DEMONSTRATING THE FEASIBILITY OF A DISTENSIBLE-TUBE WEC WITH A DISTRIBUTED POWER TAKE-OFF

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Background – Froude-Krylov theory

The operating principle of a distensible-tube WEC (wave energy converter) was first described at the 2006 Workshop [1], making the traditional Froude-Krylov assumption that the diffracted and radiated waves are negligible compared with the incident wave. An infinitely-long device, perpendicular to the wave crests, was assumed to have reached a steady state, and was analysed in the classical way ([2] Art.250) in a frame of reference moving with the water and bulge wave, in which the flow is steady. It was concluded that the pressure in the bulge wave became an increasingly large multiple of that in the water wave, as the water wave speed approached the free bulge wave speed. It is this resonant interaction which is exploited in a distensible-tube WEC, to concentrate water wave energy in a bulge wave. In the 2007 Workshop [3] experimental results were presented, confirming the operating principle, and investigating how the energy in the bulge wave might be extracted by means of a power take-off at the tail end of the device.

This Froude-Krylov analysis is extended in [4], by introducing a linear dissipation term in the elastic properties of the tube, intended to describe a power take-off distributed over the whole length of the device, rather than at the tail end of it. In this way the device can be made much longer – until the water wave energy starts to decay towards the tail of the device (i.e. the Froude-Krylov approximation breaks down – the threshold of this being established in [4]). See [5], figure13.

From an engineering point of view, it is highly advantageous to replace the linear dissipation term with a non-linear hysteresis loop, in which the pressure excursions are limited to a finite value, saving the tube from over-pressurisation in extreme conditions. See figure 1 below – the elliptic pressure-distension characteristic produced by a linear dissipation term becomes a parallelogram.

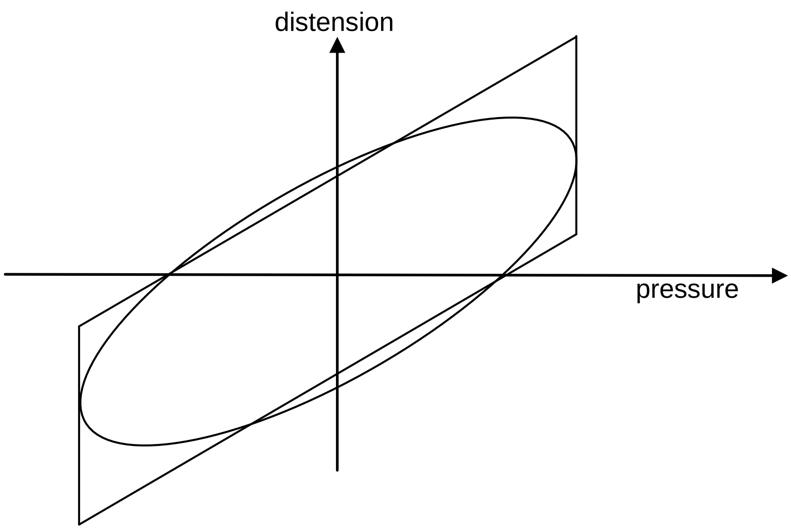

Figure 1. Linearising the pressure-distension characteristic

[1] Presenting author

In [4], an infinitely long device is considered in regular waves, and the linear dissipation is set so that the maximum pressure in the bulge wave is this pressure limit, as shown in figure 1. The power of the device can then be estimated as that dissipated by the linear dissipation term. In this way the power is obtained as a function of the pressure limit, and the water wave period and amplitude. It is then possible to consider irregular water waves on the narrow-bandwidth assumption, in which each individual wave is assumed to produce the same power as a member of a regular wave train of the same amplitude and period. The average power then follows from the Rayleigh distribution of wave amplitudes, and can be optimised by adjusting the pressure limit (up to a maximum value given by the strength of the tube). The result of this calculation is given in [4]: a 600m long device of $5m^2$ cross-section in the Benbecula wave climate produces an annual-average pneumatic power of 500kW. Maximum power, set by the strength of the tube (max bulge wave pressure = ±0.25bar), is 1200kW.

Device design

Two different designs for such a device are outlined in [4]. The simpler of these (although probably not the most economic) has a tube arranged with high-pressure pneumatic rams across it, as shown in figure 2 below.

