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Design, Analysis, & Validation of the UC-Berkeley Wave Energy Extractor

By
Prof. Ronald W. Yeung
Department of Mechanical Engineering
Ocean Engineering & Fluid Mechanics
University of California at Berkeley

Ocean Renewable Energy at UC Berkeley

- Offshore Wind Farm: **WindFloat**, Marine Innovation & Technology (MI&T), Roddier and Cermelli - Berkeley, CA

- Tidal-Current Energy Converter Using Vortex-Induced Vibrations (collaboration with Mike Bernitsas - *VortexHydro*, Ann Arbor, MI)

- Electrical Energy from Ocean Waves

  (Research on design, analysis, & evaluation of an Enabling Technology) [current presentation], specifically mechanical energy to electricity process, and the overall coupled system evaluation.

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Ronald W. Yeung*
Department of Mechanical Engineering
University of California at Berkeley
Berkeley, California, 94720
Email: rwyeung@berkeley.edu

Antoine Peiffer†
Department of Mechanical Engineering
University of California at Berkeley
Berkeley, California, 94720
Email: antoine.peiffer@gmail.com

Nathan Tom
Department of Mechanical Engineering
University of California at Berkeley
Berkeley, California, 94720
Email: nathan.m.tom@gmail.com

Tomasz Matlak‡
Department of Mechanical Engineering
University of California at Berkeley
Berkeley, California, 94720
Email: tmatlak@gmail.com

ABSTRACT

This paper evaluates the technical feasibility and performance characteristics of an ocean-wave energy to electrical energy conversion device that is based on a moving linear generator. The UC-Berkeley design consists of a cylindrical floater, acting as a rotor, which drives a stator consisting of two banks of wound coils. The performance of such a device in waves depends on the hydrodynamics of the floater, the motion of which

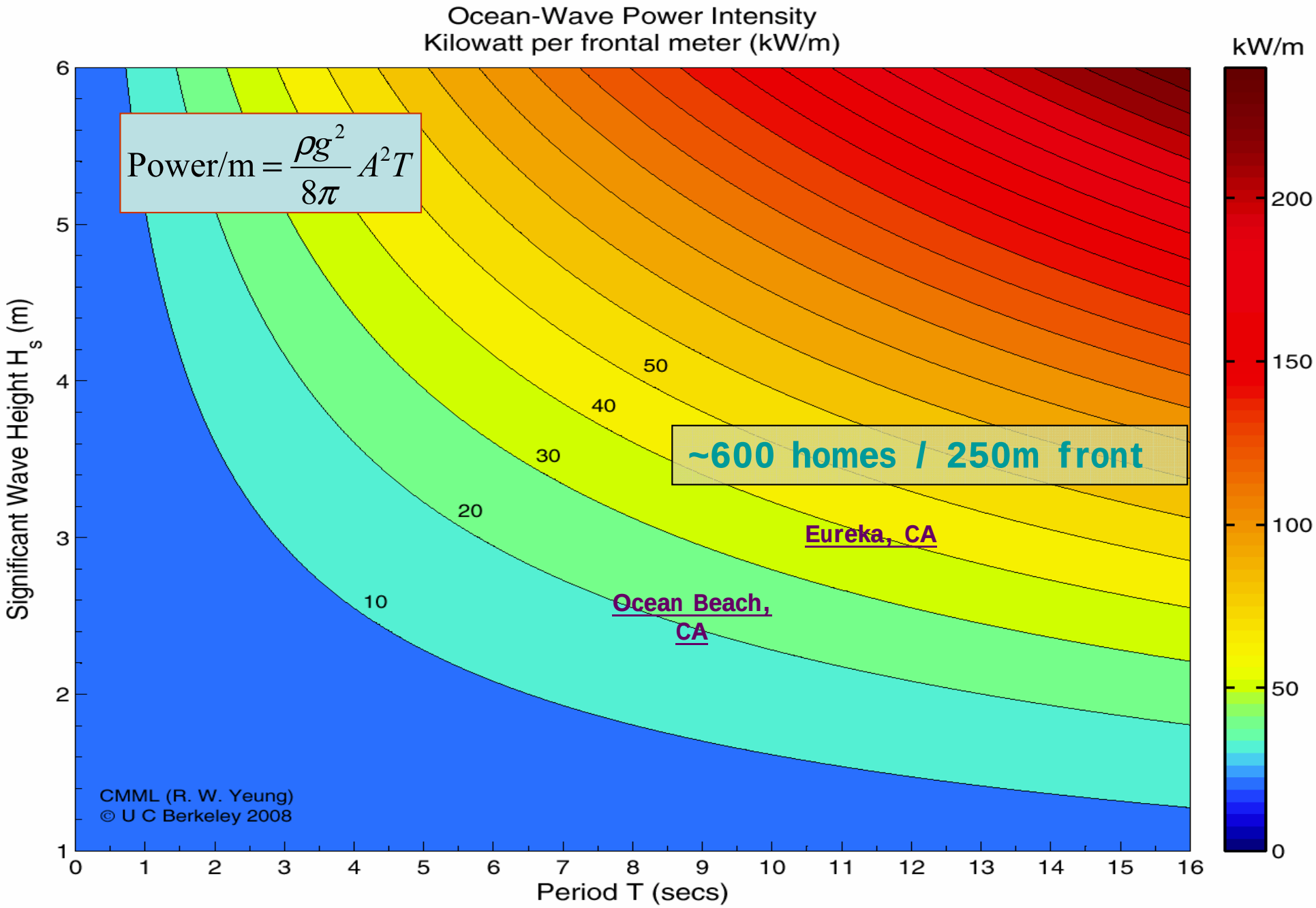
This paper is presented at the OMAE-2010 T. Francis Ogilvie Symposium, in honor of Professor Francis Ogilvie, a Berkeley alumnus who has provided distinguished leadership in education and research in the marine field. *R. W. Yeung*

1 INTRODUCTION

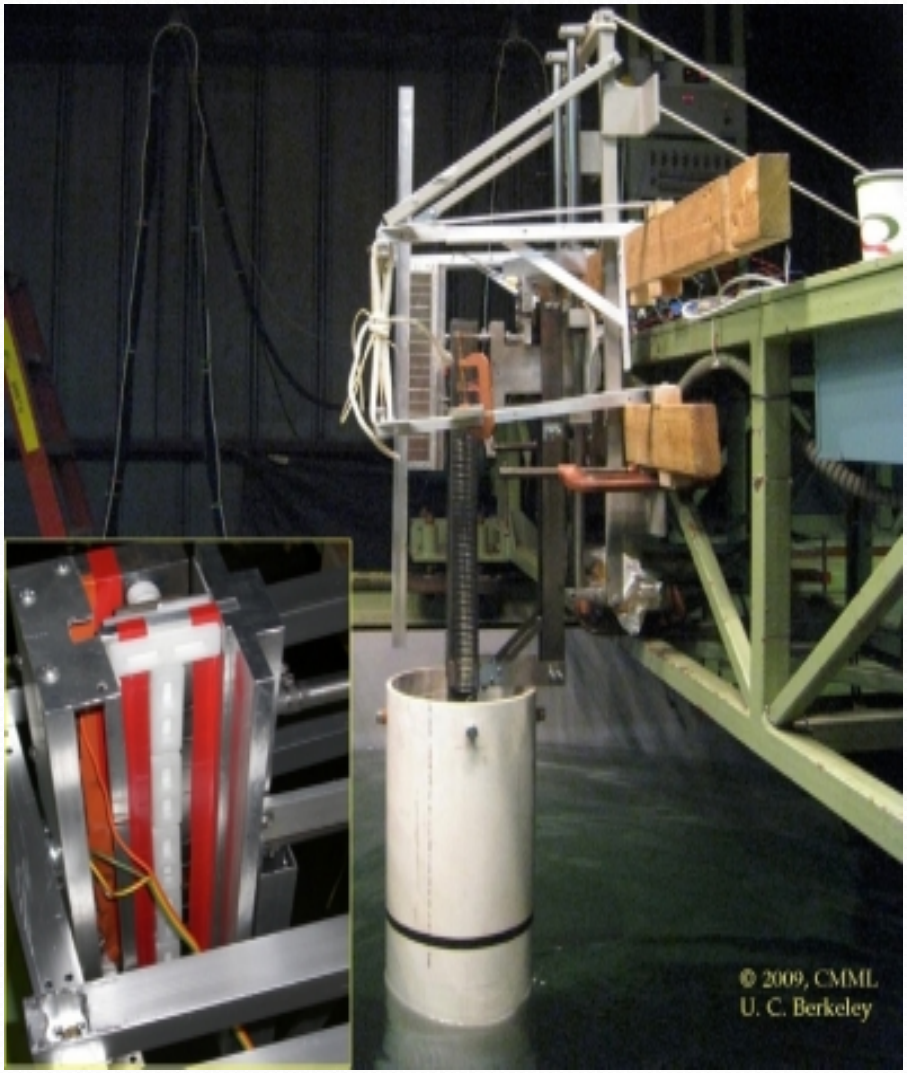
Objective:
To develop an overall math model to analyze, design, build a physical unit to validate math model & understand critical parameters.

