Small is Beautiful

How to make wave energy economic

~~A Study of Economics as if People Mattered~~

J. Falnes

~~E. F. Schumacher~~

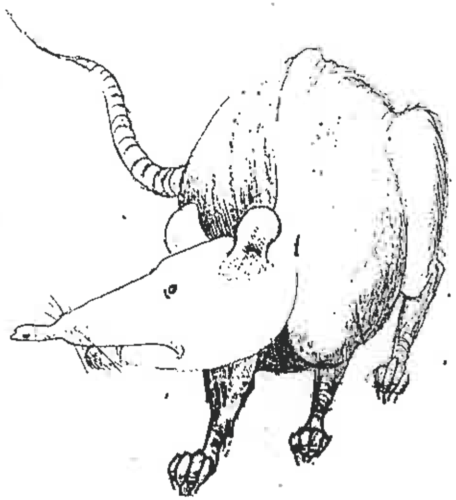
~~BLOND & BRIGGS~~

Edinburgh 1993

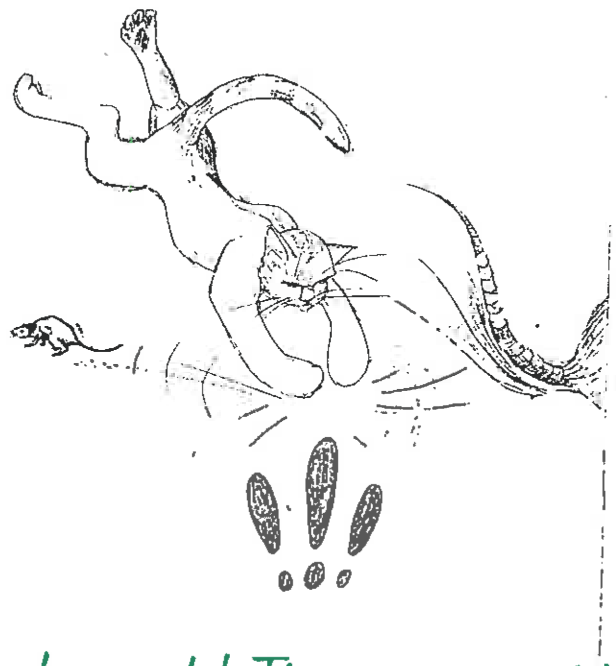
~~[London 1973]~~

Once upon a time
our cat committ'd a crime: (?)
In the basement of our house
it caught a tiny lovely mouse.

Then suddenly it saw a rat,
a lot of food for hungry cat!



Then came the time for mouse release
when cat's desire was the rat to seize.
Oh, where is the wanted food?
It's time to be in poorer mood!



MORAL: My dear cat! The coming night
stick to the mouse and hold it tight

HIGH OR LOW AVERAGE CAPTURE "EFFICIENCY" ?

Envisaged example:

Wave energy resource $J_{average} = 25$ kW/m

⇒ 1000 MW = 1 GW incident on a 40km coast line

"Efficiency"	Plant capacity	kWh cost
100 %	1000 MW	∞
50 %	500 MW	0.25 ACU
10 %	100 MW	0.15 ACU
2 %	20 MW	0.08 ACU

In this example you would go for a low "efficiency" if the market price were 0.10 ACU.

What would you do if the market price was 0.20 ACU and if more than 40 km coast line was available ?

"ACU" = arbitrary currency unit

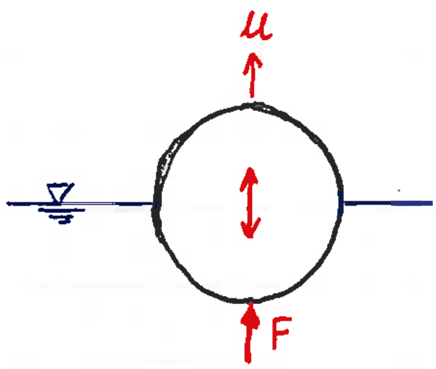
$$\frac{P}{C} = \frac{\text{Power}}{\text{Cost}} = ?$$

$$C = a_1 + a_2 S_{urface} + a_3 V_{olume} + a_4 P_{max} + \cdots$$

Difficult !

