Welcome to Vibrationdata

Acoustics • Shock • Vibration • Signal Processing **October 2008 Newsletter**

Aloha

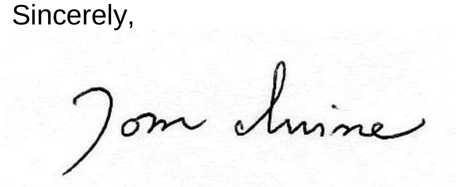
Rocket science first caught my interest when news bulletins of the Gemini and Apollo missions interrupted my favorite morning TV show *Captain Kangaroo*. The liftoff and ascent of the mighty Saturn V booster trumped Grandfather Clock, Magic Drawing Board, and Mr. Moose's ping pong ball antics.

Since then, launch vehicle vibration has become a subject near and dear to my heart. The analysis of this phenomenon provides my means of living.

I remember the suspense of the Apollo 13 mission which resulted in a "successful failure." The first article recalls this mission by discussing a pogo oscillation anomaly which occurred prior to the oxygen tank explosion in the service module.

As the next article, the Earth's ocean waves provide a potentially vast source of renewable energy, without carbon dioxide emissions. This energy can be harvested to power desalinization plants and to provide power for homes and business. Enjoy.

Sincerely,



Tom Irvine
Email: tomirvine@aol.com

Feature Articles

Apollo 13 Pogo Oscillation by Tom Irvine

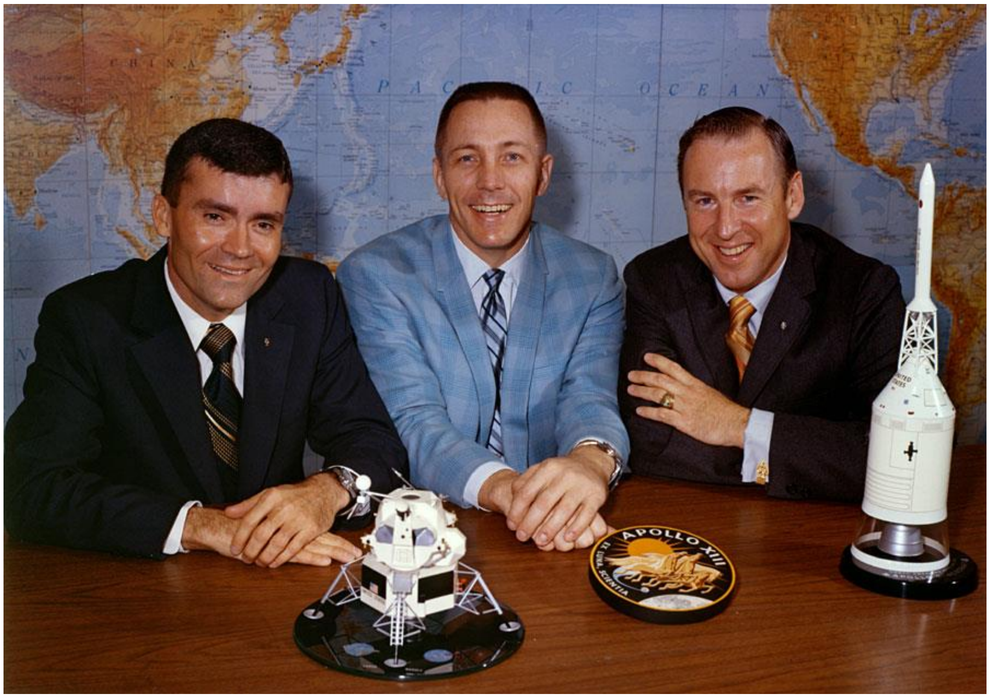


Figure 1. The crew of Apollo 13, Fred W. Haise, Jr., John L. Swigert, Jr. and James A. Lovell, Jr.

The Apollo 13 mission was launched on April 11, 1970. The astronauts safely returned to Earth on April 17 despite an oxygen tank explosion in the Service Module. The astronauts used the Lunar Module as a "lifeboat" after the explosion. The Pogo oscillation occurred before the oxygen tank explosion and was unrelated to the explosion.

Pogo

Rocket vehicles with liquid engines may experience combustion instability, which causes excessive vibration forces. This is a potential source of "self-excited" vibration, whereby the elastic vehicle structure and the propulsion system form a feedback system.

There are several types of combustion instability vibration effects. The most common effect is "Pogo," which is similar to Pogo stick motion.

In this case, a low frequency oscillation in the combustion chamber, or propellant feed system, excites the longitudinal vibration mode of the entire rocket vehicle or some other structural resonance.

This may create a cyclical energy exchange between the structural vibration mode and the propulsion system oscillation.

The propellant mass inside the tanks may also be excited into a slosh mode.

Figure 2. Photo of the J-2 Engine

The ridges on the nozzle are actually pipes. Liquid hydrogen flows through the pipes on its way from the fuel turbopump. The liquid hydrogen is thus used to cool the nozzle.

