2 Looking Back

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'... if you can hear the truth you've spoken twisted by knaves to make a trap for fools ...'

In the autumn of 1973 the western economies were given the rare chance of a ride in a time machine and saw what the world would be like when there was no longer cheap oil. Most people thought it looked rather uncomfortable but a few very powerful people made a great deal of money by exaggerating the crisis. Others, who had previously been regarded as eccentric, increased their efforts to develop what were then called alternative, and are now called renewable, energy sources. Still others set out to destroy what they saw to be a threat.

Waves were only one of many possible sources and there are many possible ways in which waves can be harnessed. There are floats, flaps, ramps, funnels, cylinders, air-bags and liquid pistons. Devices can be at the surface, the sea bed or anywhere between. They can face backwards, forwards, sideways or obliquely and move in heave, surge, sway, pitch and roll. They can use oil, air, water, steam, gearing or electro-magnetics for generation. They make a range of different demands on attachments to the sea bed and connections of power cables. They have a range of methods to survive extreme conditions but perhaps not quite enough.

Their inventors, myself included, invariably claim at first that they are simple and, after experience with the dreadful friction of reality, invariably discover that this is not totally true when they come to test in the correct wave spectra with a Gaussian distribution of wave amplitudes. An easy way to detect beginners is to see if they draw waves the same size on both sides of their device.

Appeals to simplicity are widespread and have a strong appeal to non-engineers and particularly to political decision-makers and investors. But it is hard to find any field of technology which does not get steadily more complicated as it gets faster, lighter, cheaper, more powerful and more efficient. The complications are all introduced for good reasons and, if the necessary hardware is properly researched, will produce good results. Who would abandon railways for wheel barrows because of the smaller number of wheels? Only a simpleton.

Although almost everyone knows which of the devices proposed so far will ultimately prove the best it is not certain that no improvement could be invented. This chapter describes some of the work done on several devices at Edinburgh University in the hope that future generations of wave inventors can save time and avoid mistakes.

2.1 Wave Energy at the University of Edinburgh

Many inventors of wave power devices, going back to Girard père et fils in 1799, start with heaving floats. Apart from a brief flirtation with oscillating water columns (see Chapters 3 and 7), so did I. But I had the advantage of a workshop in which I could make any mechanical or electronic instrument that I was able to design and there was a narrow tank that I could borrow. As so often in physics and engineering, a full understanding of all the energy flows leads to a full understanding of the problem and points to suitable solutions.

It was necessary to make something against which a float could do work that could be accurately measured and compared with the energy transfers from incoming, transmitted and reflected waves. While the Girards proposed the use of a ship of the line, I thought it would initially be cheaper to begin with a length of 100 mm by 25 mm varnished balsa wood, just fitting inside the 300 mm width of a small wave tank. Rotating bearings are much nicer than translating ones. But if they are at the end of a long arm they give a good approximation to a translating constraint. If you grind a 70-degree cone on the end of a length of tool steel and use it to punch the end of a light alloy or brass rod you get a beautiful socket into which you can place a 60-degree conical-point screw with friction acting at a very short radius. Grease will slow, if not stop corrosion long enough for plenty of tests. The first heaving buoy model is sketched in Fig. 2.1a.

For the power measurement I used two very strong bar magnets in a magnetic circuit which excited two coils wound like an oversize galvanometer movement and linked together in a parallelogram using the same spike bearings pulled into cones in the end of a strut by elastic bands. The parallelogram could be coupled to the float with another strut and elastic band. These acted like a universal joint with very low friction and no backlash.

Moving the float generated a nice velocity signal in one of the coils. This could be amplified and fed back to the second coil with polarity chosen so as to oppose the movement. Changing the gain of the amplifier would change the damping coefficient. A high gain made it feel as if it was in very thick honey. If the amplifier feedback connections are such that it delivers an output current proportional to the input voltage, then temperature changes in the galvanometer coils do not change the calibration.

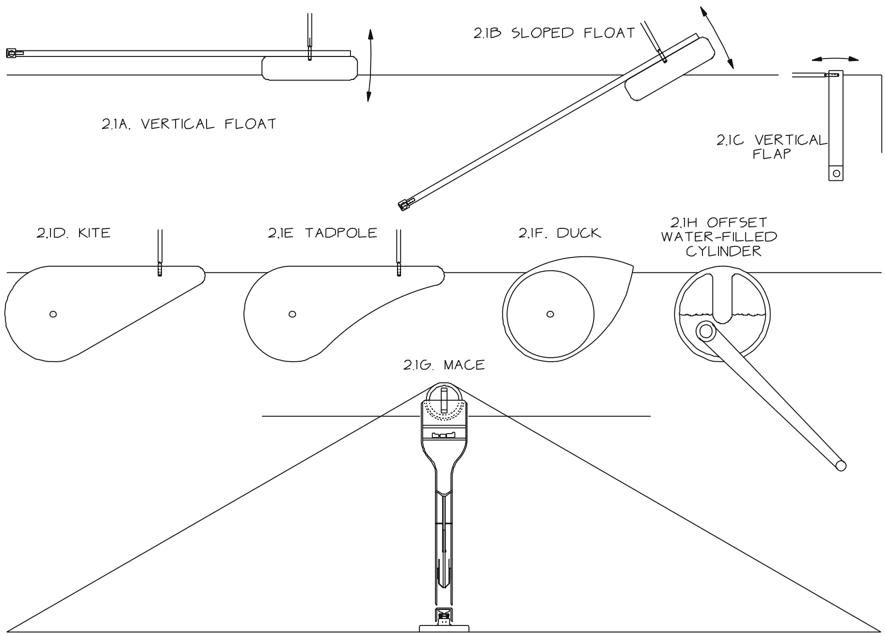


Fig. 2.1. In the beginning was a vertical heaving float...

From calculus we know that the position of an object is the time integral of its velocity history plus some constant. If the signal from the velocity coil is put into an operational amplifier circuit connected as an integrator we get an accurate position. If the parallelogram is moved backwards and forward between the jaws of a Vernier gauge, the integrator output signal will be a square wave. The field-effect transistor operational amplifiers of 1973 had low enough offset currents to allow this position signal to be read on a digital voltmeter. The force was calibrated by making the pushrod drive the pan of a weighing machine.

Measuring the waves could be done with a light float made from expanded polystyrene foam mounted on a swinging arm. A pair of micro-ammeters, coaxial with the linkage bearings, with their needles glued to the float arms, gave a very clean velocity signal from even the smallest waves. Integrating float velocity gave an even cleaner wave-amplitude signal. The float averaged wave measurements across the width of the tank and so was insensitive to cross waves. It could measure waves down to 0.01 *mm* which we could not even see, far less than the meniscus hysteresis of resistive-wire gauges which we later had to use for very steep waves.

To calculate the power you just multiply the instantaneous force signal by the instantaneous velocity signal, which will give you an offset sine wave at twice the wave frequency. You then take a long-term average with a low-pass filter.

This equipment allowed the measurement of model efficiency. The first result for the vertical heaving balsa wood float in Fig. 2.1a was disappointing – only 15 %whatever adjustments were made to the damping coefficient. Some of the energy was reflected but most went straight past the model. However the depth of the hinge was very easy to adjust. If it was pushed down so that the movement was along a slope as in Fig. 2.1b, the performance shot up to 50 %, much higher than most people would have predicted.

A vertical flap hinged below the water as in Fig. 2.1c could also be coupled to the dynamometer. This showed an efficiency of about 40 % with 25 % being transmitted on to the beach and 25 % sent back to the wavemaker. It looked as though the horizontal motion of a wave, which almost all new wave inventors ignore, was better than the vertical one. Despite rich vocabularies of nautical terms we have no word in any language for this movement of a wave.

The borrowed narrow tank had a commercial hinged-flap wavemaker with amplitude set by a crank radius and frequency set by a mechanical variable-speed mechanism. One problem was that there was no way to make mixed seas. But a more serious one was that the drive to the flap was rigidly fixed by the crank eccentricity so that the flap reflected waves just like a rigid vertical cliff. Test tank beaches are not perfect and the first designs of any wave device are likely to reflect a substantial fraction of the incoming waves. It was even worse because the amplitude of a wave created by a hinged flap for a given angular movement depends on the square of the depth of the hinge and this would be increased during the crest of any reflection and reduced during the trough, together with some Doppler shifting. Even if we could not make irregular waves with the spectrum of our choice the tank reflections would make one with a spectrum of their own. Trying to make a regular wave could lead to amplitude variations of three to one.

The vertical flap showed that it was wrong to allow the model to transmit waves behind. Was it possible to make a model with a front but no back? Figure 2.1d shows an attempt, code-named Kite. This showed an efficiency of 70 % and very low onward wave transmission. Figure 2.1e, code-named Tadpole, was meant to allow the circular motion of water particles to continue but had the same result. But waves are very good at sending energy to the next volume of water with almost no loss: the idea of allowing the water motion to continue in the way it would do in the absence of a model was powerful. Could the circular backs of 2.1d and 2.1e be combined with a shape which let the decaying orbital motion of water take place just as it would in the open sea?

I asked a computer-minded PhD student, Peter Buneman, to help while I struggled with a slide rule and drawing board. We converged on the same shape shown in 2.1f, code-named Duck. Its efficiency was measured at 90 %, which even we did not believe despite many calibrations cross-checked by Jim Leishman from the National Engineering Laboratory, Gordon Goodwin from the Department of Energy and Brian Count from the CEGB, then the big English electricity monopoly. Later, photographs by Jamie Taylor in Fig. 2.2 allowed visual proof that the calibrations were correct. It is a one-second exposure of a duck model on a fixed mounting in a narrow tank. The two wires are connections to part of an electromagnetic dynamometer, which is absorbing power. Waves are approaching from the right. Drops of a neutrally buoyant tracer-fluid consisting of a mixture of carbon tetrachloride and xylene with titanium oxide pigment have been injected to show the decaying orbits of wave motion.

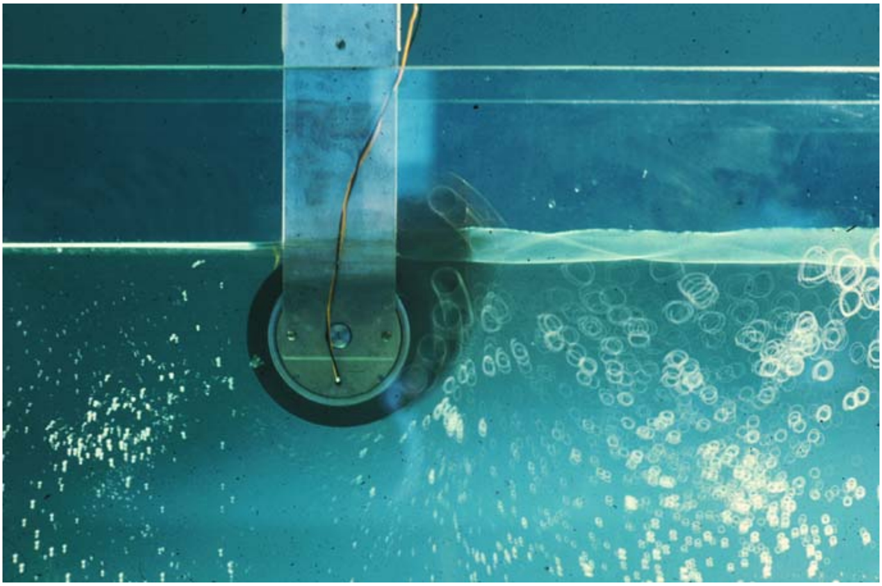


Fig. 2.2. Jamie Taylor's photograph taken in 1976 which convinced people who really knew about waves that high efficiency could be achieved

The amplitude of the incoming waves can be measured from the thickness of the bright band. Nodes and anti-nodes due to the small amount of reflection are evident. However the thickness of the bright band to the left of the model is largely due to the meniscus, as is confirmed by the very small orbits of tracer fluid in this region.

