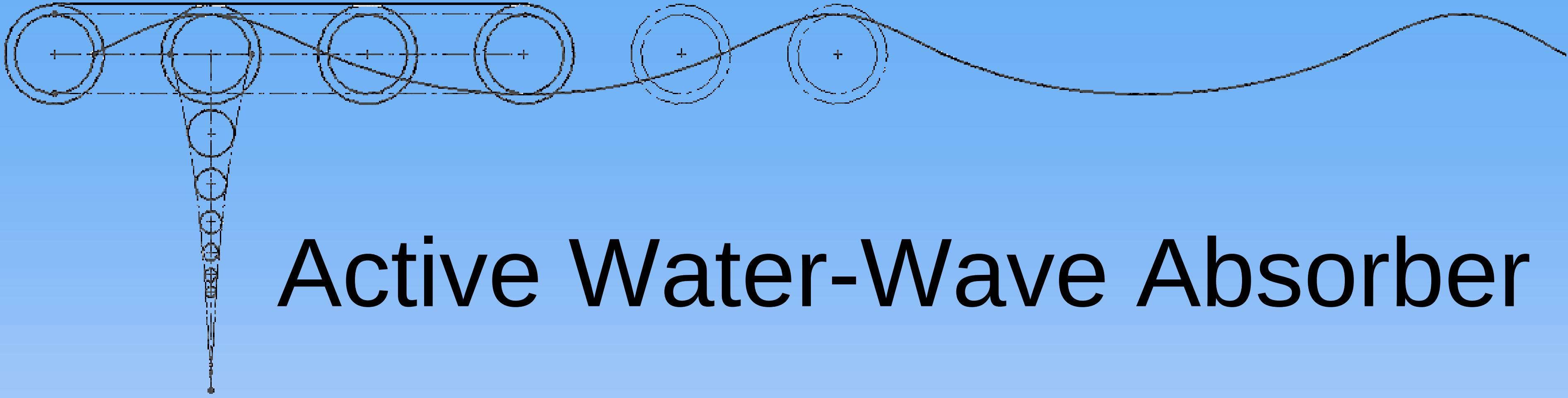

Active Water-Wave Absorber

Matthew Carney

ME236: Control & Optimization of Distributed Parameters

Professor Alex Bayen

University of California, Berkeley

04.30.2007

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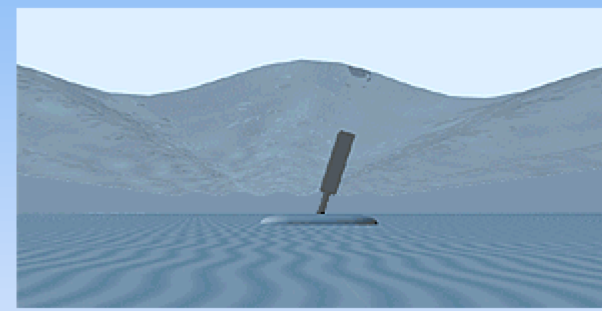
