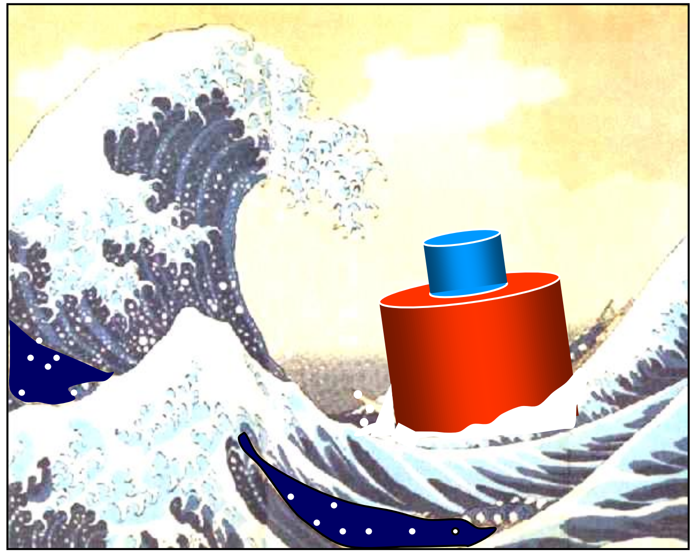
Università degli Studi di Firenze, 18-19 April 2012



WAVE ENERGY UTILIZATION

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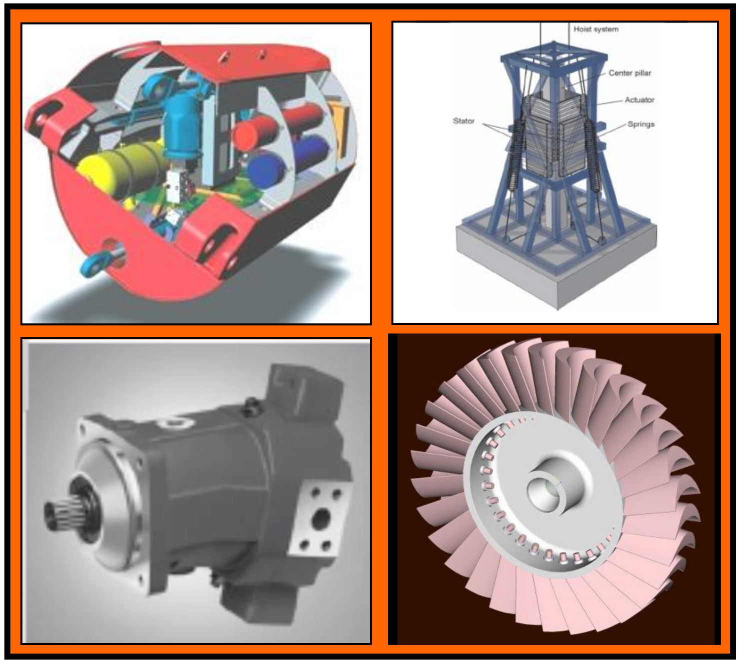
Universidade Técnica de Lisboa

Part 4
Technology

- **Introduction.**
- **Energy Storage.**
- **PTO Equipment.**
- **Mooring**



How far have we gone in 30+ yrs ? Some milestones:

Introduction

The size

While, in other renewables, the power is more or less proportional to size/area, …

… the power-versus-size relationship is much more complex for wave energy converters.

The concept of "point absorber" was introduced in Scandinavia around 1980 to describe efficient wave-energy absorption by well-tuned small devices.

Theoretically (in linear wave theory), energy from a regular wave of given frequency can be absorbed by a large oscillating body as well as from a small one, provided both are tuned.

The oscillation amplitude is larger for the smaller body.

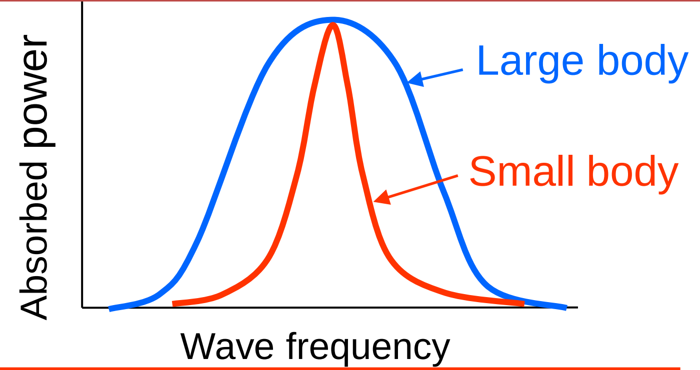
Introduction

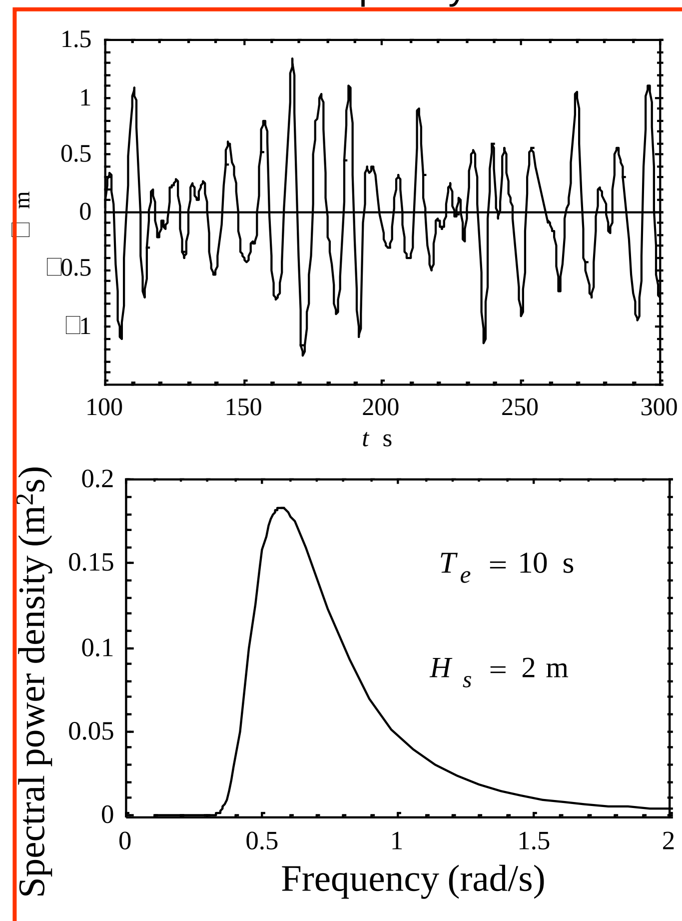
Wave energy absorption is wider-banded for a large body than for a "point-absorber".

This is relevant for **real polychromatic multi-frequency waves**.

Here smaller oscillating-bodies are less efficient than larger ones.

This can be (partially) overcome by **control (phase control)**.





Introduction

Phase control, i.e. wave-to-wave control in radom waves, is one of the main issues in wave energy conversion.

Optimal control is a difficult theoretical control problem, that has been under investigation since the late 1970s.

Control is made difficult by the randomness of the waves and by the wave-device interaction being a process with memory.

The difficulty increases for multi-mode oscillations and for multi-body systems.

Control should be regarded as an open problem and a major challenge in the development of wave energy conversion.

Introduction

Introduction

Oscillating Water Column (with air turbine)
- **Fixed structure**
  - **Isolated:** Pico, LIMPET, Oceanlinx
  - **In breakwater:** Sakata, Mutriku
- **Floating:** Mighty Whale, BBDB

Oscillating body (hydraulic motor, hydraulic turbine, linear electric generator)
- **Floating**
  - **Heaving:** Aquabuoy, IPS Buoy, Wavebob, PowerBuoy, FO3
  - **Pitching:** Pelamis, PS Frog, Searev
- **Submerged**
  - **Heaving:** AWS
  - **Bottom-hinged:** Oyster, Waveroller

RESONANCE

Overtopping (low head water turbine)
- **Fixed structure**
  - **Shoreline (with concentration):** TAPCHAN
  - **In breakwater (without concentration):** SSG
- **Floating structure (with concentration):** Wave Dragon

RUN UP

Introduction

A few basic concepts:

- **Oscillating water column (OWC)**
- **“point absorber”**
- **large oscillating-body (multi-body)**
- **run-up device, ...**

A large number of designs (>50) of which a few (≈15 ?) reached (or are close to) the prototype stage.

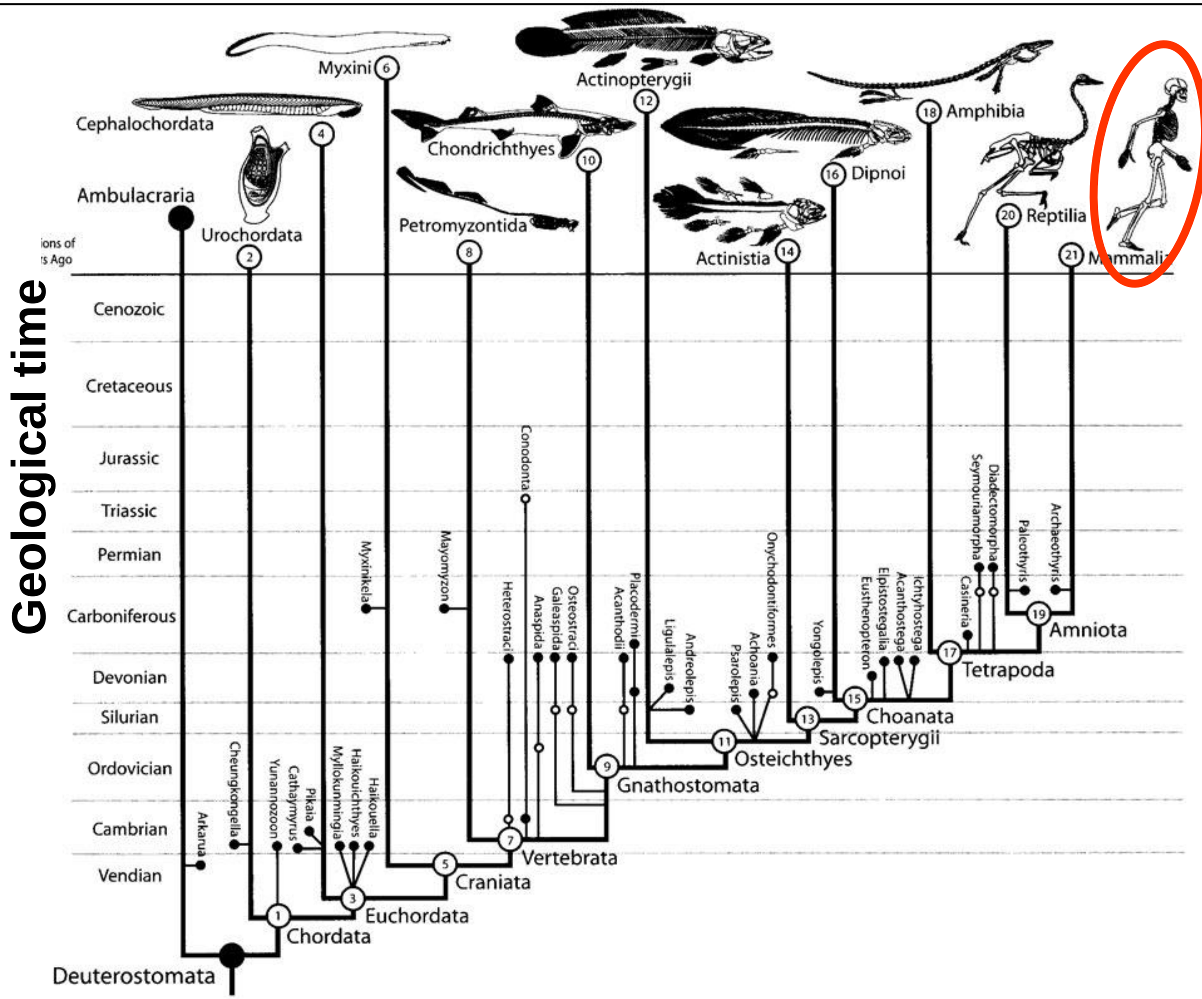
There are several effective ways of absorbing energy from the waves.