Simpler: $\frac{P}{V} = ?$ $\left(\text{or } \frac{P}{S} \right)$

Floating body in heave
due to incident
sinusoidal wave of
amplitude A and
angular frequency ω



Net force = excitation force − radiation force − friction force

$$\hat{F} = \hat{F}_e - Z_r \hat{u} - R_f \hat{u}$$

Radiation impedance $Z_r = R_r + i\omega m_r$

$R_r = R_r(\omega)$ = radiation resistance (= added damping)

$m_r = m_r(\omega)$ = added mass

Net converted power (time average):

$$P = P_e - P_r - P_f$$

"Excitation" power: $P_e = \frac{1}{2}|\hat{F}_e| \cdot |\hat{u}| \cos(\gamma)$

[γ = phase angle between $\hat{u}$ and $\hat{F}_e$]

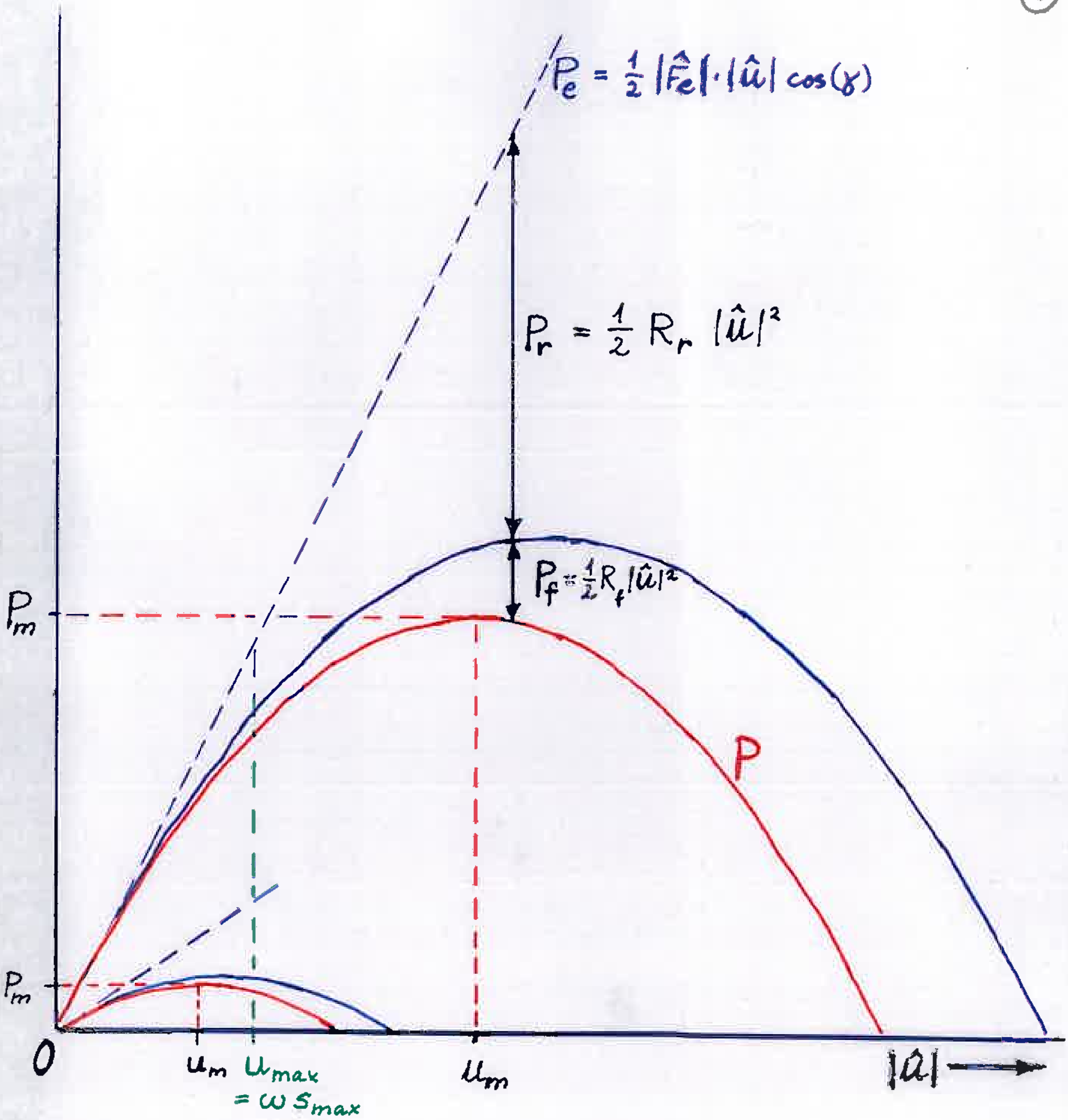
$\hat{F}_e \propto A$

Radiated power: $P_r = \frac{1}{2} R_r |\hat{u}|^2$

Lost power: $P_f = \frac{1}{2} R_f |\hat{u}|^2$

$P_e \propto |\hat{u}|$ $\quad$ $P_e \propto |A|$

P_r and $P_f \propto |\hat{u}|^2$ (independent of A)



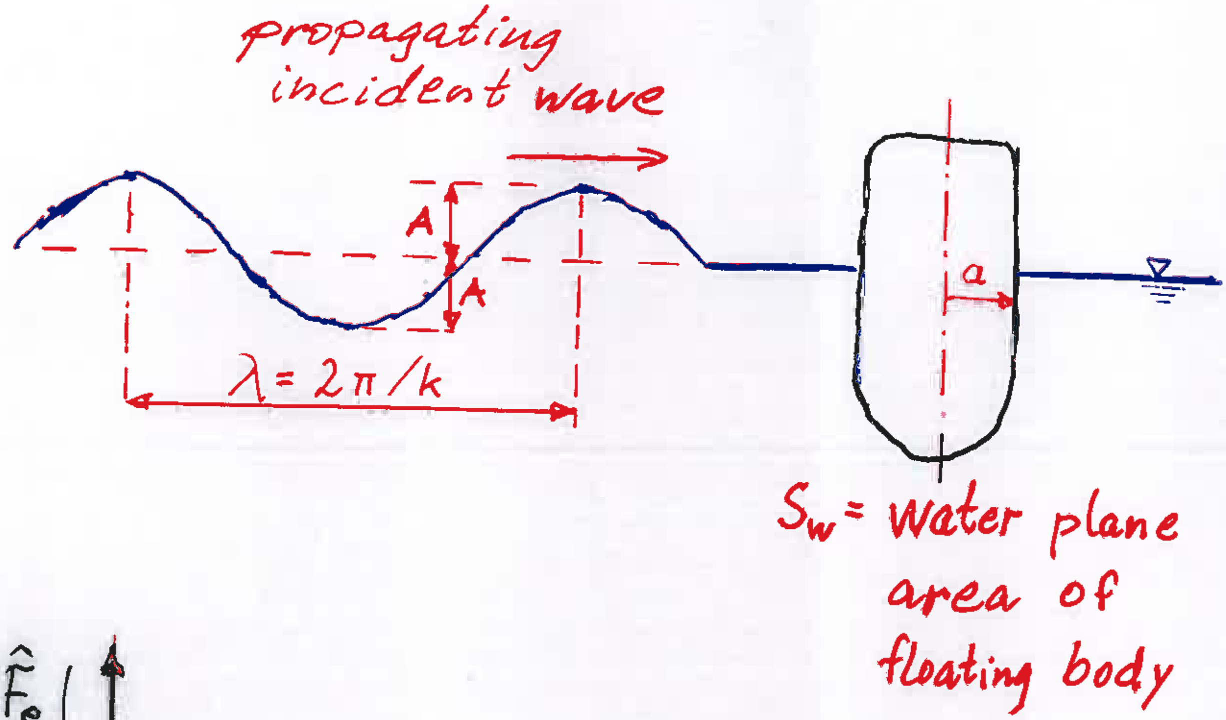
$$P_m = \frac{F_\gamma^2}{8(R_r + R_f)} \qquad u_m = \frac{F_\gamma}{2(R_r + R_f)} \qquad F_\gamma = |\hat{F}_e| \cos(\gamma)$$