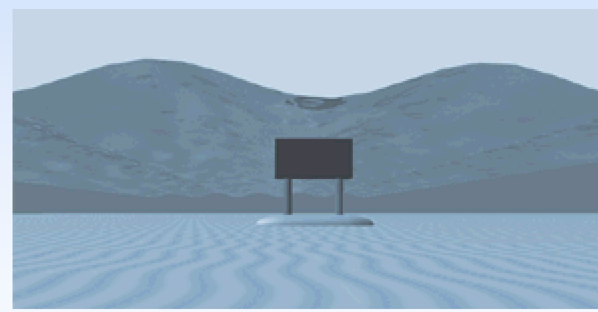
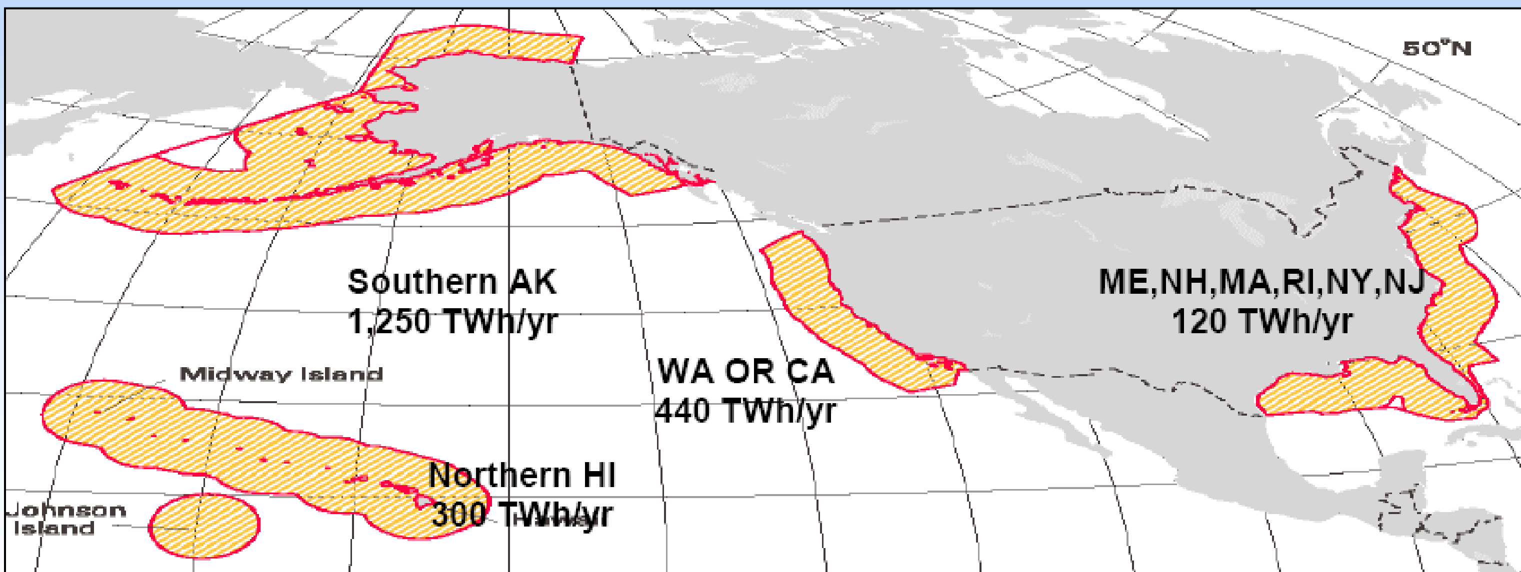




www.emec.org.uk

Motivation

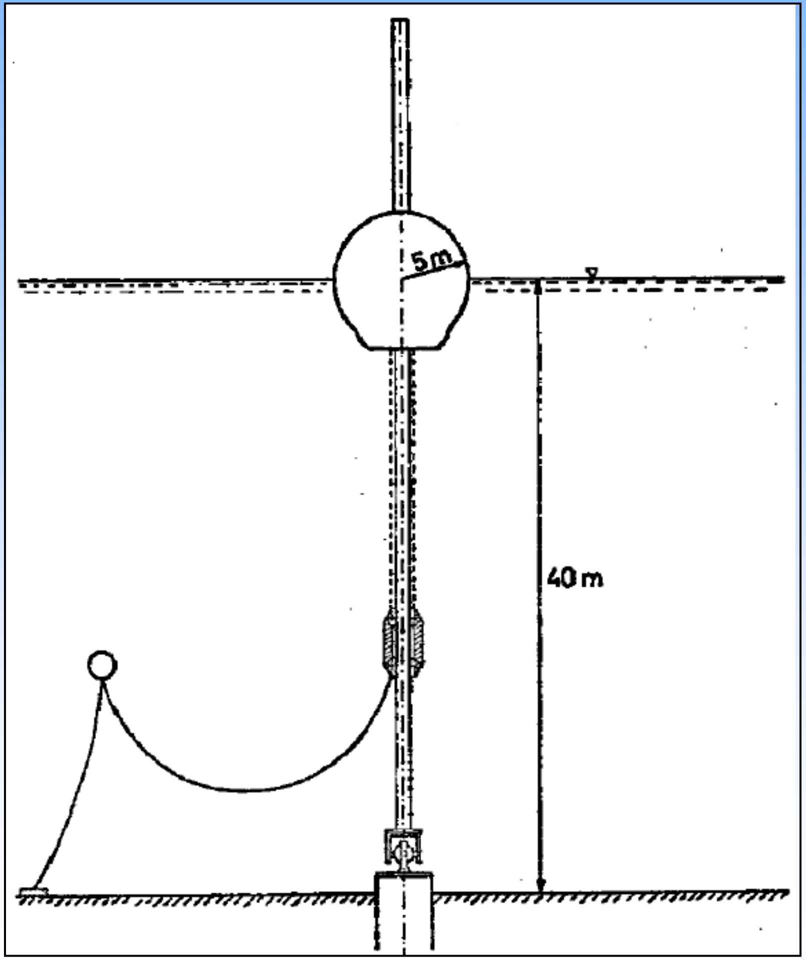
- Significant amounts of energy is stored in the ocean
- Large potential for extracting energy from waves
- Control is the key to optimizing energy extraction and economic feasibility.



