PS FROG: A POINT-ABSORBER WAVE ENERGY CONVERTER WORKING IN A PITCH/SURGE MODE

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INTRODUCTION

In studies of wave energy, notably those made under contract to the U.K. Department of Energy, capital costs have generally been found too high to compete with other sources. It has been shown elsewhere (1) that the large structural element in these costs can be avoided by using point-absorbers reacting against an internal moving mass. This early proposal (2) suffers from the disadvantage that over most of the frequency band capture can only be a fraction of the ideal capture unless some means is adopted of modifying the dynamics to ensure 'resonance' at all frequencies and with irregular waves. Budal and Falnes (3) have used 'latching', or holding the mass when it stops until the judicious moment, and have achieved excellent results with their heaving buoy, which, however, ultimately reacts against the sea bed. The authors used latching in early experiments with a free-floating buoy reacting against an internal mass, but the results were disappointing, although in earlier work with buoys moving in surge on a cable they had had good results with latching (Flounder (4)).

By generalising the idea of quasi-resonance (5) it was seen that there were many ways of achieving the necessary large buoy movements, and very satisfactory power outputs were obtained from models, approaching the ideal over much of the range (6).

AN ALTERNATIVE VERSION

In spite of the promising power outputs and small size of 'Frog', the heaving buoy, it was decided to explore an alternative version, partly to secure higher output and partly to avoid some engineering problems. The power which can be extracted from a mode which is antisymmetric with respect to the waves is twice as great as that to be had from a mode, such as heaving, which is symmetric. This alone makes it attractive to go to a pitching or surging mode. Of the six fundamental solid body modes, only heaving, surging and pitching are coupled to the waves (the others are swaying, rolling and yawing), leaving pitching/surging as the natural choice. Such a point absorber has an ideal capture (7) equal to the power flux through a length of wave front of $\frac{1}{\pi}$ x wavelength, which off the Hebrides corresponds to an annual average of about 2.4 MW.

The new device consists in essence of a rectangular plate lying square on to the seas. In practice the plate must be thick enough to permit access and to resist bending with plating of economical thickness. Moreover, it must be extended in thickness somewhere sufficiently to accommodate the necessary machinery, in particular, the moving mass and the means of modifying its behaviour. It is anticipated that the displacement may be about 3000 tons, but most of this would consist of ballast (fixed or moving) with only about 300 tons of simple ship-like steel structure. The output averaged over a year, in typical 'S. Uist' seas, is expected to be about 1 MW.

NOMENCLATURE

b	damping or radiation coefficient, e.g., damping force in surge = $\omega b_{11} x$
f	forcing coefficient, e.g., surge force in a wave of unit amplitude = f_1
k	displacement coefficient, e.g., added mass in surge = k_{11}/ω^2
m	moving mass
r	amplitude of motion of moving mass
x	surge
θ	pitch

Suffixes

1	surge
2	pitch

EXPERIMENTAL WORK

The experimental work has taken two forms
(a) measurements of hydrodynamic coefficients necessary in design
(b) measurements of power capture in regular seas.

The two sets of results were in good agreement, but not so remarkably good as in the work on the heaving buoy (6).

The hydrodynamic coefficients were measured by studying the decay of oscillations in the still tank and subjecting a fixed model to regular waves and measuring the forces on it by means of a strain-gauged sting. By using the relations between the two, satisfactorily consistent results were obtained.

The principal model used had an immersed section 200 mm x 200 mm x 40 mm, with corners radiused to 20 mm. The results for the hydrodynamic coefficients are given in Fig. 2.

Measurements of power capture were made by pivoting the model in a light frame which itself had a degree of freedom in the surge direction, so providing the necessary two degrees of freedom. Power was extracted by a string led round light pulleys on the frame and a fixed pulley on a shaft. This fixed pulley was fitted with a reversing band-brake, which had already been used with the heaving buoy models. External springs were used to tune the buoy to the waves, a role which would be performed in practice by the moving mass. On average, the powers obtained were 94% of the values calculated from the hydrodynamic coefficients, over a range of periods of 0.9 to 1.4 sec.

CAPTURE IN REGULAR SEAS

In reference 6 it is shown how with only one degree of freedom the system can be optimised, i.e., the 'damping' (power take-off) and spring constant of the moving mass can be chosen to give the ideal power extraction. It is also shown how to extract the maximum possible power when the maximum available value of the-product mr (moving mass x ½ travel) is less than the optimum.

