

Preprint of paper to be presented at IEE 'Future Energy Concepts' Conference

30th January - 1st February 1979. Please do not quote before this date.

POWER CONVERSION SYSTEMS FOR DUCKS

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SUMMARY

This paper tries to define the problems of power conversion for a wave power device. It presents a little of the background theory; it discusses design principles, existing components and modifications to them; it tries to identify the main practical difficulties. Finally, it describes four possible solutions.

THE PROBLEM

Providence has been kind to wave power. But the area in which this kindness is least apparent lies in the constants which have been chosen for the conversion of mechanical energy into electricity. At one end we have the absurdly small displacements of piezo electric devices, at the other the extremely high velocities at which a conductor must cut lines of flux in order to produce useful voltages.

The unpleasant truth is that it becomes hard to send more than about 10^8 lines of magnetic flux through a square metre of iron. If we cut them once in a second we develop only a single volt. If we try to compensate for a low voltage by drawing a large current we find that our precious voltage is dropped by the resistance of our wire. If we try to compensate for that by making the conductors fat we find that there is less room for them in the magnetic field. If we accept the values for magnetic saturation and electrical conductivity of the materials available to us we can only choose between machine size and machine speed and so increase the speed until the troubles caused by vibration or centrifugal force or bearing life dominate the gains in efficiency. A flux-cutting speed of 100 metre per second is good. But the velocities associated with waves are often less than one metre per second and are random, alternating velocities into the bargain. Unless the physicists can produce some new phenomenon the wave power engineers must struggle to match the waves to electrical generators.

High velocities are not the only goal. We need to rectify an alternating motion into direct rotation. We must also seek to combine the outputs of randomly related generators, to store energy in order to produce a regulated output and to apply safety limits so that plant can be protected.

It seems that the tasks of processing energy are best done if the energy is in fluid form. The Russell Rectifier being studied at HRS Wallingford processes raw waves (1). Several devices such as the Japanese Masuda's Kaimei (2) and the related ones under study at NEL (3) and Queen's University, Belfast (4) convert to air pressure. Sir Christopher Cockerell's rafts being developed by Wave Power Ltd. (5) and the ducks under study at Edinburgh University (6) use high pressure liquids as a working medium.

The balance of advantages between low pressure air and high pressure liquid is not easy to determine. My own feeling is that high pressure liquid offers more chances for control and better performance in the free-wheeling condition which is necessary in natural waves. The air turbines have to continue to spin and they will either stir or pump air around them. In contrast, a Pelton wheel can have its spear valve closed off and can spin in air with little loss. However, a particularly elegant air turbine has been developed by Professor Wells which gives high speed of rotation, self-rectification and a low free-wheeling loss (4).

HYDRODYNAMIC THEORY

Many parallels exist between the propagation of energy as a water wave and as an electrical signal in a transmission line. Several important ideas of wave power come easily to electrical engineers. If a coaxial cable is terminated with a resistance equal to its characteristic impedance, then all the power is passed into the resistance. Similarly, wave power devices attempt to 'terminate' the wave train. The device should drive a power take-off system which has the right damping coefficient. If a duck has too much damping, energy will be reflected with the formation of an antinode at the duck's beak. If there is too little damping, then reflection occurs with a node at the beak. If the damping is correct the water motion follows that which would have occurred in the absence of the device. Mismatches cause standing waves which can be measured with quarter-wave probes in exact analogy with electricity.

The value of the best damping coefficient can be determined in several ways. One can build a model with an adjustable dynamometer and twiddle knobs until satisfactory results are obtained. It is also possible to place a model in calm water, apply to it an exciting force and measure the ratio of force to velocity. The value of damping coefficient caused by the generation of waves is equal to that needed for their absorption. Finally, analytical methods have been developed which allow damping coefficients to be calculated (7).

We can see the effect of the damping coefficient variations from examination of Fig. 1 which shows loops like the indicator diagrams used to describe the performance of steam engines. The vertical axis shows the duck torque and the horizontal axis the duck angle. The area enclosed by the loop is a measure of the work done per cycle and our wish is to choose the damping coefficient which gives the biggest area. The loops show the result of variation of damping coefficient by successive factors on either side of the optimum. We can see that at first there is very little harm done. We can also observe that at zero damping, the duck angle is twice its value at optimum damping. We can guess that if infinite damping could have been applied, then the torque necessary to hold the duck still would be twice that of normal operation. These indicator diagrams are the result of a power take-off mechanism which develops a torque proportional to velocity. This is certainly the method most suitable for analytical treatment, even if it is not easy to build in full-scale hardware.

Well-ballasted ducks are remarkably tolerant of moderate departure from the ideal power take-off. The indicator diagrams of Fig. 2 show the result of using a different damping coefficient for each direction of movement. At one extreme the efficiency falls only 5% while at the other it remains unaffected.

If ducks can manage with large departures from the ideal of torque proportional to velocity, it is tempting to try the simplest possible 'bang-bang' power take-off. We fix a constant pressure in the pressure manifold. If a duck can raise enough torque then it will pump. If not, it will remain motionless. In regular waves the system works very well. Indeed, if the correct value of pressure is chosen there is hardly any loss. But in irregular waves there are two disadvantages. The small waves do not produce enough torque to move the duck and so are completely wasted. But more seriously, large waves will lift the duck through an angle big enough to bring its centre of gravity nearly above the point of rotation. There is now very little restoring force. But the full value of torque must be opposed before the duck can move down and so it will remain stalled. If 'bang-bang' power take-off is used, the ballast must be placed lower and so the frequency response will be drastically changed.

However, we find that quite satisfactory operation is possible in irregular waves if the duck can drive a 'bang-idle-bang' system in which a controller decides whether to offer the maximum torque or none.

Reactive Power Take-Off

Many wave power devices possess compliance and inertia analogous to capacitance and inductance in electrical networks. They will perform best at resonance and the frequency of resonance must be carefully chosen to suit the spectra of the wave climate. But at frequencies away from the natural resonant frequency, we may be able to manipulate the power take-off system to improve performance. Suppose that at low frequencies we observe that the device shows too much stiffness. Some 'negative spring' may be introduced by a torque which is proportional to the deviation angle of the device from its calm water position. The effect of negative spring can be seen in the indicator diagrams of Fig. 3. It is also possible to apply a force which is proportional to acceleration and so to introduce negative inertia. Reactive loading can broaden the band of response and improve performance away from the resonant point. But it demands higher torques and also a small amount of reverse power, neither of which are welcome. We find that if ducks are built with high centres of gravity, then they show the negative spring behaviour of an inverted pendulum. Further, if we arrange that the weight necessary to oppose the torque of the duck's buoyancy is kept close to the backbone, then its inertia is low enough not to require negative inertia. These two facts combine to remove the need for reactive power take-off from our present scheme. Nevertheless, it remains a powerful tool to be kept in reserve.

Other Possible Power Take-Off Tricks

Linear theory is much easier to develop and apply than non-linear theory. But if a wave power device is linear then it is too big. We are told by the cost estimators that physical size is the dominant cost factor. We must therefore choose sizes which are often working in a non-linear mode and it is reasonable to suppose that some non-linear elements in the power take-off system may prove useful.

