

Proposals for a Component and Sub-Assembly Test Platform to Collect Statistical Reliability Data for Wave Energy

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This paper extends work done for the EC Thematic Network on wave energy under the package on the requirements for research for fourth generation devices.

Introduction

Politicians and public relations people, who have never suffered from the friction of reality, want to see working wave energy devices generating electricity as quickly as possible. They regard work on laboratory test rigs as a boring waste of time and money - entirely lacking in visual impact and punchy sound bites. The investors must see something hard for their investment and see it soon.

The miserable reality of engineering is that it is very difficult to make new things work in new or unfamiliar conditions especially when you are short of time and money. A good project can be entirely ruined by the most trivial failure: a single defective O-ring or a chafing cable can be enough. In the world of the politician this would be the equivalent of a government report containing a comma where the purist would have used a semicolon.

Failure can be very expensive in the money and time which the investors are so keen to save. Failure of one device damages credibility of all the others. Failure is about statistical probabilities and we need to understand how large numbers of items will survive. Failure can sometimes be slow so we need to confirm the suitability of components long before they will be used in complete equipment. While failure of internal parts can be eliminated by tests in the laboratory, failure at sea is often caused by chemistry or biology, subjects in which engineers are often weak.

Statistical ideas

Engineering artefacts can suffer failures dramatically, where something suddenly breaks, or progressively through corrosion, fatigue or wear. To achieve an acceptably low failure rate it is necessary to understand both the stresses that the sea is inducing in the equipment and how good the equipment is at enduring these stresses.

Both stress and endurance have a complicated statistical pattern. Every wave is a separate experiment inducing its own peak load to each part. It is helpful to think of two probability distributions with the asymptotic upper skirt of the stress distribution approaching and overlapping,

hopefully by only the very slightest amount, the lower skirt of the endurance one. In some cases the statistical distributions will be close to the mathematically convenient Gaussian distributions shown in figure 1. In this example the load from the sea has a mean value of zero and has been normalised to give a root mean square value of unity. The mean strength of a batch of parts is taken to be four times this with a standard deviation of one tenth of the mean.

Figure 2 zooms in on the dangerous cross-over region. This shows that from a little under the stress of 2.5 times the root-mean-square value, there will be some parts with failure stresses which are below some loads that will occur.

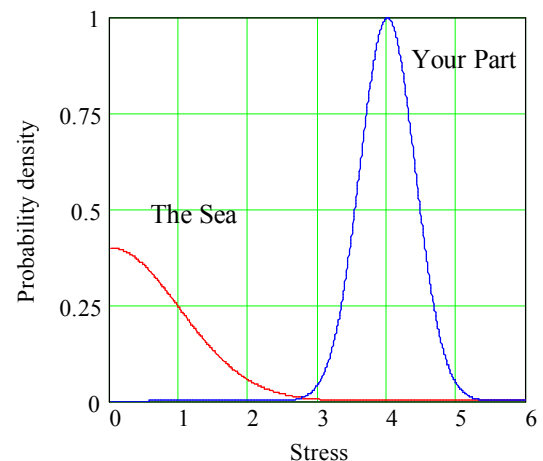


Figure 1. Stress and failure distribution

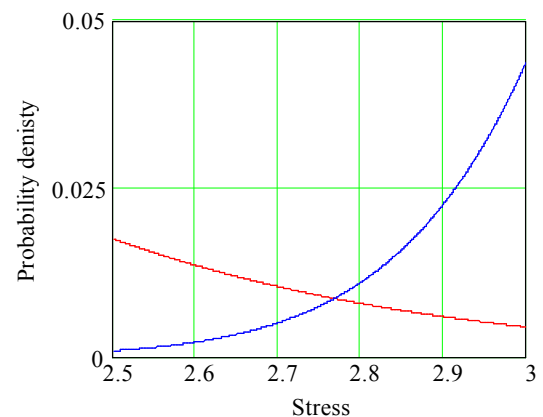


Figure 2. Zooming in on the overlap

For a mature technology, the size of any overlap is in effect set by accountants, insurance brokers and public opinion.