www.epri.com/oceanenergy

Initial Idea

- 1-Degree of Freedom Point Absorber
- Direct Drive Linear Generator
- Optimize Hydrodynamic Parameters
  - Added Mass
  - Added Damping
- Optimize Phase Control



Literature Search

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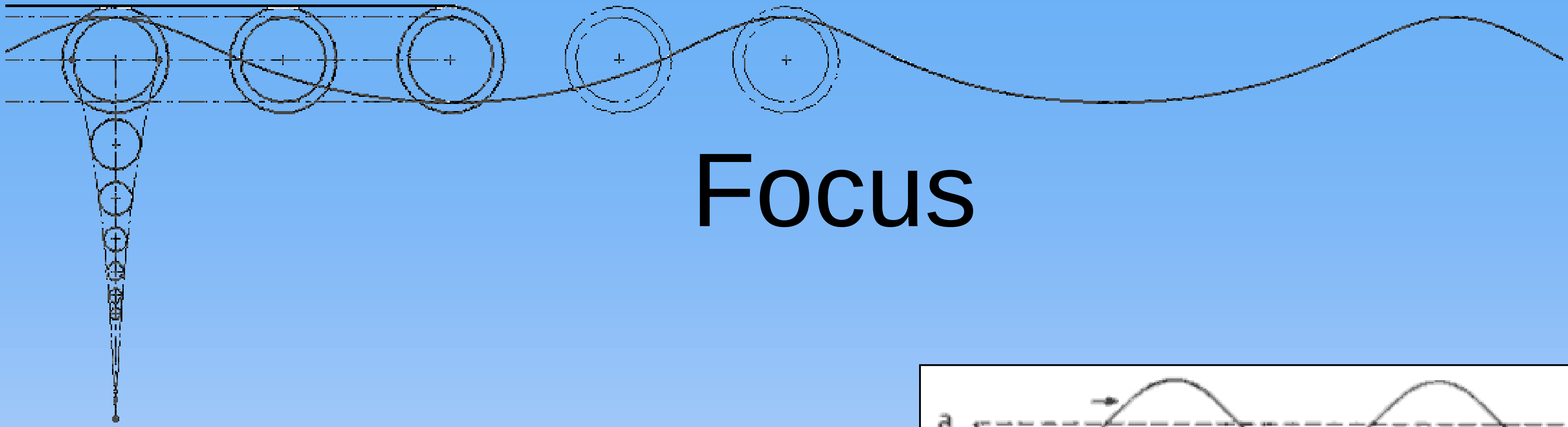
- Havelock, T. H., “Forced Surface-Waves on Water.” Philosophic Magazine of Science, vol. 8, no. 51, Oct. 1929.