- Current UC Berkeley Design Generator Design
- Floater Hydrodynamics
  - Response Amplitude Operator
- Electromagnetic (EM) Device and *Coupling Effects*
  - Modified Response Amplitude Operator
- Extraction-Efficiency Quantification
- Experimental Results and Modeling Validation
- Prediction of the Performance of Coupled System
- Conclusions

Ocean-Wave Power Harnessing Chart

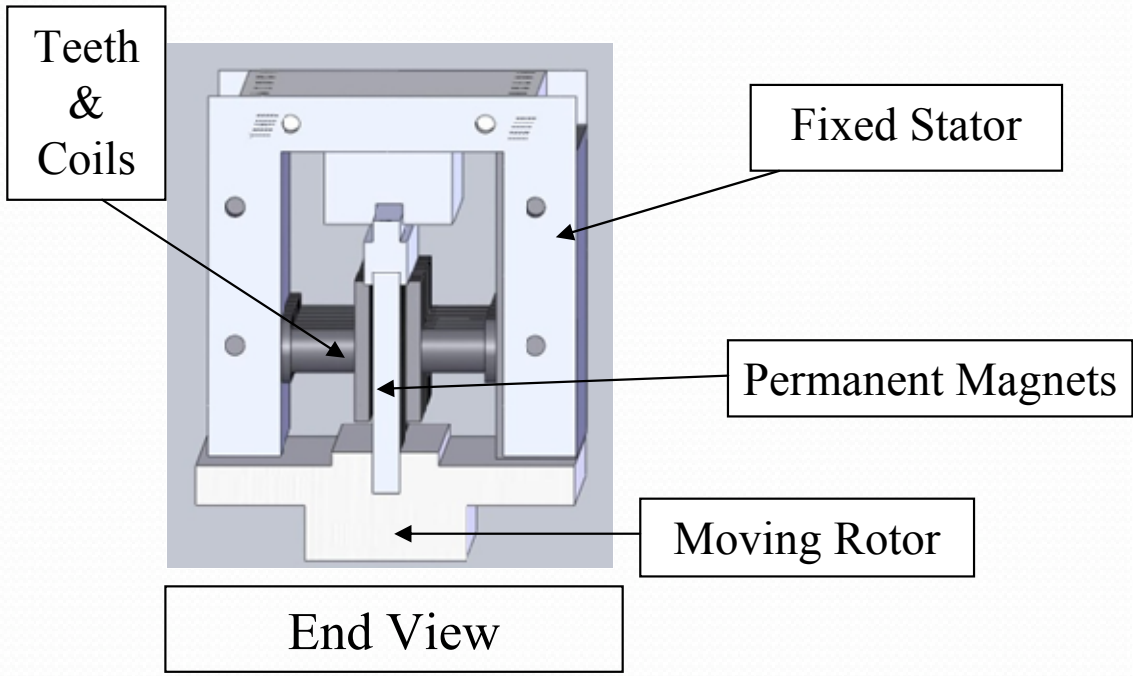


UC Berkeley Extractor Generator Design



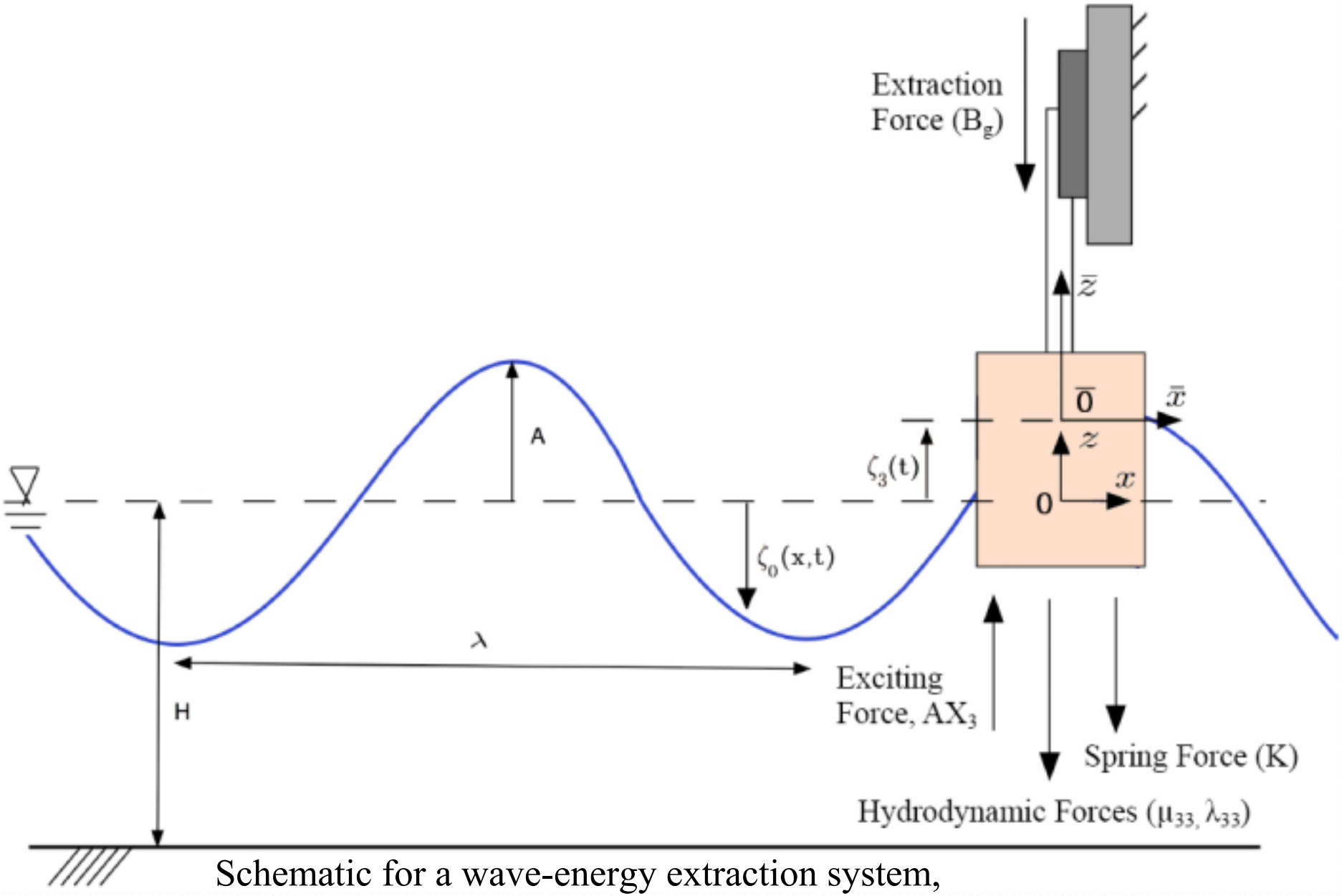
Experimental Set-Up at UC Berkeley Wave Tank

- Two Main Components
  1) Cylindrical Floater
  2) Linear Generator
     - Rotor (moving magnet)
     - Stator (wound coils)



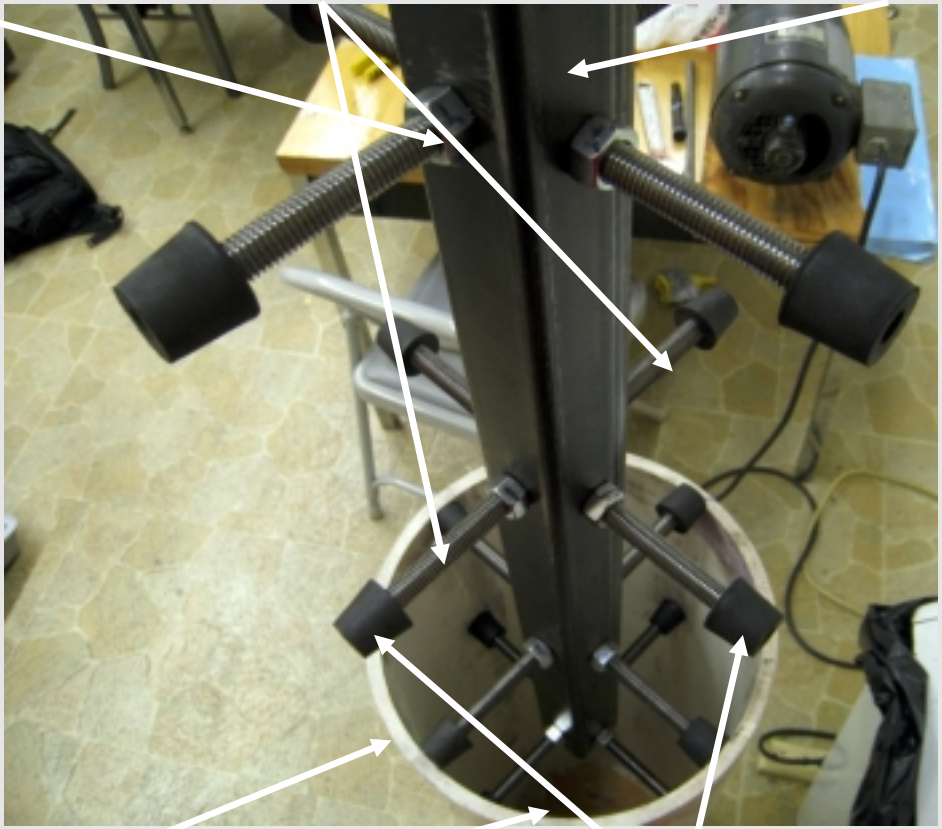
End View

Description of Problem



Schematic for a wave-energy extraction system,
showing relevant forces and the definitions related to the incident wave

Floater Design



Floater shape designed so its resonant frequency was below the first cut-off frequency of the wave tank *(Yeung & Sphaier, 1989)*.

