PROCEEDINGS OF THE CONFERENCE ON

DIRECTIONAL WAVE SPECTRA APPLICATIONS

14-16 September 1981
University of California
Berkeley, California

Edited by
ROBERT L. WIEGEL

P185 - 202

CO-SPONSORED BY
AMERICAN SOCIETY OF CIVIL ENGINEERS
Coastal Engineering Research Council
Waterway, Port, Coastal and Ocean Division
and
ENGINEERING COMMITTEE ON OCEANIC RESOURCES (ECOR)

AMERICAN SOCIETY OF CIVIL ENGINEERS FOUNDED 1852

Published by the
American Society of Civil Engineers
345 East 47th Street
New York, N.Y. 10017

Absorbing Wave-Makers and Wide Tanks

S.H. Salter*

Abstract

Experiments aimed at generating power from sea waves used models which sometimes reflected waves back to the wave-maker. The difficulty was avoided by changing the wave-maker control system so that it could absorb reflections. A wide tank using a bank of absorbing wave-makers is being used to test more advanced models in seas of controlled angular spread. A crude measure of crest-length can be obtained from measurement of the correlation coefficients between wave-gauges at different separations.

Introduction

It was with some hesitation that I accepted an invitation to talk at this conference. Until recently my only qualification to work on waves was a total absence of any preconceptions. But in 1973 I set out to examine methods of generating useful power from them. For most of the possible techniques the scaling rules operate extremely well and so a great deal of our work has involved the testing of models at scales of about 1:100 in model seas of progressively increasing realism. I believed that a wave tank should behave like the instruments on the test bench of an electronic engineer. I wanted to be able to control exactly the sizes, frequencies and angular spreads of the sea and to arrange repeatable 'freak' events at will. Furthermore it seemed clear to me that the best wave energy device would have a very long crest-spanning configuration. This meant that we would need to control a large width of sea front rather than the small patch which would be acceptable for oil-rig experiments. This paper describes the steps towards that objective.

Early problems

My first introduction to the problems of wave-making came in a borrowed narrow tank which was equipped with a hinged flap wave-maker. It was driven through a crank and push-rod by a geared-down induction motor. Although the amplitude of the angular movement of the flap was constant, the amplitude of the waves often showed variations of up to 30%, which made experimental measurements quite difficult. The trouble seemed to be caused by reflections from the models. Indeed,

* Reader in Mechanical Engineering, University of Edinburgh, Scotland.
~~tel (031) 667 1081 ext [illegible]~~ tel (031) 650 5703.

if I fitted the tank with a fully reflecting cliff, the result was a spectacular growth of wave amplitude.

Let us consider the action of the hinged flaps shown in Fig. 1. Although they are both driven through the same angle, the one on the right has its hinge deeper than the one on the left. As a result its swept volume is larger and the wave that it makes will be larger too. Clearly the amplitude of the wave-maker movement is not sufficient to define the amplitude of the waves. We also need to know about the depth of immersion of the hinge.

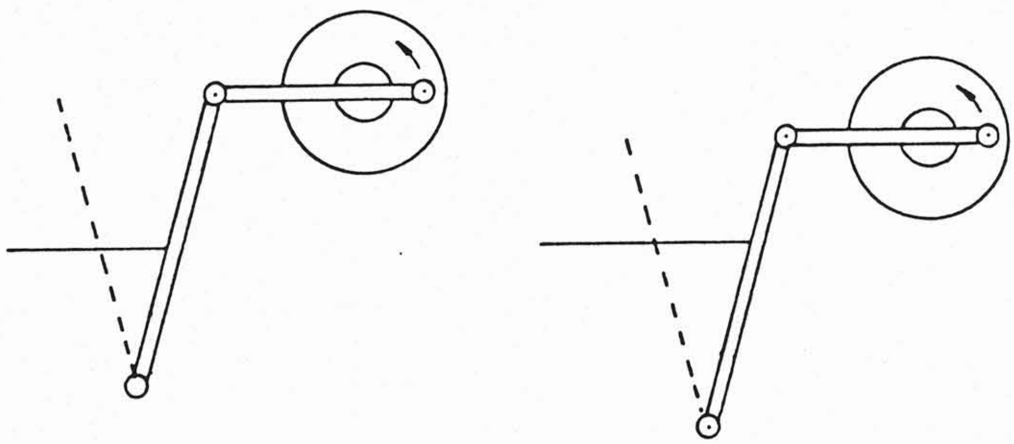

Fig. 1. Swept volume depends on hinge depth which depends on many factors. Reflections mean trouble.

If we ignore evaporation and leakage, the following factors could alter the water level in front of a wave-maker.

(1) Reflections from the model or beach.
(2) The aftermath of previously generated waves.
(3) The presence of other components of a spectrum.
(4) Waves coming sideways from adjacent units in a bank of wave-makers.
(5) Waves coming across the face of a single wide unit, which can be generated by end effects, flexure or uneven geometry.

If we take all these factors into account and recall that, for a flap, the swept volume depends on the square of the hinge depth, it seems that, despite its widespread use, displacement is a very *bad* indicator of the size of wave to be generated.

Possible solutions

Once unwanted energy is in the tank the only thing that can be done is to absorb it. The first application of absorbing principles was reported by Milgram (1)(2) in 1965 and later in 1970. The usual configuration of beach uses a lot of tank length, and performance very often falls for low values of wave steepness. Milgram wanted to make a short beach which would work well at small wave steepness. He placed a capacitance wave probe close to the front of a flap and passed its output through an active electronic filter to an electric motor driving the flap. He was able to demonstrate stable operation and good absorption but has not reported that he went on to use the equipment as a wave-maker.

