Renewable Energy: Ocean Wave-Energy Conversion

India Institute of Science
Bangalore, India
17 June 2011

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University of Wisconsin – Platteville
USA

My background

- B.S.: Mechanical Engineering
  University of Notre Dame
- M.S.: Naval Architecture
  University of Michigan
- Ph.D.: Civil Engineering
  Johns Hopkins University
  - Shared an office with 3 Indians
  - Dissertation work: modeling the performance of an ocean wave-energy device
- Associate Professor of Mechanical Engineering, University of Wisconsin – Platteville, USA

Wisconsin:

Cold winters

University of Wisconsin

- Main campus: U W Madison
  - Research university
  - State capitol

- My campus: U W Platteville
  - Undergraduate focus
  - Rural setting
  - Started as a Mining school
  - About 7000 students
  - Majority engineers

Lecture Overview

- Marine energy sources
- Basic feasibility
- Ocean wave-energy devices
- Ocean wave-energy device categorization: buoyancy, potential energy, particle momentum, and pressure devices.
- Design considerations: point-absorber buoyant devices
  - Resonance
  - impedance matching
- Design considerations: attenuating buoyant devices;
  - wavelength compatibility.

Marine Energy Sources

- Ocean waves
- Offshore wind
- Currents
- Tides
- Thermal gradients
- Salinity gradients
- Biomass

Ocean Wave Energy: Source?

- Waves come from
  - Wind, which comes from
    - Pressure differences, which come from
      - Temperature differences, which come from
        - The Sun!
- 70% of Earth's surface collects energy from the Sun and that energy works its way to the shoreline in the form of waves

18 January 2011 Last updated at 15:05 GMT

India plans Asian tidal power first

By Richard Black
Environment correspondent, BBC News

The Indian state of Gujarat is planning to host Asia's first commercial-scale tidal power station.

The company Atlantis Resources is to install a 50MW tidal farm in the Gulf of Kutch on India's west coast, with construction starting early in 2012.

The facility could be expanded to deliver more than 200MW.

The biggest operating tidal station in the world, La Rance in France, generates 240MW, while South Korea is planning several large facilities.

To claim the title of "Asia's first", the Indian project will have to outrun developments at Sihwa Lake, a South Korean tidal barrage under construction on the country's west coast.

Atlantis's recent feasibility study in Gujarat concluded that the state had good potential for tidal exploitation.

The Atlantis AK1000 turbine will be deployed in the Gulf of Kutch

http://www.bbc.co.uk/news/science-environment-12215065

- Atlantis Resources Corp
- 1 MW tidal turbines
- Farm of 50 MW
- Gujarat, India:
  up to 9 m tidal range

Wave Energy is a hot topic!

Australia invests 61 million dollars in wave energy

Written by Florina Pascula

The Australian Government has allocated 61 million dollars for a project to generate electricity from wave energy, according to Reuters. The proposed project ... ogies, which has offic...

UK invests £2.5m in wave and tidal research

07 February 2011

Three wave and tidal research projects have received £2.5 million funding from the UK Government.

By Isabella Kaminski

Ocean Power ... nnection of a Wave Energy Device in the ...

PENNINGTON, ...

Wave Energy is risky!

ABC News

News Home Just In Local

Hot topics: australia, sport, gove

Print Email Share

Huge swell sir

Posted Mon May 17, 2010 9:0

A wave energy generator w the New South Wales south sunk in rough seas.

guardian.co.uk

News | Sport | Comment | Culture | Business | Money | Life & sty

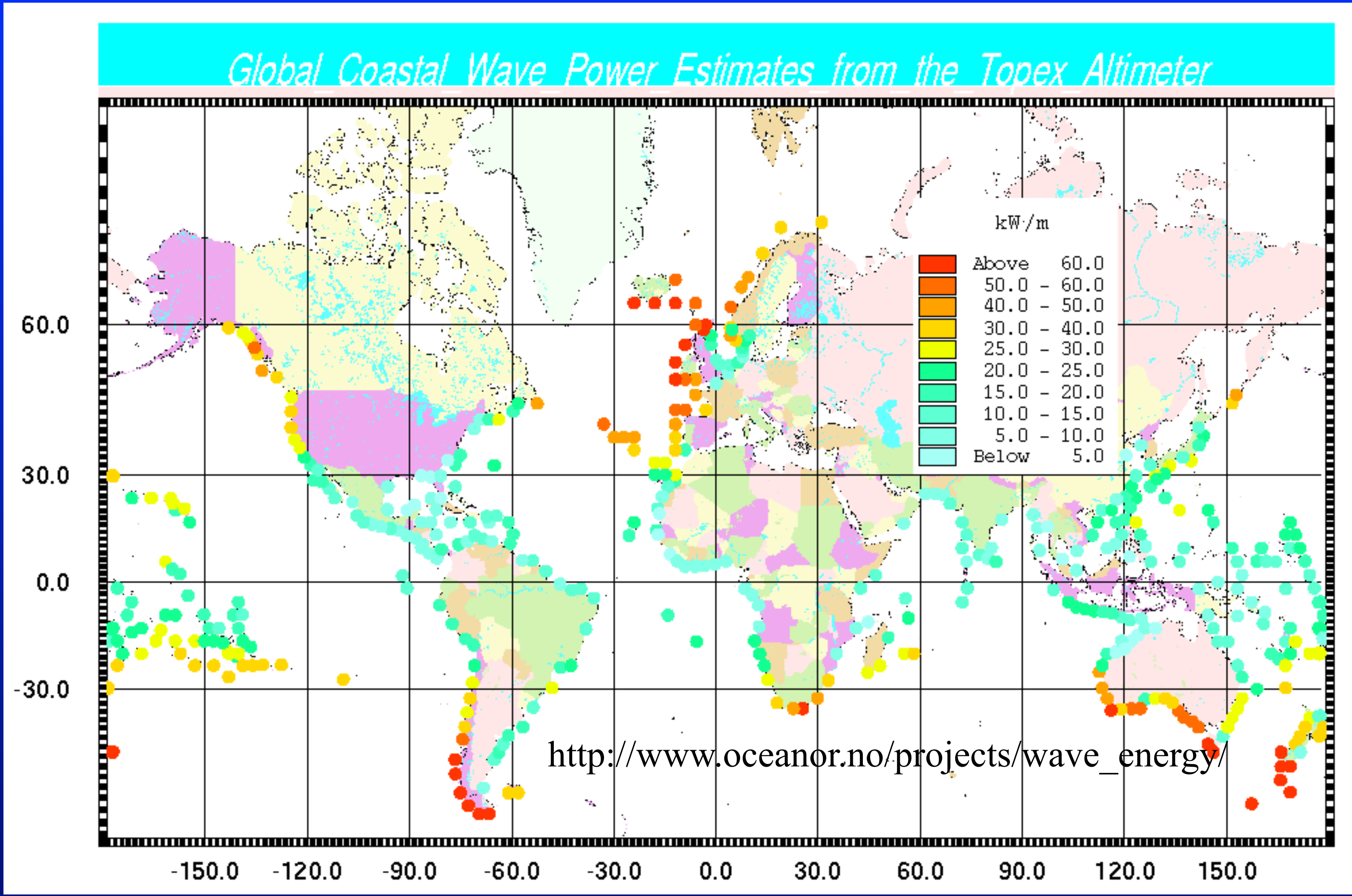
Environment > Wave, tidal and hydropower

Recession leaves Pelamis wave project struggling to stay afloat

Collapse of Australian-based infrastructure giant Babcock & Brown means 77% share in the Aguçadoura wave plant is now up for sale

Duncan Clark
guardian.co.uk, Thursday 19 March 2009 16.05 GMT

Global Wave Energy



http://www.oceanor.no/projects/wave_energy/

US Wave Energy:
Is this discussion even worth having?

USA (lower 48 states)

West coast:	1200 miles (1900 km)	(straight line)	30 kW / m
East coast:	1700 miles (2700 km)	(straight line)	20 kW / m

Calculations:
West coast:
1900 km * 1000 m/km * 30 kW / m = 57 GW
East coast:
2700 km * 1000 m/km * 20 kW / m = 54 GW
Total: 111 GW

Annual energy available:
111 GW * 24 h/day * 365 day/yr = 970,000,000 MWh/yr

Annual USA energy consumption:
3,900,000,000 MWh/yr

So, wave energy off the continental US could account for up to 25% of annual US electricity consumption.

Indian Wave Energy:
Is this discussion even worth having?

India: 2500 miles (4000 km) (straight line) 10 kW / m

Calculations:
4000 km * 1000 m/km * 10 kW / m = 40 GW

Annual energy available:
40 GW * 24 h/day * 365 day/yr = 350,000,000 MWh/yr

Annual Indian energy consumption:
680,000,000 MWh/yr (2006, http://en.wikipedia.org/wiki/Electricity_sector_in_India)

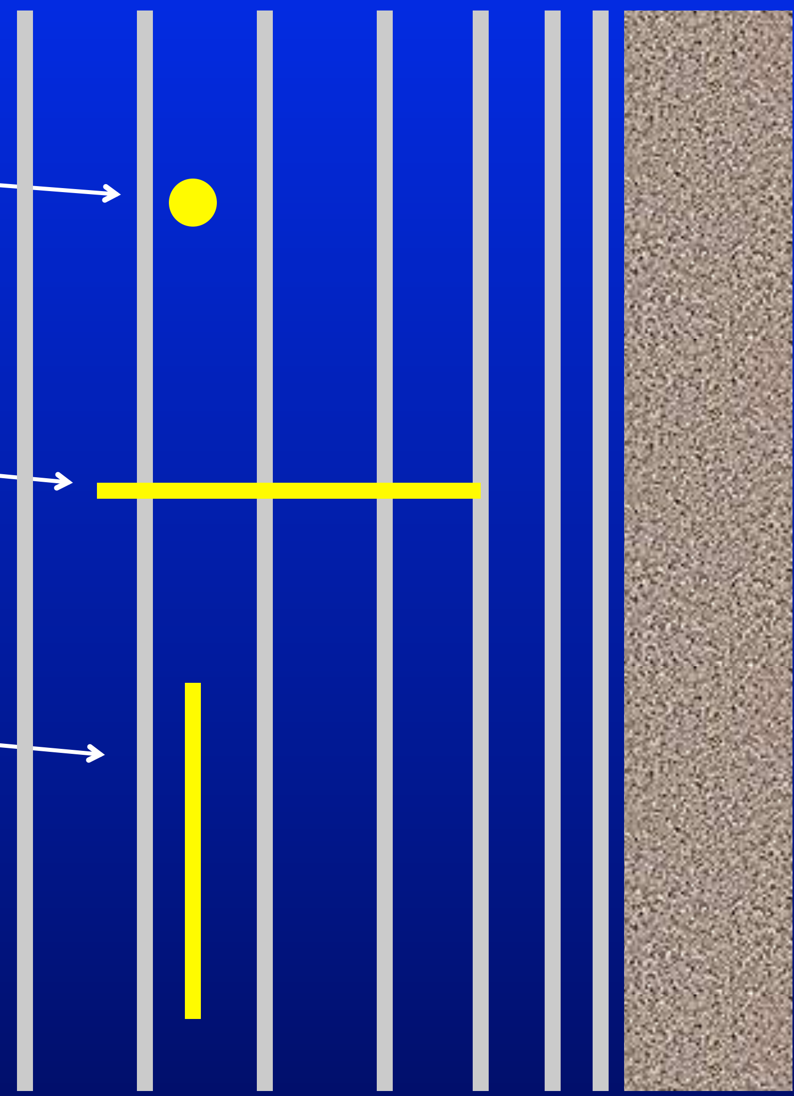
So, wave energy could account for up to 50% of Indian annual electricity consumption.

Wave-Energy Devices: Classification

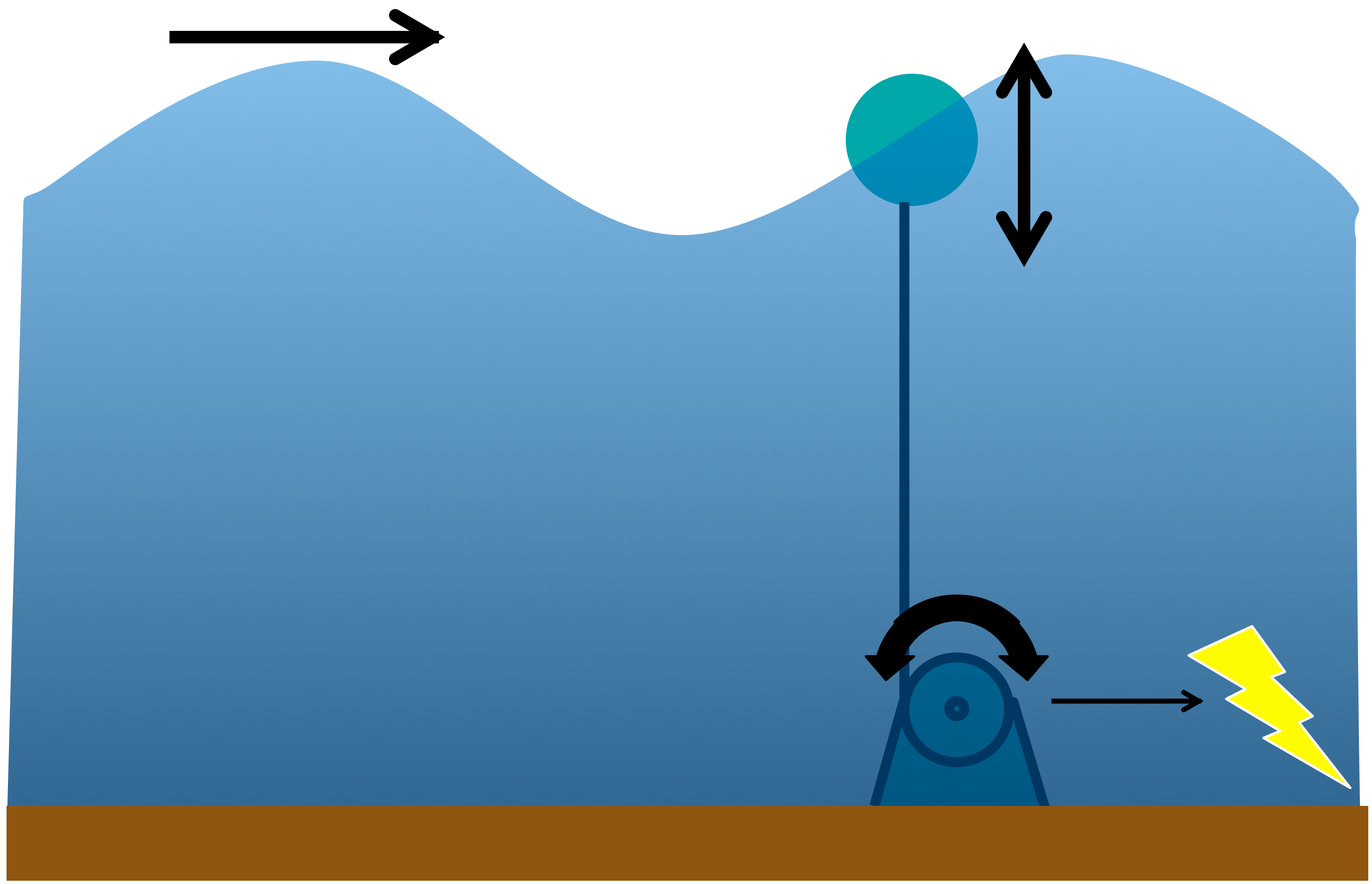
- Buoyancy Devices
  - Ground-referenced; ex: Salter's Duck
  - Self-referenced
    - Point-absorber; ex: PowerBuoy (OPT)
    - Attenuator; ex: Pelamis
- Potential Energy Devices; ex: WaveDragon
- Particle Momentum Devices; ex: Oyster
- Pressure Devices
  - Oscillating Water Column Devices; ex: OceanLinx
  - Compliant tube devices; ex: Anaconda

