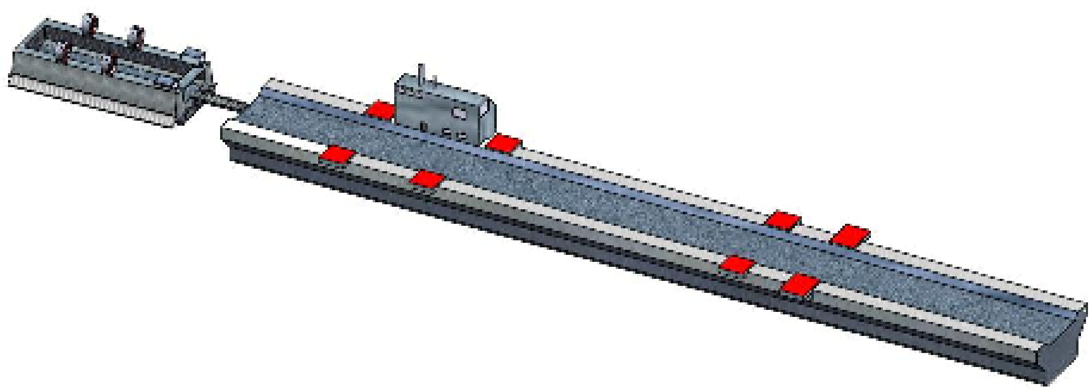
Optimization of Wave-Induced Motion of Ramp-Interconnected Craft for Cargo Transfer

Miroslav Krstic
Director, Center for Control Systems and Dynamics
University of California, San Diego



Students:
- Joseph Doblack
- Jacob Toubi
- Aleksander Veksler

Introduction

- **Problem :** Reduce oscillations, primarily of ramp, and primarily in pitch, at Sea State 4 (1.25 to 2.5 m) to allow safe cargo transfer between ships.

- **Control Methods Investigated**
  - Extremum Seeking
  - Passive Control
  - Active Control

- **Actuation Ideas Considered**
  - Ship heading
  - Ramp length
  - Absorbers at ramp joints
  - Lateral fins on T-Craft

Models of System

Wave, ship, ramp, and interconnections

Modeling the Wave Front

- $y(s)$ = force created by waves, $w(s)$ = Gaussian white noise, σ_w = wave intensity , ω_0 = primary frequency, ζ = damping coefficient

$$y(s) = \frac{2\zeta\omega_0\sigma_\omega s}{s^2 + 2\zeta\omega_0 s + \omega_0^2} w(s)$$

