Design and construction of a 360-Degree Flow Table with Control of Velocity Gradient

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Background

The flow table project is part of a response by the Edinburgh group to encouraging predictions for tidal-stream energy costs. We have been working on a large vertical-axis variable-pitch machine with either oil-hydraulic ring-cam or direct permanent magnet power-conversion systems. As such devices can be packed so as to fill a large fraction of the available channel width and depth, the stresses on rotors and moorings will be highly sensitive to spatial variations in water flow. Some of the complexity of these flow regimes will be due to the interaction of wave and tidal effects and to the unevenness of the sea-bed. Also, the extreme steepness waves possible where strong currents and sea-states are in opposition will increase stresses on components above and below the water surface. If we are to make good use of the tidal stream resource it will be essential to have deep practical understanding of such tide and wave environments. Accordingly the Edinburgh group has proposed the building of a large combined wave and current test tank, circular in planform, which would give precise control of both waves and currents in any combination.

The generation of waves by an arc of wavemakers has been demonstrated in the Edinburgh 'curved' wave tank which was built in 2002 with EPSRC support (GR/R64438/01). It replaces the wide tank of 1977 which first demonstrated the generation of accurate highly repeatable 3-dimensional wave spectra over a wide model. Its operation over 24 years provided much of the stimulus for a growing number of tanks around the world. In the new wave tank, forty-eight out of the original eighty-nine 'absorbing' wavemakers are rearranged into a ninety-degree arc of a circle and have demonstrated the practicability of operating a full circular array of wavemakers.

The primary aim of this flow table project has been to design, construct and carry out initial testing of the corresponding ideas for the flow generation component of the combined wave and current tank at the smallest possible scale. Despite this very small scale it may still be possible to make useful observations of flow patterns round variable pitch foils and flow obstructions. The project experienced a considerable degree of positive 'mission creep' particularly with regard to the control software which now offers powerful editing commands with a graphical interface which is extremely easy to use.

The flow table

Photographs 1 and 2 show general views of the flow table whilst the solid model of Figure 1 shows some key dimensions and identifies the principal components. In the descriptive text that follows, the numbers in brackets are intended to refer the reader to photographs 3 to 20.

The outer diameter was chosen to be the largest that could pass through the ISO standard door height. The system consists of three layers. The uppermost is the 1.45 metre diameter by 0.15 deep 'test region' (15-20) with an outer wall at the height of a billiard table. Below this is a sealed 'plenum' air-volume which reduces the source inertia of the water flow. At the bottom is a high-solidity, variable-speed, variable-pitch, 48 foil, vertical-axis rotor (5,12) which moves water into or out of the test region according to a locally set pitch command which can be changed at 56 points round the circumference. To minimise flow losses and turbulence, flow from the rotor to the test region is around curved 'bends' (11) made from four nesting curved vanes. Flow from the lower level into and out of the rotor is through the gaps between 216 radial, flow-straightening guide-vanes (8). Pitch is changed by 56 reduction-geared stepping-motors (4,12) which count 1200 steps from end to end of the ±25 degree foil range. The gearboxes drive eccentrics with pivoting 'see-saws' (6) that have claws to pull in or push out a stiff 10 mm diameter polyurethane 'cam band' (6,7). Rollers centred near the tail of each foil follow the cam profile and are kept in contact by coil springs (5,7).

The stepping motors and their control electronics are housed in an air-filled 'diving bell' consisting of a transparent plastic annular top-hat hat section (13). This is pressurised to the local water head but has to be open to the water through a narrow gap.

Photo 1: Flow table drained and with the nearer bends removed, showing the rotor foils, stepper-motors and electronics boards

Photo 2: Flow table complete and filled with water. The outer rim is the same height as a billiard table. The water can be quickly transferred to or from an adjacent storage tank.