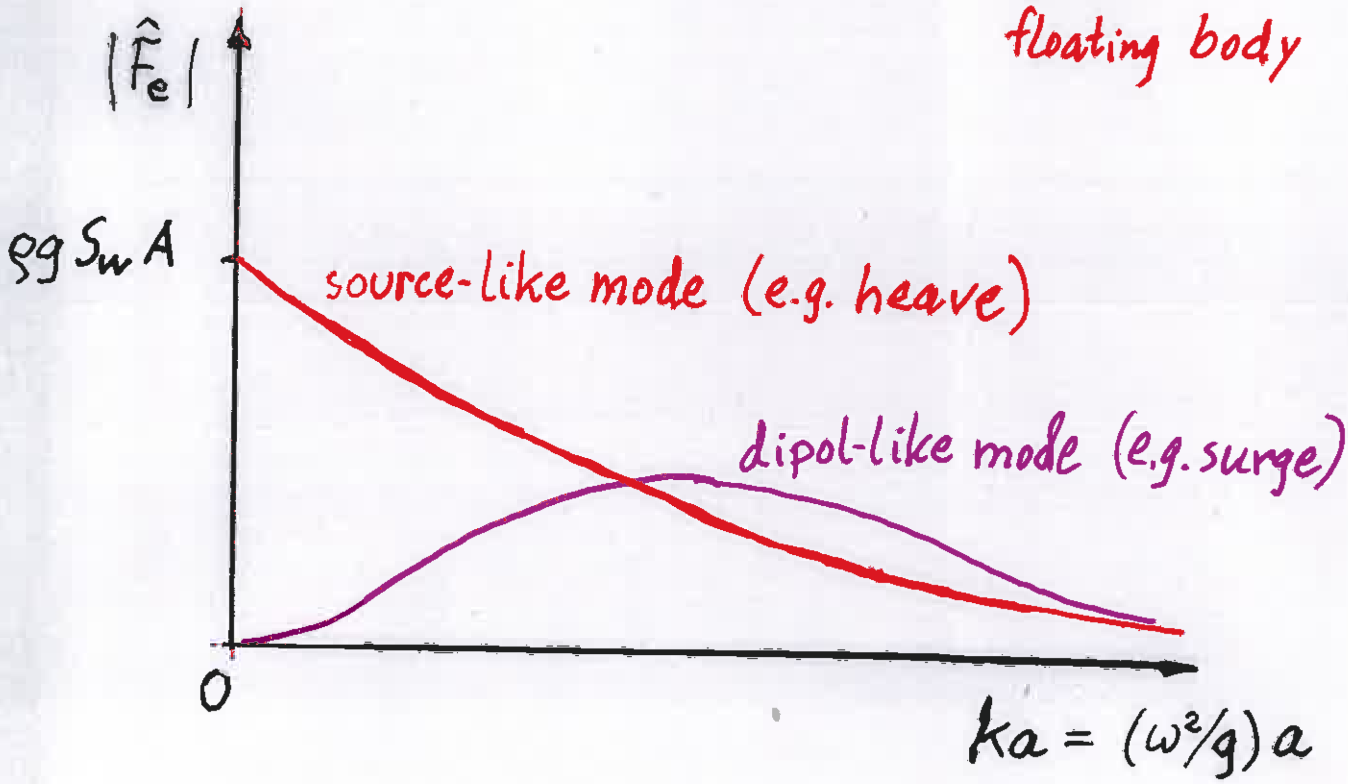
If $\gamma = 0$ and $R_f = 0$ $\qquad P_m = J\, d_{c,max}$

Maximum capture width $d_{c,max} = \lambda / 2\pi$ for a point absorber,

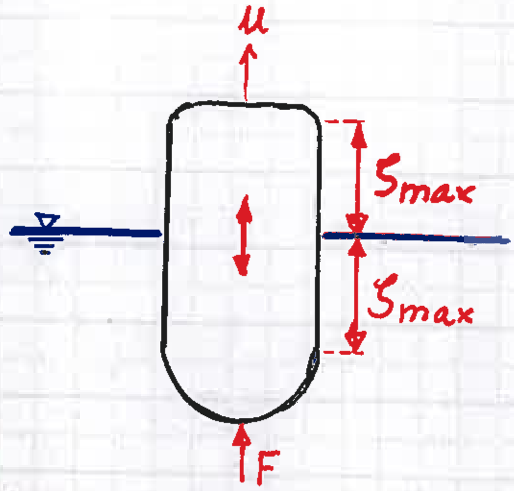
50% for an array or symmetric terminator

Approaching 100% for a suffiently non-symmetric term.


propagating
incident wave
A
A
λ = 2π/k
a
S_w = water plane
area of
floating body


$|\hat{F}_e|$
$\rho g S_w A$
source-like mode (e.g. heave)
dipol-like mode (e.g. surge)
0
$ka = (\omega^2/g)\,a$