No technology appears to be dominant (unlike wind).

<u>Slow</u> convergence to a small number of basic designs ?

Like in life, will there be a Darwinian preservation of favoured wave energy converter designs in the struggle for the market?

How long will it take ? Which one(s) will be the **winner(s)** ?



Like in life, will there be a Darwinian preservation of favoured wave energy conv ... market?

... il ... Wh ... er(s) ?

Oscillating Water Column (with air turbine)

Fixe ... stru ... e

Isol ... LIMPET, Oceanlinx

In brea ... ...kata, Mutriku

Floating: Mighty Wha...

Oscillating body (hydraulic motor, hydraulic turbine, linear electric generator)

Floating

Hea ... ...abuoy, IPS Buoy, Wavebob, ... FO3

...ing: Pelamis, PS Frog, Searev

Submerge...

Heaving: AWS

Bottom-hinged: Oyster, Waveroller

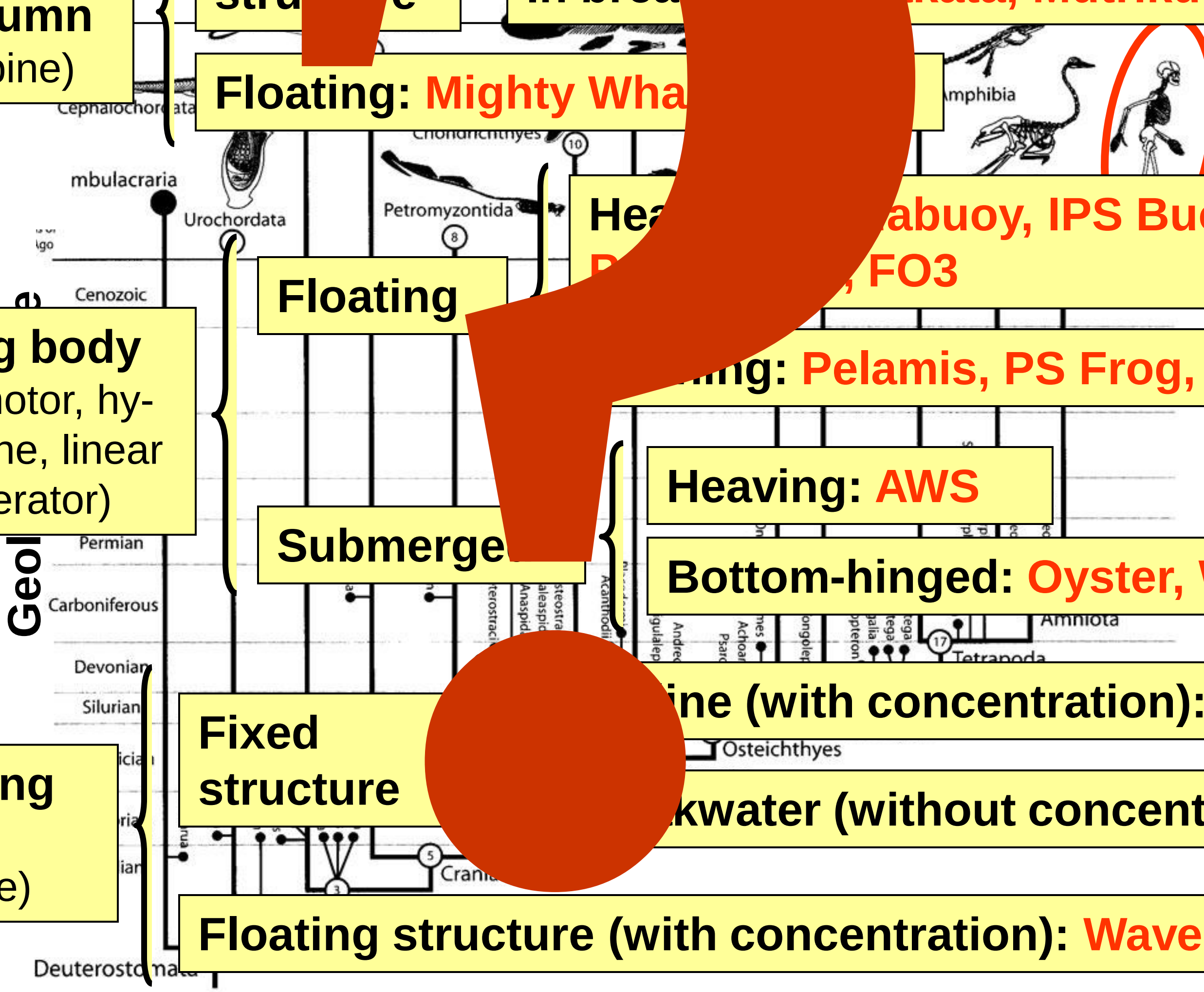
Overtopping (low head water turbine)

Fixed structure

...ine (with concentration): TAPCHAN

...kwater (without concentration): SSG

Floating structure (with concentration): Wave Dragon

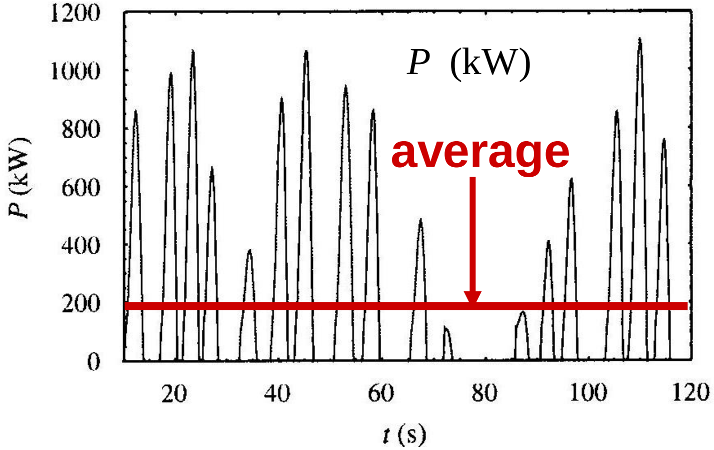


Energy Storage

Solar energy (24h period) and tidal energy (12h25m period) are intermitent sources.

Wave energy is also intermitent, on a much shorter time scale (4-8 s).

Energy absorbed from real waves is very irregular with high peaks.



Electric power smoothing is required:

- **to avoid large instantaneous overloading to equipment, especially electrical equipment (power electronics), or to reduce the rated-to-average power ratio of PTO.**
- **to improve the quality of supplied electrical energy**

This can be done with energy storage.

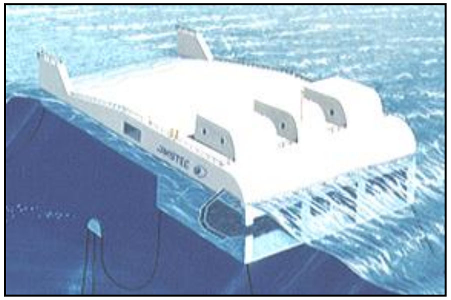
How to store energy ?

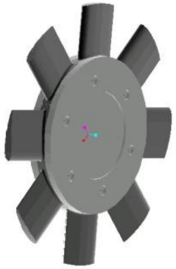
Energy Storage

How to store energy ?

Kinetic energy in <u>flywheel</u>:

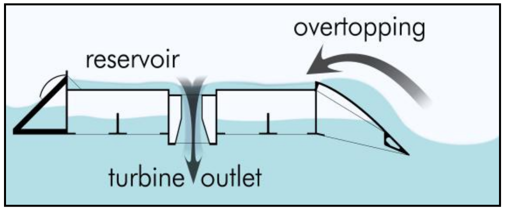
- **Air-turbine rotor (especially Wells type) in OWCs.**

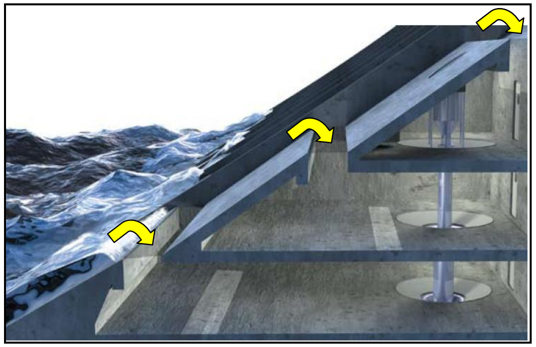




<u>Water reservoir</u> in overtopping devices:

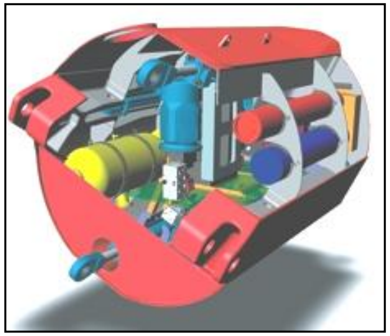
- **Tapchan, Wave Dragon, SSG.**





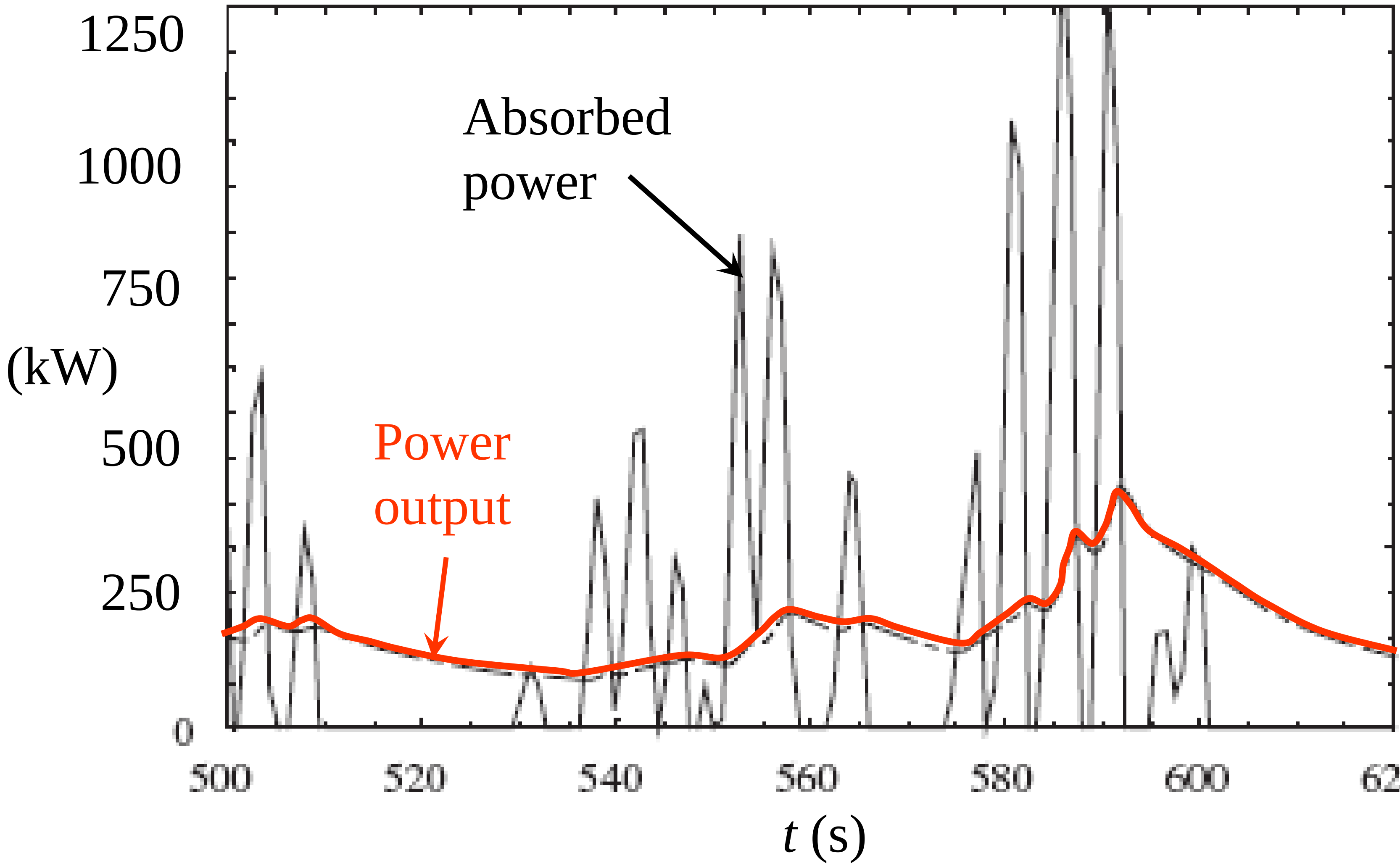
<u>Gas accumulator</u>

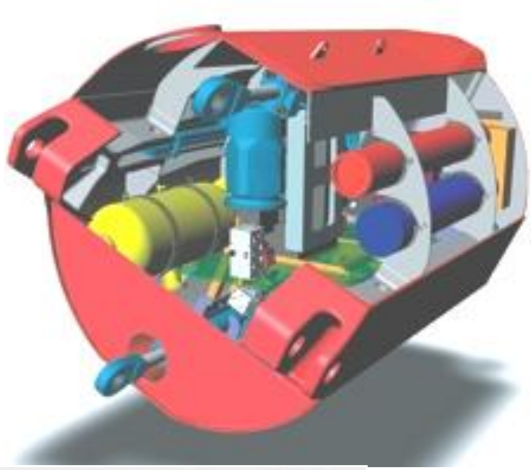
- **Oscillating bodies with hydraulic (oil, water) power take-off.**

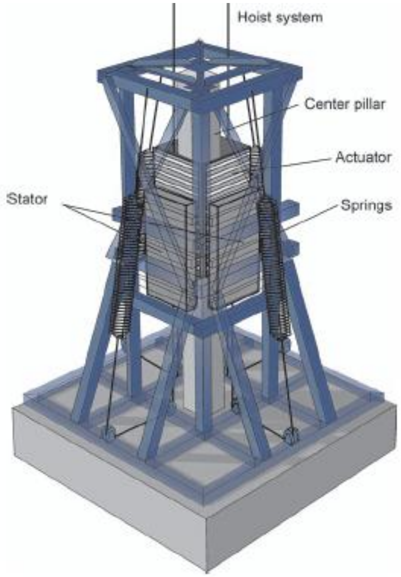


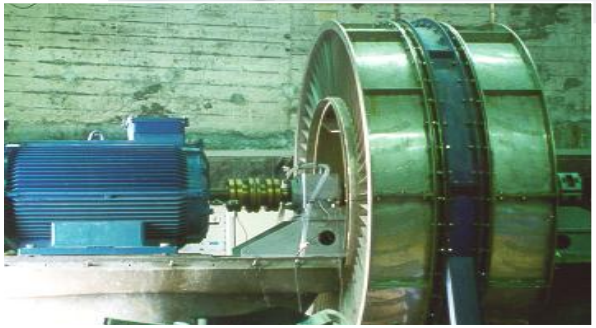
Energy Storage

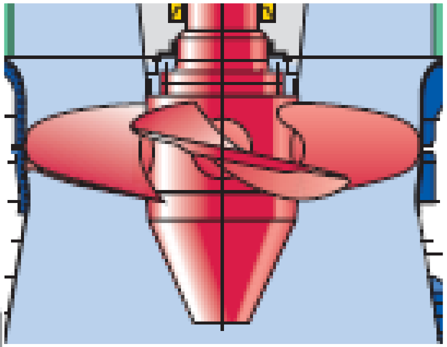
Typical power smoothing effect provided by a gas accumulator svstem. in an energetic sea state H_S = 4m.



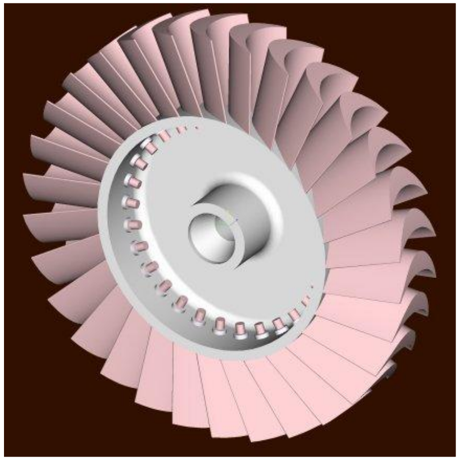


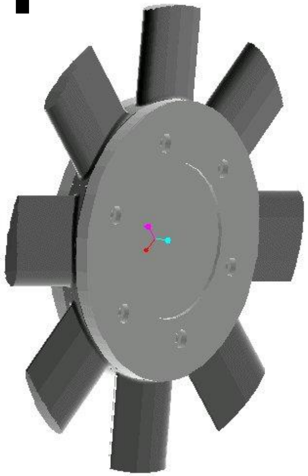


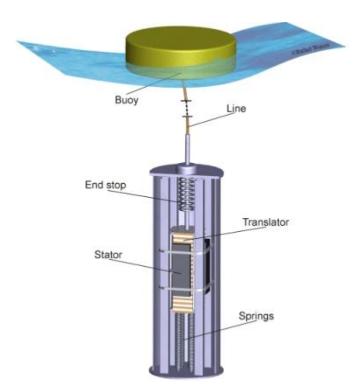


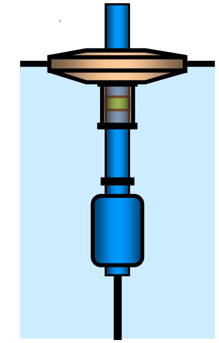


PTO Equipment



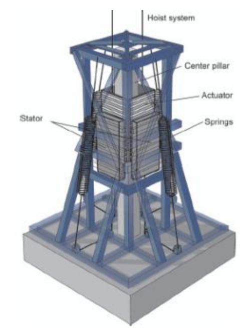






PTO Equipment

Linear electric generator

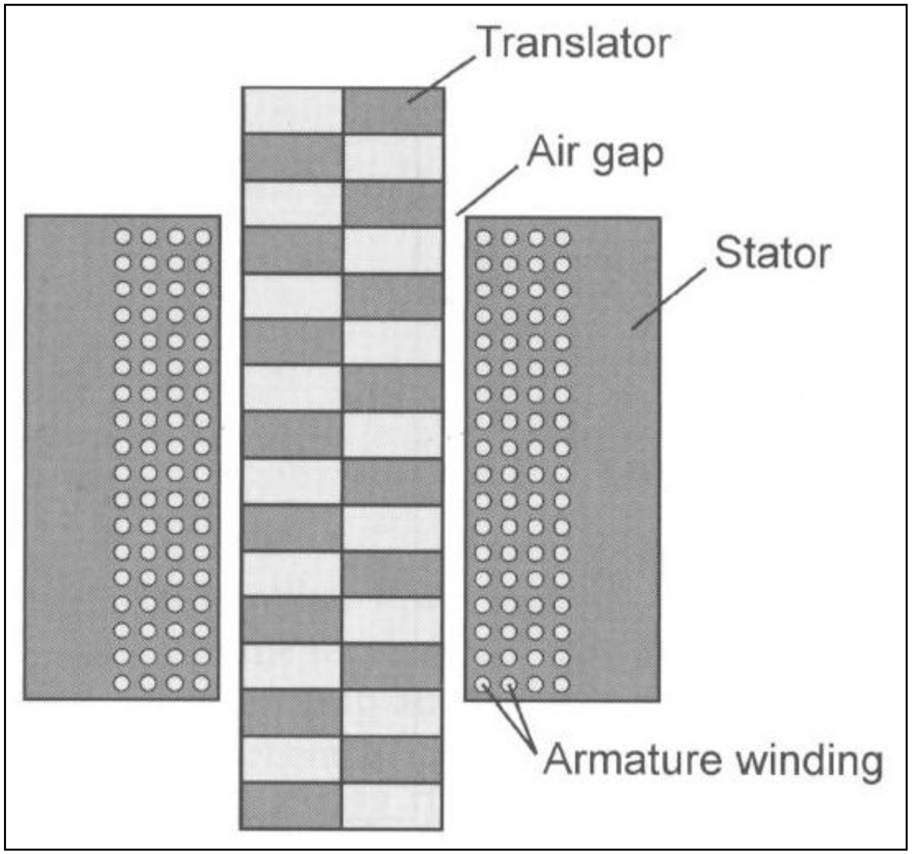


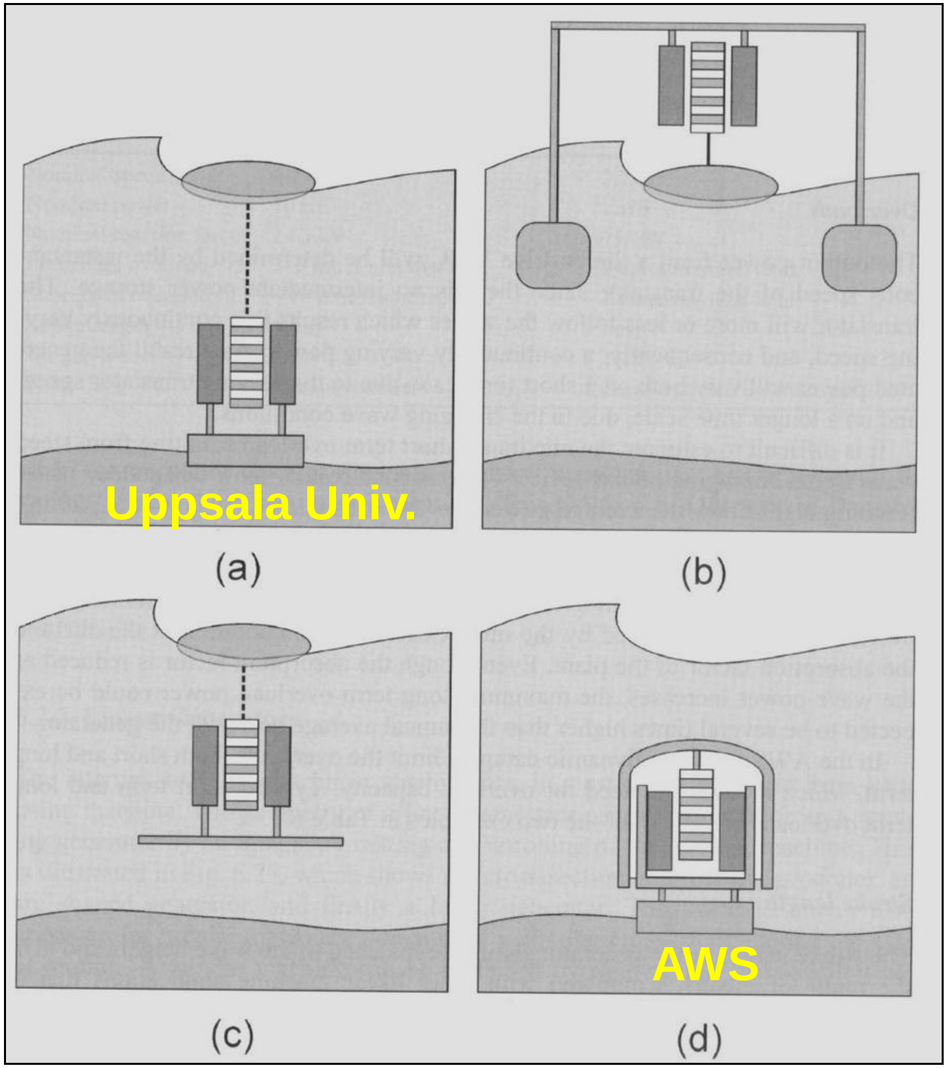
- **Used in AWS, heaving buoys.**
- **Direct conversion (no need for intermediate mechanisms)**
- **Fairly good overall efficiency (?)**
- **At prototype stage. Not commercially available.**
- **Cost ?**
- **Energy storage capacity: none or difficult to achieve (electrical capacitors).**
- **If no or little energy storage: high rated-to-average power ratio.**