As an alternative, the pogo problem may be created when a wind gust or some other perturbation excites the vibration mode. This vibration in turn causes an oscillation in the propulsion system, which further excites the structural vibration.

Saturn V Pogo

Pogo oscillation occurred in both the first and second stages of the Saturn booster. This problem was particularly severe on the Apollo 13 mission's second stage burn.

This pogo problem was unrelated to the oxygen tank explosion in the Apollo 13 service module which occurred later in flight

Early Saturn flight tests for the Apollo program revealed that vibration caused the liquid fuels in the tanks to bounce. This created a vicious cycle. The pressure in the fuel and oxidant lines began to shake, throttling the engines up and down in time with the bouncing liquids.

Saturn V Stage Configuration

The Saturn V booster was used for the Apollo program, which was carried out from 1968 to 1972. Astronauts Neil Armstrong and Buzz Aldrin became the first men to set foot on the Moon, during the Apollo 11 mission in July 1969.

The Saturn V had three liquid stages. The complete Saturn V vehicle was 363 feet tall. The engine characteristics are given in Table 1.

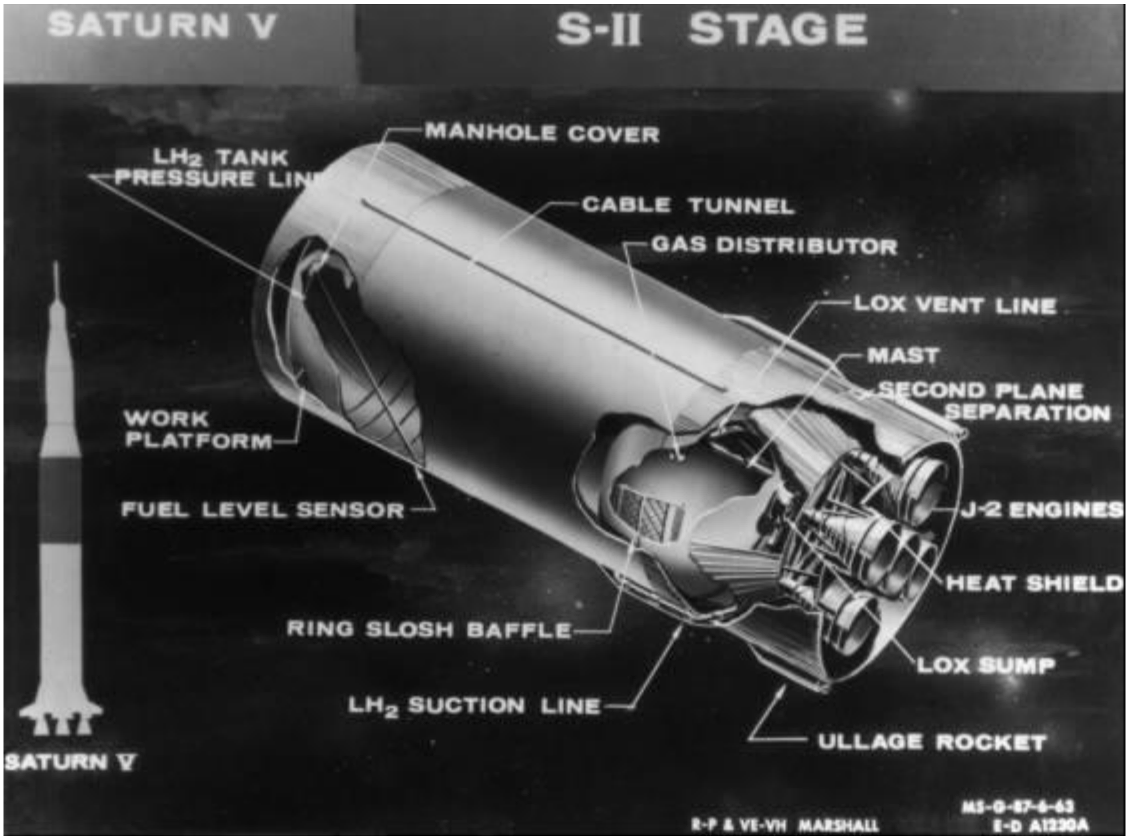


Figure 3. Stage 2 (S-II)

Table 1. Saturn V Engine Parameters

Stage	Stage Name	Fuel	Engines	Thrust (lbf)
1	S-IC	kerosene (RP-1) and liquid oxygen	Five F-1 engines	7.5 million
2	S-II	liquid hydrogen and liquid oxygen	Five J-2 engines	1 million
3	S-IVB	liquid hydrogen and liquid oxygen	Single J-2	200,000

Apollo 13 Flight Vibration

The Apollo 13 vehicle had a severe pogo vibration with the center engine during second stage burn. The engine experienced a 34 G vibration[1] at 16 Hz, flexing the thrust frame by 2.6 inches peak-to-peak.