It is more useful to think of the statistical distribution of part failure in terms the cumulative failure probability. This is the integral of the bell shape and measures the fraction of the population that would have failed at or below any given stress. This is shown in the right hand curve of figure 3.

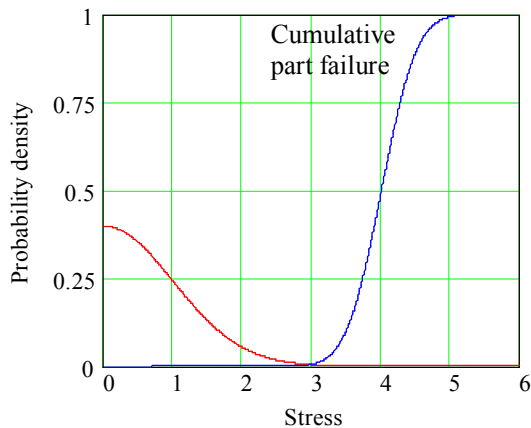


Figure 3. The cumulative failure curve.

Here the average strength of the batch of parts is four times the root-mean-square value as before so the right hand curve passes through a probability value of 0.5 at the stress value of 4. Hardly any would have failed at 2.9 and almost all at 5.1.

The attraction of the cumulative presentation is that the probability of failure at a given stress level is the product of the two probabilities and the overall probability of failure is the integral of this product. This tells us on average how many experiments in a long series of experiments would have to be done to get a failure. If we assume that a typical 'experiment' is a wave period lasting 10 seconds we can calculate on average how long a time would pass to get a failure. For values chosen above the time is only 27 hours.

If the stress was tensile and the part made from a fatigue-sensitive material, the right hand curve would drift slowly to the left at a rate that would depend on the combination of corrosion protection, paint thickness, bio-fouling cover and even local water velocity in ways of which we are ignorant.

There are four ways to reduce the overlap of the two distribution skirts. The first is to bodily move the mean value of the endurance distribution to some higher value by applying a 'factor of safety'. If we keep the standard deviation of the part strength as one tenth of the mean (typical of many engineering parts), we have to get the mean part strength to 6 times the root-mean-square wave stress to get the mean time to failure up to 3-years.

We have to increase it to 7 times the root-mean-square wave stress to get to 79 years.

In the early days of wave energy the expert consultants on mooring would say that they usually applied factors of 5 or 6. There was some uncertainty as to whether this factor was the ratio of mean endurance to mean stress or whether it was the ratio of the weakest item on the lower skirt of endurance divided by the highest point on the upper skirt of the input stress. Measuring points on skirts is difficult. Factors of safety are really factors of ignorance and lead directly to factors of waste. Clearly people are not good at thinking about asymptotes and low probabilities.

Although many natural phenomena, including wave amplitudes, do exhibit Gaussian distributions we cannot be sure that this will be true of the loads we have to face. For example a horizontal cylinder floating with one tenth of its diameter above mean water level which is subjected to waves with a height of one tenth of a diameter and length of fifteen diameters will show no upward force at any part of the wave cycle. This is decidedly skew. The underside of oil platforms can be missed by most wave crests but struck by the extreme ones. Breakwaters can sometimes suffer short-term local pressures in breaking waves far higher than any linear theory would suggest.

Desirable behaviour seems to result from shapes with double convex curvature and low freeboard. We found that horizontal forces behave better than vertical ones because the latter involve the interaction of buoyancy and inertia. To have confidence it is necessary is to carry out lots of tank tests and plot a graph of peak loads and root-mean-square loads against the amplitude of irregular waves for a range of wave steepness which is bigger than any which will occur. Does the steepness of the peak curve ever rise?

The second way to achieve survival is to reduce the standard deviations of the part strength. This can be done by research and careful inspection.