Wave-Energy Devices: Geometric Classification

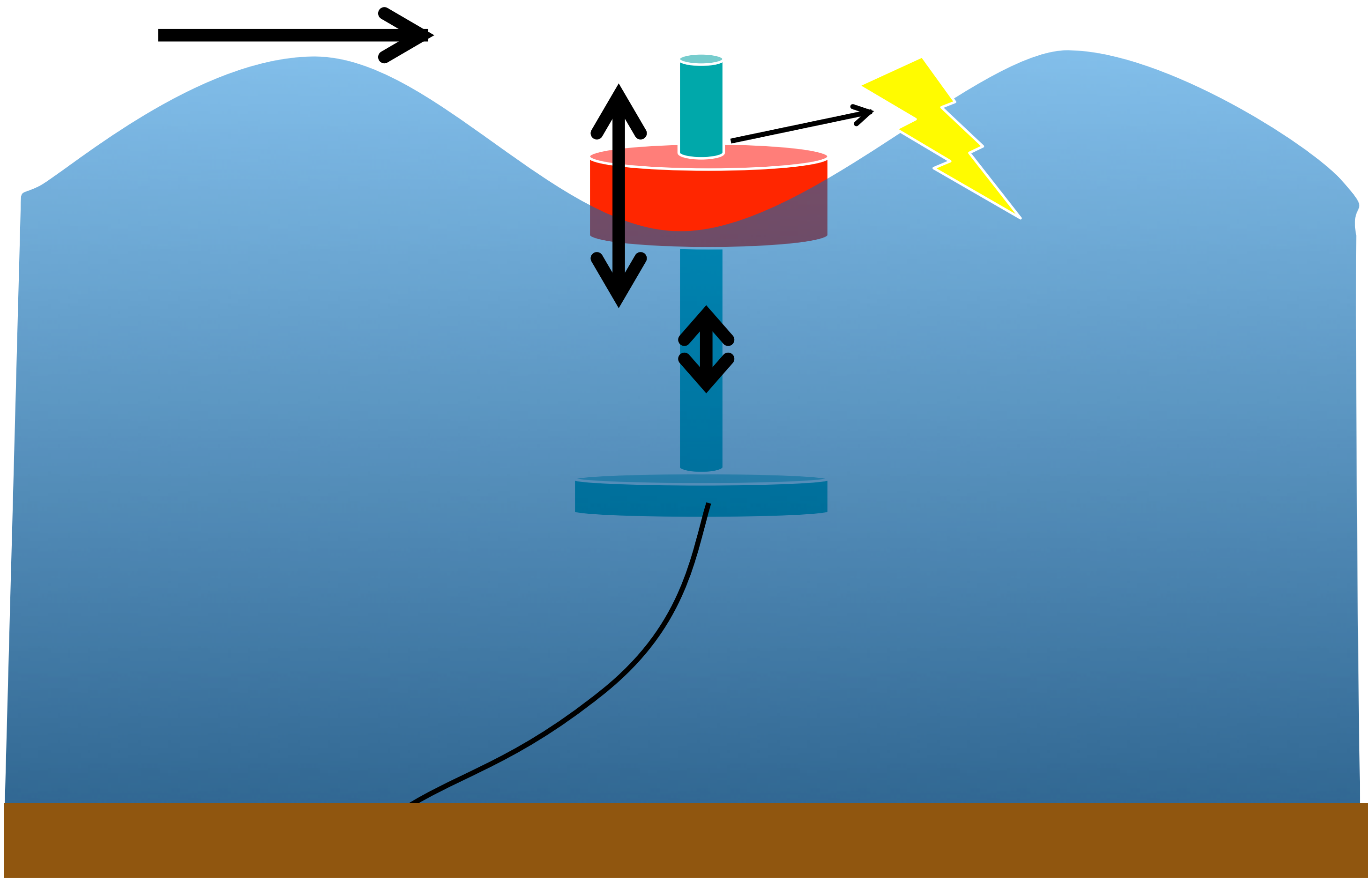
- Point-Absorber
  - Device is small relative to wavelength
- Attenuator
  - Device is long in direction of wave travel
- Terminator
  - Device is long in direction of wave crests



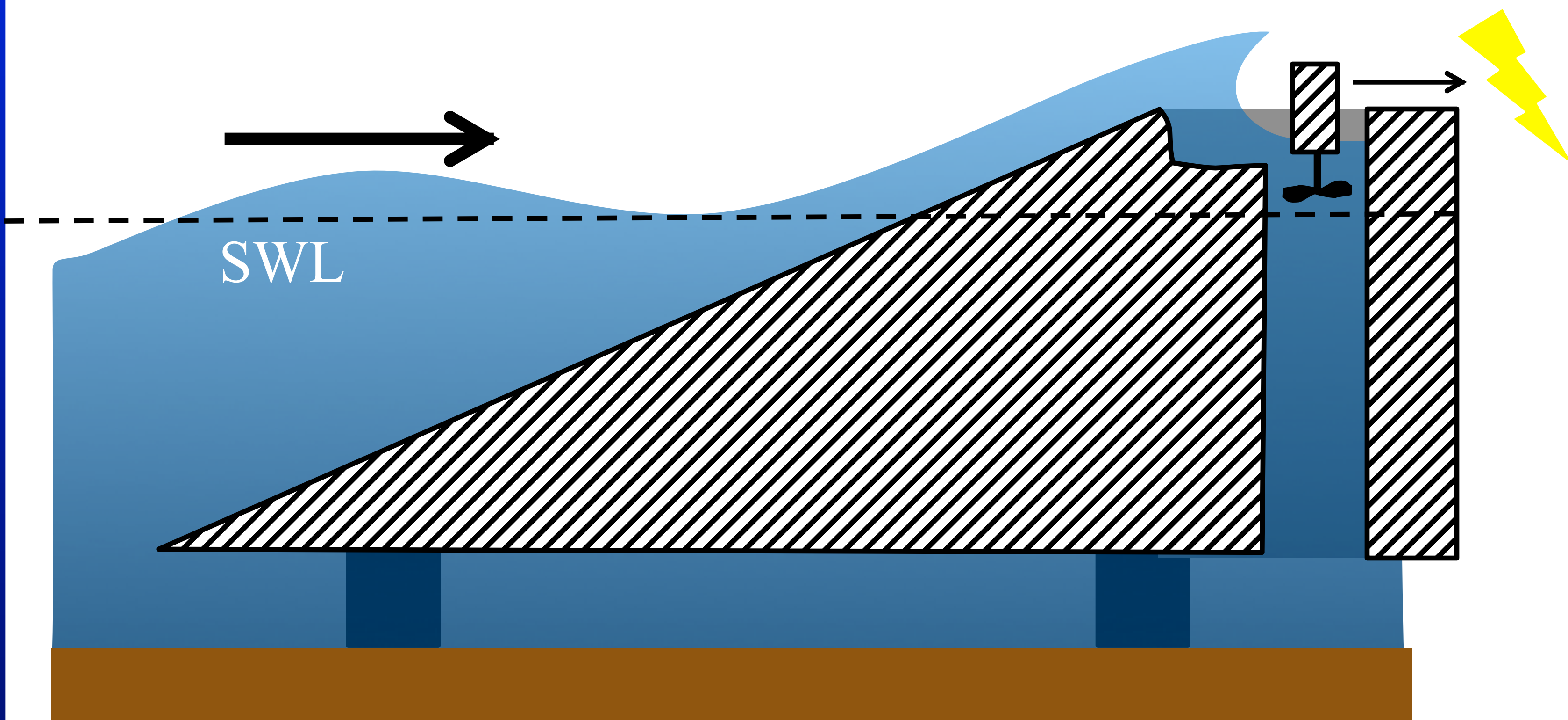
A simplistic
buoyancy ground-referenced device:



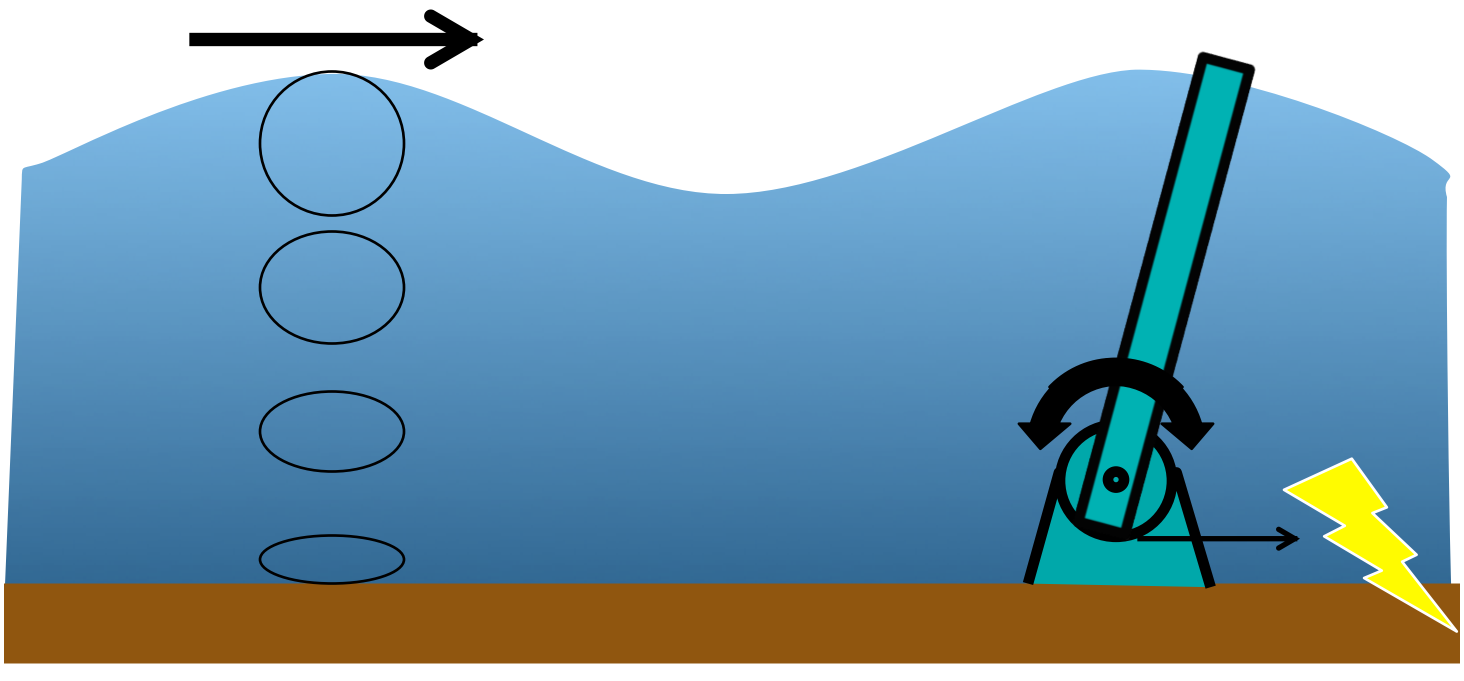
A simplistic
buoyancy self-referenced device:



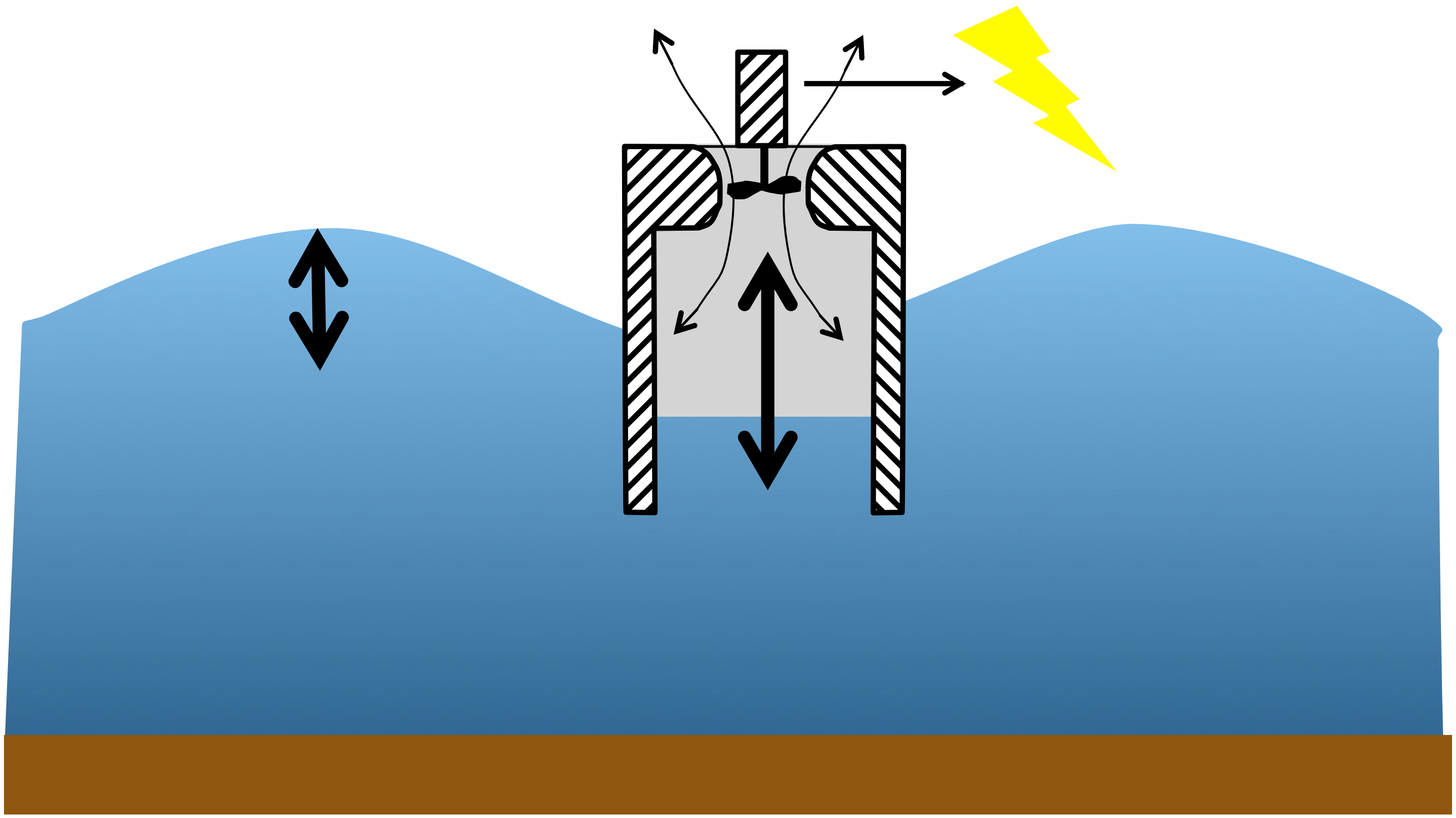
A simplistic
potential energy (overtopping) device:



