Wave Energy Converter, Anaconda as an Alternative Source of Energy
T.S.Abirami, K.C.Dhivyashree, V.Dineshkumar*
Department of EEE, SASURIE College of Engineering, Vijayamangalam, Tiruppur, Tamilnudu, India.

*Corresponding Author: V. Dineshkumar
E-mail: dineshv10@gmail.com

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Abstract
The Anaconda is a new concept for wave energy conversion. It is just a rubber tube in the sea, full of water, closed at both ends, anchored head to waves. It is squeezed or enlarged locally by pressure variations that run along its length due to the waves. Squeezing a water-filled rubber tube starts a bulge wave running. The bulge wave travels at a speed that is determined by the geometry and material properties of the tube. The Anaconda is designed so that its bulge wave speed is close to the speed of the water waves above. In these conditions the bulges grow as they travel along the tube, gathering wave energy. Inside the tube, the bulge waves are accompanied by a periodically reversing flow. One way of extracting power from the Anaconda is to use a pair of duck-bill valves to convert this into a rectified flow to pass a turbine between high and low pressure reservoirs. Power produced is fed to shore via a cable. Because it is made of rubber, the Anaconda is much lighter than other wave energy devices (which are primarily made of metal) and dispenses with the need for hydraulic rams, hinges and articulated joints. This reduces capital and maintenance costs and scope for breakdowns.

Keywords: Anchored, Anaconda, Duck-bill

1. Introduction
Anaconda is the device, which is a large distensible rubber tube that is closed at both ends and filled with water. It is designed to be anchored just below the sea’s surface, with one end facing the oncoming waves. A wave hitting the end squeezes it and causes a bulge wave to form inside the tube. A bulge wave is a wave of pressure produced when a fluid oscillates forwards and backwards inside a distensible tube. The bulge wave travels at a speed that is determined by the geometry and material properties of the tube. Inside the tube, the bulge waves are accompanied by a periodically reversing flow. One way of extracting power from the Anaconda is to use a pair of duck-bill valves to convert this into a rectified flow past a turbine between high and low pressure reservoirs. Power produced is fed to shore via a cable. Because it is made of rubber, the Anaconda is much lighter than other wave energy devices (which are primarily made of metal) and dispenses with the need for hydraulic rams, hinges and articulated joints. This reduces capital and maintenance costs and scope for breakdowns.

2. Wave Energy (Resource)
Wave energy may be considered as an integrate form of the solar energy. Winds are generated due to differential heating of Air layers and these winds blow over the water surfaces to produce waves. Energy is concentrated at each conversion stage so as to obtain waves with power levels of approximately 10-50 KW/m of wave crest length.
3. Principle of Operation

It has been known for many years that bulge waves can propagate along a fluid-filled elastic tube — they are like sound waves, except that the elasticity of the tube walls increases the effective compressibility of the fluid, slowing the wave. The best-known example is physiological: the pressure pulse from the heart propagates relatively slowly along the arteries (much more slowly than the speed of sound in blood), because of the elasticity of the artery wall. ANACONDA is a giant water-filled rubber tube, in which the natural propagation speed of bulge waves is matched to the speed of the water waves to be captured. There is then a resonant amplification of the bulge wave, and the water wave energy is captured as a bulge wave (as shown in Fig. 1). There are several different ways of viewing the mechanism by which water waves excite bulge waves which, critically, is equally effective whether the device is fixed on the seabed in shallow water, or floating just under the surface and bending to follow the wave profile.

1. If the tube were infinitely flexible like a very thin rubber balloon, the motion of the water inside would be the same as if the tube were not present. The tube would be flattened into an elliptical cross-section under wave troughs, and stretched into an elliptical cross-section under wave crests. Because its width would be the same everywhere, its cross-sectional area would reduce under wave troughs, and increase under wave crests. This suggests that bulge waves will be excited in the tube, whether it is lying on the seabed in shallow water, or floating just under the surface and bending to follow the wave profile.

2. If the tube were infinitely stiff like a rigid pipe, and were lying on the seabed in shallow water, the water inside would be stationary, and so have constant pressure. The pressure outside would decrease under wave troughs, and increase under wave crests, and so would a fluctuating pressure difference across the walls. This would clearly excite bulge waves in the tube, were it not rigid. If the tube were flexible enough to float just under the water surface and bend to follow the wave profile, but still not change its cross-sectional area, then again the axial velocity in it would be zero (or constant along it, by conservation of fluid volume, as in a pipe). The internal pressure would therefore rise hydrostatically in wave troughs and fall in wave crests. Thus although the external pressure was nearly constant (by the free-surface boundary condition on the water wave), there would again be a fluctuating pressure difference across the walls.