The displacement d is calculated from the acceleration a and from the frequency f by

$$d = \frac{a}{4\pi^2 f^2} \tag{1}$$

$$d = \frac{(34\,\mathrm{G})\left(386\,\mathrm{in/sec^2/G}\right)}{4\pi^2 (16\,\mathrm{Hz})^2} \tag{2}$$

$$d = 1.3 \text{ inch zero-to-peak} \tag{3}$$

$$d = 2.6 \text{ inch peak-to-peak} \tag{4}$$

This vibration was apparently localized to the engine frame. The engine frame's natural frequency may have been excited into resonance. The astronauts did not report feeling any corresponding vibration, at least not in the mission transcripts.

The structural vibration coupled with a pressure oscillation, as recorded by the center engine thrust chamber pressure sensor.

The pressure oscillations in the center engine diverged from a level of 10 to 500 psi (peak-to-peak) in only 3 seconds.

(Whether the vibration initiated the pressure oscillation or vice-versa is incidental.)

Also note that the oscillation was accompanied by an unexpected interaction with the cavitation in the turbopumps. Cavitation is the generation of unwanted bubbles.

Pressure Switch Trigger

The low pressure point of the oscillation triggered the "low pressure switch." The switch had apparently been designed to measure the average pressure. Fortunately, it triggered in response to the oscillating component of the pressure.

Engine Shutdown

As a result of the trigger, the flight computer shut down the center engine automatically. The outboard engines burned longer, however, compensating for the loss.

The shutdown was necessary. Otherwise, the center engine would have either torn itself off its mounts or broken the second-stage thrust frame, either of which would probably have caused the disintegration of the stage.

Design Modifications

Engineers made a number of design changes to prevent this problem for Apollo 14.

They added a helium gas accumulator in the liquid oxygen (LOX) line of the center engine. The accumulator is also referred to as a suppresser.

The accumulator reservoir served to dampen or absorb fluid pressure oscillations, keeping them out of phase with the vibrations of the thrust structure and engines.

The accumulator also lowered the first natural frequency of the propellant line,

[1] Kirk Dotson, Mitigating Pogo on Liquid-Fueled Rockets, Crosslink, The Aerospace Corporation, 2004. *The 34 G value is zero-to-peak.*

moving it down below the vehicle structural frequencies.

The accumulator was actually designed prior to the Apollo 13 mission but was not ready in time for the flight.

In addition, the propellant valves on all five second-stage engines were simplified.

The following missions, Apollos 14 through 17, Apollo-Soyuz, and Apollo Skylab, were successful.

"Failure is not an Option."

- *Gene Kranz, NASA Flight Director, Apollo 13 mission*

Harvesting Ocean Wave Energy by Tom Irvine

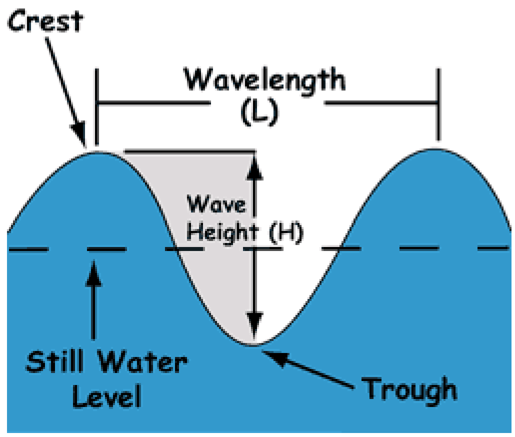


Figure 1. Courtesy of the Office of Naval Research

Introduction

Most ocean waves are driven by the wind blowing over the surface of the ocean. The coupling mechanism is friction between the wind and water.

The waves breaking against a beach result from distant winds.

Four factors influence the formation of wind waves:

1. Wind speed
2. Distance of open water that the wind has blown over, called *fetch*
3. Time duration the wind has blown over a given area, related to gust
4. Water depth

.

All of these factors work together to determine the size and shape of ocean waves. Waves are characterized by:

1. Wave height, from trough to crest
2. Wavelength, from crest to crest
3. Period, time interval between arrival of consecutive crests at a stationary point
4. Wave propagation direction with respect to North.

Wave Power

Wave energy is essentially stored, concentrated wind energy. The Sun's radiation drives the winds, so wave energy may also be considered as stored solar energy.

Wave power varies considerably in different parts of the world.

Wave-power rich areas of the world include the western coasts of Scotland, northern Canada, southern Africa, Australia, and the western coasts of the United States.

Harvesting Devices

Wave power devices extract energy directly from the surface motion of ocean waves or from pressure fluctuations below the surface.

The remainder of this article discusses some potential wave harvesting concepts as well as some devices already in service.

