The Edinburgh curved tank

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ABSTRACT
An unusually shaped directional wave tank has recently been built in Edinburgh, primarily for the testing of models of 'solo' wave energy devices. The absorbing-wavemaker paddles are arranged in a 90-degree arc rather than in a linear array so as to increase the angular spread of fully realistic three-dimensional sea-states and to reduce long-period cross-tank 'seiche' waves. Compact beach modules based on an improved design have been installed along one side of the tank. This paper describes the new Edinburgh curved tank in the light of nearly twenty-five years of operation of earlier tanks and in the context of a future circular wave and current tank.

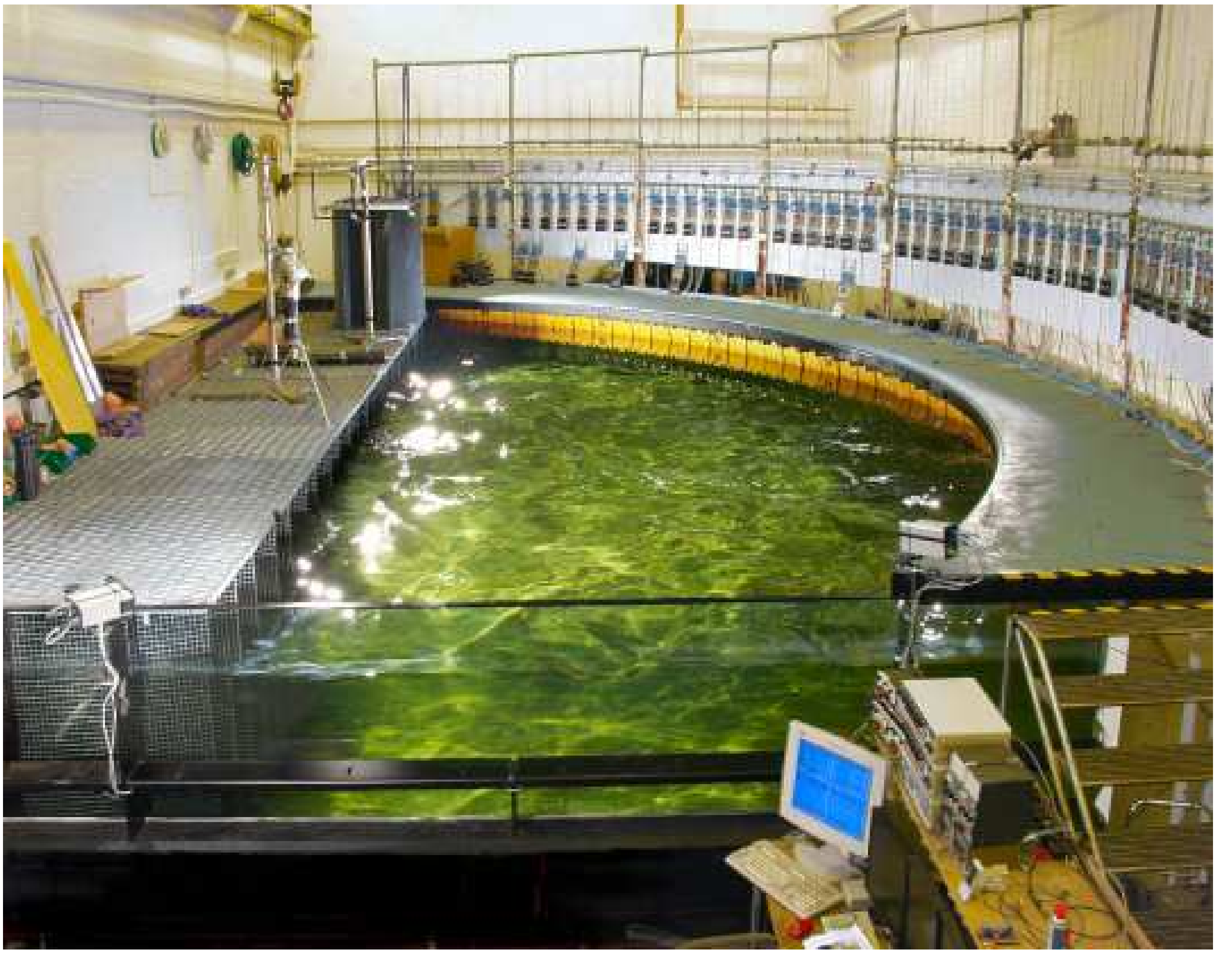


Figure 1: The Edinburgh curved tank. *The sea-state is a one second Pierson-Moskowitz with cosine spreading. The top bars of the open tubular structure at the back of the curved platform support the ends of springs that pull the wavemakers back to the centre of their working range against the hydrostatic pressure on their front faces. The paddles look static because the image is a composite of 12 photographs.*