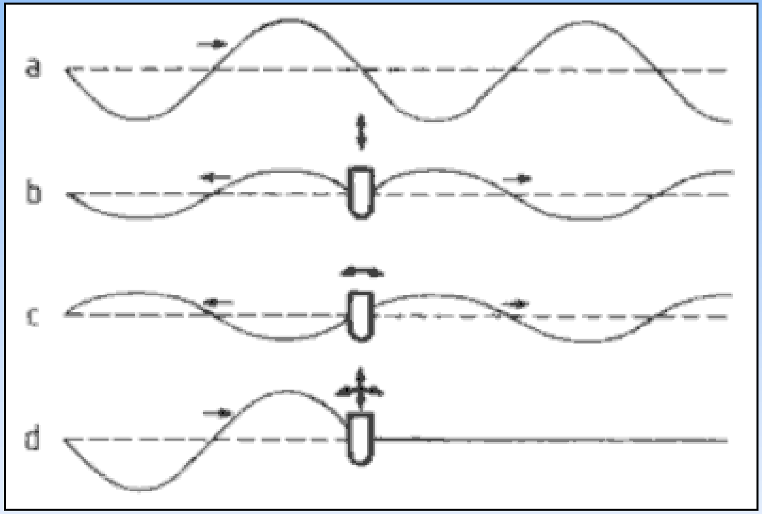
- **Milgram, Jerome H., “Active Water-Wave Absorbers.” Journal Fluid Mechanics, vol. 43, part 4, pages 845-859, 1970.**

- Yeung, Ronald W. “Added Mass and Damping of a Vertical Cylinder in Finite-depth Waters.” Applied Ocean Research, vol. 3, no. 3, pages 119-133. 1981.



Focus

- Simplify the Problem!



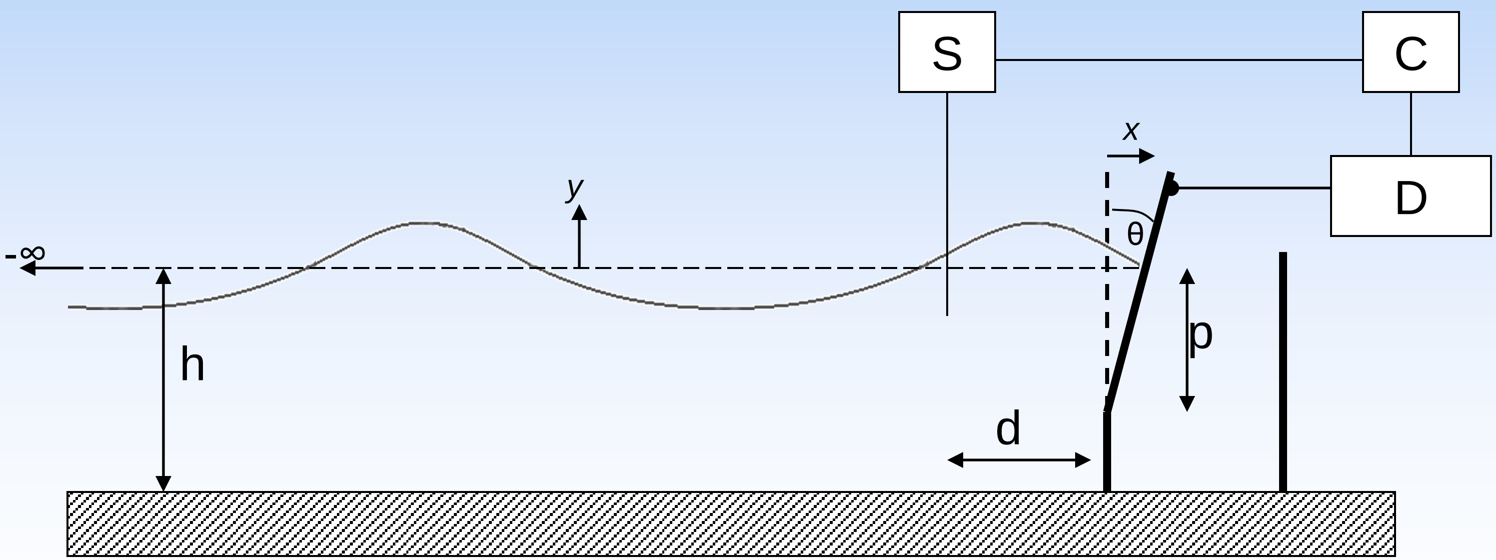
- “*To absorb a wave means to generate a wave or*, in other words: *To destroy a wave is to create a wave.” – Johannes Falnes*

