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Oscillating Water Column Wave Energy Conversion Device Response Spectra

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ABSTRACT

The objective of the present work is to serve as a practical addendum to the discrete parameter Oscillating Water Column (OWC) Wave Energy Conversion (WEC) device model proposed by Folley and Whittaker [1] at the 24th International Conference on Offshore Mechanics and Arctic Engineering. In particular, a method for the interpretation of their discrete parameter model is presented, consisting of a translation from the tuning and air compressibility parameter map reported to a response spectrum representation. In this more commonly encountered form the model is more readily physically interpreted for design and analysis application.

1. Introduction

Oscillating water column (OWC) wave energy conversion devices consist of a partially submerged chamber open to wave forces at the base. The wave forces cause the water column within the chamber to rise and fall, driving the air in and out (inhalation and exhalation) of the chamber typically through a Wells or variable pitch type air turbine. An electrical generator is then utilised to convert the oscillatory airflow established into electrical energy. The pneumatic gearing provided by the air coupling facilitates the conversion of low frequency wave power into high frequency electrical power. Oscillating water column type wave energy conversion devices can be located near-shore as a fixed structure or offshore in a floating moored-structure configuration. Much analytical, numerical and experimental work has been undertaken on fixed (e.g. the work by Morris-Thomas and Irvin [1]) and floating (e.g. Chudley, Mrina, Ming and Johnson [2]) oscillating water column wave energy etermining optimal performance and the efficacy of control strategies [14].

The model proposed by Folley and Whittaker [6] is based on the fixed OWC model proposed by Szumko [15]. Folley and Whittaker [6] modified the system to include air compressibility and turbine hysteresis. In the development of this model, it was mathematically convenient to represent the system in terms of a tuning and air compressibility parameter. This mathematically convenient

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parameter space however, does not lend itself to a solution which is readily physically interpretable. Physical interpretation of the data in this form is difficult for two reasons; firstly, the parameters have complex physical meaning and more importantly, the parameters are inter-related. The model would benefit greatly by a translation of the tuning and compressibility parameter representation into a configuration employing more commonly used parameters in offshore structure design and analysis.

2. OWC WEC Modeling

The Folley and Whittaker [6] model includes both the effects of air compressibility and turbine hysteresis. The hysteresis modelling is accomplished through the inclusion of a phase shift induced by the placement of a spring in parallel with the turbine damping. Folley and Whittaker [6] admit that turbine hysteresis is an extremely complex process and the spring introduced to model it has no physical significance. The inclusion of the spring causes inconsistencies in the dynamic behaviour of the system relative to a real oscillating water column system. This is especially evident at lower frequencies where the wave energy is predominantly located. The air pressure in the chamber for example, represented by the force exerted by the air compressibility spring, μ, does not tend to zero as the wave period tends to infinity. The spring also has the undesirable effect of storing and releasing energy that should, more realistically, have been dissipated by the turbine damping component of the model (i.e. contributed to the useful power output of the system). The authors do not support the adoption of this hysteresis model.

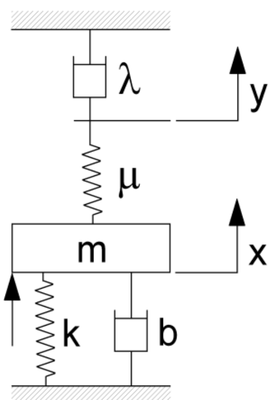

Fig. 1. Discrete mass-spring-damper model of an OWC WEC device

The Folley and Whittaker [6] model without the turbine hysteresis component is illustrated in figure 1. The parameters k, b and m are the OWC water plane stiffness, radiation damping and mass respectively. The turbine damping is modelled by the linear damping parameter λ and the air compressibility by the linear stiffness μ. The coordinate x is the OWC mean free surface elevation relative to the mean sea level.