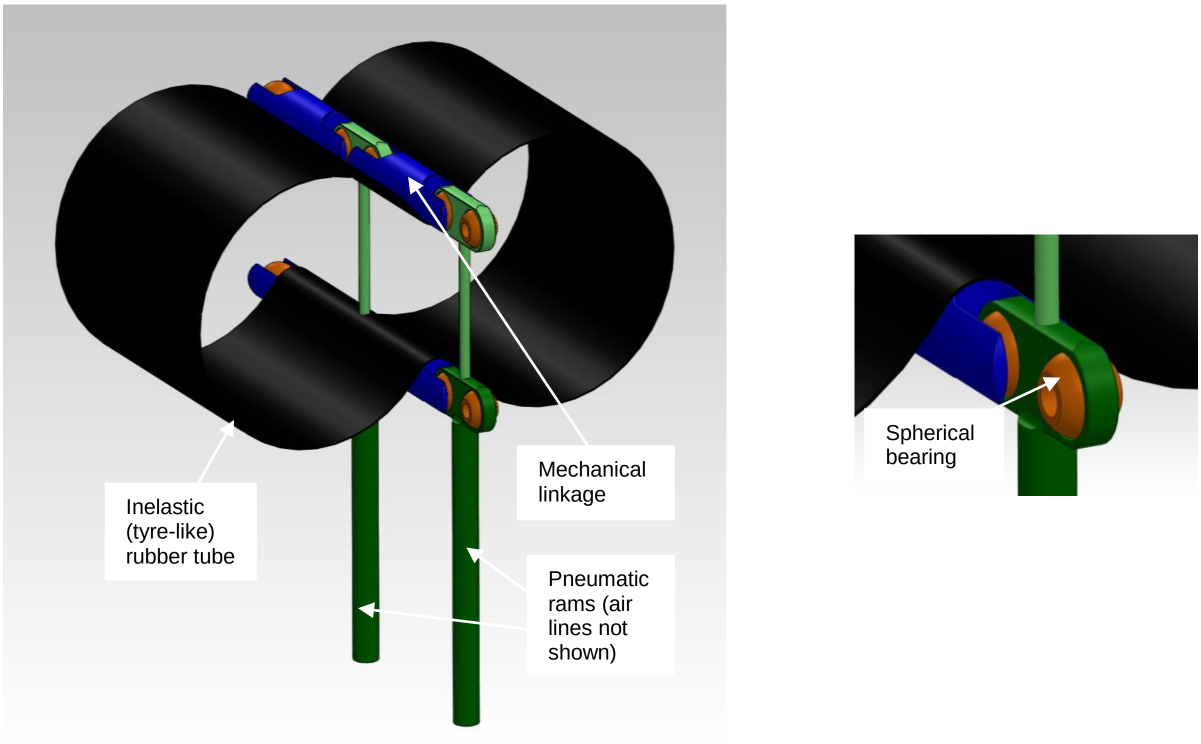

Figure 2. Section of distensible-tube WEC with distributed power take-off

The rubber tube is reinforced in the circumferential direction only, so the device can readily "snake" horizontally and vertically. Longitudinal pressure loads are carried by the mechanical linkage (0.3m diameter tubular steel members linked by spherical bearings, 1m between centres), which also transmits the circumferential pressure load in the tube to the pneumatic rams (maximum stroke ±0.9m, 1.4m between centres). It is these rams which provide the required distensibility of the tube, by virtue of the compressibility of the air in them. They have 7cm rod diameter and 17cm outer cylinder diameter (see [4], .IGS files – the bore diameter is 14cm), so their pressure amplification factor is $1.8\times1.4/\{\pi(0.14^2 - 0.07^2)/4\} = 220$. The required $0.0024kPa^{-1}$ tube distensibility (see (5)) implies that for each kPa increase in tube pressure (or 220kPa increase in air pressure), the fractional increases in cross-sectional area is 0.0024, which is an increase in tube diameter of $1.8\times0.0024/2$ = 0.0022m. This corresponds to a ram stroke of 0.0022π, which gives a fractional decrease in air volume of $0.0022\pi/0.9 = 0.0077$, and thus a fractional increase in air pressure of $0.0077\gamma = 0.011$, assuming adiabatic air behaviour with $\gamma = 1.4$. The static air pressure must therefore be 220/0.011 = 20,000kPa = 200 bar. It produces a static tube pressurisation of 20,000/220 = 90kPa, which is rather greater than the 50kPa specified in [4], but this can be remedied by pressurising the lower compartments in the rams, and inter-connecting them with flexible air lines.