With two degrees of freedom, the problem is more complicated. Treating the pitch, the surge and the motion (or motions) of the moving mass as phasors, the equations of motion of the system may bewrittenas simultaneous linear equations. Solving these equations algebraically, the power extracted can be expressed as a functionofthevariableparameters associated with the moving mass or masses, and this function can be maximised by suitable choice of the parameters (power take-off rate and stiffness). However, this analytical approach is not the most useful for design.

The general motion (x, θ) of the buoy may be analysed into two orthogonal modes (3 and 4, say) such that the power extracted is independent of mode 4. This may be seen by considering the effect at a distance of pitching about a point near- the mid depth. As this point moves vertically, the wave at a distance must change 180" in phase, with zero amplitude when the point is at some particular depth, which defines the mode 4. It follows that the ideal power is obtained when the amplitude of this point has a particular value, and the designer has a free choice in respect of the amplitude in mode 4. This free choice can be used to suit the engineering of the moving mass and its constraints, that is, the reaction system.

We are still developing our ideas about the reaction system. However, an early study indicated that design for an average annual capture of 1 MW in a 'S. Uist' sea might be about the most economical, although a larger figure was possible.

IRREGULAR SEAS AND QUASI-RESONANCE

In order to extract high powers from irregular seas, some way is needed of maintaining quasi-resonance (the aperiodic equivalent of resonance (5)). In the heaving buoy this was to be done by 'stiffness-modulation'. By valves dividing the air-spring into two chambers, the natural frequency could be switched between two values bracketing the bandwidth over which quasi-resonance was to be achieved. By switching to the higher frequency when the mass was far from the centre and back to the lower frequency when it was nearer the centre, and by choosing the switching points suitably, quasi-resonance could be maintained. This systemshowednearidealperformanceincomputer simulations using a simple algorithm to initiate switching (6). This algorithm did not use foreknowledge, and a slight improvement would be possible using a system which looked at the approaching waves.

An important advantage of the new system is a much better 'power-factor', in electrical terms, or 'work ratio', in thermodvnamic ones. The energy stored in the reaction system, which is transformed from kinetic to potential and back twice per cycle, is much less than in the heaving version, where small losses in transformation result in large losses in output. The difference comes from the absence of the need to sustain the weight of the moving mass.

ENGINEERING

We have looked at several possibilities for the reaction system, and have not settled on one yet. The simplest is a sliding mass constrained by hydraulic jacks, with large accumulators as energy stores. There is a tidal flow of energy between jacks and accumulators, with a net flow to the latter, and power is extracted bv means of aturbinedrawing on the high pressure fluid and returning it via a sump to the jacks on their 'idling' strokes. A microcomputer would control valves connecting the accumulators to the jacks.

More sophisticated systems offer advantages in reducing the reactive energy, reducing the losses involved incycling it, e.g., by permanently connecting some jacks to accumulators, or increasing reliability.

Because of the reduced cost of the rest of the system, electrical costs become a larger proportion of the whole and this means the ratio of peak to mean electrical ratings should be reduced. This mav be expressed as an increase in the utilization of the full electrical rating. If s is the average cost of energy **at** the designpointand pisthe annualised marginal cost per unit of electrical capacity, then in an optimised design the fraction of time for which output is limited by the electrical rating should be

$$\frac{p}{s}$$

Strictly, p should include the additional turbine cost.

Little thought has yet been given to moorings, and it is-appreciated these present difficulties. Also the problems of orientation and preventing wind-up (or making it acceptable) require attention. Usually, a bodv of this fo;m will of itself adopt the-requirehattitude, but this is not always the case. Dividing the reaction system into two by a median plane would provide a means of yaw control, but at some cost. All these areas require much more work.

CONCLUSIONS

Though much work remains to be done, the pitching and surging pointabsorber, reacting against an internal moving mass or masses, and using some system such as stiffness modulation to maintain quasi-resonance, offers a strong promise of an
In particular, the structural costs are low, with a structural mass of only about 300 kg/kW. Further study is justified.