O. Danielsson, K. Thorburn, M. Leijon, "Direct drive – linear generators". In: Ocean Wave Energy (J. Cruz editor), Springer, 2008.

PTO Equipment

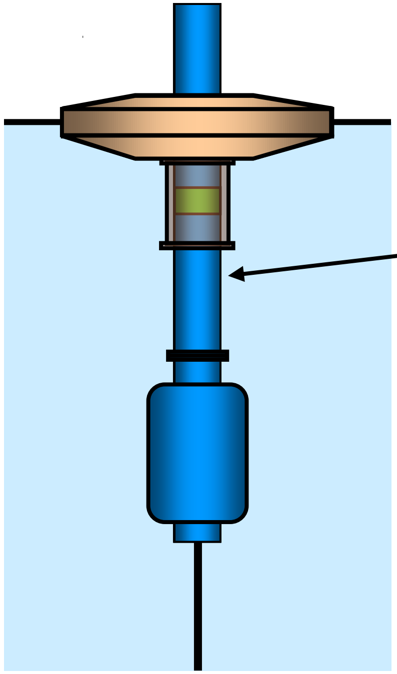
Linear electric generator



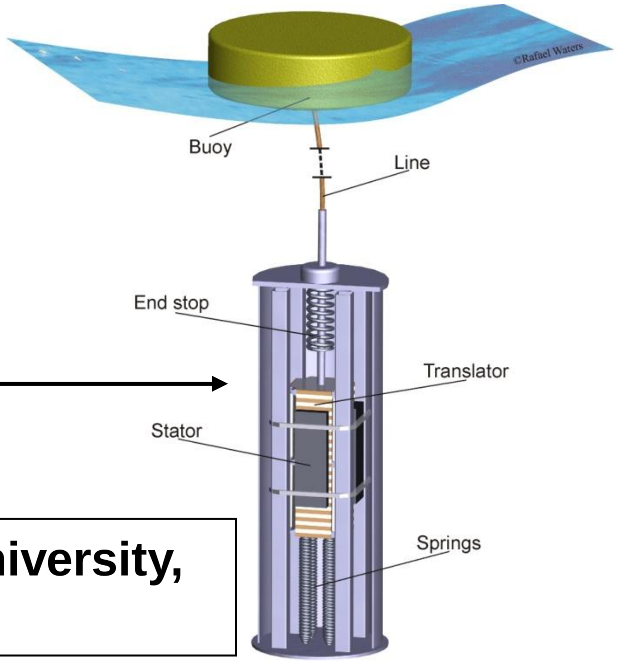


PTO Equipment

Linear electric generator

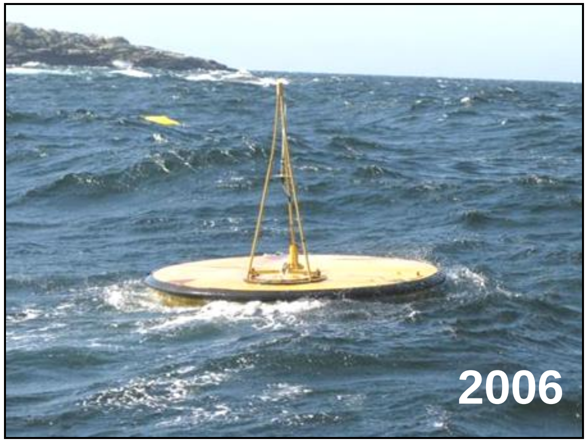


With linear electric generator



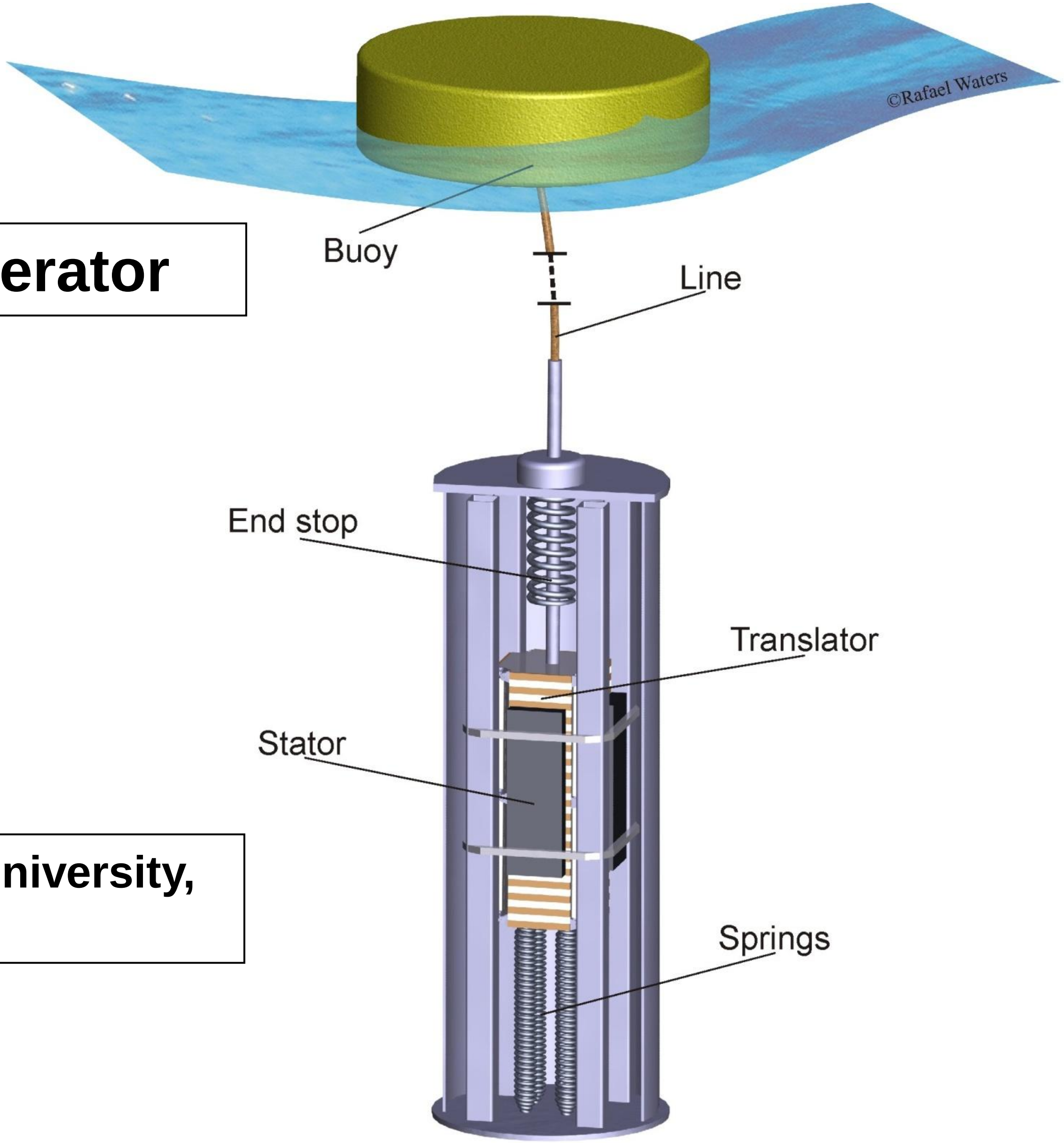
Oregon State University, USA

Uppsala University, Sweden



PTO Equipment

Linear electric generator



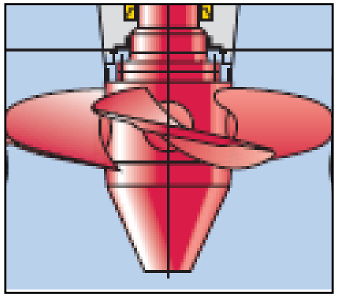
Uppsala University, Sweden

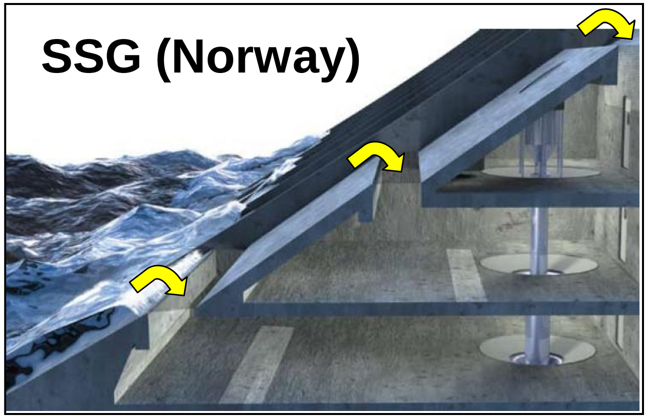
PTO Equipment

Low-head hydraulic turbines

Used in Wave Dragon and other run-up converters.