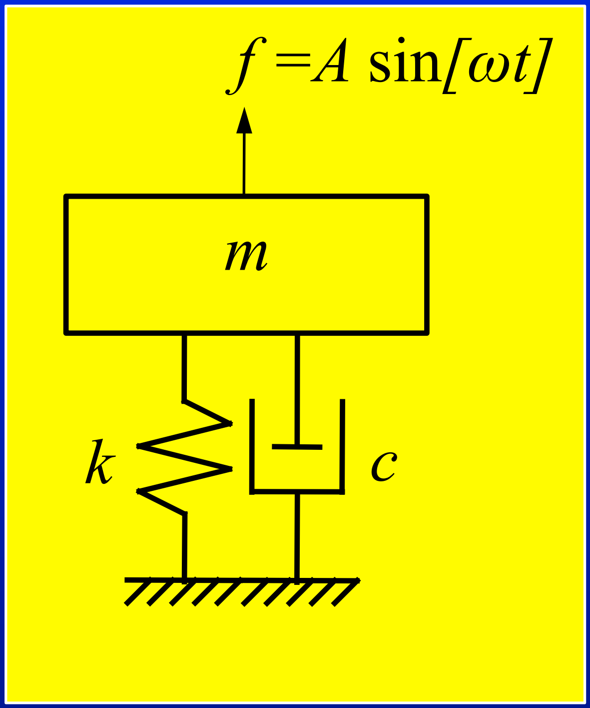
A simplistic particle momentum device:



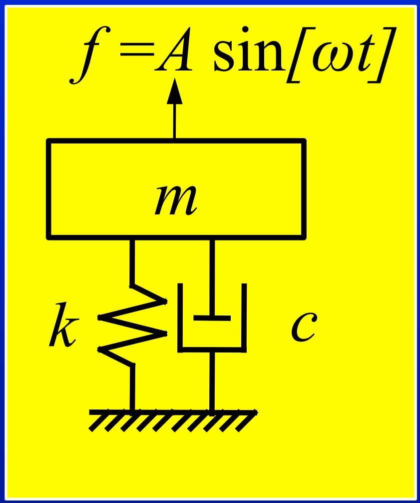
A simplistic pressure (oscillating water column) device:

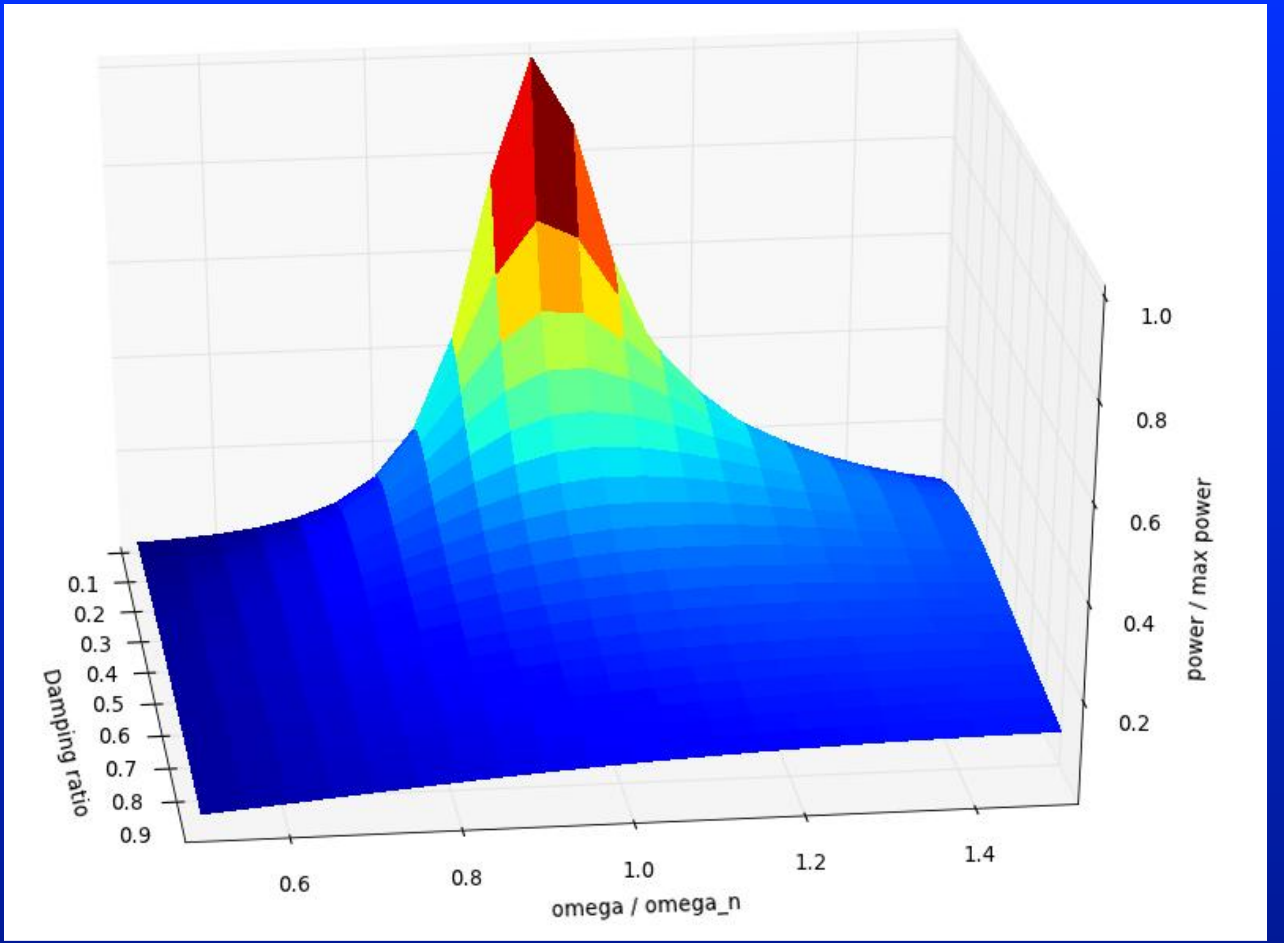


Simulation: spring/mass/damper system with sinusoidal forcing



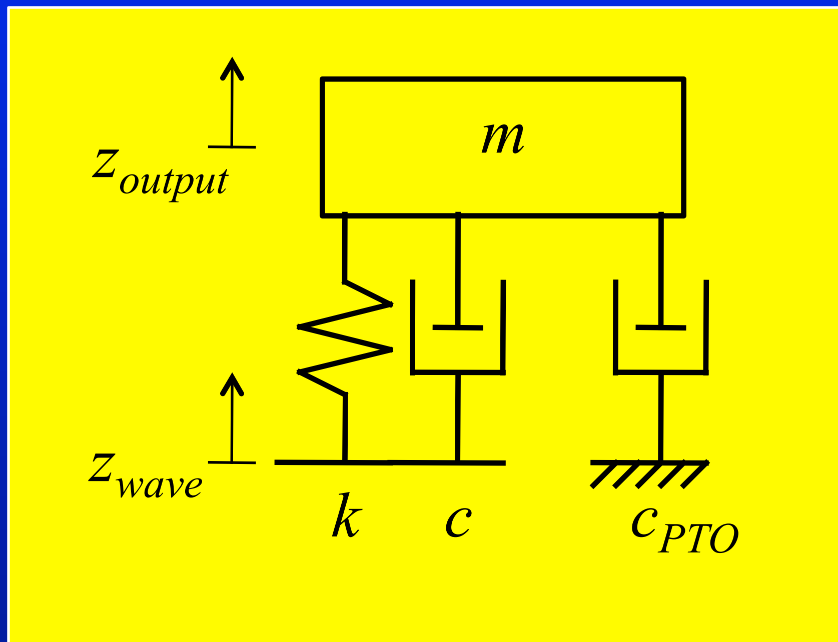
Frequency Resonance





- Wave frequency → body damped natural frequency: Frequency resonance (temporal)

Simulation: spring/mass/damper system with Power Take-Off modeled as a linear damper