Folley and Whittaker [6] derive the analytic solution of the average power capture at optimal turbine damping in terms of a tuning and air compressibility parameter (Q and R respectively) as

$$P_{max} = \frac{|F|^2 Q^2 \omega}{4\mu\left(QR+\sqrt{R^2+Q^2(1+R)^2}\sqrt{(1+Q^2)R^2}\right)} \quad (1)$$

In equation 1, the parameters $Q=\alpha/\beta$ and $R= Q=\alpha/\mu$, where $\alpha=k- \mu\omega^2$, $\beta=b\omega$ and $\Lambda=\lambda\omega$. The limiting case of incompressible air may be obtained by setting R→0 (i.e. μ→∞) and noting that $Q = \frac{\mu}{\beta}\ R = \frac{\mu}{b\omega}$.

$$P_{\max 0} = \frac{|F|^2}{4b\left(1+\sqrt{(1+Q^2)}\right)} \tag{2}$$

As reported by Folley and Whittaker [6], the ratio of maximum fixed OWC power capture ratio for the compressible and incompressible flow cases is then

$$\frac{P_{max}}{P_{max0}} = \frac{QR\left(1+\sqrt{1+Q^2}\right)}{QR+\sqrt{R^2+Q^2(1+R)^2}\sqrt{(1+Q^2)R^2}} \tag{3}$$

3. Physical Interpretation of the Model

The relationships for Q and R defined previously limit the possible solutions predicted by equation 3. These relationships imply that for any real system of interest (i.e. positive OWC radiation damping and positive air compliance) only the first and third quadrants of the parameter space plot are possible solutions. Plotting these quadrants in figure 2 produces the result described by Folley and Whittaker [6].

In the development of this model, it was mathematically convenient to represent the system in terms of the tuning and air compressibility parameters. Physical interpretation of the data in this form is difficult for two reasons; firstly, the parameters have complex physical meaning and more importantly, the parameters are inter-related. It is useful therefore to recast equation 3 in terms of the wave or excitation frequency. To accomplish this, the tuning and air compressibility parameters, Q and R, may be represented as a function of the ratio of the wave frequency to the incompressible system natural frequency as equation four consists of three physically significant and readily determined parameters; $\zeta = \frac{b}{2\sqrt{km}} = \frac{b}{c_{cr}}$, the ratio of the radiation damping to the critical damping of the system without the turbine

$$Q = \frac{\alpha}{\beta} = \frac{k-m\omega^2}{b\omega} = \frac{\sqrt{km}}{b}\left(\frac{\omega_n}{\omega} - \frac{\omega}{\omega_n}\right) = \frac{1}{2\zeta}\left(\frac{1}{\Omega} - \Omega\right) \tag{4a}$$

$$R = \frac{\alpha}{\mu} = \frac{k-m\omega^2}{\mu} = \frac{k}{\mu}\left(1 - \frac{\omega^2}{\omega_n^2}\right) = \kappa(1-\Omega^2) \tag{4b}$$

(i.e. $\lambda \to 0$), $\kappa = \frac{k}{\mu}$ the ratio of water plane stiffness to air compressibility spring rate and $\Omega = \frac{\omega}{\omega_n}$, the ratio of the excitation frequency to the undamped natural frequency.

The frequency response for the system may then be plotted (as the dashed lines for particular cases) in figure 2. Note that at the origin, Q = R = 0 (i.e. when the wave frequency equals the OWC first natural frequency), the power ratio is always equal to one. All frequency response plots for an OWC WEC device must logically pass through the origin.

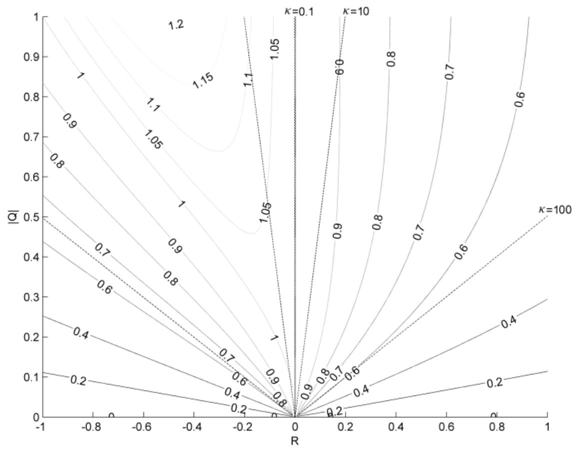

Fig. 2. Maximum fixed OWC power capture ratio for compressible and incompressible flow; the dashed lines represents the frequency response for the case κ=0.1, κ=10 and κ=100 as indicated; ζ=0.01

At this point it is worth looking at what constitutes a reasonable representative value for κ. The water plane stiffness is simply the product of water density, ρ, acceleration due to gravity, g and water plane area, A. The air compressibility spring rate expression may be determined assuming isentropic compression with only small changes in volume (relative to the total chamber volume). The water plane to air compressibility stiffness ratio may then be expressed in terms of the ratio of specific heats of air, cp/cv, atmospheric pressure, p, the OWC water surface area, A, and the chamber height, *h* as

$$\kappa = \frac{k}{\mu} = \frac{\rho g h}{\left(\frac{c_p}{c_v}\right) p} \tag{5}$$