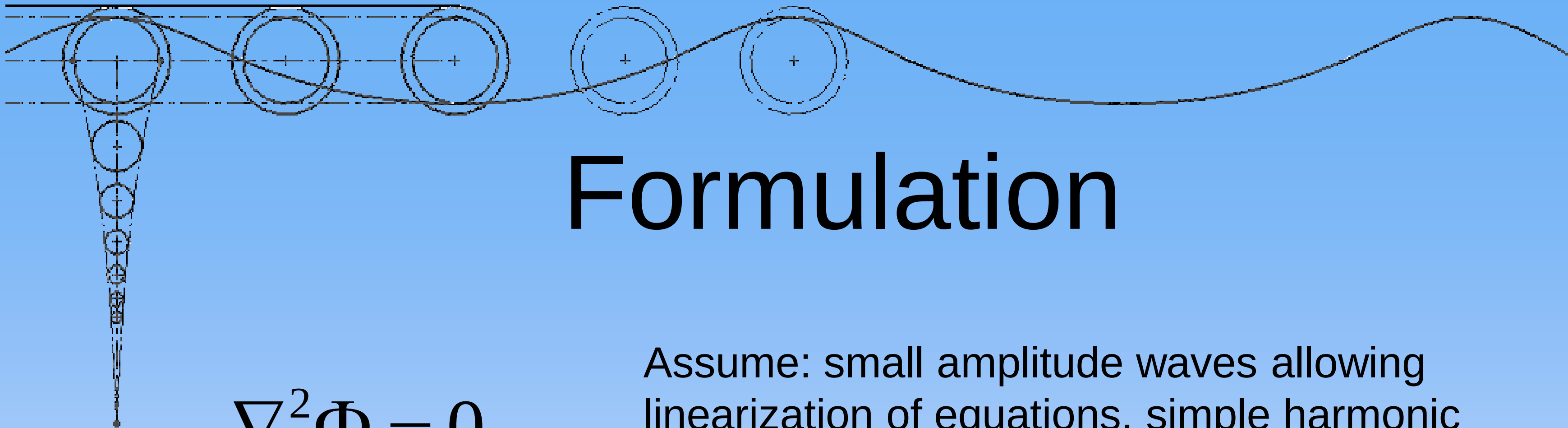
(2D Wave-Maker) $^{-1}$

Active Water-Wave Absorbers

Jerome H. Milgram

Journal of Fluid Mechanics (1970), vol. 43, pp. 845-859





Formulation

$$\nabla^2 \Phi = 0$$

Assume: small amplitude waves allowing linearization of equations, simple harmonic oscillations, initially irrotational fluid, neglect viscosity and surface tension.

Boundary Conditions

$\Phi_{tt} + g\Phi_y = 0$	on	$y = 0$	• Dynamic free surface
$\Phi_y = \mathrm{N}_t$	on	$y = 0$	• Kinematic free surface
$\Phi_y = 0$	on	$y = -h$	• Impermeable floor
$\Phi_x = \Psi_t$	on	$x = 0$	• Termination (Flapper) wall
$\lvert \nabla \Phi \rvert < \infty$	at	$x = -\infty$	• Condition at infinity

Derivations

- Separation of Variables used to solve Laplacian

$$\Phi = \Phi(x, y, t) = \sum_{k=-\infty}^{\infty} C_k F_k(x) G_k(y) e^{-i\lambda t}$$

$$F_k(x) = e^{i f_k x}$$

$$G_k(y) = \cosh f_k (y + h)$$

- Free Surface BC leads to the dispersion relation

$$\frac{\lambda^2 h}{fh} = g \tanh(fh)$$

Calculations

- Due to boundedness of the boundary condition at negative infinity the potential function leads to

$$\Phi(x,y) = A_0^{'} \cosh f_0(y+h)e^{-if_0x} + \sum_{n=0}^{\infty} A_n \cosh f_n(y+h)e^{if_nx}$$

where, the A'_0 term refers to the wave reflected from the flapper wall.

