

The Design of an eddy current dynamometer for a free-floating sloped IPS buoy

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SYNOPSIS

The creators of the Swedish 'IPS buoy' conceived of an ingenious solution to the end-stop problem that is a source of great anxiety to designers of wave energy devices. A variation of their concept, the 'sloped IPS buoy' wave energy device, responds to wave excitation by moving at an angle to the vertical heave direction. The sloped motion has the effect of reducing the hydrodynamic spring rate and increasing the damping coefficient, so improving the potential for high power capture in relation to the device size. Tank tests of a sloped IPS buoy artificially constrained to move at a number of fixed angles against an external reference showed promising power capture across a wide range of wave periods. The promise of the sloped IPS buoy for stand-alone applications has prompted detailed tank tests of a free-floating hydro-dynamically realistic device. The dynamometers will capture energy by using an internal force reference from a piston coupled to the inertia of water within open tubes. At the test scale of around 1/75th of the size of the full-scale device, it is important to minimise friction and to have exact control and easy adjustment of the damping coefficient. It is also useful to be able to use the dynamometers in reverse as motors driving the model, both for measuring added inertia and damping and to permit complex force/velocity functions in place of simple damping. Consequently each dynamometer will be constructed in the form of a three-phase tubular induction motor, although its primary mode of operation is expected to be as a DC energised damper. A long thin walled aluminium eddy-current tube coupled to each piston will move through the radial magnetic field of a wound stator. Water-fed hydrostatic bearings will constrain the eddy-current tubes to move freely within the main water tubes so as to maintain magnetic gap clearances. It is hoped that this arrangement will allow precise control and optimisation of sloped IPS buoy models such that detailed response data can be collected for a very wide range of sea conditions. Experimental results will also be compared with simulations from numerical models of the device. This paper outlines the detailed design of the dynamometers.

INTRODUCTION

Over the last decade, diverse factors such as fears over global warming and the liberalisation of the electricity market have prompted resurgence of interest in wave energy in the UK as well as in Europe generally. The current situation is distinct from the previous phase of interest that started around 1974 and had been initiated by sharp rises in petroleum prices. Whilst it is hard to imagine that we will not return to increased oil costs within a generation, an inescapable fact now, is that renewable energy technologies such as wave power, have to compete head on with the remarkably low real prices of carbon derived energy. Whether any wave power system will be economic in the medium-term is uncertain. What is clear is that potential wave power systems have to be very energy productive in relation to their size and cost in materials. They must be seaworthy, expert at survival and extremely reliable. The wave power group at the University of Edinburgh continues to believe that the only possibility of achieving this is with factory or yard manufactured units incorporating cutting-edge technology and floating offshore in relatively deep water. They also believe that, before embarking on full-scale designs, as many as possible of the almost infinite number of potential design errors must be eliminated by work with wave tanks, test rigs and numerical simulation.

FROM GIGAWATT TO SOLO DEVICE

The Duck wave power device evolved at Edinburgh as a gigawatt-scale concept (1) and is predicated on the demonstration of solutions to several interesting engineering problems. Accordingly it is sometimes described as a 'third-generation' wave energy device. It continues to be actively maintained in the form of a design and costing model (2). However the implementation of such large-scale devices seems unlikely without successful experience from more modest systems. One approach is to design a 'solo' device such as might be suitable for providing power to an isolated community or offshore facility rather than to the nation.

The authors

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After experimentally investigating several sea-bed referencing devices, including the Solo Duck and the Mace (3), Stephen Salter had another idea for a self-contained solo deep-water wave energy device. He noticed that the designers of the Swedish IPS Buoy (4) had come up with an ingenious way of dealing with the critical ‘end-stop’ problem intrinsic to linear-motion wave energy devices. The IPS Buoy is essentially a heaving device, and Salter also noticed that its natural frequency might be reduced if it could be made to move at an angle intermediate between the heave and surge directions. By reducing the device size compared with the design wavelength this might significantly lower the cost of delivered electricity.

The idea is described elsewhere (5) but it may be helpful to summarise the fundamentals. Figure 1 shows in cross-section an early proposal for a sea-going device. In essence it consists of two or more long sloping water filled ‘inertia tubes’ open at either end to the sea and held just under the water surface by a float or ‘buoy head’. The underwater construction joining the water tubes in the sway direction (into the page) is in the form of a plate or slab. Under the action of waves, and with suitable ballast arrangements, the entire structure should be most free to move in the direction of the slope angle. A large diameter water piston, able to slide within the central section of each inertia tube, is directly coupled to the added mass of the water inside the tube and so its motions tend to lag those of the structure. The pistons are coupled to high-pressure oil rams that drive the electrical generation system.