The air pressure in the upper compartments of the rams is limited by one-way valves, communicating (via short flexible jumper hoses) to low and high pressure flexible lines running the whole length of the device. These have sufficient internal diameter (10cm appears suitable) to limit flow losses, and also to enable them to act as pneumatic accumulators, smoothing the power flow. The whole device is single-point-moored from a small mooring buoy (conventional CALM type, or vertically-tethered), which also terminates the low and high pressure lines, just like the oil lines from a single-point-moored tanker. The air turbine between the two lines, like the control systems to regulate their pressure difference, is mounted on the buoy – the device itself is entirely passive, with no electrical systems.

Physical model testing

The concept of a distensible tube wave energy converter with a distributed power take-off is not one that seems to have been tested in the laboratory, although preliminary experiments have been carried out [6] with a view to using electro-active polymers. In this section we propose an experiment using a model which is designed to mimic the behaviour of the full-scale device described above, but which differs from it for various practical reasons. A scale model that incorporates a pneumatic system similar to that of the prototype is a feasible option, and would clearly have to feature in any subsequent programme of development. Careful design of the model rams could deliver both the appropriate static force across the tube, and the appropriate distensibility. But the purpose of the tests proposed here is to demonstrate feasibility in the simplest way (as in an earlier case [7]), without the complexity and expense of large numbers of inter-connected pneumatic rams operating at high pressure.

Accordingly, in the proposed model the rams are replaced by steel extension springs inside circular bellows. A sketch of one section of the laboratory model is shown in figure 3 below, with part of the bellows removed to reveal the tensioning spring inside. The longitudinal mechanical linkages of the full-scale device are replaced by upper and lower pipes which have sufficient bending stiffness to maintain the shape of the tube over the short gap between adjacent springs, while still allowing it to flex in the vertical and horizontal planes with the external wave motion. The bellows terminate internally with opposing one-way valves so that as the tube expands and contracts, they pump air (at a positive pressure relative to that of the water in the tube) through the same pipes, around a circuit which, as in the full-scale device, includes the power take-off (not shown here). In figure 3, arrows indicate the air flow in opposite directions in the two pipes. Outline calculations indicate that this arrangement is practicable at a scale of about 1:6.

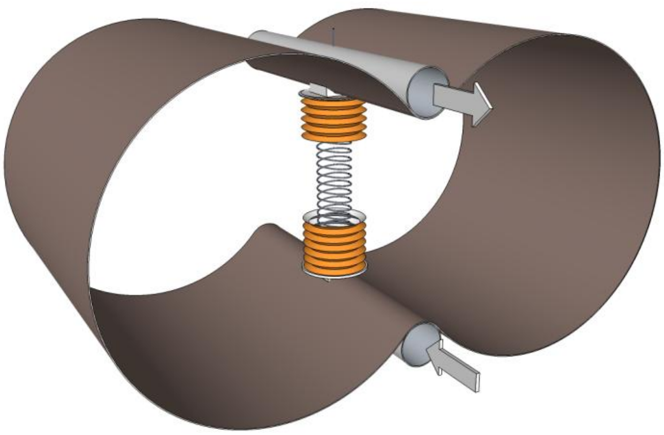

Figure 3. One section of the laboratory model of the device. Expansions and contractions of the tube cause the bellows to pump air along the pipes above and below, delivering a steady flow of air through the power take-off.

Full-scale demonstration

Because the device uses a conventional single-point mooring buoy (to which it is attached in the conventional way, with a nylon hawser), there is no need to demonstrate that part of the system. Instead, the device can be towed behind a small tug, or fishing trawler. This is much more convenient than installing it in a fixed test site, such as EMEC in Orkney. As well as the nylon hawser, the tug can take over the stern the low and high pressure pneumatic hoses. The turbine between them, and the electrical generator, can then be mounted on the tug, together with the control machinery.

In this way the performance of the device can be demonstrated in waves up to the highest from which power is required (viz. Hs = 10m, see [4]). Survivability in waves above that can be deduced from the physical model tests.

References

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