As the energy in a wave is proportional to the square of wave amplitude we can use the photograph to do energy accounting. If nodes and anti-nodes show that the reflected wave is one-fifth of the amplitude of the input it would have one twenty-fifth, or 4 %, of its energy. This means that 96 % has gone into the movement of the test model. The dynamometer showed that just over 90 % of the power in the full width of the tank had been absorbed by the power take-off, leaving 6 % loss through viscous skin friction and vortex shedding. We joked that the rate of improvement might slow because of some impenetrable barrier around 100 %.

One should be careful about such jokes. Johannes Falnes and Kjell Budal in Trondheim had found that point absorbers in wide tanks or the open sea could absorb more energy than was contained in their own geometrical width, just as the signal from a radio aerial does not depend on the wire diameter (Budal and Falnes, 1975). The terms 'capture width' and 'capture width ratio' replaced efficiency for devices in wide tanks. The Falnes Budal findings were simultaneously and independently confirmed by David Evans at Bristol and by Nick Newman and Chiang Mei at MIT.

Because absorbing energy from waves was the whole objective and making waves was very similar to absorbing them, it seemed an obvious step to build a wavemaker with the same control of force and velocity as an absorbing model.

The motors available then had too much brush friction to allow the use of current as a control so a force-sensing strain gauge was built into a drive arm. A tacho-generator measured the velocity. The displacer was the same shape as a duck but with a hollow cylindrical interior to avoid the large vertical buoyancy force. The shape was rather expensive to make in the large numbers planned for a wide tank and later versions used flaps with a textile rolling-seal gusset to maintain a 'front with no back'. Either design allowed the generation of very accurate waves even with 100 % reflecting models and gave repeatability to one or two parts per thousand.

Force-sensing does not suffer the phase lag, 90° at about 8 Hz, of the meniscus of a wire wave-gauge so, with a stiff drive path, high loop gains can be achieved. By using force and velocity to control energy and giving that energy to the water at the right frequency, we allow the water to choose the shape it likes to transmit that energy even if what are called 'evanescent modes' have the wrong waveform close to the wavemaker. The chief design problem is getting rid of any friction that could corrupt the force measurement. Many more absorbing wavemakers have been sold by a spin-off company, Edinburgh Designs, run by Matthew Rea.

The next task was to widen the band of high efficiency and move it to longer wave periods, equivalent to having a smaller device. This was done by Jamie Taylor who used systematic variations of the hub depth, ballast position and power take-off torque for various duck shapes. We built a sliding mounting with a clamp and adjustable stop, which allowed one person to remove and reinstall a model to the exact position using only one hand in three seconds. This is likely to be harder, slower and more expensive at larger scales. The models had tubes running through them into which stainless steel rods of various lengths could be inserted to adjust ballast. They had Aeroflex moving-magnet torque-motors at each end. One gave a velocity signal which could be processed by analogue operational amplifier networks built by David Jeffrey. These could implement variable damping, torque-limiting, positive or negative spring and inertia, indeed any power take-off algorithm we could specify.

Analogue multipliers needed for power calculations can perform a useful job with large input signals. The usual transfer function is 0.1 (A x B). With 10 volts on both inputs giving 10 *V* output, an error of 0.1 *V* is only 1 % and would be tolerable. But if A and B are only 1 *V* the product is 0.1 *V* and the error is 100 %. The solution is to arrange a system of pre-amplifiers and post-attenuators on a double-bank rotary switch before and after the multiplier and manually adjust gain and attenuation so that the two input signals do not quite clip.

To measure waves we used a pair of heaving-floats on mountings which could be clamped to each other at distances of one quarter or three quarters of a wavelength. The pair could slide along ground stainless steel rails aligned parallel to the calm water surface. This rail alignment had been done with a capacitance proximity sensor and fine adjustment screws with everything finally locked by a metal-filled epoxy putty. The sensor was just sensitive enough for us to pretend that the rails followed the curvature of the earth rather than being quite straight. By sliding the pair of gauges to the position which maximised the difference of their outputs we could put one gauge on a node and the other on an anti-node. Half the sum gave the amplitude of the incoming wave and half the difference gave the amplitude of any reflection.

If we set very high damping the model would be locked almost stationary and would reflect nearly all the incoming energy like a cliff with an anti-node at its front surface. If we set the damping to zero it would move violently but still reflect with a node at the front. It was easy to find the best match because David's electronics, described in Jeffrey et al. (1976), could calculate the instantaneous efficiency and Jamie would know immediately if his choice of damping, hub-depth or ballast position was good or bad. He would have accurate measurements after two tank transmission times.

Playing with different damping settings showed that wave devices were like loads on transmission lines which should be matched to the line impedance. A mismatch by a factor of two either way was tolerable but more than this would progressively lose much more output from reflections.

By integrating the velocity signal with a very low drift operational amplifier we could get a good position signal and we could combine either polarity of this with the damping feedback signal to get positive or negative spring. Although this needed a small investment of energy back to the model it was repaid with large interest, widening the efficiency band and moving it to longer waves. Rapid changes with rapid results make for rapid progress. Jamie Taylor pushed the performance band from a peak at a wavelength of four duck diameters to fifteen diameters with creditable performance at twenty-five.

David Jeffrey built two more electronic systems which turned out to be immensely useful and should be copied by others, perhaps using computer graphics. We had nearly sixty signal sources from wave gauges and model which could be sent to thirty signal destinations, such as meters, signal processors and oscilloscope displays. Getting any connections confused could negate an entire experiment and waste days of work. David built a pin-board matrix with signal sources along the top and destinations along the left vertical. Any source could be connected to any destination by the insertion of a pin at the corresponding intersection of row and column. A new experiment could be planned, set up and checked in about a minute with first results a minute later.

The second system was a display of two oscilloscopes. One had a long-persistence phosphor while the second had a storage tube which used electrostatic technology to retain a trace for about an hour. The conventional oscilloscope time-base was replaced by one which was locked to the wavemaker drive frequency. The sweep time was exactly the full wave period but also the start of the trace was always at an upward zero crossing of a wave, the crest always at 25 % of the screen width and the trough always at 75 %. We could also plot any variable against any other.

When the long-persistence tube showed that the tank conditions were steady, the press of a button would write the next trace to the storage tube. The conditions could be changed for the next test and the next trace written. Provided we could finish a series within the tube storage time we could build up families of curves and take a Polaroid photograph such as the ones in Fig. 2.3.

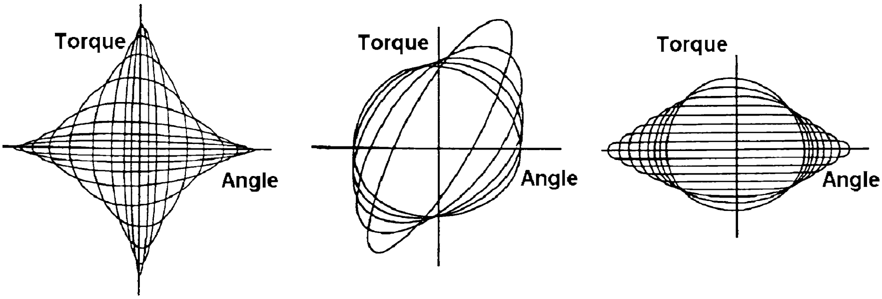


Fig. 2.3. Families of Lissajous plots of duck torque against angle for variable damping, variable amounts of negative spring giving reactive loading and a selection of torque limits. These are from actual oscilloscope photographs of tank models

This shows torque to angle diagrams for variations in damping, torque limit and reactive loading with negative spring. The area inside the loop measures useful work. These are analogous to pressure-volume indicator diagrams for steam engines.

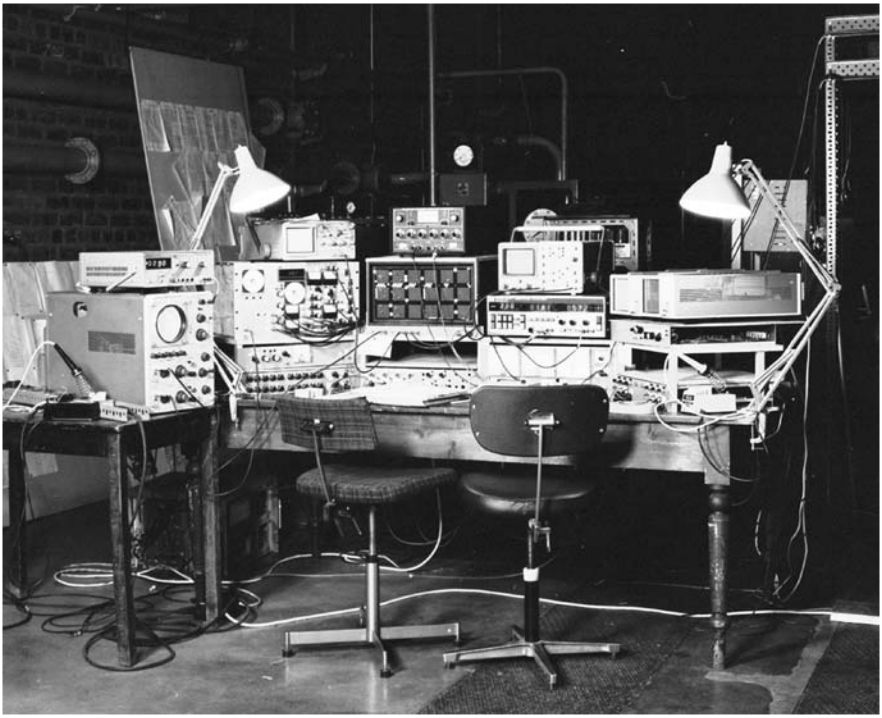


Fig. 2.4. The all-analogue tank-control bench with direct-reading efficiency calculation, pin board, transfer-function analyser and wave-locked pair of oscilloscopes

Another very useful commercial instrument was a transfer-function analyser which combined a very accurate, crystal-locked low-frequency signal generator with two digital voltmeters giving the in-phase and quadrature magnitudes of signals at that frequency or at harmonics of it.

The control desk allowed two people to sit in comfort within reach of every control knob and with eyes at wave level. It is shown in Fig. 2.4. Some people think that this photograph was contrived but this was the actual working setup. Despite enormous advances in digital computing power since 1976 and wonderful data collection and analysis software, I have never since worked with such a fast and convenient tank control system as one using entirely analogue electronics. Glen Keller even built analogue circuitry which allowed to control design features of a gyro power take-off with correct torques fed back to the model in the water.

Until then all data analysis had been performed with the Hewlett Packard HP 65 hand-calculator which had a magnetic strip reader that could store programmes with as many as 64 steps. In order to work with multiple spectra we went to the dreadful expense of £7000 of getting a Tektronix 4051 computer which had an enormous memory of 16 k, a graphics display and even a cassette tape reader for programmes and data. This cost the annual salaries of three research associates but allowed measurements of every possible wave and model signal in realistic wave spectra.

If the large forces from waves are to do useful work there must be some reaction path to oppose them. By now we knew enough about wave forces to realise that providing this with a rigid tower for the largest waves in deep water would be very expensive and we wanted a way in which the structures would never be stressed to any level above that which would arise at their economic power limit. We wanted something that would experience large forces and high relative velocities in small waves but not in large ones.