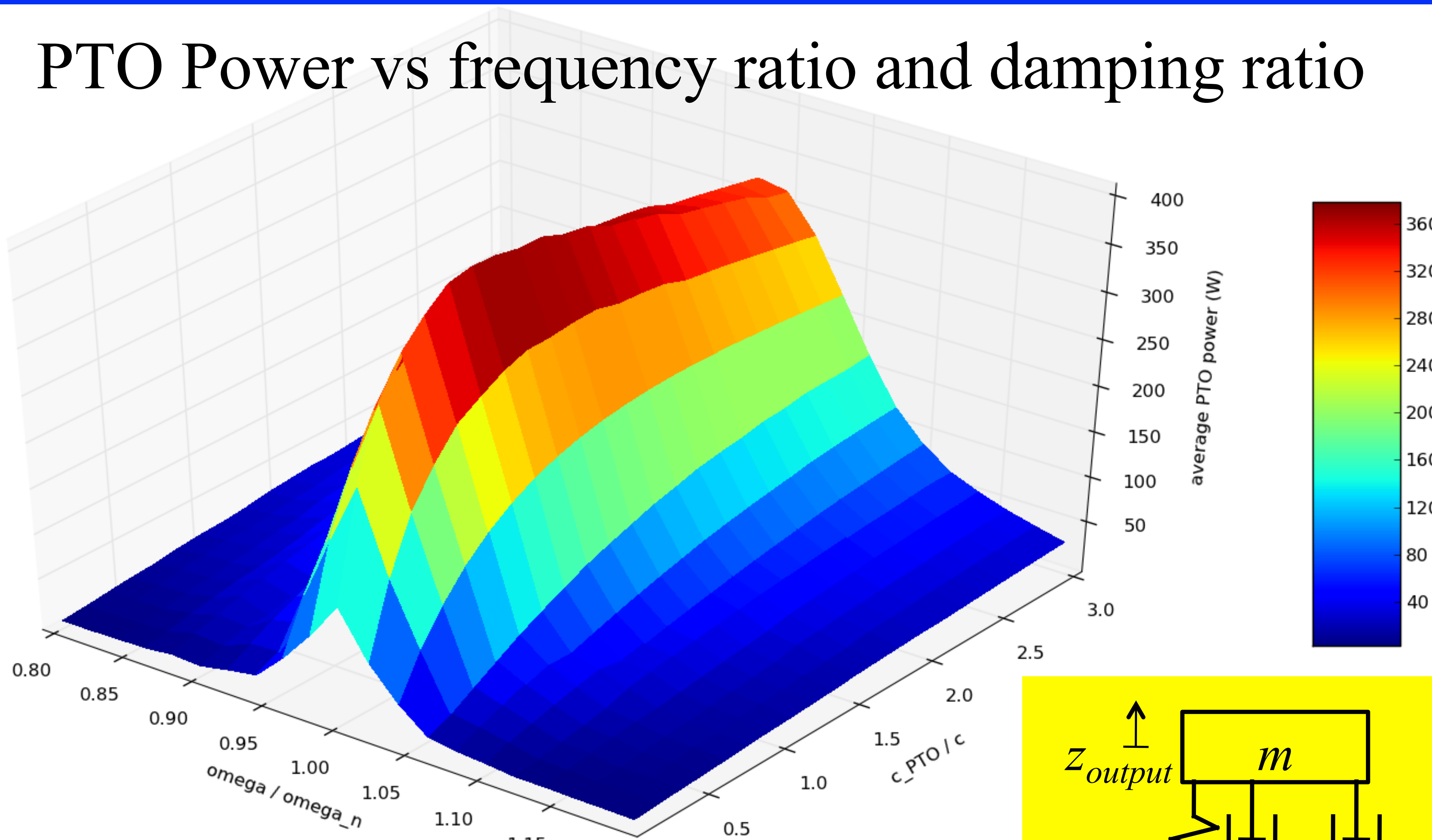
PTO damping

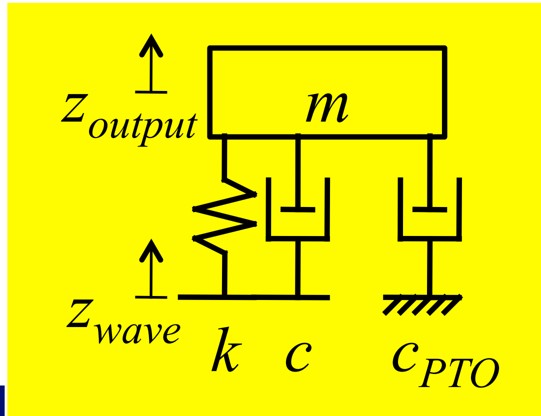
wave surface: sinusoindal displacement

buoyant stiffness

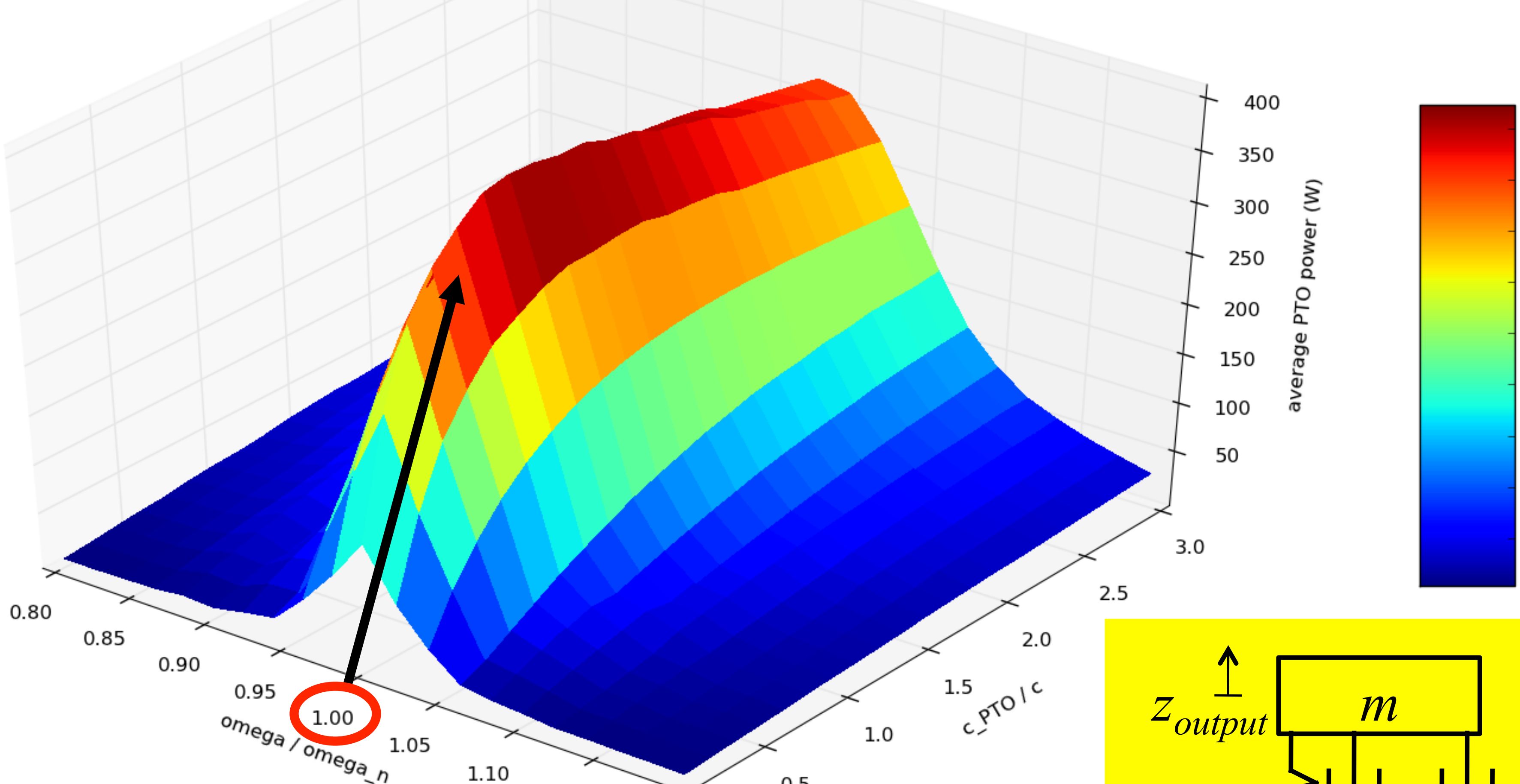
radiation damping

PTO Power vs frequency ratio and damping ratio

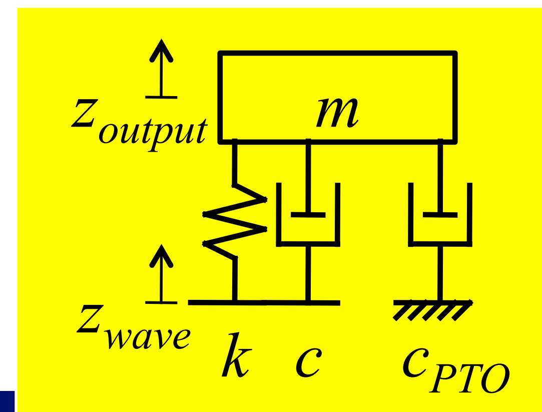




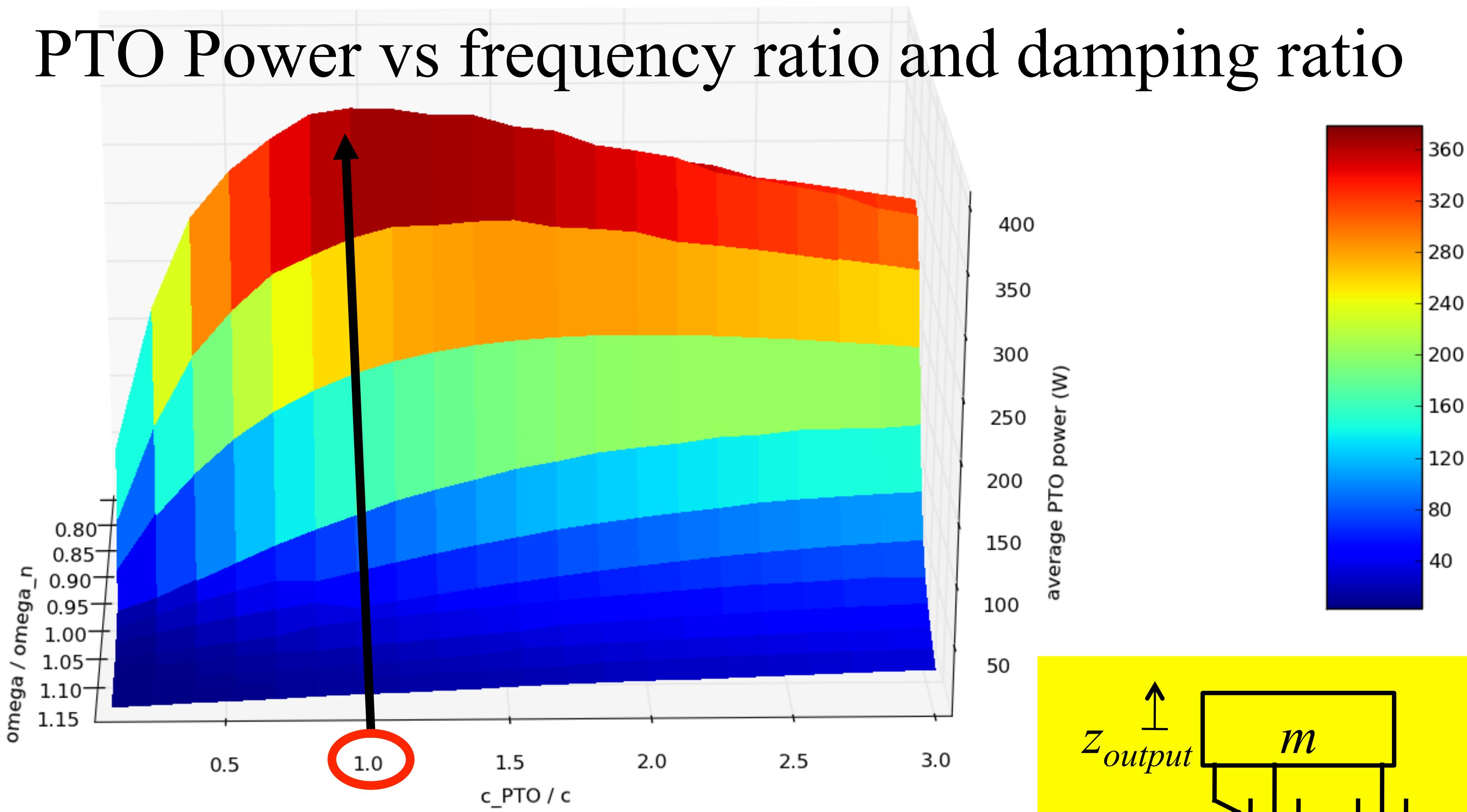
PTO Power vs frequency ratio and damping ratio



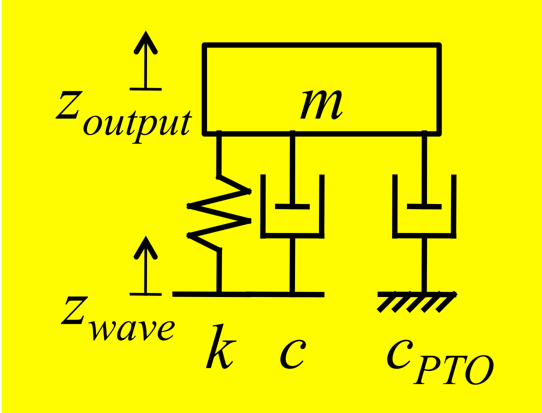
Resonance
where $\omega \approx \omega_n$



PTO Power vs frequency ratio and damping ratio



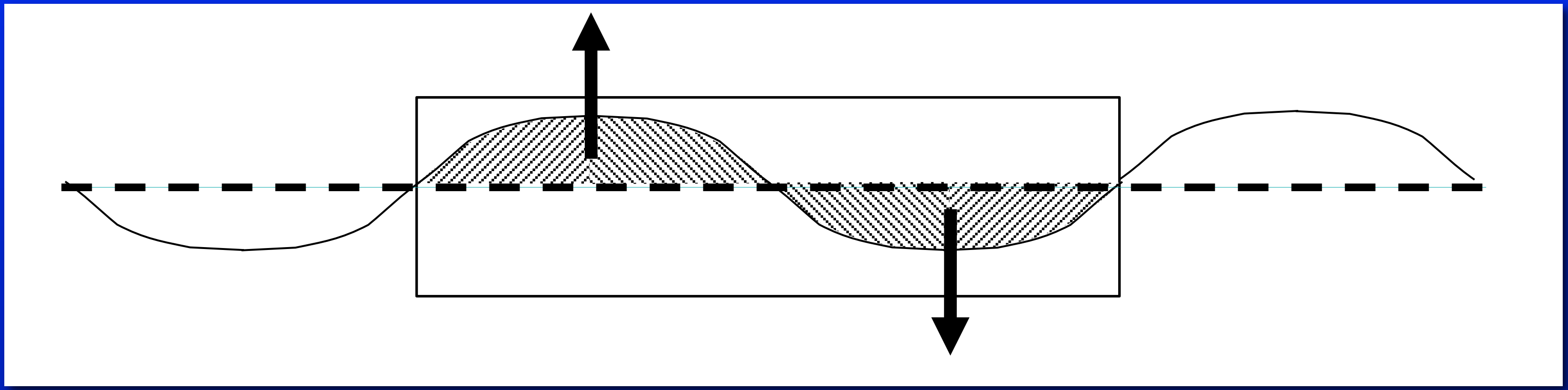
Impedance matching where $c_{PTO} \approx c$

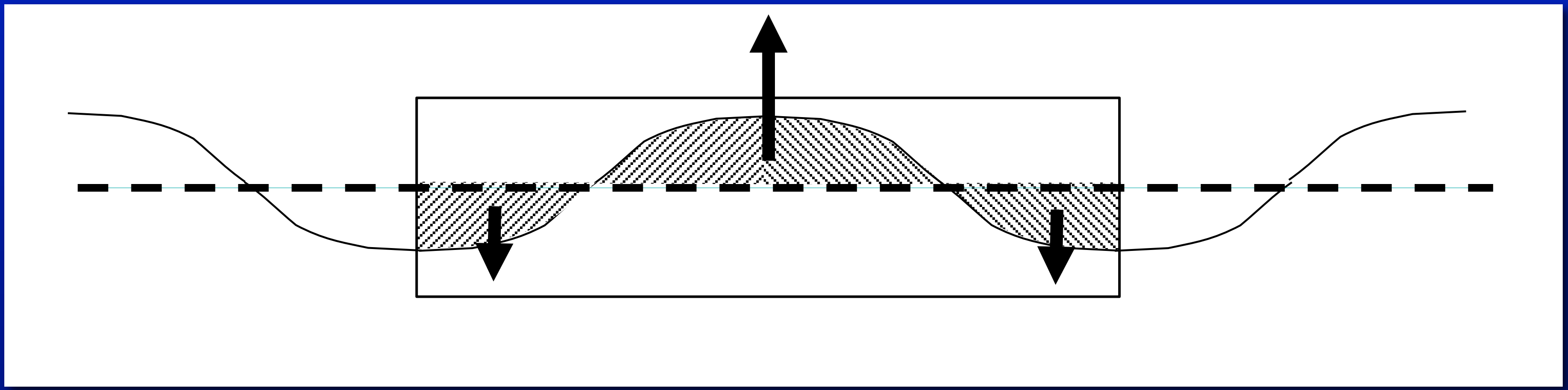


Alternate approach: Wavelength "Resonance"

- Wavelength → (multiple?) of body length: Wavelength "resonance" (spatial)
- Normally, wavelength and frequency (period) are linked directly (dispersion equation)
- Wavelength can change independent of the period (shallow water)
- Barge geometry can change the
  wavelength-to-barge length ratio
  independent of the
  frequency-to-natural frequency ratio.