The third way, better still, is to design mechanisms which chop off the upper skirt of the stress distribution at a chosen value, even if these mechanisms have to be complicated. We can then work at the safe stress limit for a large fraction of the time getting a better value for the capital investment. This chopping can be done by methods such as yielding in the duck spine, by pressure relief valves in hydraulics, by over-topping of wave-concentrating walls, by submergence as in the Pelamis or by enlarging the diameter of the water cylinder of the IPS buoy.

This magic ideal is shown in figure 4 where the input load has been limited to 1.5 times the root-mean-square value it would have had. With the standard deviation of the part reduced to 6% and a mean strength of 2 twice the root-mean square input, we get a mean time to fail of four thousand years.

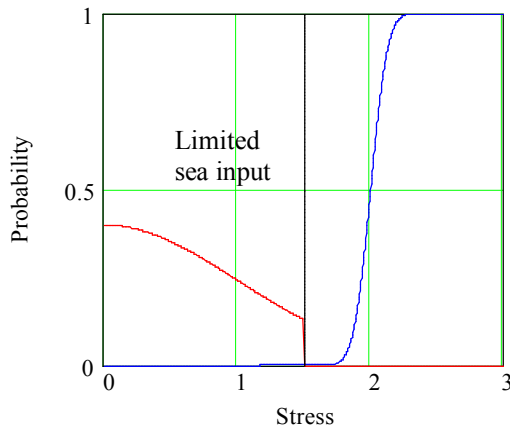


Figure 4. Cropping the stress.

A large part of the capital cost of wave energy plant is associated with the strength of the primary structure. If this fraction of the cost is proportional to strength, limiting the stress to that at the economic limit should reduce the cost of Atlantic plant by a factor between 6 and 10 so that there is plenty of money to pay for some complexity.

The best way of all to minimise the distribution overlap is to have the stress-skirt chopping-point externally adjustable so that, if there are unpleasant surprises in the shape of the endurance distribution, we can still back away from disaster. This also gives the commercial option to sacrifice some plant life for electrical output at times of unusually high electricity values which are a feature of recently introduced, and perhaps foolish, electricity trading arrangements. We can even nurse elderly plant in the years before retirement.

Such external controls will also allow us to do useful things like switching off the input power during installation, inspection and maintenance, a requirement often forgotten in the excitement of early invention. There is therefore a need to understand possible stress-limiting mechanisms and the effects of stress limitation of power production and increased range of movement.

These arguments are all very well if we know the shapes of the probability distributions and the values of means and standard deviations. Unfortunately we are often ignorant of them even in well-established fields but especially where new designs are working in unfamiliar conditions. How can the data be obtained?

Design for a test platform

Laboratory test rigs are quick, safe and comfortable for internal parts but are not sufficient for items which are exposed to the external influences of the chemistry and biology of sea-water.

A possible test facility for sea experiments would consist of a floating platform or raft (see figure 5). It consists of two pontoons joined together by the largest tubes we can get (42 inch gas pipes) so that the combination resembles a horizontal ladder.

It will allow us to expose statistically significant numbers of components such as cable entries and fasteners and exercise subassemblies such as seals and bearings. The platform would be moored close enough to shore to be able to draw electrical power to drive the three-phase induction motors through variable-frequency inverters mounted on the platform. These can drive shaft seals and ram exercisers. Such an experiment would also confront many of the mooring, and electric-cabling problems of wave and tidal-stream plant.

The key design problem seems to be the safe location of fairly heavy test rigs by a coupling which also allows easy inspection and replacement. This is not easy on a moving platform where a shift of the position of the centre of gravity is undesirable. We must recall the expression 'loose cannon'.

Each test rig would be built on a pair of plates (see figure 6) joined by rectangular section tubes which carry plastic bearing pads. The combination would act like a saddle and be tied to the rungs with a girth strap. The equipment would be designed so that its centre of gravity was close to the centre of the tube. To examine submerged parts the girth would be loosened a little and the saddle rotated by pulling with a Tirfor winch at a suitable connection point. The contact between plastic bearing pads and mounting tube would be nicer if it could be clad with a thin shim, say 0.5 mm of cupro-nickel or stainless steel, with junction to the mild-steel protected by epoxy paint.