UPPER BOUND TO POWER-TO-VOLUME RATIO:



Water plane area: S_w

Volum of body: V

$$V > 2\,\zeta_{max}\,S_w$$

$$P = \tfrac{1}{2}|\hat{F}_e|\cdot|\hat{u}|\cos(\gamma) - \tfrac{1}{2}(R_r + R_f)|\hat{u}|^2$$

$$< \tfrac{1}{2}|\hat{F}_e|\cdot|\hat{u}|\cos\gamma < \tfrac{1}{2}|\hat{F}_e|\cdot|\hat{u}|$$

$$|\hat{u}| < \omega\,\zeta_{max}$$

$$|\hat{F}_e| < \rho g S_w |A|$$

$$P < \tfrac{1}{2}|\hat{F}_e|\cdot|\hat{u}| < \tfrac{1}{2}\rho g S_w \zeta_{max}\,\omega|A| < \frac{\rho g}{4} V \omega |A|$$

$$\frac{P}{V} < \frac{\rho g \omega}{4}|A| = \frac{\pi \rho g |A|}{2T} = \frac{\pi \rho g H}{4T}$$

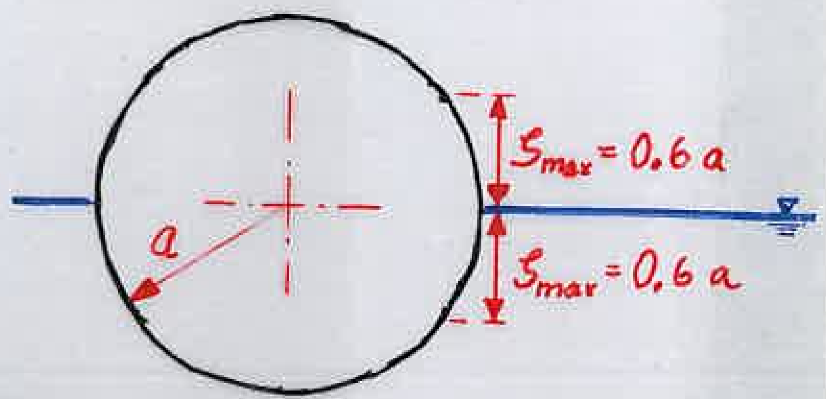
$\rho = 10^3\ kg/m^3$ $\quad g = 9.8\ m/s^2$