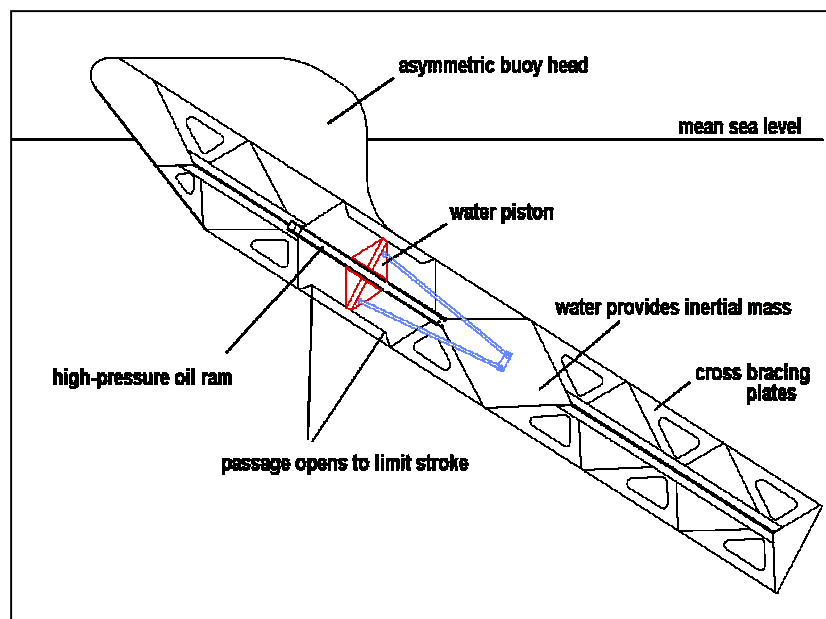


Figure 1: Cross-section of the sloped IPS buoy and one of its water tubes. Waves approach from the right

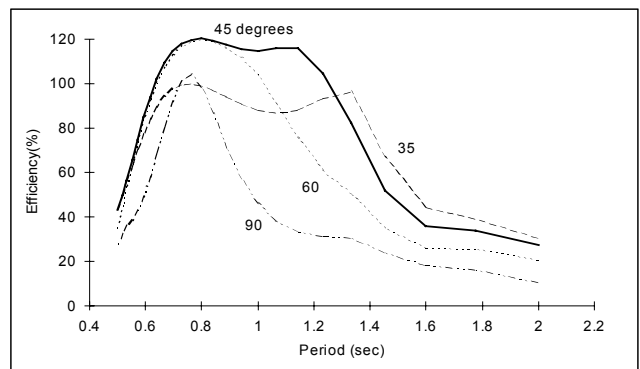
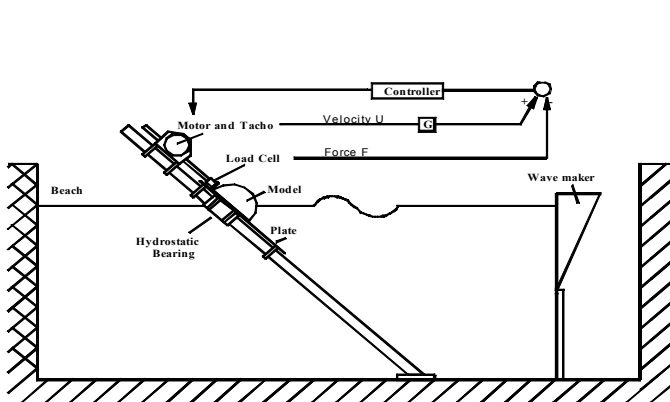
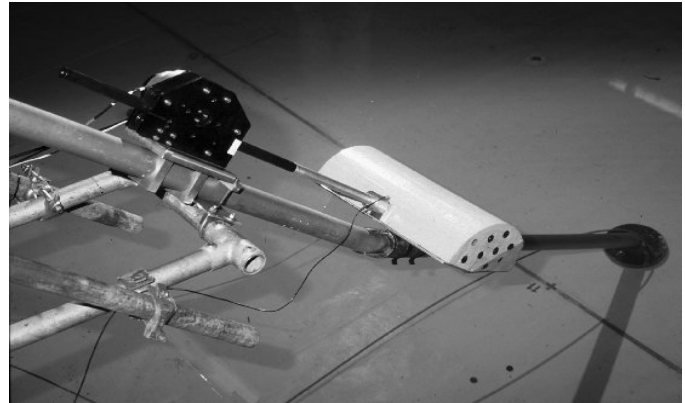
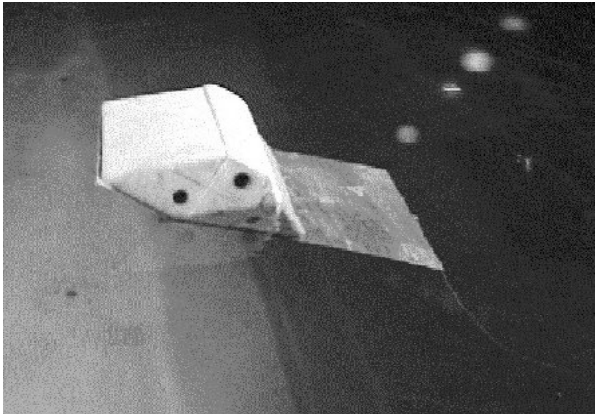
The piston passages in the inertia tubes bell out at either end to limit the stroke of the water pistons and hydraulic rams in large waves by providing a progressive water bypass route. This ingenious Swedish idea is the key to surviving heavy weather. The buoy head is shaped so as to maximise energy absorption from waves coming from the right in Figure 1, and to minimise wave transmission to the left. Imagine the buoy oscillating along the slope line in still water. It would clearly be good at making waves to the right and bad at making them to the left.