3. If the tube were lying on the seabed and propagating bulge waves of the same length and speed as the water waves, then by appropriate choice of the phase difference between them, we could arrange that the radial velocity of the tube wall (due to the bulging) was outwards when the external pressure was low (i.e. under a wave trough) and inwards when it was high (i.e. under a wave crest). The external water would then always be doing work on the tube, so wave energy would be extracted. However, if the tube is floating just under the water surface and bending to follow the wave profile, then the external pressure will be nearly constant. It is shown that the work done by the wave on the tube is now in lifting the tube, which bulges to weigh more when it is being lifted up on the front of a wave, than when it is going down on the back. So again energy is extracted from the wave. There are also several different ways of viewing the resonance which occurs when the speed of the water wave matches the natural propagation speed of bulge waves in the tube. If the water wave is travelling at speed \( C \), say, and then its pressure excitation on the tube (e.g. the external pressure on a device on the seabed, as in (2) above) produces a bulge wave of the same speed \( C \). But a bulge wave can propagate at its natural propagation speed \( C^* \), say, without the need for
any pressure excitation. Hence the pressure excitation from the water wave merely “makes up the difference”

Fig. 2 The power of the bulge wave in a 150m long 7m diameter ANACONDA with a dispensability such that the free bulge wave speed matches the speed of water waves of period 10s. The dashed line assumes zero losses in the rubber. Continuous lines assume hysteresis losses of 10%, 20% and 30% of the energy stored and recovered in each cycle.

Needed in the excitation, that arises because $C$ is not equal to $C^*$. If $C$ is close to $C^*$, this difference is small, so a small excitation from the water wave produces a large bulge wave in the tube. The final steady-state amplitude of the bulge wave is calculated, if the device were infinitely long, using the classical device of a frame of reference moving at the wave speed. The ratio of the pressures in the bulge and water waves is shown to be $(1 - (C/C^*)^2)^{-1}$, so the bulge wave amplitude is infinite on this analysis when $C = C^*$. This is exactly analogous to the resonance in a simple pendulum, excited by a lateral motion of its pivot, with an angular frequency $\Omega$ close to the pendulum’s natural angular frequency $\Omega^*$. Again, the pendulum needs no excitation to oscillate at its natural frequency, so the external force merely “makes up the difference” which arises because $\Omega$ is not equal to $\Omega^*$, and there is a dynamic amplification by a factor $(1 - (\Omega/\Omega^*)^2)^{-1}$. The performance of a device 150m long and 7m diameter is calculated, with various levels of hysteresis loss in the rubber. Figure 1 below is the computed capture width (i.e. bulge wave power/ {water wave power per unit crest length}) is suggests a power output, before conversion losses, in the region of 1MW, at a site with an annual average incident wave power is 50kW/m.

4. Capture Widths Measured Experimentally

A model tube, about 2.5m long and 78mm in diameter, was made from rubber sheet 0.15mm thick. Its Young’s modulus $E$ and loss coefficient $\beta$ in the stress/strain relation $\sigma = E (\varepsilon + \beta \dot{\varepsilon})$ were approximately $E = 1.94$ MPa and $\beta = 0.0059s$. The tube was installed at an elevation just below still water level on the centre-line of a wave flume 0.42m wide, 18m long, with a still water depth of 0.7m. Figure 2 below shows the model in place, responding to waves coming from the left. In these experiments, the tube was pressurised to an excess head of about 70mm, and then sealed. A transducer recorded the internal pressure at one end. Regular waves could be generated in the tank with a flap-type wave maker with active absorption, and those that passed the ANACONDA model were efficiently dissipated in a vertical wedge of firm polyether foam from which reflections are less than 3%. Wave gauges recorded water surface elevations ahead and behind the model. 0.6 Initial estimates of bulge wave speed were made from observations of bulges started by hand. Propagating along a water-filled tube lying on a horizontal surface in air. In these conditions the cross section of the tube was inevitably non-circular, but measured speeds were within 10% of the theoretical value for a circular tube of the same area. Theoretically the natural bulge wave speed $C^*$ (in the absence of hysteresis, which has a weak effect on it) is equal to $(\rho D)^{-1/2}$, where $D$ is the dispensability and $\rho$ the water density. For a circular tube of diameter $d$ and wall thickness $\delta$, the dispensability $D = d/(E \delta)$. In the wave
Fig 3. On the above, photographs of the model ANACONDA in waves in a narrow tank. The upper image shows the end of the tube in waves propagating from left to right. The view below is of bulge waves travelling in the same direction, as seen through the glass floor of the tank. On the bottom, are shown capture widths inferred from internal pressure measurements (circles) and from measurements of incident, reflected and transmitted waves (crosses).