Example: Wave height $H = 2|A| = 2m$

Wave period $T = 10\,s$

$$\frac{P}{V} < 1{,}6\ kW/m^3$$

HEAVE-LIMITED SPHERE IN IRREGULAR WAVE



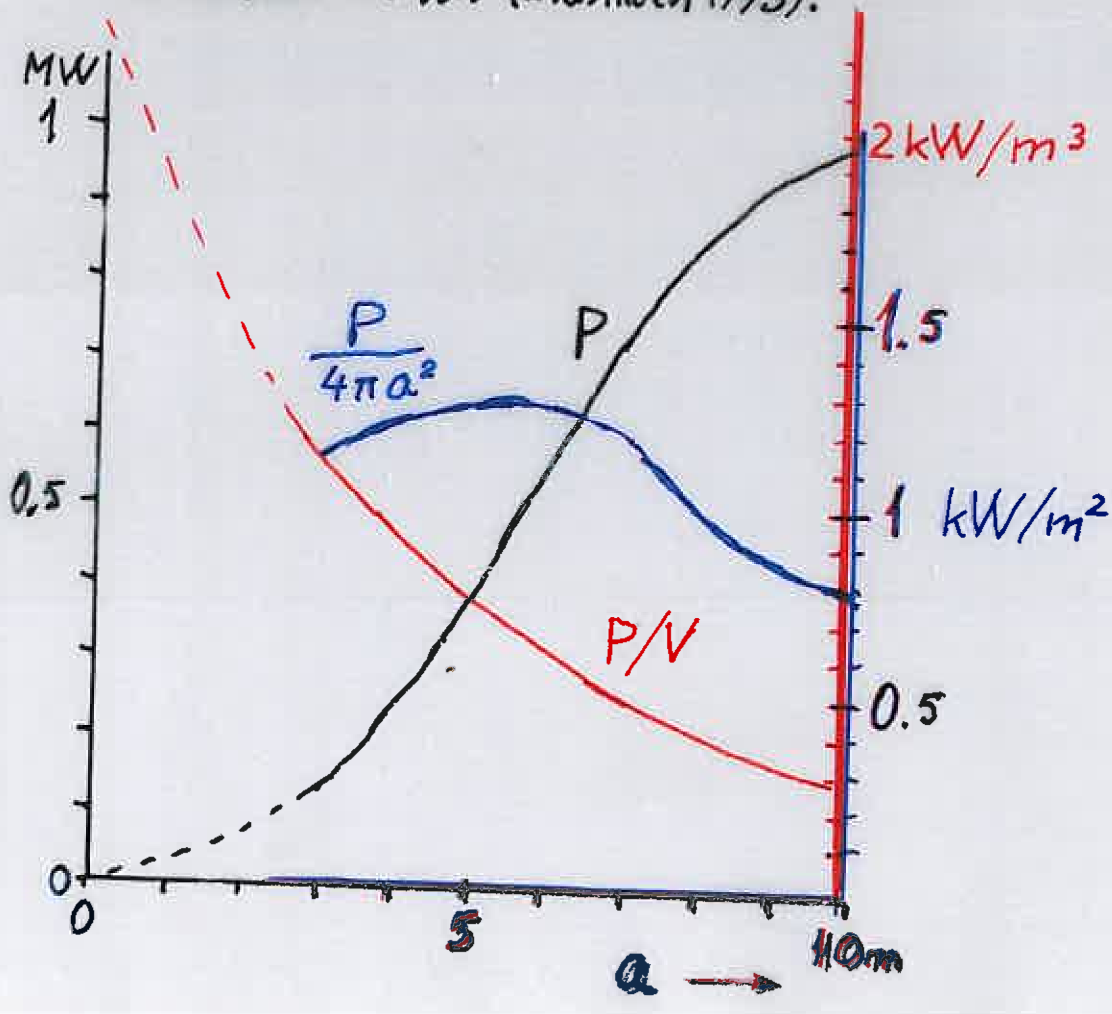
Optimum phase

Optimum heave amplitude if $< \zeta_{max}$

Radiation resistance R_r (Hulme 1982, Falnes 1984)
Loss ("friction") resistance $R_f = 10^4$ Ns/m (assumed)