EXPERIMENTS WITH A CONSTRAINED MODEL

In 1999 Chia-po Lin was awarded a PhD based on his experimental investigation of the power capture of a sloped wave energy device (6,7). At the start of his studies he showed, with the simple un-damped model of Figure 2, that a sloped buoy with tail plate tended to constrain itself to ‘sloped’ motion. He then developed the apparatus shown in Figures 3 and 4.

As a fully realistic free-floating model was beyond his resources, his rig consisted of a half-cylindrical float constrained to respond to waves by moving up and down a fixed tube that could be set to different slope angles. To reduce friction, the slide between float and tube used a water-fed hydrostatic bearing. To load the buoy and simulate a full-scale power take-off mechanism he used a fast-response linear-drive electric motor unit that had earlier been developed by Richard Yemm. This was mounted above the water with a load cell between connecting rod and float. Lin did his experimental work in the Edinburgh wide tank and some of his results are shown as Figure 5. These show efficiency (defined in relation to the width of the model) plotted against wave period over a range from 0.5 seconds to 2 seconds. The two octave period range corresponds to the full range of the tank. Each efficiency curve is constructed from the results of many fixed period regular wave tests. Wave incidence was parallel to the model, and the damping was optimised for

each wave period and slope angle. The results can therefore be considered to be optimal, and lower efficiencies would generally be expected in fully realistic multi-directional spectra. Many of the values are greater than 100%, showing the effect of point absorption.