Flume, with one end of the model mounted on the actuator, small bulge waves could be launched along the tube in still water by driving one end vertically with a servomechanism, with a step input of very small amplitude. A pressure transducer at the other end clearly recorded the arrival of the resulting bulge wave, and the measurements indicated a speed of 1.36 m/s. The theoretical speed was \((\rho D)^{-1/2} = 1.93\) m/s. It seems reasonable to link the difference in this case to the presence of the surrounding water. Figure 3 gives the results obtained from the experiments, as a function of the ratio of the tube length \(L\) to the water wavelength \(\lambda\). Those plotted with crosses were calculated from measurements of incident, reflected and transmitted waves. Those plotted with open circles represent the energy losses in the rubber over the entire length of the tube, calculated from the damped bulge wave equation

\[
\frac{\partial^2 p_b}{\partial t^2} - \beta \frac{\partial^3 p_b}{\partial t^3} = \frac{1}{\rho D} \frac{\partial^2}{\partial x^2} (p_b + p_w)
\]

Where \(p_b(x, t) + p_w(x, t)\) are the pressure inside the tube; \(p_w\) is the external pressure, and \(p_b\) the excess internal pressure that is supported by tension in the tube wall. Pressures at all points along the tube were estimated by using this equation with appropriate closed end boundary conditions, and by matching the pressure at the down wave end of the tube with the measurements. From the resulting hoop stresses it was then possible to calculate hysteresis losses and the associated capture width.

5. How It Works

JUST A RUBBER TUBE IN THE SEA full of water, closed at both ends, anchored head to waves. The velocity of the bulge wave in the tube and the waves in the sea is the same; then the wave energy is transferred gradually to the tube. At the bow, the wave squeezes the tube and starts a bulge running. But as it runs the wave runs after it, squeezing more and more, so the bulge gets bigger and bigger. The bulge runs in front of the wave where the slope of the water (pressure gradient) is highest. In effect the bulge is surfing on the front of the wave. Here's a model in the wave tank. The wave period is 1.4 seconds, amplitude 8 cm. Figure 4 shows how the waves are attenuated as energy is captured by the tube. The fat bulges
Fig. 4 in this picture the waves come from the left. The arrows show the oscillating flow of water inside the tube.

Propagating outwards, surfing on the front of the wave. The wave power over a wide frontage is concentrated at the end of the tube. We can use it to drive a turbine, generate electricity or pump water. Rubber tubes can live forever in the sea. Anaconda won't break no hinges, no joints and it's cheap. Typically a rubber tube filled with water will bulge locally when squeezed; and this bulge will propagate along the tube at a speed \( c \) given by

\[
\frac{c^2}{d} = \frac{Eh}{d\rho}
\]

Here \( E \) is the tensile modulus of the rubber, \( d \) the diameter of the tube, \( h \) its wall thickness and \( \rho \) is the density of water. The speed can be controlled by choosing the dimensions of the tube and the properties of the rubber. The bulge wave is a wave of pressure, associated with a longitudinal oscillation of fluid, forwards and backwards along the tube. When the pressure is high, the water is flowing forwards; when it is low the water is flowing backwards. This wave carries energy. The mathematics of a bulge tube in the sea has been worked out. If the bulge in the tube travels at the same speed as the wave, then there is a resonant interaction and the bulge grows linearly along the tube. Typically, a tube 7m in diameter and 150m long would collect an average power over the year of about one megawatt. The capital cost per megawatt is likely to be about £2-3 million, much less than existing wave power converters.

6. Power Take-Off

The elastic tube in ANACONDA is merely the first stage in the power conversion process, concentrating the wave power into a bulge wave. It is then necessary to convert the bulge wave power into electricity. The oscillatory flow in a bulge wave resembles the air flow in a WEC of the oscillating water column (OWC) type, so the most obvious possibility is to follow OWC practice and use a Wells turbine (or similar), operating in water rather than air. The low conversion efficiencies of these turbines (typically 20%) are well-known, however, and arise because of the very large fluctuations in instantaneous power.