It would be interesting to see if a row of pressure sensors placed on the duck's outer skin could produce more precise information about the best value torque than is available from a simple measurement of the duck velocity.

Efficiency is not always the only goal. Some benefits may be won at higher power levels when efficiency is of no concern. We may decide to anticipate or defer the generation of power to help with smoothing in the pressure manifolds or to relieve bending moments of the backbone. We may perhaps increase the damping coefficient if it seems worth forestalling a capsize, or reduce it afterwards to help recovery. By changing the amount of energy reflected from ducks at one end of a string, we can induce a yaw if it seems wise to lie oblique to long crested swell.

There seems to be so many options open as well as some yet to be discovered that I believe that we ought to design a system which can call for any torque up to the maximum at the decision of some, as yet unspecified, electronic black box. If we do this, we will have the chance to exploit all the new non-linear hydrodynamic knowledge which will certainly emerge in the future.

Torque Limits

Torque is expensive. What happens when a limit is imposed? The results are shown in Fig. 4. We find that there is an increase in angular movement such as to compensate for the loss in torque. As the duck can manage quite well with less than optimum damping, the loss of output is at first quite small. As torque limit is reduced further, we find that power output is no longer proportional to the square of wave amplitude and the ratio of peak to mean output is reduced. To decide the best value for torque limit, we have tested models in pseudo-random sea states covering rather more than the range expected. By controlling separately the energy period, the wave amplitude and the torque limit, we have assembled a data base which can provide a part of the answer. It is still necessary to get measurements of a wave climate, a figure for the cost of torque and a decision on the seasonal value of electricity.

We find that as wave power devices will be operating under torque limits for a large fraction of the time, there is a sensible power limit which is immediately determined by the torque limit and is proportional to it. It turns out that the maximum economical torque and power limits for a 15 metre duck in an offshore Atlantic wave climate are about 10^6 newton metre and 100 kilowatt per metre width of duck. Some inshore and North Sea sites might need only one third of this. If transmission costs dominate and duty factor is more valued than winter output, we might decide on even lower power limits. The preference for low limits and high duty factor is endorsed by Vimukta et al (8).

Some further reduction in torque requirement may be achieved by a modification to the shape of the duck. A small reduction in the length of its beak causes a large drop in the optimum value of its damping coefficient. The price to be paid is a loss of performance in large waves. We believe that a reduction by a factor of two could be considered if it turns out to be too expensive to develop the high torques needed by the longer beaks.

The Irregular Wave Input

Statistical theory predicts and observations confirm that the displacement of the water surface follows a normal distribution. So do many of the characteristics of a wave power device at low and moderate power levels.

Fig. 5 shows a typical sample of a wave record together with the torque induced in a power system in which torque is directly proportional to duck velocity. Also shown is the record of the instantaneous power output. The unpleasant occasional spikes far above the mean level are all too apparent. The instantaneous power signal looks rather like the square of the wave record. Its histogram resembles the Chi-squared distribution. Fig. 6 shows the results when the same wave train is absorbed by a torque-limited duck.

These figures could be used for many wave power devices and for many sea conditions by simple adjustment of the axis numbers. The only modification necessary might be to accommodate measurements in a narrower spectrum than that used for this test, which would have produced longer envelopes for the wave groups. However, the histograms of the signals would be unaffected.

There is a simple relationship between duck velocity and wave size. For a 15 metre duck diameter we get about .1 radian per second of duck velocity per metre of wave almost independent of wave period. (This may be used for prediction of amplitude, peak-to-peak values, or RMS measurements if both wave and duck velocity are measured in the same way. However, the maximum duck velocity is limited to .8 radians per second even in very large waves because of its limited swept volume.) This gives relative peripheral speeds between duck and backbone which are about twice the velocity of the water particles.

The ideal wave climate would allow the operation of devices at a constant level. But our climate offers a range of wave amplitudes from zero to about 4 metres RMS and this calls for a range of working philosophies. There is an abrupt transition at the point where the power output of a device exceeds the rating of its transmission lines. Below this level we resort to every trick of engineering and hydrodynamics to increase the efficiency of the system. Above the power limit we care nothing about efficiency and concentrate on the problems of smoothing and regulating, prolonging equipment life and ultimately survival itself. The transition point probably occurs at a wave height of about one metre RMS or even a little less.

Simplicity

I have frequently heard the advocate for a technique advance the argument that simplicity is a desirable feature. In many cases I believe that this is wrong, and merely an excuse to save the effort of thinking about a complicated solution. Our modern power stations, computers and aeroplanes are all very complicated. The complications have been introduced as technology has developed to make the equipment cheaper, more reliable and more effective. All too often, simplicity requires a component to do several things at once and all of them badly.

The more we understand about apparently simple things, the more complicated they become. Consider, for example, water flowing in a pipe. It appears simple enough. But look now at the boundary layer and the effects of laminar or turbulent flow. Add a few parts per million of a chemical with a long molecule and try to explain why the pressure drop can be cut by a factor of twenty. The fact is that simplicity is irrelevant. The simplicity dimension usually lies orthogonal to the direction in which we have to go. This philosophy has led to many confrontations with engineers who have experience in the civil, marine and heavy electrical fields. I am totally convinced that reliability and efficiency in wave power will be the result of the extensive use of complicated electronic methods for control, inspection and fault correction (9). Semiconductor technology is moving at a pace unbelievable even to people working on it. Performance and reliability rise and costs fall without apparent limit. In 1978 a fully assembled microprocessor, complete with terminal, can be bought for less than the cost of a ton of mild steel. By 1998 a computer and memory will cost less than a few kilograms. The exchange should be made without hesitation. All that it is necessary to consider at this stage is the provision of instruments to acquire information and actuators to respond to decisions. I would be perfectly happy to have a computer for every pump and even one for every valve and bearing. I hope that this statement provokes some discussion at this conference. To further fan the flames, I will observe that enthusiasm for electronics tends to be inversely proportional to age!

Reliability

Just as countries get the politicians they deserve, so the reliability of the things we make rises to the standards which the consumers demand and will pay for, and then stops. We find a balance between the cost of purchase and servicing on the one hand and the cost of breakdown and disposal on the other. If equipment fails, we choose whether to repair it or throw it away. While we are happy for our cars to be serviced several times a year, this would be intolerable now for a watch or refrigerator. If, during a car service, the points are forgotten, we may be stuck by the side of the road. But if the engines of an aircraft stop working, then hundreds of people can be killed. So we apply higher standards to aircraft maintenance and fit airliners with several engines which work with separate systems.

It is foolish to take reliability figures from one field and apply them thoughtlessly to another. We have to decide the levels of reliability which are appropriate for wave power and find the best way to achieve them. If millions of pounds are lost by a failure, then it will be well worth spending hundreds of thousands to prevent it. There are strong reasons to make wave power components last for periods of 10^5 hours which is much longer than most land-based plant.

I believe that three things are essential. Firstly, we must have complete understanding of the duty to which our components will be exposed and the way in which they behave under test. Secondly, we must really understand the difference between the words 'serial' and 'parallel'. Thirdly, we must devise systems of quarantine and isolation to ensure that the faults which do occur do not propagate.