The only solution for deep water seemed to be a spine long enough to span many wave crests to get stability but with joints that could flex before the bending moments could cause any damage. We needed to know how such an elastic and yielding system would behave. We built the nearest approximation to replicate a spine in a narrow tank. It was a mounting called a pitch-heave-surge rig, shown in Fig. 2.5, which allowed the support stiffness, damping and inertia to be set to any desired value but also to yield at forces above a chosen value. It could also be used to drive a model in calm water to measure the relationship between force and velocity so as to give hydrodynamic coefficients of damping and added mass.

The rig proved to be ideal for testing the Bristol cylinder invented by David Evans (Evans et al., 1979). Whereas we had worked for days to discover the best ballast position and power take-off settings of a new model shape, he was able to calculate directly what the values should be. We already had a 100 *mm* diameter neutrally buoyant cylinder which we had used for force measurements. We set the stiffness and damping to his values and the model achieved almost 100 % efficiency immediately. The Bristol cylinder does this by combining movements in both horizontal and vertical directions so that a long wave, which might be expected to propagate below the cylinder, is cancelled by the wave generated by the cylinder movements. David Evans suggested that this would also be true for our duck system and so it was. The long wave performance could be greatly improved by reducing the mounting stiffness. Fortunately the correct stiffness values were lower than those which could be supplied by post-tensioned concrete at full-scale.

Jamie Taylor explored the effects of mounting stiffness and produced a map with two regions of high efficiency separated by a valley of very low efficiency at a particular heave stiffness. We called this Death Valley. The angular movements of the duck and its movement relative to the water surface could be reduced to almost zero in quite large waves. This could be very convenient for gaining access.

Computers are like bacteria. Once you have one it breeds others at exponentially increasing rates. The Tektronix was joined by a Commodore Pet which could generate seas in which the phases of each component could be combined with cunning malevolence to produce extreme wave events such as those as shown in Fig. 2.5. It could also trigger flash photographs at any time with microsecond precision. The force records against time in Fig. 2.6 and as heave against surge forces in Fig. 2.7 are the result of freak waves hitting the model placed at a series of positions relative to the nominal break point. It was a surprise to discover that there was a strong downward and seaward tendency, that the most dramatic production of white water could occur with quite low forces and that the peak force occurred during the second trough following the instant of wave breaking. We clocked up half a million years worth of hundred-year waves. Any developer who does not follow this path does not deserve insurance but will certainly need it badly.

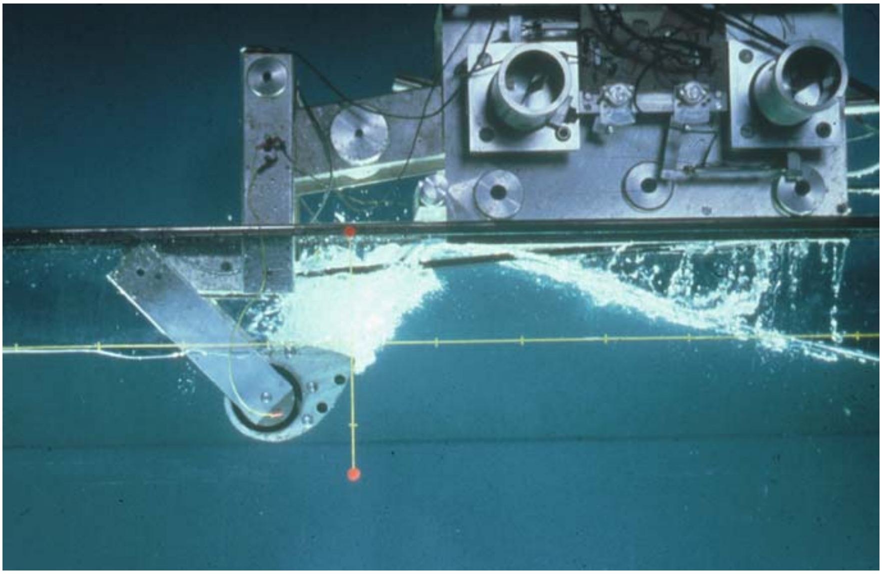


Fig. 2.5. The hundred year wave with maximum possible steepness achieved by selection of the phases of a mixed sea hitting a duck on a locked pitch-heave-surge rig

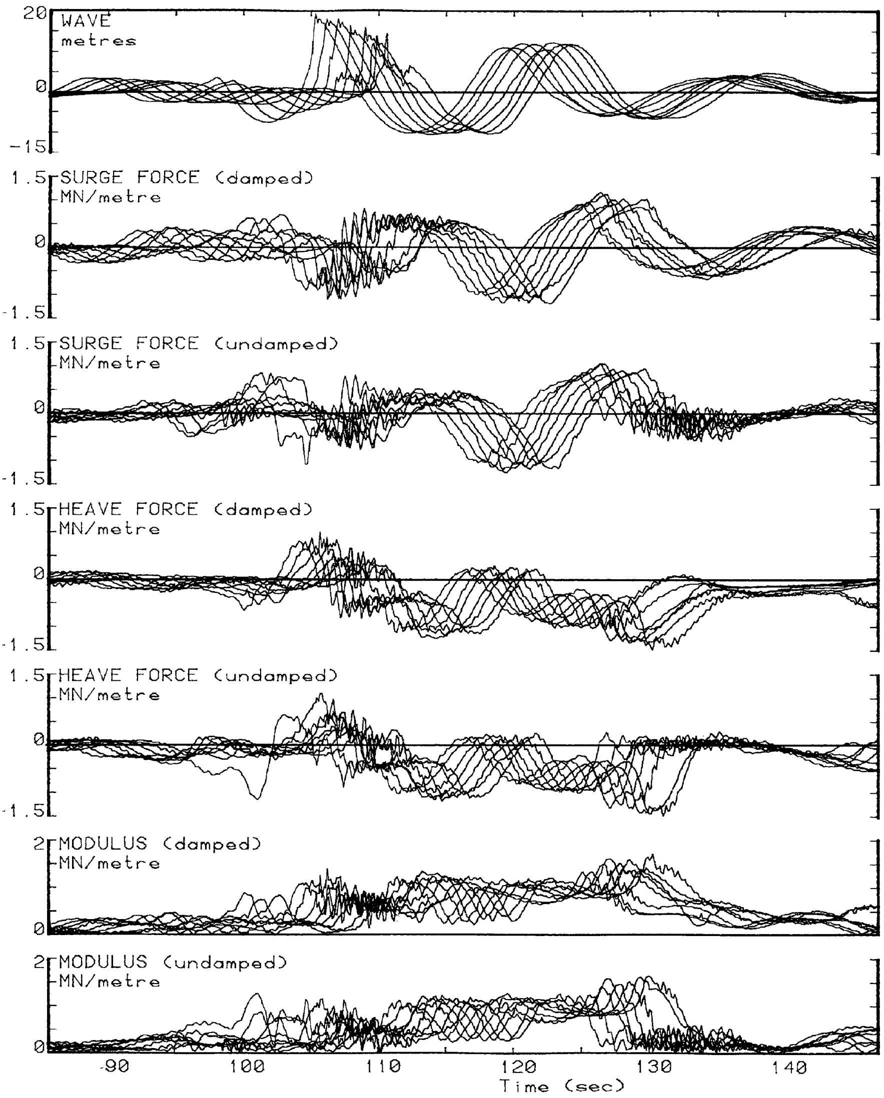


Fig. 2.6. The superposition of a set of time series records of the forces during a freak wave on a duck on a rigid mounting. The records are taken with the model axis at each of the vertical tick points along the water line. Note the downward forces and the larger total force at 130 seconds – long after the nominal break. ‘Damped’ means the normal operation of the duck power take-off which had rather little effect in such large waves. Half the testing was done with none

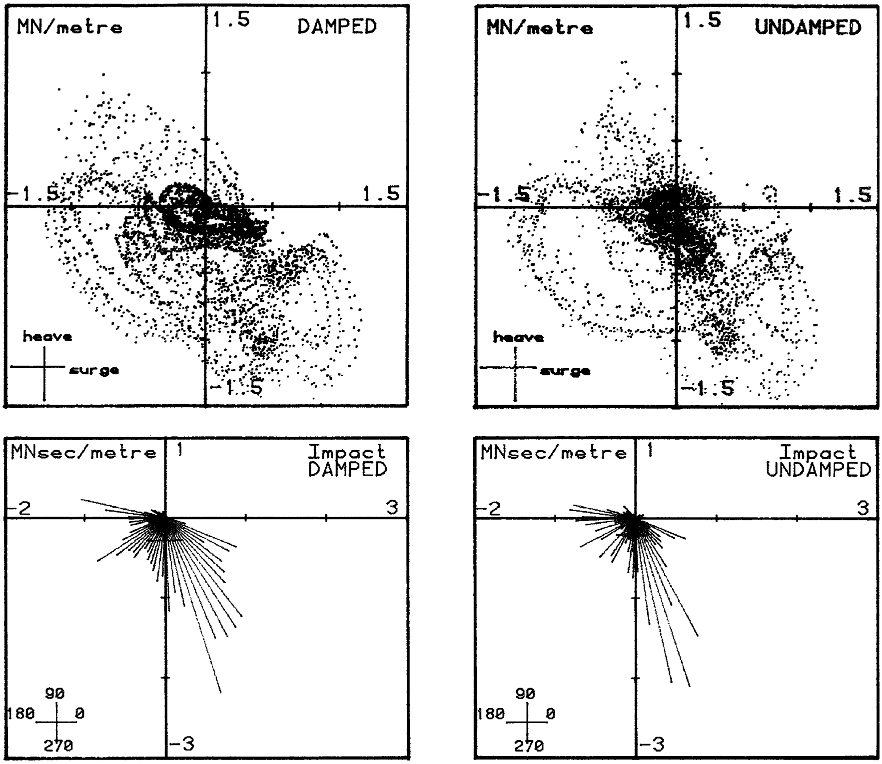


Fig. 2.7. Lissajous plots of the vertical heave forces plotted against surge forces. Note the low upward and forward force

There were always anxieties about whether results from small models at around 1:100 scale could apply to full-scale but the leading experts assured us that we were just clear of the scale where surface tension becomes a significant restoring force and insects can walk on water. We did hire a 1:10 scale tank for a week. The results were within 2 % of our narrow tank ones but while you could lift a 1:100 scale model with one hand and make it in a day, dropping a 1:10 scale model could easily kill somebody. The 1:10 scale tank took twenty minutes instead of forty seconds to settle. Everything was far slower and more expensive but, for shapes like those of most wave devices, no more accurate.

The results of the work with the pitch-heave-surge rig were convincing enough to justify building a wide tank to test long-spine models. This had to be designed backwards from £100,000, the maximum amount of money which could be authorised by the programme manager, Clive Grove-Palmer, without going to a superior committee which had a member who was certain to oppose it. We got the go signal on 1 June 1977.

Meeting the cost was made possible only by the purchase of 120 scrapped printed-motors which had been stripped out of ancient IBM disk drives. Some of the armatures had been overheated and had come unglued. Opening the case to re-glue them broke the magnetic path and destroyed the magnetisation of the alnico disks which energised the gap. Each of these magnets was wrapped by one and a half turns of wire leading to terminals outside the case. We calculated that it needed a current pulse of $7000\,A$ for one millisecond to reset the magnets but that a pulse of $10\,ms$ would melt the wire. The resetting of the magnets was done by Glen Keller but the method he used has been removed from this contribution for fear of prosecution by the Health and Safety Executive. He recovered over 100 good motors, most of which are working still, thirty years later.