In principle there are many techniques available which would give a wave-maker information of what the water is doing. We could use resistive or capacitive wave gauges like Milgram. We could use radar, sonar or lasers. We could measure pressure or force. The signals from any such sources could be processed to produce any of the others and, provided that the instruments are working properly, there is little theoretical distinction between them.

Unaware of Milgram's work, I decided to measure force on the wave-maker. I believe that this has three advantages. Firstly, a single force sensor takes a mean value of water conditions across the whole of the wave-maker front. To obtain as good a statistical sample in the presence of cross waves would require taking an average from probes at many points across the wave-maker.

Secondly, force sensors can be entirely free from the chemical and biological vagaries of tank water. We have found that, despite attempts to compensate for conductivity changes, we have not been able to guarantee long term stability from every member of a large batch of resistive gauges. We have also found that capacitive gauges will eventually develop a surface film which introduces a lag to the output signal for falling water levels. The trouble is that tank water is an ill-defined medium. Minerals are present. Corrosion inhibitors are added. Biological growths and slimes form. Biocides are used to kill them. People spill oil. Dust settles. Residues are left by evaporation. Conditions of the probe are different above and below water level. Examination of glass tank-windows after six months shows how dirty the surfaces of our gauges must be. We have not yet developed a wave gauge which can be trusted without frequent cleaning and calibration and this is not acceptable for a large bank of wave-makers.

A third advantage of force measurement is that it is easy to combine the signal from the force transducer with that from a velocity transducer, and thereby fix the rate at which *energy* is given to the water. I have a great respect for the soundness of the principle of the conservation of energy. Many successful machines have been built which demonstrate its usefulness. While we all treat water waves as if they were sinusoids we know that, as the steepness increases, this approximation becomes quite seriously wrong. The troughs are shallower and the crests are sharper and higher than in a sine wave. I argue that it is better to provide the right amount of energy at each frequency than to try to enforce a sinusoidal form that the waves do not like. We should leave the waves to decide for themselves which order of Stoke's corrections is appropriate, how to mix the frequencies together, and what shape suits them best.

Gilbert (3) rejects force measurement on the ground that the force signal is corrupted by the need to accelerate the displacer. However the mechanical inertia is constant and it is not difficult to make it small. If this is done, the force needed to accelerate it will be small in comparison with the force needed to move the water and can be allowed for. Furthermore the laws governing force, mass and acceleration are by now rather well understood.

To summarise: there are many ways to control a wave-maker. The displacement of the moving element is the worst. Force techniques have the virtue that they sample the whole frontage, that the transducers are isolated from both chemical and biological properties of tank water thereby achieving good long-term stability, and that by controlling *energy* they bypass many of the problems of non-linearity involved in generating steep waves.

Wave-maker design

If we decide to measure force we must ensure that the force signal does not include contributions from waves created behind the wave-maker. This could be arranged by fitting the wave-makers with a force-sensitive front panel. But I believe that it is better to avoid the problem altogether by using an asymmetric arrangement with no waves created behind. In this way we halve the rating of motors and power amplifiers and also halve the energy consumed.

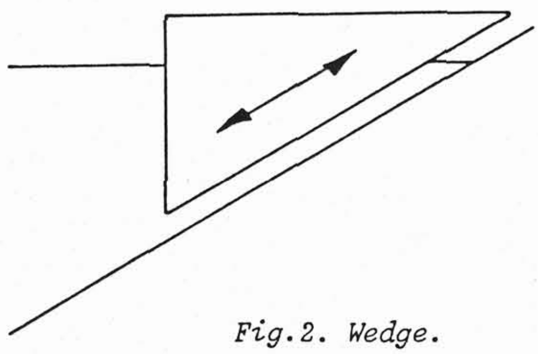

Fig.2. Wedge.

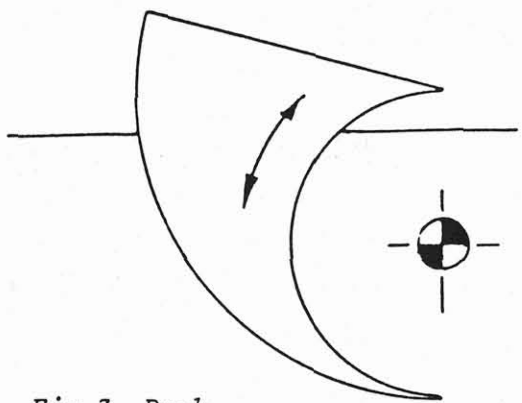

Fig.3. Duck.

There are several ways of producing the asymmetry, three of which are shown in Figs. 2,3,4. It is generally the case that sliding constraints are more difficult to implement than rotating ones, and this is particularly true underwater. We have therefore not used the sliding wedge. But we have obtained satisfactory results with both the 'duck' and the sealed flap.