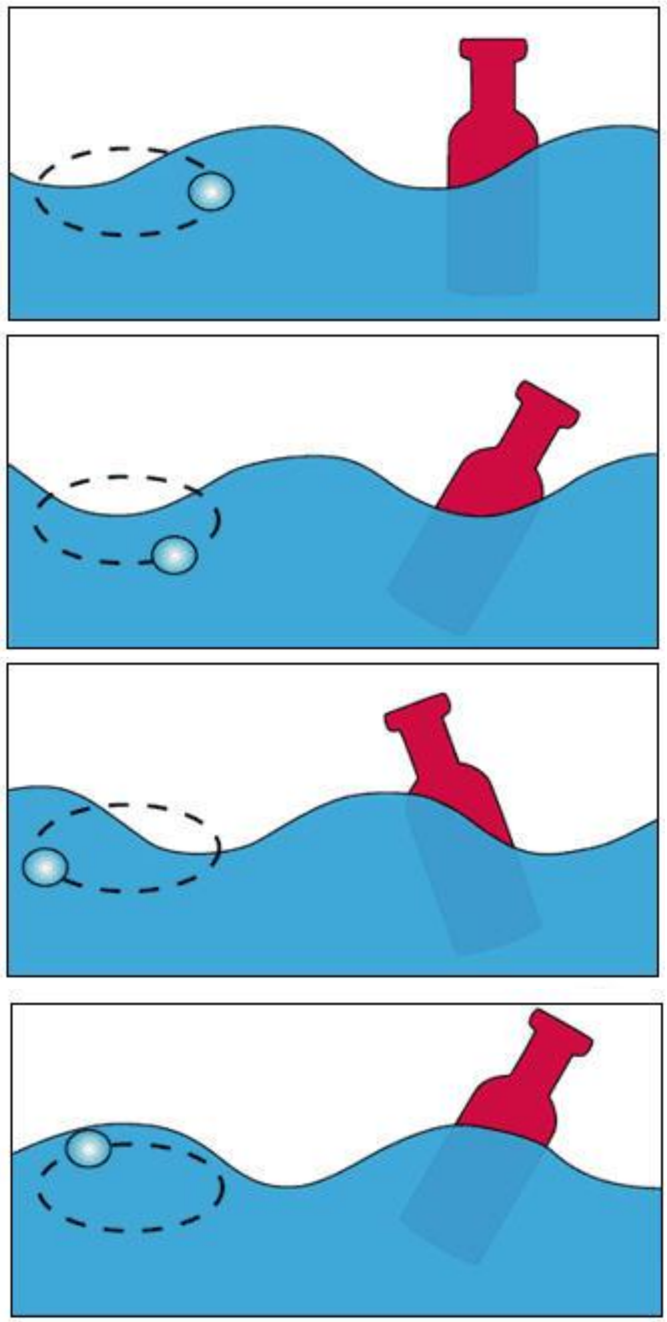


Figure 2. Wave Motion

A deep-water wave provides forward motion of energy.   The water molecules do not move forward with the wave, however.   Rather they sweep through a circular pattern. As the depth increases, the effect slowly diminishing until completely disappearing about half a wavelength below the surface.

Figure 3. Pelamis Wave Energy Converter (PWEC)

Aguçadoura Wave Park

The Aguçadoura Wave Park in Portugal is the world's first commercial, full-scale "wave farm." It was officially opened on September 23, 2008.

The power is generated by three Pelamis wave energy converters, which are located three miles off of the coast.

Each converter is made up of connected pontoon sections which are partially submerged. The segments are connected via hinges to one another. The segment diameter is 3.5 meters.

The segments flex and bend as waves pass. The motion is resisted by hydraulic rams which pump high pressure oil through hydraulic motors which in turn dive electrical generators. Furthermore, the converter functions with either up-and-down or side-to-side motion.

The power is brought ashore by a submarine cable and fed directly into the national distribution grid.

The wave farm is currently generating 2.25 MW, enough to meet the average electricity demand of more then 1500 Portuguese homes.

A second phase of the project is now planned to increase the installed capacity from 2.25 MW to 21 MW using a further 25 Pelamis machines.