1. Introduction

Wave energy devices have to be strong enough to survive storm conditions, good at capturing power in small and moderate waves and as cheap as possible. Every fresh idea for a way of doing this creates a daunting new list of design variables. Somehow or other these have to be brought to some sort of collective design optimisation before considering the risks of going to full-scale prototype. Optimisation requires a choice or a combination of modelling techniques - analytic, numerical or physical. Prediction of detailed behaviour in any conceivable sea-state is probably beyond the reach of even the most gifted analytical mathematicians. Vast improvements in computing performance have made numerical hydrodynamic modelling much more accessible, however these simulations remain generally restricted to the sort of conditions associated with waves of small height. So tank tests with regular waves and with spectrally and directionally realistic conditions at power levels up to the statistical extremes are still indispensable.

The 'wide tank' built in 1977 at the University of Edinburgh was the first multi-directional mixed wave tank to be built specifically for wave energy research. It was designed to test a crest-spanning free-floating 'duck' string [Salter et al, 1976, Salter 1993] at scales down to 1/150 in waves that would accurately represent deep-water conditions to the west of the UK.[1] In 2001 the completion of a long-delayed building project sadly required the demolition of the wide tank but raised the possibility of its partial reconstruction in another smaller space. The result is the new 'curved tank' shown in Figure 1, which is now being used for wave energy experiments with 'solo' devices [Parkin et al, 2003].

The success of the wide tank led to a number of companies becoming involved in the commercialisation of the wavemaking technology. Latterly one of these, Edinburgh Designs Ltd., has gone on to design and install wavemaking systems around the world that to a greater or lesser extent are descendents of the wide tank. They were also responsible for the design and construction of the new curved tank and the writing of the control software.

2. The narrow tank

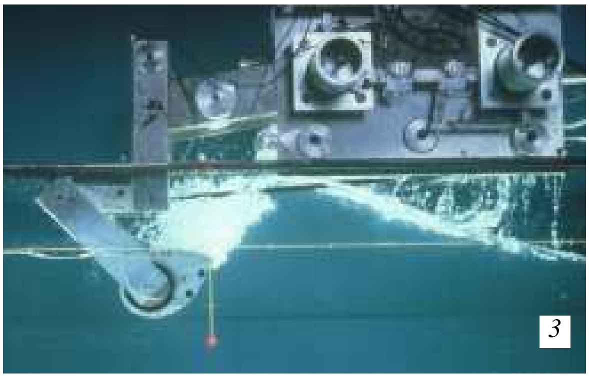
The concepts of wave-energy extraction and wave making are so closely related that they were developed in parallel during the early years of wave energy research at Edinburgh [Salter, 1981]. It was immediately apparent that stable and highly repeatable waves were essential if accurate and repeatable predictions of full-scale device behaviour were to be made. This required wavemakers able to simultaneously drive the intended waves toward the model whilst absorbing a large fraction of the energy of any return waves.

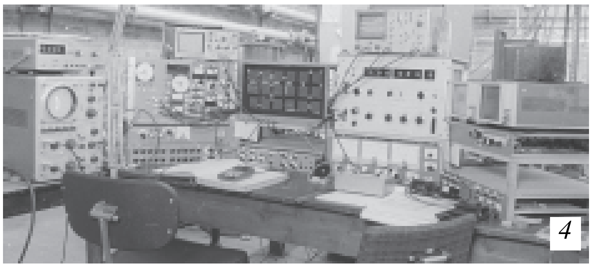
The experimental optimisation of 100mm nominal diameter models of the duck in a narrow tank (10m long, 0.3m wide and 0.6m deep) was greatly assisted by the development of a wavemaker (Figure 2) in which the profile of the displacer paddle was similar to that of the duck model (though two and a half times its radial dimensions). Fundamental to the design was the idea of *force* control based on strain-gauge measurement of the force between paddle and drive system and the related use of a *current* amplifier to power the motor. Force control is analogous to demanding the appropriate energy in the wave but allowing the paddle movements to conform to whatever departure from purely sinusoidal motion is instantaneously appropriate. By sensing motor speed with a tachogenerator, a velocity feedback term was introduced into the control loop so that a high percentage of the energy of any waves returning as reflections was 'absorbed' by the damped response of the paddle. The duck wavemaker radiated strikingly clean unidirectional waves and if faced by a rigid vertical wall in place of a model, would indefinitely maintain standing waves of constant height by providing just the right amount of energy to compensate for losses.