- **Conventional equipment (special design may be required).**
- **Good efficiency (about 90% at b.e.p.).**
- **Water reservoir provides energy storage.**





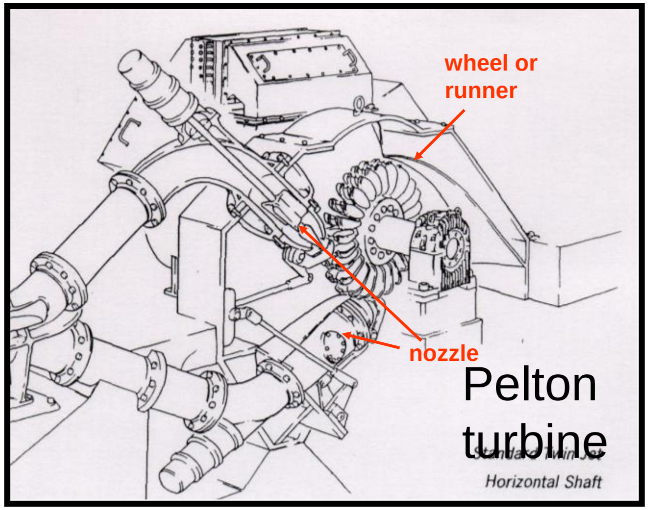
PTO Equipment

High-head hydraulic turbines

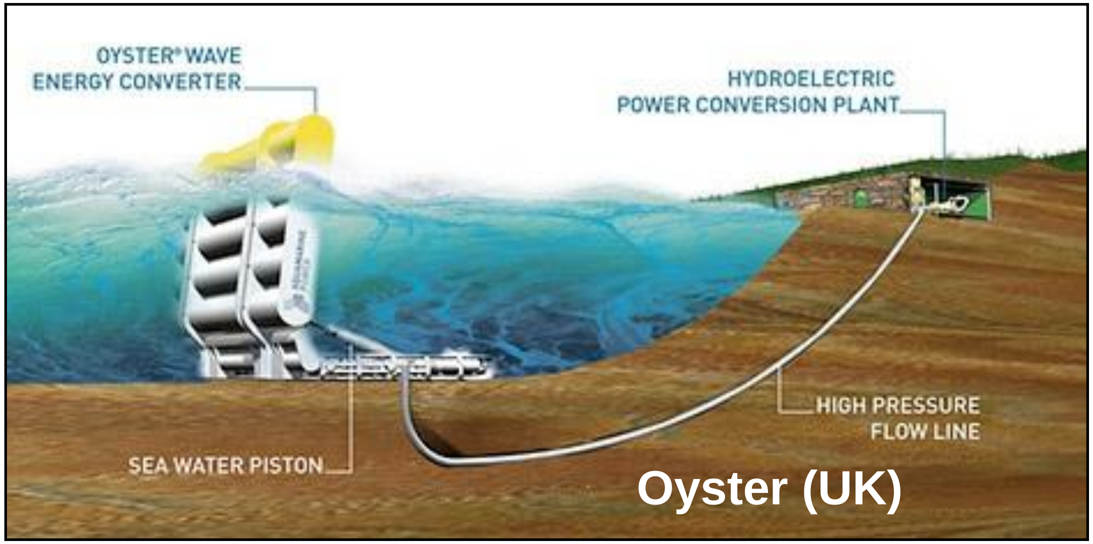
In general of <u>Pelton type</u>

Used in Oyster, AquaBuoy, Hyperbaric WEC.

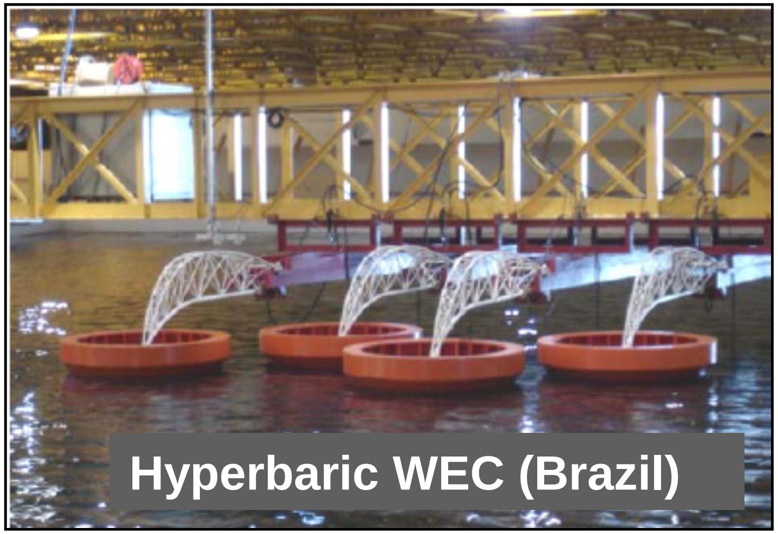
- **An alternative to high-pressure oil.**
- **Conventional, high efficiency equipment.**
- **May require an air-accumulator energy storage system.**
- **May be open circuit (sea water).**



Pelton turbine



Oyster (UK)


Hyperbaric WEC (Brazil)

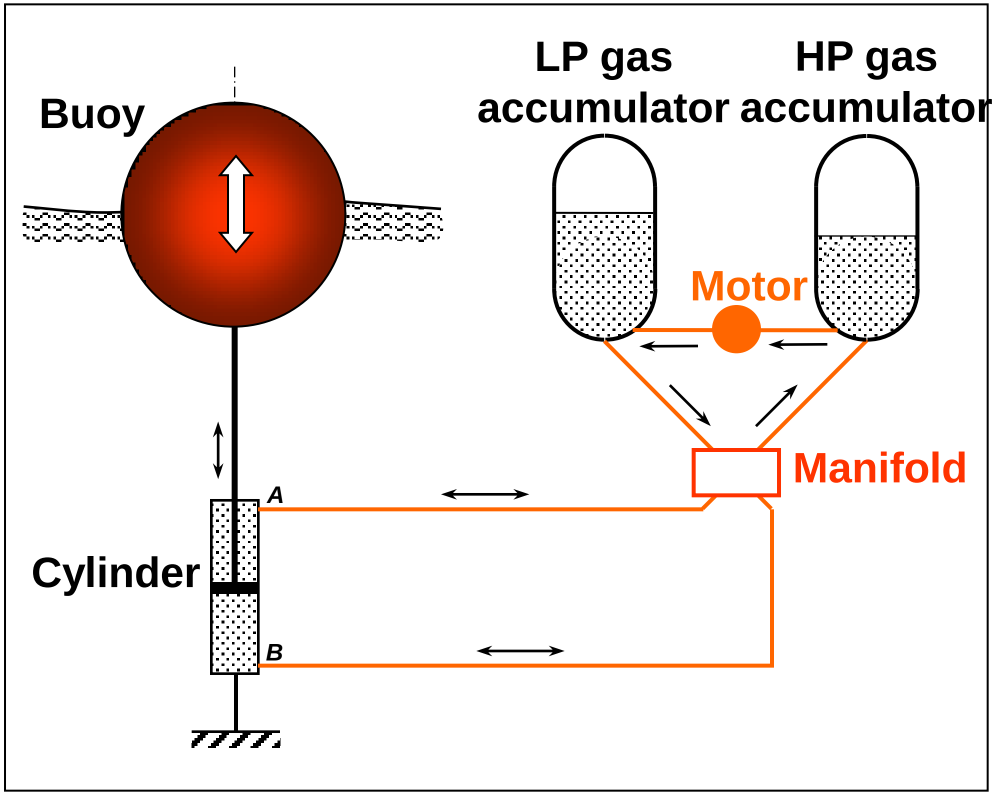
PTO Equipment

High-pressure-oil PTO

- Used in, or proposed for, a large part of oscillating-body WECs.
- Unconventional use of mostly conventional equipment.
- Special designs may be desirable at later stages ? (S. Salter !)
- Fairly good efficiency (lower at partial loads).
- Gas accumulators may provide energy storage.
- Biodegradable oil may be required by environmental constraints.

PTO Equipment

High-pressure-oil PTO

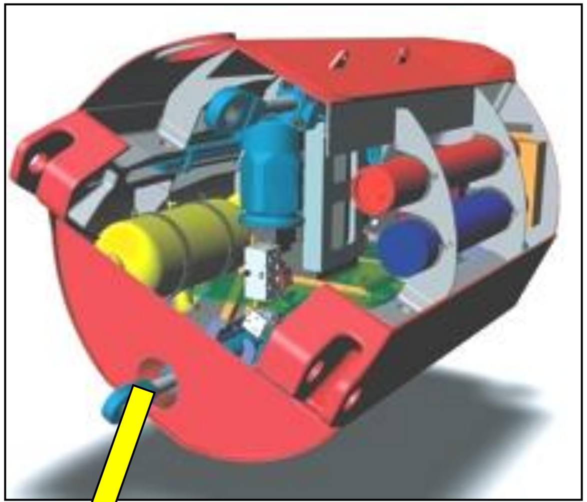


A.F. de O. Falcão, "Modelling and control of oscillating-body wave energy converters with hydraulic power take-off and gas accumulator", *Ocean Engineering*, Vol. 34, pp. 2021-2032, 2007.

PTO Equipment

High-pressure-oil PTO

Pelamis



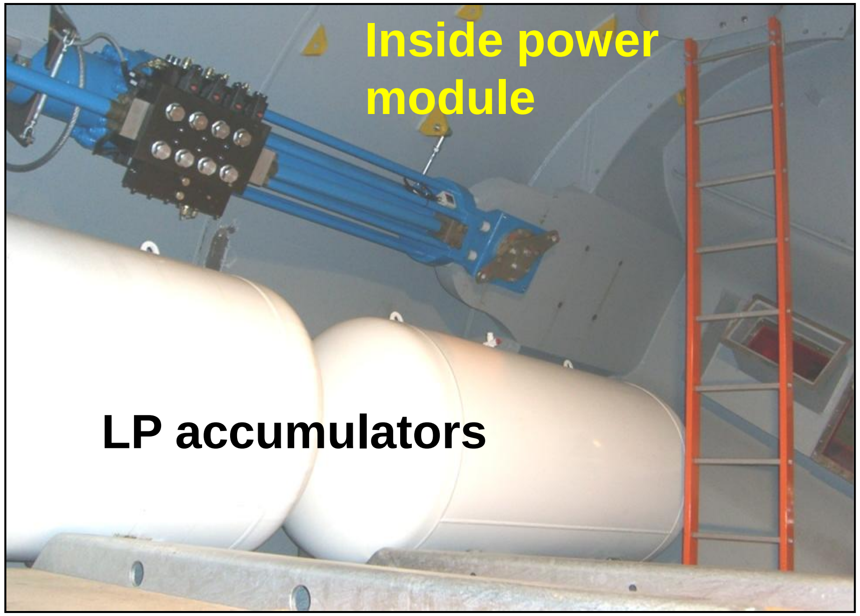
One of the three power modules of a Pelamis