PRACTICAL DIFFICULTIES

Duck Location

Ducks are mounted on a long backbone and must be constrained to rotate about it. The backbone will be subjected to large bending moments and so it will be neither straight, round nor parallel. We should not consider any power take-off mechanism which places demands on the accuracy of the duck location. We ought to expect radial misalignments of up to 150 mm.

It also seems very difficult to produce seals at 15 m diameter. The space between duck and backbone will have to contain salt water. All that we can hope is that the rate of exchange with seawater outside will be slow, so that nutrients will be absent and toxin concentration high. It is possible to make mechanical seals work in seawater. But they should be used on an accurately defined rotation and on a shaft of moderate diameter and well ground surface finish.

Radial Forces

The early days of offshore engineering produced a comprehensive theory for fluid loading. The equations were based on measurements of static, submerged, vertical objects which were small compared to the wave amplitude. They consist of about thirteen inches of hyperbolic algebra with two empirical constants. When we came to work on moving, surface-piercing, horizontal objects with diameters larger than the wave amplitude, several more inches of hyperbolic algebra were necessary to make the equations fit the facts. There seemed little chance that we could ever get the same answer on our calculators twice running, let alone understand what the equations really meant.

We turned instead to comprehensive model testing which predicts that a rigidly held duck would have bearing loads of about 200 tonne per metre width in the notorious '50 year wave'. But nothing can be rigid at sea. If we can devise a backbone which can become compliant when things get rough then all that is necessary is the acceleration of the mass of the backbone. For this the loads are much less, 'only' about 70 tonne per metre. If this sort of load could be evenly spread over a large part of the duck-to-backbone interface, then no very serious pressures would result.

Perhaps a flexible duck could be made to conform to the shape of its backbone. But most civil engineers are used to more rigid structures and we are at present planning to locate the duck with pneumatic tyres. Rolling speeds are low compared with those of road vehicles and I am advised that tyres can be expected to have a reasonable life. Their inner walls can have a low permeability layer and pressure can be maintained by evaporation of a volatile liquid. If plain bearings are used between duck and backbone, a large fraction of the power is wasted by friction.

HARDWARE

Pumps Presently Available

Some quite horrible materials can be pumped. A possibility which we eliminated from the outset was the use of seawater itself as a working fluid. While there will always be a plentiful supply and the losses of a return loop are avoided, it seemed unwise to mix engineering and biology. The ducts of a wave power device offer a convenient foothold, a refuge from predators, a constantly renewed supply of nutrients and even some warmth. They will appear as highly desirable residences to innumerable sea creatures. We could never be sure that the problem would stay solved because even if by a long and expensive development process, we got a design which could resist our natives, immigrants would appear from across the world.

The last twenty years have seen rapid developments in oil hydraulic components which have taken over many of the jobs previously carried out by direct mechanical drives using shafts, chains, etc. The big attraction is flexibility of application and smoothness of control. Good examples are found in earth-moving machinery. A diesel engine running at several thousand rpm drives an axial piston pump, the displacement of which can be varied either by the angle of a swash plate or a drive axis. Valves direct the flow of oil to the jacks of a bulldozer blade working at, say, two seconds per stroke or to slow-speed radial-piston motors working caterpillar tracks or winch drums working at one hundred rpm or less. These hydraulic components are already designed for use in unpleasant conditions and are regularly used in seawater.

A number of pumps use mechanisms like the helical screw and the spur gear which involve a pure rotation. These work very well at high speed but become less satisfactory if they have to be operated over a wide speed range because of the leakage losses at low speeds. It seems to be very difficult to make anything with better seals than a reciprocating piston in a well-finished cylinder.

The rotary motion of a shaft can be converted to the reciprocating motion of a piston either by an eccentric crank or by a cam track. The 'Staffa' range of motors made by Chamberlain Industries use the eccentric while those made by MacTaggart Scott, Poclain and Hägglund use the cam track. The Staffa motors use controlled leakage of oil to provide hydrostatic bearings while the others use roller bearings. The cam track motors have eight or ten lobes and so drive their pistons at a substantially higher rate than the shaft rotation. All the units have distribution valving similar to the commutator of an electrical brush motor which connects each cylinder to the ports at appropriate times. Excellent use of the bearings results from a mounting which clamps the shaft and applies the drive to the motor body. This requirement gives the cam track motors an edge over the eccentric ones. Just as in permanent magnet brush motors, the direction of rotation follows the direction of oil flow and the units can be and are operated either as pumps or motors, even though the use as motors predominates.

There are three problems about their application to wave power. The first is that the slow speed motors are not suited to variable displacement operation. Some manufacturers offer units with two different displacements which can be selected by valve gear and there is a Staffa model with an adjustable eccentricity; but it was not designed for the speed and number of operations which would be necessary for wave power. By and large, the hydraulics industry has the good sense to do its variable displacement control with high speed axial piston machines.

The second problem is that the selector valves require sliding face seals. Not only are these the part most subject to wear (MacTaggart Scott employ a subtle wear-compensation method), but they lead to leakage which spoils their volumetric efficiency.

The third problem is that while these pumps run very well with clean oil, their life is short and unpleasant if they try to digest fragments of metal. If we pass the entire flow through a fine filter, we lose some valuable pressure and we can only do it for rectified flow rather than the alternating flow which would naturally occur. These considerations make it difficult for many pumps to share a common oil supply. One defective unit will spread destruction to its comrades so the life of the group will be equal to that of the least healthy member.

Let us summarise the problem. The ducks need to feel a variable force which may be computed according to some complicated algorithm but the pipe work and turbines want to see a constant pressure. Each pump wants to wallow in its own oil and keep its broken fragments to itself. But the secondary stages want to gather power from many devices. Full-flow filters drop too much pressure and need direct flows while the pumps would supply alternating flows. Oil is expensive and causes objections if it is spilt. If it is good at lubricating pumps it will be bad for sending long distances through pipes. Water is cheap and flows easily but grows bugs and corrodes things. All these difficulties can be resolved with a scheme which has been developed in conjunction with engineers from MacTaggart Scott.

The valve ports of conventional motors are not strictly necessary for our purpose. They cause a loss of volumetric efficiency, cost money and shorten the life of the unit. Our present scheme uses a conventional pump/motor body stripped of all valve gear. The oil is taken directly from each cylinder as an alternating flow. We will choose an oil to give long pump life rather than low pipe losses. We place an efficient filter in the path of pump leakage rather than the cylinder output.

The oil flow passes to a chamber in which a flexible membrane like the bladder of a pressure accumulator separates it from fresh water treated with anti-corrosion additives and flow-assisting polymers. We now have alternating pressures in a fluid which is cheap, which can easily be pumped through long pipes and which can be spilt without any biological hazard. But it is still an alternating flow and it must be rectified.

By far the most attractive valve is the poppet used in the four-stroke internal combustion engine. It leaks less than a sliding face valve, it can tolerate wear, can pass small amounts of grit and provides a large open area for a small movement. The working conditions of the exhaust valve of a car engine are far worse than we demand for wave power, but the number of operations it performs can exceed 10^8 and so approaches the number we need. If we fit two poppet valves to the water chamber, we can draw water from a low pressure manifold and pump it into a high pressure one.