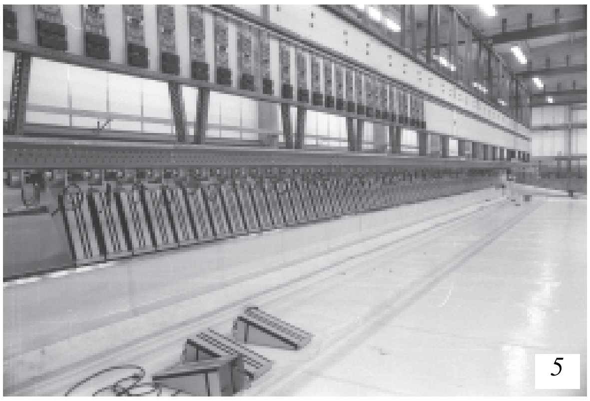
The push for maximum realism in the narrow tank test work [Greenhow et al, 1982] required higher amplitudes, longer periods and breaking waves. A deeper (500mm hinge depth) displacement wavemaker was developed which would also lend itself to production in larger numbers for the new wide tank. The design of the new wavemaker was optimised for 1Hz waves and was based on a mixture of experimention and design curves published by Gilbert et al [1971]. The paddle was in the form of a light riveted aluminium box and used a polyurethane-coated nylon fabric 'rolling-seal' [Taniguchi and Kasai, 1972] so that only its front surface displaced water. A low inertia dc motor drove the paddle via a multi-stranded drive wire and a speed-reducing pulley arrangement. The free end of the drive wire was 'grounded' through a low rate spring to provide a near constant bias force to trim the paddle back to the centre of its working range. A piezo-electric transducer sensed the alternating component of force on the paddle. As in the duck wavemaker, a function of this force signal was combined with velocity derived terms to give force-based performance with absorption of unwanted waves.

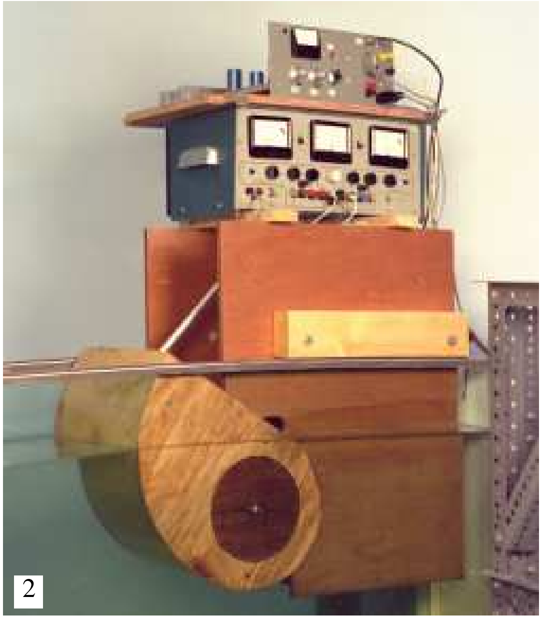
A new kind of compact and efficient beach was developed for the narrow tank consisting of loose sheets of 'Expamet' (expanded metal - slit, stretched and corrugated aluminium foil) held in a triangular wedge shaped cage. The actively controlled reactions of a 'surging-heaving rig' (Figure 3) allowed the axis of the narrow tank duck model to move realistically as if it were part of a duck string. The tank was fitted-out largely with analogue instrumentation (Figure 4) so that as far as possible information was processed and displayed in real time. The advent of micro-computers allowed the generation of very realistic breaking waves. In terms of realism, only multi-directional waves were missing, hence the need for a wide tank. With the hindsight gained from working with the additional freedoms of multi-directional tanks, the narrow tank was a remarkably productive test environment.