![Diagram](image)

Fig. 5. Powertake off scheme for seabed device. A conventional hydroelectric (not shown) operates in the smoothed flow between the accumulators.
Most modern WEC designs therefore feature a hydraulic power take-off, incorporating hydraulic accumulators to smooth the power flow, allowing unidirectional hydraulic motors with a much higher efficiency to be used. In the case of ANACONDA, the water in the tube can be used as the active fluid. One-way valves in the tail of the device allow the water to pass into high and low pressure accumulators, as shown in Figure 5, which illustrates the case of a device on the seabed, where the accumulators can be fixed. A turbine (not shown) then operates in the smoothed flow between the accumulators – the head difference between them is several times the wave height, which is ideal for conventional small-scale hydroelectric turbines, which have conversion efficiencies of about 90%. The equivalence between one-dimensional waves and electrical circuits is well-known voltage is an analogue of pressure, and current is an analogue of volume flow rate. If the incoming bulge wave has a pressure \( P(t) \) at the tail, and the reflected bulge wave has a pressure \( R(t) \), then the total pressure \( T(t) \) at the tail is \( P(t) + R(t) \). If the cross-sectional area of the tube is \( A \), and we assume that the incoming bulge wave is travelling at its free propagation speed \( c \), then the volume flows is

\[
P(t)/(pc/A) - R(t)/(pc/A) = \{2P(t) - (P(t) + R(t)))/(pc/A) = \{2P(t) - T(t))//(pc/A)\}\ (3)
\]

Thus the equivalent circuit is as shown in Fig. 5, where the valves and accumulators are represented by diodes and capacitors. Assuming a sinusoidal incoming bulge wave and large capacitors (accumulators), the power absorption is readily calculated as matter of electrical engineering – it reaches a maximum of 92.3% of the incident bulge-wave power, if the accumulators are set to plus and minus 80% of the peak value of \( P(t) \). And it remains over 50%, if they are set between 24% and 146% of it. The reflected wave (which will be re-reflected at the nose, so its power is not lost) is readily obtained too - at 92.3% absorption it is all higher harmonics – the 3rd and 5th have 6.7% and 0.8% of the incident power. For floating versions of the device, the seabed is not available as a fixed reference. Instead, an additional length of non-distensible tube can be added, as an inertial reference.

This modifies the equivalent circuit as shown in Figure 6. (Note that a free end is zero reactance and thus a short circuit.) If the length of this additional tube is \( \lambda/2\pi \) (\( \lambda = \) wavelength), then its reactance \( X \) will have the same impedance \( pc/A \) as the main tube. Thus a moderate additional length of tube is sufficient to make a good inertial reference, and give comparable performance to a seabed-mounted device. This is a reflection of the fact that the power is already concentrated, compared with the original water wave. To maintain the advantages of all-rubber construction, the accumulators and reactor shown in Figure 6 can also be rubber tubes. For the reactor, the rubber can be fibre reinforced like a deacon (or a car tyre), to give the necessary rigidity when pressurised. By contrast the accumulators require maximum dispensability to give the required low entry impedance – ideally the pressure should not rise at all with entry velocity, like its electrical equivalent of a large capacitor. This can be accomplished by reinforcing the outer skin as in the reactors, but then adding an internal gas-filled bladder, as in a hydraulic bladder accumulator. The complete system is then as illustrated in Figure 7. The gas-filled bladders in the two accumulators are shown in dark blue, and can communicate with each other because their height difference is (very conveniently) equal to the required head difference between them. Effectively, the power take-off is operating like a WEC of the “overtopping” type, with high pressure water entering a high-level reservoir, and low-pressure water leaving from a low-level reservoir. Except that all the pressures are magnified, because they are the pressures in the bulge wave, not the water wave outside. Unlike an “overtopping” WEC, the head difference between the reservoirs is variable, rising to suit the wave conditions. The gas-filled bladders also communicate with two external bladders, which give the necessary pressurisation, and allow for volume fluctuations.