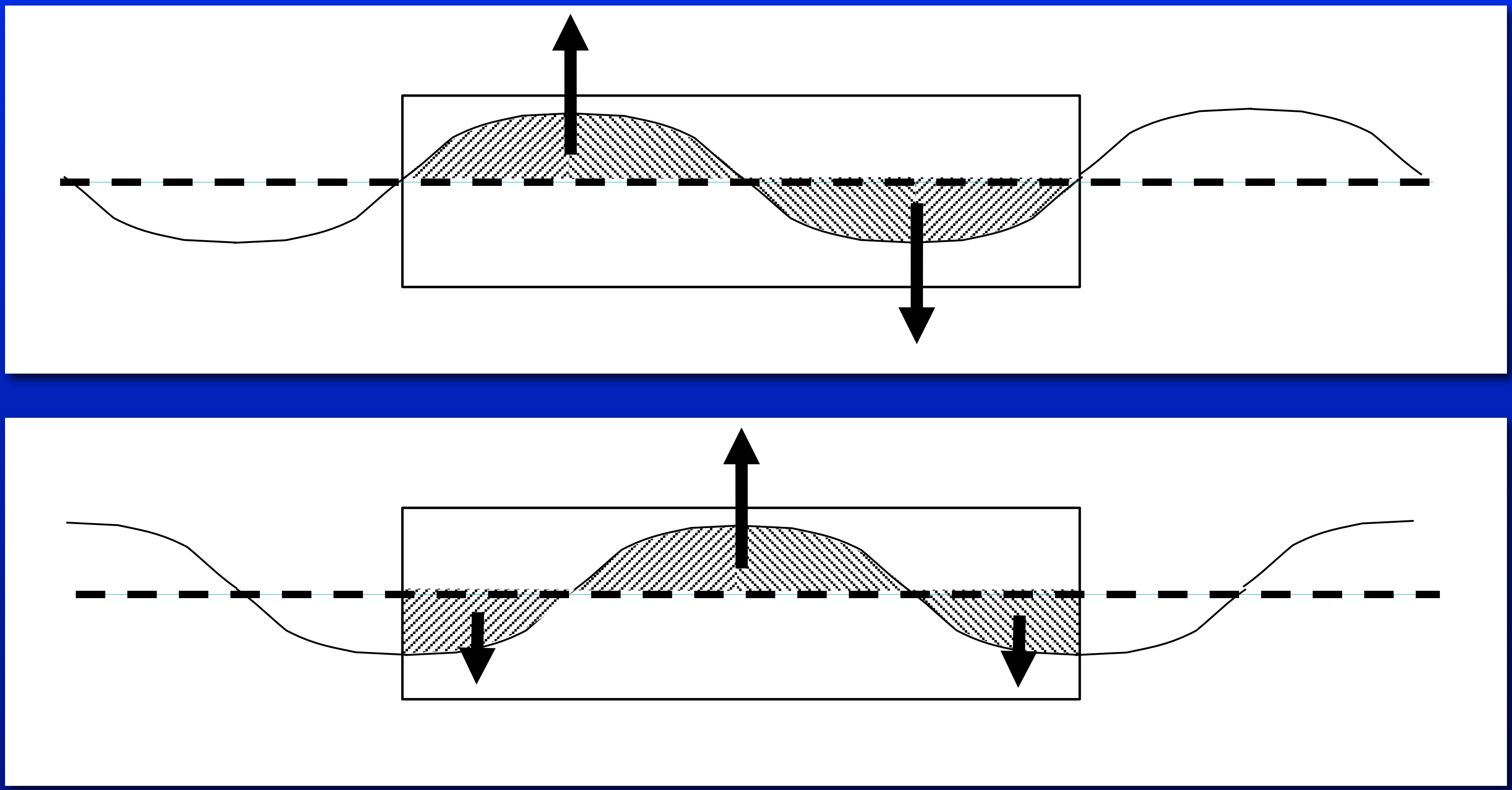
Wavelength = Barge Length





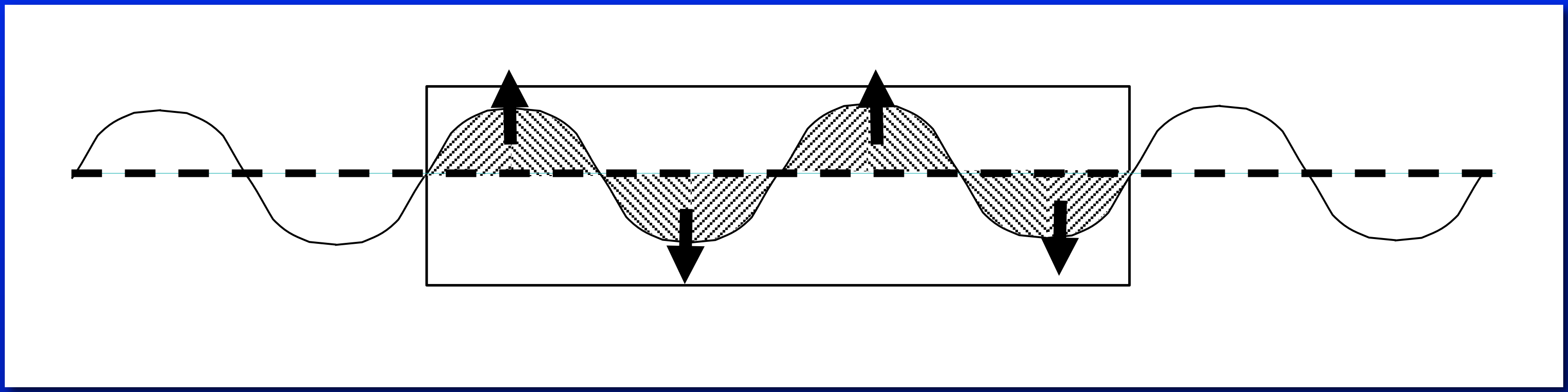
- Net <u>HEAVING FORCE</u> is small; forces cancel

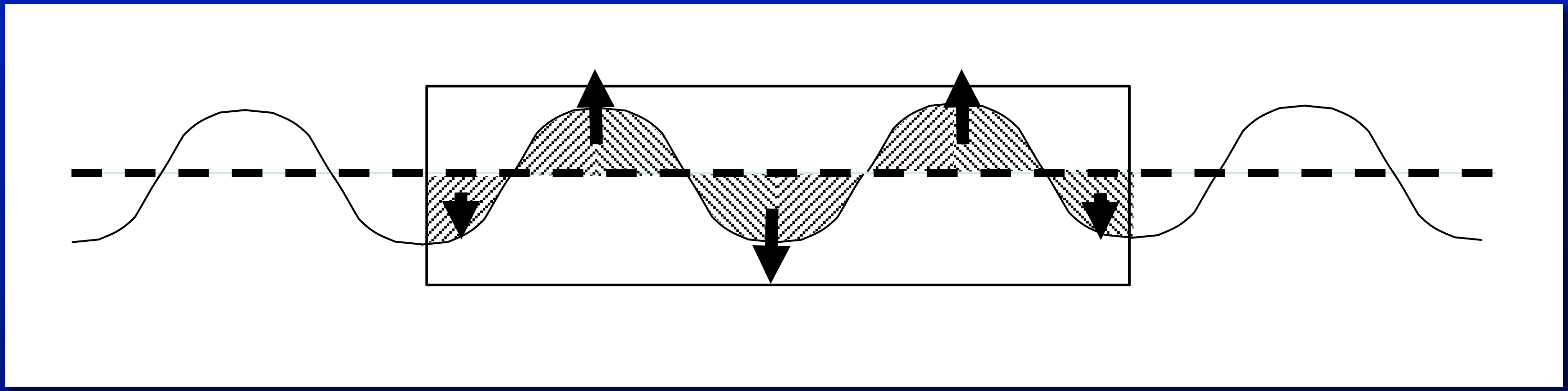
Wavelength = Barge Length



- Net <u>PITCHING MOMENT</u> is large;
  forces create alternating moment about center

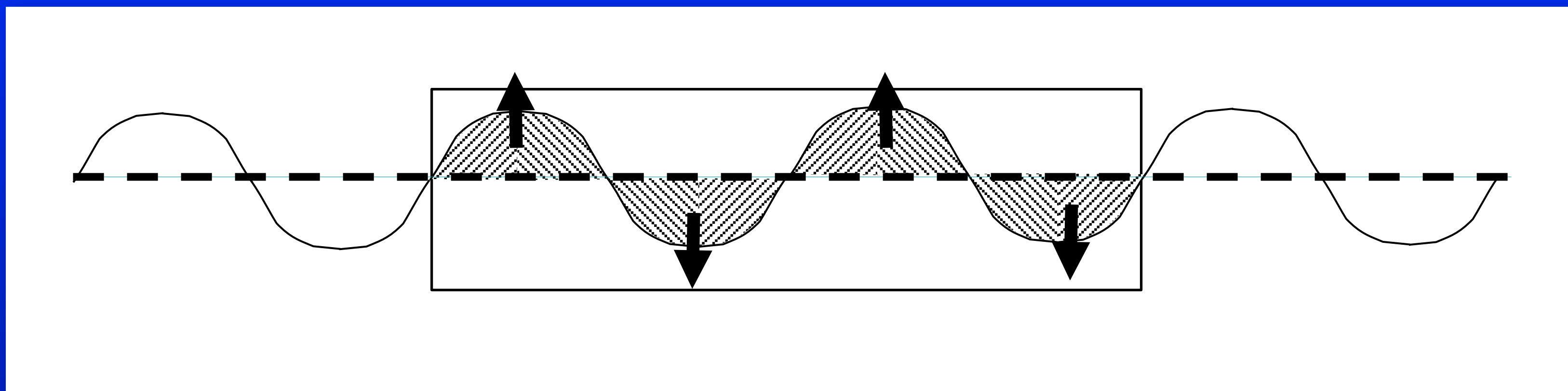
Wavelength = 1/2 Barge Length

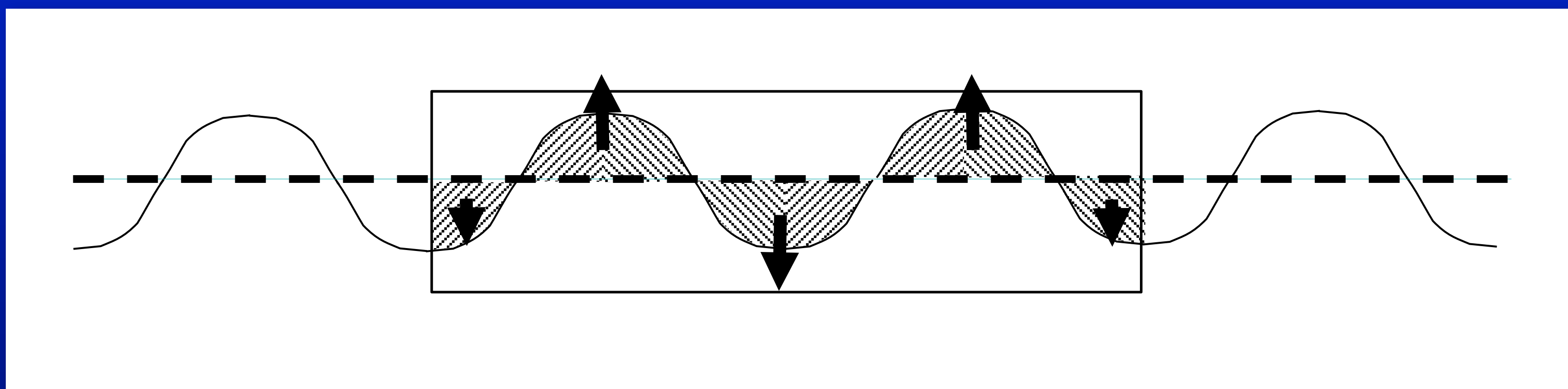




- Net HEAVING FORCE is small; forces cancel

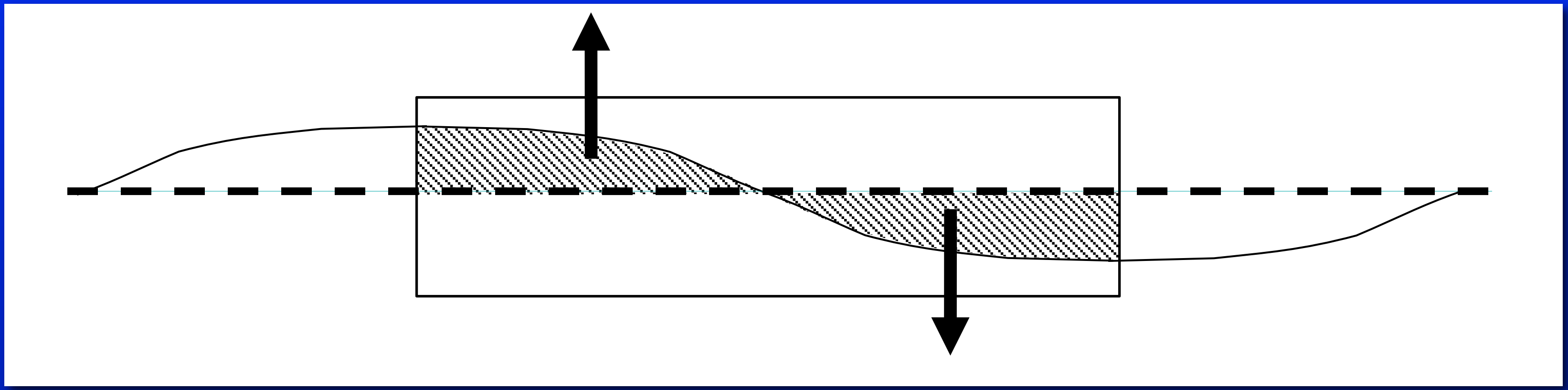
Wavelength = 1/2 Barge Length

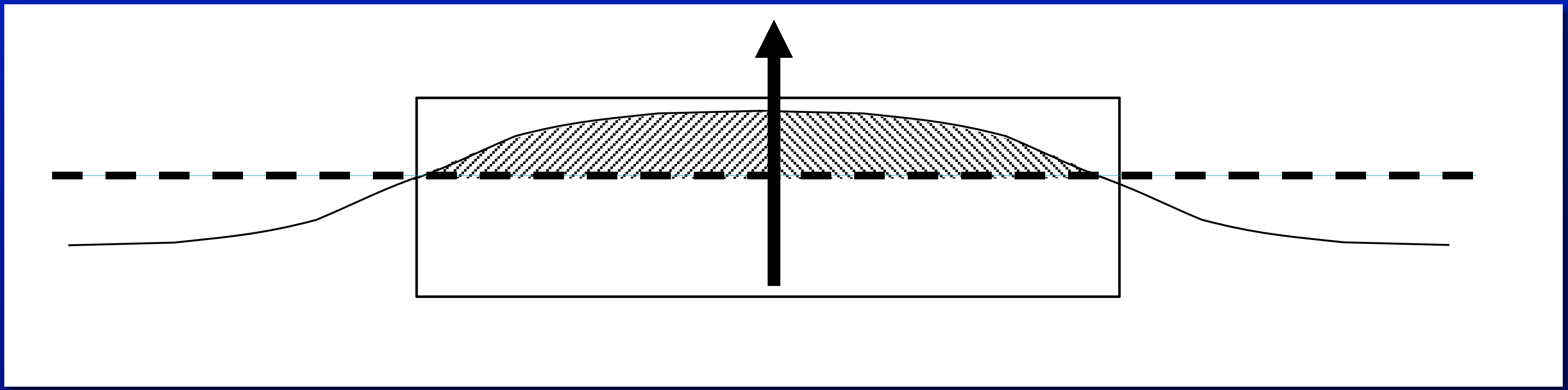




- Net <u>PITCHING MOMENT</u> is small; forces balanced on either side of center

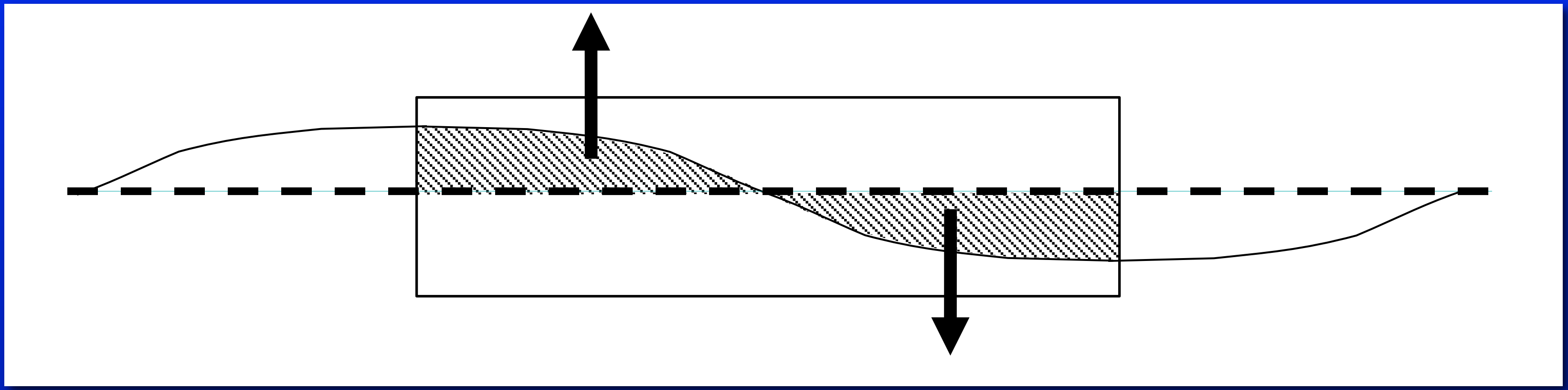
Wavelength = 2 Barge Lengths

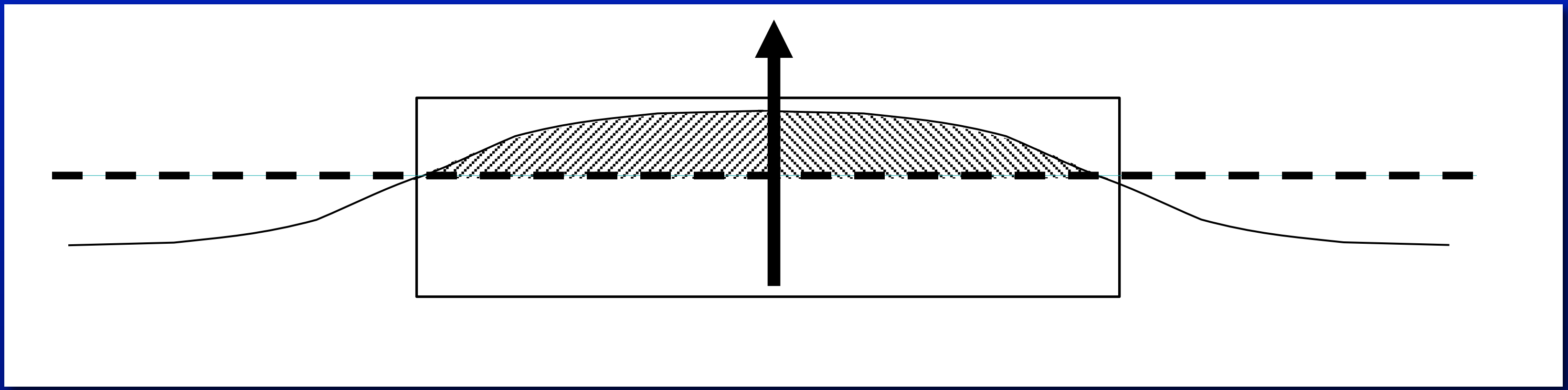




- Net <u>HEAVING FORCE</u> is large

Wavelength = 2 Barge Lengths





- Net PITCHING MOMENT is large

Simulation

- Box barge motions in regular waves
- Three degree-of-freedom model: surge (x), heave (z), pitch (θ)
- Three-dimensional flow assumed to be potential flow (irrotational, inviscid, incompressible)
- Boundary element method used to find radiation and scattering forces (results taken from Faltinsen and Michelsen [1974])

