Commentary

A materials wish list for wet renewables

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Materials will always determine the performance of any engineering product and the most successful technologies are those for which the right materials have evolved as the technology matures. For example, early aircraft were made from cloth, wood and bicycle parts but then pushed the development of aluminium alloys and later carbon fibre composites. Jet engines were made possible only by the development of the high temperature nimonic alloys. The semiconductor industry needs incredibly pure silicon with carefully calculated additives. Such advances in materials can improve the cost-effectiveness of the original idea by many orders of magnitude. Sadly there has not so far been enough time for such dreams to come true for wave and tidal stream energy, which still need costs down by a factor of two or three. This note lists a number of dreams.

Large structures

We can separate materials needed in large amounts for the structure where the need is for cheap strength from those such as seals and bearings where a small amount of something special does a particular job very well.

Steel

Except during extreme steel shortages, large ships are made of steel. This will be true for many early wave-power and marine-current devices made in small numbers.[1] Steel has low tooling costs with the opportunity for self-jigging of complex shapes. Wave plant can lose efficiency from vortex shedding at sharp corners but steel plate rolled to a single curvature will reduce the problem so there is no need for the beautiful aerofoil sections needed for wind turbine blades. Steel has consistent properties, designs are easily modified, holes can be drilled and lugs welded on. Although its fatigue and corrosion properties are often not very good they are, at least, well understood except for regions round welds. We know how to use cathodic protection to reduce corrosion rate, but not quite to zero.

The negative features of steel are the relatively high energy content which could lead to higher costs in future, the expense of painting (which can double the cost) and the need for frequent repainting, which requires return to a dry dock. All plastics and paints are permeable and so oxygen and water vapour will eventually reach the metal. Corrosion below the paint surface occurs and the expanding iron oxide breaks it away. The permeability problem can be reduced with paints containing flakes of less permeable material such as glass and metal-clad glass.

A dream development would be an especially tough, flake-filled alkaline super-paint which could be applied to welds to give them the very long-term endurance in sea water that the parent metal would have in dry or oily conditions.

Ship drag is very seriously affected by biological fouling. Tank tests of at least one wave device show very little loss of performance as a result of fouling, perhaps because relative velocities are quite low. It might be expected that the problem would be serious for tidal-stream plant but photographs of the first Marine Current Turbines system after 27 months of immersion show almost no fouling on blades painted with a copper-filled epoxy resin material known as Coppercoat.[2]

Concrete

For wave devices in multiple production there are many attractions in concrete. Concrete structures can be made with double curvature, which gives excellent strength. They need no painting. Concrete gives an ideal alkaline environment for internal steel. Samples taken from the Mulberry harbours built for the 1944 Normandy invasion[3] and from the tower of the recently demolished 60 m, 3 MW wind turbine on Orkney[4] show that internal steel is in excellent condition, even still shiny. With the correct quality control and a slight excess of cement, cracks can repair themselves. The very low tensile strength of concrete can be countered by post-tensioning to exploit the excellent compressive strength. The fatigue problems vanish if concrete can be put into an initial compressive stress by members which are kept at a constant tension. There is concern about the corrosion of high-tensile steel wires used for post-tensioning in bridges where salt is used to disperse ice. Wave energy would benefit from the non-ferrous post-tensioning materials now being developed. While most steel ships are scrapped after 25–30 years, the hulls of concrete ships from the First World War are still in remarkably good condition.

The negative features of concrete are that normal manufacture requires shuttering, which can cost more than the delivered material and is usually thrown away after the production of each single item. The shuttering may have to be strong enough to take the entire weight of the structure in air, which may well be above the stresses the device will suffer in the largest waves. Shuttering is particularly expensive if the device has to use internal compartments to achieve buoyancy. Apart from the need for buoyancy, wave-power plant does not need many large internal compartments and foamed concrete can be made with a density low enough for solid items to float. Unfortunately the foamed material slowly absorbs water. Furthermore the heat released during curing cannot easily escape from inside a large volume of foam and can give rise to behaviour like cooking porridge!