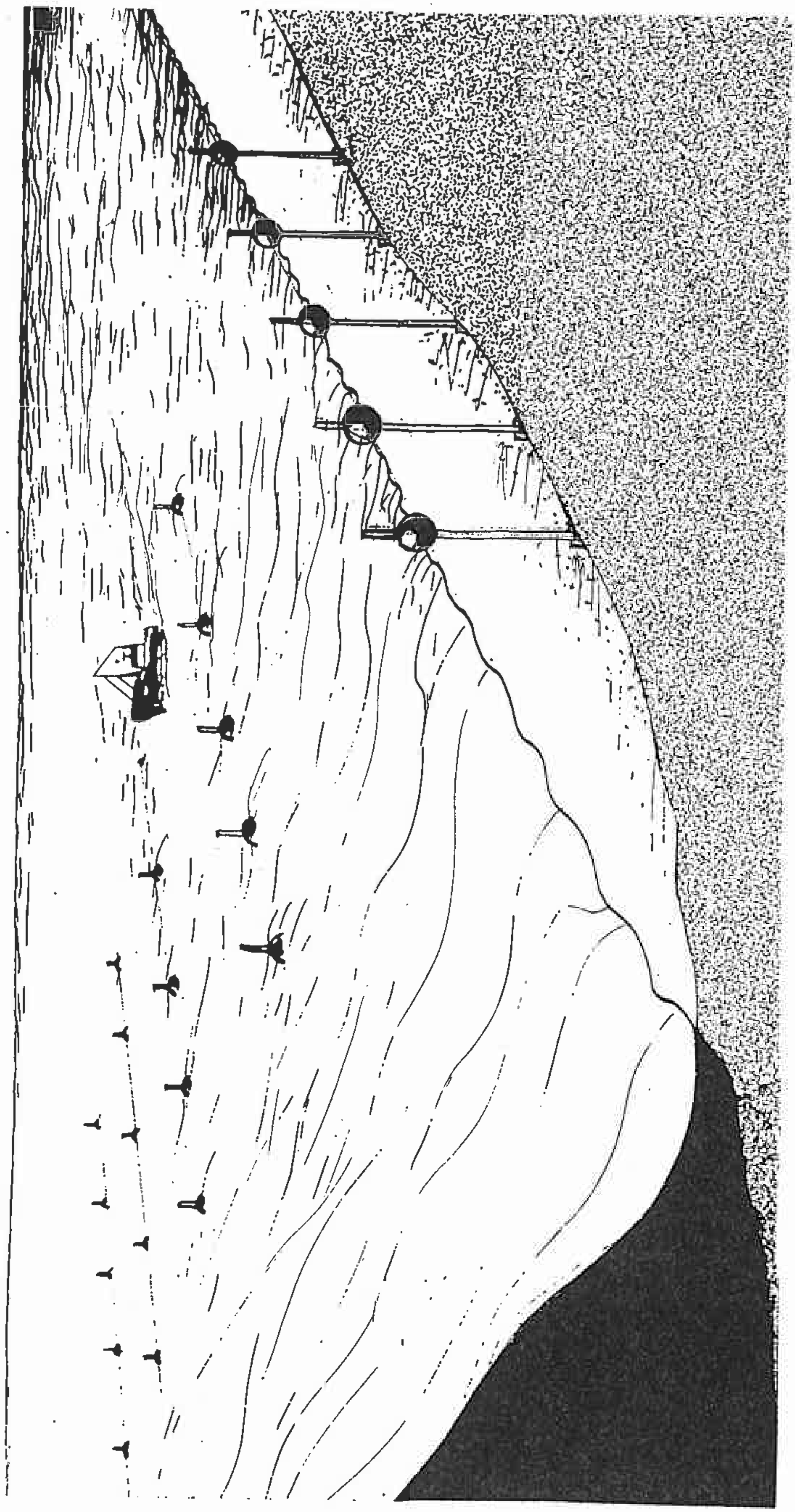
Given a typical winter wave in the Norwegian Sea
$H_{m0} = 3.2$ m $T_{m02} = 7.0$ s $T_{m-10} = 8.5$ s from a 2048 s time series (Barstow, 1993)

Numerical results (Eidsmoen 1993):



How ~~big~~ small should one sphere be?

a = ?



100 MW wave-power plant
(50-100 km long array offshore)

200 units each 0.5 MW or 1000 units each 0.1 MW

(Mass production of units)

R&D required

Demonstration of full-scale WE converters

for which markets exist!

Stages

1. Develop 10 kW unit.

   After successful testing:

2. Develop 20 kW unit.

   After successful testing:

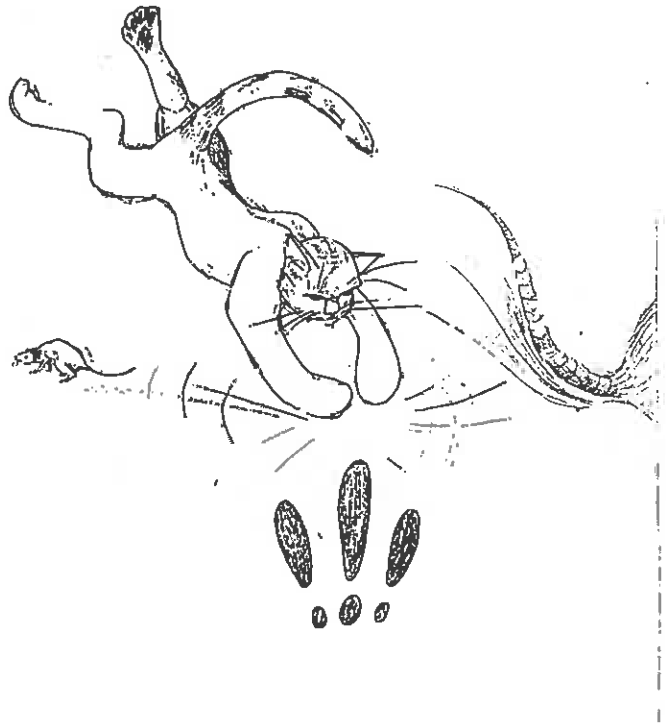
3. Develop 40 kW unit.

   After successful testing:

4. Develop 80 kW unit.

   After successful testing:

5. Perhaps develop 160 kW unit.



Before hunting the rat we must learn to catch the mouse