So far we have achieved pump isolation, the change from an expensive lubricant to a cheap, less viscous fluid and the essential process of rectification. (We could even have taken the chance of a change of pressure level by means of a piston intensifier rather than a membrane separator but this may not be necessary.) So far the scheme involves minor modifications to existing and well-proven components. But we have not achieved the variable displacement of a primary pump which will be important for high performance at low power levels. This can be provided by foiling the closing action of the inlet valve and so pumping water back into the low pressure manifold without force being developed at the pump or work being done. Some careful design of the passages will be needed to ensure that the fluid losses on the idling stroke are kept small.

The Valve Actuator

The scientific exponent notation is a convenient way for physicists and mathematicians to express very large or very small numbers. But it may mask some implications for the mechanical engineer. We must recall that 10^8 is much closer to zero than it is to 10^9 . And yet 10^9 should be the target life for our valve actuator if we exploit the speed-up characteristic of the multi-lobe pump. The problem is formidable but not, I believe, impossible.

Let us count the factors on our side.

1. We never need to operate the valve against any pressure. It will always be operated at a slack point in the cycle and actuating power will be low.
2. The final instant of closing will be cushioned by fluid.
3. Operation is only needed at a few hundred strokes per minute.
4. Failure is not catastrophic. A reasonable number of units can fail with no loss of output.
5. Temperatures will be low.

We propose to develop an actuating mechanism shown in Fig. 7 which resembles a permanent magnet stepping motor in linear form. It will have a bi-stable action with end positions defined by a magnetic field. A momentary pulse of current will be used to close the valve if a working stroke is needed. Its amplitude should be chosen to be just enough to get the valve to the closed position without excessive velocity. A separate shorting ring in the magnetic circuit can soften the closure. The force required to hold the valve open need only be enough to hold it against fluid flows of about 20% of the maximum. At duck velocities above this, the pumps will operate at every stroke and electronic control is unnecessary. The force required to hold the valve shut may be less, and should be present for only a short distance so that valve opening is assisted by the magnetic field. The friction between valve stem and its guide adds an ill-defined complication to the design of the electro-magnetic system, as well as a source of wear. We plan to use beryllium copper spiders to constrain the valve motion. This means that the valve becomes much more like a loudspeaker movement than a conventional solenoid. If fatigue can be prevented in the spiders and the closing velocities kept small so as to reduce valve seating damage, then the life of the mechanism will be very long. If the valve can be made neutrally buoyant, then it will not be affected by accelerations or changes of attitude.

If the high side of the water system is held at constant pressure, the force felt by the duck will be proportional to the number of valves operating. If we have, say, forty pumps per duck and five valves per pump, a smooth operation can be achieved. However, it does not seem possible to distribute control information from a central unit to each valve with

reliability. Wires penetrating waterproof boxes are to be avoided. Instead, we propose that the control strategy is determined separately in each pump. No coordination between pumps is necessary if the following technique is used. Each pump knows the velocity and velocity history of its duck and can therefore calculate how many valves ought to be in action. It can generate a random number which will lie between zero and the maximum number of valves. If the random number exceeds the calculated number, then we decide not to pump. But if the calculated number exceeds the random number, then pumping occurs. It will be found that the laws of probability work with greater reliability than waterproof plugs and wires. Note too that electrical power is not needed for calm conditions. We will use C-MOS for the computer and we hope to supply the power necessary from a variable reluctance generator in each pump unit rather than risk a centralised supply.

Lebensraum

It is annoying that in a device which seems so large, there is a problem about finding space for power take-off. The outside shape is sacred. The upper surface may be swept by water moving at 1.6 times the phase velocity (10), i.e. about 30 metres per second and so has to be hydrodynamically fair. The backbone must be strong and has to have as large a diameter as possible. The gaps between ducks do not offer enough room for bearings, pumps and the joints which are needed for bending moment relief.

We have recently discovered however, that the backbone may not need strength or rigidity in the vertical direction. This means that we can perhaps have flats on the top or bottom and these can be used for power take-off.

Another choice is to put all the equipment into the duck itself where its weight is welcome as ballast and where it can be a little more accessible. Enthusiasm for transferring pumps to the duck is moderated when we realise that this is not really a convenient place for power to be. While it is no harder to take power from individual ducks to the sea-bed than it will be for isolated wave power devices, we ought to be reluctant to throw away the advantages of power-sharing over long strings and the collection of gigawatts rather than single megawatts. Self-coiling spools can be used to pay out and rewind hoses and cables between duck and backbone but the nicest arrangement would be to take power to the neighbouring ducks. The angles between adjacent ducks are quite small. We have to await tests with a free-floating string to see whether capsizing causes too many problems.

Gears

The difficulty of maintaining accurate alignment between duck and backbone raises problems with the use of gears. However, it should be possible to follow the irregularities by the movement of a swinging arm such as that in Fig. 8. Two pump bodies mesh with a large internal gear formed on the inside surface of the duck.

I am reluctant to use too many pumps on one sector of track because the failure of one tooth can spread to all the units which try to mesh with it. But if about three-quarters of the inside width of a duck is made into a gear, we can keep good isolation and a moderate tooth loading. It would be convenient if the gear teeth could be moulded in concrete during the casting of the duck. Unfortunately, normal concrete has very little strength in tension and so is not widely used for gears. However, a number of fibrous additives can be included in the mix for the duck's inner skin and we might also be able to use larger pressure angles than those used for steel teeth. We should also recall that modern gear-tooth forms provide a constant velocity of transmission at the expense of some sliding movement. They also allow meshing between a wide range of gear diameters. Neither of these factors is necessary for our application and perhaps they may provide a loophole. However, we do not at present expect gears to be the best solution despite the attraction of keeping power on the backbone.

Plain Belts or Toothed Belts

If we decide to put pumps on the duck instead of the backbone, there are two straightforward ways of driving them. The first scheme (as shown in Fig. 9) uses plain, flat tapes wound once round the backbone and several times round each of the pumps. The tape tension at torque limit is only 140 kN per metre width of duck and this can easily be taken by steel wire reinforcement. A fine drawn wire should be used with a diameter small enough to avoid fatigue when wrapped around the pump body. Energy used to stretch the tapes may not be recovered and so steel reinforcement is preferred.

The advantages of this scheme are that it is extremely tolerant of duck alignment and that extra tapes and pumps can be added at a later stage if we should change our policy about winter supplies. The chief disadvantage is that the pumps are working on alternate halves of the cycle. They will have to be fitted with small pony motors for re-coiling the tape on the return stroke.

Toothed belts have become well-established for cam-shaft drives and are used in our second scheme. The Power Grip HTD series has been developed by Uniroyal with a new tooth form which makes very efficient use of the shear strength of the tooth material. The largest type now available has a tooth pitch of 14 mm and can very nearly meet our requirements. It is clear that a 28 mm version will be adequate.

Toothed belts like to have a large angle of wrap around the pumps and the arrangement shown in Fig. 10 allows this by using two pumps driven by a belt with teeth on both surfaces. Belt tension can be maintained by a torque applied to the link holding the pump shaft. We have now achieved a more satisfactory duty cycle.