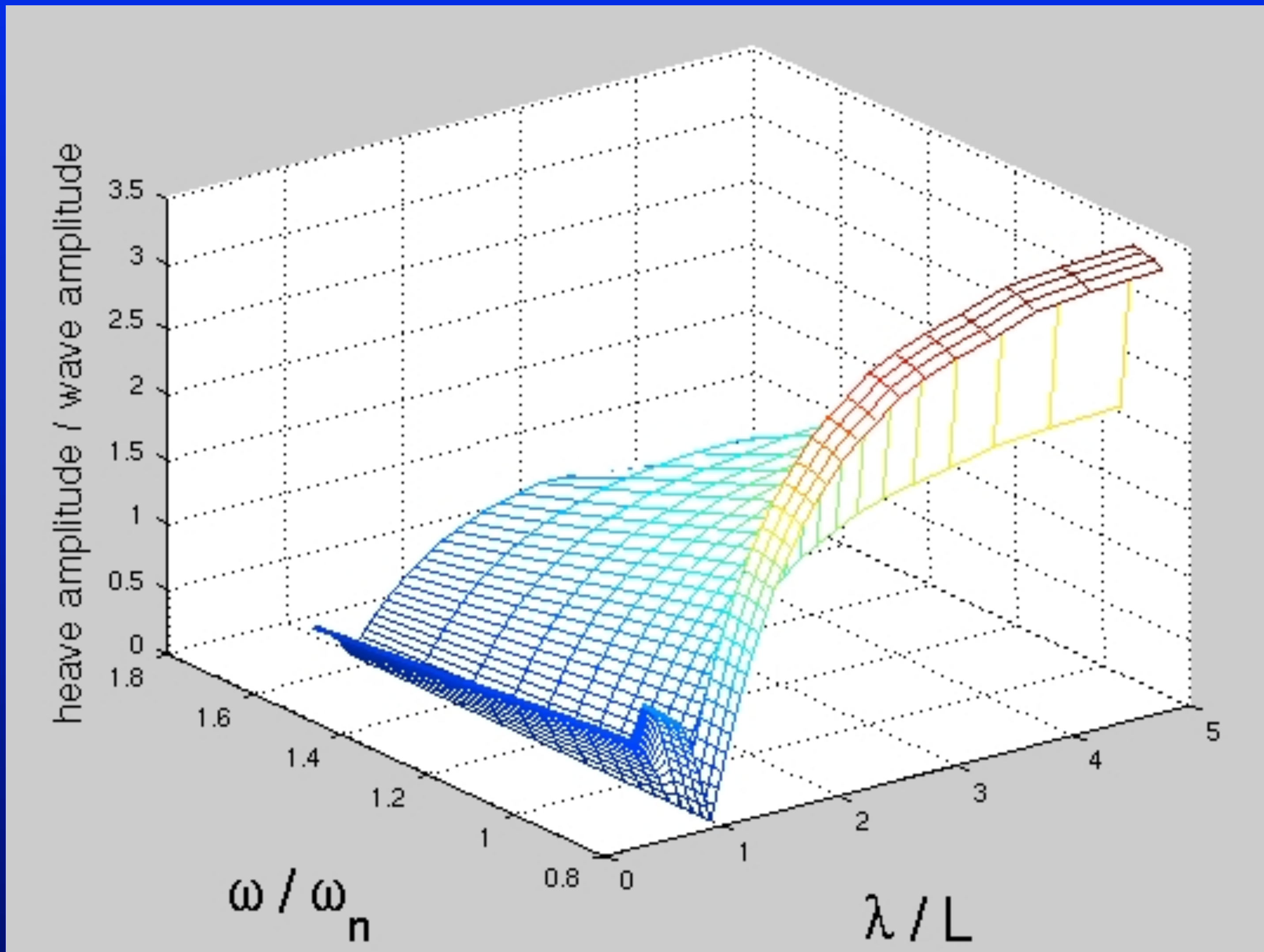
Simulation, continued

- Initial-value problem solved by numerical integration using Euler's method
- Calculations and post-processing: MATLAB
- Wave height held constant at 2 m
- Wave period held constant at 14 sec
- Barge displacement held constant
- Length, beam, and draft varied to change wavelength (λ / L) and frequency (ω / ω_n) ratios independently

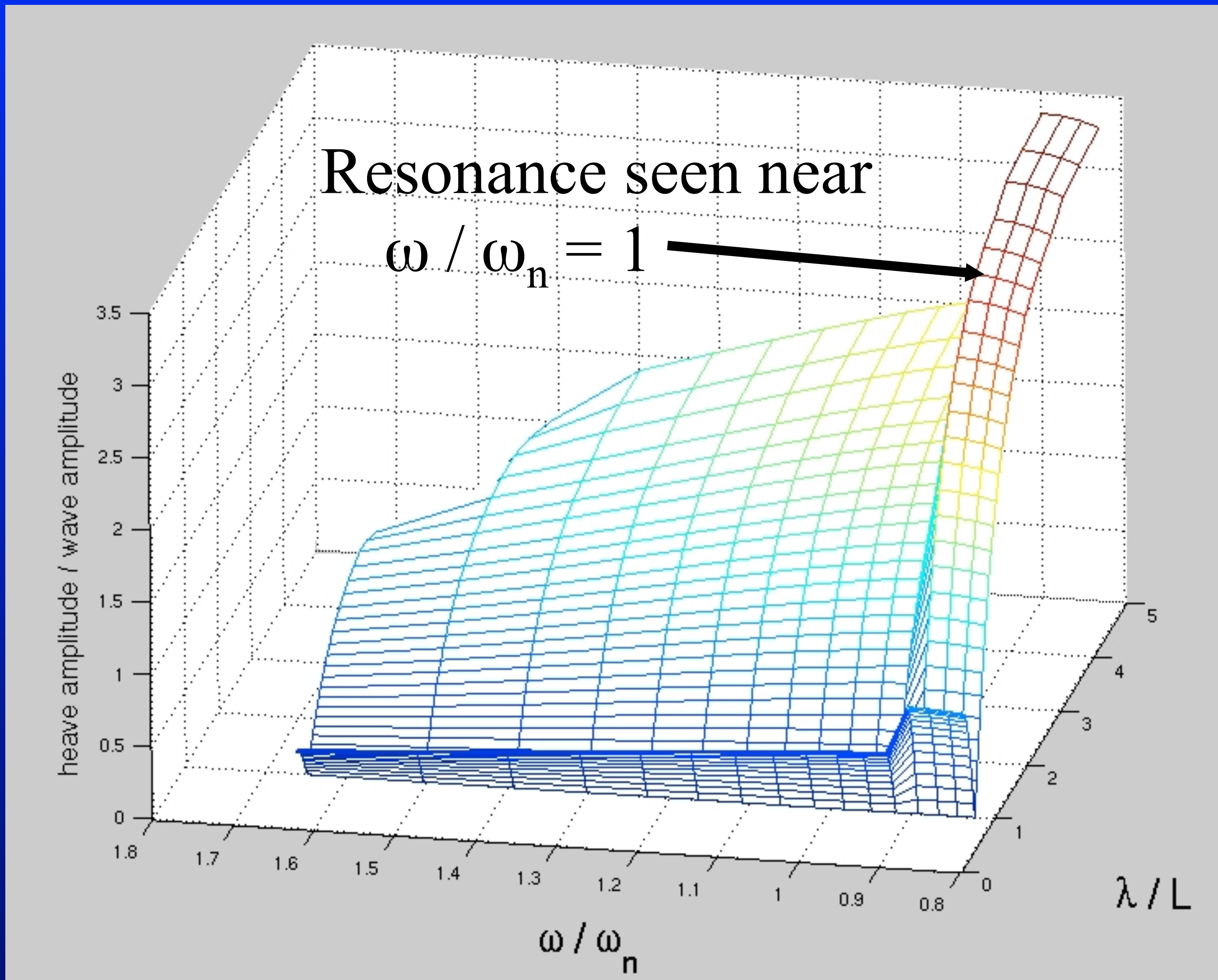
How to change λ/L and ω/ω_n independently?

- Period T is held constant (therefore λ and ω)
- Displacement $V = L\ b\ d$ is held constant
- Example: Heave
  - Change $L \uparrow$, so $b \downarrow$
  - Keep $A_{wp} = Lb$ constant, so stiffness is constant and therefore ω_n is constant
  - So $\lambda/L \downarrow$ and ω/ω_n is constant

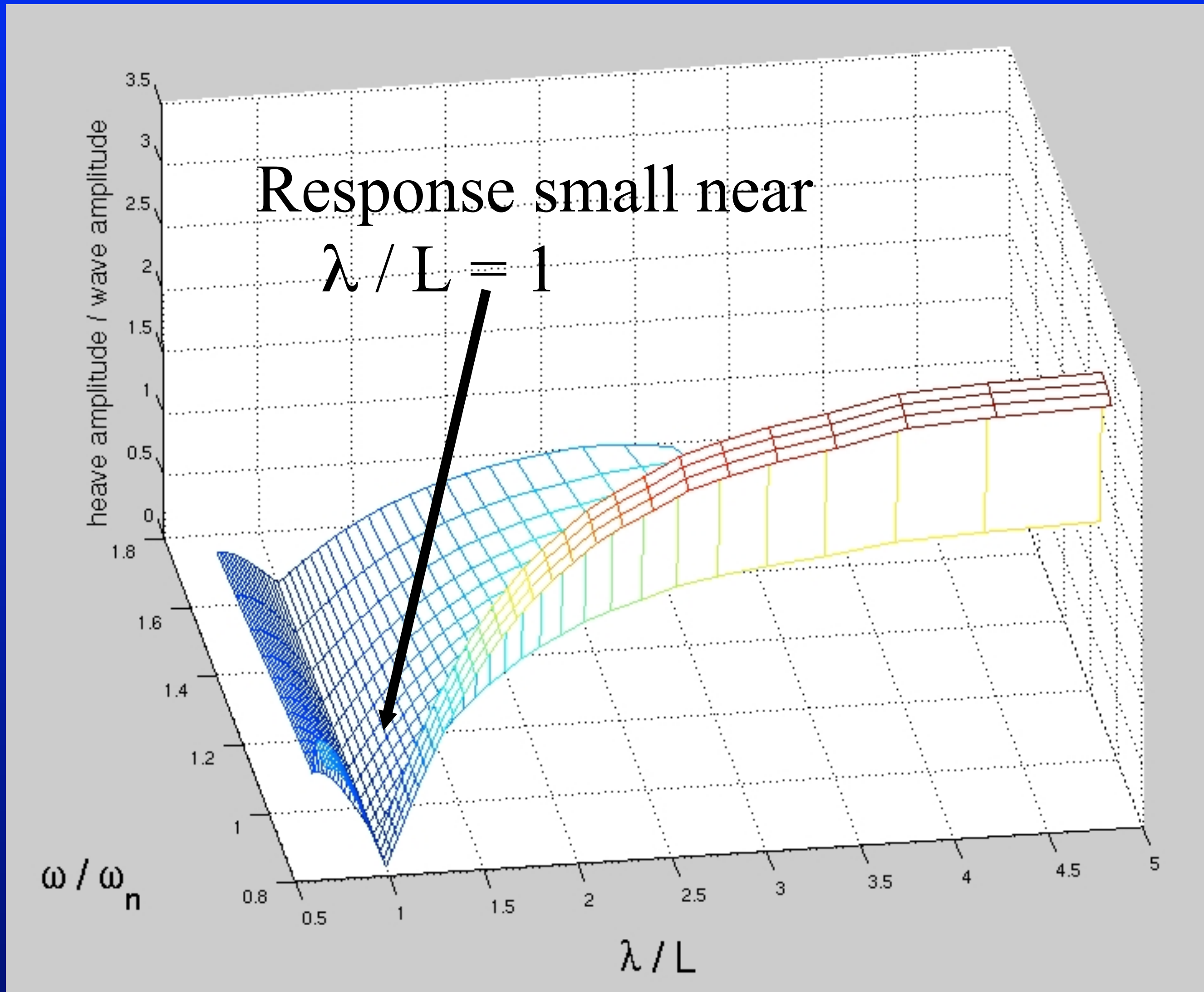
Heave response vs. frequency and wavelength