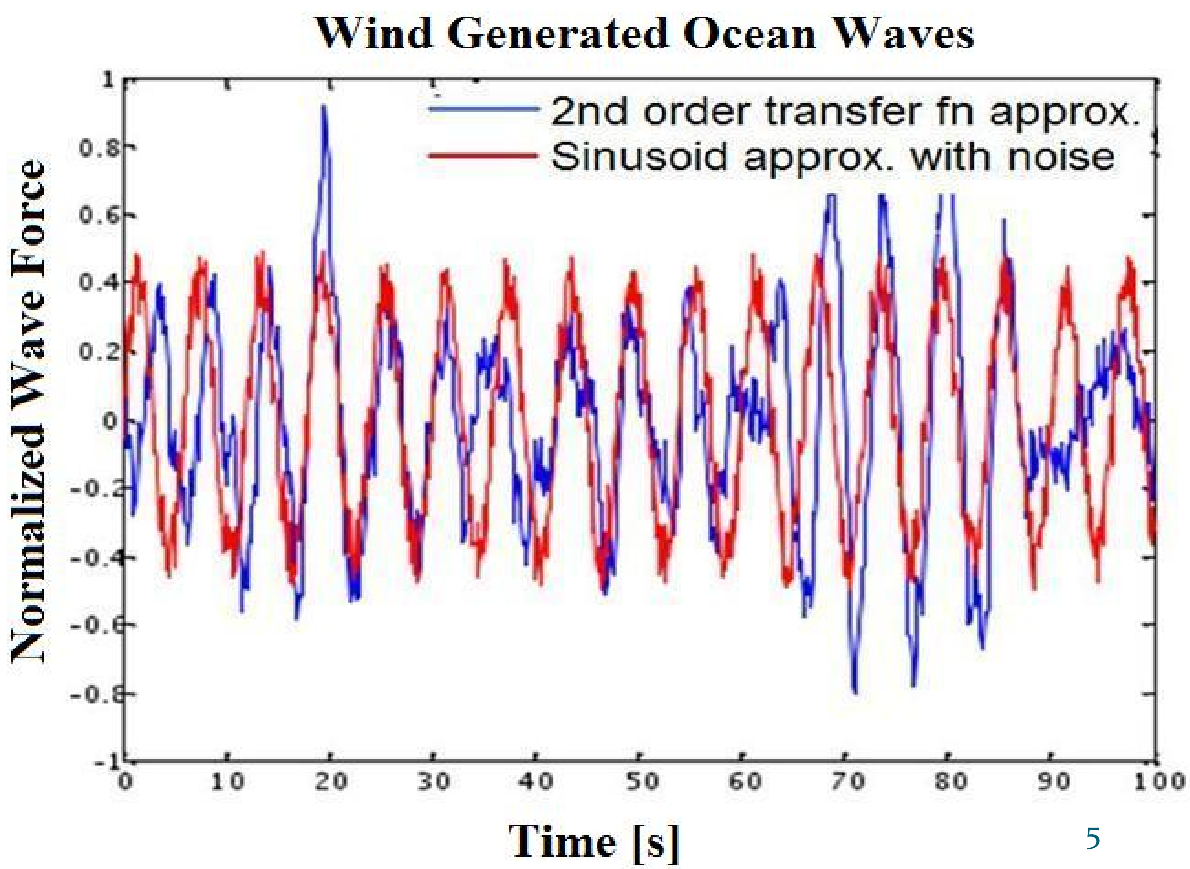
- Power spectral density of wave force (noise spectrum $\Phi_w(\omega) = 1$):

$$\Phi_y(\omega) = \left| \frac{2(\zeta\omega_0\sigma_\omega) j\omega}{(\omega_0^2 - \omega^2) + 2\zeta\omega_0 j\omega} \right|^2 = \frac{4(\zeta\omega_0\sigma_\omega)^2 \omega^2}{(\omega_0^2 - \omega^2)^2 + 4(\zeta\omega_0\omega)^2}$$

Modeling the Wave Front

Even simpler representation of ocean wave as sine wave with superimposed noise: $y(t) = A\sin(\omega_0 t + \varphi) + w(t)$

Comparison of second order approximation and sinusoid with additive noise:



Ship Equations of Motion

- Uncoupled ship equations of motion (resemble spring-mass-damper eqs):

Roll: $$J\ddot{\alpha} + 2Jb\dot{\alpha} + g\Delta GM_R\alpha = g\Delta GM_R\xi_0 \sin(\omega t)$$

Pitch: $$J\ddot{\beta} + 2Jb\dot{\beta} + g\Delta GM_P\beta = g\Delta GM_P\xi_0 \sin(\omega t)$$

Heave: $$m\ddot{x} + b\dot{x} + \rho g A_W x = \rho g A_W \xi_0 \cos(\omega t)$$

- β, α, x = pitch, roll, heave, J = mass moment of inertia, Δ = mass of water displaced, GM_P /GM_R = pitch/roll metacentric heights, A_W = waterplane area, ξ_0 = amplitude, ρ = water density, ω = wave freq
- Ocean waves modeled as force disturbances at vessel corners
- Surge, sway, and yaw dof not opposed by hydrostatic restoring forces

Ship Equations of Motion

Final values of spring constants:

$$k_{heave} = \rho g A_W = \rho g 2L\sqrt{r^2 - (r-T)^2}$$

$$k_{roll} = g\Delta GM_R = g\Delta\left[r - \frac{\frac{2}{3}r^3 \sin^3\left(\cos^{-1}\left(\frac{r-T}{r}\right)\right)}{r^2\cos^{-1}\left(\frac{r-T}{r}\right) - (r-T)\sqrt{r^2-(r-T)^2}} + \frac{\frac{Lw^3}{12}}{L\left[r^2\cos^{-1}\left(\frac{r-T}{r}\right) - (r-T)\sqrt{r^2-(r-T)^2}\right]} - \left(r - \frac{4r}{3\pi}\right)\right]$$

$$k_{pitch} = g\Delta GM_P = g\Delta\left[\frac{1}{2}T + \frac{\frac{wL^3}{12}}{L\left[r^2\cos^{-1}\left(\frac{r-T}{r}\right) - (r-T)\sqrt{r^2-(r-T)^2}\right]} - \frac{r}{2}\right]$$