While the tank building was being put up we built the wavemakers and drive electronics with the help of students and school leavers, many of whom are now successful engineers. Filling with water was complete on 1 January 1978. The electronics for 89 wavemakers and the drive software were debugged in two weeks and a rival wave power team began testing on 1 February 1978. A second tank with 60 identical wavemakers was built near Southampton and soon both were working 24 hour shifts. An even bigger one with flatteringly similar but very much bigger wavemakers was built in Trondheim. It took us 18 months to get money to build duck models to test in our wide tank because politics had reared its ugly head.

2.1.1 Politics

To understand any research programmes you must understand money flow. Money for wave energy came from several sources. Firstly there were the pockets of private inventors with enough confidence in themselves and their devices to spend their own money rather than other people's. Secondly there were firms who are risking some of their shareholders money. Thirdly there were the Foundations such as Nuffield and Wolfson. Fourthly there was the Science Research Council, now renamed the Engineering and Physical Sciences Research Council. Largest of all were the Government Departments, initially the Department of Industry, later the Department of Energy and now the Department of Trade and Industry. Usually devices with promise were taken over by the Department of Energy when it appeared that more substantial amounts of money were needed. While private sources of money enjoy flexibility, the Department of Energy was and is locked into the timing of the Treasury Financial Year which begins in April.

The Department of Energy had a better chance of defending its decisions if they had been supported by advice from outside and so there existed a committee known as ACORD. This stands for the Advisory Council on Research and Development (in the fuel and power industries). It gave advice on fission, fusion, oil, gas, coal, tidal, geothermal, wind, hydro and wave power, and, one also hopes, conservation. As it met quarterly and as its membership was selected from the busiest, most senior experts, one can readily calculate how much time could have been devoted to any one topic.

ACORD did not suggest programmes or experiments. It passed opinions on those submitted to it by the Wave Energy Steering Committee, or WESC. This met at monthly intervals and dealt solely with waves. But its members were all fully employed in other fields and so received advice from six separate advisory groups, specialising on technical aspects, and two groups of consultants: Rendel Palmer and Tritton, on marine and civil aspects, and Kennedy and Donkin on electrical problems. These consultants worked closely with one another and became abbreviated to RPT and K and D, or “the consultants’. They could assign people to work full-time on assessing proposed designs and visited the device teams regularly. Their mandate was to provide professional criticism, to spot flaws in the arguments and mistakes in the calculations of the starry-eyed enthusiasts in the laboratories. We had to fight hard for every milliwatt against people paid to act the part of pessimistic misers who gave us no benefit of any doubts. This meant that the consultants’ opinion would always reflect a maximum price and a minimum resource size. The distinction between proven and probable reserves of oil is relevant. I do not know whether our comrades in the other renewable energy fields have ever been subjected to such hard-nosed scrutiny, but it would have been very good for improving design.

The day-to-day administration of the programme was carried out by the Energy Technology Support Unit (ETSU) at Harwell, part of the UK Atomic Energy Authority which controlled research into all the renewable sources. The Programme Manager had a number of Project Officers who actually visited the laboratories. They helped device teams shape research proposals, they monitored progress and they approved claims for expenditure.

Six Technical Advisory Groups (abbreviated TAGS) dealt with the assessment of new devices, the acquisition of wave data, the measurement and calculations of fluid loading, the problems of mooring, the problems of generation and transmission and finally the subject of environmental impact, which seemed to be the very least of our difficulties. There were somewhere between six and nine rungs in the ladder between the men in the laboratory and the men with the money and power.

The financial year

The cycle of events began with the Treasury Financial Year in April. There had to be time for the Department of Energy officials to consider the ACORD advice and for ACORD to approve its own minutes. This meant that the advice must be given at an ACORD meeting in February. The proposals put forward to ACORD had to be discussed by one meeting of WESC and modified for approval by a second. This meant that WESC must have all the information it needed in early December. The most important piece of information required was the report by the Consultants. If they worked flat out they could finalise reports on a number of devices in about a month, but this meant that they must bring down the chopper on the work of the device teams by the beginning of November. Everything they saw was a flash photograph of the position in October. There is no chance of a device team saying “There. It is finished. Nothing can improve it. We have spoken.” The drawings and graphs carried long streaks as the paper was wrenched from beneath their pencils at 23.59 on October 31st.

After April the Department of Energy would tell the Programme Manager how much he would have to spend. This would be unlikely to be the same as the amount he wanted and so he would have to talk with device teams, Project Officers, Consultants and TAGS and arrive at a new revised programme. If he worked with the tireless devotion for which programme managers are selected he might have this done by the end of May, ready for discussions by WESC in June and for modifications and re-approval in July. The sums of money involved exceeded the amount which could be authorised without signature by officials of the Department of Energy, who are of course on holiday in August. But when they returned in September it took no time at all to authorise and issue the formal contracts from the Harwell contracts branch. It was just possible to get one out by mid October, leaving two weeks for the ordering of equipment and the recruitment if not the training of staff before the consultants' axe descended. A single hiccup in any part of the procedure could make the official working time go negative and often did. When the contracts arrived they could be amazingly complicated. In one the work programme was split into four time periods and four different work topics giving sixteen different pots of money and no certainty that it could be transferred between them.

The delays in issuing contracts were matched only by the delays in paying for the work done. Harwell had a rule that if there was any irregularity in an invoice sent by a contractor, all subsequent invoices would be blocked until the matter had been cleared up. I can quite see that this would be a good way to encourage contractors to avoid irregularities. However there was no obligation on Harwell to tell the contractor the nature of the irregularity. All we knew was that the cheque was not in the post. In 1979 the Atomic Energy Authority set up an account to pay for feeding members of its committees including the Wave Energy Steering Committee but did not trouble to tell me anything about it or the numbers to use. I went on paying for their lunches from my research grant as before. In 1980, when UK annual inflation rate was 18 % and a senior University researcher was paid £12,000 a year, the backlog in payments reached nearly half a million pounds, all because of a lunch bill for £25 had the wrong account number.

Eventually, in desperation, I told Harwell payments branch that I would have to get help from the University Rector. In England the word 'rector' means a slightly senior vicar or parish priest and no doubt the Harwell payments branch imagined that I would be seeking tea and sympathy. But in Scottish universities the Rector is elected by the students to defend their interests. He also defends those of research staff. While students from some unmentionable universities have tried to elect a pig as their rector, Edinburgh students have much higher standards and former holders of the post include Gladstone, Lloyd George, Baldwin and Churchill and Gordon Brown. In 1982 our Rector was David Steel, then leader of the Liberal party when the Liberal SDP Alliance was on the rise. When this became known by the Atomic Energy Authority, the problems of getting paid vanished over a weekend like the morning dew.

Jumping the gun

The traditional, and sound, engineering approach for many projects has been to measure or calculate all the loads on a structure before finishing the design and then to make a series of design modifications in the light of cost calculations before arriving at the final optimised result. But politicians and investors want to know the bottom line before making any initial investment and are in a position to enforce their wishes for continuous assessment and early Figures for the cost of electricity. This is very much like people wanting to know the winning horse before placing a bet.

Work on the full-scale design was carried out long before we knew enough about bending moments and mooring forces. We had help from the big civil engineering company Laing, who taught us lots about the advantages of post-tensioned concrete in sea water. The first power take-off was based on getting a torque reaction from a pair of gyros spinning in opposite directions. If they were allowed to precess freely they would lock a frame against which a ring-cam pump could do useful work. Two advantages were that the gyros could also be used as flywheels to store energy for tens of minutes and that everything was hermetically sealed in a super clean vacuum. The disadvantage was that the full duck torque had to go as a radial load through high speed gyro bearings. Robert Clerk designed some amazingly efficient hydrostatic ones with active impedances and fine clearances despite large deflections.

The choice of a gyro reference frame called for new types of hydrostatic bearing (Salter, 1982). Digital control had profound effects of the design of high pressure oil pumps and motors (Salter, 1984; 2005). We tried to design for the level of technology which would be available at the time that the energy crisis really hit, rather than for things that would be obsolete by then. Many of the ideas, such as the use of microchips to change mechanical design, seemed wild at the time and were questioned by people responsible for power generation issues. All were outside the field of the civil and heavy electrical engineers who were employed to assess our work. Accordingly the task of assessing ducks was transferred from Rendell Palmer and Tritton to an outside consultant Gordon Senior. He subjected us to a sharper scrutiny than the civil engineers, who had missed a serious mistake we had made with the 1979 reference design. He checked calculations, quotations and data from tank experiments. His questions and comments were a great help in improving the design.

The consultants had to consider many sorts of data. There were the heights, spectral shapes and angular distributions of the raw wave input. There was the hydrodynamic performance of the devices. There was the conversion efficiency of the mechanism used for generating electricity, collecting it and transmitting it ashore. There was the reliability of the overall system. There was the capital cost of building yards and of the devices and transmission cables. There was the rate of interest charged for the loans. There were charges for installing the devices and charges for maintenance. Finally there was the ultimate life. Some of these data are well known. Some can be measured by experiment. Some have to be guessed. Some are unalterable. Some can be changed by better understanding or more intelligent design. Many can be misinterpreted through accident, malevolence or enthusiasm. Some remain unknown. If input data are false, no amount of subsequent processing can improve the conclusion. But it has always been necessary to decide policy with imperfect assumptions. With skill and luck some of the mistakes cancel others. The history of official cost predictions up to 1982 is shown in Fig. 2.8.

The accounts of the Central Electricity Board for 1979–80 showed that generation from oil was 6.63 pence, coal was 3.35 pence and nuclear 2.2 pence per kilowatt hour. We now know that this latter Figure could not have included the correct amount (£90 billion) for waste disposal and decommissioning but, at the time, this cost of nuclear was accepted as gospel truth. Even so the gap between waves and conventional sources was closing and the trend of cost reductions made us confident of further ones.

Our confidence was misplaced. It was on the basis of this information that the ACORD committee recommended the closure of the wave programme at their meeting of 19 March 1982, a meeting from which Clive Grove-Palmer was excluded. He resigned as programme manager. The Consultants 1981 report had been circulated in draft but withdrawn from publication. The report that they released in June 1983 showed that ACORD had been very wise to recommend closure.