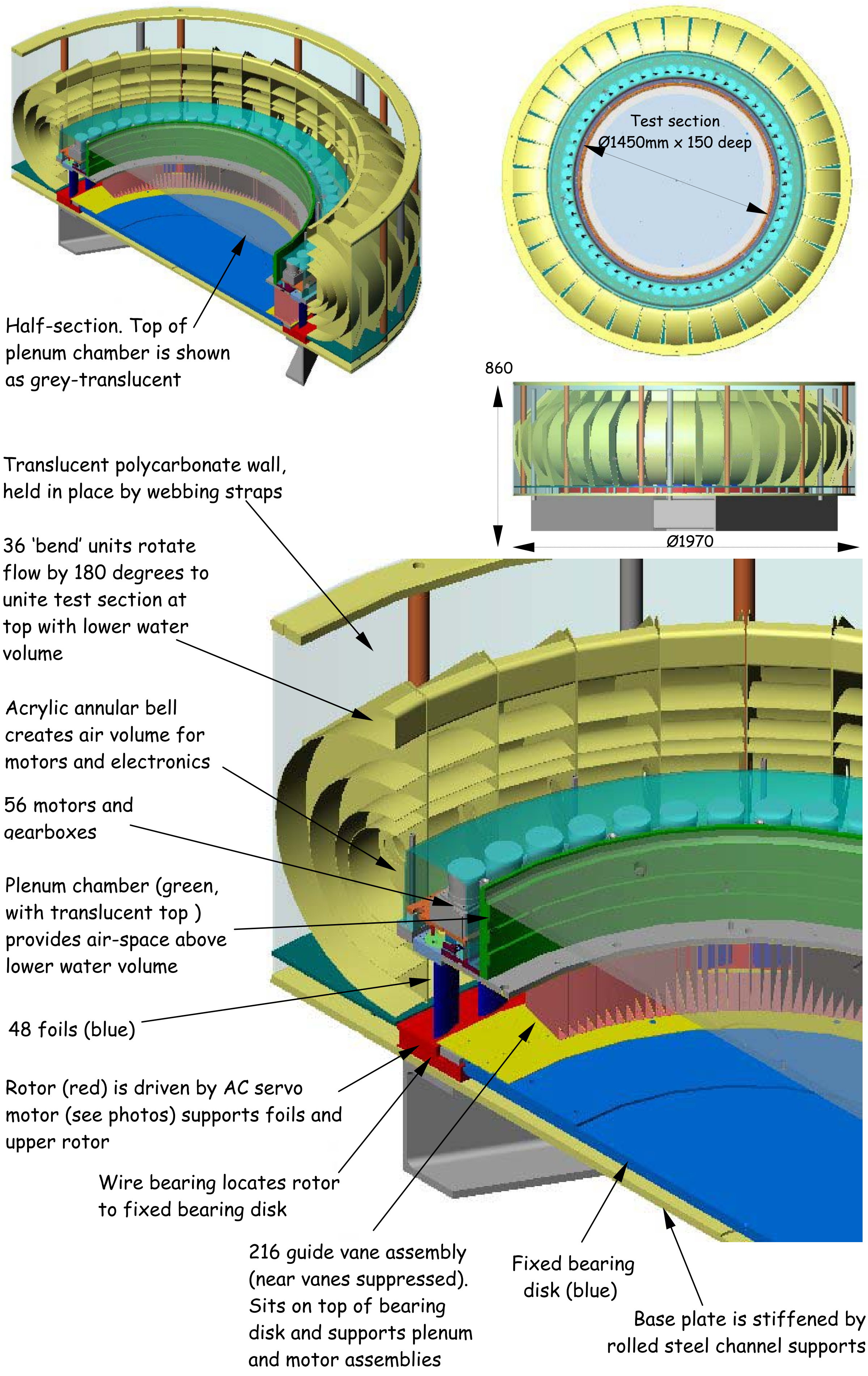
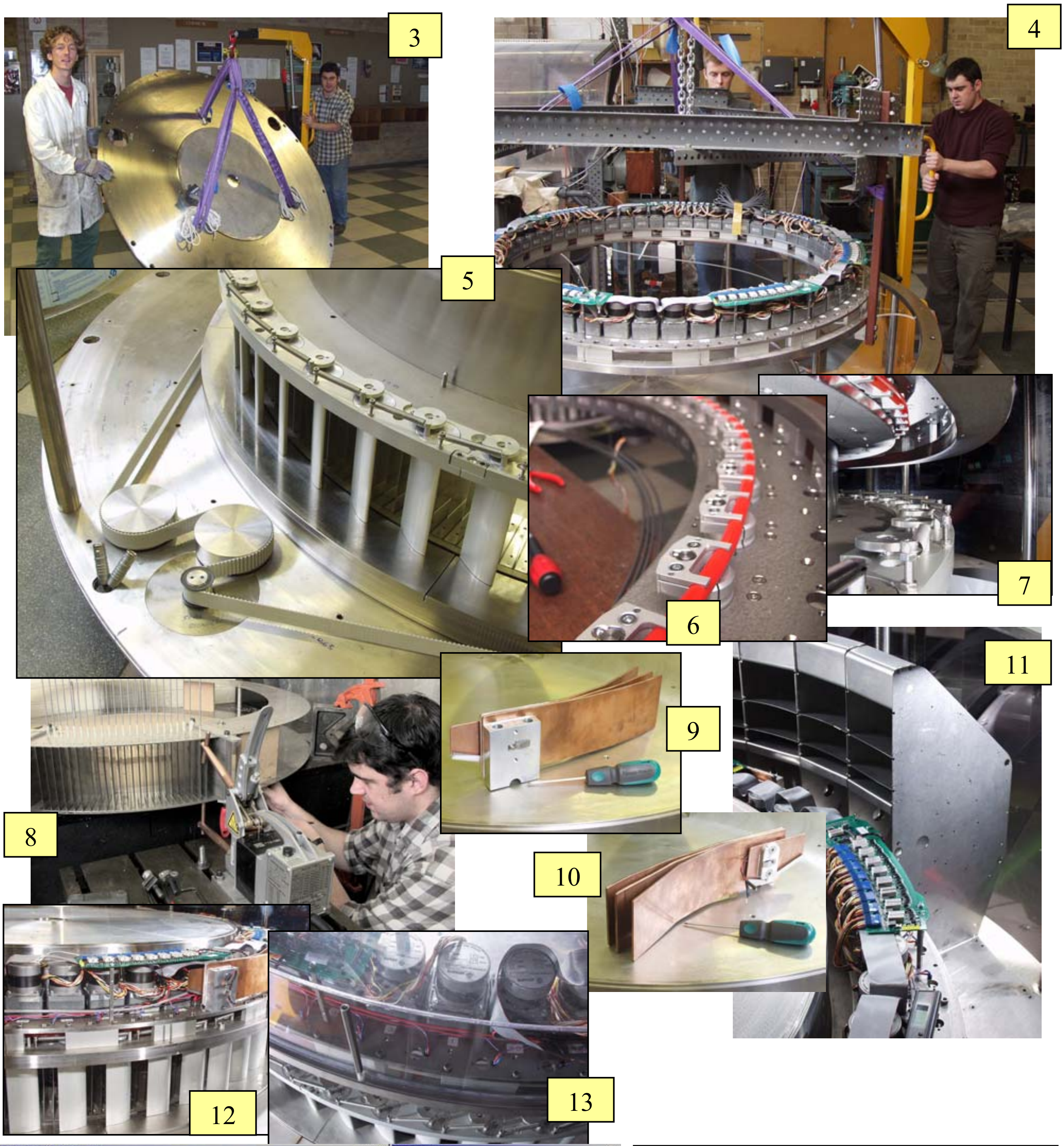