Wave Dragon

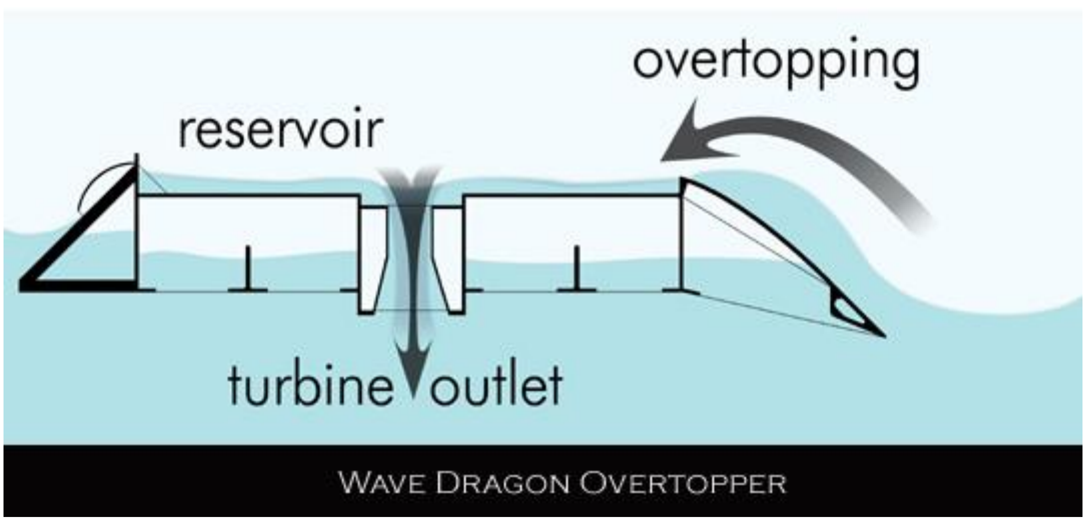


Figure 4. Wave Dragon

The Wave Dragon is large floating barge that produces energy directly from the power of the water. The water flow is directed to turbines, which are the only moving parts.

The Wave Dragon has outstretched collector arms pointed towards the oncoming waves. The arms concentrate 300 meters of wave front towards 140 meters of ramp at the front of the structure.

This focusing increases the wave height at the ramp, which in turn acts like a beach and causes the waves to break over its top and into the reservoir behind it.

The water is thus elevated and given potential energy, which is transformed into electricity by simply flowing the water down through the turbines in the bottom of the structure.

The Wave Dragon produces energy in almost exactly the same way as a low-head hydro power station. The low-head turbines are the same as those used in the hydropower industry.

A subscale prototype was deployed off the coast of Denmark in 2003, as the world's first offshore grid-connected wave energy conversion device. This test unit has accumulated over 20,000 hours of experience supplying electricity to domestic homes

There are plans to deploy a full-scale unit off Pembrokeshire, Wales, UK. The unit is expected to generate 7 MW.

Sea Wave Slot Cone Generator (SSG)

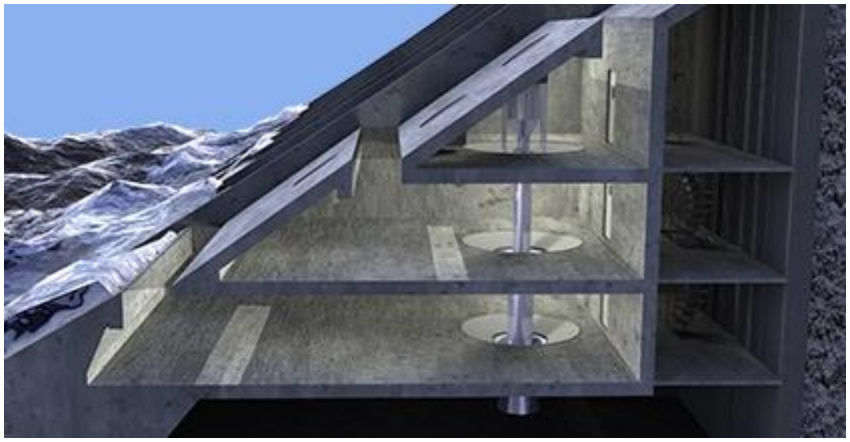


Figure 5. Sea Wave Slot Cone Generator

The SSG concept is a wave energy converter based on the wave overtopping principle utilizing a total of three reservoirs placed on top of each other, in which the potential energy of the incoming wave will be stored.

The water captured in the reservoirs will then run through the multi-stage turbine for electricity production. Using multiple reservoirs will result in a high overall efficiency.

The SSG gives the advantage to harness the wave energy in several reservoirs placed one above the other, resulting in high hydraulic efficiency.

The SSG is built as a robust concrete structure with the turbine shaft and the gates controlling the water flow as virtually the only moving part in the mechanical system.

The SSG is flexible with regard to range of application. It can be utilized as a floating or a fixed offshore installation or at a shoreline integrated in a breakwater barrier.

The SSG can be utilized for:

- Production of electric power
- Production of hydrogen by use of electrolysis
- Production of clean drinking water by use of osmosis

Reference:

http://www.waveenergy.no/Technology.htm

Oscillating Water Column (OWC)