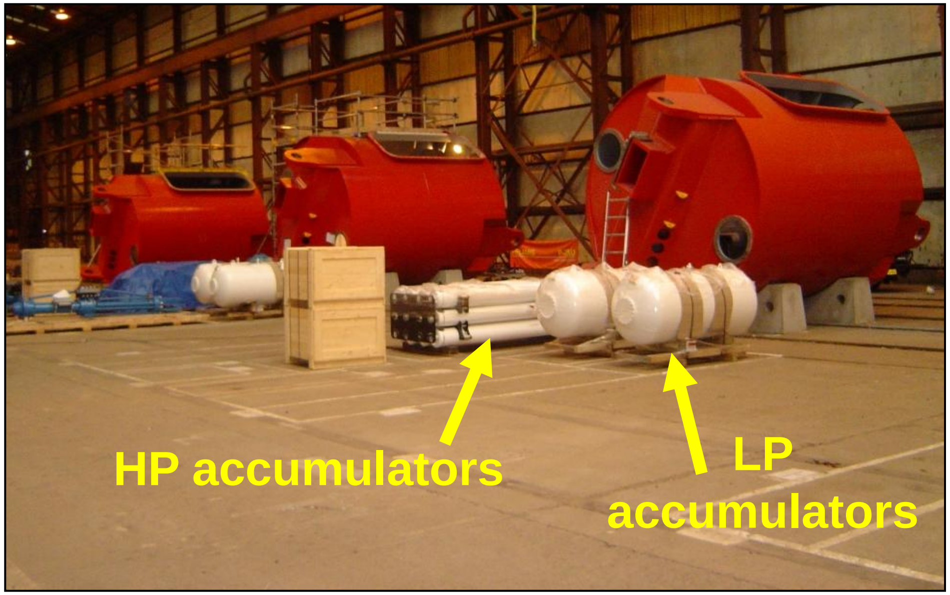
Peniche shipyard, Portugal, 2006

PTO Equipment

High-pressure-oil PTO

Pelamis



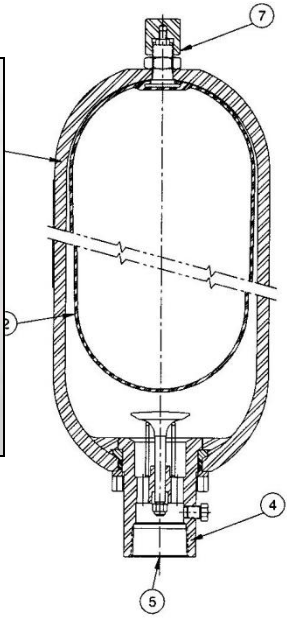


PTO Equipment

High-pressure-oil PTO

High-pressure accumulators

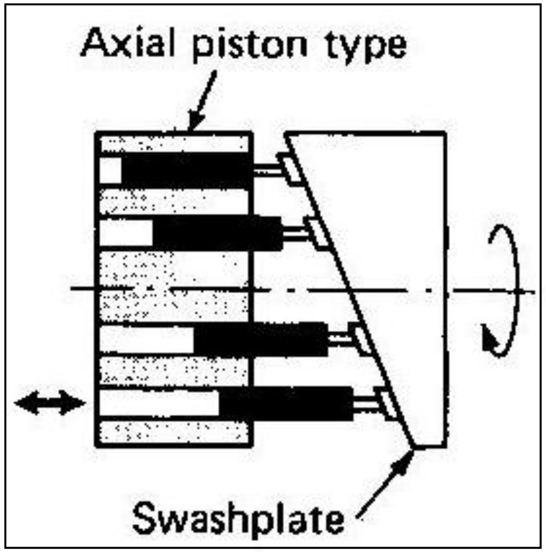
- Commercially available
- Bladder or piston types
- Gas: Nitrogen
- Max. working pressure up to ~ 500 bar
- Banks of unit required for full-sized WECs



Thermodynamics of gas in accumulator (isentropic process):

- pressure-volume $pV^{\gamma} = \text{constant}$ $\gamma = 1.4$ for air and Nitrogen
- pressure-temperature $p = \text{constant} \times T^{\gamma/(\gamma-1)}$
- <u>energy storage</u> (internal energy) $\boxed{\Delta U = C_v \Delta T}$

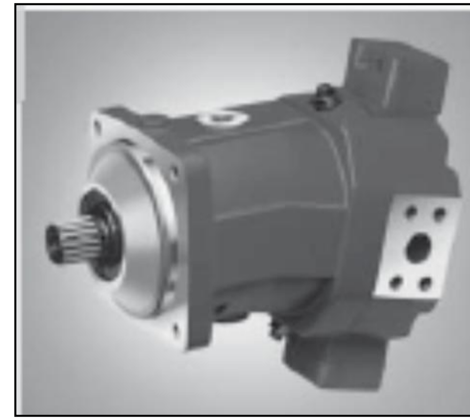
PTO Equipment

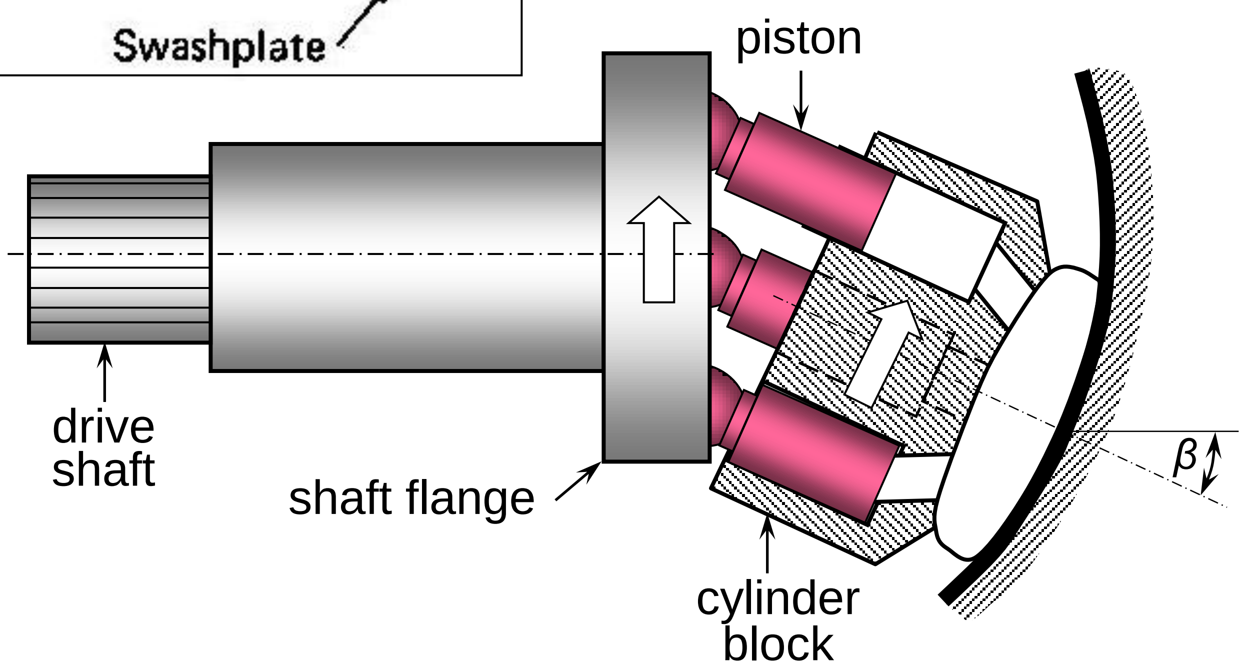


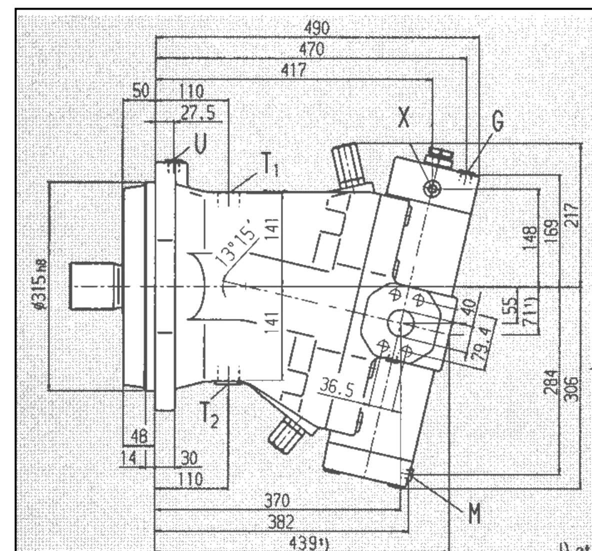
High-pressure-oil PTO

Hydraulic motor

Bent axis type







PTO Equipment

High-pressure-oil PTO

Hydraulic motor

- **Positive displacement machine.**
- **Max. power up to ~ 300 – 500 kW at > 1000 rpm.**
- **Direct drive of electric generator.**
- **Relatively compact.**
- **Variable displacement (double flow control capability).**
- **Fairly good efficiency at maximum flow.**
- **Reversible (as pump).**
- **Available from a few manufacturers.**
- **Not “too expensive”.**

PTO Equipment

Air turbines (self-rectifying)

A difficult challenge:

- **Reciprocating air flow**
- **Highly irregular flow**
- **Spray**
- **Noise**
- **Energy storage (flywheel)**
- **Has to match OWC hydrodynamics**
- **Efficiency**
- **Cost**

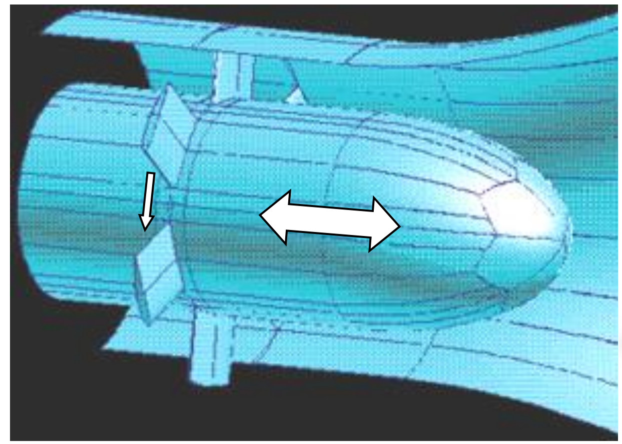
The present situation:

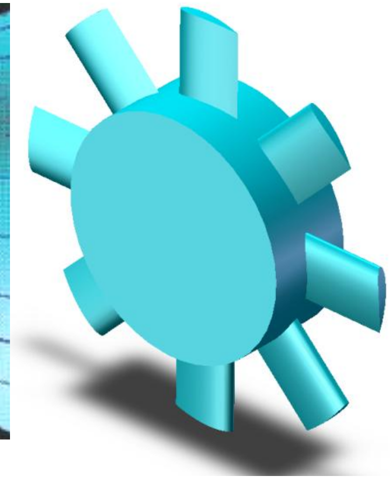
- **Several types competing (self-rectifying)**
- **Time-averaged efficiencies up to 50-65% ?**

PTO Equipment

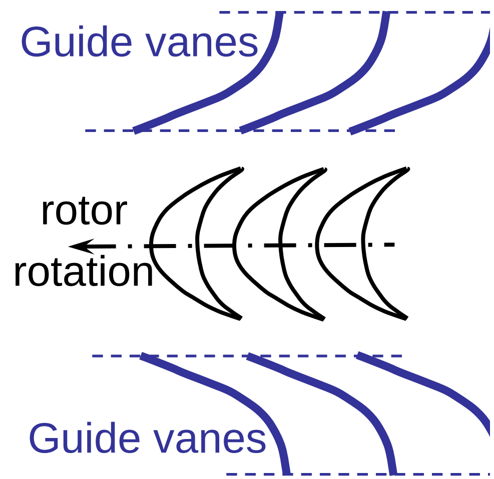
Air turbines

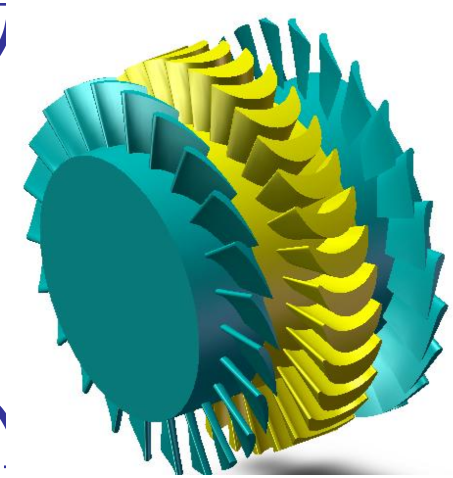
Wells turbine (mid-1970s)
- Several versions
- Used in most OWC prototypes





Impulse turbine (mid-1970s)
- Several versions
- Based on De Laval steam turbine (1889)
- Used in Indian prototype & CORES

