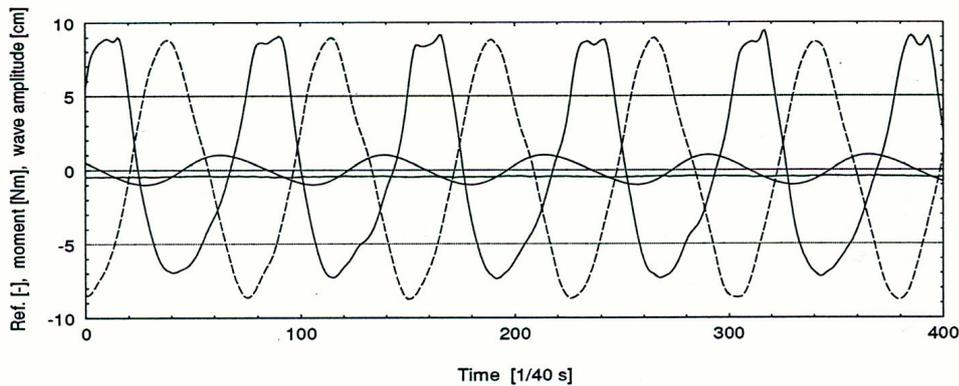


Figure 6 : Wave elevations , foil position and shaft torque in a regular wave

In Figure 6 the dotted line is the incoming wave, the large solid line the down-wave elevation, the small amplitude harmonic is the foil position signal and the constant , just below zero the shaft torque. Noticeable is that the torque is almost constant with little or no higher harmonics.

A final experiment concerns the application of the concept to a wave direction measuring device. Since the foil is always “down stream”, if the shaft of a short span version is attached to a vertical , freely turning axis and a “rudder” used to connect foil and shaft , a system is created that automatically seeks to position the rudder in the vertical plane of the flow. This property can be used to determine wave direction in a regular wave. The concept is shown in Fig. 7 on the left and right the measuring device based on the concept. Results of measurements of wave direction in MARIN’S Wave & Current Basin are compared with prediction in Fig. 8. As can be seen, the measurements with the device follow the theoretical wave direction (snake wave maker with fixed phase difference between the flaps) very well.

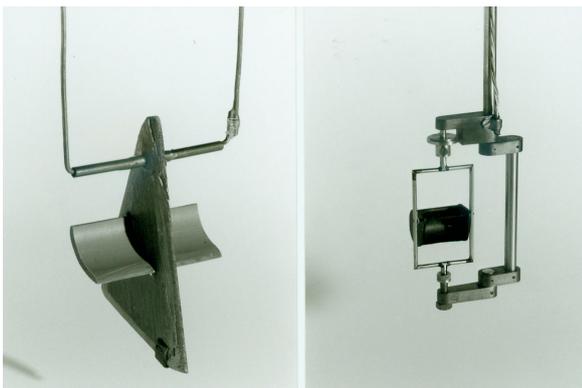


Figure 7 : Device for measuring wave direction

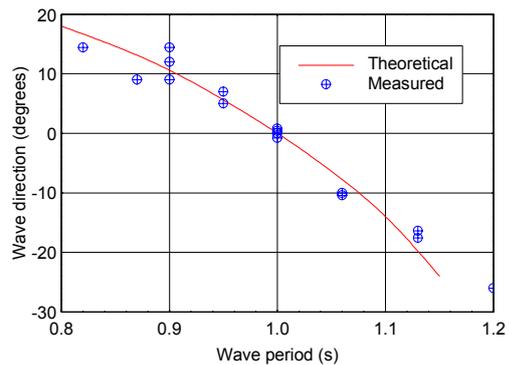


Figure 8 : Measured and adjusted wave direction

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