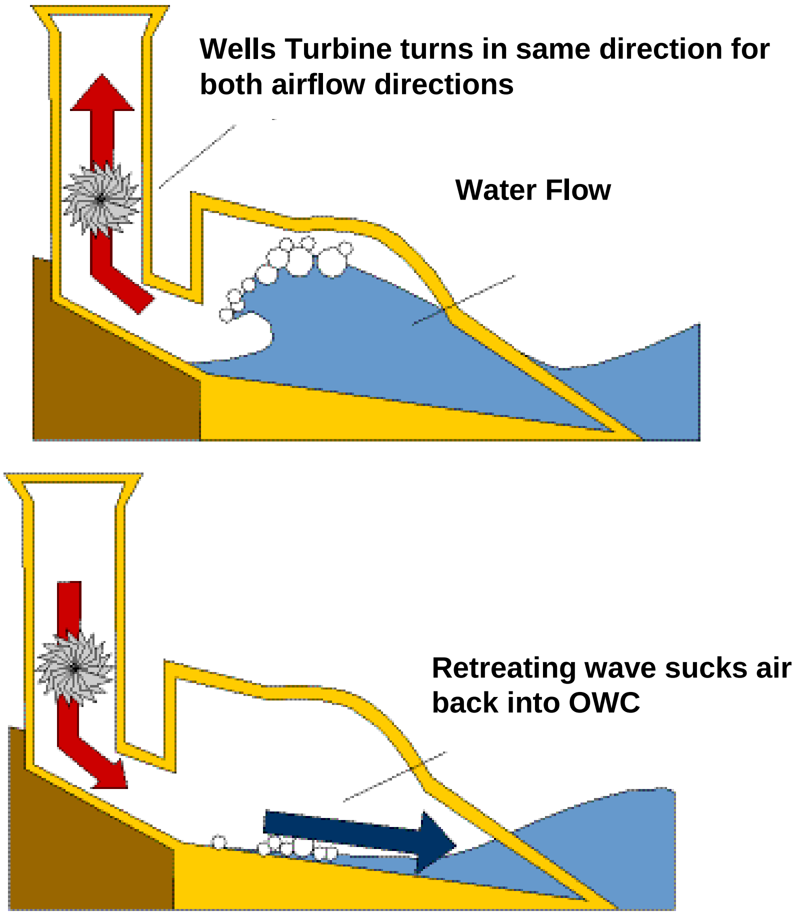


Figure 6. Oscillating Water Column Concept

The Oscillating Water Column generates electricity in a two step process. The air column is forced upward as the wave enters the column. Next, the air is drawn back past the turbine due to the reduced air pressure on the ocean side of turbine as the wave retreats.

The Land Installed Marine Powered Energy Transformer (Limpet) is a shoreline energy OWC converter located on the island of Islay, off Scotland's west coast.

The current Limpet device, Limpet 500, was installed in 2000 and produces up to 500 kW of power for the Scottish national grid.

The Limpet has two Wells Turbines, which are low-pressure air turbines.

Reference:

http://earthsci.org/mineral/energy/wavpwr/wavepwr.html

Wells Turbine

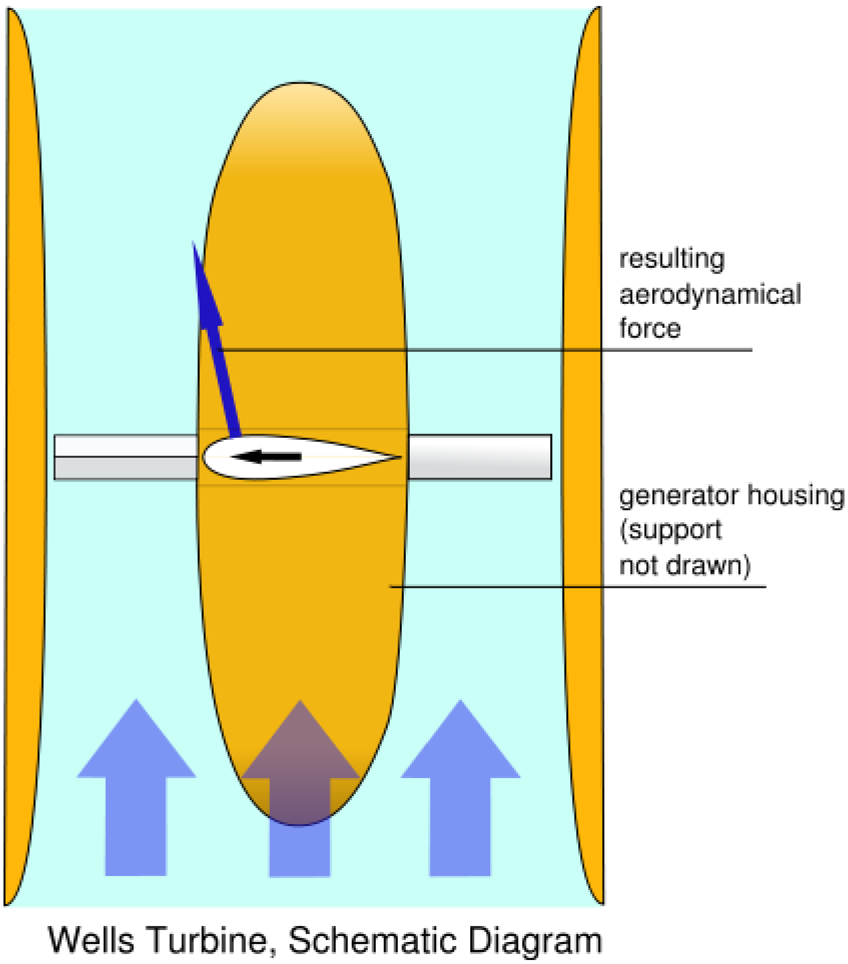


Figure 7.