[1] In fact, due to the running down of the UK wave energy program in the early 1980s, the duck string, though built, was not fully tested in the wide tank. However an extensive program of tests on the associated (and generic) flexible 'spine' was conducted (Figure 10).









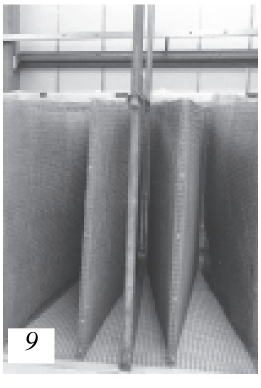
Figures 2 to 10: *(anticlockwise from top right)*

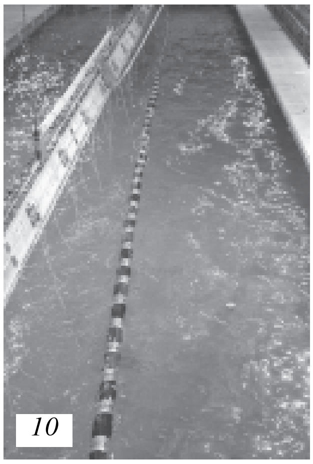
Narrow tank wavemaking

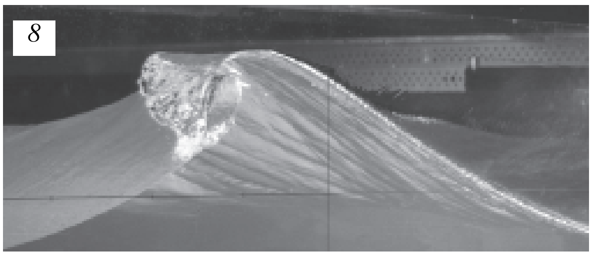
2 *First force-sensing absorbing wavemaker.*
3 *Duck model on surging-heaving rig in extreme wave.*
4 *Control desk - real time analogue electronics.*

Wide tank wavemaking

5 *Array of wavemaker paddles during construction.*
6 *Control desks and tank window.*
7 *Short-crested Pierson Moskowitz sea.*
8 *Bullseye - three dimensional plunging breaker.*
9 *Expanded metal beach wedges.*
10 *Multi-section spine model under test.*







3. The wide tank

A total of 89 of the new rolling-seal flap-type wavemakers were installed at a one-foot pitch (305mm) along one side of the wide tank (28m wide by 11m long by 1.2m deep. Figure 5). The opposite side and one of the shorter sides were occupied by the expanded-metal beach wedges (Figure 9). Most of the remaining side was taken up by a 0.6m deep glass window which faced the operator control area (Figure 6). Complex sea states were modeled by combining up to 75 sinusoidal 'wavefronts' each of which was described by its amplitude, frequency, starting phase and angle relative to the line of wavemakers. Command signals sent to each wavemaker twenty times per second (later reduced to 16Hz) were computed as the wavemaker-specific sum of the instantaneous amplitudes of the component wavefronts. The limit of 75 wavefronts was imposed by the high cost of computer memory in the 1970s and so most of the wavemaking maths was done in real time. An 'expert' computer algorithm asigned the available 75 wavefronts with frequencies and angles such that each multi-directional sea-state was best reproduced with regard for energy distribution. Sea states, such as shown in Figure 7, were typically based on the parametric model of Pierson and Moskowitz [1964] with $\cos^n$ or Mitsuyasu [1975] spreading functions and with optional extreme wave peaks of up to 12.25 (the square root of twice the number of wavefronts) times the rms value available on demand at any chosen time and place.

A particularly interesting set of sea-states was used for bending moment tests on the spine model shown in Figure 10 [Edinburgh Wave Power Project, 1984]. These were based on work by Crabbe [1980] on the synthesis of a directional wave climate. The 'South Uist 46 spectra' were based on extended sets of measurements from three Waverider buoys stationed off the Western Isles of Scotland and were intended to be typical of a 'standard Hebridean year'. Each spectrum was expressed as a combination of 'wind sea', 'swell sea' and 'old wind sea' with directionality being assigned to each of the components by reference to local and distant wind data. In the wide tank versions of the 46 spectra the separate wind, swell and old wind components were often clearly visible. For instance the wavefronts corresponding to swell waves would be tightly bunched in direction showing their origins in distant storms, whereas wind sea wavefronts would be at higher frequencies and spread over a wide range of angles.