- Channel termination (Flapper - active absorber)

where, $\Psi(y,t) = B\psi(y)e^{-i\lambda t}$

$$\psi(y) = \begin{cases} y+p & y \geq -p \\ 0 & y < -p \end{cases}$$

- The channel termination boundary condition then requires the following:

$$\Phi_x = \Psi_t$$

$$(A_0 - A_0^{'})\cosh f_0(y+h) + \sum_{n=1}^{\infty} A_n f_n \cosh f_n(y+h) = -B\lambda\psi(y)$$

Orthogonality

- The condition of orthogonality must be satisfied at the moving termination.

$$\int_{-h}^{0} G_k(y) G_n(y)\, dy = 0 \qquad for \qquad k \neq n$$

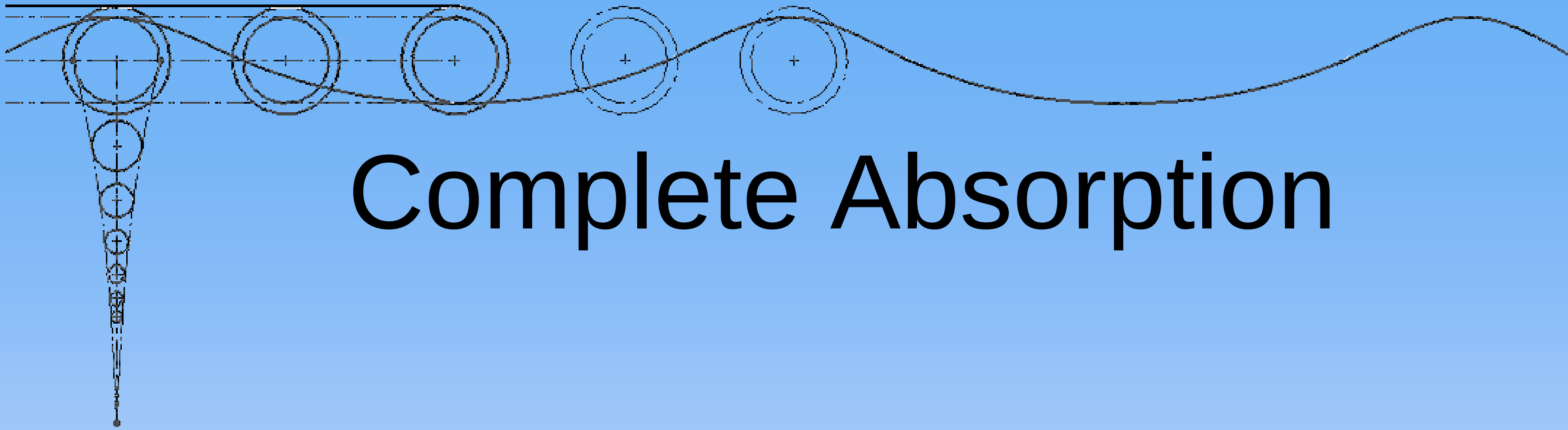
- This condition applies to the results of the previous page and allows the definition of the following integrals,

$$\mathrm{I}_n^{(1)} = \int_{-h}^{0} \cosh^2\, f_n(y+h)\, dy = \frac{1}{2} h \left[1 + \frac{1}{2 f_n h} \sinh 2 f_n h \right]$$

$$\mathrm{I}_{\mathrm{n}}^{(2)} = \int_{-h}^{0} \psi(y) \cosh\, f_n(y+h)\, dy = \frac{p}{f_n} \sinh\, f_n h + \frac{1}{f_n^{\,2}} \left[\cosh\, f_n(h-p) - \cosh\, f_n h \right]$$

- These integrals can then be used to define the ratio of coefficient values

$$\left.\begin{array}{lll} \text{for} & n = 0, & \mathrm{A}_0 - A_0' \\ \text{for} & n \neq 0, & A_n \end{array}\right\} = -\frac{\lambda}{f_n} B \frac{I_n^{(2)}}{I_n^{(2)}},$$



Complete Absorption

- For complete absorption the term A'$_o$ =0. So we can use the ratio from the previous page to define the complex coefficient of motion, B.

$$B = \frac{-A_0 f_0^{\,2}\left[2 f_o h + \sinh 2 f_0 h\right]}{4\lambda\left\{f_0 p \sinh f_0 h + \cosh f_0 (h - p) - \cosh f_0 h\right\}}$$

- Surface elevation can be calculated using the velocity potential and the kinematic free surface condition.