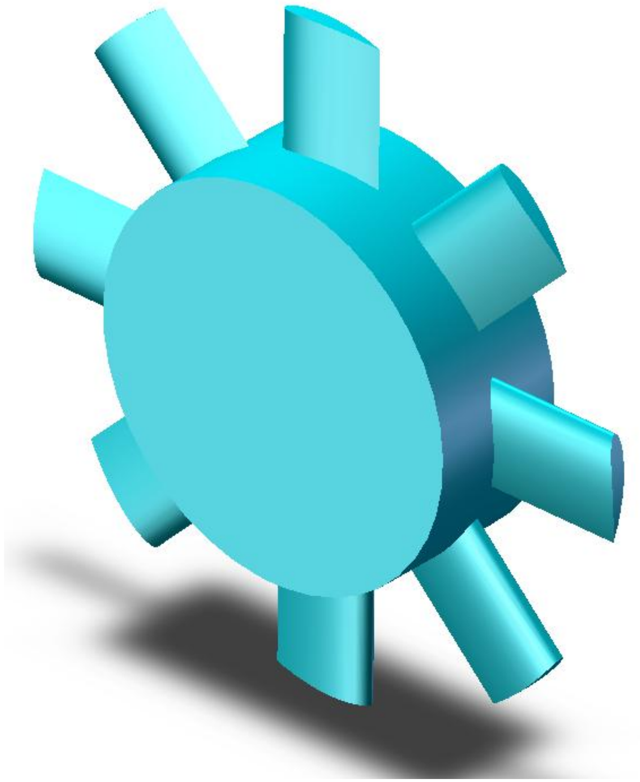


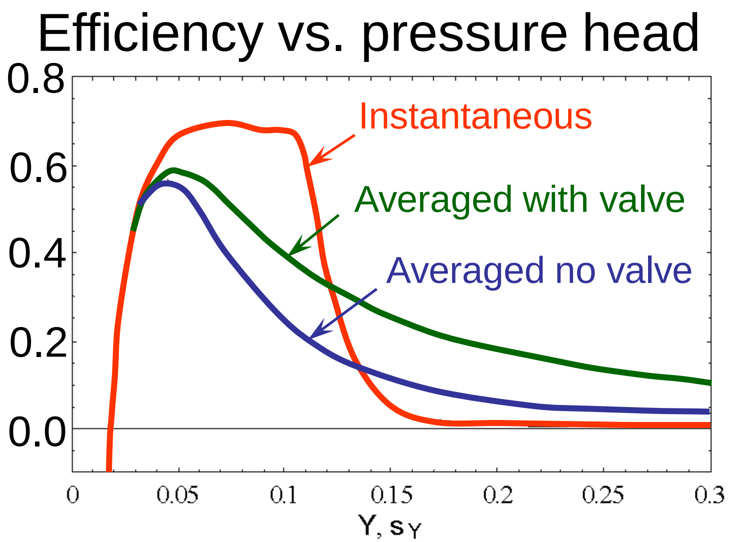


PTO Equipment

Air turbines

Wells turbine





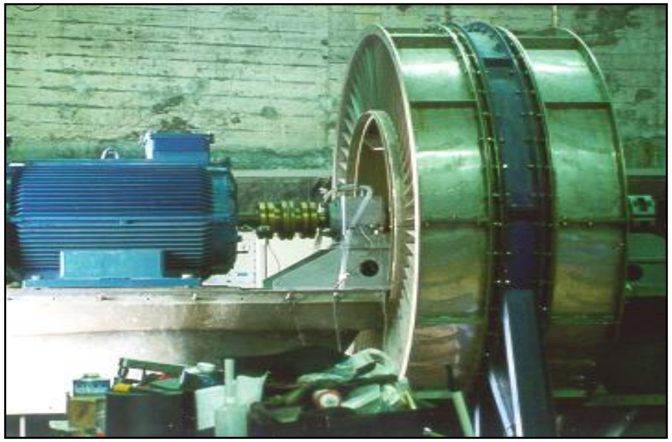
Main features:

- Relatively large diameter
- High rotational speed (1000-2000 rpm)
- Fairly good peak efficiency 0.7
- Very sensitive to aerodynamic stalling
- Relatively easy to construct
- Enhances energy storage (flywheel)

PTO Equipment

Air turbines

Wells turbine



- Pico, Azores plant
- 400 kW
- single rotor
- D=2.3m
- with guide vanes

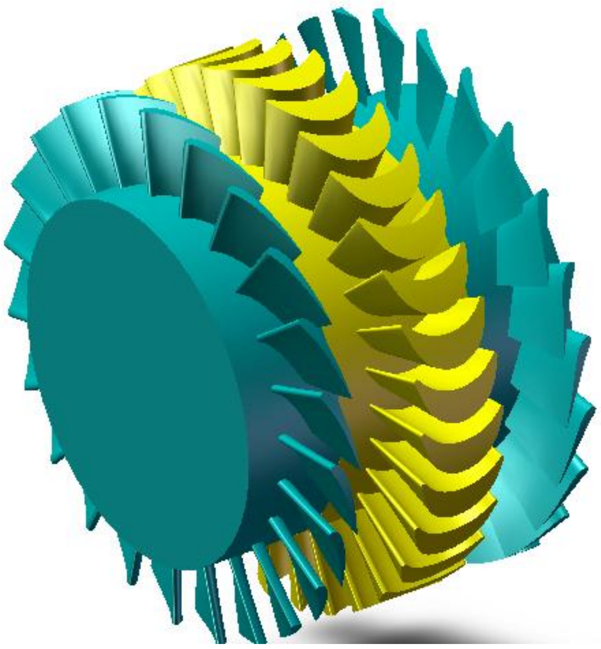
- OSPREY plant, UK
- 2×1 MW
- twin counter-rotating rotors
- D=3.5m
- no guide vanes

- Sakata plant,Japan
- tandem Wells turbines
- 2 x 30 kW
- D=1.337m
- with guide vanes

PTO Equipment

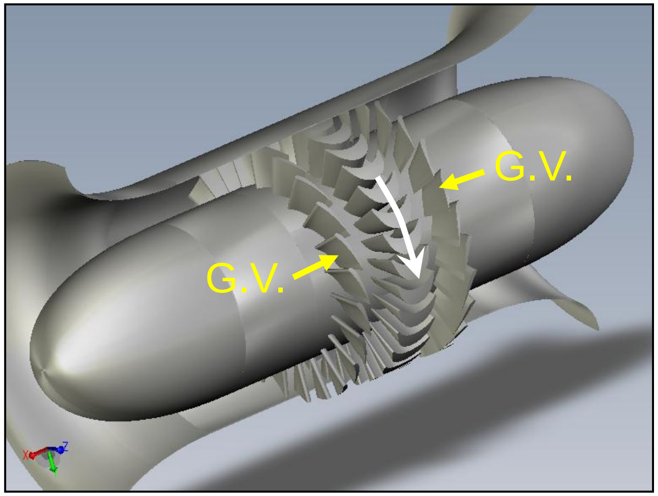
Air turbines

Impulse turbine



Main features:

- **Relatively small diameter**
- **Relatively low rotational speed**
- **Less noisy**
- **Guide vanes are essential:**
  fixed versus variable pitch guide vanes
- **Maximum efficiency < Wells turbine**
- **Less sensitive to aerodynamic stalling**
- **Little energy storage capacity**
- **Has room for improvement**