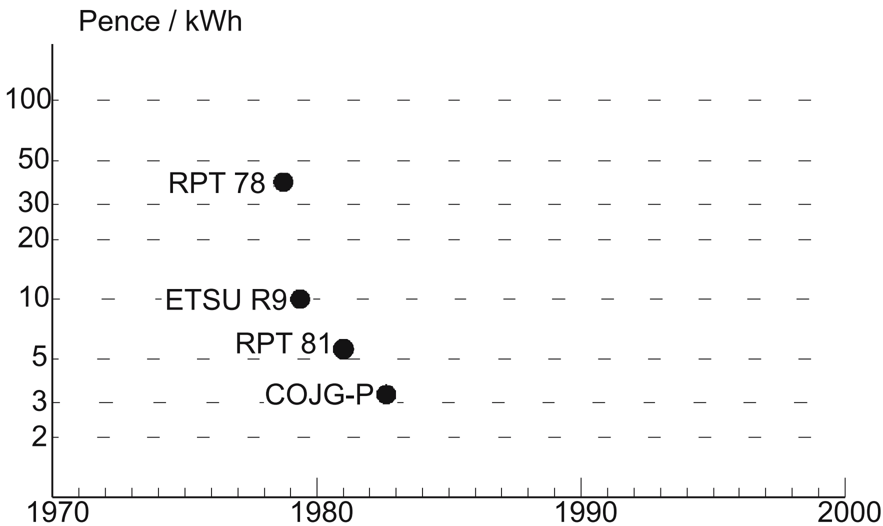


Fig. 2.8. Official electricity costs for spine-based ducks during the first part of the UK wave energy programme from Rendel Palmer and Tritton, the Energy Technology Support Unit and the programme manager, Clive Grove-Palmer, whose Figure was based on final development

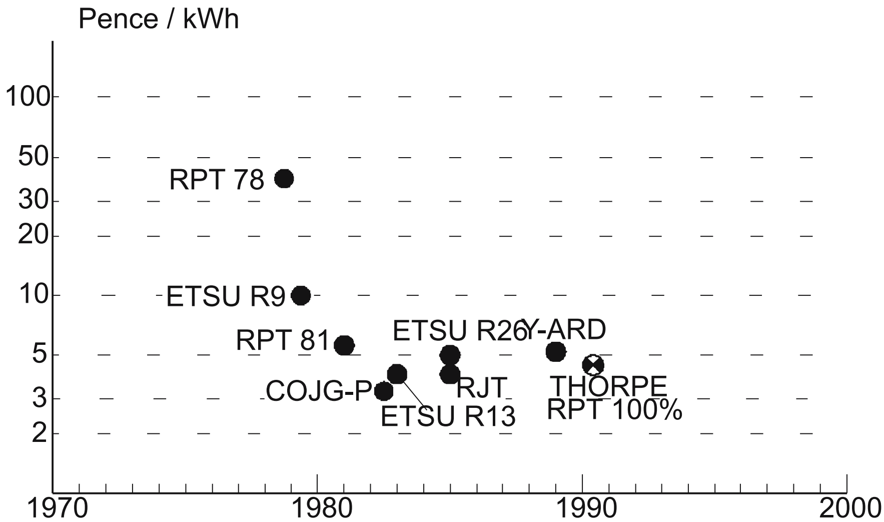


Fig. 2.9. Official cost predictions for spine-based ducks except for an infinite one resulting from the cable failures. The 2007 payments in Portugal are about 16 pence

Many arguments followed such as whether the cost per tonne of steel work for anchors of a wave device really was three to five times higher than that of a Colchester Magnum Lathe. There was also the problem that Harwell's cost estimating consultants insisted that the cost of a stack of very big steel washers with a weight of 100 tonnes had to be based on navigation gyros. The cost predictions from this series of re-estimates are drawn in Fig. 2.9 again in the money values of the date concerned.

But the real killer for deep water devices like the duck was the values used for reliability and, in particular, the failure rates of marine cables. In an early consultants report (Clark, 1980) they suggested a cable survival rate of 333 kilometre years of operation per fault. But in the final report (Clark, 1983) this was reduced to just 10 kilometre years. This was much worse than the data from the North of Scotland Hydro Electric board who operated 80 undersea cables some of which had never failed since installation in the 'thirties. It was far worse than the then Figure of 625 kilometre years per fault of the large Norwegian marine cable network which was easily available.

By an ironic stroke of fate in the summer of 1982, at the very time that the Consultants were adjusting their numbers, a cable was laid from the mainland across the Pentland Firth to Orkney. Its length was 43 kilometres and so by June 2007 it had achieved more than 1000 kilometre years in similar waves and much worse currents.

Gordon Senior reported to a House of Lord Select Committee that somebody in the Rendel Palmer and Triton office had reversed what he had written about Duck technology (Senior, 1988). The reversals even included the insertion of the word NOT in the middle of one of his sentences. Strenuous but unsuccessful actions had been taken to prevent him discovering the changes. The correspondence can be downloaded from http://www.see.ed.ac.uk/~ies/.

2.1.2 Life after politics

During the delay in getting money for a proper wide tank model we tested bits of plastic drain pipe and learned that spanning wave crests was indeed a good way to get a stable reference. We also found that long, free-floating, low freeboard spines would move gracefully out to sea when waves began to break over them instead of ending up on the beach and that they liked to lie beam-on rather than head-on to waves.

The model we did eventually get to build had electronic control of stiffness and limiting bending moment at the joints and realistic power take-off for each duck. Figure 2.10 shows David Jeffrey with the set of spine joints and Fig. 2.11 the model in the tank. But by this time we were told by Harwell that we were not to do any duck tests and to merely confine ourselves to ‘generic spine research’.

We found that bending moments were highest about half a crest length in from each end of a very long spine, rather than in the middle. There were also some interesting results with some oblique sea states inducing very large bending mo-

Fig. 2.10. David Jeffrey with the complete spine model. Beam elasticity could be varied electronically from the control bench. Two illicit generic absorbers can be seen, lower left

ments at the down-wave end. The reason was revealed when Jamie Taylor plotted results of bending moments in the same matrix format as a ‘pox-plot’ diagram which showed the distribution of period and angle in the 46 sea states selected for testing all UK wave devices (Taylor, 1984).

In Fig. 2.12 upper, each sea has been represented by 75 points carrying equal energy. One coordinate of a point represents the period of the energy from zero to 20 *s*. The other represents the angle from which it comes as ‘hindcast’ by the Institute of Oceanographic Sciences from knowledge of weather systems at the time. In Fig. 2.12 lower we can see the surge and heave bending moments along the spine for a 46 joint model with joint stiffness set to 1000 *Nm/rad*, model scale. The surge bending moment is always larger than the heave. The high down-wave bending moments are evident in sea-states 220, 360, 366 and 371 with their obvious cause in the corresponding pox plots. The build-up occurs when the propagation velocity of the flexure wave along the spine coincides with the velocity of the wave crest which causes it. As the flexure wave is a function of joint stiffness, which is under our control, it is not a cause for concern and can indeed be turned to advantage as in Pelamis. The largest credible wave at the most sensitive joint produced a deflection angle of only 4 degrees giving the full-scale design a factor of safety of three. Measurements of the fatigue bending angles showed that we had a factor of 400 relative to cable bending tests carried out by Pirelli.

Despite the official Atomic Energy Authority ban on testing ducks, careless management and an unfortunate breakdown of internal communications meant that some ducks were in fact tested with proper moorings and a realistic power take-off. The performance was in line with what had been predicted from the narrow tank models at the time that the long spine models had been designed. It was a surprise that a fault in one duck could not be detected in the total power generation of a group of them because the neighbours teamed up to help. The group also produced an efficiency of 25 % based on the spine length when the waves ran directly parallel to it.

Work had continued in the narrow tank. We found that sharp corners shed far more energy in vortex shedding than we expected. We found that the benefits of negative spring could be achieved without reverse power flow. Henry Young developed an iterative learning program that today would be called a genetic algorithm (Young, 1982). It started with Jamie’s best settings and then ran the same pseudo-random sea repeatedly with slight random changes to the power take-off and mount stiffness, keeping the good changes and abandoning the bad ones. Overnight Henry’s model could ‘learn’ to increase performance by as much as 20 %. It was clear that improvements to control strategy would never cease and that the power take-off hardware would have to be compatible with unforeseen future improvements. Figure 2.13 shows his results.

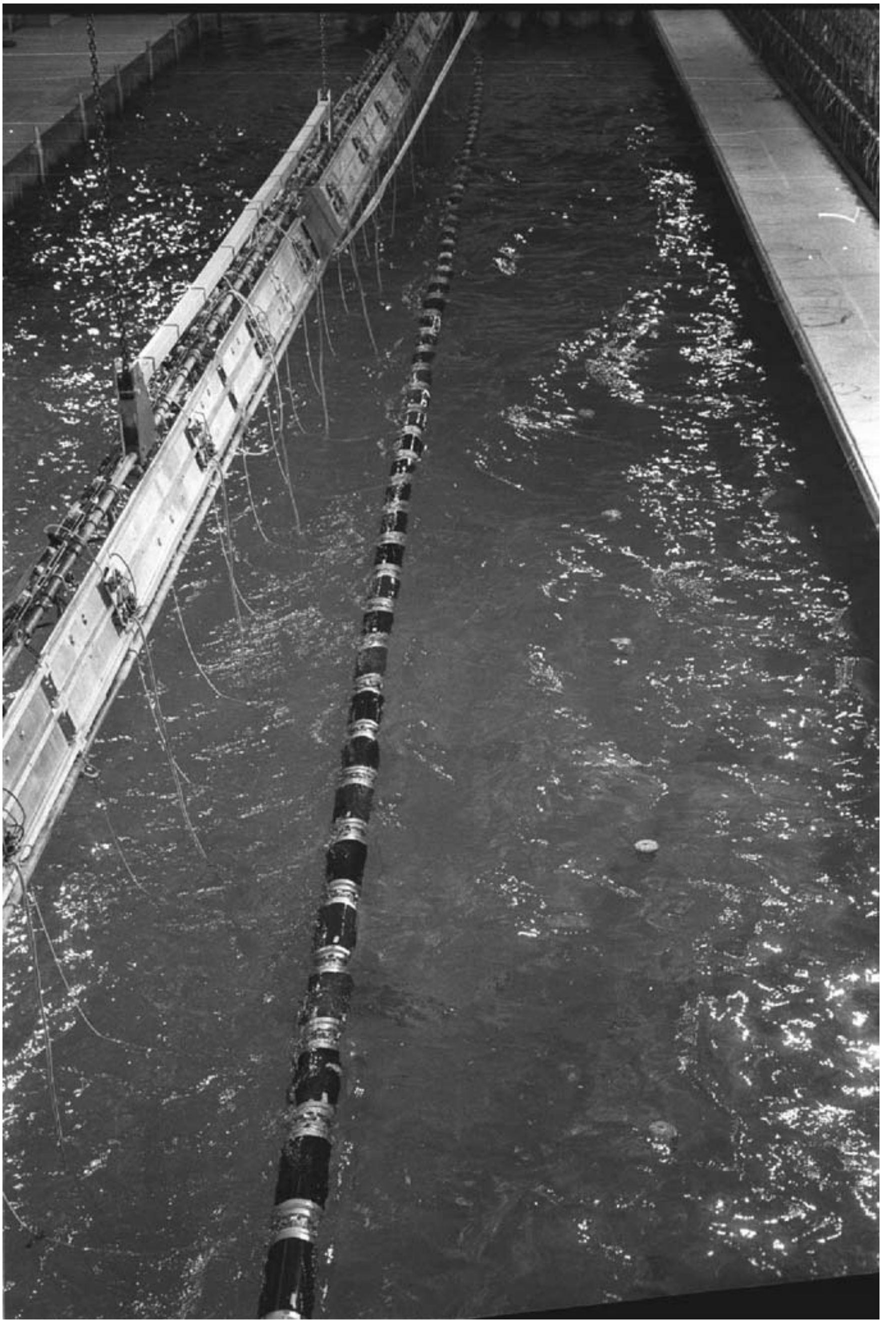


Fig. 2.11. The long spine model on the wide tank. The dynamics of each joint had electronic control of stiffness, damping and yielding bending moment with measurement of bending moment and joint angle