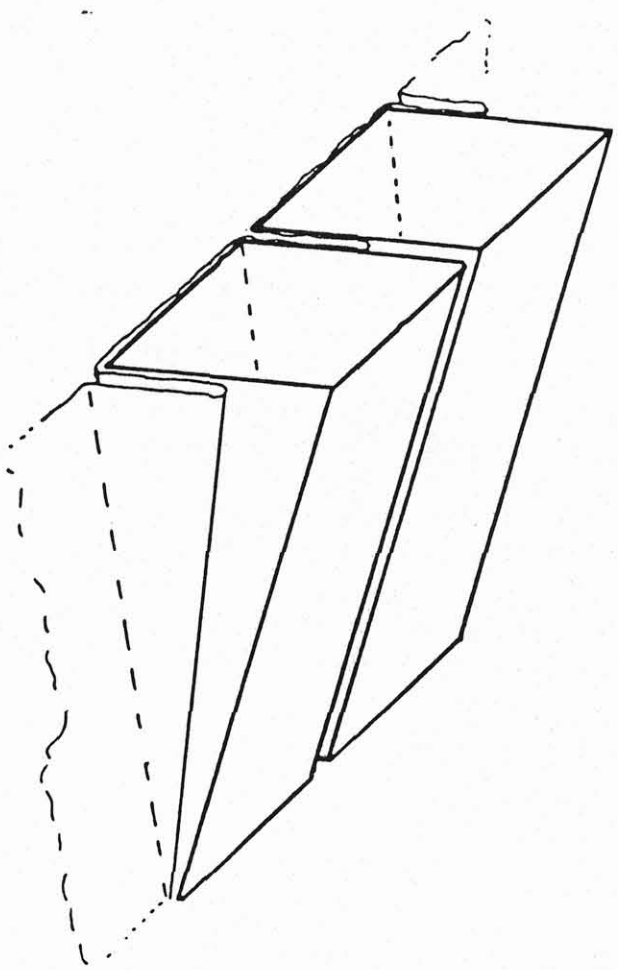

Fig.4.The 'Belofram' membrane seal.

Sliding seals are used successfully at the large manoeuvering tank at Gothenburg in Sweden but as we wanted to avoid friction forces we preferred the membrane "Belofram" principle reported by Taniguchi and Kasai (4) in 1972. We find that polyurethane-impregnated nylon fabrics are excellent. But it is essential that they are *not* required to bend in two directions at the same time in the same place. This difficulty is most acute at the point where the back line of the gusset meets the line of the hinge, and careful design is necessary to avoid early failure.

Figure 5 shows the arrangement of our current design. The flap consists of a riveted 18 gauge light-alloy prismatic box which is both light and rigid. The drive comes from a low-inertia printed armature motor. It is connected by a multi-strand stainless-steel wire wrapped seven times round a screw-threaded pulley on the motor shaft. Some careful development was necessary to choose the size of the pulley. We want it to be small so that the electric motors can run fast and be efficient. But if we make it too small we run into fatigue problems from bending the wire round too tight a curve. Our present combination has not given a fatigue failure for three years from a sample of eighty units.

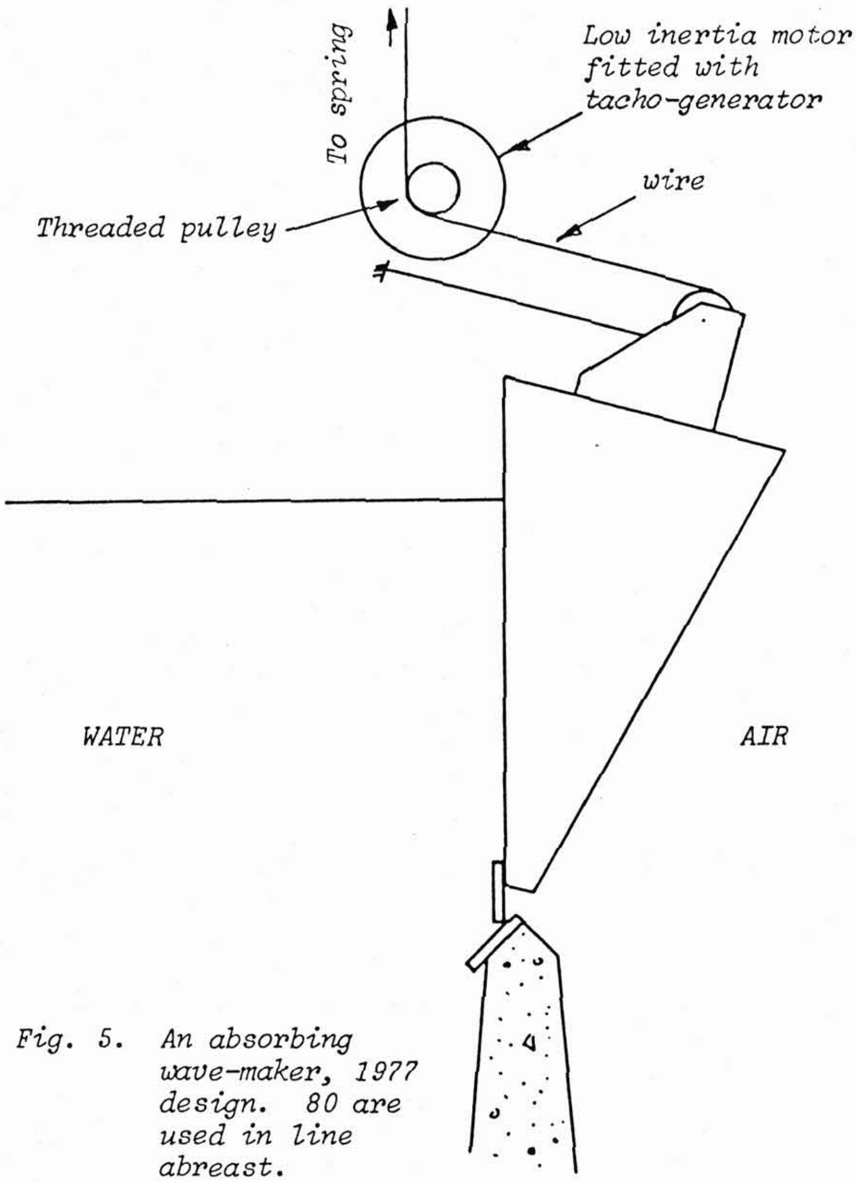

Fig. 5. An absorbing wave-maker, 1977 design. 80 are used in line abreast.