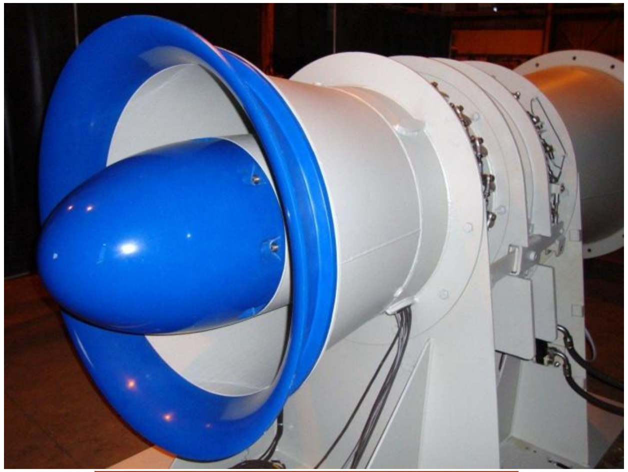


PTO Equipment

Air turbines

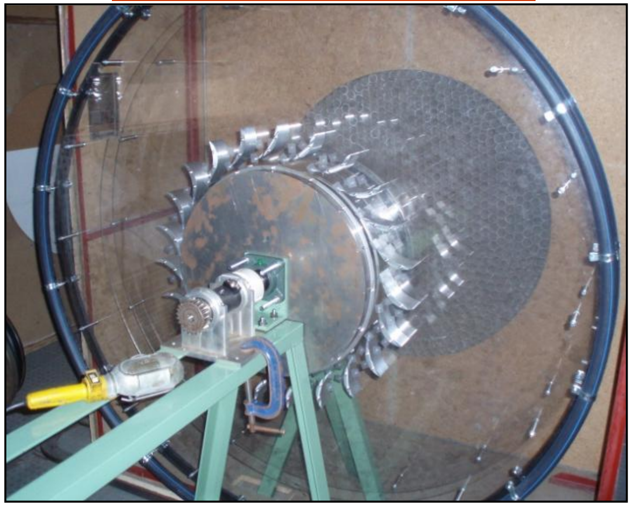
Impulse turbines

HydroAir, UK, 2010



CORES project, Portugal, 2011

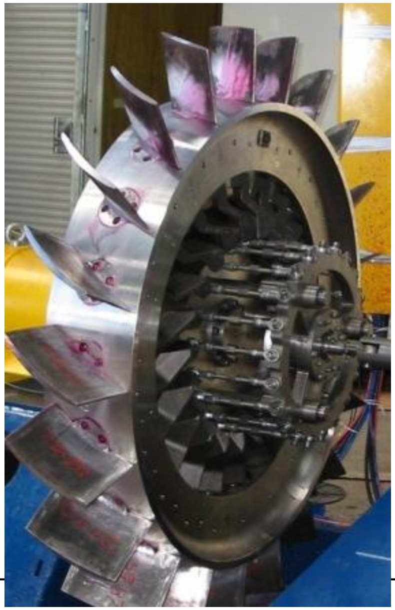
Biradial, Portugal, 2011

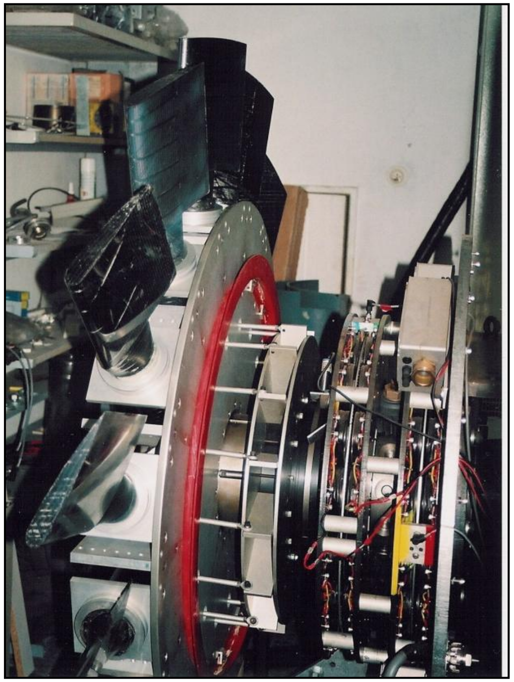


PTO Equipment

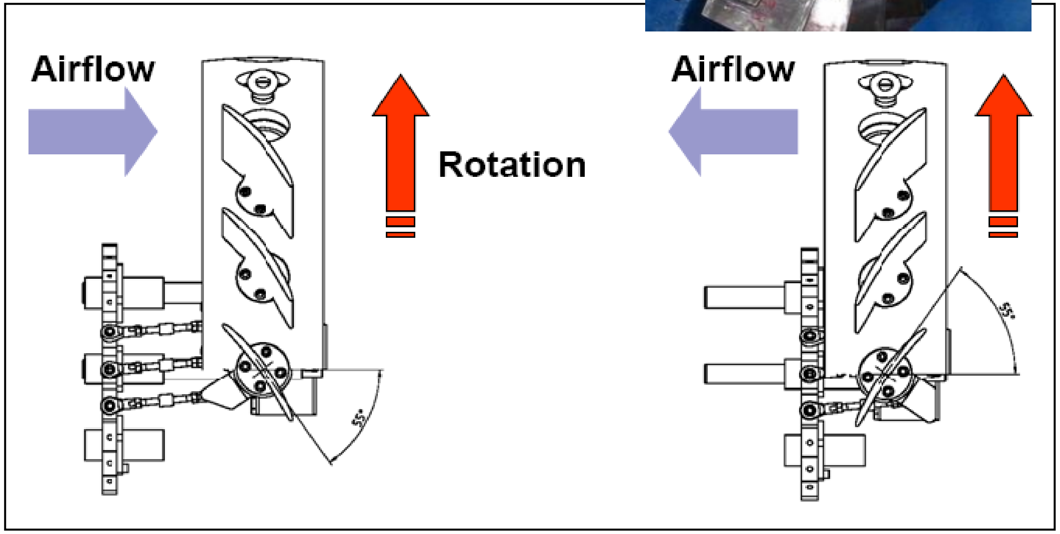
Air turbines

Variable pitch rotor blades





Variable-pitch Wells turbine, 400 kW, UK-Portugal, 2001



Denniss-Auld turbine, Australia

PTO Equipment

Mooring

- **The mooring is primarily required to restrain the motion of the floater and ensure that it stays "on station" even under extreme environmental wave and current loadings.**

- **There can be significant differences in the requirements for the station keeping of a WEC, depending on the method that it uses to extract energy from the waves.**

- **Mooring can affect (in general negatively) the dynamics of the WEC.**

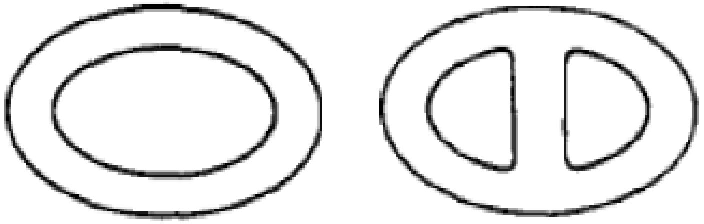
- **Mooring experience derives mostly from ships and offshore oil-drilling platforms.**

- **Due to the reduced risks to human life, the factors of safety can be relaxed in the mooring design of a WEC to improve economic prospects.**

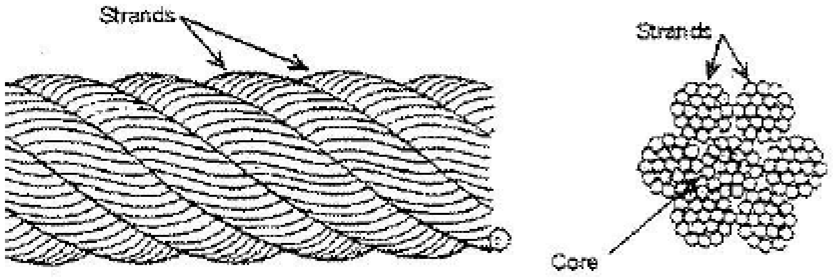
PTO Equipment

Mooring

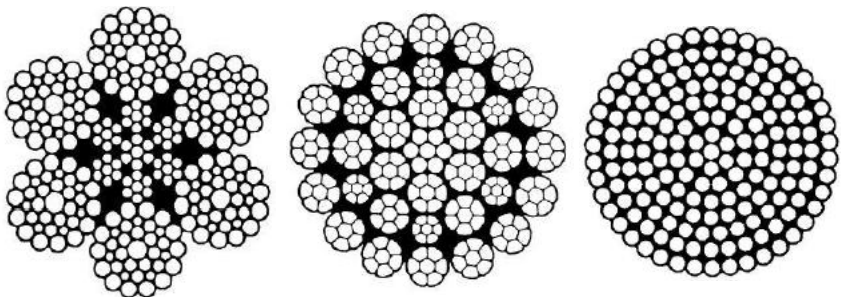
Chain



Synthetic ropes
(polyester, nylon, ...)



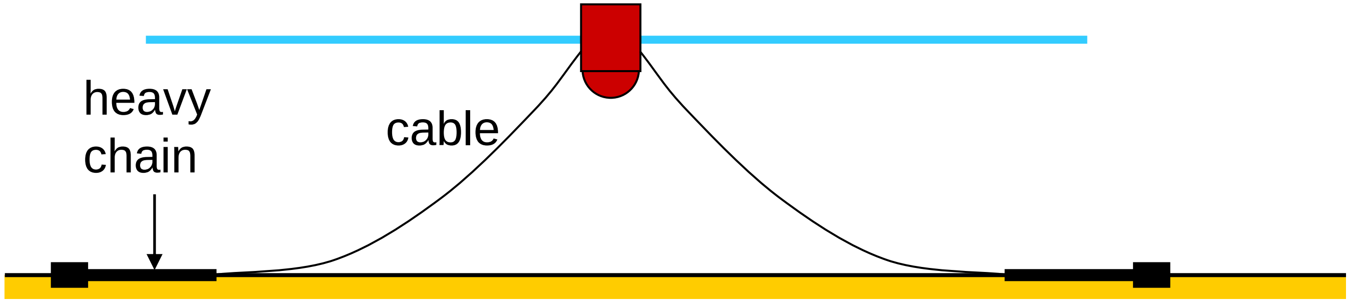
Wire ropes

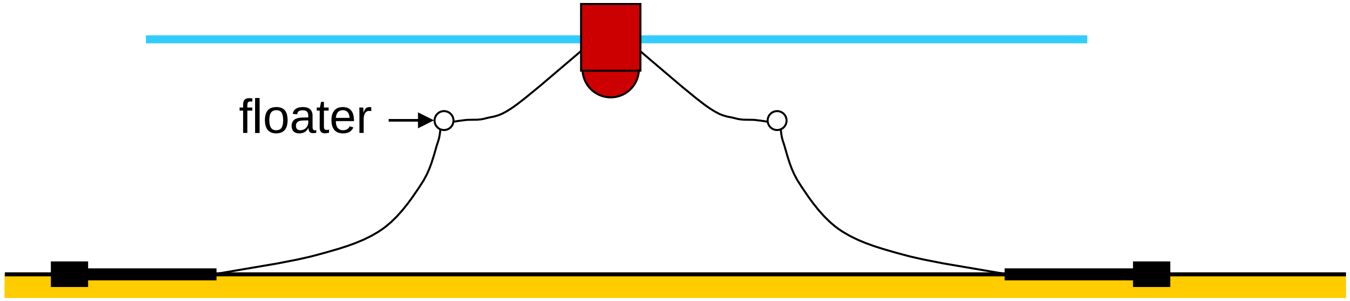


PTO Equipment

Mooring

Most floating devices adopt slack-mooring.

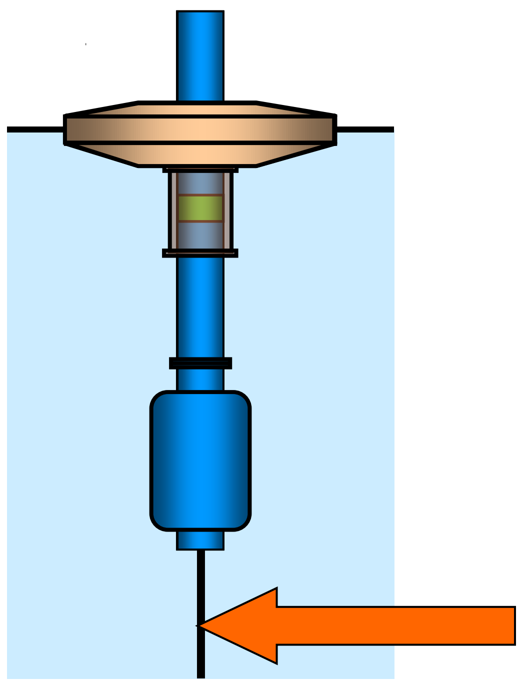


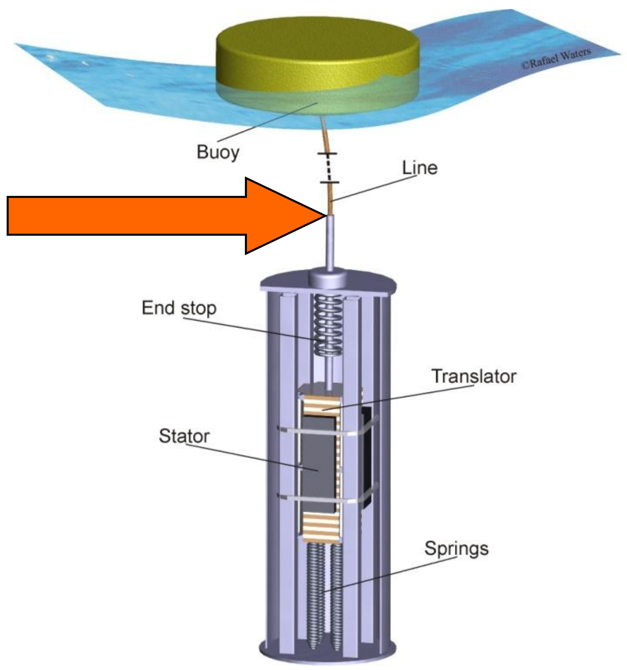


PTO Equipment

Mooring

Taught-mooring may be required by the adopted device conception (floater reacts against sea bottom)

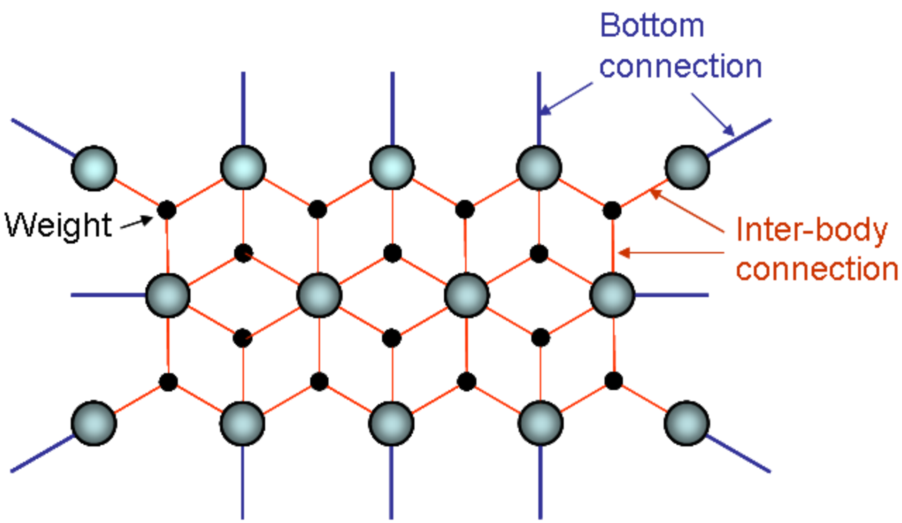




PTO Equipment

Mooring

Compact arrays of floating WECs may required complex mooring arrangements.



Model testing of moorings for WEC arrays in the large wave tank of Trondheim, Norway, 2008

END OF PART 4
TECHNOLOGY