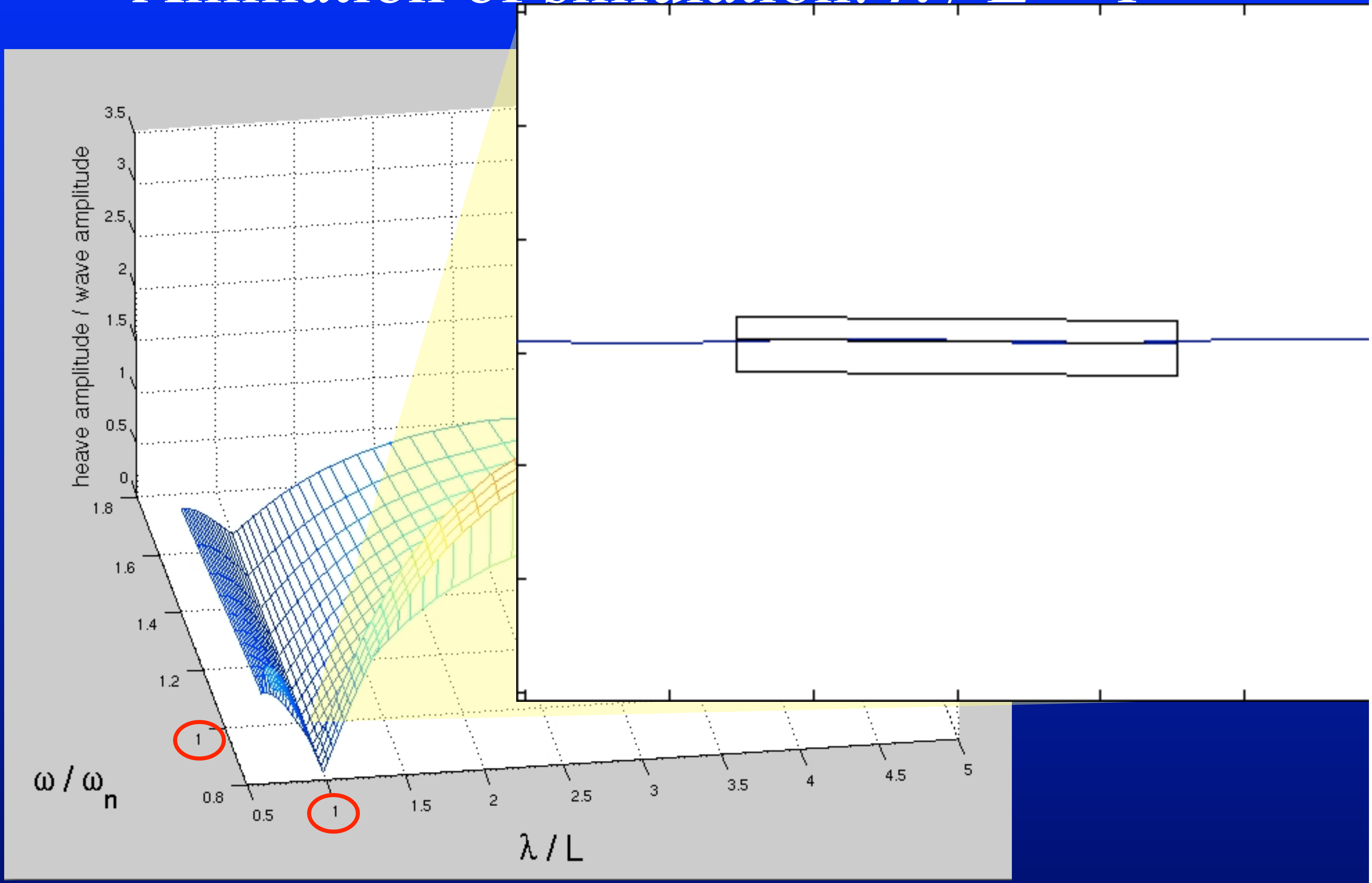
Heave response: frequency resonance



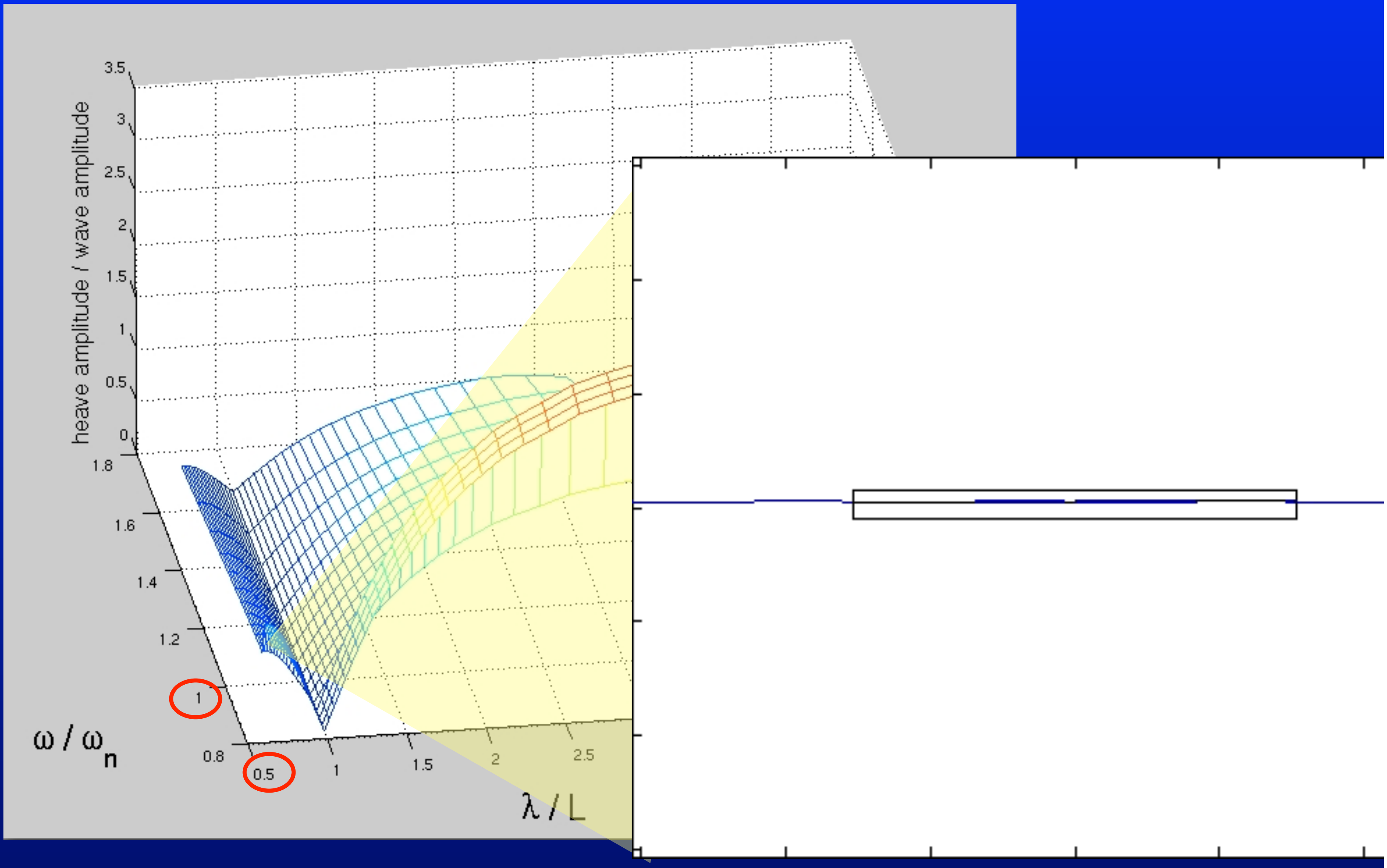
Heave response: wavelength effect



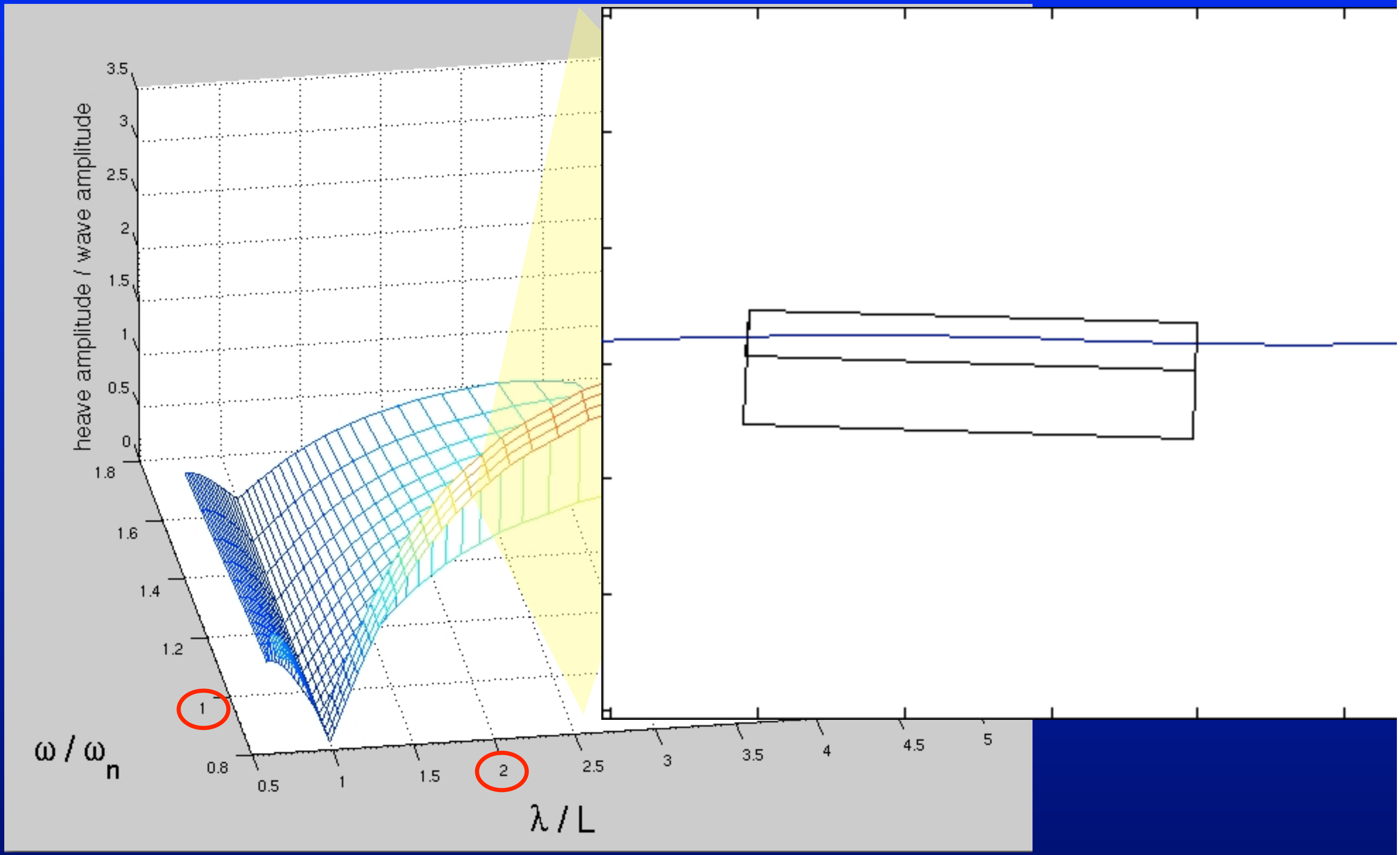
Animation of simulation: λ / L = 1



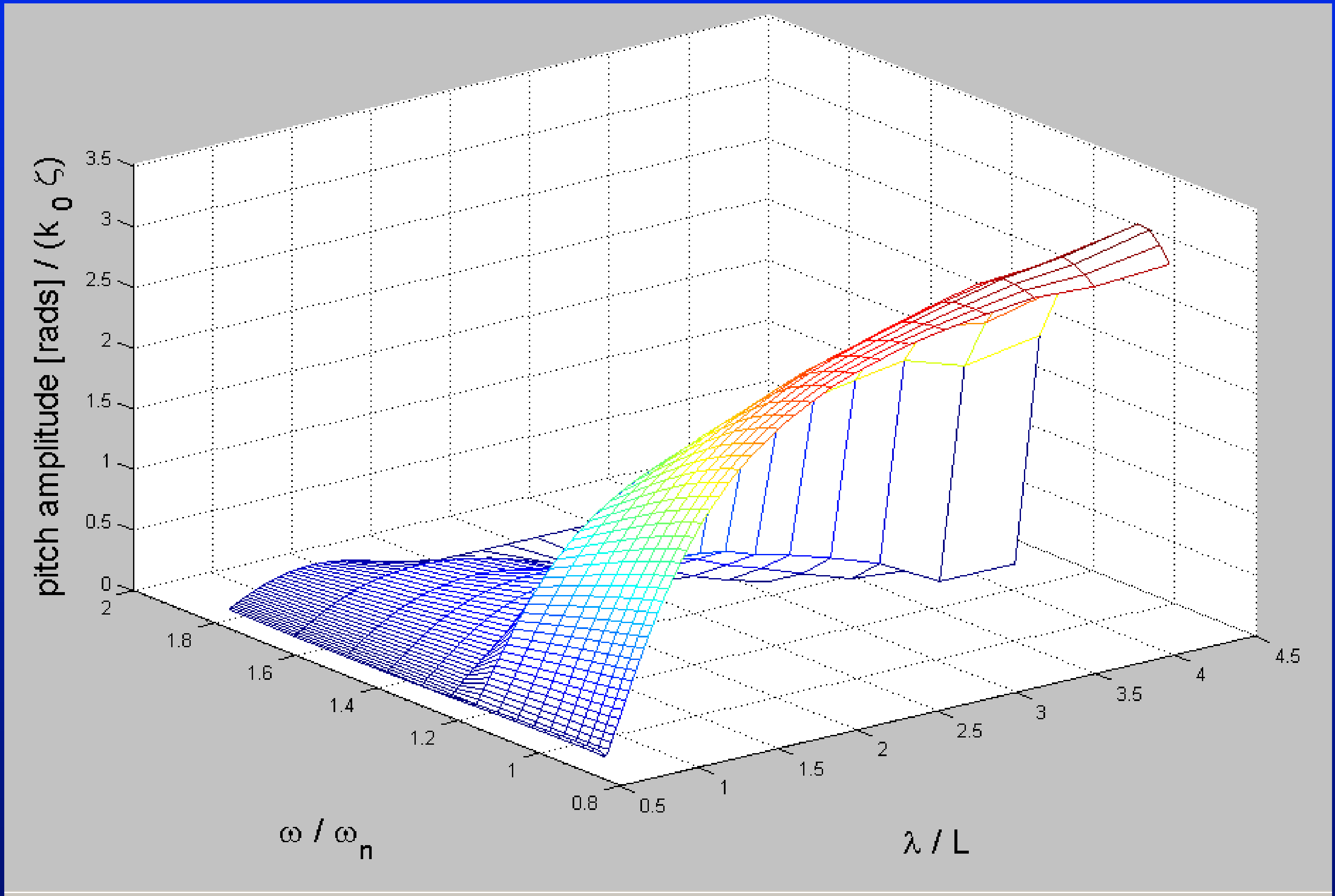
Animation of simulation: λ / L = 1/2



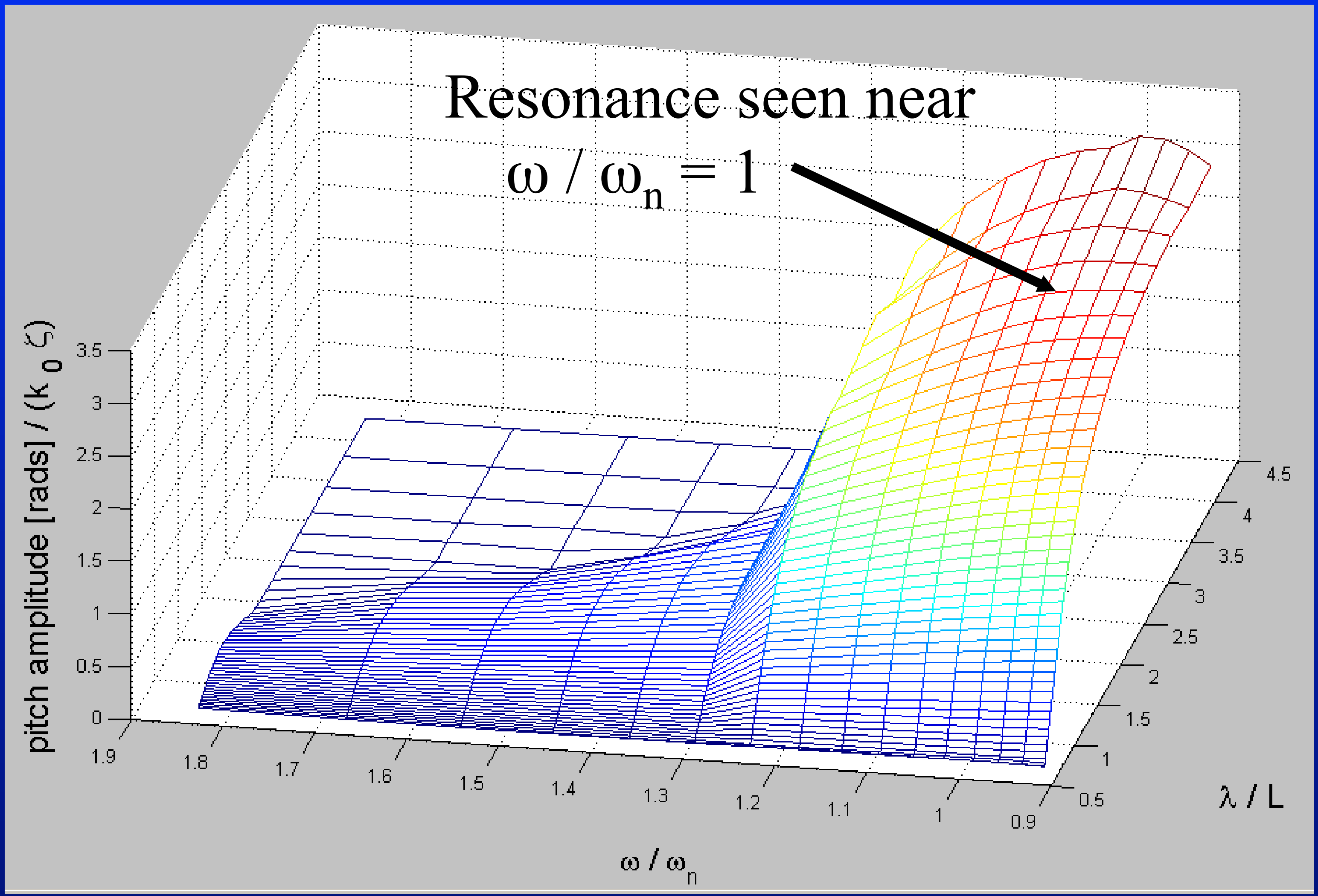
Animation of simulation: λ / L = 2



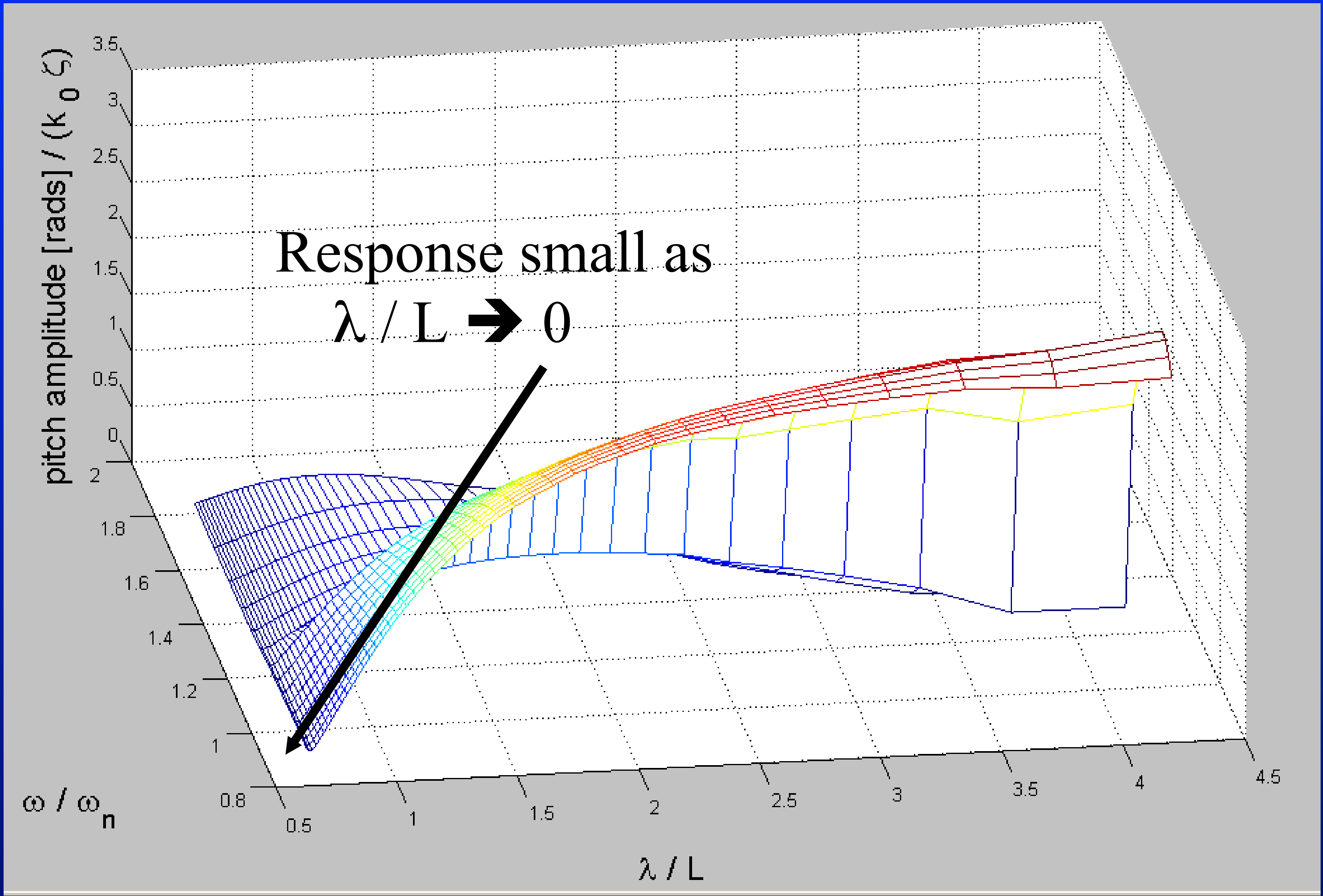
Pitch response vs. frequency and wavelength



Pitch response: frequency resonance



Pitch response: wavelength effect



Wavelength Compatibility Conclusions

- Wavelength to body length ratio has a strong effect on a floating body's response to waves
- Response Amplitude Operator (RAO) graphs should be plotted versus wavelength as well as frequency

Conclusions, continued

- To minimize heaving motions, floating bodies should be designed so that
  length = expected wavelength
  (to maximize, length << wavelength)

- To minimize pitching motions, floating bodies should be designed so that
  length >> expected wavelength
  (to maximize, length ~ 1/5 wavelength)

Future work

- Experimental verification!
- Vary wave period; results should not change
- Extend range of results:
  - What happens when $\lambda / L \rightarrow 0$?
  - What is the ratio of λ / L that yields peak pitching response?

Discussion

David Kraemer
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Nondimensional numbers in fluid mechanics

- Reynolds number: ratio of inertial to viscous forces

$$\mathrm{Re}_L = \frac{VL}{\nu}$$

- Strouhal number: nondimensional frequency

$$\mathrm{St} = \frac{fL}{V}$$

- Froude number: ratio of inertial to gravity forces

$$\mathrm{Fr} = \frac{V}{\sqrt{gL}}$$

- Weber number: ratio of inertial to surface-tension forces

$$\mathrm{We} = \frac{\rho V^2 L}{\sigma}$$

Wave-tank testing

- Geometric similarity:
  - Model must be to scale; Length scale factor:
  - Wave steepness must be the same:

$$n_L = \frac{L_{\text{model}}}{L_{\text{prototype}}}$$

$$\frac{H_m}{\lambda_m} = \frac{H_p}{\lambda_p}$$