Figure 6A shows a rig for exercising the seals of hydraulic rams at working pressure. The energy can be recycled so that only the losses need to be supplied. Figure 6B shows a rig to bend belts or cables round a defined curvature. Figure 6 C is a cavitation tester driving hydrofoils. Figure 6D shows six disks with candidate anti-fouling treatments spinning at speeds representing the expected water velocities. Figure 6E shows how easy it is to forget an important but boring box to enclose electronics. Who has proved beyond doubt that we can do even this?

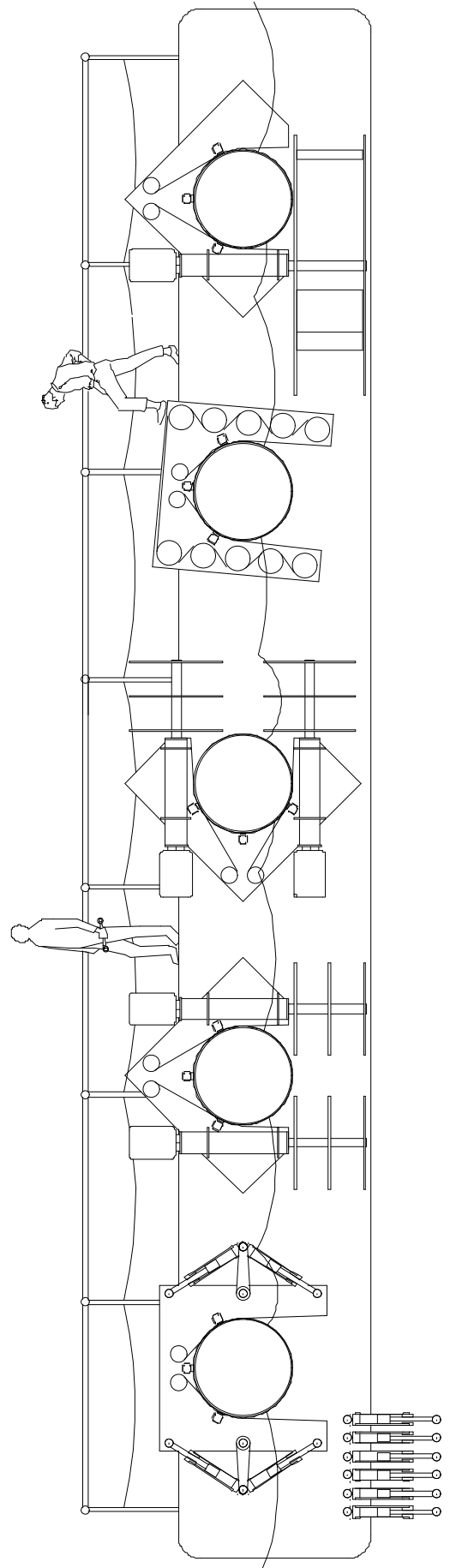
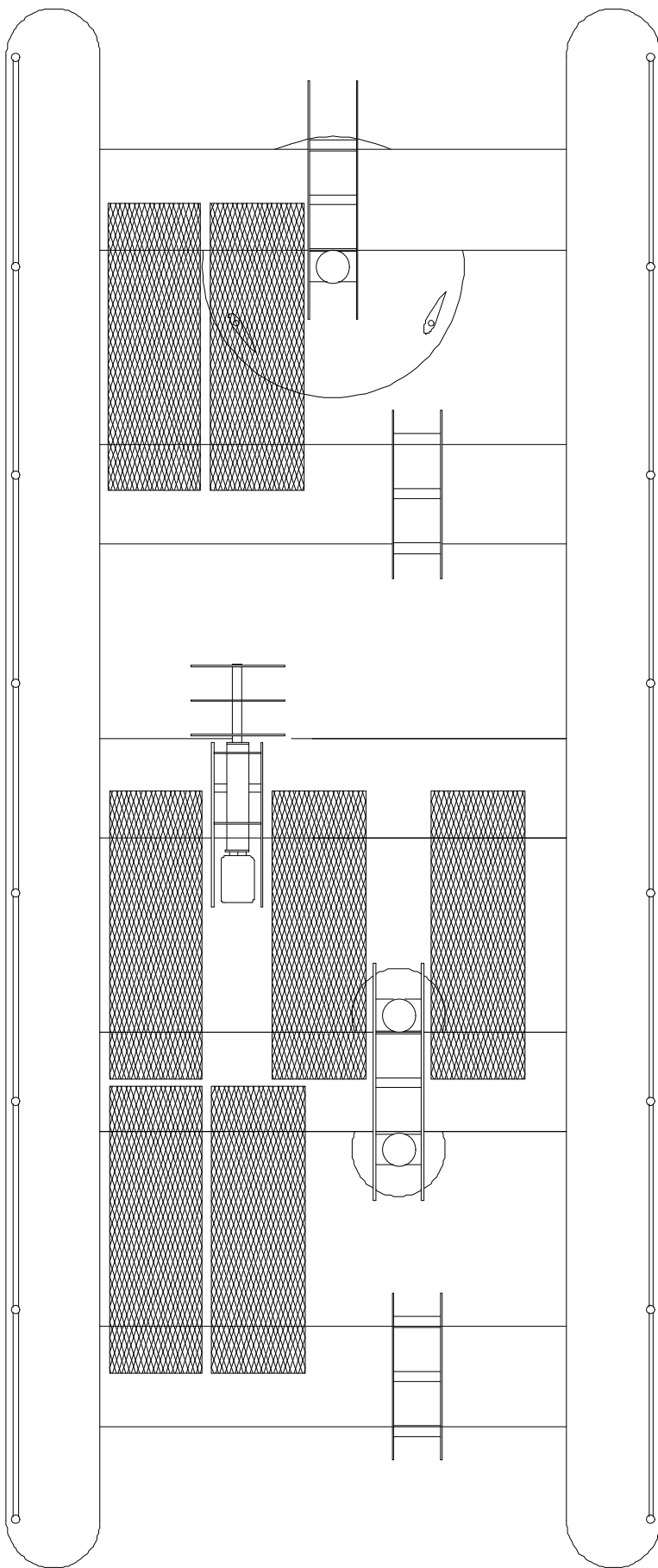