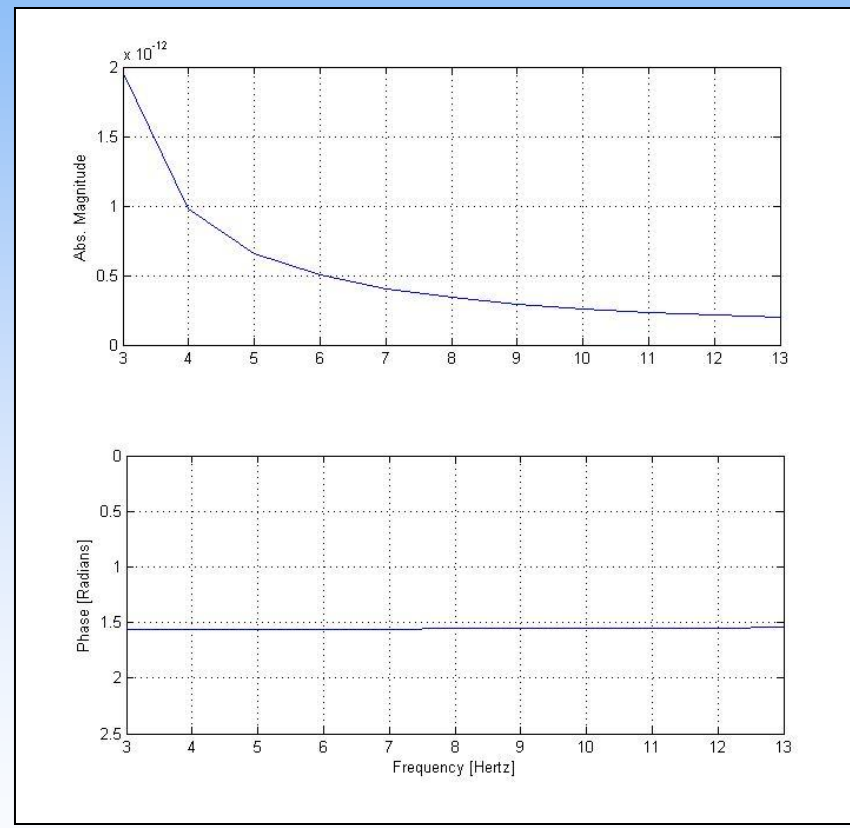
$$\eta(x) = \frac{-1}{i\lambda} f_0 \left(A_0' e^{-if_0 x} + A_0 e^{if_0 x}\right) \sinh f_0 h - \frac{1}{i\lambda} \sum_{n=1}^{\infty} f_n A_n \sinh f_n h e^{if_n x}$$

Transfer Function

- Frequency dependent ratio of complex termination motion to surface elevation at the location of the sensor x = -d.

$$H_a(\lambda) = \frac{i}{\sum_{n=0}^{\infty} \frac{I_n^{(2)}}{I_n^{(1)}} \sinh(f_n h) e^{-i f_n d}}$$

- Frequency response matches Milgram's data (sort of: magnitude figure shows correct values but many order of magnitude off)
- Phase response is pretty close to Milgram's.



Future Work

- Investigate scaling issue with magnitude.
- Simulink model to simulate Milgram’s test data.
- Rework the problem as a standard wave-maker problem and modify Howard Wilson’s MatLab visualization code for a harmonically driven oscillating string.
- Further modify the code for the active wave-absorber problem.
- Implement differential flatness control on the wave-maker boundary condition. Use code to intuitive visualization