7. Full Scale Design

A preliminary design for a tube 7 m in diameter and 150 m long, which would capture 1 MW average power, is shown in fig 8. A mean positive water pressure inside the tube is established by water entering through the one-way “duck bill valve” (DBV) at the stern. At the end of the tube there is a large oscillating pressure: when this oscillation, combined with the positive bias, swings negative, water is sucked in through the DBV. The result is that the mean pressure builds up to equal the amplitude of the pressure oscillation, typically about 4 m water head. The
water entering through the stern flows along the tube and exits through a standard low-head turbine located at the bow. The dispensability of the tube smoothest the flow. Thus the power in the wave is converted into a smooth flow of water through the turbine at the bow, generating electricity. A more elaborate arrangement (“pressure amplifier”) can be used at the stern to inflate the tube, ensuring that the pressure never swings negative. When the Tube bulges, energy is stored in the rubber walls. For 1 MW average output the peak power would be about 3 MW. With wave velocity 15 m/s corresponding to 10 s waves, the energy to be stored per metre length is 800 kJ/m. Comparing this with 250 kJ/m3 stored in rubber with $E = 2$MPa at strain 50%, the wall thickness required for 7 m diameter tube comes to 15 cm. But this is only needed at the end of the tube: half way along the bulge energy is four times smaller, so less rubber could be used. Less rubber would also be required if it had a higher modulus. To get the correct bulge velocity requires the right combination of modulus $E$ and wall thickness $h$. This applies to the simplest case of a uniform tube. To use the rubber most effectively the tube will have a composite wall, partly rubber and partly inextensible polymer-coated fabric. The weight of rubber required for a 1 MW installation will then be only a few hundred tonnes and, on preliminary estimates, the cost of the structure less than £1 M. Our target for a complete system is £ 2 k per average kilowatt out. Note that the power output is proportional to the cross-sectional area of the tube. The wall thickness scales as the radius, so the volume of rubber required is also proportional to the cross-section. This means that the amount of rubber needed to capture a given amount of power is the same, whether there are many small tubes or one large one. A single large tube with One large generator could ultimately be the best solution. But with little increase in cost one can start with small tubes, say 1.5 m in diameter, which would each capture about 50 kW on average. As well as capital cost, survivability and operational cost are important for wave energy converters. Being flexible, Anaconda should be a good survivor and simple enough to require little maintenance. Rubber is a supremely durable material, used at sea in the rubber dinghy and dragons for transporting fluids, virtually no maintenance and is unaffected by fatigue.

8. Advantages

The ANACONDA appears to be more advantageous as compared with other wave energy converters, which are mentioned below:
- It has a good capture width.
- Maintenance is very low as compared to other wave energy converters.
- Its design is simple and convenient.
- High durability
- It is estimated that the cost per Kwatt of the energy produced will be low.

In addition to this advantages, it is also advantageous for the environment in different ways as shown below:
- Millions Of tons of carbon -dioxide production around the world are reduced.
- It produces roughly electricity consumption of 2000 houses.
- It is a closed circuit system so issues with ingestion of marine animals will not arise. Because it is under the surface and rubber can be formulated to be non polluting, environmental impact will be minimal.
- Although around twice as much as coal-fired power stations, this compares very favourably with other leading wave energy concepts.
- Its ultra-simple design means it would be cheap to manufacture and maintain, enabling it to produce clean electricity at lower cost than other types of wave energy converter. Rubber tubes can live forever in the sea. Anaconda won't break no hinges, no joints ... and it's cheap.
- Which has the potential to produce a significant amount of clean “green” energy? While it certainly will not solve all of the West’s energy problems, it could be a significant step toward reducing dependency on fossil fuel.
- We can reduce “global warming”.

9. Comparison with Other Sources

- Compare to thermal power plants there is no air pollution.
- It is not affected by weathering compare to hydrological power plant.
- Comparing to nuclear power plant it is non-hazardous.
- Compare to solar power plant it has high efficiency.
- Rubber anaconda placed in-depth of 40m-100m so there is no problem in Marine transport comparing to tidal power plant.

10. Conclusion

After some decades, the fuels present in world will expire, and also in future we need more electricity with the increase in population. Renewable energy is the only solution for producing required amount of power generation with low cost. This new technology called “Anaconda” is a promising device for satisfying the present energy needs to some extent. Using this we can produce required amount of power with low cost and without pollution comparing to other sources and high efficiency compare to other renewable sources. Now-a-days our world is affected by GLOBAL WARMING. So we need a novel renewable power generating source that should not affect our earth. This type of a new source is this “ANACONDA”. From these, we can conclude that this is one of the best alternative energy sources without any pollution.

References: