Wave energy

Extracting power from ocean waves
Some basic principles

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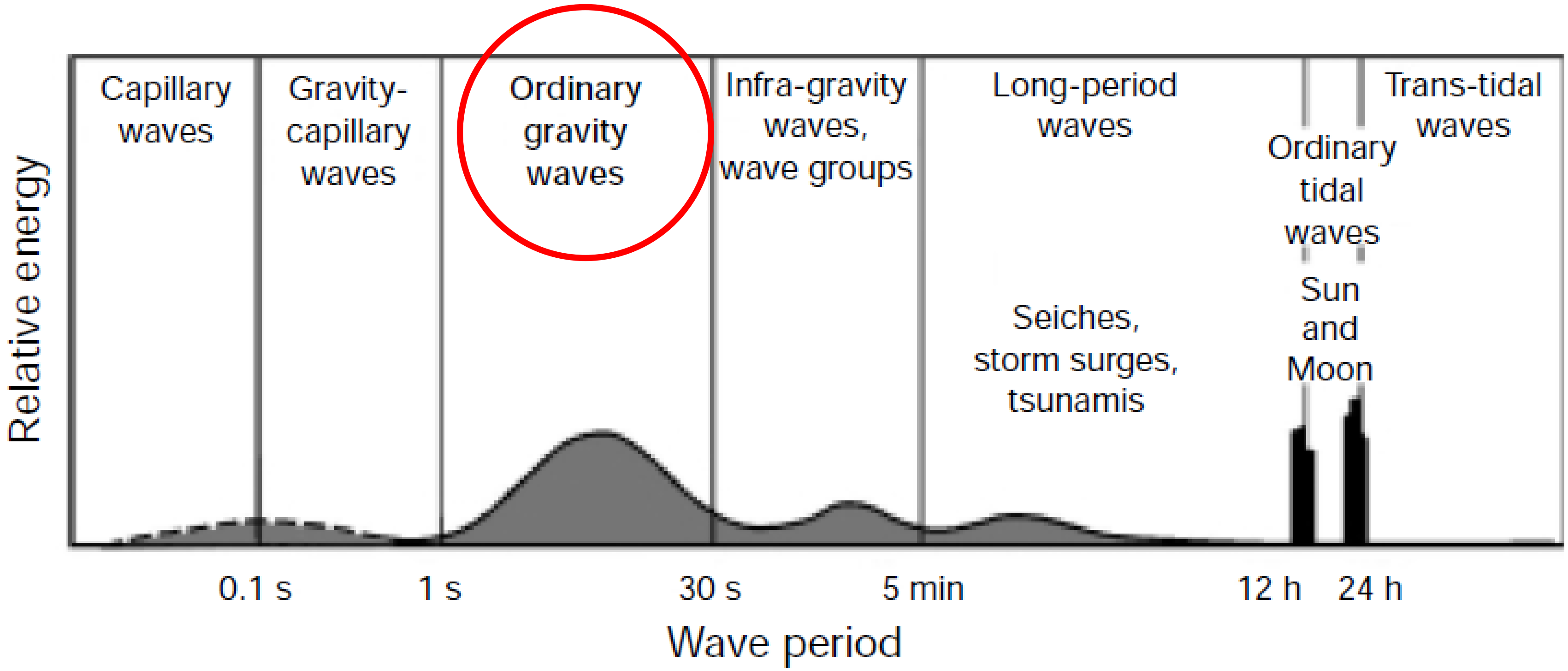
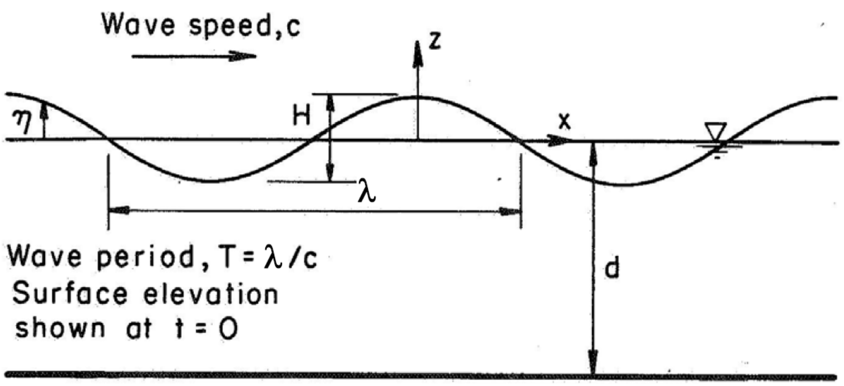
Issues to be discussed

- A reminder on the nature of (deep water) gravity waves
- The Global picture
- Examples on wave energy converters
- Extracting wave energy by an oscillating system
    - "To absorb wave energy is about generating waves"
- Theoretical efficiencies
- Two simple numerical examples

Classification of ocean waves



Linear, deep water waves (Airy waves)



Dispersion relation:

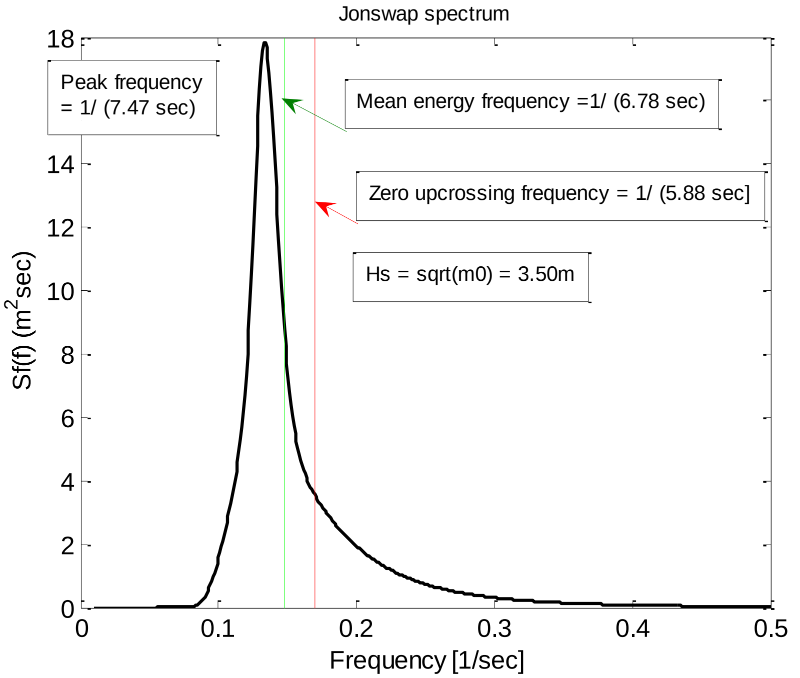
$$c^2 = \frac{\omega^2}{k^2} = \frac{g}{k}\tanh(kd)$$

As $\quad d \to \infty, \quad \tanh(kd) \to 1, \quad \mathrm{c} \to \sqrt{\frac{g}{k}}, \quad \omega \to \sqrt{kg}$

Kinetic = potential energy (per unit surface area): $E_p = E_v = \frac{1}{4}\rho g \left(\frac{H}{2}\right)^2$

Energy flux: $P = c_g\left(E_p + E_v\right) = \frac{1}{2}\frac{\omega}{k}\frac{1}{2}\rho g\left(\frac{H}{2}\right)^2 = \frac{1}{4}\rho g\left(\frac{H}{2}\right)^2\sqrt{\frac{g}{k}}$

Energy flux in a wave spectrum



Spectral moments:

$$m_n = \int \omega^n S_\zeta(\omega) d\omega$$

Significant wave height $\quad H_s = 4\sqrt{m_0}$

Average period $\quad T_{01} = 2\pi \frac{m_0}{m_1}$

Zero up-crossing period $\quad T_{02} = 2\pi \sqrt{\frac{m_0}{m_2}}$

Energy mean period $\quad T_{-1} = 2\pi \frac{m_{-1}}{m_0}$

Energy flux: $\quad P = \frac{1}{2}\rho g^2 m_{-1} = \frac{1}{4\pi}\rho g^2 T_{-1} m_0 = \frac{1}{64\pi}\rho g^2 T_{-1} H_s^2$

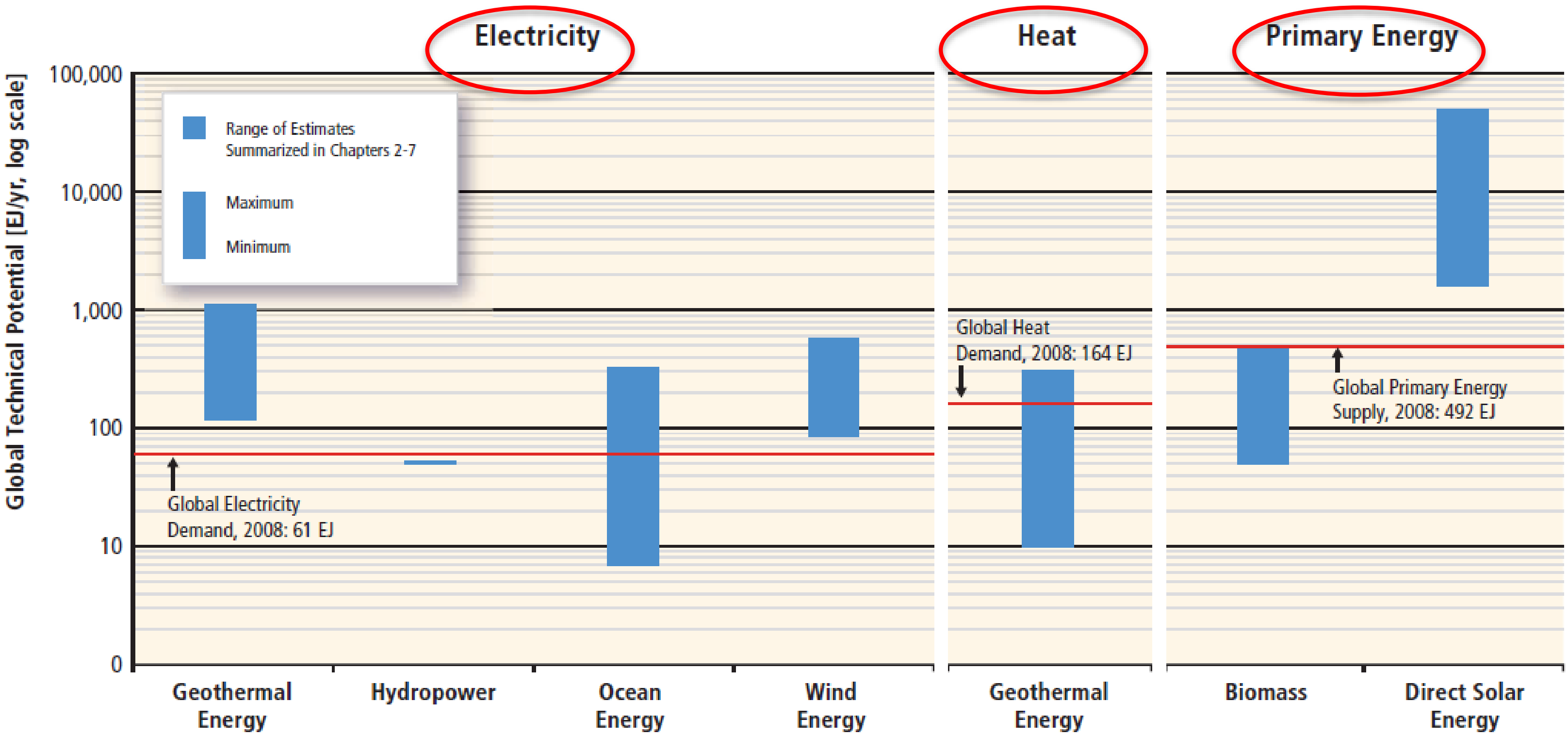
RESOURCES Waves

(From World Energy Council)

Average energy densities:
20 – 100 kW/m wave front

50 kW/m, 30% efficiency:
130 MWh/ym
100TWh/y: 760km

The potential exceeds the demands.

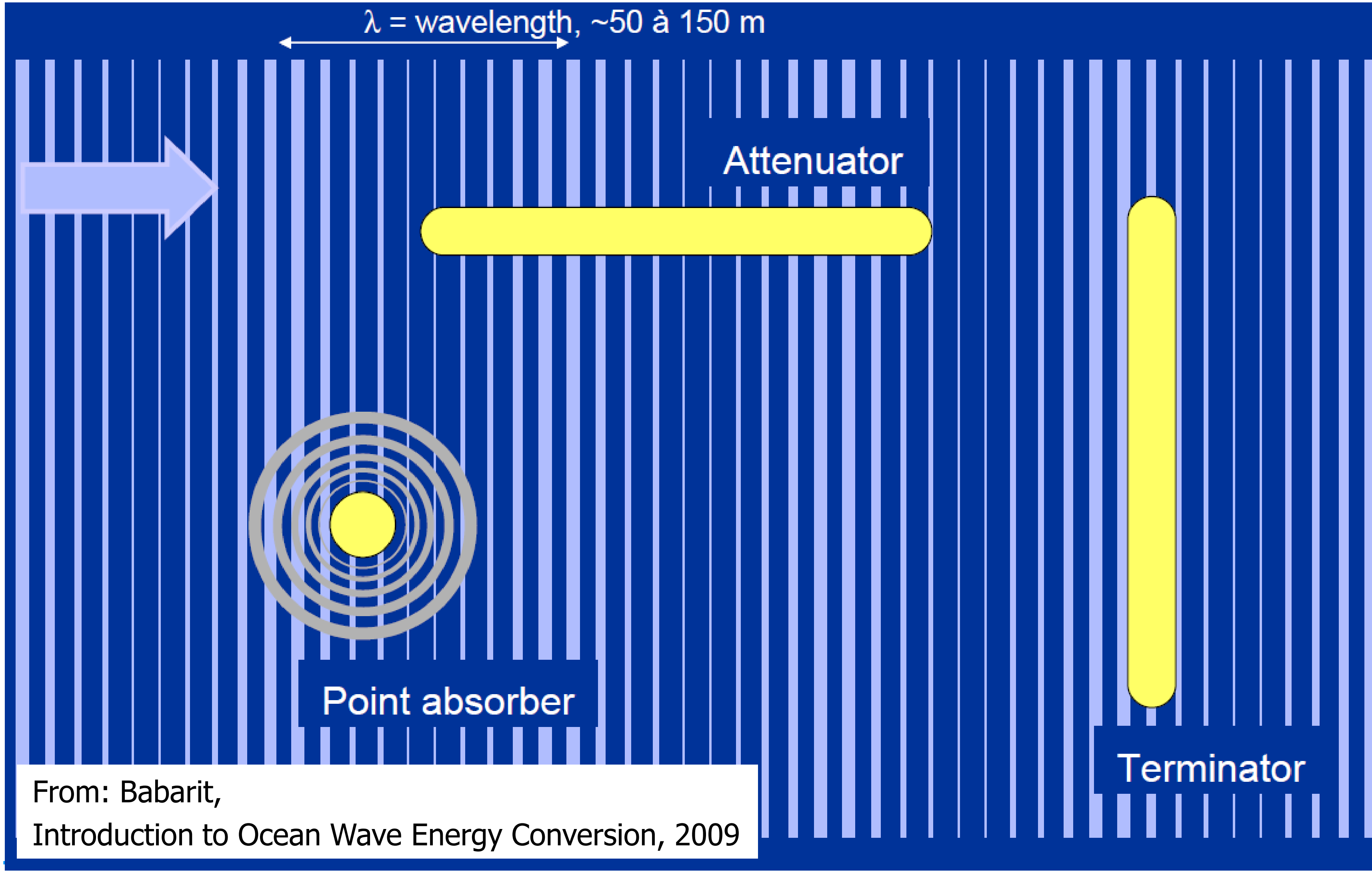


Range of Estimates of Global Technical Potentials

Max (in EJ/yr)	1109	52	331	580	312	500	49837
Min (in EJ/yr)	118	50	7	85	10	50	1575

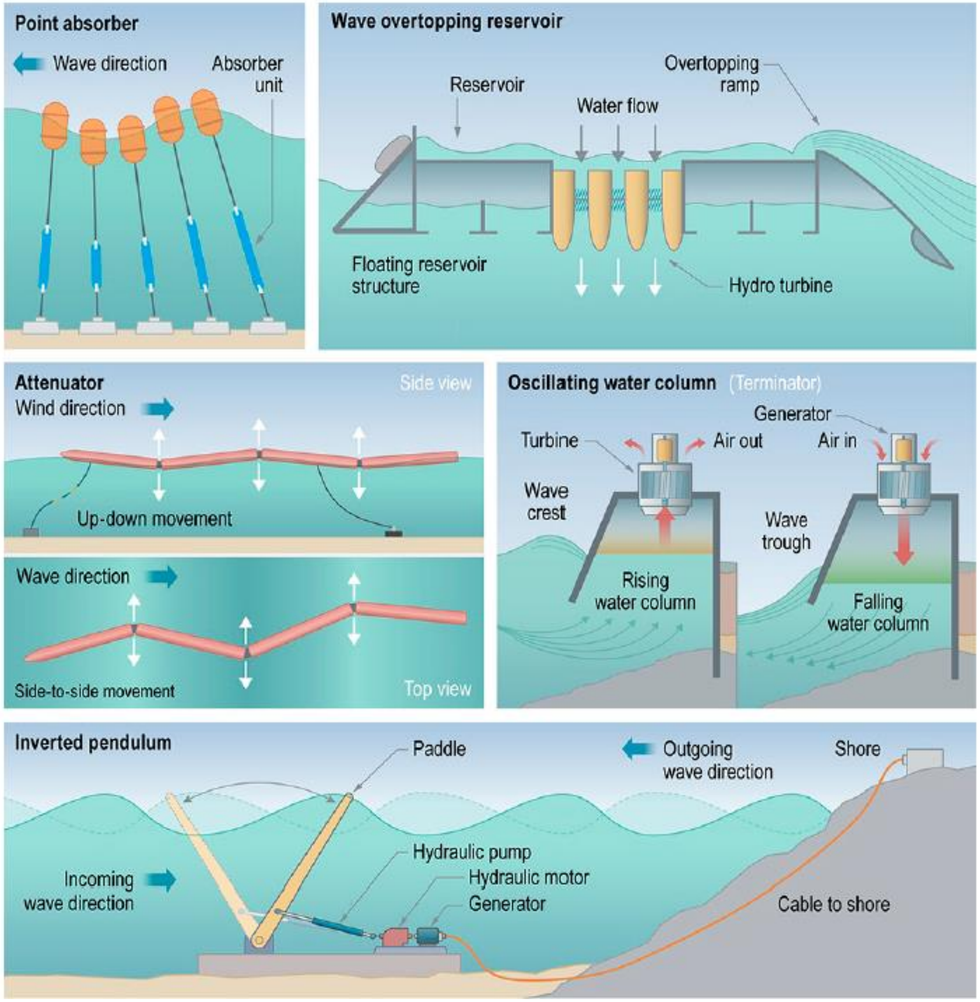
Source: IPCC SRREN, 2011

Main principles



From: Babarit,
Introduction to Ocean Wave Energy Conversion, 2009

Illustration of main principles



Source: Bedard(2006)»overview: EPRI Ocean Energy Program» Presented to Duke Univerisity Global Change Centre.

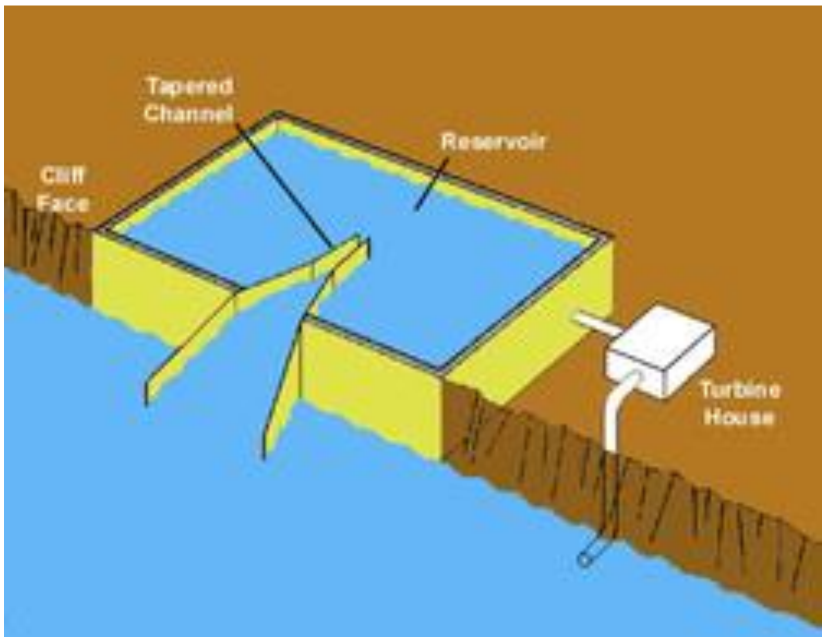
Key principles for extracting wave energy

- Remember:
  - Waves are not only quasi-static change in surface elevation
  - Energy absorption requires a force working together with a velocity

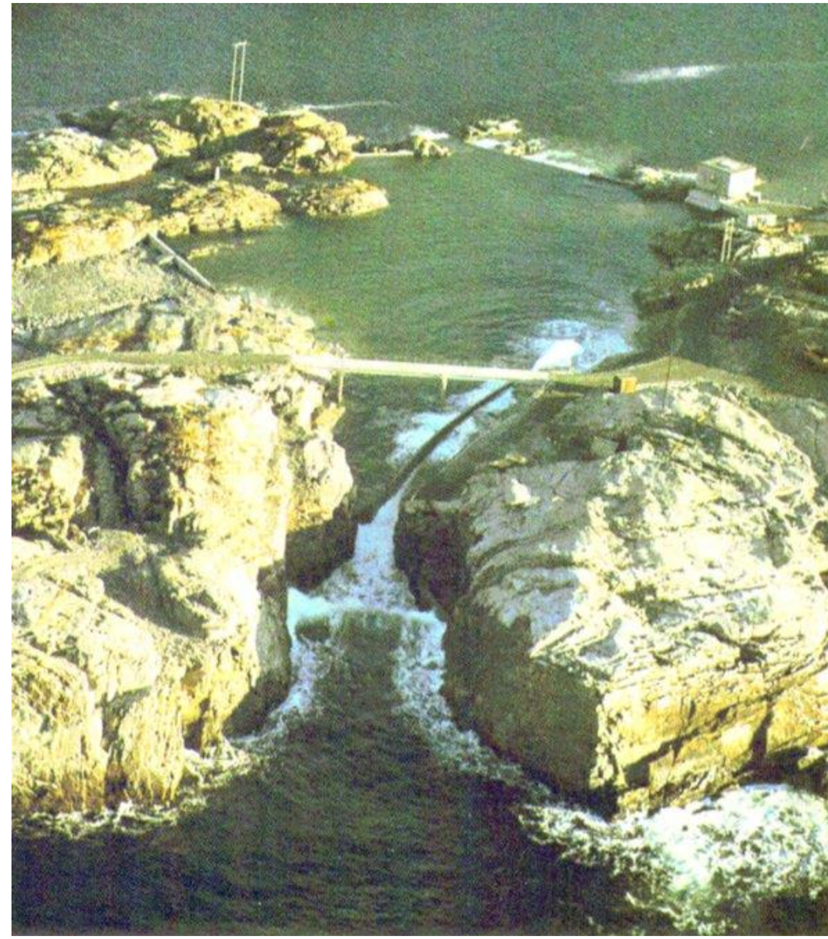
'Falnes and Budal (1978):

'In order for an oscillating system to be a good wave absorber it should be a good wave generator".

The Tapchan project at Toftestallen, Øygarden
(finished 1985)



Principle.

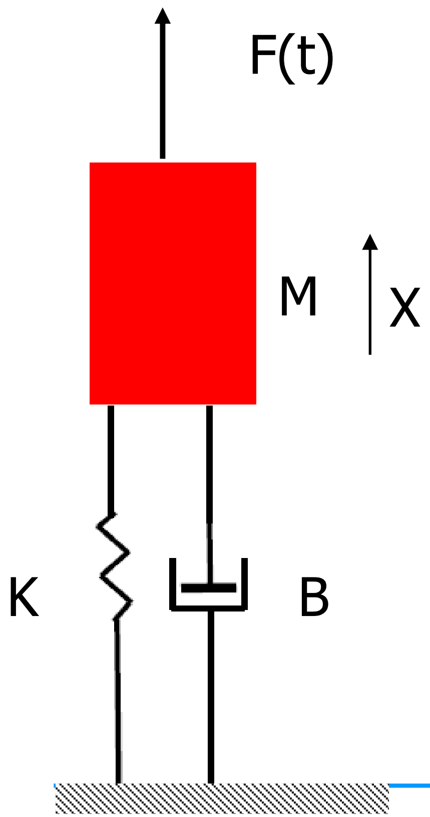


Test site

How is energy extracted?

- Key principles
- Linear considerations
- Linear oscillator – interaction with waves
    - Heaving buoy as example

Linear oscillator



Dynamic equilibrium:

$$M\ddot{x} + B\dot{x} + Kx = F(t)$$

$$\ddot{x} + 2\zeta\omega_0\dot{x} + \omega_0^2 x = F(t)$$

$$\omega_0 = \sqrt{\frac{K}{M}}$$

$$\zeta = \frac{B}{2M\omega_0}$$

Harmonic oscillation, stationary solution.

$$F(t) = F_A \cos(\omega t) = F_A \,\mathrm{Re}[e^{i\omega t}]$$

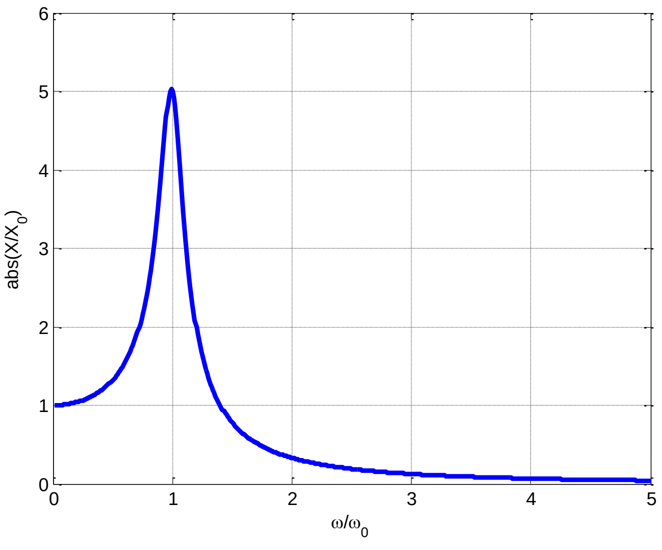
Dynamic equation, frequency domain:

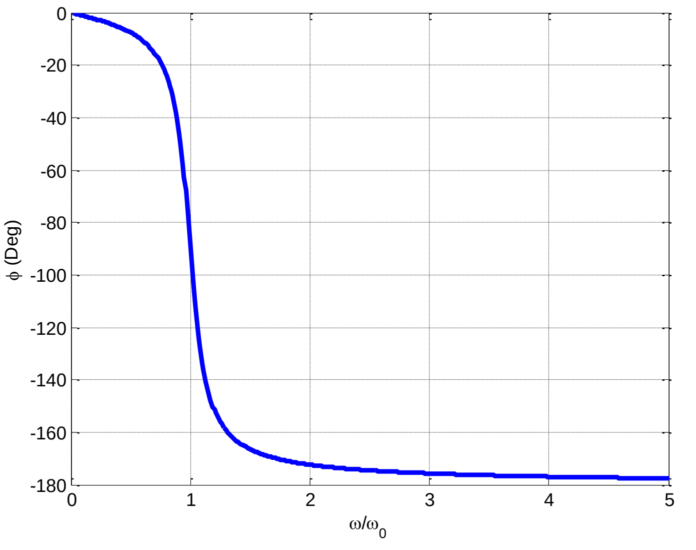
$$\left(-\omega^2 M + i\omega B + K\right) x = F$$

Linear oscillator - solution

$$x(\omega) = x_A \cos(\omega t + \phi) = x_A \operatorname{Re}\left[e^{i(\omega t + \phi)}\right]$$

$$x(\omega) = \frac{F}{-\omega^2 M + K + i\omega B}$$



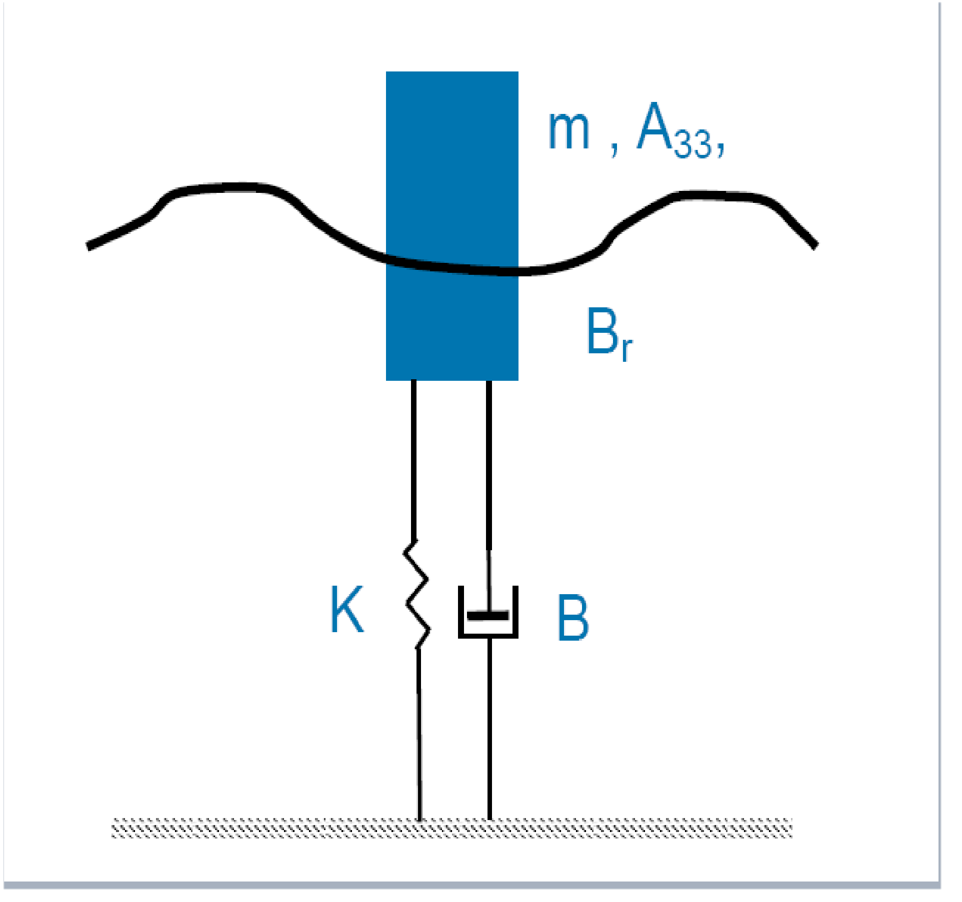


At resonance: Response controlled by damping!

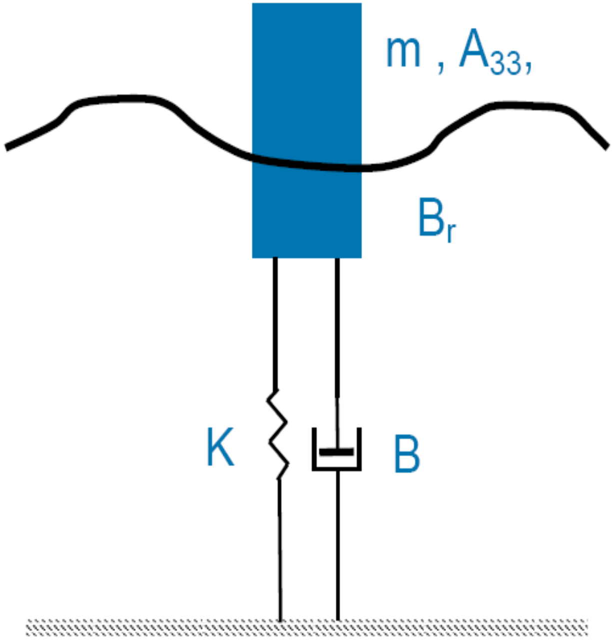
Estimating the energy absorption by a heaving buoy

Assumptions:

- Heave motion only
- Linearized analysis
- No viscous effects



The heaving point absorber, a linearized approach (1:3)



Equation of motion (1DOF):

$$m\ddot{x} = F_{ex} + F_R + F_P$$

In frequency domain:

$$\left[-\omega^2\left(m + A_{33}\right) + i\omega\left(B_r + B + B_l\right) + k_{wl} + K\right]x = F_{ex}\left(\omega\right)$$

Wave radiation force:

$$F_R = -A_{33}\ddot{x} - B_r\dot{x} - k_{wl}x$$

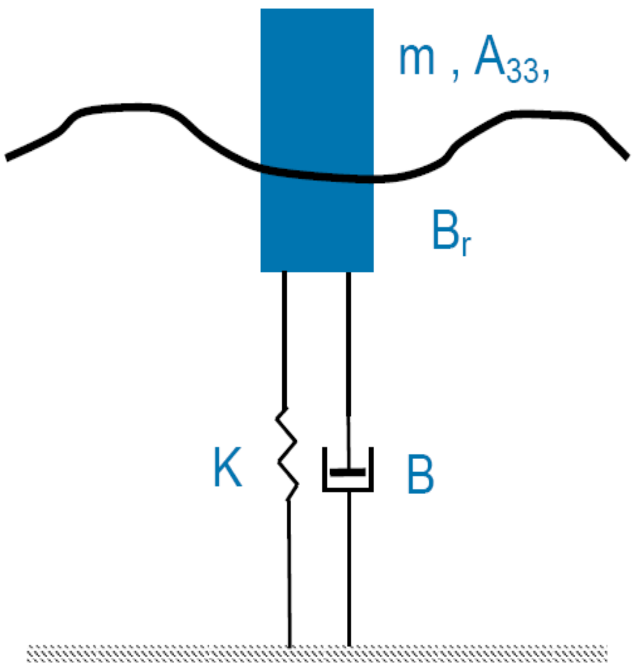
Force due to power off-take:

$$F_P = -B\dot{x} - Kx$$

Heave motion:

$$x = \frac{F_{Aex}\cos(\omega t + \phi)}{\sqrt{\left[-\omega^2\left(m + A_{33}\right) + k_{wl} + K\right]^2 + \left[\omega\left(B + B_r + B_l\right)\right]^2}}$$

The heaving point absorber , a linearized approach (2:3)



Instantaneous power:

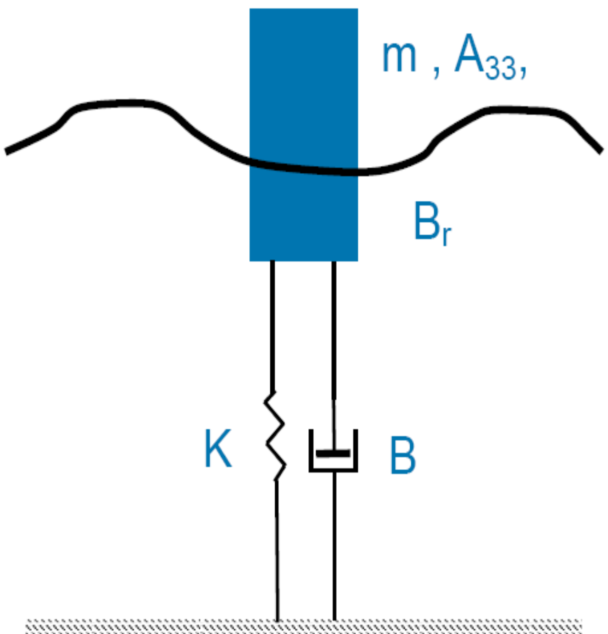
$$P_P(t) = -F_P \dot{x} = \left[Kx + B\dot{x}\right]\dot{x}$$

Integrated over one wave period:

$$\bar{P}_P = \frac{1}{2}\frac{F_{Aex}^2 \omega^2 B}{\left[-\omega^2\left(m + A_{33}\right) + k_{wl} + K\right]^2 + \left[\omega\left(B + B_r\right)\right]^2} = \frac{1}{2}\omega^2 B x_A^2$$

Maximum power at resonance

The heaving point absorber , a linearized approach (3:3)



Optimum damping in power off-take:

$$d\bar{P}_P / dB = 0$$

Obtained for $B = B_r$

Maximum mean power:

$$\bar{P}_{p\_\max} = \frac{F_{Aex}^2}{8B_r(\omega_0)}$$

Theoretical limits for power extraction – 3D axisymmetric body (deep water)

Invoke "Haskind relation" (relates wave excitation force to wave radiation damping.)

3D symmetric, heaving buoy:

$$B_{r33}(\omega)=\frac{\omega^3}{2\rho g^3}\left|\frac{F_{ex3}(\omega)}{\frac{H}{2}}\right|^2$$

Falnes and Budal , 1978: ***"In order for an oscillating system to be a good wave absorber it should be a good wave generator".***

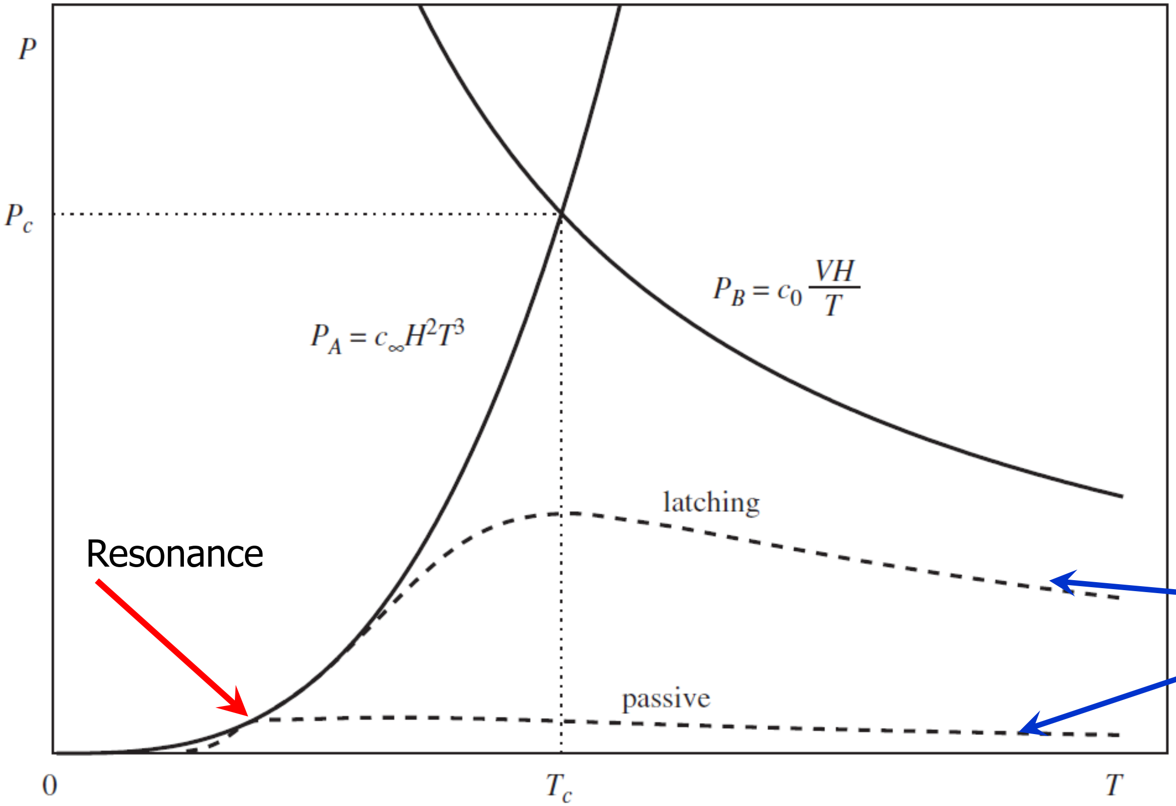
I.e. max power:

$$\bar{P}_{p\_\max}=\frac{F_{Aex}^2}{8B_r(\omega_0)}=\frac{\rho g^3\left(\frac{H}{2}\right)^2}{4\omega^3}=\frac{\rho g^3}{128\pi^3}H^2T^3$$

"Capture width":

$$L_{cap}=\frac{\text{max power extraction}}{\text{power in wave per meter}}=\frac{\frac{\rho g^3}{128\pi^3}H^2T^3}{\frac{1}{32\pi}\rho g^2TH^2}=\frac{g}{\omega^2}=\frac{\lambda}{2\pi}$$

Heaving point absorber – Theoretical versus "Budal limit".
- Or the implication of limited physical size.



$$C_0 = \frac{1}{4}\rho g \pi = 7.90 \text{ kWs/m}^4$$

$$C_\infty = \frac{\rho g^3}{128\pi^3} = 0.244 \text{ kW/(m}^2\text{s}^3)$$

Capture width (P_A):
L=λ/2π (Heave only)
L = 3λ/2π (Heave & surge)

Semisubmerged sphere

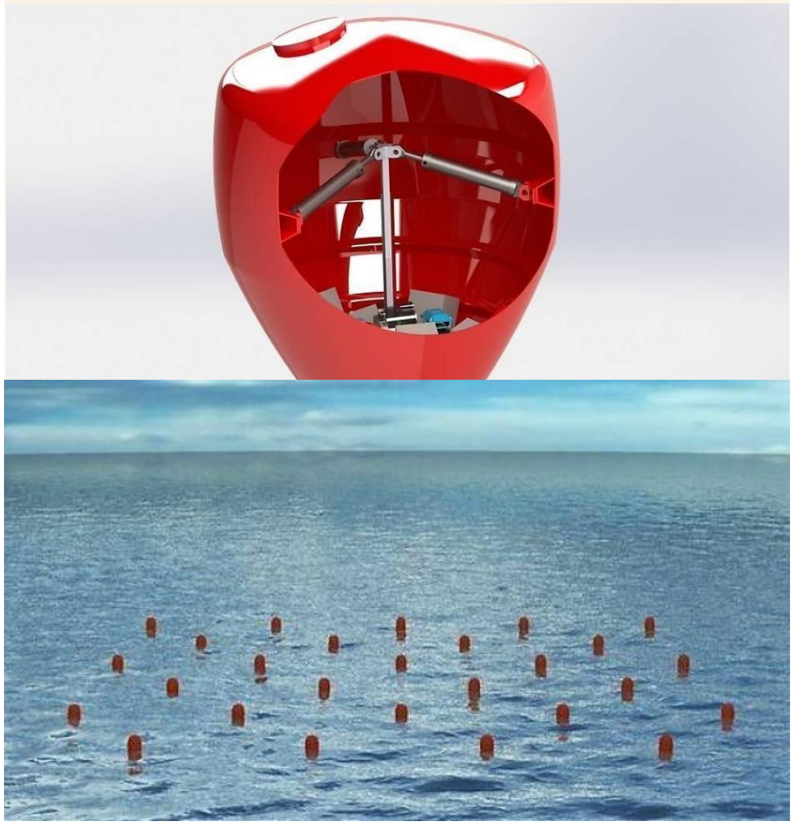
From Falnes (2007)

E24 /TU 31.05.15

E24! FØRST MED ØKONOMINYHETENE LOGG INN MENY

Nytt kraftverk løser en av bølgekraftens aller største utfordringer

Virker som et menneskehjerte.



Endret oppførsel

Den opprinnelige teknologien gikk ut på at ballongen blant annet ble holdt fast under vann, for så å bli sluppet løs og fare opp til overflaten når en bølge kom.

Etter at det svenske selskapet inngikk samarbeid med NTNU- og Marintek-forsker Jørgen Hals Todalshaug om kontrollteknologien WaveSpring, endret ballongens oppførsel i vannet seg.

Den norske forskeren ble nylig ansatt i Corpower Ocean.

– Torsdalhaug har utviklet en helt ny teknikk for å kontrollere og styre bøyer, som gjør at sparbøyen nå hele tiden beveger seg optimalt og i ressonans med bølgen. Vi har kombinert teknologien med vår mekaniske løsning. Dermed forsterkes bevegelsene og evnen til å fange energi , sier Möller til Teknisk Ukeblad.

NTNU-oppfinnelsen sørger for at bøyen hele tiden beveger seg optimalt med bølgen, gjennom en negativ fjærkonstruksjon.

– Den forsterkede lineære bevegelsen forvandles til rotasjon ved hjelp av en patentert girkonstruksjon vi kaller kaskadegir. Giret har egenskaper som gjør at det effektivt kan forvandle stor, lineær last med høy hastighet om til rotasjon, sier Möller.

Giret ligner et planetgir, som deler stor belastning på mange små tannhjul.

Les også: Den flytende byen skal romme tre fjell og 50.000 innbyggere

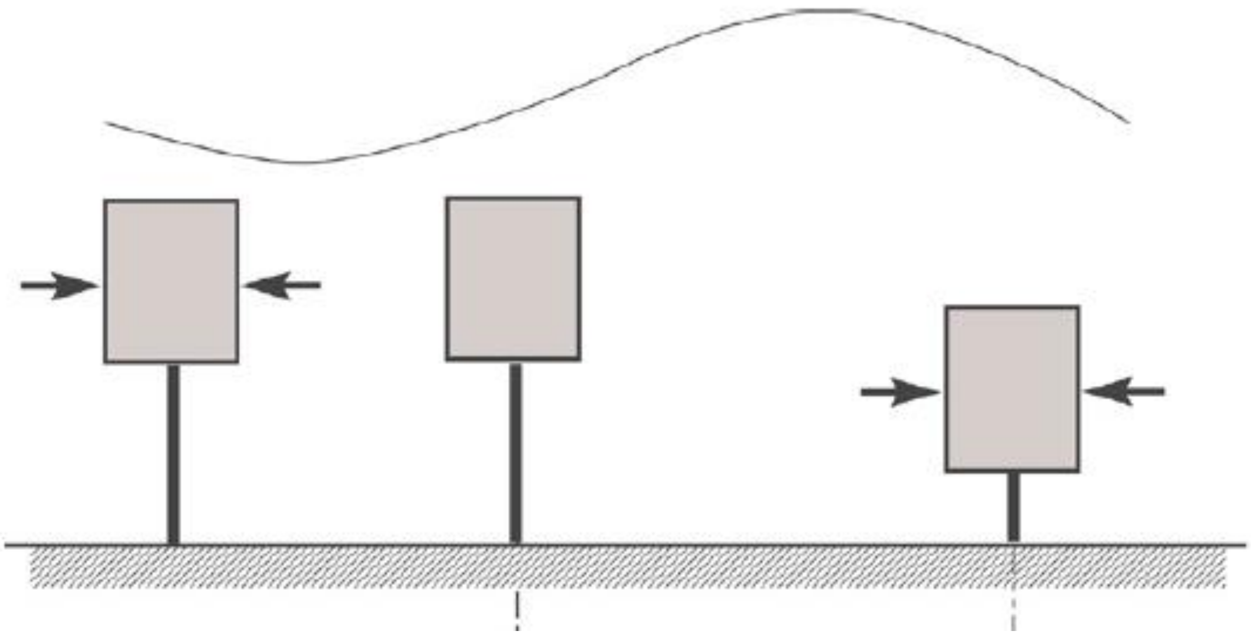
Roterende bevegelser

Energien lagres i to trinn: Den første bevegelsen er inspirert av den hydrauliske energilagringen i hjertets kammere, mens den andre bygger på lagring av kinetisk energi.

Energien omdannes altså til en roterende bevegelse ved hjelp av et dobbelt generatorsett, som genererer elektrisitet både på vei opp og ned.

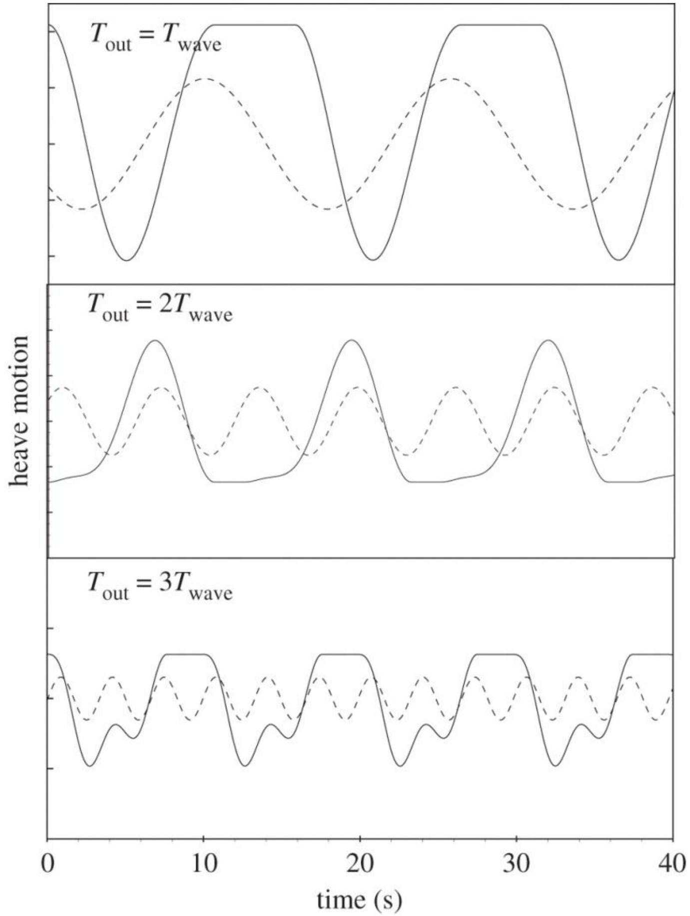
Det er skrevet en lisensavtale med NTNU, og den nye løsningen er testet i laboratorier i Frankrike.

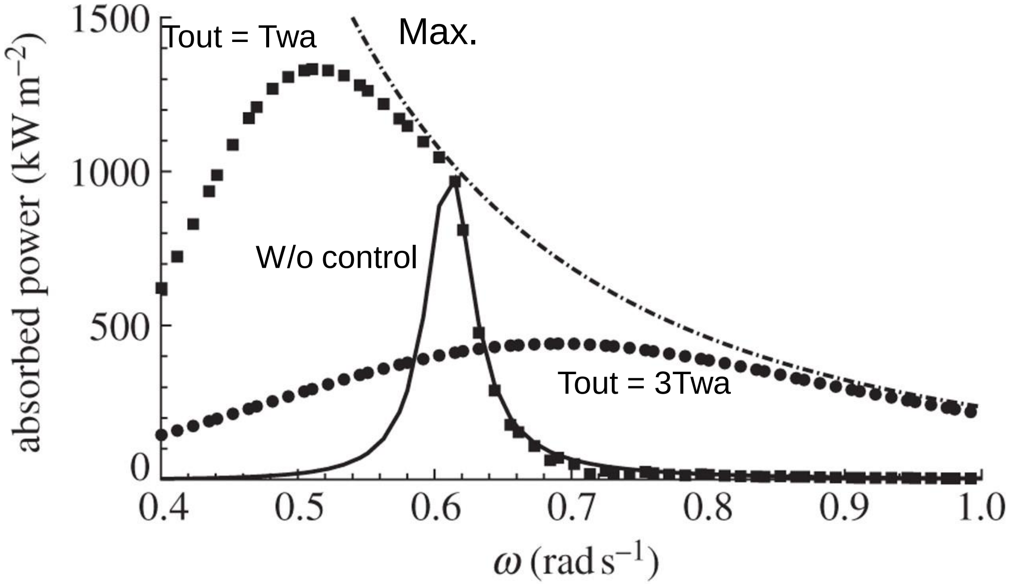
The idea of latching (1:2)



A. Babarit, G. Duclos, A.H. Clément: Comparison of latching control strategies for a heaving wave energy device in random sea

The idea of latching (2:2)





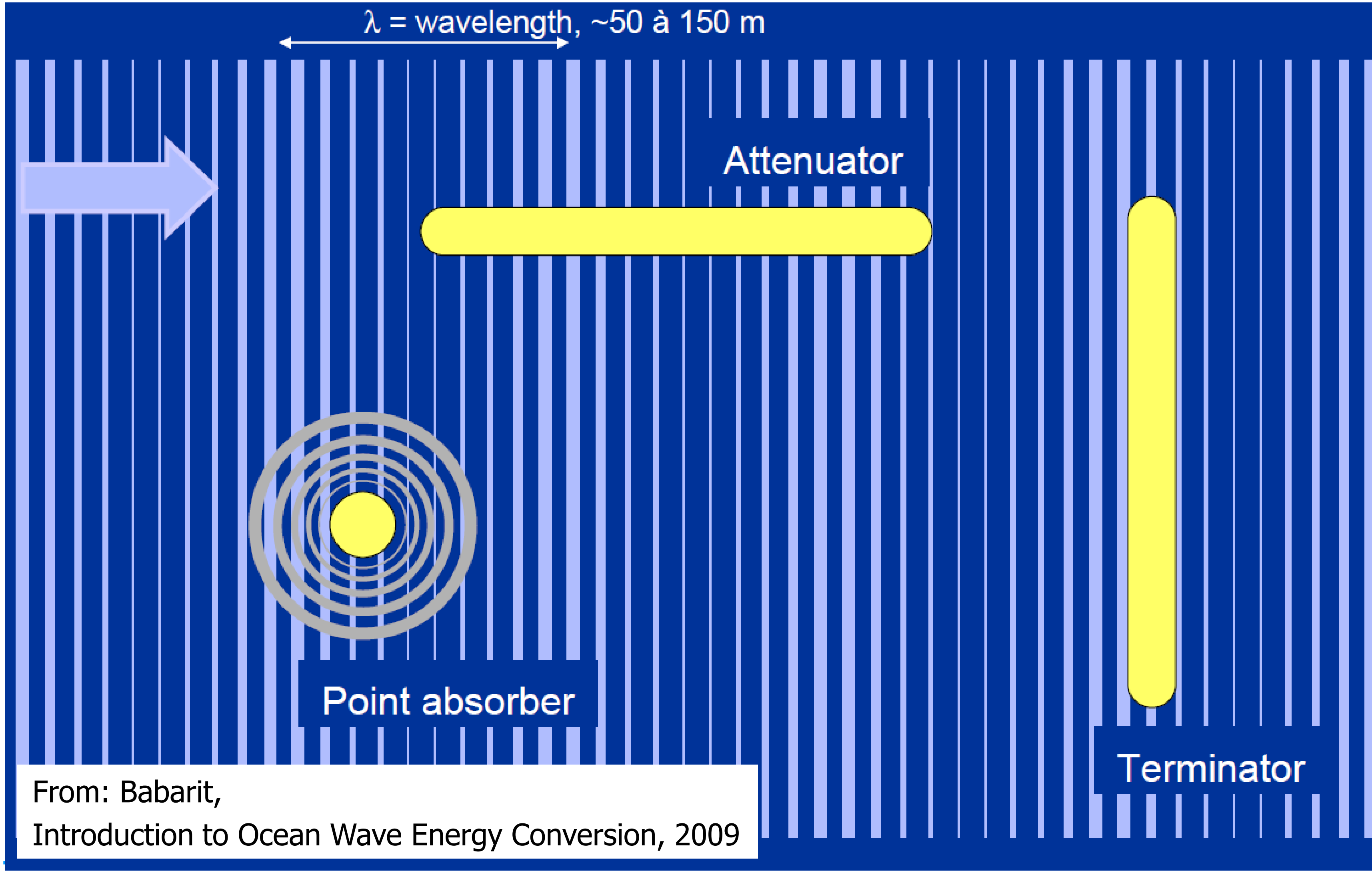
Source: Clement and Babarit (2012)

1DOF system.

Power absorbed in harmonic and first sub-harmonic latching modes, compared with uncontrolled, and ideal modes.

Solid line, without control; squares, latching, Tout=Twa; circles, latching, Tout=3×Tin; dashed dotted line, max power

Main principles



From: Babarit,
Introduction to Ocean Wave Energy Conversion, 2009

Interaction between waves and body - 2D

Energy flux in incident wave:

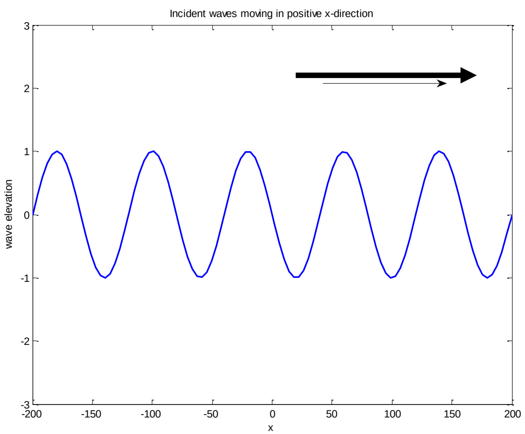
$$J = c_g E = \frac{1}{4}\frac{\rho g^2}{\omega} A_0^{\,2}$$

Net absorbed wave power per unit length:

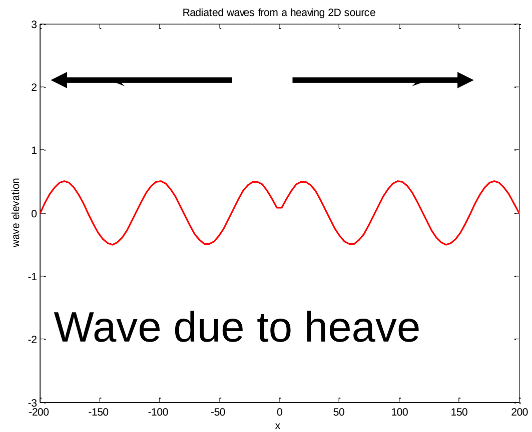
$$P_{2D} = \frac{\rho g^2}{4\omega}\left[A_0^2 - A_R^{\,2} - A_T^2\right]$$

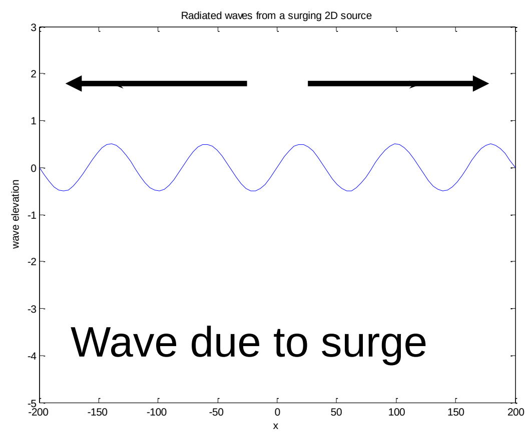
A_T: amplitude of transmitted wave
A_R: amplitude of reflected wave

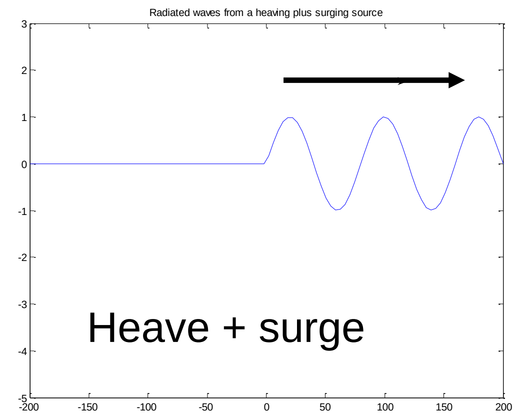
Interaction between waves and body 2D Incident wave plus heaving and surging body.

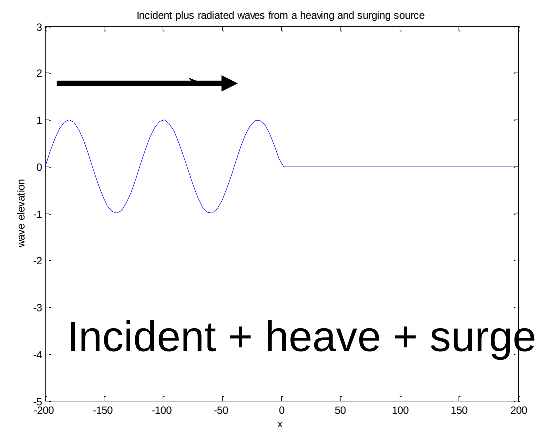


Incident wave









Note importance of phasing

Example – heaving buoy, motions

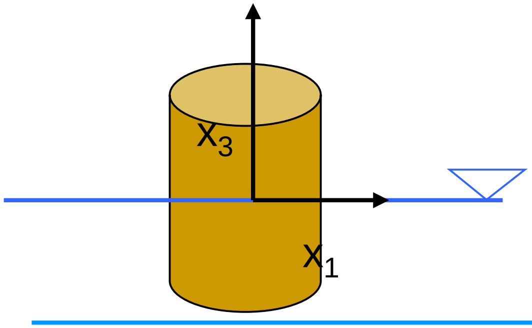
INPUT

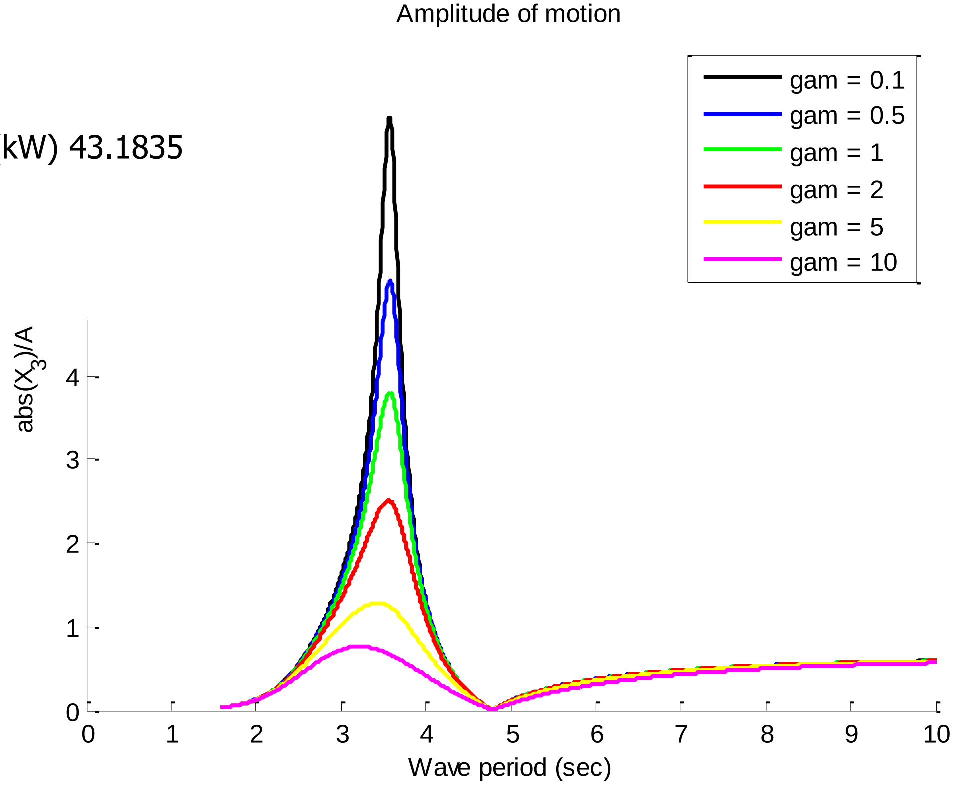
Radius	1 m
Draft	5 m
Wave amplitude	1 m
Mass	12880.5299 kg
Water line stiffness,	31.5787 kN/m
Power offtake stiffness	15.7894 kN/m
Natural period	3.539 sec
Radiation damping at T_0	1947.692 N/(m/s)

Theoretical maximum energy absorbtion, at resonance (kW) 43.1835

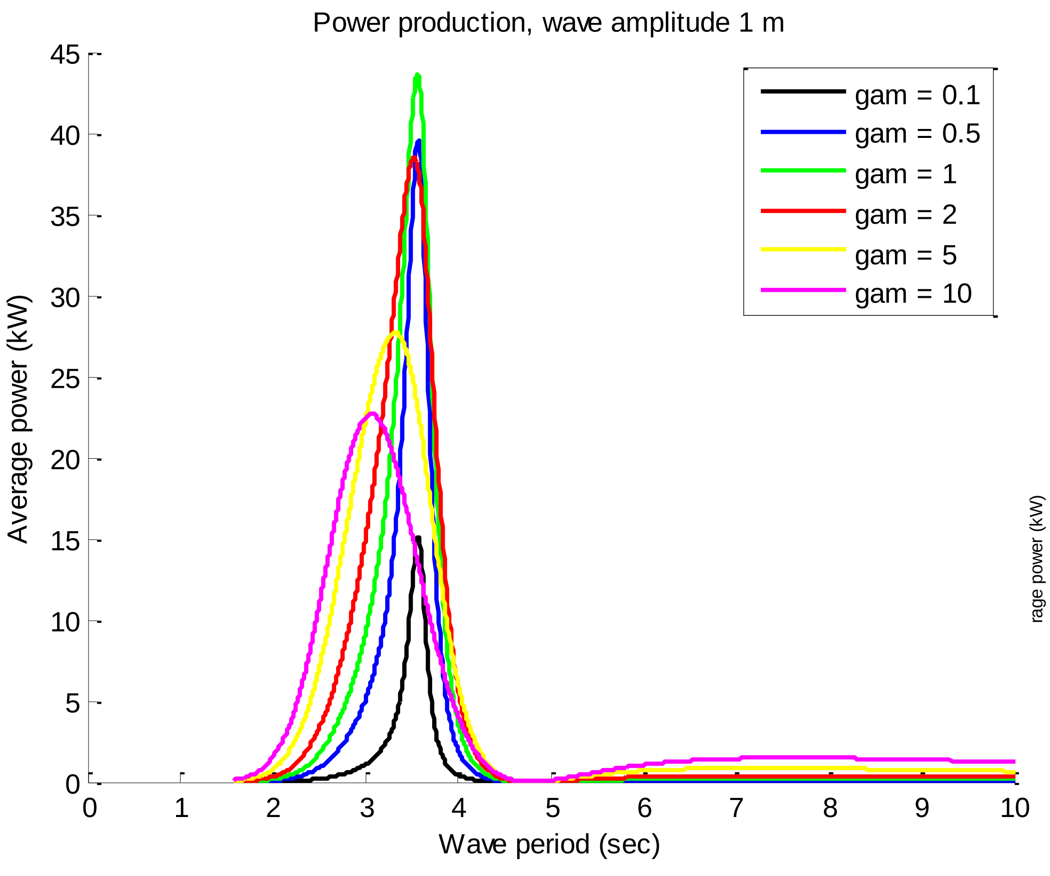
$Gam = B\_{poweroffake} / B\_{radiation}\ (T_0)$

$B\_{powerofftake}$ independent of frequency (not optimum)

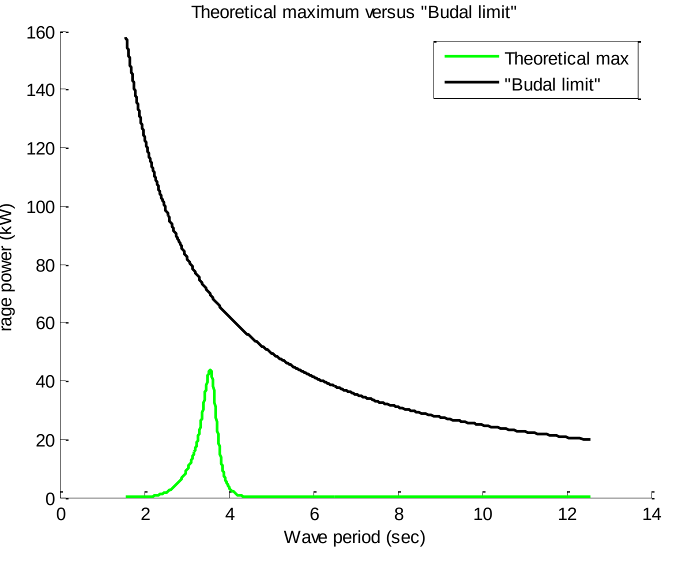




Heaving buoy - Power production



Budal limit with A= 1m



Power production off resonance - passive system

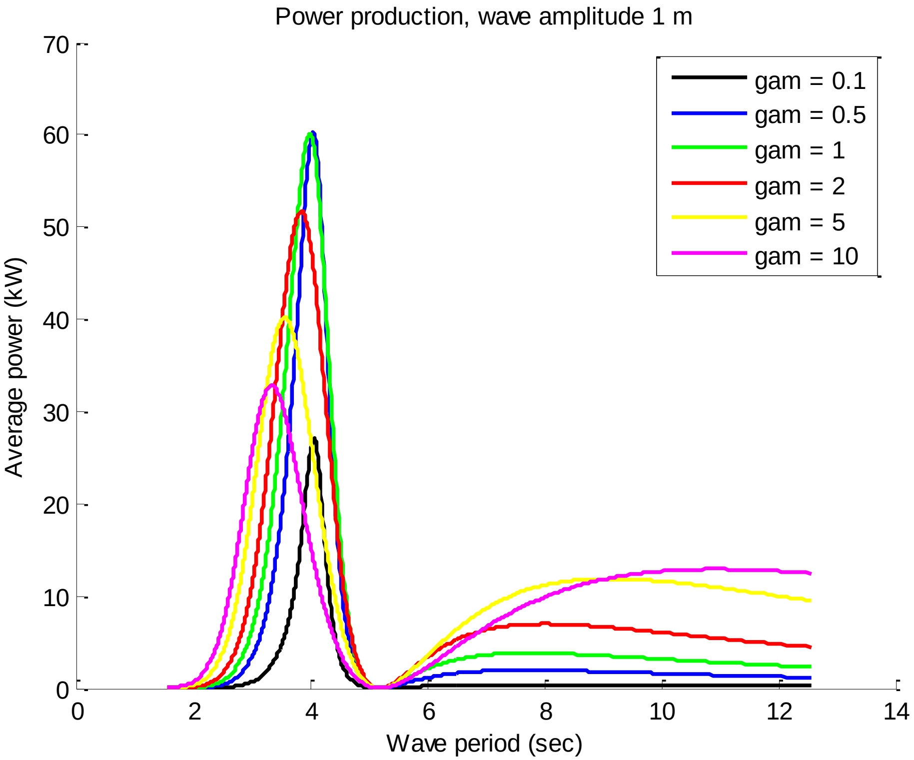
INPUT

Radius	2.5 m
Draft	5 m
Wave amplitude	1 m
Mass	80503.3117 kg
Water line stiffness,	197.367 kN/m
Power offtake stiffness	98.6835 kN/m
Natural period	3.8998 sec
Radiation damping at T0	49277.4514 N/(m/s)

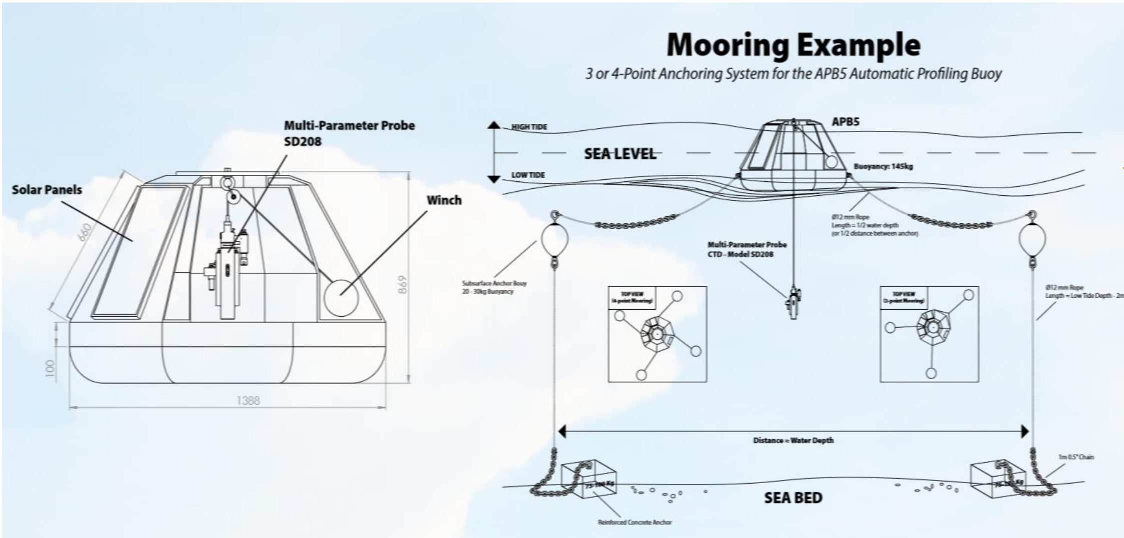
Theoretical maximum energy absorbtion, at resonance (kW) 57.7829

Gam = B_powerofftake / B_radiation (T0)

High damping in power off-take important to extract energy at periods above resonance



Example: Gabriell



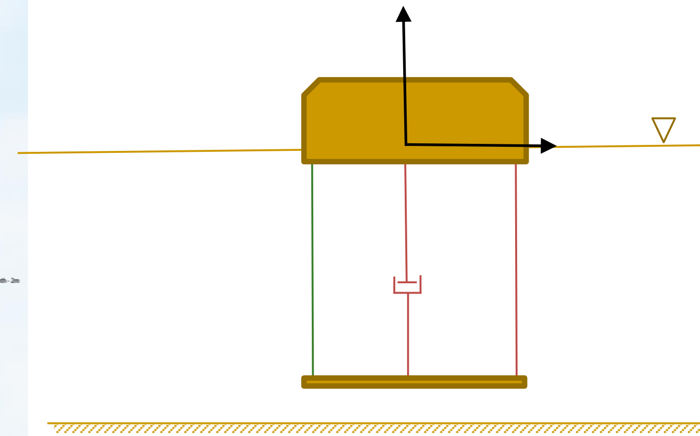
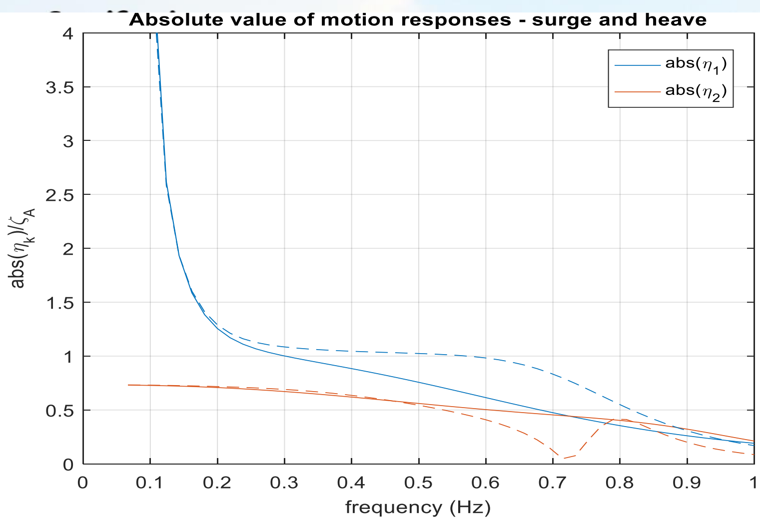
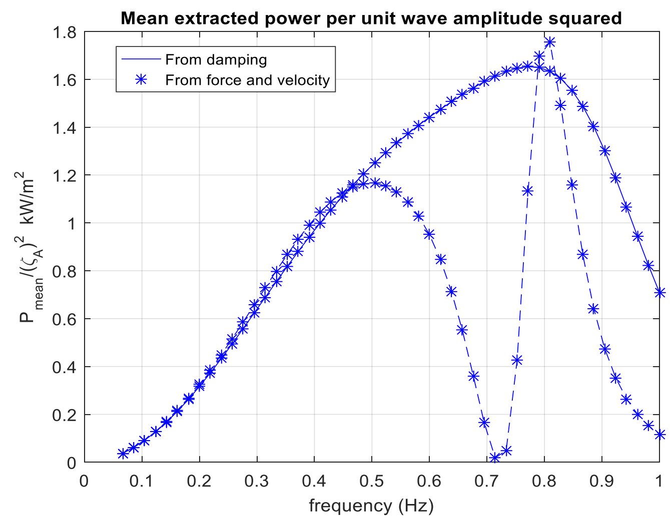


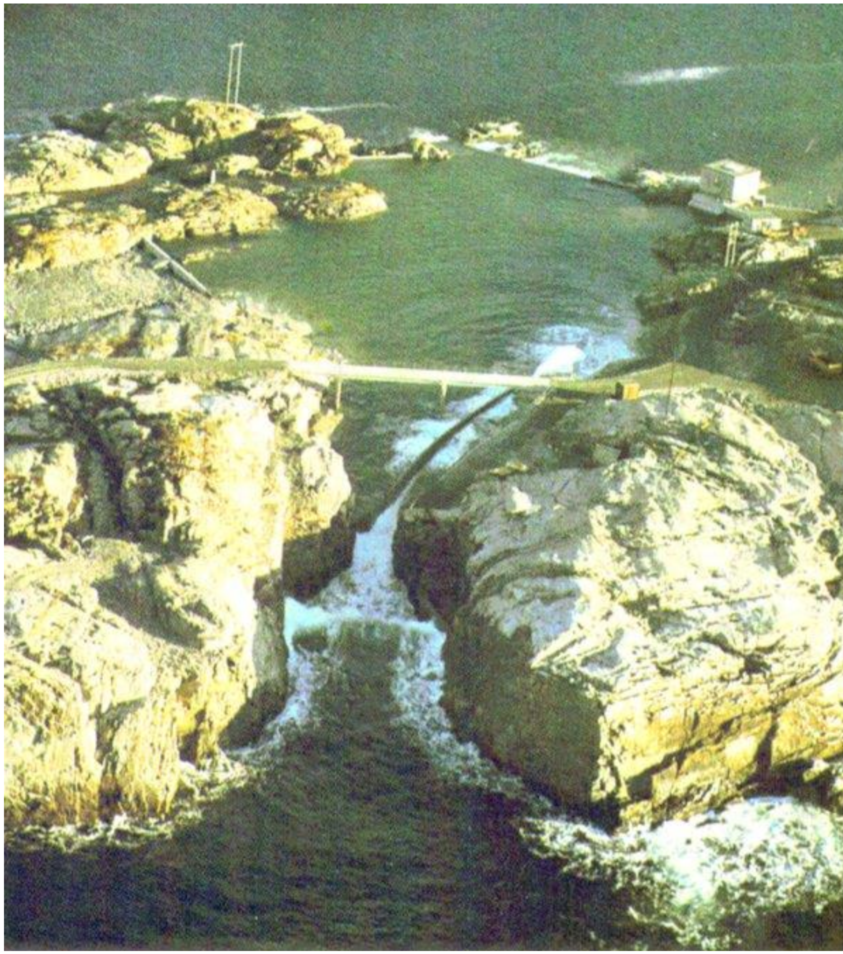
Figure 2. Illustration of the buoy with a horizontal plate attached underneath.





Toftestallen

In the 1980'ies



..and in 2014

Wave power converters -

Examples on installations in full / reduced scale (2:2)

Bostrøm et al. (Sweden, 2006-)

- Heaving buoy. Linear generator

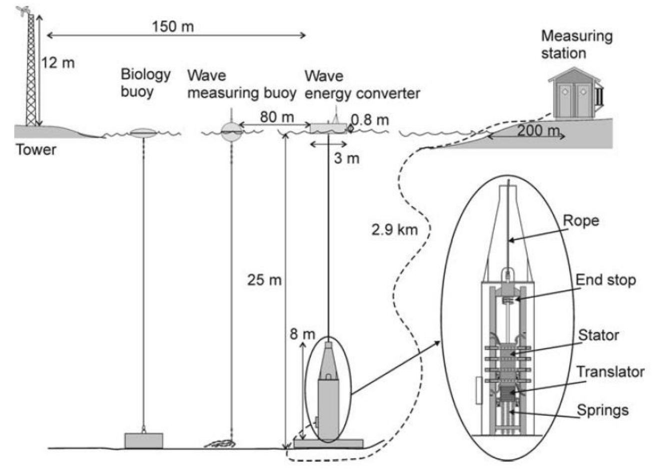
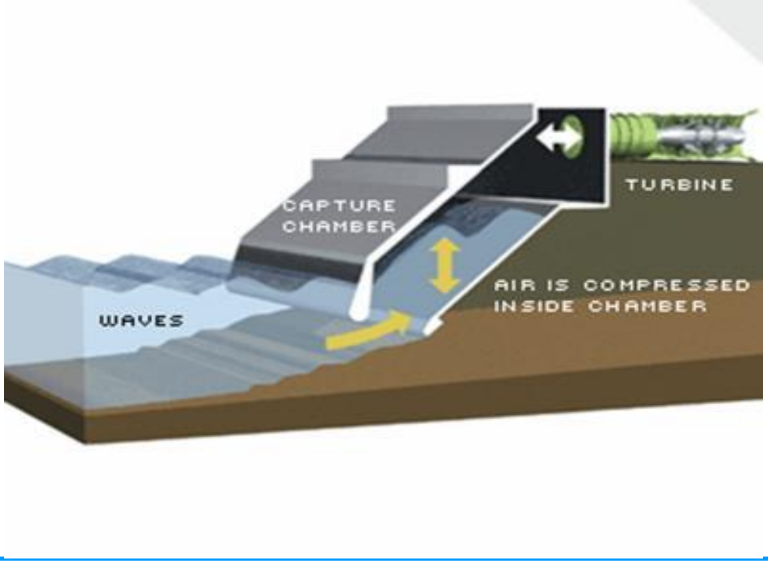


Fig. 1 Overview of the various types of components installed at the Lysekil research site

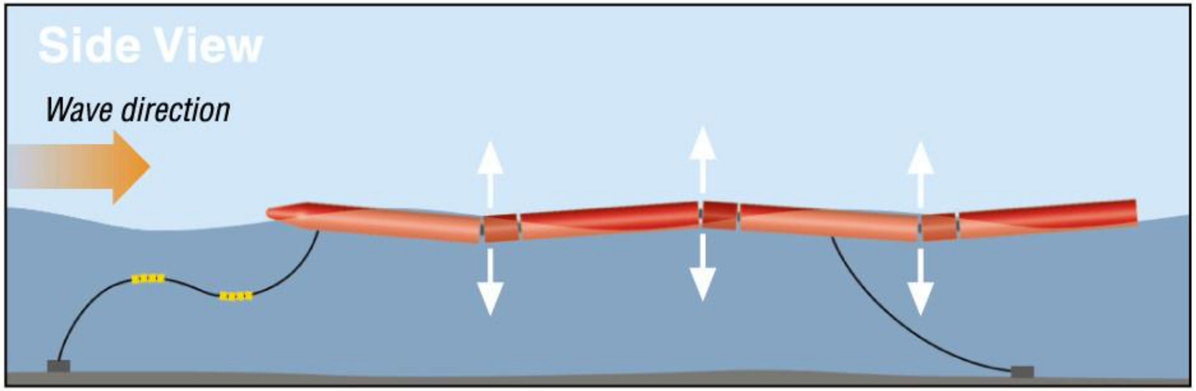
Fred Olsen, "Buldra". (Norway 2004-)

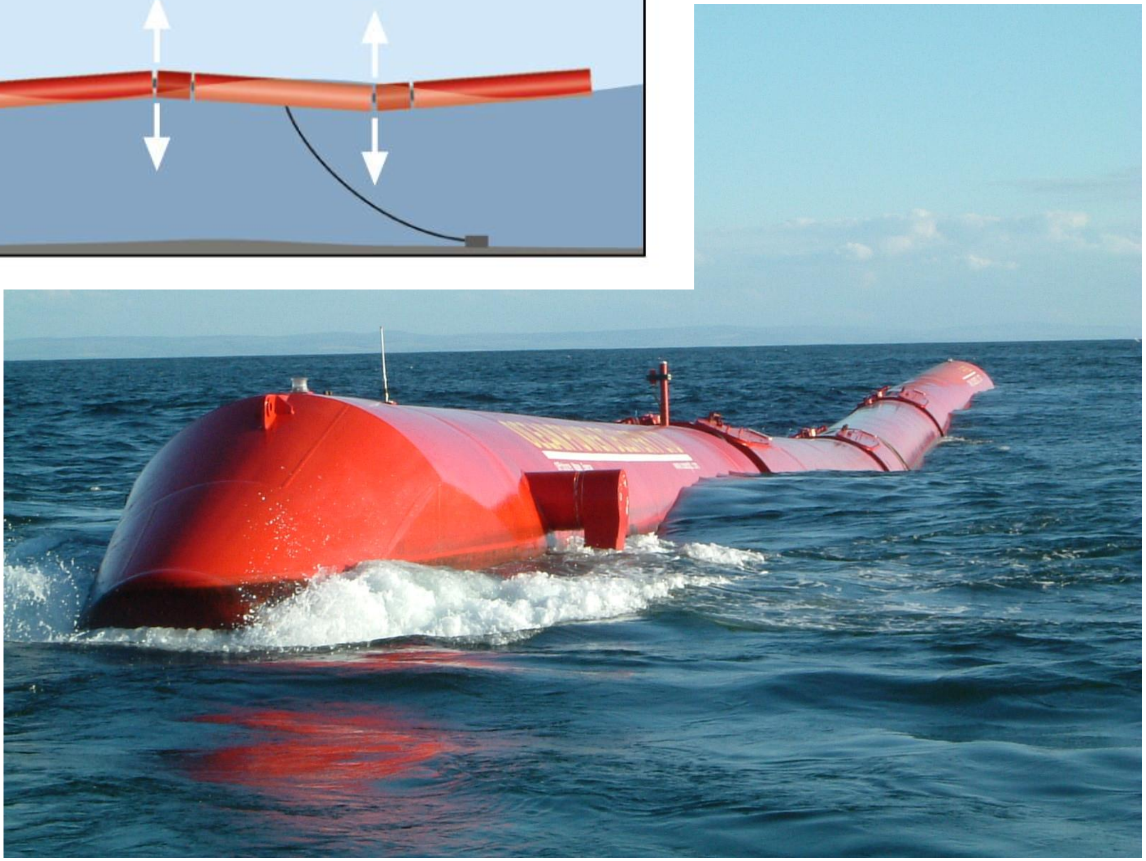
- Array of heaving buoys. Semisubmersible

Oscillating water column (OWC) **LIMPET**

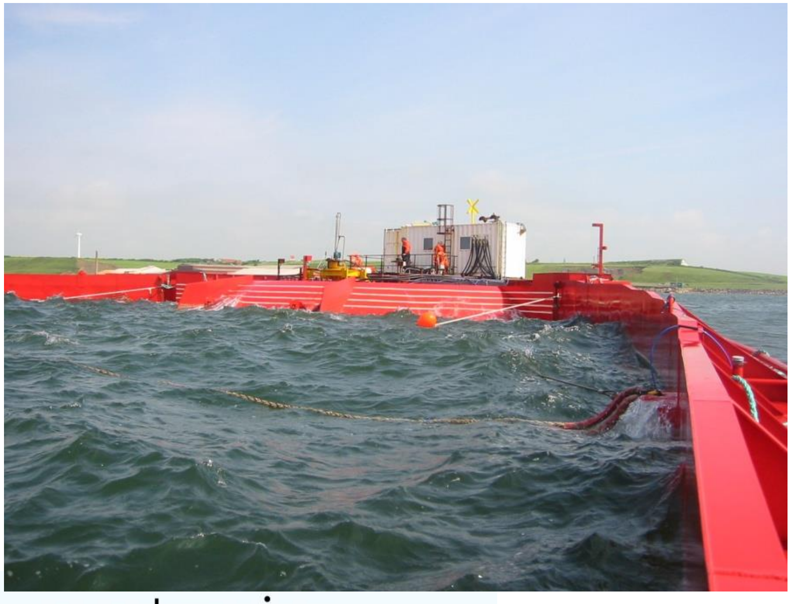


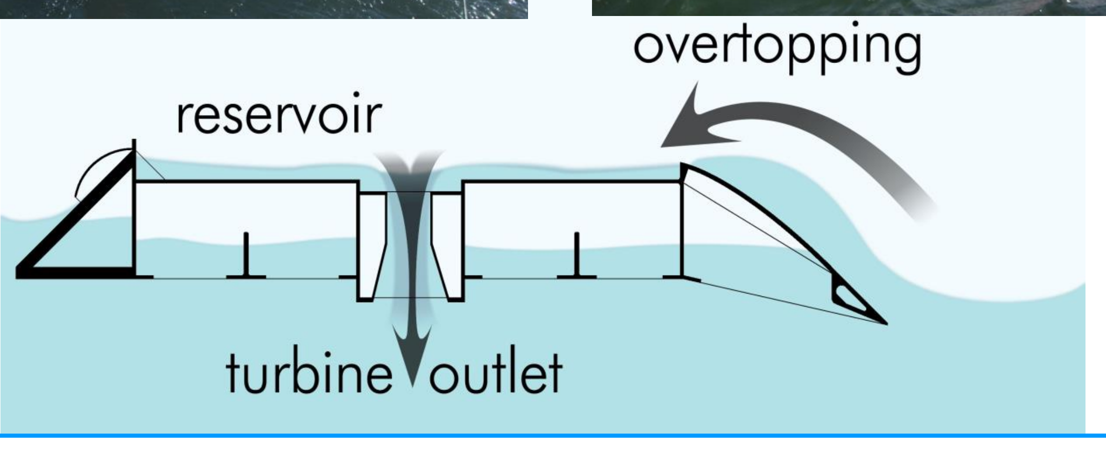
Relative motion device attenuator – Pelamis (750 kW device)





Overtopping – Wave Dragon (prototype 20kW, 4-7MW demonstrator)





New ideas - floating hose

Ill. EPSRC

The ANACONDA concept.

Water inside the tubes are propagating in longitudinal direction.

Summary

- Vaste amount of wave energy available. Technical availability uncertain.
- No convergence on technical solutions
- For an oscillating system to extract energy, it has to generate waves
- Advanced control needed to enhance power offtake.
- Survivability has shown up to be a critical issue.