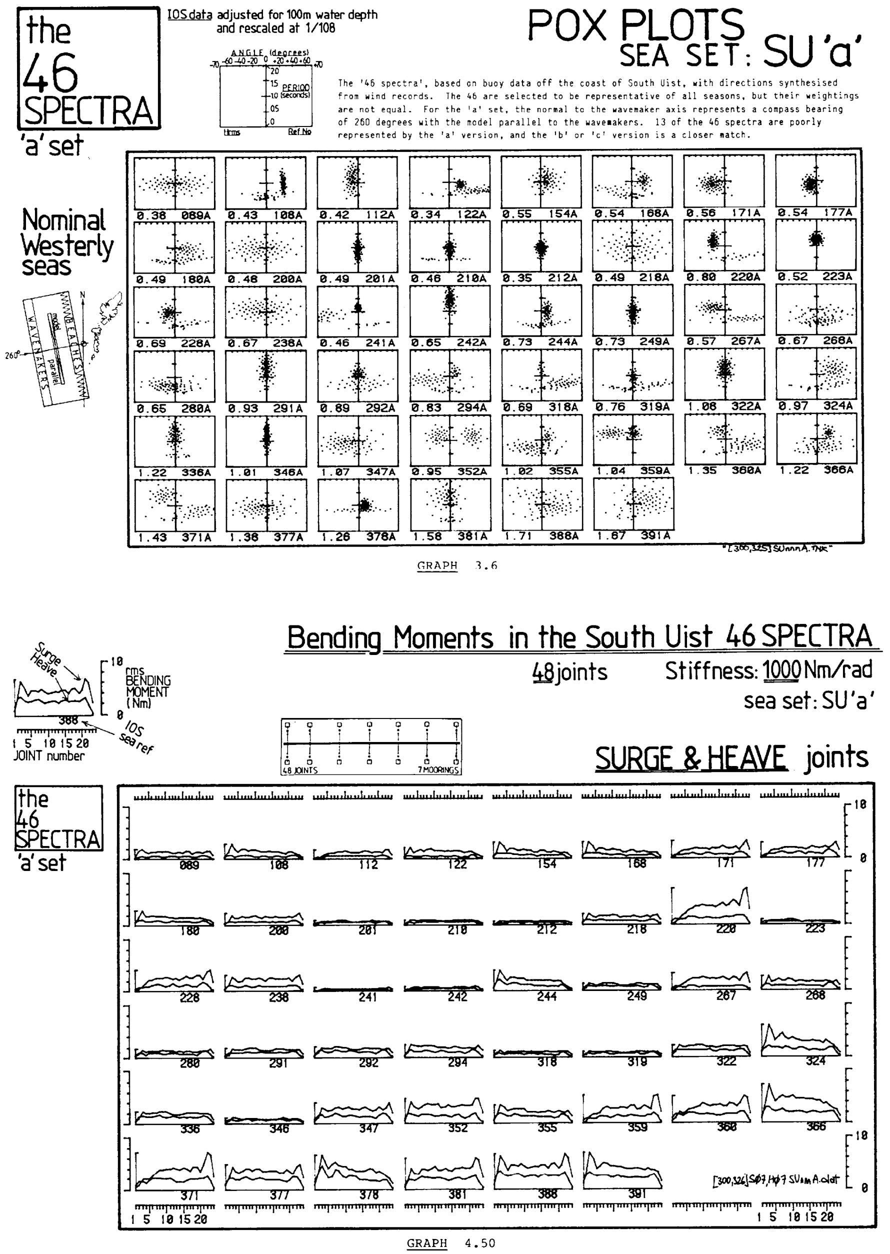


Fig. 2.12. Top: shows a pox-plot of the 46 sea states. Lower: resulting bending moments

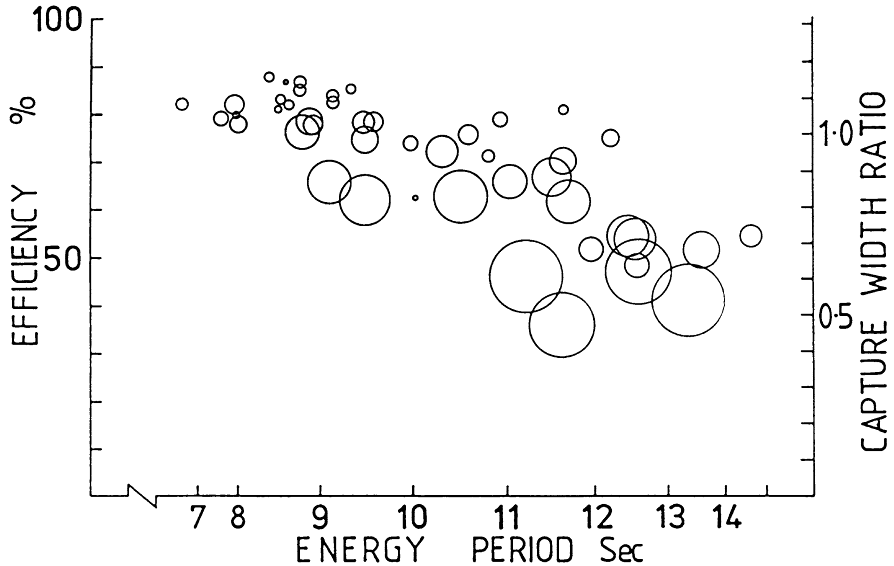


Fig. 2.13. Henry Young's narrow tank results for duck efficiency in the 46 sea states specified for the UK programme. Circle diameter is proportional to output power with the effects of torque and power limits showing in the largest seas. The period axis has been stretched to reflect the energy content of the Atlantic South Uist wave climate with clipping of any sea states above 100 *kW/m*. Harwell reported to the UK Department of Energy that 'efficiency of wave plant was typically 40 %.'

However it was by then clear that the Edinburgh strict adherence to the UK target of designing a 2000 *MW* power station as a first step was a serious political mistake and certain to make ducks appear far too risky to investors. To get adequate stability from a crest-spanning spine needed an initial installation of at least ten units with a power rating of 60 *MW*. In contrast the wind industry had started with units of a few kilowatt and most other countries were building wave devices of a few hundred kilowatt. While Johannes Falnes had frequently urged very small devices in large numbers spaced well apart, I lived in a country with much less per capita sea front than Norway and wanted to use every millimetre to best advantage. While this might eventually be the right way, in 1983 it was as wrong as giving Bleriot the specifications for a Boeing 747. We wanted to build smaller systems of solo ducks, or even just parts of solo ducks to build confidence.

David Skyner moved the pitch-heave-surge rig to the wide tank and achieved capture widths of 1.8 for most of the useful Atlantic spectrum with a scale model of a 10 *m* diameter unit (Skyner, 1987). However, for the first time we were facing forces with nothing like spine bending to limit them and the tension-leg moorings of the solo duck showed nasty snatching if ever they went slack and then retightened. We badly needed a small system to build confidence in components even if it was nothing like a duck.

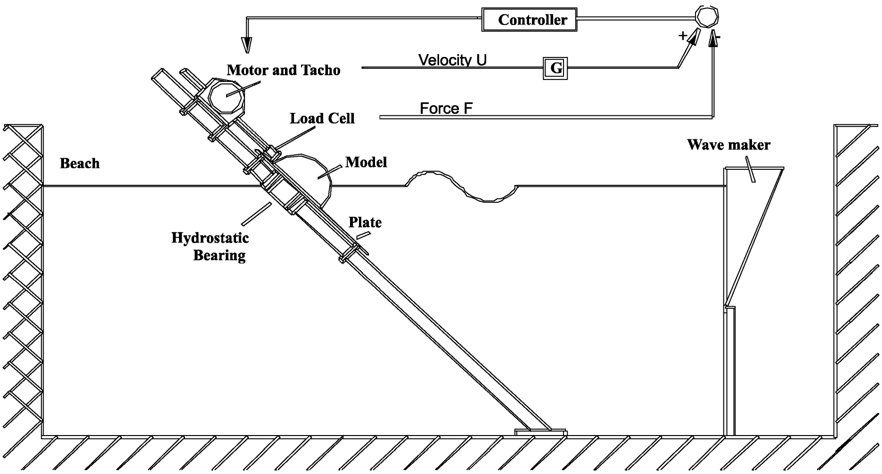
The next attempt was the Mace, Fig. 2.1 g, a vertical, inverted pendulum meant for testing ring-cam power take-off and driven through tapes wound round the cam leading down to sea bed attachments. It had a very wide but rather low efficiency band at much longer wave periods than any heaving buoy but extraordinary survival features and no need for end stops.

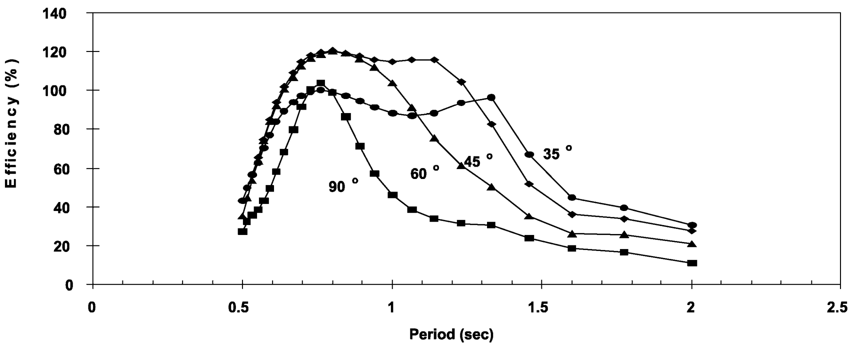
If buoys moving vertically were too stiff and flaps moving horizontally not stiff enough, it was interesting to ask if movement along a slope direction would be a happy compromise. David Pizer used his own numerical prediction software to show that this indeed was so for a wide range of device shapes (Pizer, 1994). My phobia about translations and end-stops in wave devices was reduced by the stroke-limiting feature of the Swedish IPS buoy.

Chia-Po Lin built a test rig to find out how a sloped version would behave (Salter and Lin, 1995; Lin, 1999). He used a half cylinder to avoid rear transmission of waves as shown in Fig. 2.14. He supported it on a straight slide with water-fed hydrostatic bearings and was easily able to adjust the slope of the slide. He drove it in calm water to measure the hydrodynamic coefficients and used these to draw theoretical efficiency curves for a selection of slope angles as shown in the middle graph and then confirmed them with true power generation.

The 45-degree prediction shows a capture width ratio above unity for a two-to-one range of period, so wide that we would not really need to vary the slope to suit changes in wave spectrum. The results are in agreement with experimental ones as shown the lower graph. It is clear that that movement along a slope increases efficiency and widens the efficiency band in both directions but especially towards longer periods. It is not easy to make sloped slides at full-scale and our attempts to make a free-floating one stabilised by an inertia plate have not so far been as good. But it is clear that water displacement in the slope direction, as shown in the 1973 models which led to the duck, make for good wave devices.

The change from testing in regular waves to more realistic irregular ones with a Gaussian distribution of wave amplitudes is an unpleasant experience for wave inventors. The power signal is the square of the Gaussian distribution with frightening peaks of energy which are determined to go somewhere but are totally incompatible with electrical grids. It was clear that storing energy for about 100 *s* would make the output much more acceptable. The only way to do this and still retain intelligent power take-off seemed to be with high pressure oil hydraulics. But the designs then on the market were too low in power rating, too low in efficiency especially at part load and were bad at combining energy flows from multiple uncorrelated sources. We did a rigorous energy analysis of every loss mechanism and ended up with a design using digital control of displacement with electro-magnetically controlled poppet-valves on each chamber (Salter and Rampen, 1993). It did for hydraulics what the thyristor and switching-mode control have done for electronics. It allowed us to move away from swash-plate and port-faces in an axial configuration to a radial one with eight or even more separate machines on a common shaft, some motoring, some pumping and some idling all under the control of a microcomputer costing a few euros. Figure 2.15 shows the design. There has also been work on ring cam pumps for absorbing the very high torques at low speeds needed for wind turbines and tidal stream generators, (Salter, 1984; 1988).