The hydrostatic force trying to push the wave-maker backwards is balanced by a spring. Its rate is chosen to resonate with the mass and added mass of the flap system at a frequency a little above the centre of the working band. This means that most of the power goes into making waves rather than accelerating and decelerating inertia. Two power transistors working in class B are more than enough for fully developed waves at 1 Hz. The resonance of the flap is so damped that its effects are spread over a large fraction of the working band and the transfer function of the wave-maker is a gentle curve. We try to make the wave-maker behave like a correctly matched source impedance analogous to an electronic pulse generator driving a co-axial cable. An electronic network produces the effect of "negative spring" at low frequencies and arranges that the damping coefficient of the flap varies correctly over the frequency band. The design has to compromise between the requirement of generating large waves at low frequencies and that of absorbing at high frequencies.

The wire drive allows considerable tolerance in motor-to-wavemaker alignment and avoids the extra bearings that would be needed for the coupling of a more rigid actuator to the arc of movement of the wave-maker flap. The wires are happy in the splash zone and need no lubricant. They are stiff enough for the required gain-bandwidth product.

Clearly wires cannot push the wave-maker. All the force to push it backwards comes from the water. It is never necessary to move the flap backwards faster than the water can follow it. If we tried to do so, the water would be left behind and we would be trying to make waves in air.

To summarise: wire drives can provide the right speed ratio and can be designed to escape bending fatique. They are tolerant of misalignment and can work in dusty, wet conditions. Their frequency characteristics are adequate. But above all they are very, very cheap.

Force sensing

Our first force-sensing transducers used etched foil strain gauges. But we found that it was easier to achieve a high stiffness value with piezo-electric crystals. These have the further advantage of not needing a stable energising supply and not minding a large standing bias force. The availability of cheap field-effect operational amplifiers has opened up many low frequency applications for piezo-crystals, but they cannot, of course, work down to zero frequency. This means that the low frequency as well as the high frequency characteristics of the control loop must be carefully designed to ensure stability.

We were concerned that the humid conditions of a wave tank would not be compatible with high-impedance circuitry. This worry proved groundless. Every transducer had to survive an initial 24 hours immersion in 60 cms of water. The few failures showed up at the very start and we have not had a wet piezo crystal for three years. All our experience of doing electronics in and under water confirms the belief that impedance is irrelevant when the circuits get wet. Indeed high-impedance circuitry has the possible advantage that it takes longer for the wires to be electro-plated away!

Velocity sensing

Velocity is just as important as force. Our velocity transducers are coupled to the rear shaft of the drive motors. Although we intended to use purpose-built tacho-generators we were forced by delivery problems to use ordinary ironless-rotor D.C. electric motors. The only difference appeared to be a slightly wider spread of calibration constant. All brush-commutated tacho-generators have small spikes present in their output signal which are caused by the segments of the commutator. The spike repetition frequency is far above the working band and so they cause no problems. But the spikes can be used to good advantage for calibration purposes. It is possible to use them to trigger a discriminator and thus obtain very precise digital calibration.

It is most desirable, particularly where multiple units are concerned, to avoid any calibration adjustments which are not absolutely necessary. We put a good deal of effort into an electronic circuit design which gives uniform behaviour with fixed resistors. We managed with only one potentiometer.

We designed the units for multiple production and tested a single one in a narrow tank. Its hinge depth was 500 mm and it was optimised for operation at 1 Hz. The long-term stability of wave amplitude has proved satisfactory. Even with a totally reflecting cliff giving a complete standing wave the variations amount to only a few parts per thousand.

With the help of the unit in the narrow tank we were able to develop the models of our wave energy devices so that they reflected very little of the incoming power. This had excellent results as far as our predictions for full-scale mooring forces were concerned but that is part of another story. It was time to go to multi-directional seas.

Controlling Direction

An earlier multi-directional tank at the Hydraulics Research Station Wallingford (5) employs amplitude variations to control direction. A bank of 10 wave-makers are arranged in a crescent and, if it is required to increase the power from one direction, the amplitude of the units in that direction is increased. The technique works well for the area at the centre of the crescent but would not cover the frontage needed for long crest-spanning devices.

The approach we selected owes much to the guidance of Longuet-Higgins and the method he used to teach us about directionality. Familiarity with Huygen's principle in optics or phased-array radars may be helpful.

We assume that a sea state is the result of the superposition of a large number of 'fronts'. A front is a long-crested regular train of waves specified by four numbers:-

(1) The amplitude
(2) The frequency (or period or wave length)
(3) The angle made to the side of the tank
(4) A starting phase relative to other fronts.

A front would be generated by a bank of a large number of narrow wave-makers if there was a progressive phase shift ϕ of their command signals. In Fig. 6 the front angle is given by