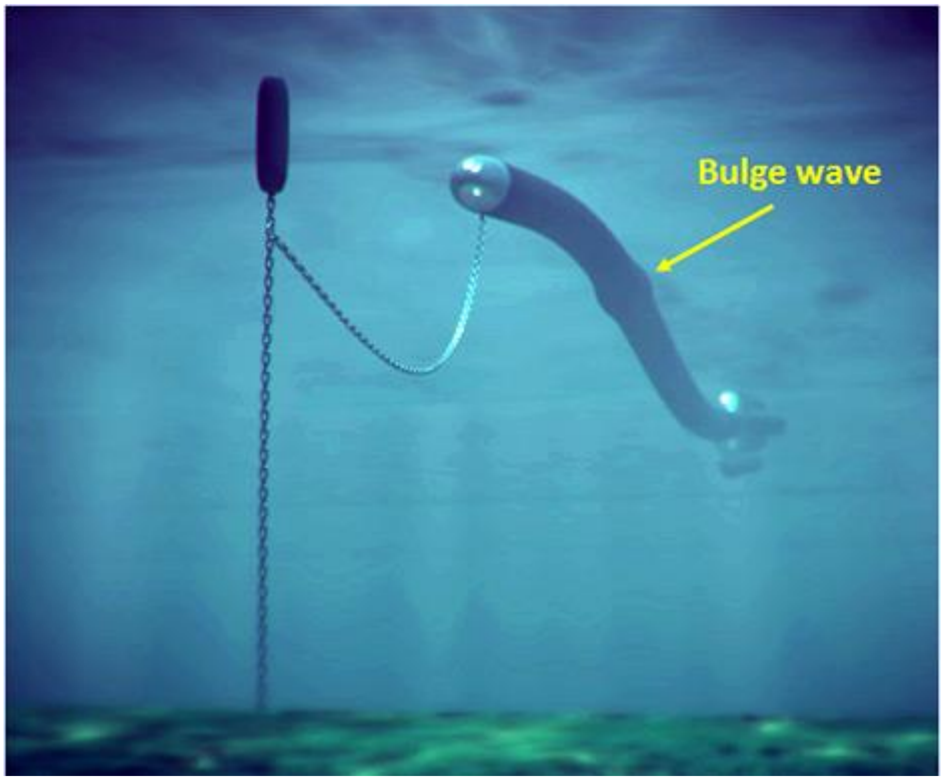
The Wells turbine is a fixed pitch machine with only one direction of rotation. This simple but ingenious device was developed by Professor Alan Wells of Queen's University Belfast in the late 1980s.

To achieve this, the rotor profile must be symmetrical and the blade may neither be twisted nor oriented under an angle towards the rotation plane. The complete rotor is symmetrical with respect to the rotation plane.

The turbine is not self-starting and has to be accelerated to reach a minimum speed.

Wells turbines can be operated at very high speeds (up to 4000 rpm) due to the low density and viscosity of air compared to water. Therefore, OWC technology does not need gearboxes and allows for small generators.

Anaconda Bulge Wave Energy Converter



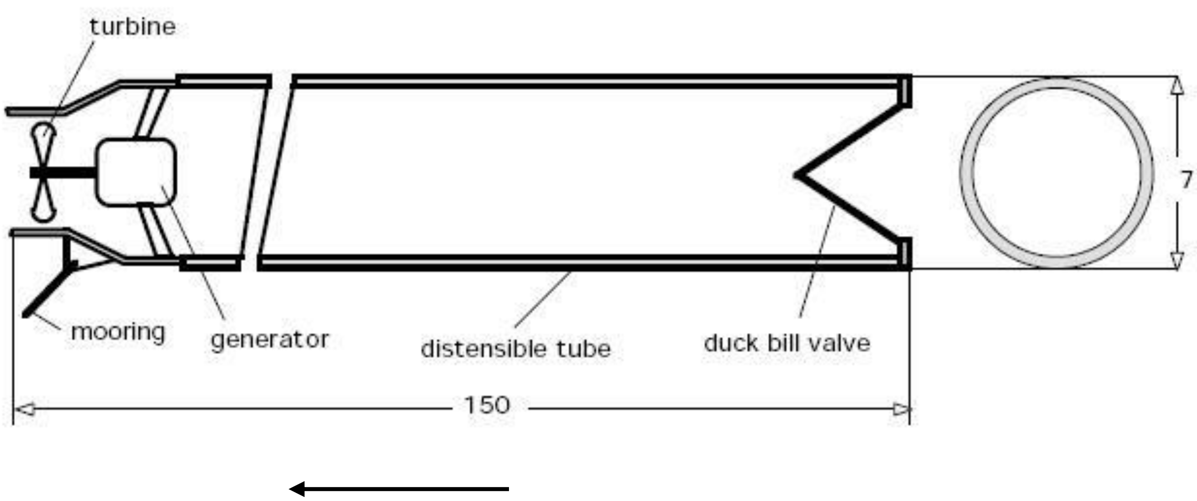


Figure 8. Anaconda Concept

Researchers at Maritime Developments Ltd. are working on a concept using an elastic rubber tube to deliver wave energy to a turbine electrical generator.