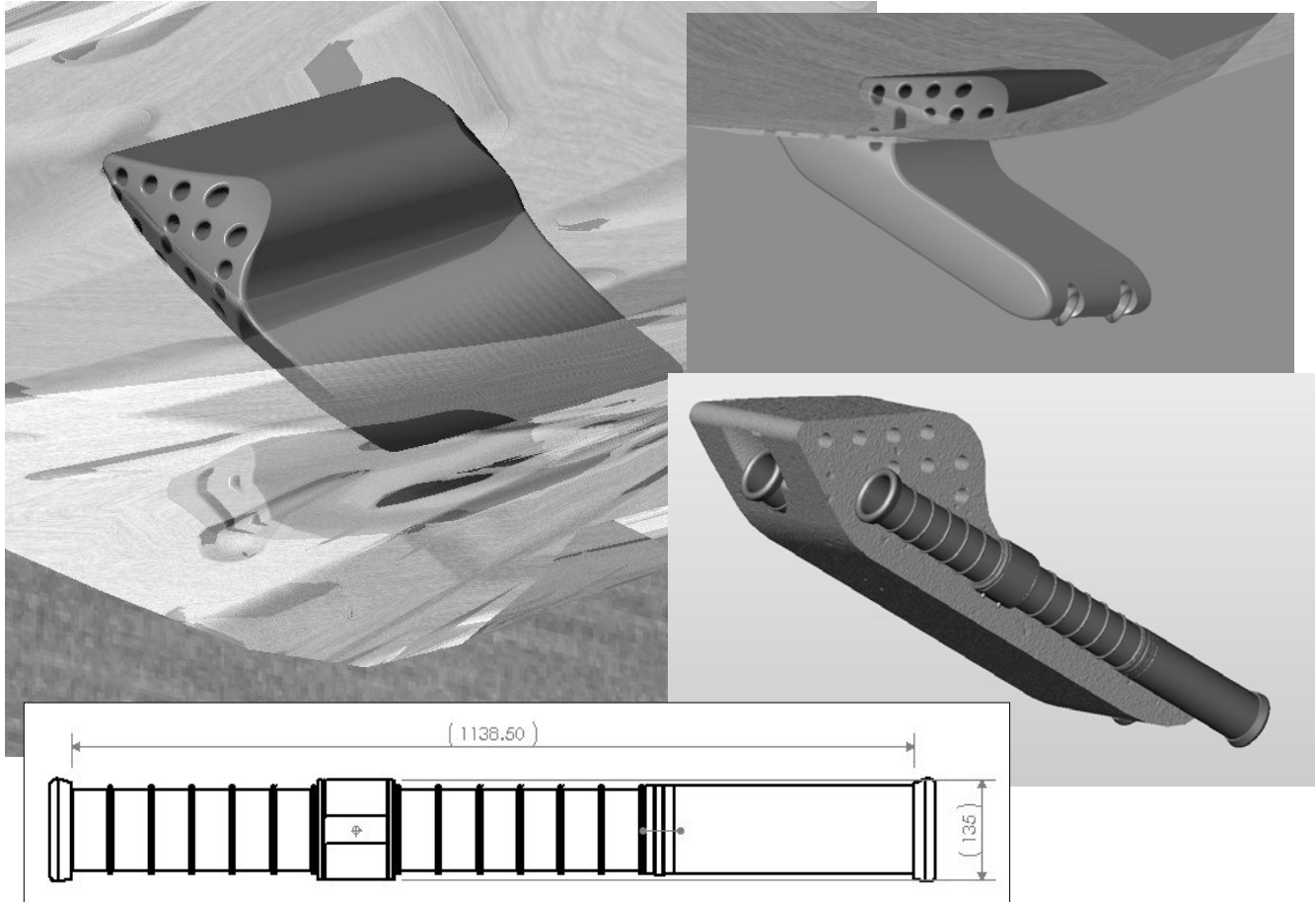


An invaluable feature of the arrangement used by Lin was that it enabled him to establish the 'hydrodynamic coefficients' of his model. These are useful for correlating experimental and numerical work. In this respect, Lin's work was influenced by an outstanding series of experiments in 1987 on a solo duck in the Edinburgh wide tank by David Skyner (8). There are two kinds of hydrodynamic coefficients, corresponding respectively to the forces experienced by a moving model due to wavemaking and to the forces on it due to incident waves. The combination of an electric motor based dynamometer and a force measuring load cell allows both of kinds of parameters to be characterised. A further advantage is that such a system allows investigation of power take-off strategies that require forces partially out of phase with velocity. These may hold the key to the highest electricity productivities at sea (9).

Lin's results clearly demonstrated the beneficial effects of slope on efficiency bandwidth. The curve corresponding to a slope of 45 degrees is particularly exciting and his work laid the foundation for further study of the sloped IPS buoy. As his model was artificially constrained to a slope angle, major uncertainties remain with regard to the feasibility of the concept and of how well Lin's results would predict the performance of a notional sea-going device. However, support has subsequently been obtained to confront these concerns by building and testing a model of the sloped IPS buoy that is as fully realistic as possible hydrodynamically and also to carry out related numerical analysis.

THE FREE FLOATING MODEL

The solid model images of Figure 6 show various views of the new sloped IPS buoy model. The array of holes in the buoy head are for metal ballast rods used for buoyancy trimming. The image at top right shows how the lower ends of the inertia tubes are open to the water, and a complete inertia tube is shown in the part section below it. The outer shape of the buoy will be subject to much modification through experimentation and numerical analysis to develop a seaworthy shape with the best resistance to motions in directions other than the slope angle. The relatively hard corners of the solid models shown in these images will evolve toward the preferred 'sucked toffee' look.