To avoid undesirable interferences, the following condition was met.

$$\frac{kw}{2\pi} \leq 1 \qquad (1)$$

[designed ~ 0.53]

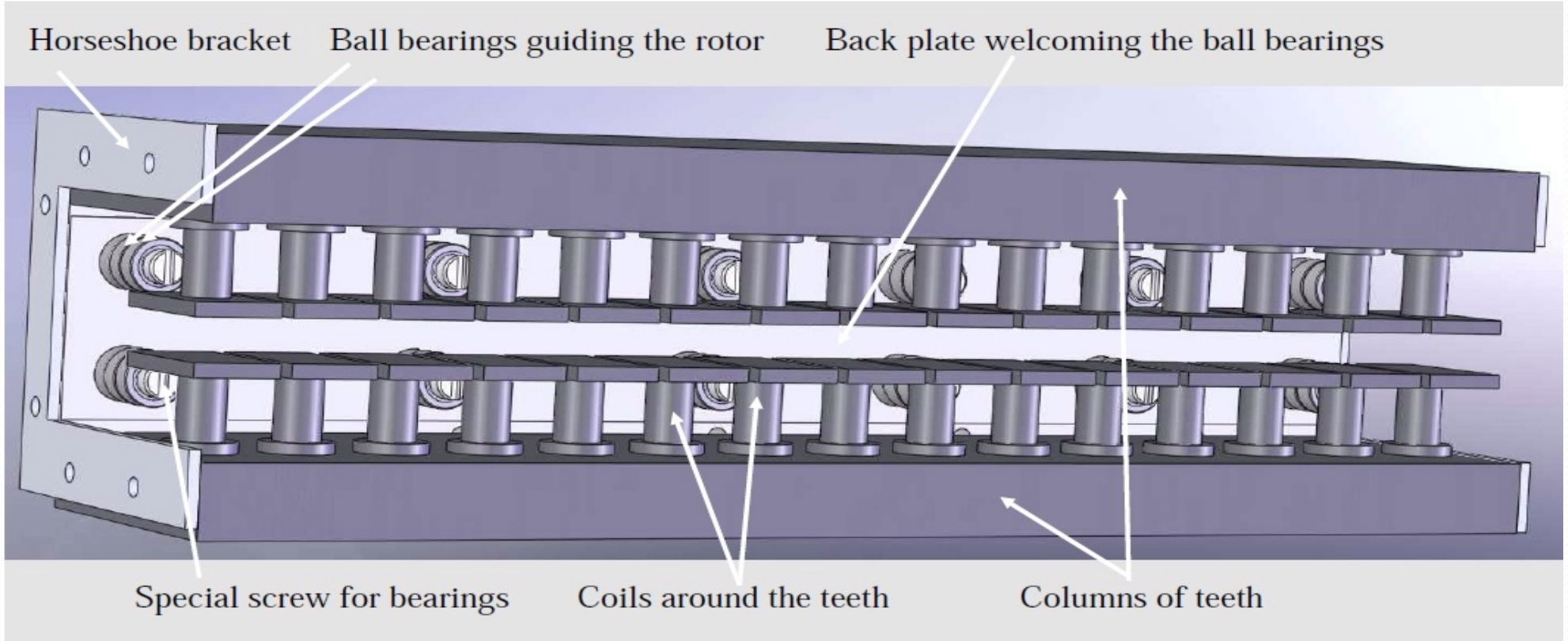
k is the wave number associated with the resonance σ and *w* is the tank width

D (dia) = 2a = 0.273m	d (draft) = 0.6126m Vol = 0.0356m^3
d/D = 2.244	r (corner radius)/D = 0.035
σ_{res}(target) = 3.695 rad/s	T_{res} = *1.7s*
(Tank width,w)/D = 4.487	(Tank depth,*H*)/*w* = 0.612