Composing complex sea-states by the superposition of many sinusoidal components is analogous to Fourier synthesis and easy for non-specialist engineers to understand. Generally the frequency components are selected harmonics of a particular base frequency and this produces sea-states which repeat exactly after a certain time. Typically frequencies in the wide tank were chosen so as to give a repeat period of 64 seconds. Whilst offering great realism as models of actual ocean conditions, the perfect repeatability of such 'pseudo-random' sea-states make it easy for experimenters to isolate and evaluate the effect of any intentional change to their model

Good underwater views are essential in wave energy tank tests and a large wide glass window retains some of the important intimacy that is otherwise lost when moving from a glass-walled narrow tank to a large directional-wave tank. However there are two serious drawbacks. The first is that reflections off the glass introduce symmetrical 'ghost' wavefronts at one side of the tank. Moving models some distance away from the glass generally minimises the effect of these. The second problem is the setting up of long period transverse standing waves ('seiche' waves) between the window and any other reflecting walls of the tank. In some tanks, multiple wave reflections between parallel side walls can build up enough to compromise 'steady-state' conditions and can lead to long waits for tank settling between test runs. In the wide tank seiche waves were generally not a problem because only a small fraction of the tank perimeter was reflective - the window only accounting for 5m out of a nominal perimeter of 65m that included 27m of absorbing wavemakers and 33m of beach.

Figure 8 shows the first of several mesmerising and useful wave discoveries made in the wide tank. The 'bullseye' is a repetitive deep-water plunging breaker, considerably steeper than the nominal limiting value of one in seven for two dimensional waves. It is a 'monochromatic' wave produced by causing many wavefronts of the same frequency but spread over a range of angles to converge in phase at a chosen point. The development of cheap data storage removed the need for real-time computation of wavemaker command signals and permitted the generation of other statistically unlikely waves, by allowing virtually unlimited numbers of wavefronts to be combined. For instance the 'sneak', another deep-water plunging breaker, which appears almost by surprise out of a generally calm sea, is made by arranging that the angles and phases of each of the hundreds of wavefronts of a *spectral* sea-state converge at some point and time.

A measure of the enthusiastic reception given to the wide tank is that two years after its completion, an almost identical copy (60 wavemakers instead of 89) was built with government funding near Southampton in the south of England so that the wave energy researchers would have a specialised test facility at either end of the UK.

4. The curved tank

There were five fundamental sets of requirements for the new tank. The first was that none of the functionality, intimacy and user-friendly nature of the wide tank should be lost. There should be very good beaches, rapid settling between tests and users should have the closest access and best possible underwater view. The second set of requirements was that, although it would inititially be mainly used to test models of solo wave energy devices, it should also be possible to accomodate models of longer devices such as Pelamis [Yemm et al, 2001]. The third requirement was that the angular spread of waves at the model position should be at least as good as in the wide tank, and preferably better. The fourth requirement was that it should be possible to retro-fit some sort of driven carriage or arm to give users easy access to the test area, to deploy wave measuring gauges and perhaps also for towing models of tidal stream devices. Finally, the tank should be built as quickly and as cheaply as would be consistent with the other requirements and with the maximum re-use of wide tank wavemaking equipment.

To make the best use of access routes and space (less than one-third of that of the wide tank) it became clear that the window side of the tank (and hence principal wave direction) should be across the 8m width of the available laboratory. When compared with the 11.3m width of the wide tank, this implied a very significant reduction in fetch between wavemakers and beaches compared to the wide tank.

A plan view of the new tank is shown in Figure 11. Forty-eight out of the wide tank's linear array of eighty-nine wavemakers are reconfigured into an arc of a circle. Consecutive paddles in the wavemaking arc are rotated by 2 degrees relative to their neighbour so that the included angle of the arc is just over ninety-degrees. The centre of the wavemaker arc is *outside* the laboratory. Above the array of wavemakers is a rolled steel beam which is also in the form of a circular arc. The beam forms the front edge of a work platform. The work platform arc is of smaller radius than the wavemaker arc and has its centre just *inside* the laboratory wall. The curved beam will interface with or support the moving outer end of a future hinged or rotating 'boom' that will be the functional equivalent of a towing carriage. A wide and deep glass window and a line of newly designed wedge shaped beach units complete the tank.