A Magic Answer?

The previous schemes which I have described represent conventional solutions. Their success depends on careful choice of materials for belts and gear teeth. But there is an unconventional approach to the problem which I find particularly fascinating. It is based on suggestions by Professor Laithwaite from whom I had sought advice on very low speed electrical machines.

We build into the duck two very large gyros and arrange that they spin in opposite directions. In calm water the spin axis lies radial to the duck backbone and the gyro frame has a bearing perpendicular to both backbone and spin axis. Nodding of the ducks causes precession of the gyro frame and this is used to do work by driving pumps. The output of the pumps is used to drive a turbine or hydraulic motor on each gyro and energy is taken out by generators built into the gyro discs.

There are several intriguing features of this idea. There is no torque reaction on the backbone so that its structural design is simplified. Secondly, there is no need for a mechanical motion to pass through watertight seals. Advice received from marine engineers has been uniformly depressing about the problems of sealing. The gyros can operate in hermetic conditions or even a vacuum or specially chosen gas. They need know nothing about being at sea. Thirdly, the gyros can store prodigious amounts of energy, enough to provide a completely smooth output.

Let us examine the numbers. If the gyro inertia is J and the rate of spin Ω and T and ω are torque and angular velocity,

$$T_{\text{frame}} = J\Omega\omega_{\text{duck}}$$

$$T_{\text{duck}} = J\Omega\omega_{\text{frame}}$$

$$\frac{T_{\text{duck}}}{\omega_{\text{duck}}} = J^2\Omega^2\frac{\omega_{\text{frame}}}{T_{\text{frame}}}$$

But $\frac{T_{\text{duck}}}{\omega_{\text{duck}}}$ is the damping coefficient. For our design

it is $7.7 \times 10^6 \text{ Nm sec rad}^{-1} (\text{metre width of duck})^{-1}$. Small damping coefficients will look like large damping coefficients when seen through the magic mirror of gyro rotation.

The duck shape will allow the gyro diameter to be about half the duck diameter, i.e. about 7.5 metres. If we get 50 tons of material at the rim, J values will be about $6 \times 10^5 \text{ kg m}^2$.

The speed of the disc is limited by the centrifugal bursting forces and depends on the square root of the ratio of allowable stress to density times disc radius. We should be able to get $\Omega = 100$ rad/sec (950 rpm), or perhaps more with high-strength low-density materials which are, surprisingly, best for fly wheels.

If we decide to make precession angle equal to duck angle, we find that the $J\Omega$ product is sufficient for a duck width equal to the gyro diameter.

The energy stored in each gyro spin is $\frac{1}{2}J\Omega^2 = 3 \times 10^9$ joule. This is about the same as the kinetic energy of a 747 airliner in flight and is enough to run a megawatt for three-quarters of an hour. The problems of smoothing power flow are solved at a stroke. We might even be able to consider synchronous machines.

One snag is that whereas most wave power conversion methods suffer from large forces in low speed bearings, this one has to pass large forces through bearings rotating at about 1,000 rpm. The duck torques are felt at the ends of the high speed axis which will be about 6 metres long. In addition, the weight of the gyro disc and the effects of duck acceleration will bring the bearing loads up to at least 150 tons. This combination of load and speed does not promise long life for rolling bearings. The best solution appears to be a hydrostatic/hydrodynamic bearing running coaxial with a rolling bearing which is only engaged when the lubricant pumps fail.

If any readers think that this proposal is far-fetched, I draw their attention to the method of ship stabilisation developed by Sperry and used successfully in the Italian liner "Conte di Savoia" of 41,000 tons and nearly 250 metres waterline length. Sperry used three gyros of 100 tons weight spinning at the speed which we are suggesting and solved the high bearing load with pre-war technology.

Gyros become more attractive as disc diameters and rotation speeds increase and weights reduce. But the biggest attraction of all is that we have no contact with salt water. If the gyros can work in the laboratory, we can make them work at sea without having to become biologists as well as engineers.

CONCLUSION

Dr. Johnson said of a woman preaching that it was "like a dog's walking on his hinder legs. It is not done well but you are surprised to find it done at all". The main problem with wave power is that unless we do it quite well, quite early, it will remain as a token insurance or as a sop to the environmentalist lobby. To get the economics right requires the solution of some challenging problems. But the engineers who solve them can always reflect on the superiority of waves over any process involving thermodynamics.

ACKNOWLEDGEMENT

Wave power research at the University of Edinburgh is supported by the Department of Energy.

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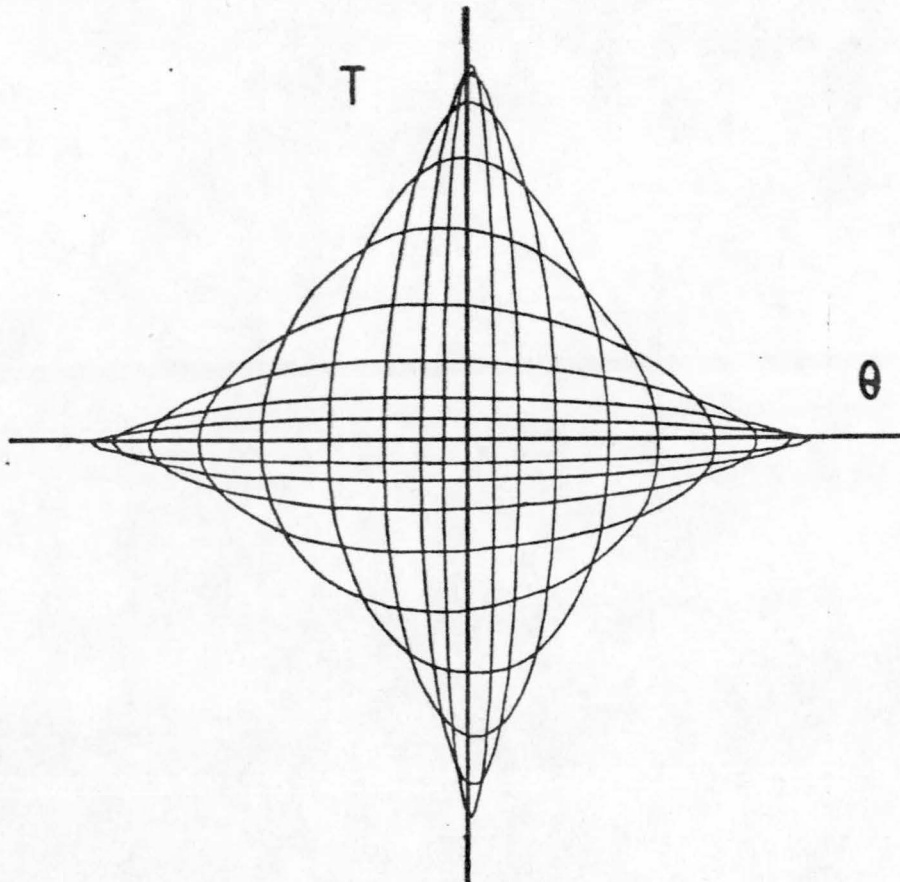