Floater Characteristics

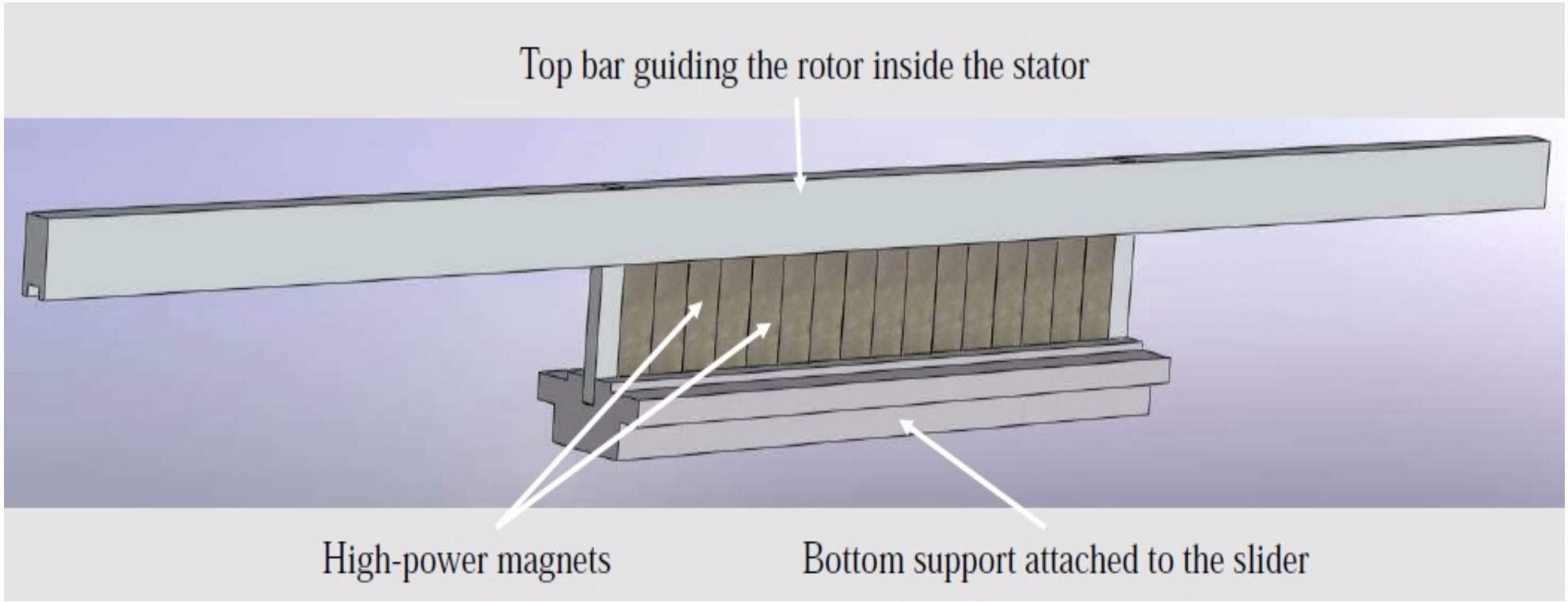
Linear Generator Design

15 Slot / 16 Pole Configuration



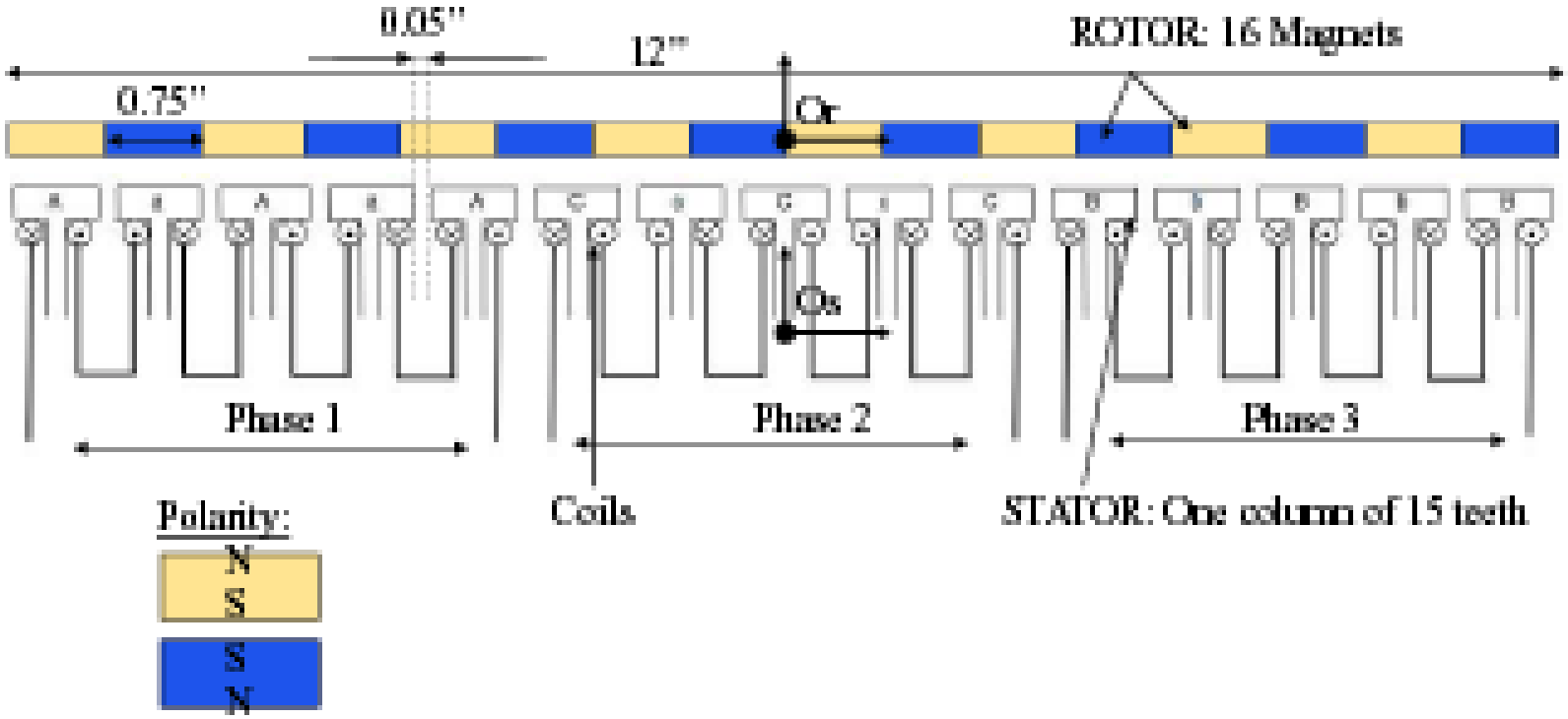
- Stator composed of two columns of 15 teeth
- Each tooth is wound with copper wiring
- Each set of 5 teeth are wired in series to form 1 phase
- Composition is made of 1018 and C1215 steel

Linear Generator Design



- Rotor composed of 16 magnets, NdFeB, grade 42, 0.3048m long
- Magnetization is through the thickness of the magnet
- Adjacent magnets have opposite polarity
- Lateral movement restricted by roller bearings on the stator mounting
- Magnetic flux can be controlled by adjusting gap between the two columns of teeth

Coil wiring configuration for 3-phase circuit.



(c) Diagram showing the dimensions and electrical wiring of the linear generator.

Theoretical Performance of Generator

- Prediction of the theoretical performance of the linear generator is of interest
- Based on ***Faraday's Law*** the voltage of the *j-th* set of coils can be modeled as follows:

$$e_j(t) = -\sum_{i=5(j-1)+1}^{5j} NS\frac{dB}{dt} = B_m \frac{\pi\dot{\zeta}_3(t)}{\tau}\cos\left(\frac{\pi\zeta_3(t)}{\tau} + \varphi_i\right) \qquad (2)$$