The included angle of the wavemaker array seen from the nominal central model test position is now 160 degrees compared with around 140 degrees in the wide tank. As there are no parallel walls in the tank, the possibility of systematic multiple-reflections and seiche waves is greatly reduced.

5. Some constructional details

The wavemakers are mounted in groups of six within eight galvanised steel fabrications that are suggestive of upright pianos rolled into slight curves (Figures 12 & 13). By the installation of new pulleys, the long low-rate hydrostatic force trimming springs have been moved backward relative to their positions in the wide tank to give a more open walkway above the wavemakers and thus make best use of the relatively small size of the laboratory (Figure 1).

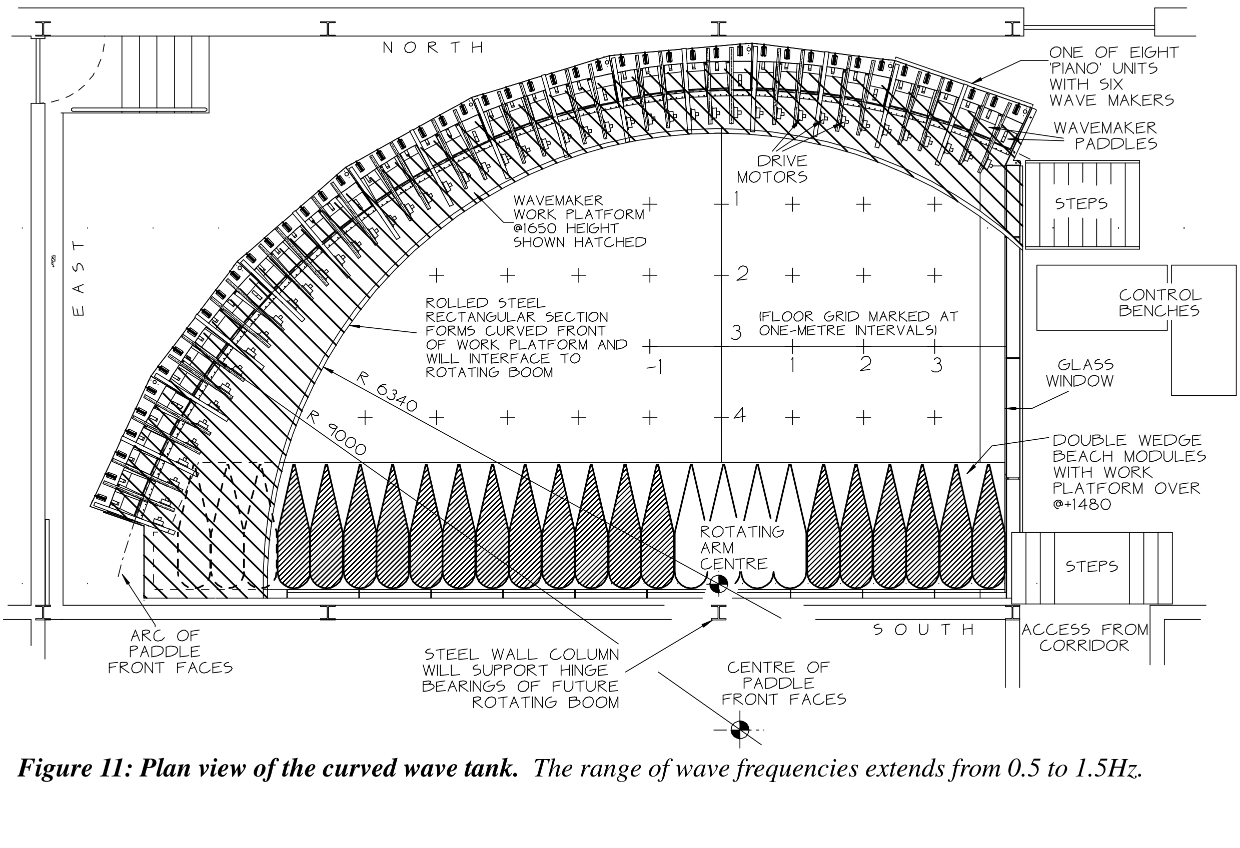
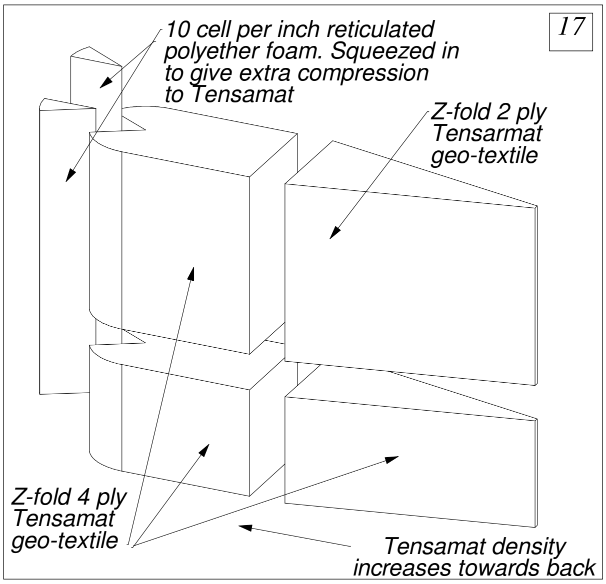