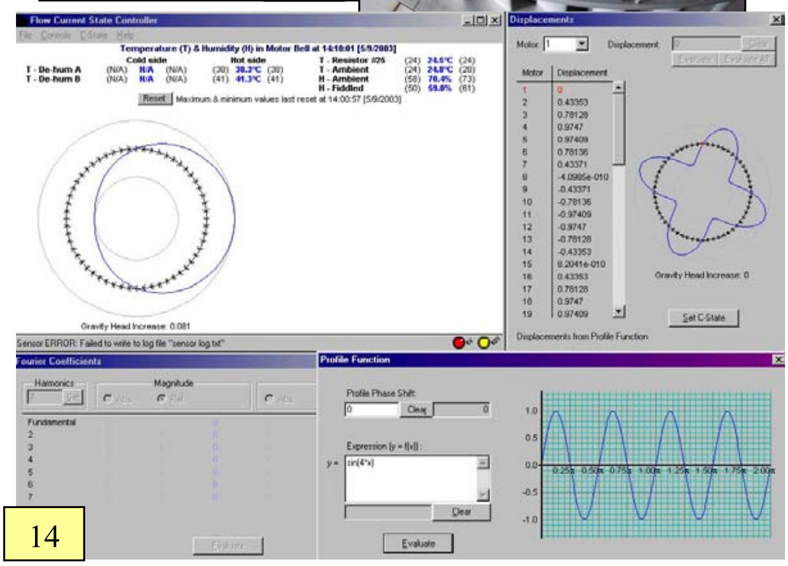