where φ_i = phase difference between each tooth,

B_m = magnetic field,

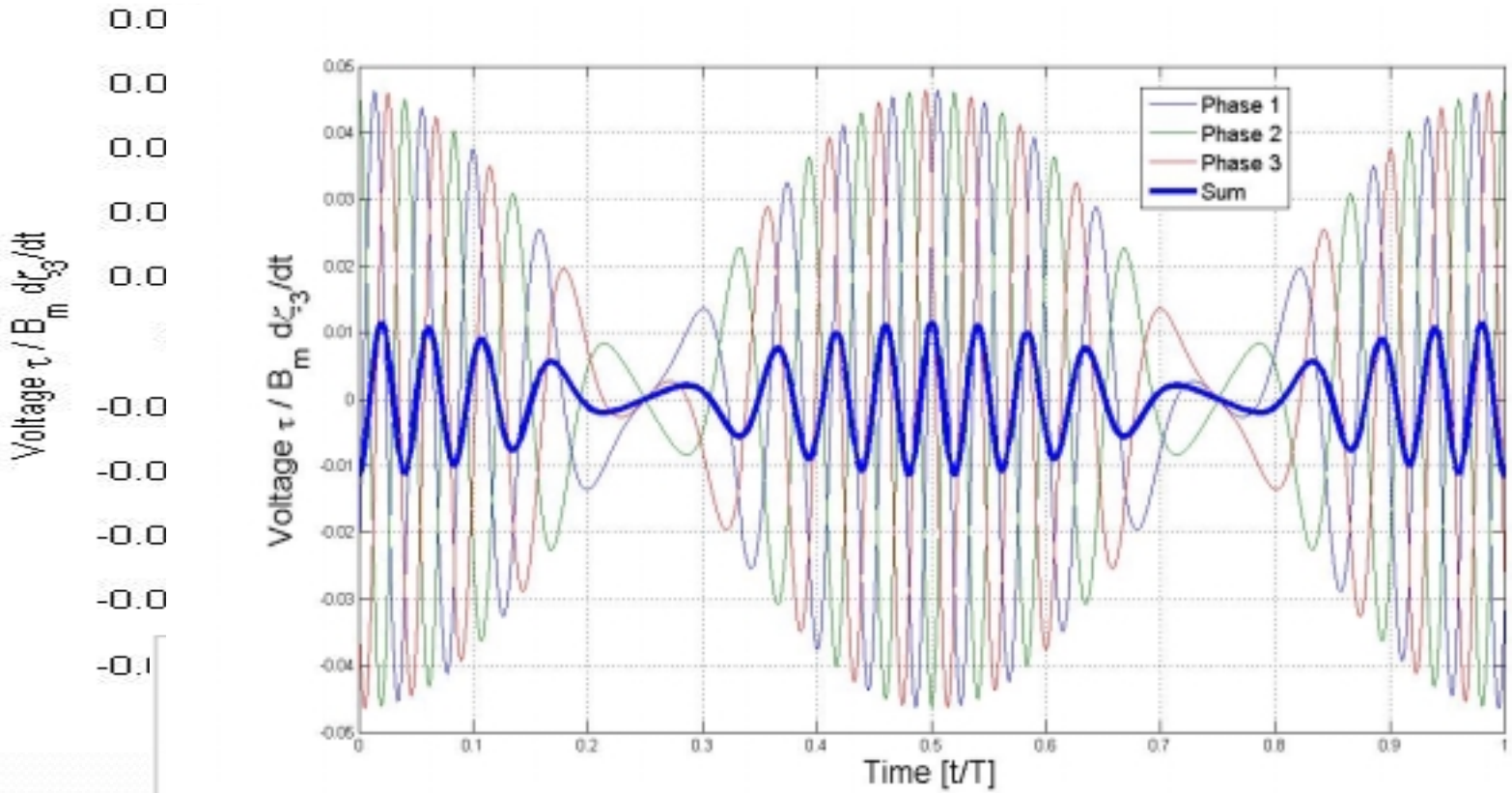
$\zeta_3(t)$ = axial position of rotor,

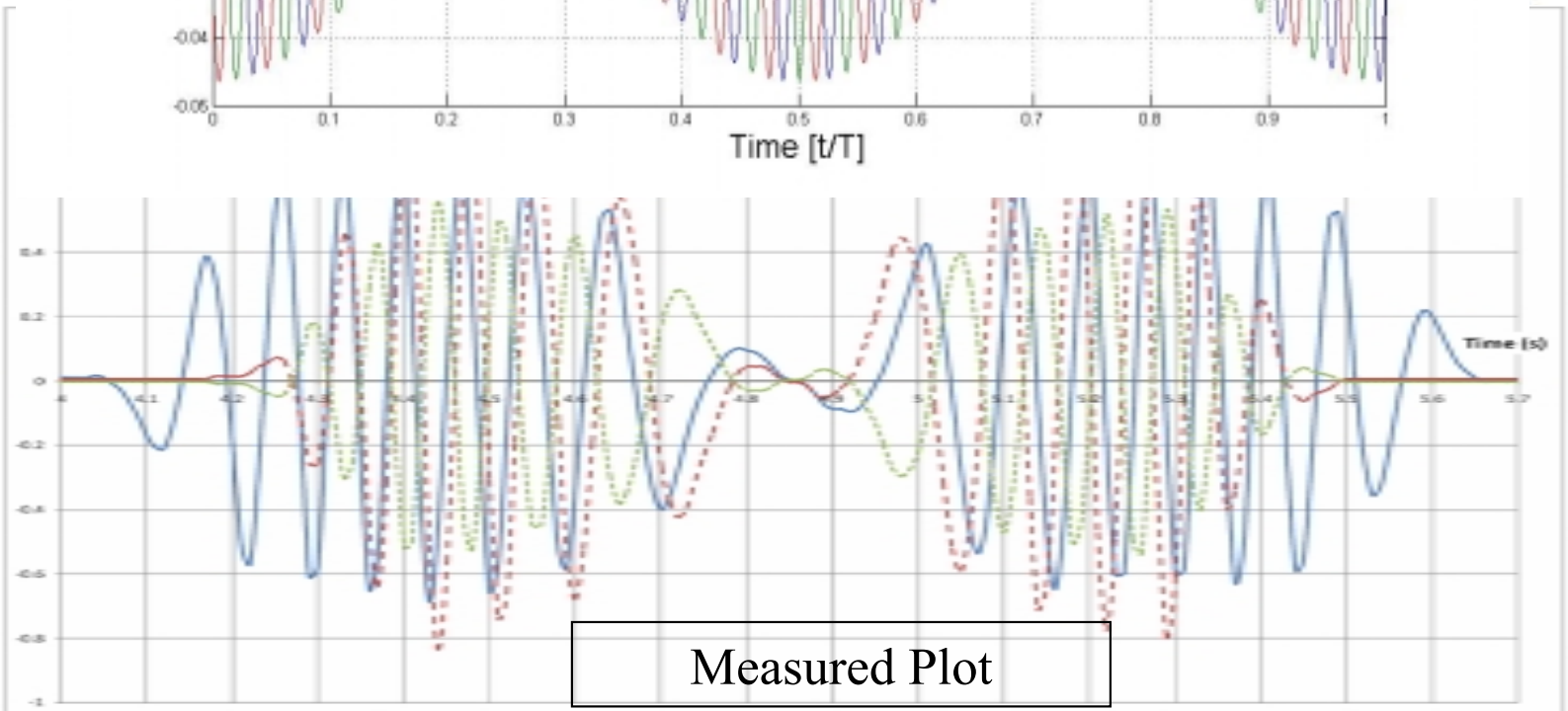
N = number of coil windings,

S = cross sectional area of the coil tooth,

τ = length of the pole (width of one magnet).

Theoretical vs Measured Induced Voltage





Theoretical Model of Extractor Performance

- Complete modeling requires prediction of the motion of the floater which interacts with the generator
- The physical properties of the floater and generator can be investigated separately
- Coupled performance is desired and will determine viability of the device

Floater Hydrodynamics

Yeung et al. (2010)

For a given incident wave, $\zeta_0(x,t)$ of amplitude A and frequency σ, the heave response of the cylinder is given by $\zeta_3(t)$

$$\zeta_0(x,t) = \mathrm{Re}\{Ae^{i(kx-\sigma t)}\} \qquad (3)$$

$$\zeta_3(x,t) = \mathrm{Re}\{A_3 e^{-i\sigma t}\} \qquad (4)$$

where k is the wave number, A_3 is the complex(-time) response amplitude.

Decomposition of the total potential, Φ , into a diffraction Φ_7 and a radiation component Φ_3 leads to the following:

$$\Phi = \mathrm{Re}\{A[\phi_0(x,y,z) + \phi_7(x,y,z)]e^{-i\sigma t}\} + \mathrm{Re}\{\phi_3(x,y,z)\dot{\zeta}_3(t)\} \qquad (5)$$

Heave Response-Amplitude-Operator

The energy extractor has a mass m, spring constant $K = \rho g A_{wp}$, and initially in floating equilibrium ($\rho\forall = m$), the following response amplitude operator (RAO) A_3/A can be derived:

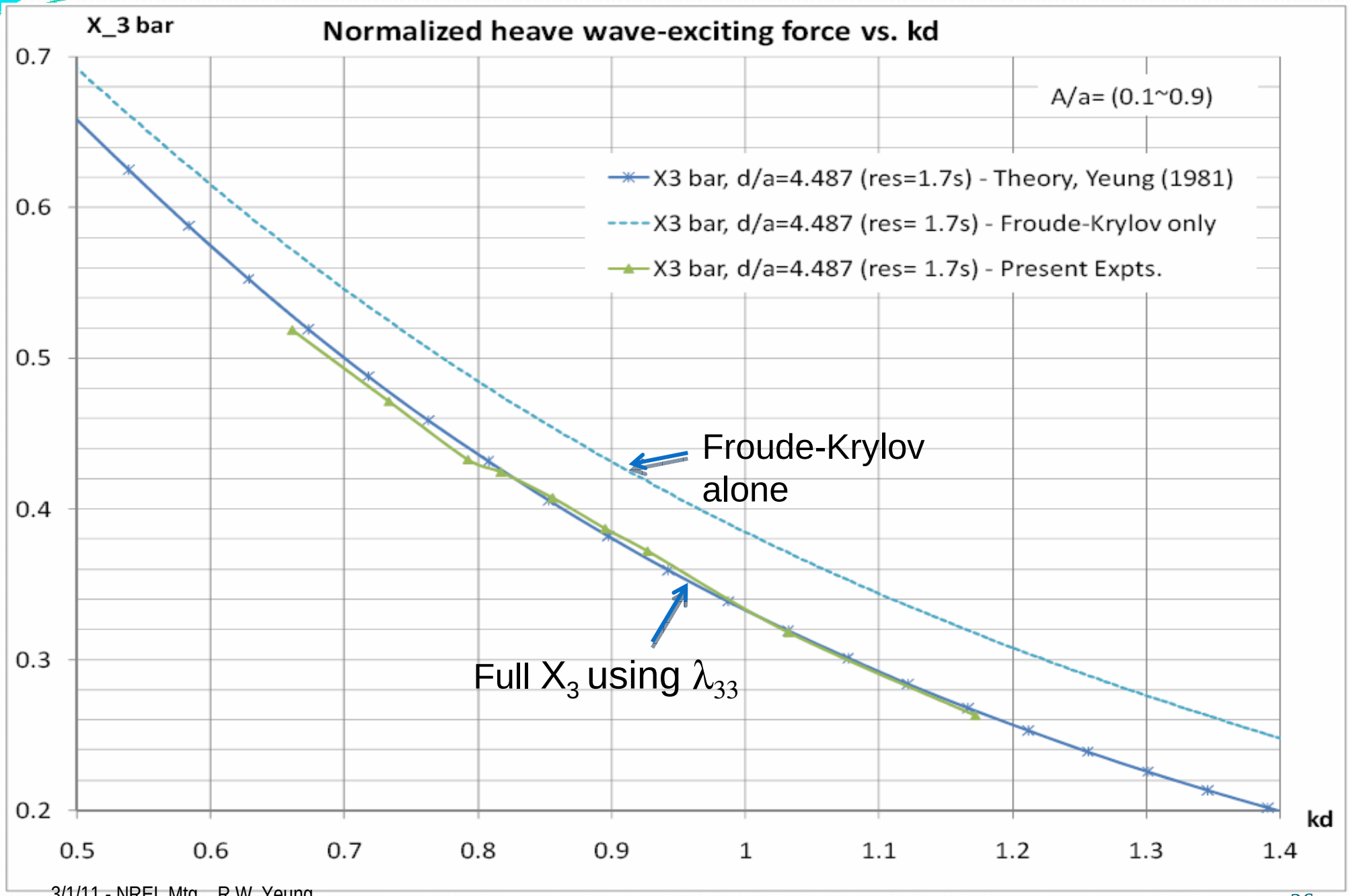
$$\left|\frac{A_3}{A}\right|^2 = \frac{|X_3|^2}{[K-\sigma^2(m+\mu_{33})]^2+[\sigma\lambda_{33}]^2} \qquad (6)$$

$$= \frac{|\overline{X}_3|^2}{[1-\overline{\sigma}^2(\overline{d}+\overline{\mu}_{33})]^2+[\overline{\sigma}\,\overline{\lambda}_{33}]^2} \qquad (7)$$