$$\alpha = \mathrm{Sin}^{-1} \frac{\phi\lambda}{2\pi P}$$

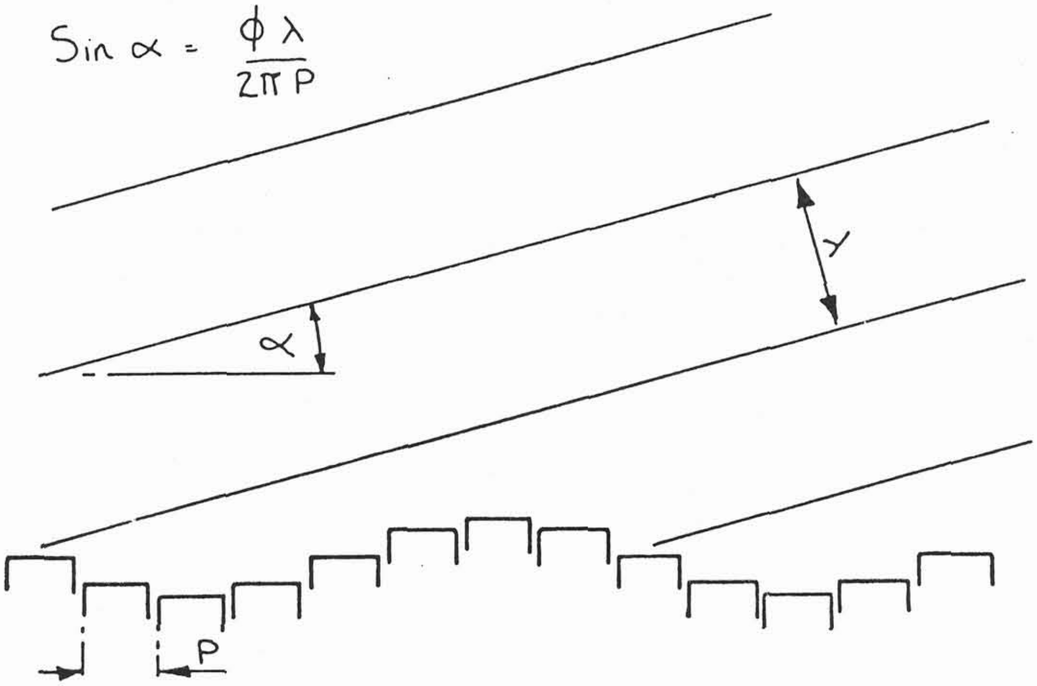

Fig. 6. A phased array of wave-makers.

Several tanks have used this principle to generate regular monochromatic single fronts. The drive is taken along a common rotating shaft and the angle of the crank driving each element is adjusted manually.

There are two minor limitations. The wave-makers will move in the same way if $\phi = 0, \pm 2\pi, \pm 4\pi$ etc. This means that there are a number of possible values of α. If we try to make $\alpha = 0$ and apply a large command signal at a high frequency we will sometimes generate a spurious pair of oblique fronts in addition to the intended one. This is one way to produce cross waves in a narrow tank.

Secondly there is a restriction on making short waves at large values of α. We cannot get α up to 90° if $\lambda < 2P$. This means that we should make the pitch of the wave-makers as small as we can afford and use a large number of them.

The mechanical drives could only produce one frequency at a time and must have been laborious to adjust. But modern electronic technology allows the superposition of many sinusoidal command signals and instantaneous changes of sea state.

A measure of the difficulty of the computing task is given by the product of the number of wave-makers times the number of fronts times the number of samples per second. The computer we use can run at a 'difficulty product' above 10^5. The Edinburgh tank has 80 wave makers. We update the command signal 20 times per second. This means that we can compute the command signals for 75 fronts. The newer model of the computer is faster and so the large wave-makers in the new tank at Trondheim can be updated at the lower rate of 10 per second. This allows them to produce more than one hundred fronts. If it should be thought that a spectrum with one hundred discrete teeth is not a proper representation then it is not very expensive to add more computing power. Indeed it will probably turn out better in future to split the task between several slower machines. An alternative is to dither the teeth of the spectrum continuously. But we believe that neither of these is necessary because of an interesting effect noticed by Glenn Keller.

Keller's Tooth-Breeding Experiment

Keller generated two long-crested fronts with frequencies close to one another. He chose the frequencies so that they would both fit exactly into the repeat period of his sampling time and also would both lie on single lines of a fast Fourier transform. He used four test conditions, generating both small and moderate amplitudes and measuring them close to, and far from, the wave-makers. The small amplitude case behaved as one would expect. But at a steepness of only 1 to 30 the results showed a very interesting display of extra teeth in the Fourier transform which is shown in Fig. 7. The effect is more marked at a distance from the wave-makers. The extra teeth are spaced at intervals equal to the original separation frequency but also occur *below* as well as above the original pair. Furthermore the envelope of the group reminds one of the shape of many theoretical spectra. If we were to let the process continue we would be able to produce a proper broad spectrum from a single pair, like rabbits in Australia. If two teeth can do this in a few metres then 75 can do so as well.