Figure 1: Solid model of the flow table with principal components and main dimensions





3. Sub-contracted large machined parts
4. Dropping ring of 56 steppers into place
5. Rotor drive - spindle, belt & pulleys
6. Red cam-band gripped by ‘sea-saws’
7. Cam-band, roller followers & springs
8. Spot-welding the stator assembly
9. Peltier effect de-humidifier - hot-fins
10. Dehumidifier – small cold fin at right
11. Bends, stepper-motors, electronics
12. Ready for protective annular bell
13. Bell in place over stepper-motor ring
14. Software - current (sin x) pattern at left, next pattern (sin 4x) at right

Photos 3 to 14: Flow table details

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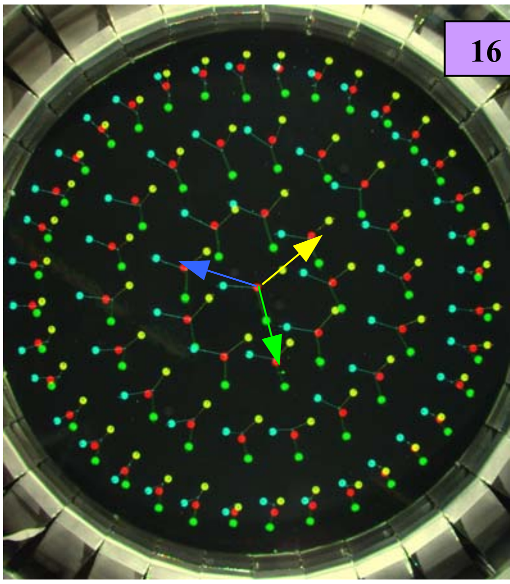

15. Tethered sub-surface wooden balls create their own turbulence but give quick guide to flow
16. Red: still water. Superimposed yellow, green & blue photos show 120 degree rotation of flow
17. Red-blue vectors show simple sin(x) flow.
18. Sin(2x) cam profile gives simplest contra-flow