Figure 1 Variation of damping coefficient

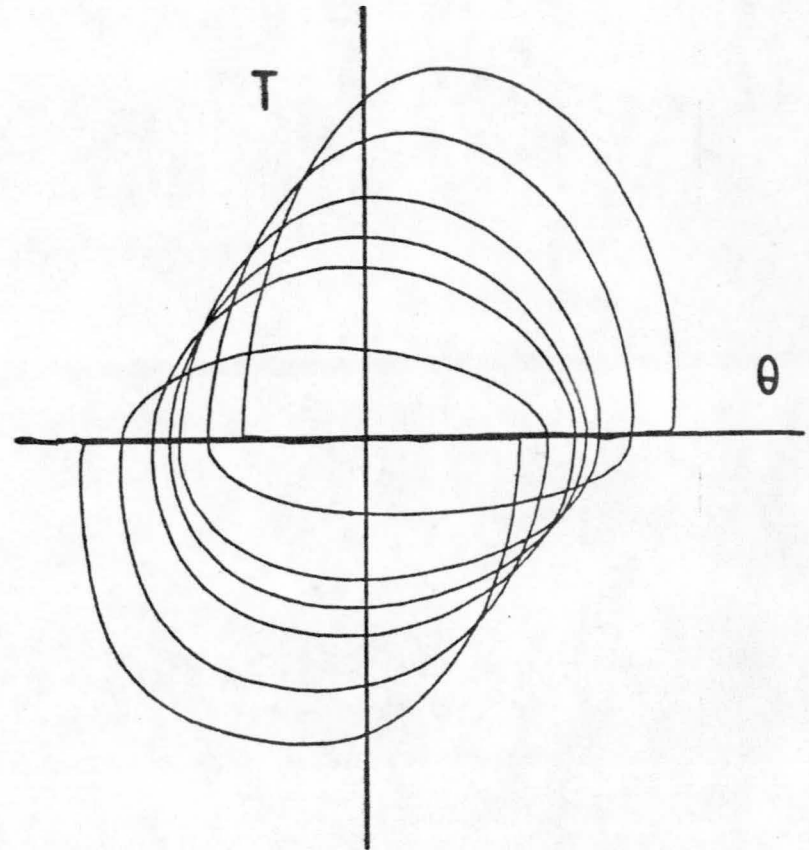


Figure 2 Asymmetric coefficient

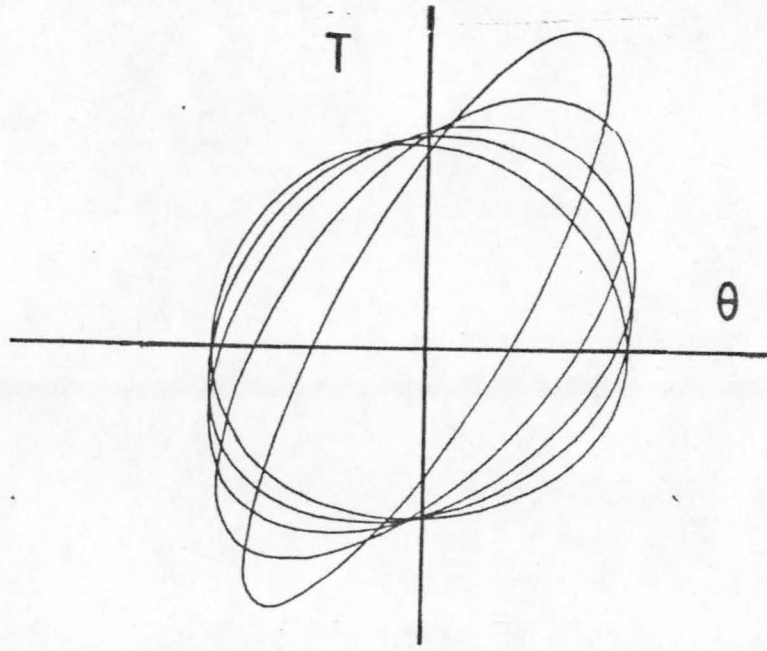


Figure 3 Negative spring

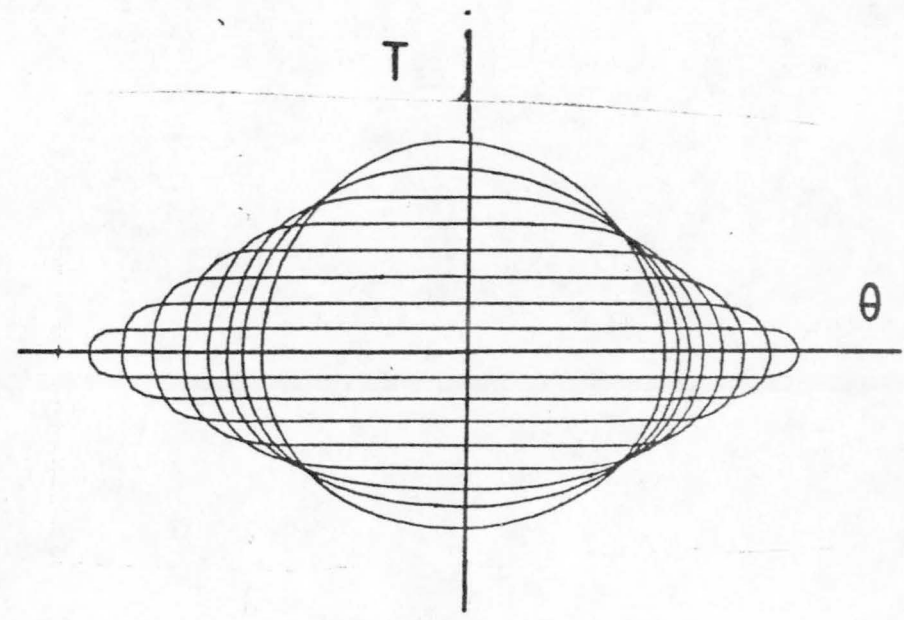