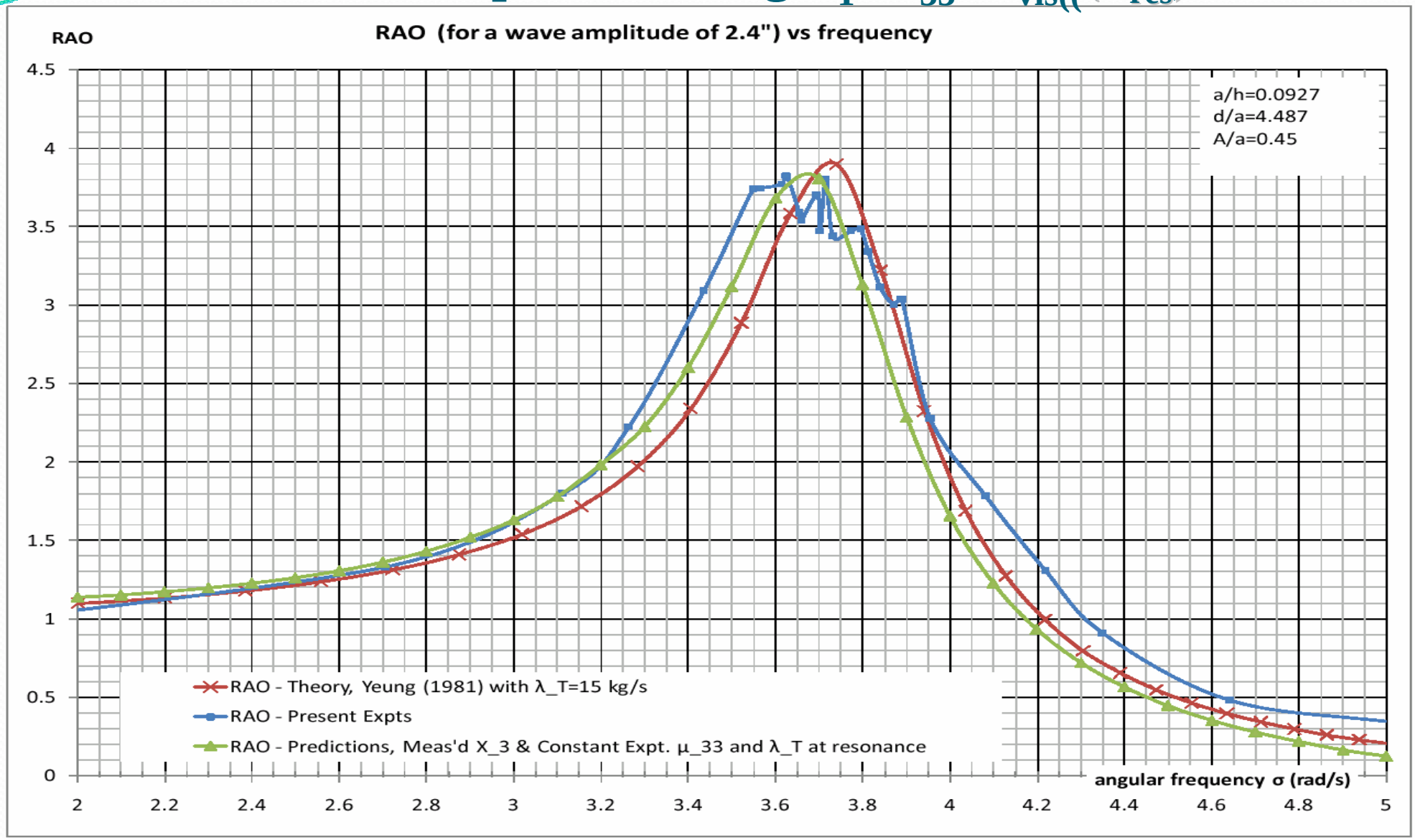
X_3, μ_{33}, and λ_{33} are the heave wave-exciting force, heave added mass and heave (inviscid) damping coefficients respectively. Over-barred quantities are normalized. Applied Ocean Research (Yeung, 1981)

$$\text{Haskind Relation}: \frac{|X_3|^2}{\lambda_{33}} = \frac{2\rho g^3}{\sigma^3} \qquad (9)$$

Measured Wave-Exciting Force



Measured Free-Motion Response vs Predicted Response, using $\lambda_T = \lambda_{33} + \lambda_{vis((}(\sigma_{res})$



Free-motion response of floater as a function of frequency σ for a floater ballasted to have a target T_{res} = 1.70s (σ = 3.7rad/s)

Electromagnetic (EM) Device and Coupling Model

In the frequency domain, the force created by the linear generator is modeled by the following equation.

$$F_g = -[K_g(\sigma) - \sigma^2 \mu_g(\sigma)] \times \zeta_3(t) - B_g(\sigma) \times \dot{\zeta}_3(t) \quad (12)$$

where K_g, B_g, and μ_g are respectively the spring, damping, and inertia of the generator, time-averaged at the frequency in question.

These coefficients depend on the following properties, or physical variables

- winding geometry,
- configuration of the stator-rotor, z_*gap*
- driving frequency, σ
- delivery resistive load, R

A (dry) bench test was performed to evaluate these coefficients under various operating conditions.

RAO with Coupling from EM Device

- The RAO can be modified to incorporate the E-M force
- The viscous damping λ_{vis} is significantly larger than radiation damping λ_{33}

The following normalized coefficients and parameters are introduced as follows.

$$\left|\frac{A_3}{A}\right|^2 = \frac{\left|\overline{X}_3\right|^2 \overline{K}^2}{[\overline{K} - \overline{\sigma}^2(\overline{d} + \overline{\mu_{33}})]^2 + [\overline{\sigma}^2 \overline{\lambda_T}(1+\tilde{f})]^2} \qquad (13)$$

With $\overline{\lambda_T} = \overline{\lambda_{33}} + \overline{\lambda_{vis}}, \quad \overline{K} = 1 + \frac{K_g + K_{sp}}{K}, \quad \tilde{f} = \frac{B_g}{\lambda_T} \qquad (14)$

Extractor Efficiency & Capture Width

The time-averaged mechanical power $\overline{\dot{W}}$ input to the generator relative to unit-width energy wave energy influx :

$$C_w = \text{capturewidth} = \frac{\overline{\dot{W}}}{\frac{1}{2}\rho g A^2 V_g} = \frac{\frac{1}{T}\int_0^T B_g \dot{\zeta}_3(t)^2\, dt}{(\rho g^2 A^2)/\sigma} \qquad \tilde{f} = \frac{B_g}{\lambda_T}$$

$$= \frac{\pi a}{2} \left. \frac{\overline{K}\, \left|\overline{X}_3\right|^2}{\overline{\lambda_T}} \right|_{\text{Res}} \times \frac{\tilde{f}}{(1+\tilde{f})^2} \qquad (15)$$

Optimal conditions : Resonance $\Rightarrow$ Total inertia force cancels spring force

$$\text{Also,} \qquad \tilde{f} = 1, \quad \text{or } B_g\big|_{OPT} = \lambda_T \qquad (16)$$

$$\text{Increasing } C_w \Rightarrow \left|\overline{X}_3\right| \uparrow, \text{ and } \lambda_T \downarrow \qquad (17)$$

$$\text{Inviscid - fluid only :} \quad C_w = \frac{\lambda}{2\pi} \qquad (18)$$

Electrical Efficiency

The efficiency of the generator η_{el} can be defined to quantify the electricity conversion process within the E-M generator with the mechanical motion input:

$$\eta_{el} = \frac{P_{el}}{P_{mech}} = \frac{\frac{1}{T}\int_{t}^{t+T} i^2(t)R\,dt}{\overline{\dot{W}}} \qquad (24)$$

where the time-averaged power from an electrical current of intensity *i(t)* going into a "power-take-off (PTO)" resistor of value ***R*** is shown by the integral.