- Dynamic similarity:
  - Match Froude number
  - Match Strouhal number
  - Reynolds number can't normally be matched

Match Froude number

$$\mathrm{Fr}_{\mathrm{model}} = \mathrm{Fr}_{\mathrm{prototype}}$$

$$\frac{V_{\mathrm{m}}}{\sqrt{gL_{\mathrm{m}}}} = \frac{V_{\mathrm{p}}}{\sqrt{gL_{p}}}$$

$$\frac{V_m}{V_p} = \frac{\sqrt{gL_m}}{\sqrt{gL_p}} = \frac{\sqrt{L_m}}{\sqrt{L_p}} = \sqrt{\frac{L_m}{L_p}} = \sqrt{n_L}$$

Match Strouhal number

$$\mathrm{St}_{\mathrm{model}} = \mathrm{St}_{\mathrm{prototype}}$$

$$\frac{f_m L_m}{V_m} = \frac{f_p L_p}{V_p}$$

$$\frac{f_m}{f_p} = \frac{V_m}{V_p}\frac{L_p}{L_m}$$

since *T* = *1 / f*

$$\frac{T_m}{T_p} = \frac{V_p}{V_m}\frac{L_m}{L_p}$$

from Froude scaling

$$= \frac{1}{\sqrt{n_L}} n_L = \sqrt{n_L}$$

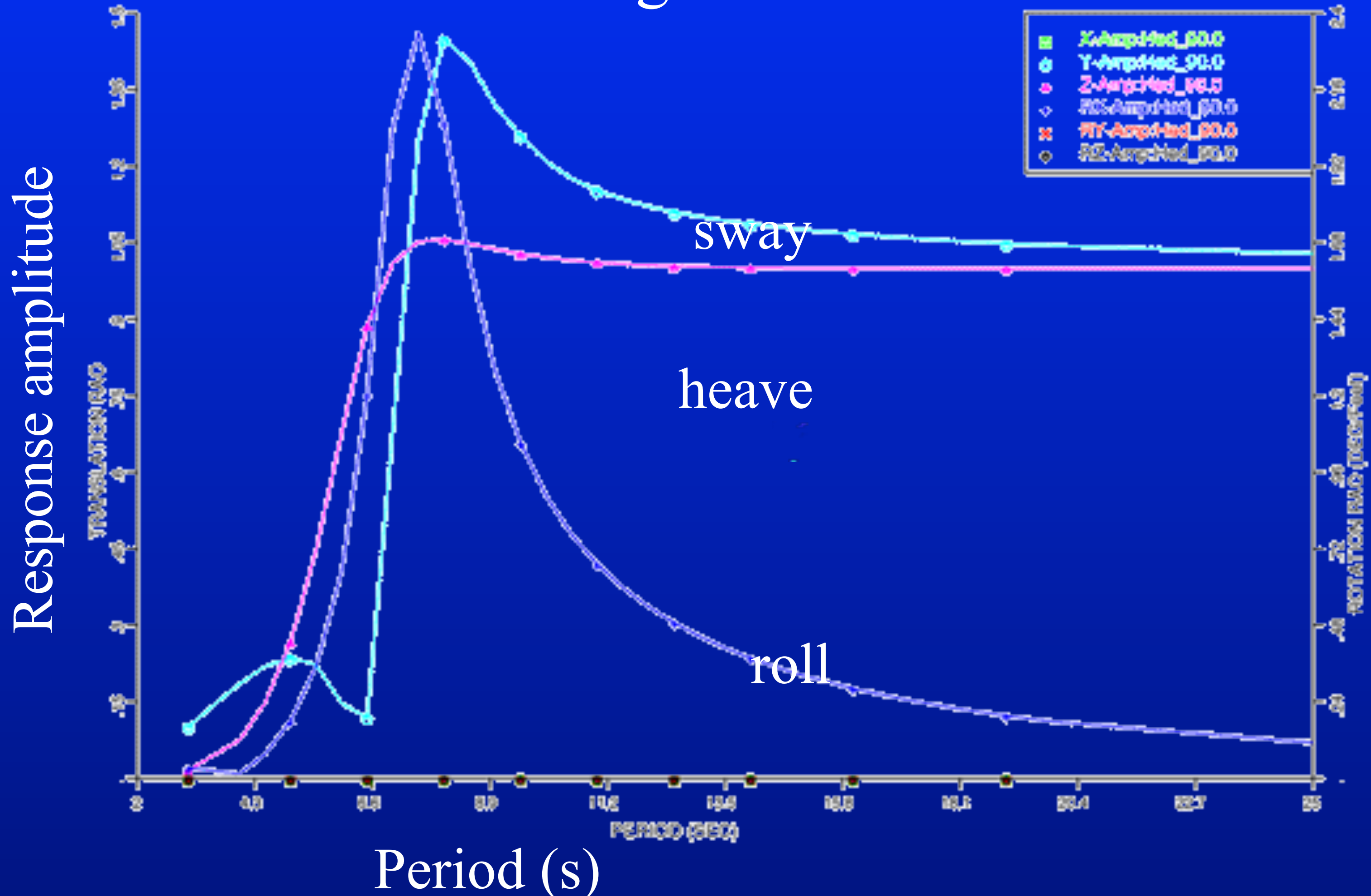
Time Scaling

- Match Froude number
- Match Strouhal number

→ time-scaling relationship:

$$\frac{T_m}{T_p} = \sqrt{n_L}$$

Example Response Amplitude Operators (RAOs): Barge in beam seas



http://www.ultramarine.com/hdesk/runs/samples/sea_keep/doc.htm

Wavelength compatibility: a problem with RAOs?

- Example: Say L_p =100 m, and L_m =10 m:

$$n_L = \frac{L_{\text{model}}}{L_{\text{prototype}}} = \frac{1}{10}$$

- Say T_p =10 s:
  So T_m =3.2 s

$$T_m = T_p \sqrt{n_L}$$

- Say the prototype is in deep water, while the model is tested in 2.0 m
- From the dispersion relation, λ_p =156 m, λ_m =12.3 m
- So

$$\frac{\lambda_p}{L_p} = 1.6 \quad \text{while} \quad \frac{\lambda_{\text{m}}}{L_{\text{m}}} = 1.2$$

Wavelength compatibility: a problem with RAOs?

$$n_L = \frac{L_{\text{model}}}{L_{\text{prototype}}} = \frac{1}{10}$$

- Example: Say L_p =100 m, and L_m =10 m:
- Say T_p =20 s:
  So T_m =6.3 s

$$T_m = T_p \sqrt{n_L}$$

- Say the prototype is in deep water, while the model is tested in 2.0 m
- From the dispersion relation, λ_p =625 m, λ_m =27 m
- So

$$\frac{\lambda_p}{L_p} = 6.3 \quad \text{while} \quad \frac{\lambda_{\text{m}}}{L_{\text{m}}} = 2.7$$

Discussion

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