ACKNOWLEDGEMENTS

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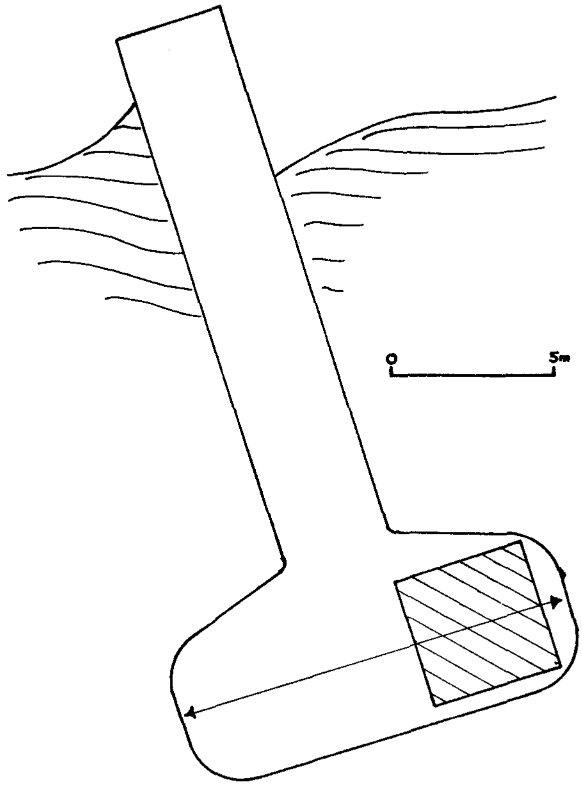

Figure 1 Pitching/surging Frog (diagrammatic)

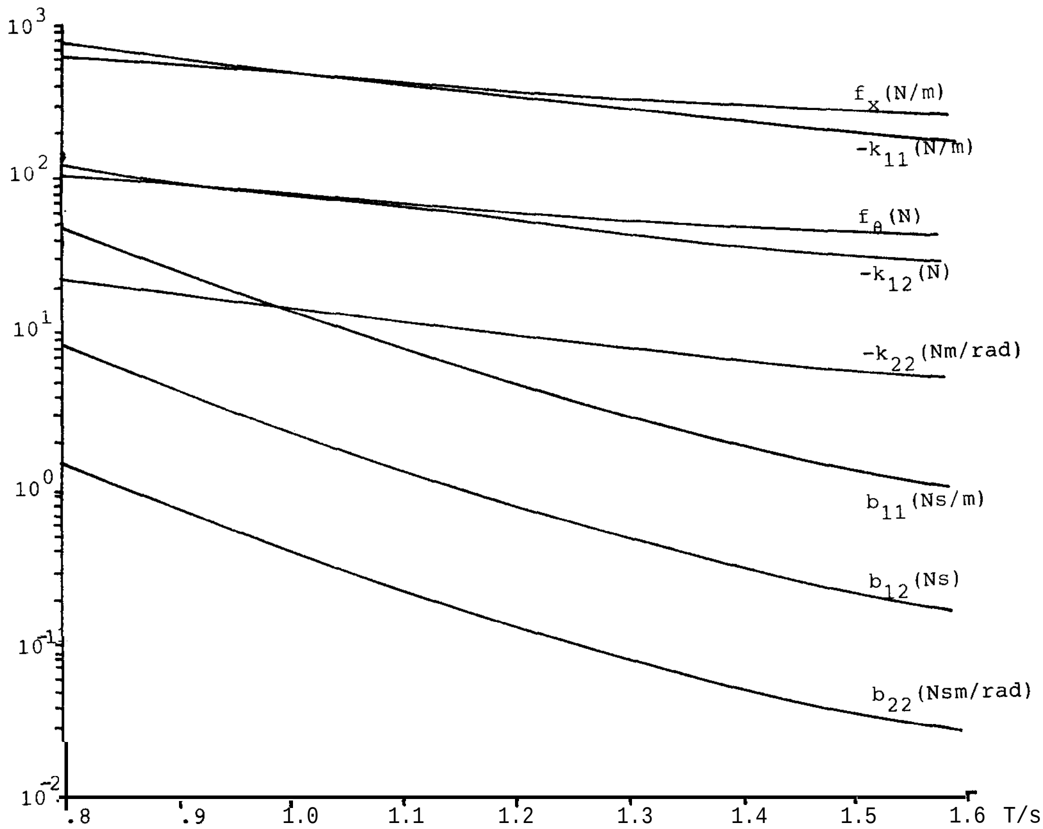

Figure 2 Table of Coefficients