Developing countries in the Far East make much greater use of concrete in the form of ferrocement, which uses finely divided reinforcement and a fine aggregate with a consistency that can be applied by a hand trowel to steel mesh, avoiding the need for shuttering. Very large structures can be produced

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with low capital investment. The nearest equivalent in the West is slip-forming, in which concrete is continuously poured into a short length of shuttering ring that is slowly advanced at the rate at which the concrete sets. This is very economical for right circular cylinders but has also been used to make tapered legs for oil platforms. An extension of the technique might involve the simultaneous spraying of fine concrete and short lengths of reinforcing material in the same way that glass strands are sprayed along with resin. If resistance to bio-fouling is required, the spray for the outer layers could include strands of copper.

The dream material would average the properties of concrete and expanded polystyrene to give a solid body of chosen density just less than that of sea water. It should have a low exotherm and low permeability. The devices should be manufactured by pumping a liquid into a flexible and reusable bag in water so that the structure is afloat for its entire life, never needing support in air. An interesting 'out-of-the-box' solution which meets many of these requirements is ice reinforced with wood pulp. This was proposed by Geoffrey Pyke for very large aircraft carriers able to take heavy bombers in the Second World War, in a project codenamed Habbakuk.[5] Calculations show that a very small fraction of the output energy would be needed to keep the structure frozen.

Small details

Seals

Three wave devices have proposed the use of completely sealed power generating plant using either simple inertia or gyroscopic effects to avoid shaft penetrations. However, many designs require sealing a rotating or sliding part with sea water or spray on one side. Belofram rolling seals can handle translating motions such as those of a linear hydraulic ram. Airmounts can handle smaller translations combined with quite large angular movements. Wave energy could use larger sizes and larger ranges of movement than other applications and the dream wish would be for a combination of a reinforcing textile such as tyre cord, which can be laid in an arbitrary shape and then sprayed to a controlled thickness, with an elastomer which will withstand long term exposure.

Ceramax

One disruptive seal technology for the rods of hydraulic rams has been developed by the Dutch company Hydraudyne.[6] It is a material known as Ceramax and the company shows hydraulic rams with the cylinder thickly encrusted with barnacles but a glossy black rod emerging from the body. Ceramax resists both the corrosive and biological hazards of sea water. It can even incorporate transducers to measure the extension of hydraulic rams The dream wish would be for Ceramax to be made available for large face-seals.

PEEK poppet valves

A second wonder material known as PEEK (poly-ether-ether-ketone), in combination with carbon fibre, has proved very good for the manufacture of poppet valves in pumps and motors in which displacement is controlled digitally by a microprocessor.[7] Its low density makes possible very light valves which let multi-megawatt machines work at the high speeds of synchronous generators and do 'energy-processing' of arbitrary complexity. The high strength but low modulus of elasticity reduce the fatigue problem caused by Hertzian stress at valve seats.

Diamond for rolling contacts

Digital displacement control can also be used for low-speed pumps with ring cams on which each of a large number of rollers is actuated by every one of a large number of cam lobes. Work goes through many hundreds of line contacts which give much better torque-to-weight ratios than conventional gears as well as a continuously variable gear ratio. The power rating is strongly driven by the Hertzian stress between roller and cam. A recent development by SKF involves vapour deposition of diamond coatings on the tracks of roller bearings to give a large increase in permissible working stress.[8] This could also be applied to parts of ring cam pumps.

Droplet erosion

A difficulty with the use of air turbines for power conversion in oscillating water columns is that high rotation speeds are needed to develop pressures to match wave-induced ones. These high speeds induce centrifugal stresses, which can be accurately predicted, but also problems with erosion at the leading edges of turbine blades. For many promising materials there is a sharp onset of erosion damage at around 120 $\mathrm{m\ s^{-1}}$. This is made worse if pores and micro-cracks allow high liquid pressures to act within the body of a component. Carbon fibre composites have a good ratio of strength to density and so are excellent for resisting centrifugal stress. But we have to expect rather poor resistance to water droplet erosion. It might be possible to reduce this if carbon fibre could be given a thin, defect-free coating of electroless nickel.