MODEL POWER RATING

One of the objectives of a model-testing programme must be to determine the size of the proposed full-scale device. So the scale of this new model is not known for certain. However initial estimates suggest a sea-going sloped IPS buoy having a width of around 40 metres, corresponding to a new model scale of perhaps $1/75^{\text{th}}$. A reasonable way of estimating the full-scale electrical generating capacity is to assume a power limit of 200 kilowatts per metre of wave exposure (assuming locations to the west of the UK or Ireland), equivalent to a total of 8MW or 4MW per inertia tube. Power scales with linear dimension raised to the power 3.5, so the tank-scale dynamometers would then be rated at just over one watt. In order to explore the effects of using different power limits it will be useful to have a reserve of power available. This suggests that most of the time the model dynamometers will be working at average powers of below one watt but with occasional excursions up to several watts.

They must work underwater with little friction or backlash, be able to resist hydrodynamic motions with linear damping forces and be easy to control. Ideally they should be able to provide more complex control functions and it would be useful if they could directly drive the model, so that hydrodynamic coefficients can be measured. Finally they should, if possible, fit neatly within a space equivalent to or not much bigger than that of the scaled-down sea-going inertia tubes and they should not sink the model or interfere unduly with its motions.

THE DYNAMOMETER IN OUTLINE

In the new dynamometers force reaction is provided by a tubular electrical machine that is directly coupled to the inertia-tube piston. Distinct electrical arrangements allow it to function either as an eddy current damper or as a three-phase induction motor, and possibly as a combination of the two. The piston bypass arrangement of the full-scale sloped IPS buoy will not be modelled physically because its dimensions need to be established. Instead it will be simulated by combining an over-long piston stroke with stroke-locked limiting of the current supplied to the tubular motor. Figure 7 shows the general construction of a dynamometer tube.