Valid for *small displacements* for cylindrical bodies

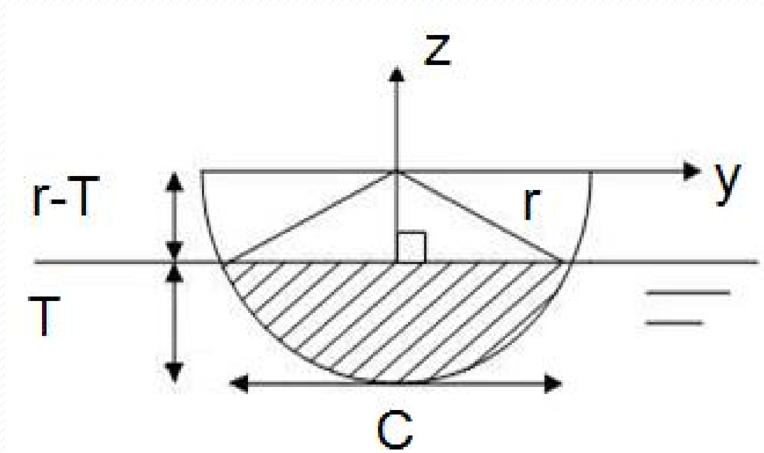
Ship Equations of Motion

Spring Constants:

$$k_{roll} = g\Delta GM_R \qquad k_{pitch} = g\Delta GM_P \qquad k_{heave} = \rho g A_W$$

Waterplane Area (shaded):

$$A_W = 2L\sqrt{r^2 - (r-T)^2}$$

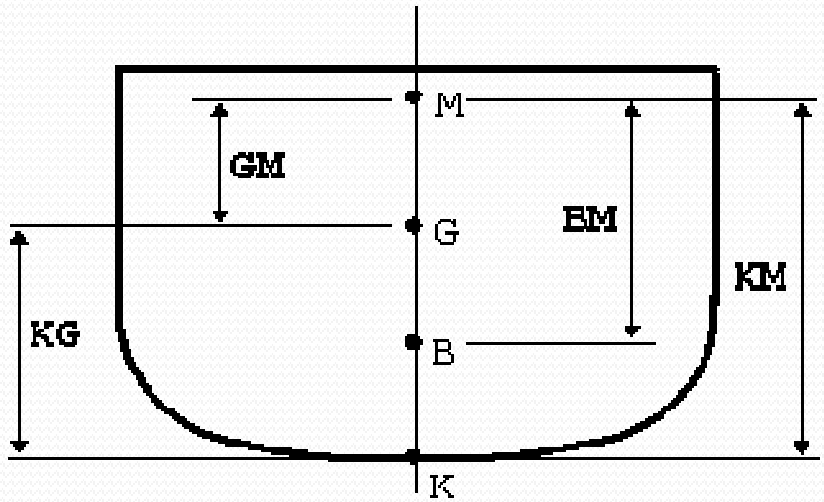


Ship Equations of Motion

- Metacentric Height:

  distance between center of gravity and metacenter

$$\vec{GM} = \vec{KB} + \vec{BM} - \vec{KG}$$

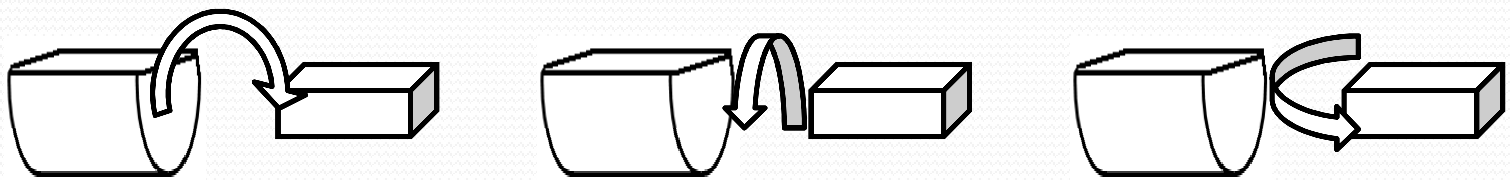


- KB = keel to center of buoyancy
- BM = metacentric radius
- KG = keel to center of gravity