Figure 4 Torque limiting

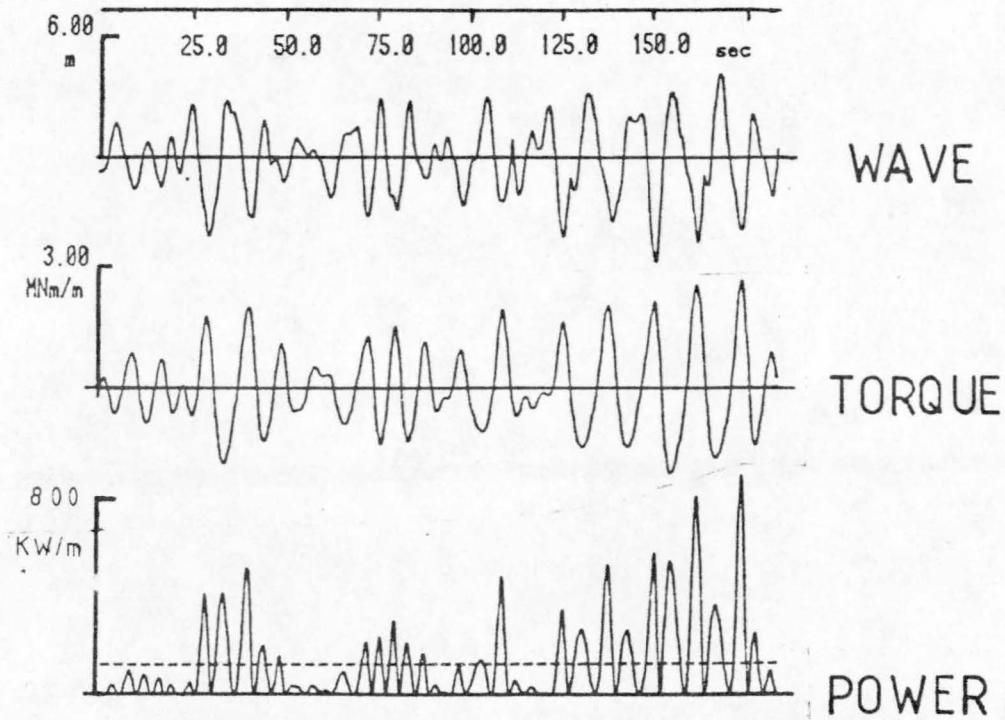


Figure 5 Irregular wave, torque and power records

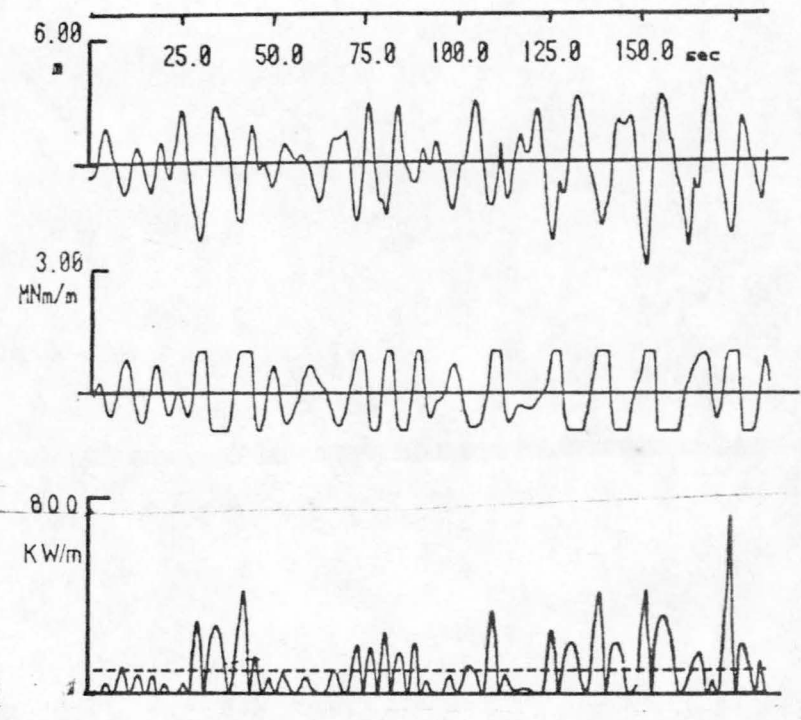


Figure 6 Torque limiting in the same irregular waves

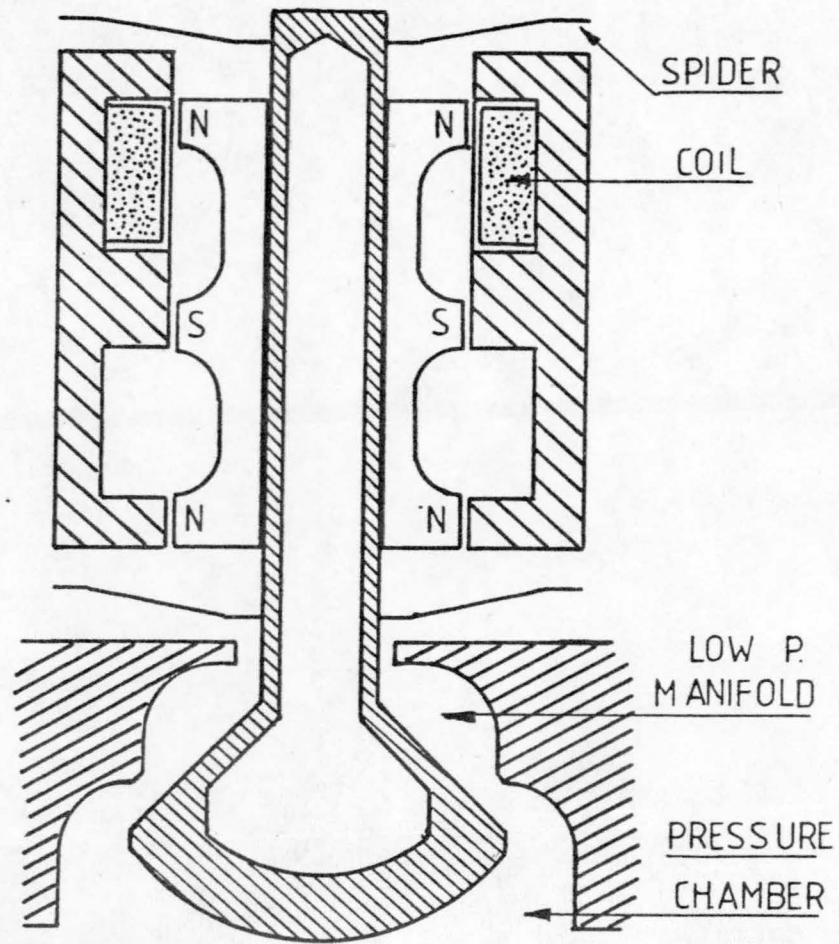