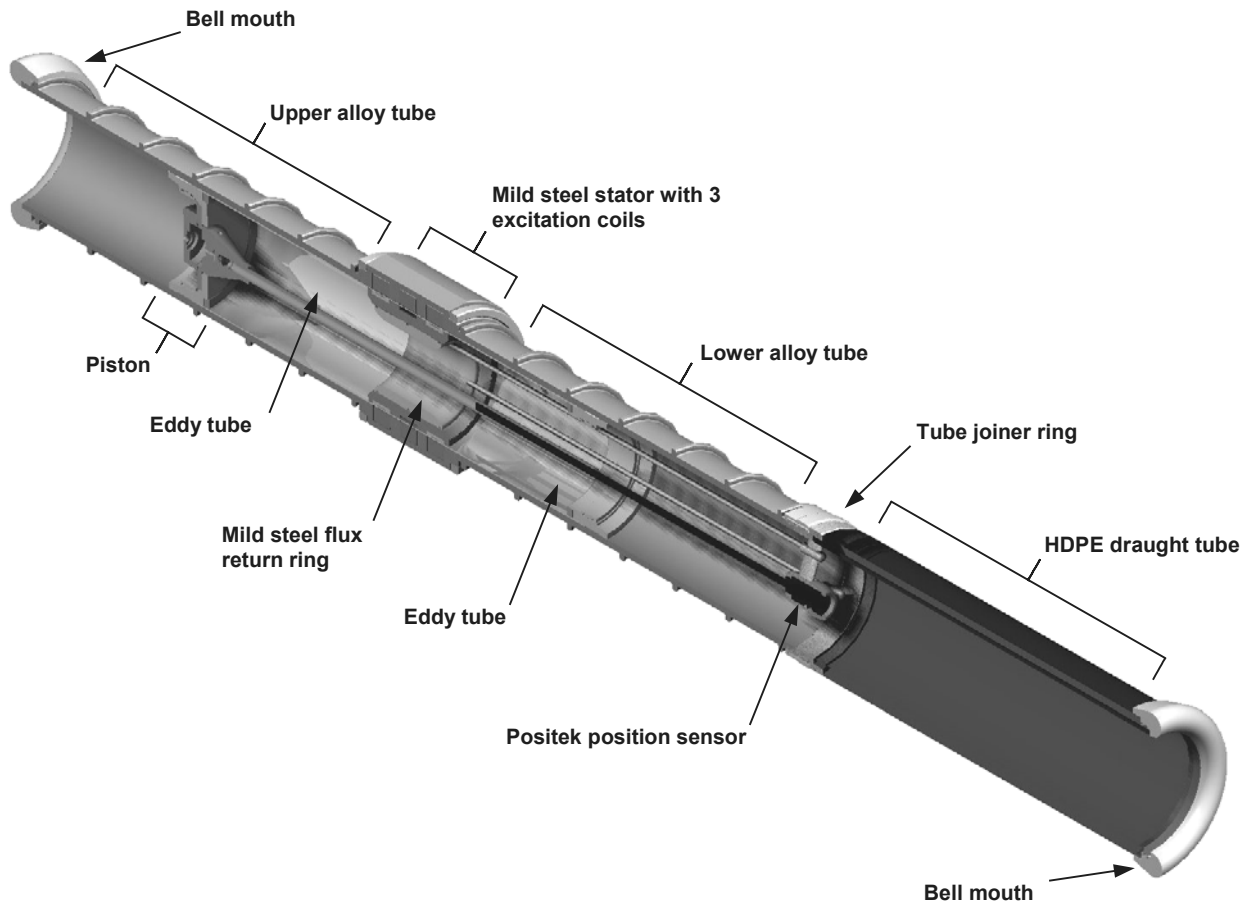


Figure 7: Half section of dynamometer tube

The inertia tube is made up of a number of discrete sections. At the low end is a draught tube of high-density polyethylene (HDPE) whose only function is to increase the volume of water coupled to the piston. This is quick to make and easy to change to study the effects of different lengths.

A short 'tube joiner' ring connects the HDPE tube to the rest of the assembly, acts as a manifold for the supply to four water-bearings and locates the active part of a Positek linear piston displacement sensor. Above it, the remaining sections of the inertia tube form an accurately bored assembly. A short mild-steel stator-tube is mated between a pair of 330mm long ribbed aluminium-alloy tubes. The stator bore contains three annular cut-aways to accommodate excitation coils. At either end of the inertia tube assembly a 'bell-mouth', probably more bulbous than the ones shown, reduces losses as water flows in and out of the tube.

A second assembly, about 450mm long, is free to slide inside the outer tube assembly. This consists of the piston, a thin-walled 'eddy-tube' and its water bearings. Located inside the eddy-tube but constrained axially to remain centred under the stator is a mild-steel 'flux return ring'. Within the piston body and coupled across the water masses on either side of it is a differential pressure sensor. The piston also holds one end of tubular stainless-steel sheath which, as the piston moves, progressively covers and uncovers the sensor rod of the displacement transducer.

For protection against corrosion the steel components are nickel-plated and aluminium-alloy components are hard-anodised.