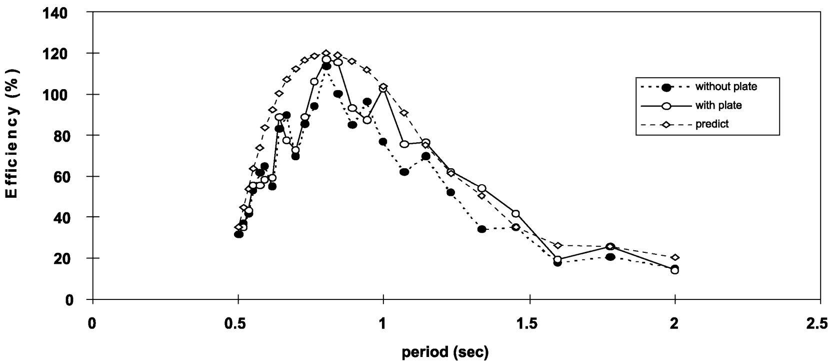


Fig. 2.14. Chia-Po Lin's results for a half cylinder moving on a fixed slope. Top, model set-up. Centre, efficiency from hydrodynamic coefficients. Bottom, measured efficiency at 60-degrees

There is now a growing need for flexible control and high part-load efficiency in vehicle transmissions and suspensions and it turned out to be possible to fund development by work on machines for the motor industry. A good regenerative braking system could reduce urban fuel consumption and pollution by 30 %.This development is being carried out by Artemis Intelligent Power, who hope to increase sizes to suit wind and tidal-stream generation as well as waves.

While the new digital hydraulics was being developed it seemed interesting to investigate a device which would inherently give the ideal torque proportional to velocity but deliver an output which in some places could be even more valuable than energy. The result was a desalination device using vapour compression rather than the normal reverse osmosis (Salter, 2005; Cruz and Salter, 2006). Figure 2.1h shows the arrangement. A plain cylinder which can rotate about an offset axis has a vertical partition and is half filled with water. The inertia of the water makes it tend to stay fixed. Movements of the cylinder about the offset axis will vary the volumes either side of the partition so that they become enormous double-acting pumps but with no machined parts. The pump chambers are full of steam and the movements suck and then compress it from and then to opposite sides of a large heat transfer surface contained in the partition. The result is two or three thousand cubic metres of pharmaceutically pure water a day in a tropical wave climate. A cross-section view showing internal details is given in Fig. 2.16. Figure 2.17 shows a 1/30 scale model under test pumping air through a blanket instead of steam in an out of a heat exchanger.

Whales and elephants do not need fur coats or wet suits because objects of that size and shape lose heat very slowly. With a metre of foam concrete for thermal insulation, the desalination system will cool at only 4º*C* per month. With a heat exchanger to transfer heat from the outgoing to the incoming flows, and all the heat from internal fluid movements tending to raise the temperature, we have to be careful not to overheat.

The main application will be in places with severe water problems which usually do not have such large waves as the Scottish Atlantic climate. However this is the first Edinburgh device to have a stiff mooring and so we are extremely concerned about peak loads. One possible approach is to allow the hull or legs to fill with water if severe weather is expected and lower the system below wave action. Many sites have sandy sea beds and it may be possible to use a combination of water jetting to sink a tripod anchor into the sand and then suction to consolidate it. This would mean that deployment and recovery could be done from light inflatable work boats with water pumps and air compressors but no heavy lifting gear.

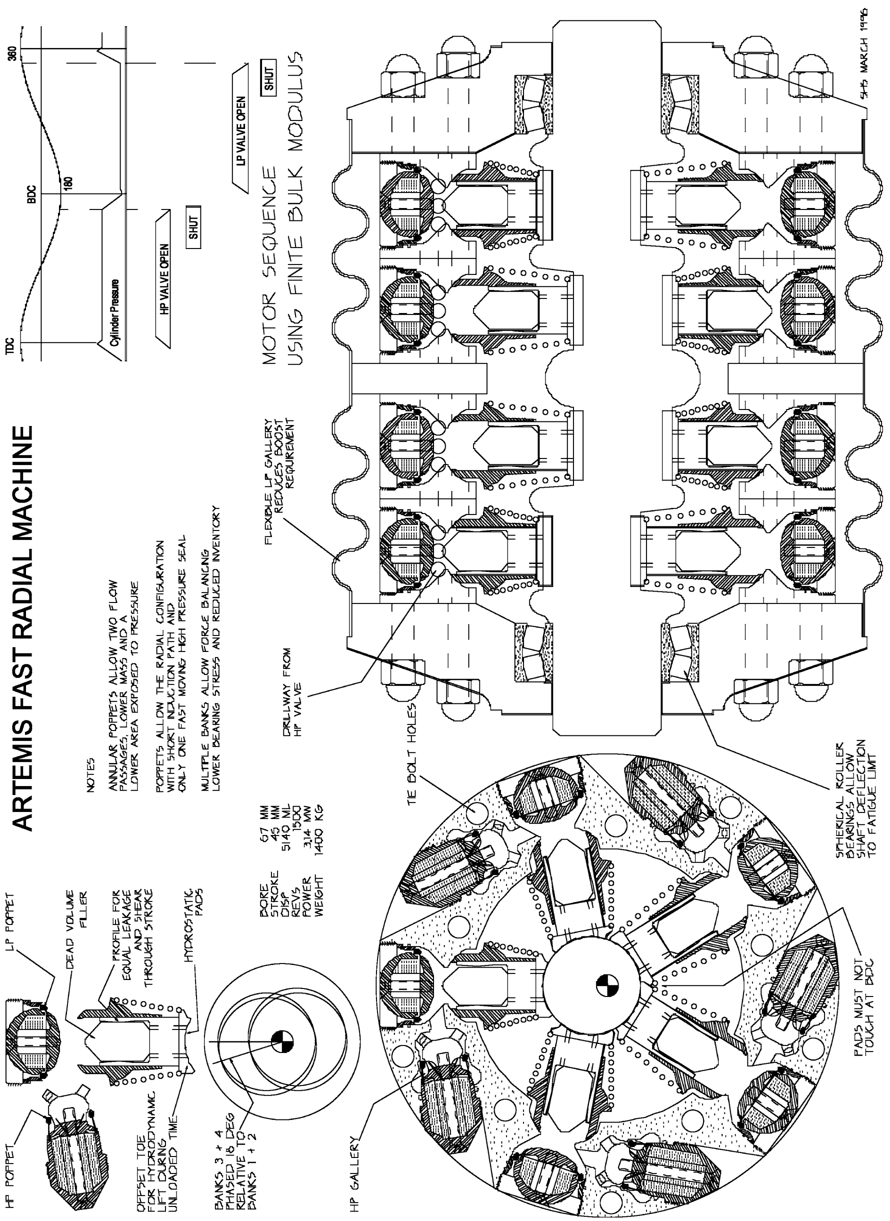


Fig. 2.15. A fast multi-bank, radial piston machine with digital poppet-valve control of pumping, motoring and idling

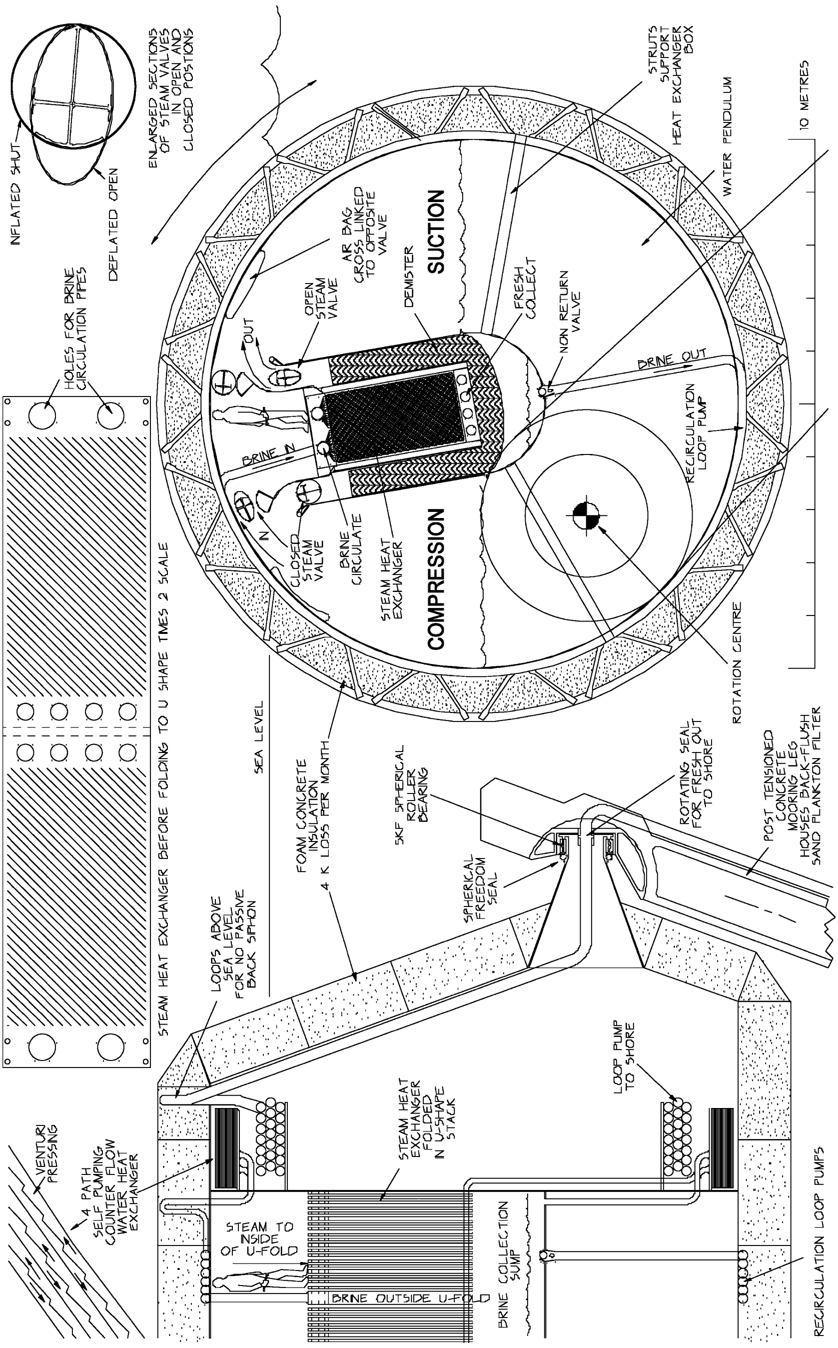


Fig. 2.16. Section through the desalination duck… People would not be present during operation!