Ship Modeling: Joints

Degrees of freedom for joints between ships and ramp:

Pitch dof Roll dof Yaw dof



Ship Ramp Ship Ramp Ship Ramp

Joint Cases Considered:

- Pitch Joint
- Pitch-Roll Joint
- Pitch-Roll-Yaw Joint

Number of differential eqns in the model:

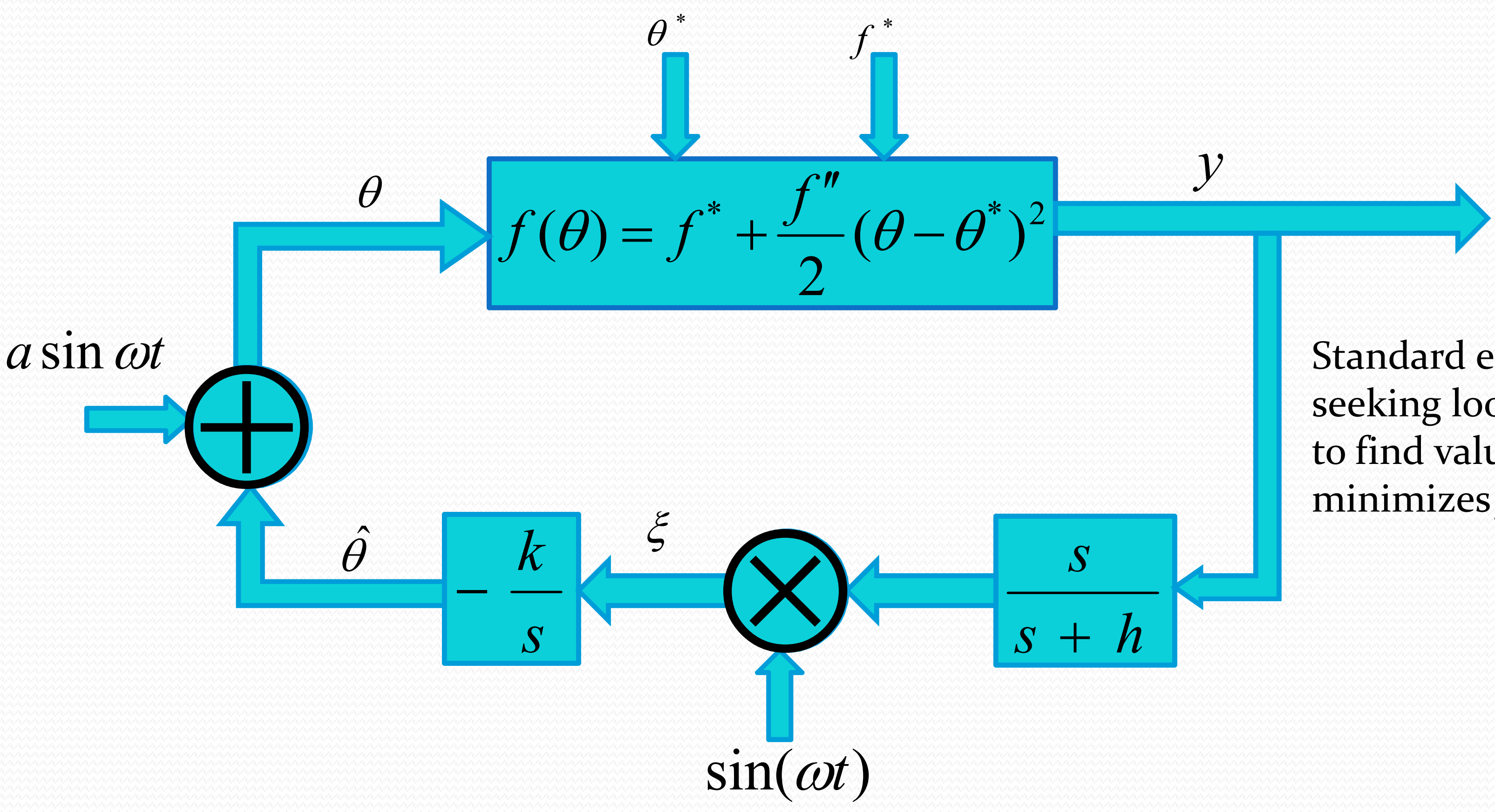
- Using Pitch Joint: 16
- Using Pitch-Roll Joint: 20
- Using Pitch-Roll-Yaw Joint: 24