With reference to figure 3, it may be seen that for the incompressible air case (i.e. a single degree of freedom system) there exists a natural frequency at approximately

$$\omega_n^2 = \frac{k}{m} \tag{6}$$

With the inclusion of air compressibility (i.e. a two degree of freedom system), a second natural frequency is visible as expected. The second natural frequency corresponds well with

$$\omega_n^2 = \frac{k+\mu}{m} \tag{7}$$

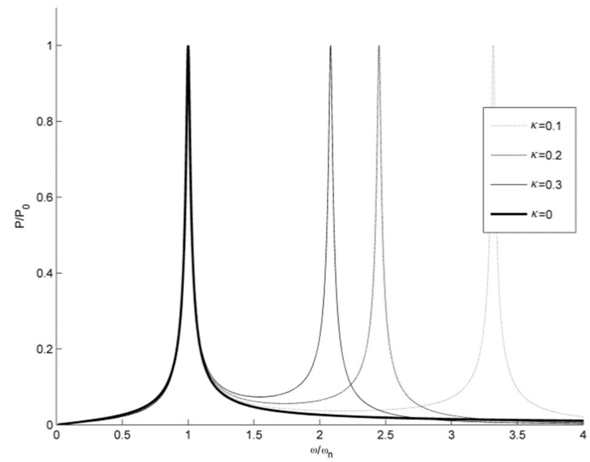

Fig. 3. Fixed OWC maximum normalised power capture for compressible flow frequency response curve; ζ =0.01

The maximum power ratios (i.e. compressible to incompressible power capture ratio) are plotted in figure 4. The power ratio at the first natural frequency (Q = R = 0) is, as mentioned previously, equal to one. The power ratio at the second natural frequency is much larger. This ratio however, has little physical significance as there is no resonant response at this frequency for the incompressible air case. The plots may therefore be used to compare the effect of parameter variation on the OWC power capture when the peaks are near coincident (i.e. high values of κ) as illustrated in Folley and Whittaker [6]. However, the usefulness of this power ratio comparison is limited at practical values of κ (i.e. of the order of 0.1), when the peaks are separated. It is more useful in this case, to normalise the maximum power capture by the peak frequency response power capture value as presented in figure 3.

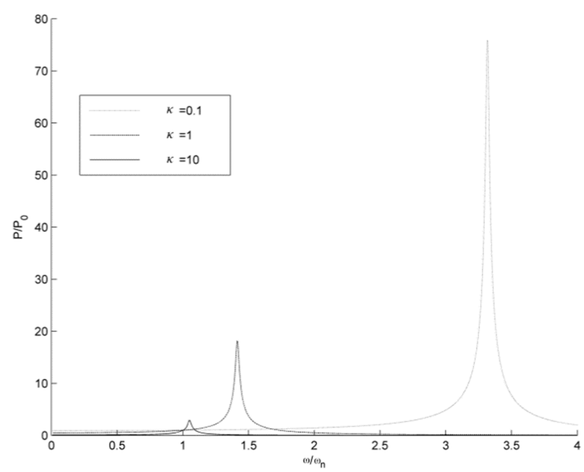

Fig. 4. Fixed OWC maximum power capture ratio for compressible and incompressible flow frequency response curve; ζ=0.01

4. Conclusion

The adoption of the hysteresis component of the Folley and Whittaker [6] discrete parameter model is not supported. The spring introduced to mimic the turbine hysteric behaviour through a phase lag, has undesirable low frequency dynamic effects on OWC model performance. The turbine hysteresis is better modelled through a non-linear turbine damping function.

The maximum power capture parameter map as reported by Folley and Whittaker [6] in terms of a tuning and air compressibility parameter may be translated into more commonly employed offshore engineering parameters (i.e. the damping ratio, the water plane to air compressibility stiffness ratio and the wave to natural frequency ratio). The model is then more readily physically interpreted.

At practical values of the water plane to air compressibility stiffness ratio (i.e. of the order 0.1), the presentation of the Folley and Whittaker [6] model as the ratio of the maximum power capture of the device with compressible and incompressible flow is of limited use. Examination of the model in terms of absolute power or power normalised by the peak power capture is more appropriate.

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