Composite turbine blades

The runners of turbines are cast in bronze and then machined to hydrodynamically fair but mathematically complex shapes. They are consequently very expensive. For the blades of tidal stream generators perhaps we could make a low-precision blade core in steel from box sections and plate which would have only to stand up to imposed loads. This core would then be placed inside a mould into which would be injected a dream material, perhaps a polyurethane elastomer which would include a cocktail of additives to achieve low permeability to delay corrosion of the steel core, abrasion resistance to withstand silt, non-fouling and anti-cavitation properties. The mould would be as expensive or even more expensive than a single rotor in solid bronze but would be used thousands of times.

Magnetic assemblies

Despite the rather low velocities of waves some people are trying to design directly-coupled electrical generators.[9] There are two main problems. The first is that the very high performance neodymium–iron–boron magnets, which give high flux density and coercivity, behave rather like sugar lumps when exposed to water. Machine designers are trying to minimise air gap length so any protective layer must be thin. Some machine designs require variation in the flux density at a magnet pole and this can cause eddy currents to circulate in any conductive protection. However, other designs allow the flux through a permanent magnet to remain constant and for these, electroless nickel looks attractive.

The second problem, particularly serious for linear generators, is that the attractive forces between opposite poles can get very large and have to be restrained by a long path round the machine frame. It is interesting to ask if the attractive forces could be taken by hydrostatic pads acting directly on pole faces and even more interesting if the hydrostatic fluid could be sea water. Sadly the working clearances of hydrostatic bearings are often in the range 5–25 μm while the distortion under load (let alone the initial manufacturing tolerance of an economically designed wave device with a size between 10 and 20 m) could easily be 1000 times greater.

Very big compliant hydrostatic bearings

Let us suspend disbelief for a paragraph or two. We choose a construction site with very stable rock strata close to the surface and build something like a skating rink with a level concrete floor and accurate overhead cranes. We apply a hoop post-tension to the concrete to prevent cracks. We produce a super-flat surface by pouring liquid resin over the concrete. This resin should have a very slow curing time, but because disbelief has been suspended, I can asked for something which solidifies when exposed to ultra-violet light but can then liquefy under infra red! Failing this we can use temperature adjustments with the right kind of wax.

We spray a mould release over the hardened resin and build a low fence in the shape of the outline of the magnetic assembly. Inside the fence we spray a cocktail of fillers with a resin to bind them together. Before this has cured we lower the magnetic assembly, likely to be a stack of magnets and soft iron laminations, into the fenced area. When the second resin has cured it will have a flatness and smoothness of the original liquid surface and the material properties of the chosen fillers.

Whatever slides on this must have local smoothness to the micrometre levels needed for the lands of hydrostatic bearings but compliance over a longer distances which will allow it to conform to any subsequent curvature of the magnet structure under load. We need something that would behave like a slug crawling on a corrugated surface.

The slug layer can also be made in the resin (or wax) rink. First we lay down a number of wax profiles in places where we want hydrostatic pockets. We can then build a wax structure in the form of a network of galleries connecting pads to flow control impedances. We can include open cell foam shapes in the form of concertinas. We can add steel plate segments to give local rigidity and attachment points to external parts. We can lay down textile reinforcement such as Kevlar. We then spray the entire assembly with an elastomeric resin, allow it to cure and melt out the wax.

If the force taken by the hydrostatic pockets also goes through the concertina shapes and if these have a smaller projected area than the pockets, there will have to be a higher pressure in the concertinas than in the pocket in inverse proportion to the ratio of the areas. This means that liquid from a concertina can flow through some flow impedance and energise the pocket. We will have achieved a self-pumped bearing exuding fluid under load like the synovial fluid in hip joints. The liquid supply can continue much longer than a wave load and perhaps as long as the rotation period of a large vertical axis tidal stream generator, but a unidirectional load would need an external supply. This leads to a final wish for materials suitable for a filter-pump system which can draw water from a silt- and plankton-rich source and deliver clean high-pressure sea water to hydrostatic bearings.

Conclusion

The necessary advances for wet renewable energy technologies will need a combination of the right materials placed by the right tools in the right places in the right designs. The limits to the dreams of the designer will always be set by the materials available but you have to make a wish before you can expect it to come true.

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