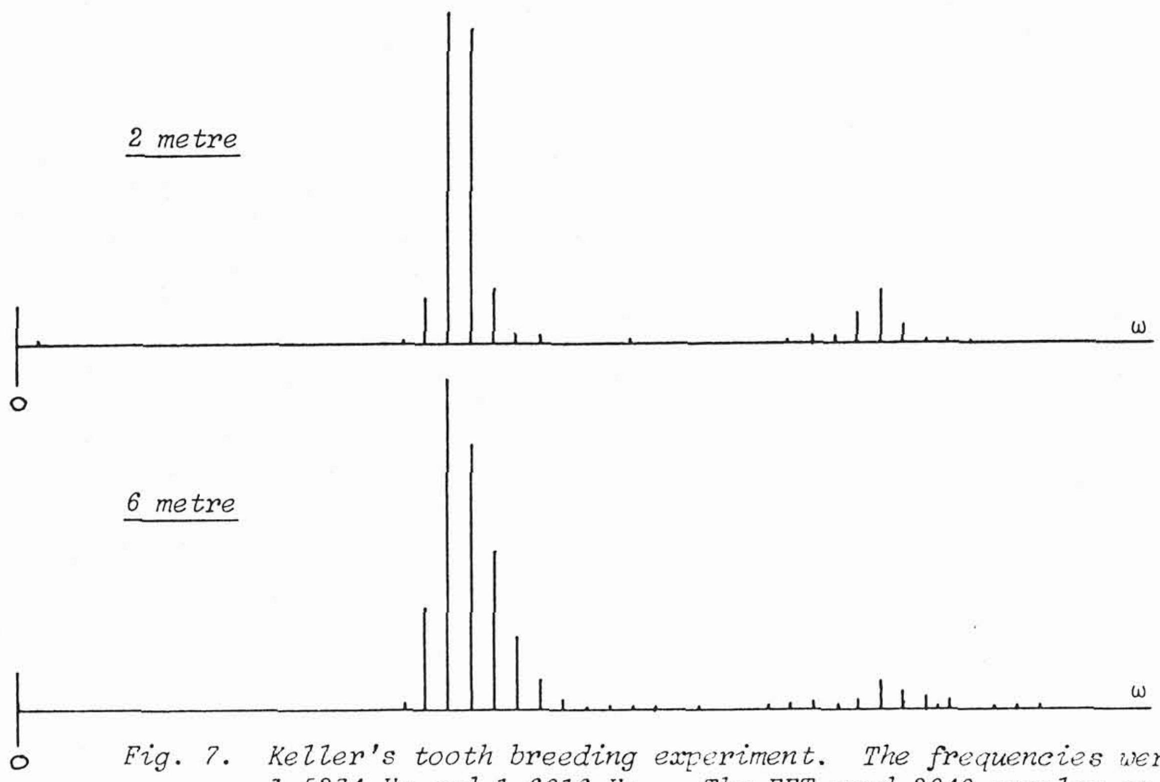

Fig. 7. Keller's tooth breeding experiment. The frequencies were 1.5234 Hz and 1.6016 Hz. The FFT used 2048 samples at 20 Hz. Teeth are bred at intervals equal to the original separation above and below the parents.

Choosing the fronts

The computer which generates the wave-maker command signals (a Plessey Miproc) runs with an efficient but obscure machine code program. The instructions are produced by a slower high-level language machine which offers a great variety of editing facilities.

The most basic, called "brewing", allows us to choose the fronts by typing in four parameters for each. This is used for single fronts and the binary front "quilt" but is tedious for large numbers of fronts. Programs have therefore been written which produce machine code for the various theoretical spectra, with options to select any of the spreading functions in their original or a modified form. We can specify them by wind-speed or energy-period and introduce a model scale factor. For example we can ask for a Jonswap with cos↑2.4 spread or a Pierson-Moskowitz with Mitsuyasu spread, modified so that the crest lengths are all, say, 1.5 times Mitsuyasu's recommendations. We can rotate the whole bank of fronts through a specified angle, modify individual fronts, and carry out a variety of global editing functions.

The amplitudes, frequencies and front angles are chosen so that each contributes a roughly equal amount of energy to the final result. The algorithms for this are due to Mollison, who has developed some elegant statistical methods to ensure that the results are "more randomly distributed than plain chance".

If the model to be tested has some unusual property such as a particularly narrow resonance band, we will obtain better results by concentrating more fronts round that frequency and reducing their amplitudes to keep the energy content correct. Alternatively if we want to exaggerate resonant behaviour we can add a strong extra tooth to the comb spectrum. We do everything possible to make our wave energy devices exhibit broad-band damped behaviour in every mode, and we have not found structures with resonance peaks narrow enough to be lost between sensibly chosen teeth.

The relative starting phases of the fronts are usually selected on a pseudo-random basis with a seed number which can be changed to get a different second sea with the same statistical properties. But we can ask for the starting phases to be chosen with devilish malevolence so that fronts combine at an exactly specified place in the tank at an exactly specified time after the sequence starts. This produces a freak wave with very low, but not zero, statistical probability. It is usually devastating for ship models and so we can exercise mercy with a lower specified ratio of peak-to-RMS value. The maximum ratio is given by $\sqrt{2N}$ where N is the number of wave fronts. For N = 75 this comes out to 12.25. If we specify a high ratio of peak to RMS value in a large sea at a point which is a long distance from the wave-makers, we may find that premature breaking stops us getting the expected ratio. But by putting the models closer to the wave-makers (two or three metres at 1/100th)scale we can be sure of testing in conditions beyond anything that ships are expected to take. We argue that the 'malice aforethought' method gets tests done more rapidly than a more random method because we do not have to wait for chance to come round. The question is whether it is better to play until the dealer hands you a royal running flush in spades, or persuade him quietly before the game begins. A hundred years is a long time even at model scale.

We found that a particularly spectacular pattern results from making all fronts have the same frequency but choosing the angles and phases so that they converge to one central "bulls eye". Even though the wave is monochromatic and the water deep relative to the wavelength, this procedure produces a plunging breaker with a vertical internal face and a height-to-length ratio of about 1 to 4.5. As energy is contributed by all the wave-makers, the technique gives a method of making very large waves. The trough-to-crest height can be as large as the hinge depth of the flaps.

Testing Testing Tanks

An accurate representation of the sea surface is and looks like a complicated mixture of frequencies and angles. A rigorous proof that one is achieving the desired objective is not easy. We are at the early stages of a programme of work on multiple gauge measurements.

If we choose an artificially short repeat-period for a pseudo-random sequence and measure the output from gauges at points all over the tank for the exact repeat period, we should expect that the RMS value at each point would be the same. However the arrangement of our tank does not quite do this. We have wave-makers along one of the long sides of the tank which are faced by beaches on the other. But while one of the short sides of the tank is also fitted with beaches it is faced by a glass observation window which will, of course, reflect oblique wave fronts. It is no surprise to discover that the side beach causes a triangular area of reduced wave height. But we also found an *increase* along a ridge parallel to the glass about two metres away from it. Other anomalies can probably be traced to sections of beach with slightly inferior absorption. We would also expect that any wave-breaking would deplete the wave heights of a fan-shaped area down wave.

However the variations in wave height over the central three-quarters of the tank are lower, and a good deal less than would occur at sea because of chance. It is gratifying to report that wave records are very repeatable from run to run, and that the differences are about the same as our level of confidence in the wave gauges.