Photos 15 - 18: Simple flow visualisation

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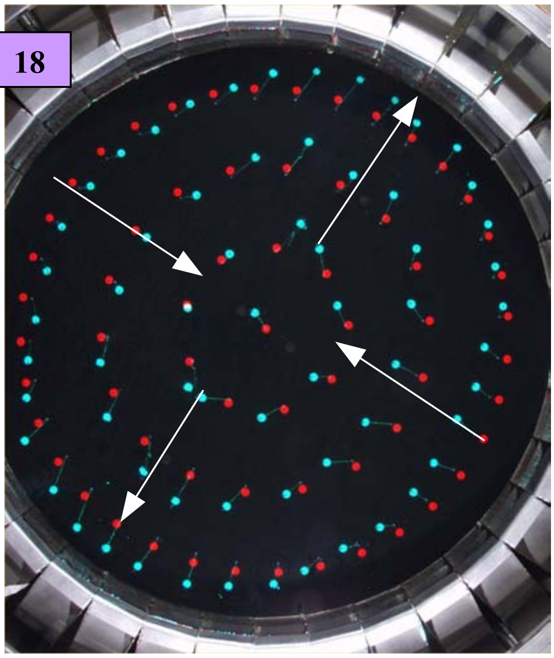

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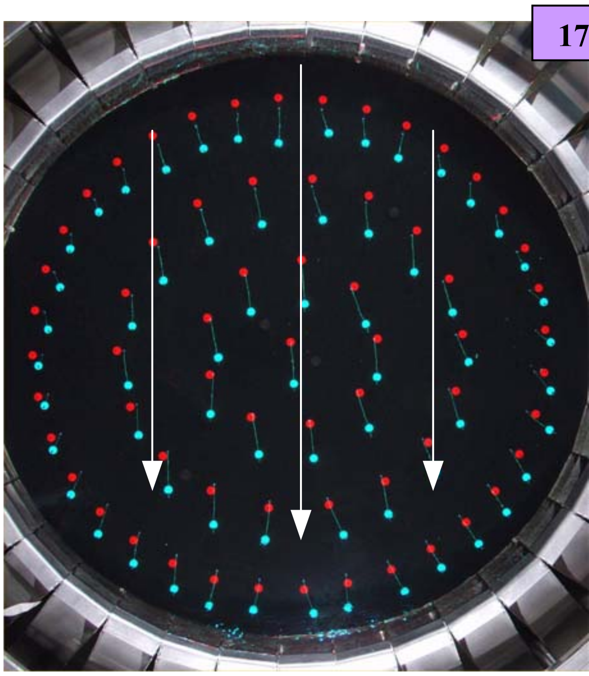

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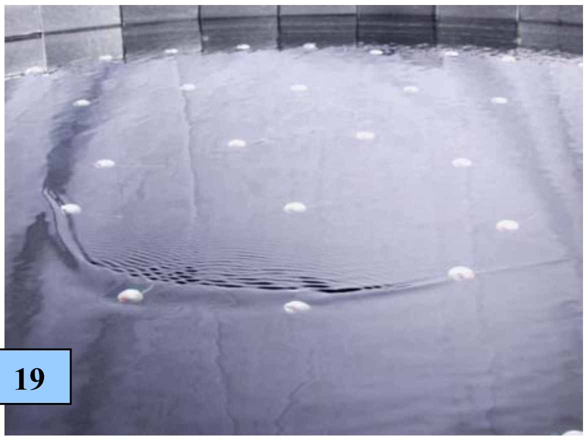

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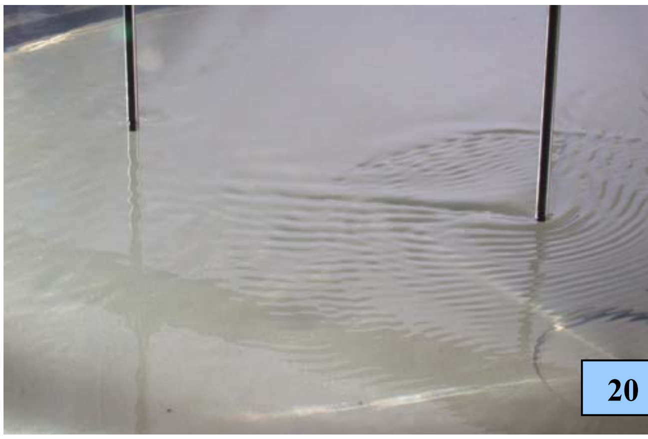

19. Unidirectional flow (top right to bottom left). The standing-wave pattern progressively moves from the flow source-side to the sink-side as the flow speed is increased
20. Unidirectional flow (lower right to upper left). 5mm rod on right immersed to 10mm & inside standing wave, creates wake. Second similar rod, outside of standing wave makes no wake.