Bench Test of the Linear Generator

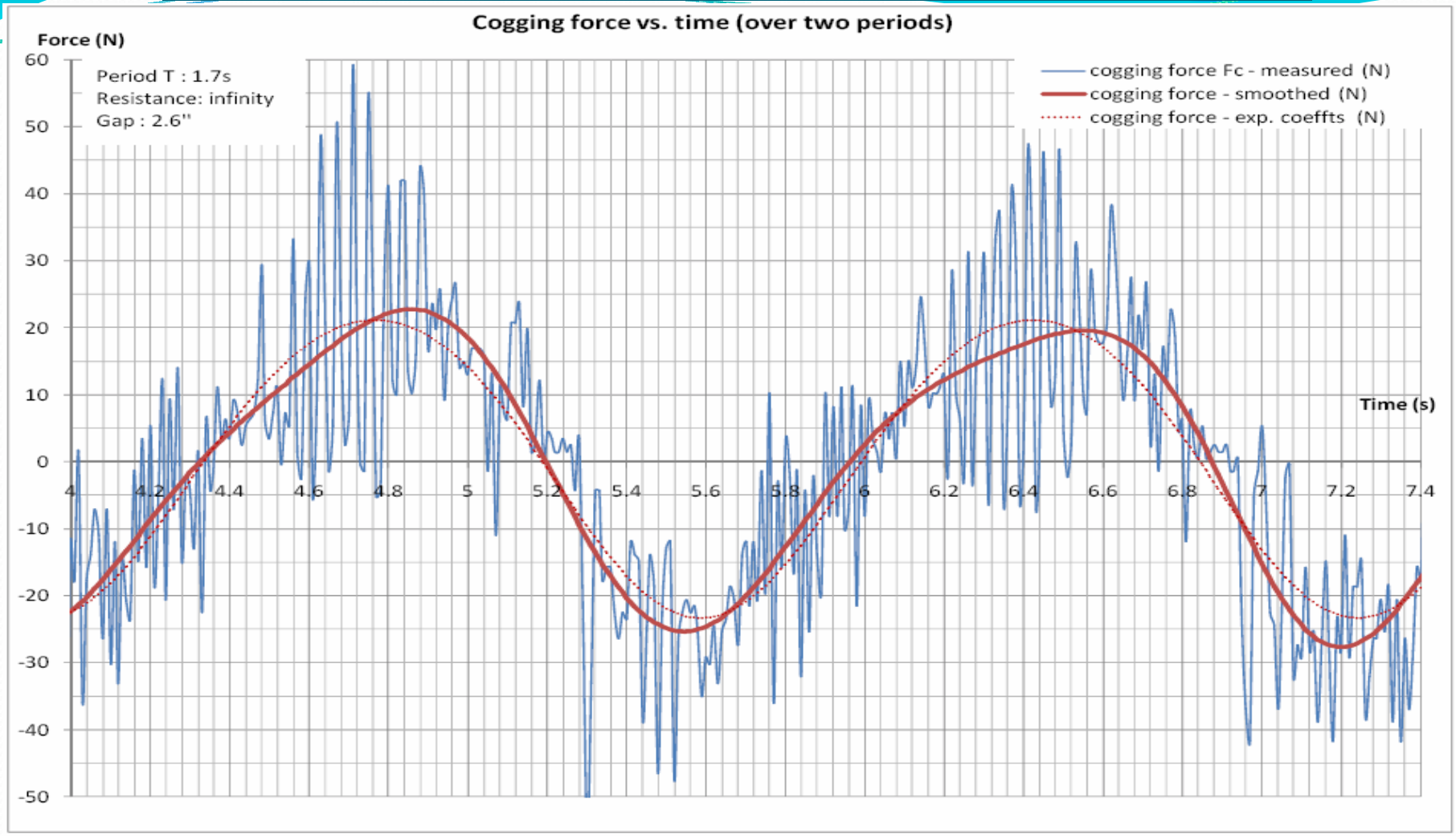
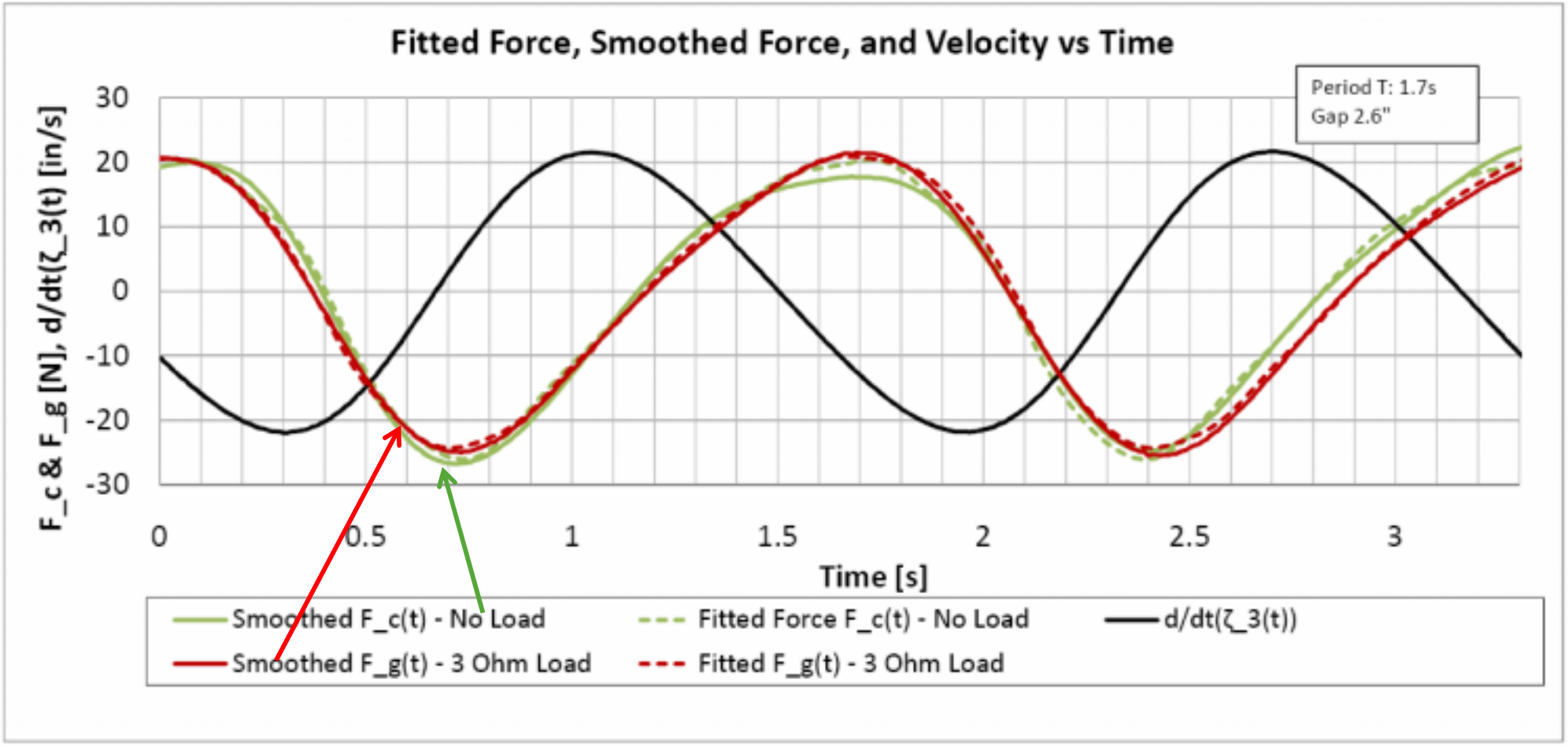


Figure contains typical force trace coming off the dynamometer. The force signal of F_c is smoothed and Fourier analyzed so that the primary-frequency coefficients of the generator can be identified.

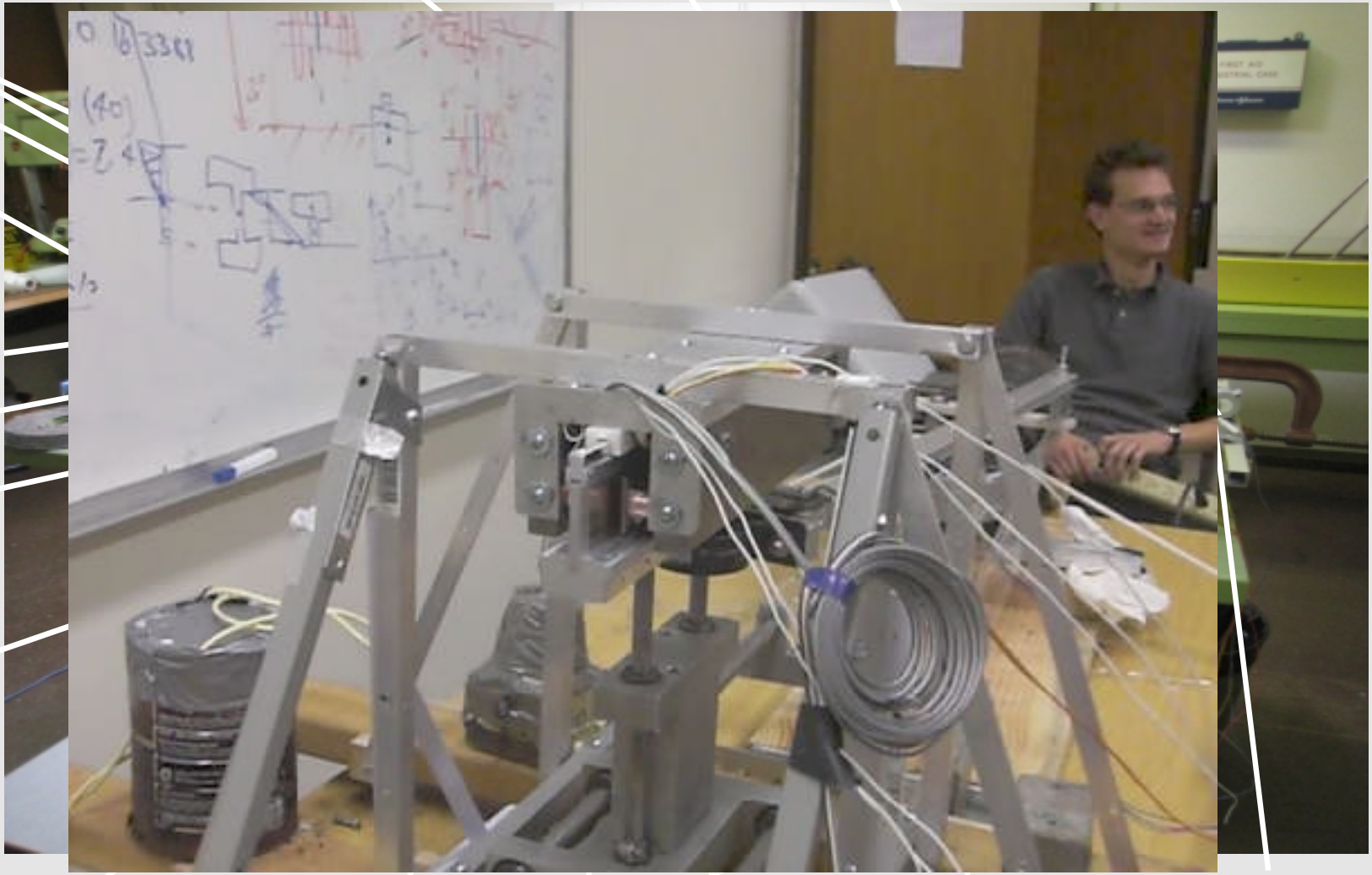
The highly oscillatory nature of the force is not a noise, but a consequence of the alignment of the poles and slots.

Bench Test of the Linear Generator – Cogging Force



The above figure shows the smooth and reconstructed force curves with no load and with a resistive load of R = 3 Ohms. The closeness of these two curves indicates that F_g is dominated by F_c, which is undesirably dissipative.