Figure 5. Plan and elevation sketches of the test platform.

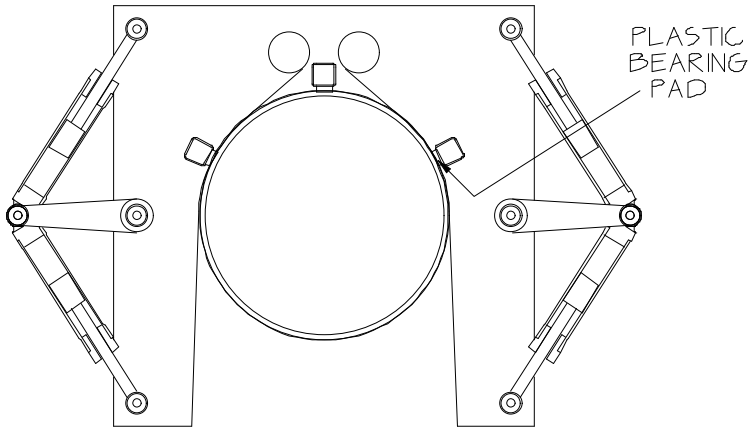


FIG 6A RAM EXERCISER

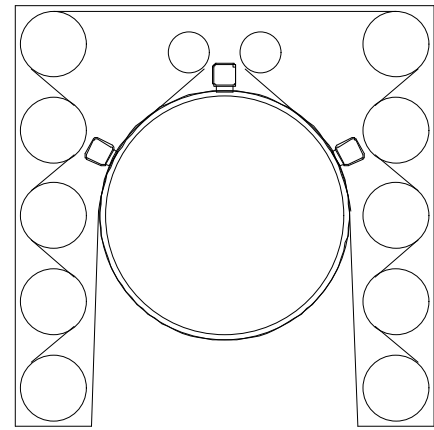


FIG 6 B. BELT AND CABLE BEND CURVATURE TEST

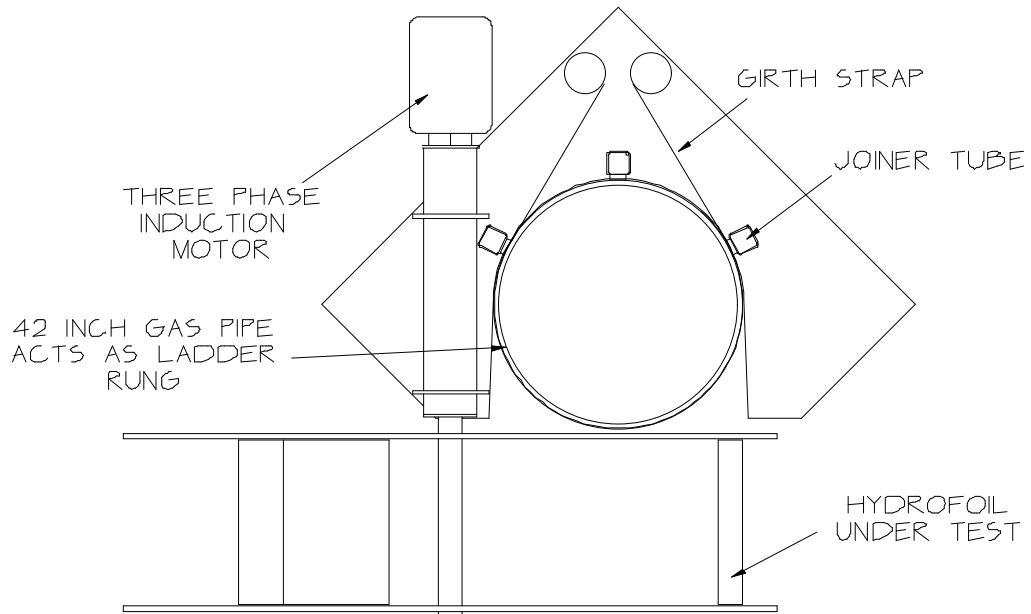


FIG 6 C. HYDROFOIL CAVITATION TEST

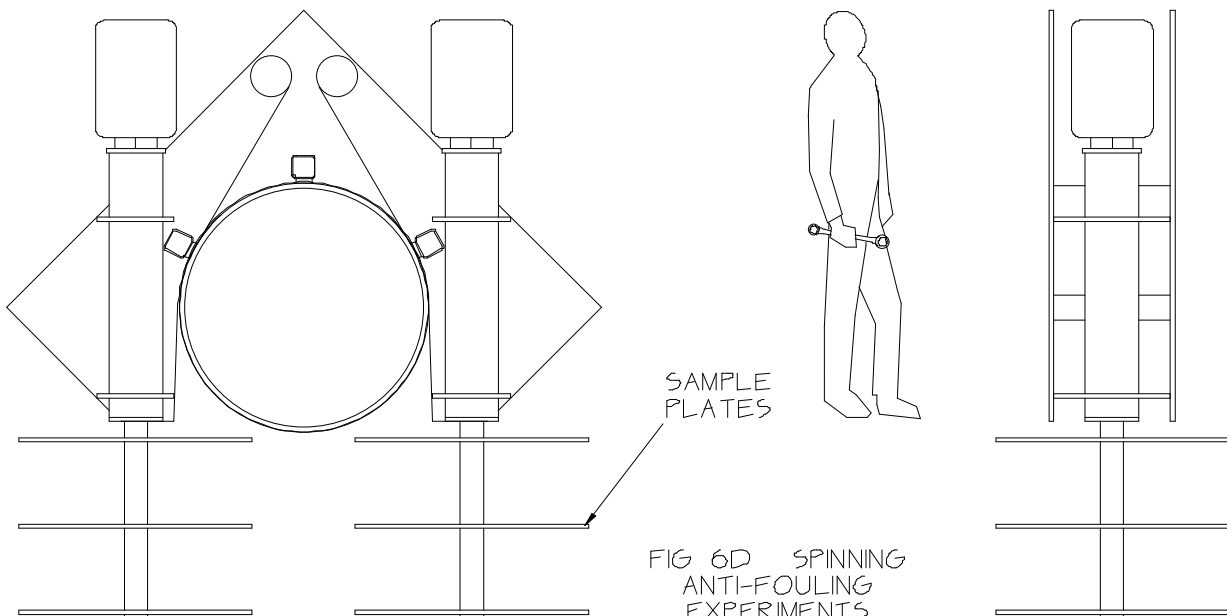


FIG 6D SPINNING ANTI-FOULING EXPERIMENTS

The biological problems are significant because layers of fouling can produce changes in chemistry with substances like hydrogen sulphide which, in turn, change the rates of corrosion and fatigue. The drag increase due to fouling does not reduce performance of wave devices but will be very serious for the blades of tidal stream plant.

The experiments should be planned so that the stressors cover a range which goes beyond the most pessimistic expectations. We want lots of failures if we are to understand them properly. A series of mishaps to items on the platform would be much less of an embarrassment than any to a complete power-generating device. We also have to avoid needless over-design which results from excessive caution.

Calculation of the sea water fatigue endurance is particularly difficult for welds to the point where the Edinburgh group will go to any lengths to avoid them. Fatigue research requires large samples of test specimens. The experiments are very boring, incompatible with investor deadlines and with the need for rapid publication rates in the RAE-harassed universities of today.

Minor changes in surface preparation or design detail, like small holes, can have large effects so there is a wide range of conclusions. There are also wide variations in allowable stress limits between different Classification Societies. This means we should test components identical to those we expect to use. The ones we forget will be the ones that will lead to disaster.