The test which shows up the defects in a wide tank most easily is that of producing long-crested monochromatic wave fronts as in a narrow tank. Wide, rigid, non-absorbing wave-makers cannot do this for any length of time without building up ever larger amounts of cross-wave. We can detect the presence of cross-waves in our tank but their amplitude does not continue to grow. Two very quick subjective tests can be carried out. In the first of them we generate fairly large long-crested regular waves for several minutes. We then switch off the wave-makers and observe the tank-surface after the end of the train has reached the beach. In a short wide tank the cross-waves will still be present. In the second test we generate the same wave train and then reduce wavelength and increase height, so that spilling breakers are just formed. The amount of breaking activity should be the same along the whole frontage. The position of aberrations is clearly marked.

A Variant for Shallow Water

We have a strong preference for the hinged flap for wave making in deep water tanks. Flaps give a reasonable approximation to the exponential decay of orbital motion and do not have too much added mass. But many people engaged in coastal engineering need to make large waves with long periods in shallow water. They require a flat elliptical motion of water particles and find that there is inadequate depth for a hinged flap. We have carried out design work on absorbing wave-makers suitable for these applications.

The arrangement is shown in Fig. 8, and is the subject of provisional patent applications. It consists of two moving elements. A flap which can generate and absorb at high frequencies is mounted with gusset seals inside a carrier. The carrier is mounted from a second hinge well above the water. Its rear surface is part of a circular arc centred on its axis of rotation so that water behind remains undisturbed. The carrier hinges have to resist a substantial upward force. The wave-maker operates as if the flap was the 'tweeter' and the carrier the 'woofer' of a hi-fi system. The correct command signals to each provide nearly the correct displacement at each depth for a wide range of frequencies.

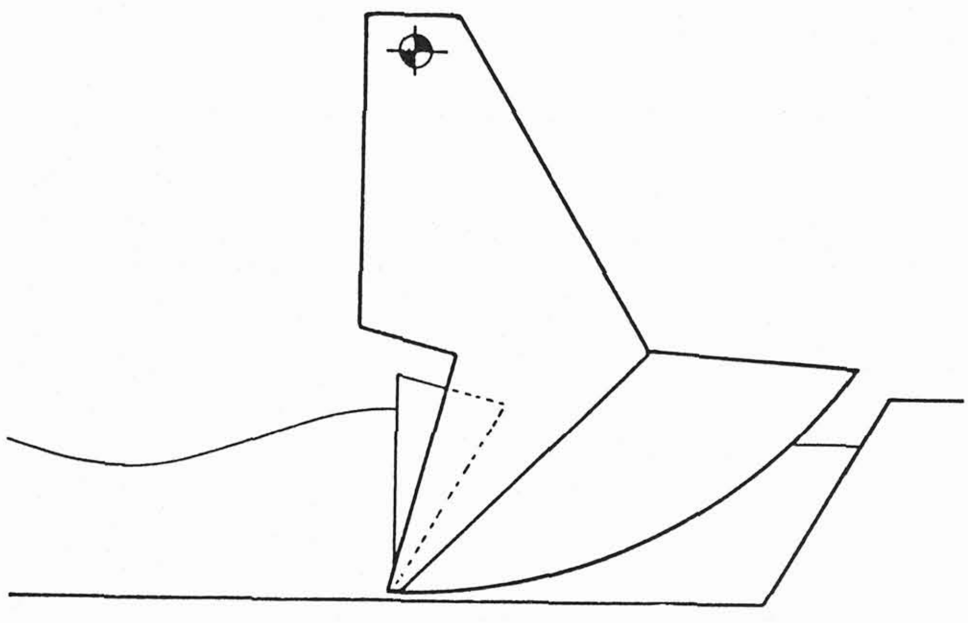

Fig. 8. The woofer tweeter combination for shallow water.

An extra complication is caused by the fact that people who work in shallow water nearly always vary the depth. We have had to make provision to raise and lower the carrier hinge.

Directionality and Crest-length

The newcomer to oceanography is deeply impressed by the enormous achievements in the understanding of the heights and lengths of waves. There is a wealth of experimental data. The statistics for season and place are splendidly detailed. Accurate predictions can be made from wind speed, duration and fetch. Non-linear wave profiles can be calculated to an extraordinary degree of accuracy. Exact answers are instantly provided to every question. The newcomer believes that oceanographers are truly omniscient, that is until he inquires about crest-length.

We needed to know about crest-length because our wave energy devices are mounted on a very long spine (several kilometers) and the bending moments induced by waves in that spine are clearly of extreme importance. We could measure all the forces acting on a section of the device in a narrow tank. If we knew about the lengths of the crests of waves in the sea we could try working out the bending moments, shear forces and deflections of our long spines using the established theory for beams, suitably modified for dynamic applications. Bending moments for a static beam should be proportional to the square of crest-length and deflections proportional to the fourth power. What we needed was an extra dimension to the scatter diagram which specified crest-length rather than wavelength. We could then go ahead and design yielding joints to limit the bending moments and select the optimum value for the amount of post-tensioning steel in the concrete between them. But it was not to be.

Admittedly we were vague about how we would define crest-length in anything but a quilted sea but we knew that the answer ought to be in units of length. Instead we were shown kidney-shaped plots of directional spectra and assured that these contained all the information. It turned out that only a few *hours* of observations had ever been made and that the angular resolution of the measuring instruments was, to one who had previously worked with astronomers, rather low. The wave gauges used to measure directionality seemed to be much too close together. The last straw was that one of the techniques of analysing the outputs of the gauges was called "the maximum likelihood" method but could only be understood by an unusually able Ph.D. student attached to our group. We encouraged him to make it work. He did so and I am pleased to see that he will be contributing to this conference.