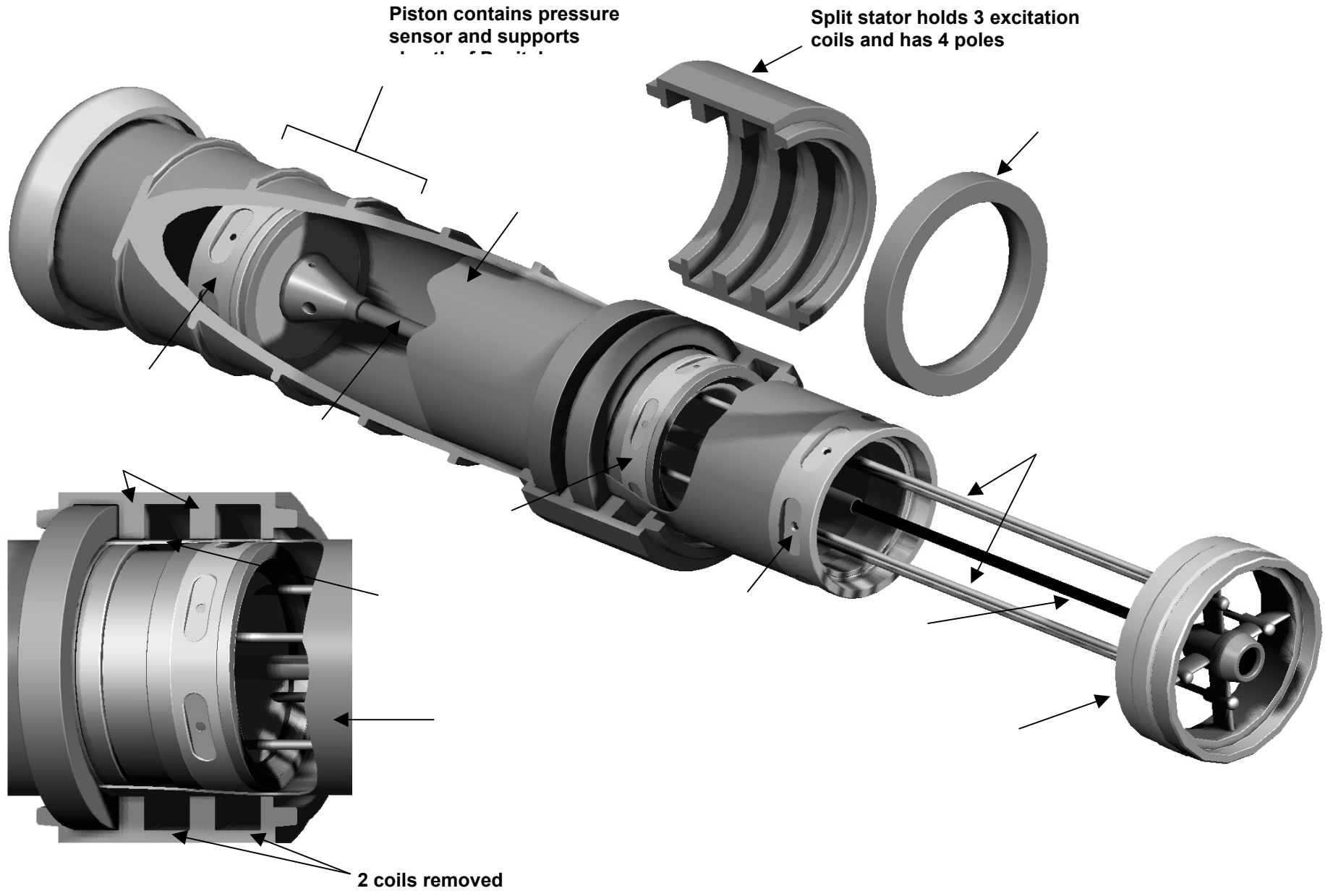


Figure 8: Dynamometer components with inset at left showing more detail of magnetic gap

DYNAMOMETER OPERATION

The operation of the dynamometer may be more easily understood by reference to the detailed views of Figure 8. Previous work on hydrostatic bearings and eddy-current dampers is described elsewhere (10,11).

The piston, eddy tube and water bearings

A 400mm long, thin walled (1mm) aluminium-alloy 'eddy' tube is attached at either end by a tapered compression-ring to an annular water bearing. A series of six shallow circumferential pockets is machined into the outer surface of these bearings. The outer surfaces of the bearings are slightly proud of the outside of the eddy tube. The nominal radial gap between the bearings and the bored inner surfaces of the outer alloy tubes is 25 microns (about 1 'thou' in old British units). This is a small clearance and the roundness errors of the alloy tubes have to be better than this, hence their stiffening ribs. Water is supplied to each pocket by its own 'restrictor', a porous plug of sintered bronze. It escapes through the 25micron gap between the 'land' around the bearing surface and the inside of the alloy tube. The restrictors act like series resistors and allow pocket pressures to vary independently according to flow. This gives the bearing radial stiffness. If the radial clearance around one side of the bearing is forced to close a little, the flow through the smaller gap is reduced and the pressures of adjacent pockets increase. The opposite pockets experience correspondingly reduced pressures. The hourly flow rate per bearing using water at a typical mains supply pressure of 4 bar is around 7 litres for the nominal 25micron gap.

The water-bearing component at the top end of the eddy tube is blanked off completely to form a piston. Within the piston is housed a differential pressure sensor with tappings going through to the inner and the outer water volume, so that the net force on the piston can be known. It also carries one end of the sheath of the position sensor.

The magnetic circuit

The magnetic circuit is made up of a relatively thick tubular stator that encloses three coils, a relatively thin tubular flux return-ring and the radial water-filled gap between them. To facilitate coil design and location, the stator is made as two separable halves. The inner surface of the stator and the outer surface of the flux return-ring are machined to form a linear sequence of four pairs of annular poles with 1.5mm radial gaps. The eddy-tube moves through this gap with a clearance on either side of 0.25mm and so cuts magnetic flux produced by the coils. Two of the inter-pole gaps on the flux return-ring support annular water-bearings similar to those of the eddy tube. These bearings locate the flux return-ring *radially* inside the eddy tube. It is located *axially* by the four water-supply tubes attached to the tube joiner ring further down the assembly. Water is supplied from the flux return-ring to the moving bearings at either end of the eddy-tube by coiled nylon hoses that are not shown in the figures.