Figure 7 Poppet valve actuator

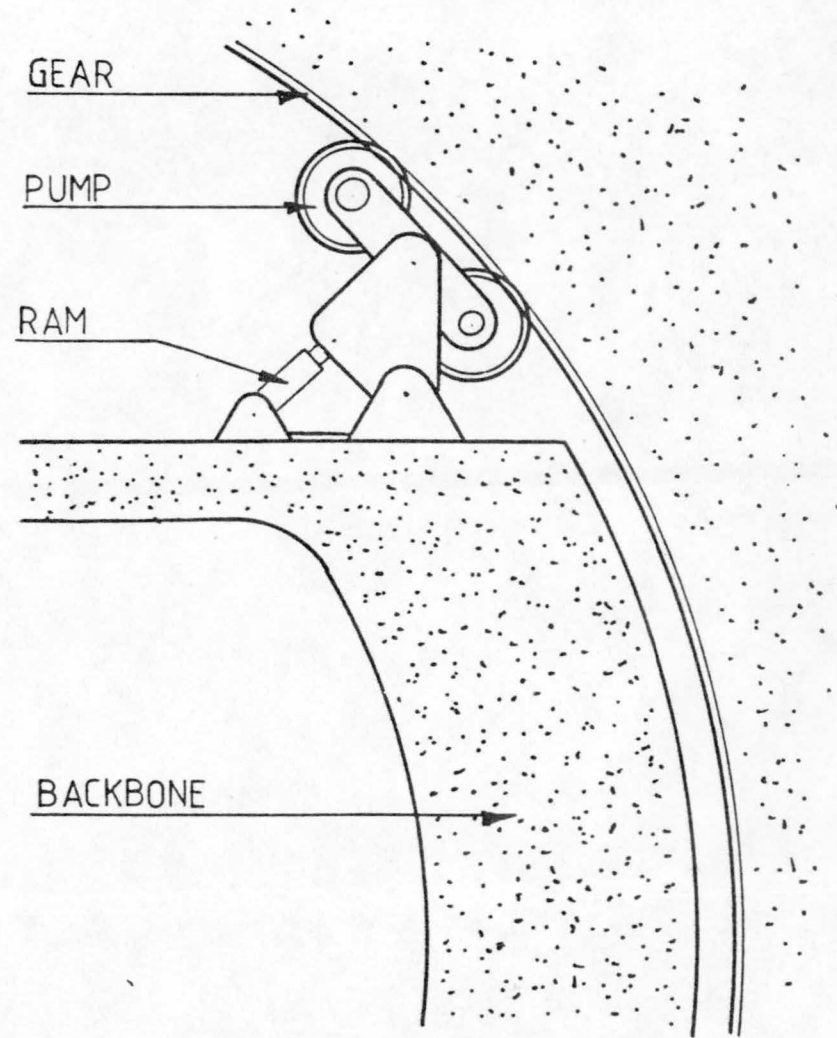


Figure 8 Gear drive and follower

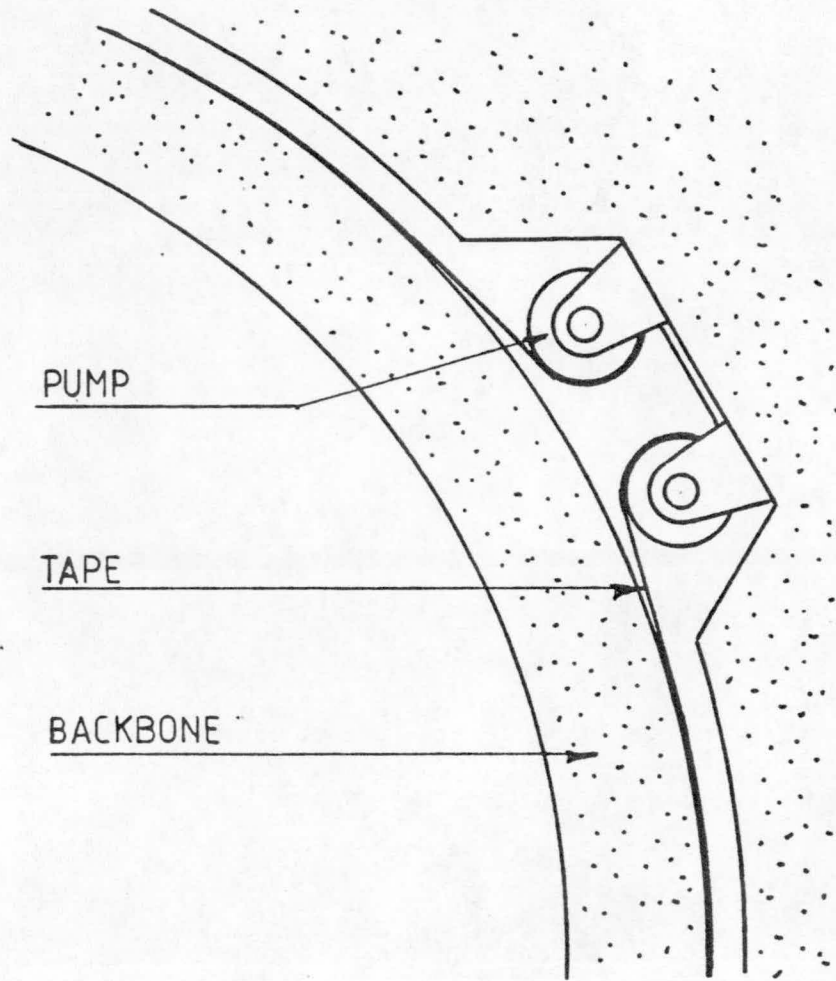


Figure 9 Plain tapes

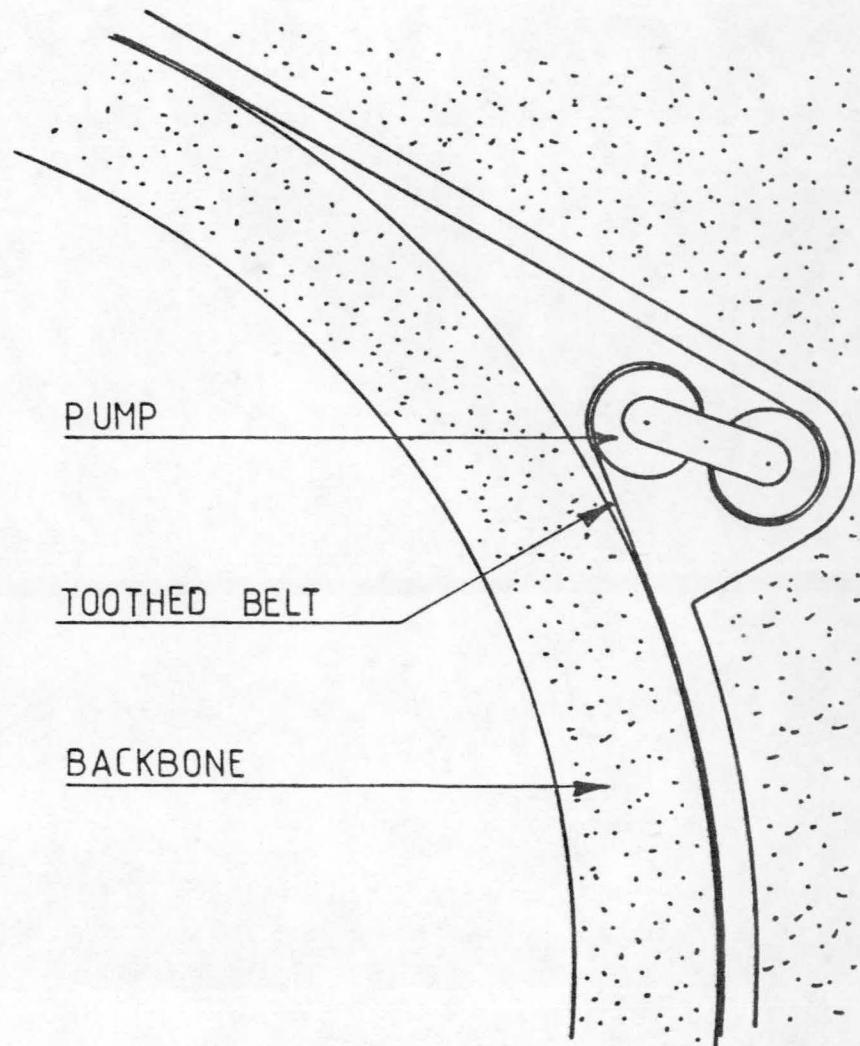


Figure 10 Toothed belts