There are two things calculated to make an engineer anxious. One is having to rely on data analysis methods that he does not truly understand. The other is having the results in the wrong units. I hope that this conference will relieve my anxieties.

With the greatest hesitation I offer for your derision a method for getting an indication of crest-length on which we have done a few experiments. It is based on the calculation of the correlation coefficients between the output signals of a group of wave gauges arranged in line abreast. The correlation coefficient is much despised by statisticians because its value can be unity for data streams which are not causally related and zero for those which are.

But for our work it has two advantages. The first is that it can be computed 'on the fly' without storing long data streams by even the most feeble microprocessors. The second is that it is very easy to understand.

Fig. 9 shows some typical results. The points are experimental measurements and the continuous curves are output from a 75 front computer simulation. Between correlation values of 0.9 and 0.2 the results are fairly linear. It would be possible to make a reasonably accurate interpolation of the separation necessary for a value of 0.5 and then to use this distance as an indicator of crest-length. For a simple quilt sea we should multiply this distance by 6 to obtain the crest-length.

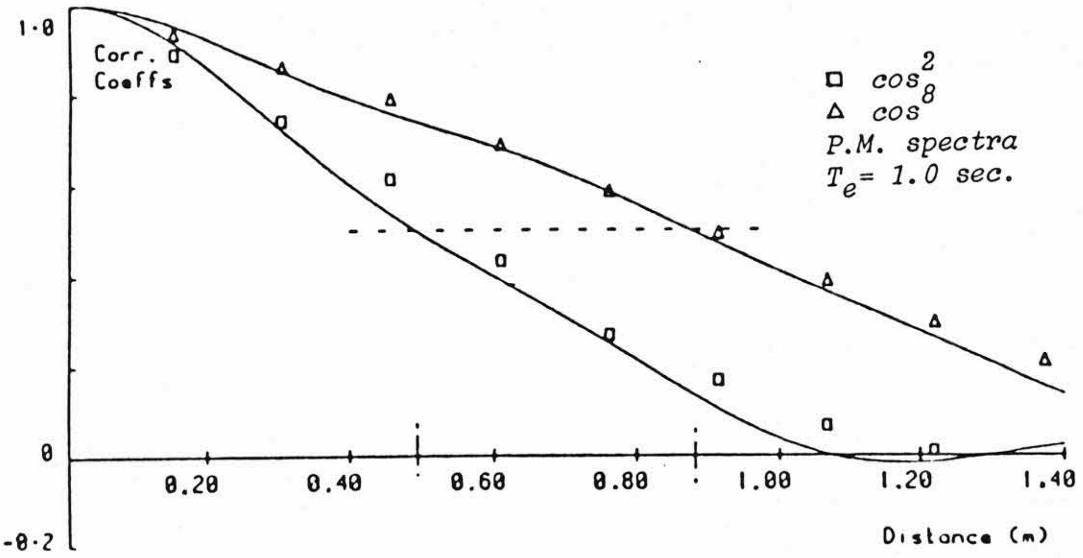

Fig.9. Simulated and measured correlation coefficients for two spreading functions.

One further item will exhaust my knowledge on the subject. We had read (6), that, in a wind sea, "crest-lengths" would be about 1.7 times wavelengths. Glenn Keller and I had the chance to fly in an R.A.F. Nimrod and make simultaneous recordings of an accelerometer and the aircraft's radar altimeter. We flew an accurate circle at constant speed over a new wind sea and compared encounter zero-crossing lengths across and along wind. The ratio was 1.66. Our faith in the omniscience of oceanographers was instantly restored.

Summary

The displacement of a wave-maker is a bad signal to use for control. The size of wave created is affected by reflections and waves from adjacent units. Several techniques can be used to absorb unwanted waves but force measurement is attractive on practical grounds. Absorption makes for good stability. Asymmetric wave-makers save power and the cost of power control elements. Asymmetry can be

achieved for piston displacers for shallow water but flaps are good for deep water. Directional spectra can be generated by the superposition of discrete monochromatic wave fronts. Provided that sufficient fronts are used it is difficult to distinguish the sea state from that of a continuous spectrum. The discrete method enables the controlled composition of abnormal seas.

Acknowledgements

Wave energy research at the University of Edinburgh is supported by the United Kingdom Department of Energy. They paid for the tank and allow a generous sum for maintenance and improvements. I would like to thank the officials who are keen to see the successful development of renewable energy and in particular the official who authorised the construction of the tank in the face of an expert recommendation that it would never work. (He was reprimanded for doing so.) To complete construction within the budget required a great deal of hard work from students and school-leavers who added temporary strength to the wave energy research group.

This paper was written for the Directional Wave Spectra Applications'81 symposium, Berkeley, California and is reprinted with permission from the American Society of Civil Engineers.

References

(1) Milgram, J.H., Compliant Water-wave Absorbers. M.I.T. Department of Naval Architecture and Marine Engineering Report no. 65-13. 1965.

(2) Milgram, J.H., Active Water-wave Absorbers. J. Fluid. Mech. vol. 43, part 4, pp 845-859, 1970.

(3) Gilbert, G. Absorbing Wave Generators. H.R.S. Notes, no. 20, pp 3-4, 1978.

(4) Taniguchi, K., Kasai, H., A New Flap-type Wave-maker without Water on Back Side. J. Soc. Nav. Archit. of Japan, vol. 132, pp 129-136, 1972.

(5) Russell, R.C.H., Hydraulics Research 1973, pp 18-19, HMSO, London, 1974.

(6) Rye, H., Relative Crest-length of Sea and Swell. J. Phys. Oceanography, vol. 3, pp 492-493, 1973.