Figure 11: Plan view of the curved wave tank. *The range of wave frequencies extends from 0.5 to 1.5Hz.*



Figures 12 to 17: curved tank during construction *(clockwise from top right)*

12 Galvanised steel curved 'piano' units. Seven out of the eight are visible. Each will hold 6 wavemaker paddles. Motor at top right drives paddle via stranded steel wire.

13 Circular array of paddles with electronics boards above.

14 Filling'weldmesh' cage for rear section of a beach unit. Z-folded 4-ply Tensarmat is in place. Lighter coloured material at top is reticulated polyether foam which also increases the compression of the Tensarmat.

15 Two front cages in position within beach frame fabrication. Note higher density 4-ply Tensarmat at bottom, lighter density 3-ply material at top.

16 Installation of last unit completes back wall beach array. Additional free units can be placed around models or in front of glass.

17 Exploded diagram showing six component parts of each beach wedge. Two-ply Tensarmat at top front is least dense part to minimise wave reflection. The polyether foam at the back is the most dense component. The packing density is increased towards back.

The 15mm toughened glass of the windows is supported in such a way as to give the least visual obstruction. The window is one metre deep and is divided into a large upper area and smaller lower area by an intermediate steel channel running its entire length. This water pressure support arrangement allows the central 3.5m length of the 6.15m window to be in the form of a single piece of glass which gives a superb unobstructed view.

The labour-intensive and ultimately unsatisfactory initial waterproofing of the wide tank was in the form of a loose lining made up from rolls of a polyurethane coated terylene felt. Latterly it was replaced with a very successful hand-laid glass-fibre polyester lining. The company responsible had moved out of the lining business and so the new tank has been waterproofed with a very tough polyurethane system sprayed directly onto the concrete and steel. Initial impressions are that it is more susceptible to mould growth than was glass-fibre.

6. The new beaches

Figures 14 to 17 show some details of the construction of the new beach units. The absorbers units are, as before, wedge shaped and contained within steel mesh cages. Pairs of wedges are placed inside galvanised steel frames whose upper panels ('diamond' grid industrial flooring) form a continuous walkway. The top panels are positioned above identical bottom panels by supports which are almost entirely within the volume occupied by the wedges (Figure 15).

The beaches of the wide tank dissipated waves by having them exhaustively traverse the countless sharp edges and interstitial spaces of multiple layers of expanded metal. The material was relatively expensive and hard to distribute throughout a large number of beach units so as to give consistent packing density. It also tended to compress and corrode, particularly in areas exposed year after year to multiple occurrences of extreme waves.

The filling for the new beaches is a mixture of cut blocks of polyether 'skeleton' foam and Z-folded rolls of a three-dimensional geotextile material known as 'Tensamat', which is woven from sub-millimetre diameter pvc filaments. The action of both types of material can be analysed in terms of the drag force presented by the total length of filaments to the moving water. The ideal material would oppose water motion with force proportional to velocity. It would present the same impedance to waves as would unobstructed water in an infinitely long tank.

Estimation of Reynolds numbers for different conditions suggest that although the elemental beach forces will tend to be proportional to the first power of velocity for small long period waves, they will rise to be proportional to the second power of velocity for steeper waves. Accordingly, the compromise used for the design of the new beaches is to increase the density progressively with depth and with distance down wave as shown in Figure 17. The less dense upper front section of the beach is designed to present a good 'impedance' match to higher and shorter waves so that they suffer minimal reflection off the front surface. That impedance is then too small for less steep waves so there will be more reflection. However the geometry of the wedge shape ensures that most of the energy of those reflections bounces back into adjacent wedges.