A rubber tube filled with water will bulge locally when squeezed. The bulge will propagate along the tube at a speed

$$c^2 = \frac{E\,h}{d\,\rho} \qquad (1)$$

where

- E is the tension modulus of the rubber
- d is the diameter of the tube
- h is the wall thickness
- ρ is the fluid mass density

This principle is being implemented in the design of a wave energy device called an Anaconda after the South American snake.

A wave hitting the end of the Anaconda tube squeezes the tube, causing a bulge wave to form inside the tube.

As the bulge wave runs through the tube, the initial sea wave that caused it runs along the outside of the tube at the same speed.

The sea wave squeezes the tube further, causing the bulge wave to grow larger.

The bulge wave then turns a turbine fitted at the far end of the device, and the power produced is fed to shore via a cable.

When built, each full-scale Anaconda device would be 200 meters long and 7 meters in diameter, and deployed in water depths of between 40 and 100 meters.

Initial assessments indicate that the Anaconda would be rated at a power output of 1MW.

Buoy Generators

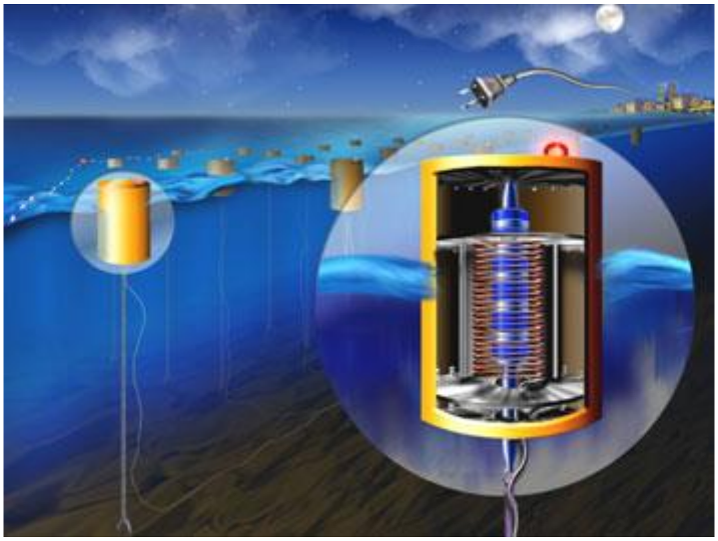


Figure 9. Buoy Generator Wave Farm Concept

Some researchers are also developing concepts that would use an electromagnetic generators housed in buoys.

A simple power-generating buoy has a natural frequency and will work most effectively only when waves arrive at that frequency. Advanced designs may have control systems to adjust the buoy frequency to match that of the waves.

Each buoy would have a power cable dropping down along the tether to the anchor, which would then be routed to a central junction box located on the seafloor at the front of the wave park.

The unregulated voltages from all of the buoys could be "combined" and conditioned as regulated DC power at the junction box for delivery to the shore through a single submarine cable.

The DC power provided by the wave park could be inverted to AC at the shore substation, and connected to the grid.

The buoys would be placed in water depths of 100 to 200 feet at about one to three miles offshore, before the waves start to break and dissipate their energy.

Reference:

http://www.memagazine.org/dec06/features/harvesting/harvesting.html

SeaGen, Tidal Generator

Figure 10. Tidal Generator

Another approach is to use tides rather than waves.

Peter Fraenkel of Marine Current Turbines Ltd. designed the SeaGen system, which has two rotors that each span 16 meters (52 feet) in diameter.

The first full-scale SeaGen marine current generator was installed recently in Strangford Lough, a large inlet on the coast of Northern Ireland.

It is designed to catch both the incoming flow and outgoing ebb tides by rotating the pitch of its two rotors by 180 degrees.

The tidal current flow rate is up to 8 knots or 4m/s.

The maximum power output of the SeaGen will be 1.2 MW

The SeaGen is expected to operate for 20 hours per day, supplying power to 1000 homes.

Cost

The construction, installation and maintenance of each system are expensive.

Each of the systems is still more expensive than a coal or natural gas generator plant in terms of cost per unit power.

Challenges

There are numerous challenges and obstacles associated with each wave farm concept.

Wave power is available in intermittent low-speed form with high forces. On the other hand, most readily-available electric generators operate at higher speeds, and most turbines require a constant, steady flow.

Furthermore, the welds, mooring lines, bearings and other mechanical components must be able to withstand the saltwater corrosion effects.

Each system must also withstand the pressures from storms, waves, and tidal currents, including hurricanes.

The systems may also pose a hazard for ships and marine wildlife.

But as Plato said, “Necessity is the Mother of invention.”

But I am the LORD thy God, that divided the sea, whose waves roared:
The LORD of hosts is his name.

Isaiah 51:15