Photos 19 & 20: Catenary standing-wave pattern

Humidity is controlled by two Peltier effect coolers . These have hot fins (9) which warm the air and a cold fin (10) which condenses water so that it dribbles out to a drain. Unfortunately the subcontractor for the bell was not able to achieve a base flatness that would permit the intended sealing arrangement and so the internal water level is about 25 mm higher than desired. At the very highest rotor speeds there is a small amount of internal splashing. This enforces an upper water velocity limit of 1.25 m/s which we hope to be able to double with a new annular bell.

The rotor bearing uses 8mm diameter silicon carbide balls which have 45 degree contact with four hardened stainless steel 'wires' ground to form a bearing track. This gives both radial and axial location and seems happy underwater. The bends and guide vanes were made from laser-cut 0.15 mm stainless steel profiles. These were self-jigged into their assemblies by using long thin dowel rods and then spot welded (8).

It had been planned to control the profile of current shear velocity using movable guide vanes in the 180-degree bends. Unfortunately the early retirement of Dr George Alder meant that we lost our expert FLUENT user. However we realised that very good control of velocity gradient could be achieved with non-rectangular sections of skeleton foam pushed into the rectangular passages of a removable flow modifier. This way the local density of the foam can be made to vary with depth in accordance with the initial un-squeezed foam profile.

Items which were too large for our own workshop were machined by Ross Deeptech of Stonehaven (3). There were very few problems during assembly. We experimented to choose the best ratio of hot and cold plates for the Peltier cooler. A major crisis caused by the discovery of asbestos panels in the wall through which we had planned drainage pipes was averted by the provision of a separate water holding tank. When not in use, the flow table can be drained to it through filters. This takes about 20 minutes. If the flow table design goes into production it will be cheaper to replace the many stainless steel items with a single GRP shape.

Control

The RS P700 stepping motors were chosen because they have a particularly high detent torque of 53 mNm and so can hold position when not energised. This is important because, to reduce cost and space requirements, they are sequentially connected to a single set of external power-electronics by a combination of steering diodes and MOSFET ground switches. They do 200 steps per revolution and are fitted with 50:1 gearboxes. Their absolute positions are initially determined by driving them at reduced torque up to their end-stops during an automated motor ‘verification’ routine. Coil drive is through a current source. Contact is detected by the consequent change in the drive voltage.

Flow patterns can be set and edited in several ways (14). The cam settings can be defined by an algebraic equation of arbitrary complexity including IF, THEN logic statements. They can also be set in terms of the amplitude and phase of the Fourier components of a polar equation. The individual table entries produced by either of the above methods can separately edited and there are global amplitude and angular controls to modify existing flow states. Any state can be saved. The system can automatically step through a series of saved flow patterns. The existing cam settings are displayed in polar or Cartesian form alongside the proposed new settings. The progress of the cam pattern changes are shown as ‘morphing’ diagrams.

Test results

Within a few minutes of the first run we noticed an interesting standing-wave pattern in the form of a catenary which could be moved across the diameter of the test region by controlling the current velocity. At the centre of the catenary was a group of standing ripples. Most puzzling of all was the observation that an object inside the catenary produced a prominent wake but an identical one outside produced none, even though the flow velocities appeared identical.

Conclusions

- The design has generally proved to be robust but improvements are required in the motor bell and its sealing
- Further work is also required to calibrate the flow generation system and to provide good flow visualisation
- An interesting flow phenomenon has been observed: – the ‘catenary standing wave’
- The table is expected to be a useful research facility for studies of tidal stream energy components
- During the course of the project, increased concern has been noted from the renewable marine energy research community regarding the complexity of wave and current interaction.
- The flow table successfully demonstrates the proposed system for current generation in a large combined wave and current tank