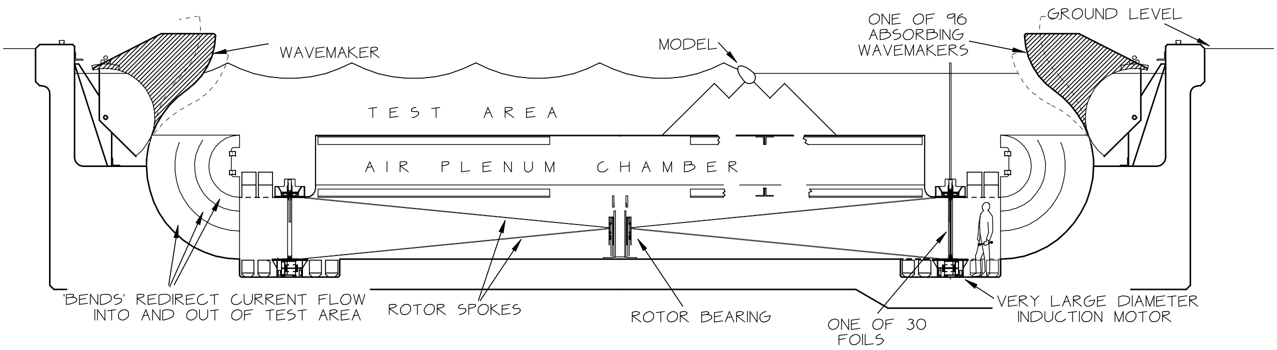


Figure 18: Section view of proposed circular combined wave and current tank. *The hatched units at either side are elements of the circular array of wavemakers. The moorings of the duck model show the position of the test area floor. At the bottom below the test area is a vertical-axis current generator. Circular 'bends' or guide vanes below the wavemakers direct water from the current generator into and out of the test area. Note the scale of the maintenance engineer at lower right.*

Figures 19 & 20: The flow table. *The EPSRC financed and recently completed flow table demonstrates the flow generation concept proposed for the circular tank and provides a useful test facility for small scale tidal stream research. The foils of the verical axis rotor are visible in the dry and unclothed view at left. Above the foils is a ring of 56 stepper motors which are computer commanded to set the shape of a deformable multi-lobe cam band. Individual foils track the cam profile so as to cyclically vary pitch and thus either push or pull water into or out of the test region above. Twelve flow re-directing bend units can be seen at the back. In the operational wet view at right the complete ring of 36 bends is in place .*

7. The circular tank and the flow table

Tidal-stream generating devices are sensitive to the action of waves and offshore wave energy installations are sensitive to the actions of currents. The interaction of waves and currents is complex and there may be a need for a scale test facility which offers variable combinations of both. Salter [2001] has proposed the construction of a large combined wave and current tank that would have a complete circle of absorbing wavemakers.

Figure 18 is a simplified drawing of the circular wave and current tank. Beaches are dispensed with and a circular array of 96 wavemakers generates wanted waves and removes unwanted ones. A current generator situated below the test area is coupled to the test area by nesting double-curvature annular ducts or 'bends'. It consists of a motor-driven annular carriage carrying thirty variable pitch foils. The pitch angles of the rotating foils are made to vary in accordance with their circumferential position (rather like the cyclic pitch variation of helicopter rotor blades) so that they push or pull water to or from the test area. Different pitch-patterns can be set so that multiple currents can be generated simultaneously.

The generation of linear wavefronts from the ninety-degree wavemaking arc of the circular tank provides useful confidence-building experience for the complete circle of wavemakers in the circular tank. The generation of stable standing waves by sending a long packet of regular waves directly toward the glass window of the curved tank and then their subsequent absorption, largely by the same wavemakers, provides a convincing demonstration of the feasibility of a test tank without beaches.

A new facility has been built to develop and demonstrate the proposed system for generating currents. Figures 19 and 20 show two views of this 'flow table'. In addition to successfully demonstrating the current generation concept proposed for the circular tank it provides an versatile laboratory facility for experiments with tidal-stream rotors.

8. Acknowledgement

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