Bench Test of the Linear Generator

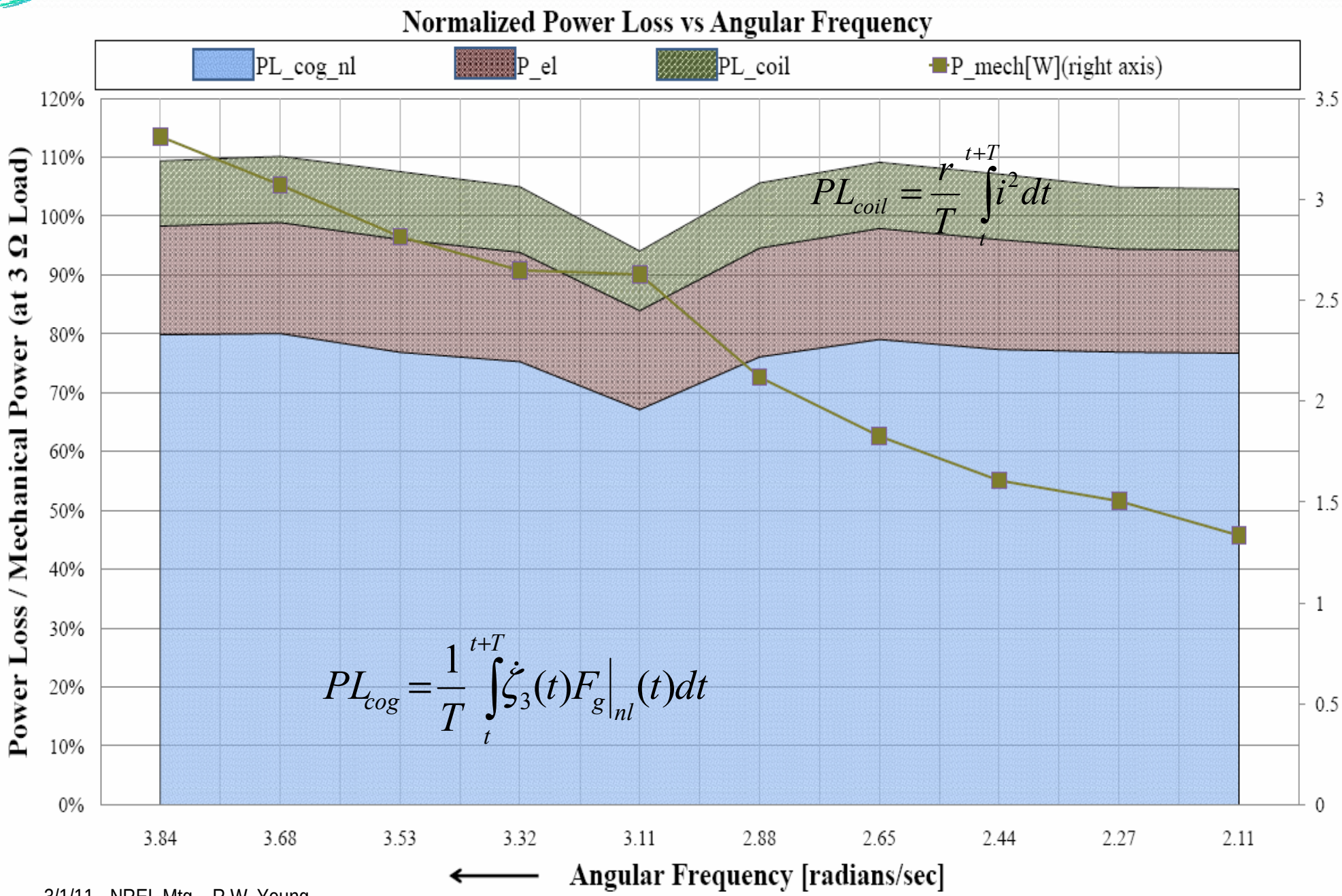


Video of Experimental Bench Test

Bench Test of the Linear Generator - Details

- The "spring-inertia" coefficients are relatively small compared to the corresponding values of the floater.
- The generator damping B_g varies almost linearly with the angular frequency σ
- At a period of 1.7s, the highest electrical power P_{el} is obtained with a resistive load R of 3 Ω.
- The resistive load, R=3 Ω, is great than r = 1.6 Ω, the coil resistance in series for each of the three phase circuits.
- Neglecting the inductance of the coils, due to relatively slow speeds, the location of the maximum P_{el} may not correspond to the simple condition of $R=r$, which is the criteria for maximum power under basic circuit theory.

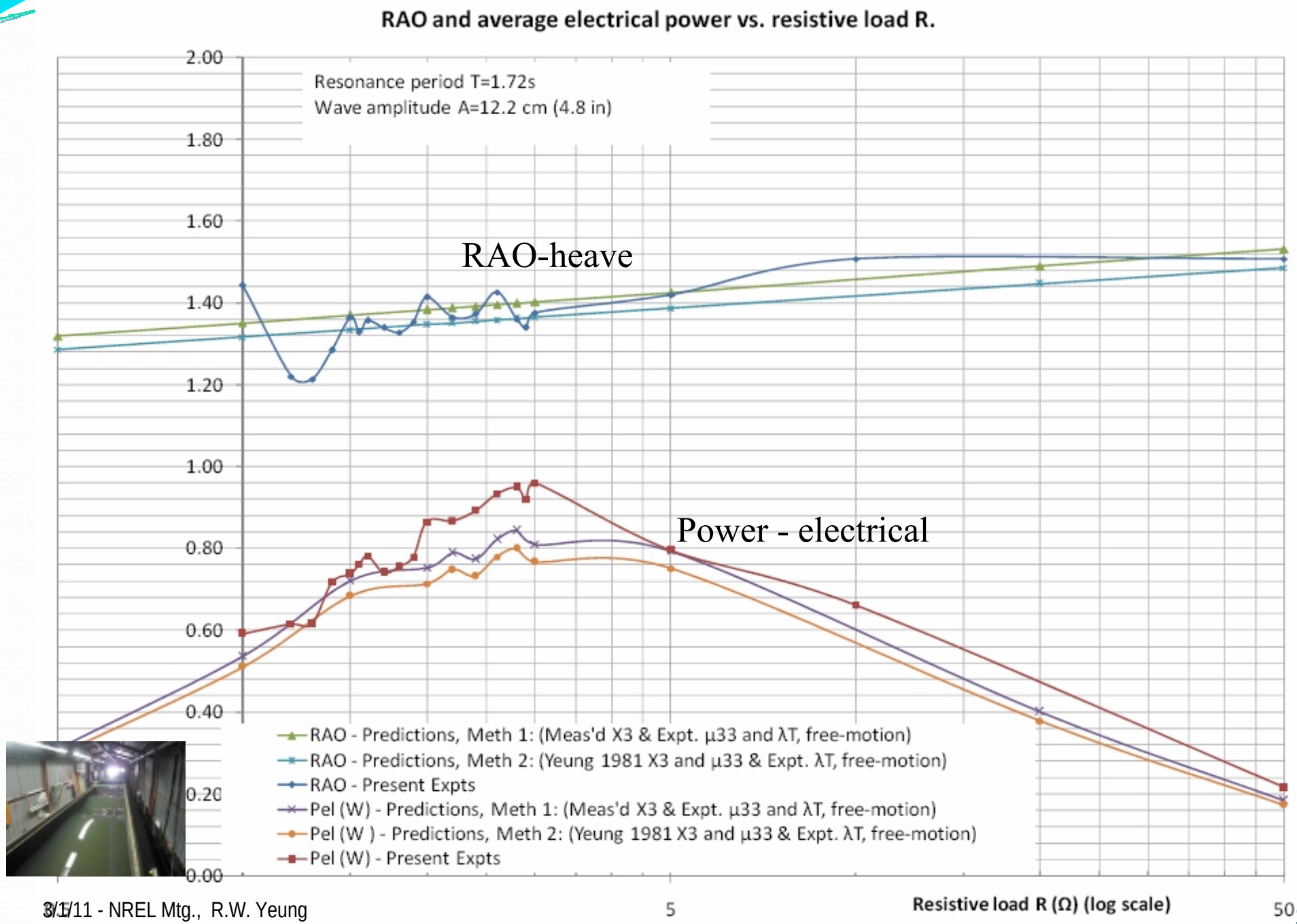
Quantification of Power Losses



$$PL_{coil} = \frac{r}{T}\int_{t}^{t+T} i^2 dt$$

$$PL_{cog} = \frac{1}{T}\int_{t}^{t+T} \dot{\zeta}_3(t) F_g\big|_{nl}(t)\,dt$$

Prediction of Performance of the Coupled System, vs PTO R



Conclusions

- Object of this research is to demonstrate the technology of generating electricity from ocean waves, and to control and optimize this generation process by developing the proper coupling models.

- Both theoretical and experimental models are used to obtain the hydrodynamic properties of the floater and the generator characteristics of a specific design.

- Floater performance can be determined by inviscid-fluid hydrodynamics theory, but improved by test data (to take into account of viscosity effects in damping)

- Generator characteristics are determined by electromagnetic theory and measured with a (dry) bench test. Primary loss in the electrical process has been identified: a large cogging force that needs to be reduced.

- Fabrication of a 2-piece design is in progress. A new generator has been designed and tests are planned; anticipating $\eta_{el} \equiv P_{el} / \overline{\dot{W}} \sim 60\%$ with a passive system, w/o a real-time controller.

Thank you for your attention.

Questions & Comments?