The results of the tests must be circulated to everyone, just as the entire world aircraft industry is given information from crash enquiries. Some industrial groups refuse to release the detailed information about failures which they have painfully and expensively discovered, perhaps in the hope that their competitors will lose money by repeating the mistakes. This action is questionable if they have received any public funding. Full size renewable energy work is a slow and expensive way to relearn the basic and painful lessons of marine engineering.

The longer the test platform is operated the higher will be the value of the results and so it should be launched as soon as possible. Would any wave engineer take a bet on the level of political support that this proposal can expect?

Conclusions

Factors of safety are really factors of ignorance and lead to factors of waste.

We must understand the statistics of wave loading. While many random natural phenomena show variations that follow the Gaussian probability distribution, some objects with concave shapes and high freeboard can show fluid loading with higher than Gaussian extremes, which will need careful study in test tanks.

It will be expensive to provide strength to resist the rare asymptotic extremes of even the Gaussian distribution and so we should find ways to limit the input loads to those which occur at the economic power limit.

To ensure that wave power structures survive we must understand how the endurance of components is affected by the interactions of corrosion, fatigue bio-fouling and the passage of time. We must therefore provide a facility to expose quite large numbers of any new components and sub-assemblies at sea before they are chosen for use.

The important problem of moving heavy items in and out of the water without risking the 'loose cannon' effect can be solved with a platform having tubular rungs and girths to retain saddles made from pairs of plates.

Acknowledgements

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Useful reading

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Did you notice anything about figure 6E?