In summary, the arrangements are such that the piston can move with little friction within the inertia-tube assembly. It is constrained only by forces due to water pressure and by those transmitted to it by a thin walled conductive tube which moves with it whilst cutting the magnetic flux created by a set of three coils.

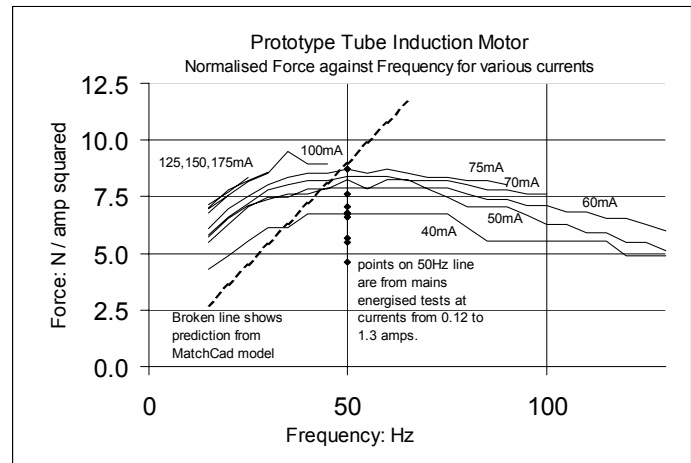
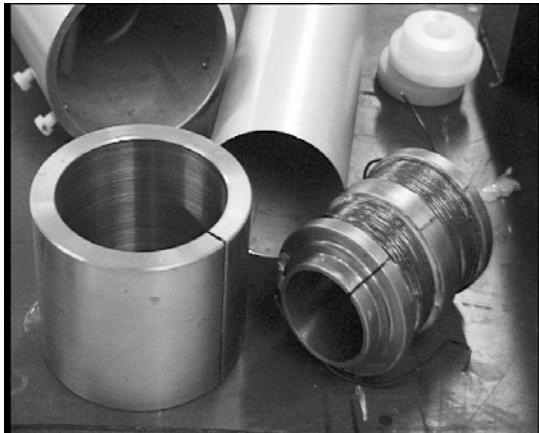
Eddy-current damper operation

By energising the three coils from a DC current source the machine behaves as an eddy-current damper. The combination of radial flux and axial motion induces circumferential voltage in the eddy-tube. The voltage drives a current proportional to the conductance of the tube (hence aluminium which is nearly as conductive as copper). The combination of that circumferential current and the same radial flux produces a force on the tube proportional to and opposing its velocity. Because both the voltage to velocity ratio and the current to force ratio are proportional to flux, the damping coefficient is proportional to the square of flux density and thus to the square of excitation current. It is hoped to include Hall effect sensors in the pole faces so that the damping ratio can be actively controlled.

Induction motor operation

By energising the three coils from AC current sources that are mutually 120 degrees out of phase, the machine behaves as a tubular induction motor comparable to a conventional linear induction motor. (12) Properly designed AC machines use insulated steel laminations to reduce losses due to currents induced into their cores. These would be difficult to incorporate in the present design. However the two halves of each stator can be easily insulated from one another to reduce circulating currents. The two-phase tubular induction motor shown in Figure 9 was built in order to measure static torque at various drive frequencies and to investigate the substitution of insulated laminations by current interrupting slits in the stator parts. Interestingly the best performance was obtained at around 50Hz. The main difficulty of driving the dynamometer with AC currents is due to the electrical inductance of the coils. Compared with DC excitation the voltages required to produce comparable magnetic flux are considerably higher. In air this would not be unduly worrying, but in this underwater application, it would probably be unwise to operate at rms AC voltages higher than 24. The voltages can be reduced by winding the coils of thicker copper wire. However the coils become harder to

make, and the required currents demand much heavier connections to dry land. In the present model, it is likely that induction motor operation will mostly be used for comparatively small amplitude motions. However it is hoped to implement a coil drive system that uses a combination of DC and AC components.



CONCLUSIONS

The free-floating model currently being built should allow the feasibility of the sloped IPS buoy wave energy concept to be established. The incorporation of low friction directly coupled tubular eddy-current dampers within the physical space of the inertia tubes, is made possible by the use of water-fed hydrostatic bearings. The dynamometers should be able to act as motors to drive the model in smaller waves.

ACKNOWLEDGEMENTS

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