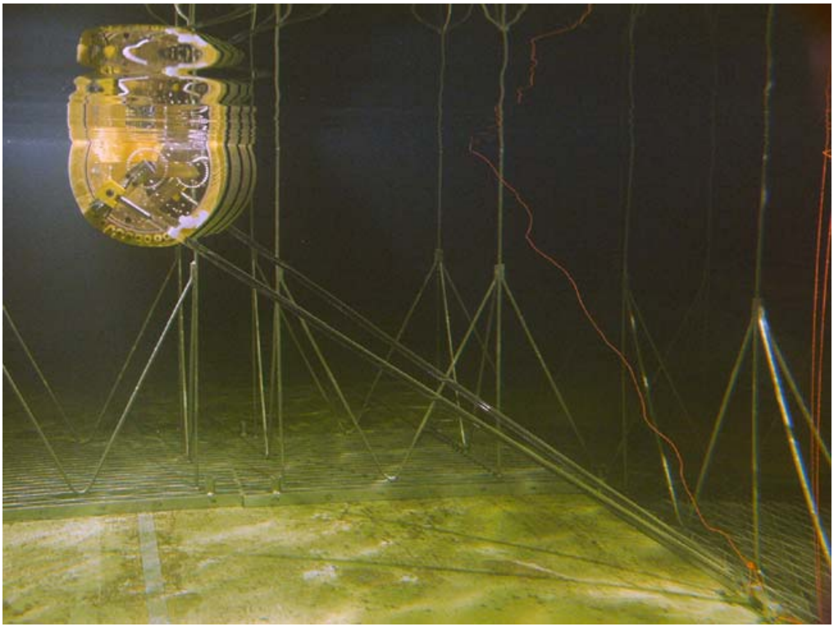


Fig. 2.17. A fish eye view of a 1/30 scale offset cylinder. The mooring will be a V-pair of post-tensioned concrete tubes with adjustable buoyancy going to a single-point attachment at the sea bed via a universal joint. The structures behind the Vee-legs are work platforms for use in the tank

2.2 Looking Forward

The challenge eventually must be to reduce costs of wave energy by a factor of about two. We may not be able to wait for the costs of fossil fuel generation to rise because that rise may push our construction costs up in direct proportion. However the initial task is to ensure that early wave power devices survive and produce the output predicted by their designers, even if the first wave electricity is as expensive as the first from coal or wind.

Survival depends on the full understanding of the statistics of the loads induced by waves and the strength of our parts. Every wave is a random experiment. We must understand the overlap of the upper asymptotic skirt of the load histogram and the lower skirt of the part endurance histogram. Separating them with large safety factors (which are really factors of ignorance and waste) is too expensive. If possible we must try to clip the load skirt to the economic limit and narrow the standard deviation of the strength histogram.

Large systems can fail because of very small components. While we can do lots in computers and indoor laboratories we must test large numbers of quite basic components such as bearings, seals, grommets, fasteners, surface coatings, cables and connectors in parallel in the chemistry and biology of the sea to know which ones will actually work. Building entire generating devices to test cheap parts, one by one, is a very expensive and very slow way to relearn the painful lessons of marine engineering. We should therefore have a test raft on which parts and sub-assemblies can be subjected to accelerated life tests.

We must try to maximise the ratio of the swept volume of any displacer to its own volume and the idle volume of the supporting structure. Low freeboards allow waves to break over a structure and so reduce, or even reverse, the mooring forces. The freeboard should therefore be chosen to suit the economic power limit. Concave shapes, like the corner at the foot of a breakwater or the focus of a shaped explosive charge, can amplify peak stresses in breaking waves so everything must be convex. Sharp edges, which we see in a great many designs of wave energy devices, waste lots of energy by shedding vortices so the convexities should have a large radius like a sucked toffee.

We must realise that it will never be possible to apply a restraining force for the largest waves and that a loss of the grid connection, even one due to some event on land, will mean that sometimes we cannot apply any restraining force at all. Devices with a low inherent radiation damping, such as smooth cornered buoys, can move an order of magnitude more than the wave amplitude and can build up very large amounts of kinetic energy which no end-stop can absorb. If we cannot use rotary mechanisms we must provide some other means for load shedding.

When we know how to make devices survive we can start to make them more productive. It has been a long term dream to design and test wave power devices in a computer with seamless links between the original drawing and the final results and with new ideas tried as quickly as Jamie Taylor could change models in a narrow tank. It is still a dream but we may be getting closer.

I predict that this will show that we must overcome the instinctive preference for movements in the vertical direction. Just because vertical motions are obvious to eyes and cameras and because we have instruments to measure them and a vocabulary to name them, does not make vertical the best mode. The horizontal forces and velocities can be just as useful. Movement in a slope direction or a combination of both as in the Bristol cylinder can give more than twice the power for much less than twice the cost. It is wrong to pay to resist large horizontal forces and then not get any power from them but nearly every beginner does exactly that.

Phase is the key to efficient transfer of energy. We must understand the inertia, damping and spring of our displacing mechanisms. We want a large swept volume for waves to move into but without the spring and inertia that is the usual accompaniment, except for Even Mehlum's Tapchan and the over-toppers. Work that is put into accelerating masses or deflecting springs will have to be returned. Only those forces that are in phase with a velocity are useful. We must maximise damping, reduce inertia to the minimum and have only enough spring to resonate with the undesirable inertia at the most useful part of the spectrum.

We must find ways to choose and control, instant by instant, the amplitude, phase and upper limit of the force going to the power-conversion mechanism. Asymmetry can shed about half the added inertia and slope reduces spring by a controllable amount. It is quite wrong to think about ‘tuning’ wave power devices. In radio terms tuning is the way not to get signals from unwanted transmitters. Good wave devices would be very ‘low Q’ resonators with a high ratio of damping resistance to reactive impedance. Half the spectra in Fig. 2.12 show that energy is coming from more than one source. Unlike the designers of radio receivers we want to receive simultaneous signals from as many transmitters on different frequencies as possible. We need to understand why the performance in irregular waves falls off with increasing amplitudes at a rate larger that would be predicted by non-linearity or torque and power limits of regular wave tests.

We should all use accurate common transparent costing methods, such as those developed by Tom Thorpe, based on material weight and safe working stresses. He even produced graphs of cost prediction plotted against the rate of interest so that people could see the effect of the 15 % return required of wave energy investments and compare it with the 2.6 % achieved by the CEGB or the 0.5 % required by Japanese banks.

We must find ways to install and remove devices more quickly and much more cheaply than the towing methods inherited from the offshore oil industry. This may require the design of special vessels with high thrust, agile manoeuvring, instant connection and disconnection but short range.

Some wave devices may be vulnerable to currents and many marine current devices may be vulnerable to waves. Waves and current interact with one another in complicated and often dangerous ways. We must build tanks and develop software to understand the effects of these interactions.

Every new technology makes many painful mistakes. Many boilers burst, ships sank and planes crashed before we got them reliable. The mistakes only become less painful if people learn from them. They will learn only if full details of every mistake are circulated throughout the industry. This is certainly not happening now. The requirements for raising private investment require the concealment of expensive disasters in the hope that commercial rivals will repeat the mistakes.

We must find ways to get the right amount of money to front-line engineers as and when they need it. Over elaborate rules for tenders and contract management will not stop crooks embezzling public money but they certainly are too complicated for honest engineers to follow unless they also have a PhD in contract law. Perhaps we should try flexible agreements for people who have shown that they have earned trust with cruel and unusual punishments if they betray it.

We must have a management structure which can reach sensible decisions in a few days not the year or more required by the Dof E, ACORD, ETSU, RPT, TAG maze. Such committee trees are designed to make the post-disaster audit trail so complicated that no individual can be identified to take the blame when things go wrong as they so often do when decisions take so long. The community needs to believe that political leaders and officials genuinely want the technology to succeed rather than appearing to want it because they feel that this will win votes. When instead, they write letters to The Times boasting of how they stopped the programme or are given promotions to senior positions in the Nuclear industry, we all feel betrayed.

Acknowledgements

Wave research at Edinburgh University was enormously helped by a succession of vacation students and school leavers who learned engineering skills envied by local industry in an amazingly short time. Many reported that they learned as much as from a degree and many are now senior industrialists.

I cannot name several people working for the Atomic Energy Authority who risked their jobs to send us documents about dirty tricks which were very clearly not intended for us. One included a note to say that just because I was not paranoid that did not prove they were not out to get me!

The resurrection of the UK wave programme would not have occurred but for the evidence given by Gordon Senior to the House of Lords. Gordon Senior died in 2007 but will be remembered by his many friends in the wave community he saved.

References

Bott A (1975) Power Plus Proteins from the Sea. J RSA, pp 486–503

Budal K, Falnes J (1975) A resonant point absorber of ocean-wave power. Nature 257:478–479

Clark P (1980) Consultants working paper 22 WESC(80). Future Energy Solutions AEA Technology

Clark P (1983) Final Report on Wave Energy (2A/B/4) – A.3.2(5). Future Energy Solutions AEA Technology

Cruz J, Salter S (2006) Numerical and Experimental Modelling of a Modified Version of the Edinburgh Duck Wave Energy Device. Proc IMechE Part M. J Eng Marit Environ 220(3):129–147

Dixon A, Greated C, Salter SH (1979) Wave Forces on Partially Submerged Cylinders. J Waterway Port Coastal Ocean Div Am Soc Civil Eng 105:421–438

Evans D (1976) A Theory for Wave-power Absorption by Oscillating Bodies. J Fluid Mech 77:1–25

Evans D, Jeffrey D, Salter S, Taylor J (1979) Submerged Cylinder Wave Energy Device: Theory and Experiment. Appl Ocean Res 1:3–12

Jeffrey DC (1976) Edinburgh wave power project second year interim report, pp 24.1–24.39 (Download from http://www.see.ed.ac.uk/ ~ ies/)

Lin C-P (1999) Experimental studies of the hydrodynamic characteristics of a sloped wave energy device. PhD Thesis, The University of Edinburgh

Pizer D (1994) Numerical Modelling of Wave Energy Absorbers. University of Edinburgh wave project report 1994, from http://www.see.ed.ac.uk/ ~ ies. (Note: Compare his Fig. 39 with Fig. 42)

Skyner D (1987) Solo Duck Linear Analysis. Edinburgh wave power project, 1987. Download from http://www.see.ed.ac.uk/ ~ ies/

Salter S (1982) The Use of Gyros as a Reference Frame in Wave Energy Converters. In: Berge H (ed) Proceedings of 2nd International Symposium on Wave Energy, pp 99–115
Salter S, Rea M (1985) Hydraulics for Wind. In: Palz W (ed) Proceedings of European Wind Energy Conference, pp 534–541
Salter S, Rampen W (1993) The Wedding Cake Multi-eccentric Radial Piston Hydraulic Machine with Direct Computer Control of Displacement. BHR Group 10th International Conference on Fluid Power
Salter S, Lin C (1995) The sloped IPS Wave Energy Converter. Proc Second Eur Wave Power Conf, pp 337–344
Salter S (1998) Proposal for a Large, Vertical-Axis Tidal Stream Generator with Ring-Cam Hydraulics. Proc Third European Wave Energy Conference
Salter S (2002) Why is Water so Good at Suppressing the Effects of Explosions? UK Explosives Mitigation Workshop
Salter S (2005) Digital Hydraulics for renewable energy. World Renewable Energy Conference
Senior G (1988) Evidence to Lords Select Committee on European Communities. 16th report on Alternative Energy Sources, pp 204. 16 HL paper 88. HMSO, London, June 1988. Can be downloaded from http://www.see.ed.ac.uk/ ~ shs
Taylor J (1978) Edinburgh University wave project report 1978. Download from http://www.see.ed.ac.uk/ ~ ies/
Taylor J (1984) Edinburgh University wave power project 1984. Download from http://www.see.ed.ac.uk/ ~ ies/
Young H (1982) Parrots and Monkeys. Edinburgh wave energy project report 1982. Download from http://www.see.ed.ac.uk/ ~ ies

Weblinks

Aeroflex torque motor http://www.aeroflex.com/products/motioncontrol/torque-intro.cfm
Interproject Service website http://www.ips-ab.com/
Office of Naval Research. http://www.onr.navy.mil/Focus/ocean/motion/currents1.htm
Edinburgh Designs web home page. http://www.edesign.co.uk/