Basic Parameters

Vessel	Length [m]	Width [m]	Weight [ton]
T-Craft	**40**	**16**	**2,000**
Sea Base	**200**	**30**	**50,000**
Tank	8	3.7	60

Extremum Seeking (brief intro)

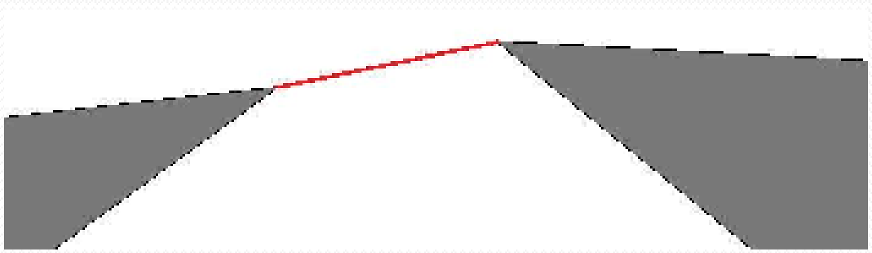
- Method of non-model based real-time optimization
- Applies sinusoidal perturbations to extract gradient info



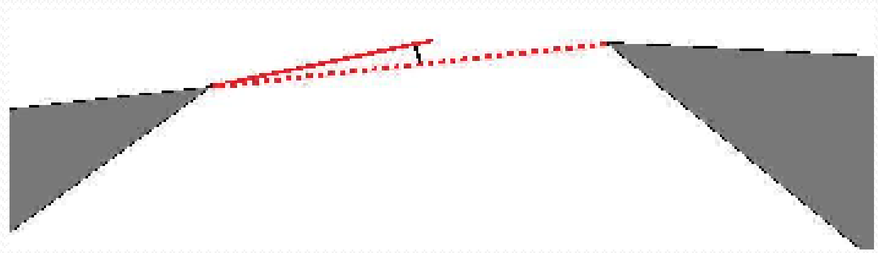
Standard extremum seeking loop designed to find value of θ^* that minimizes $f(\theta)$

Using ES for optimization of ramp length and ship orientation

- Lengthening ramp, and thus distance btw vessels, reduces pitch ampl
- Ship orientation has non-intuitive effects on pitch ampl.
- Ramp length and ship heading controlled through ES algorithm



Relative heave and vessel separation determine pitch angle

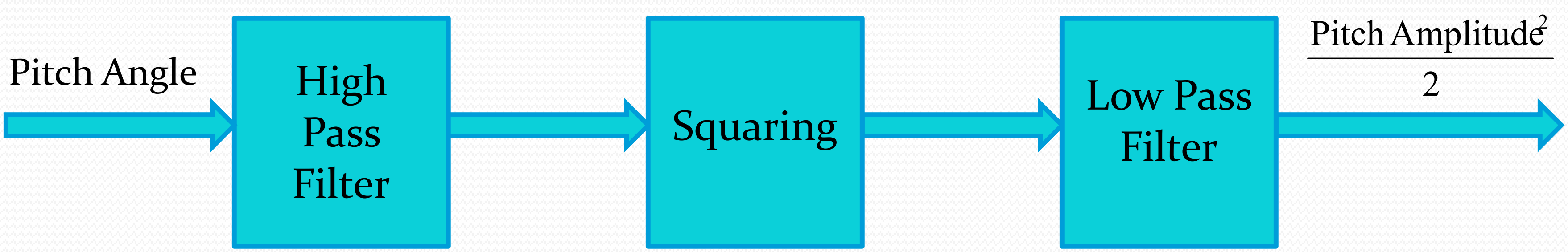


With similar heaves, an increase in ramp length directly reduces pitch as seen in old pitch (solid line) to new pitch angle (dashed line)

How ES is applied to the model

Pitch angle is required to formulate cost:

$$\text{Pitch}(t) = \text{Pitch}^{\text{nom}} + P_a \sin(\omega t + \phi)$$



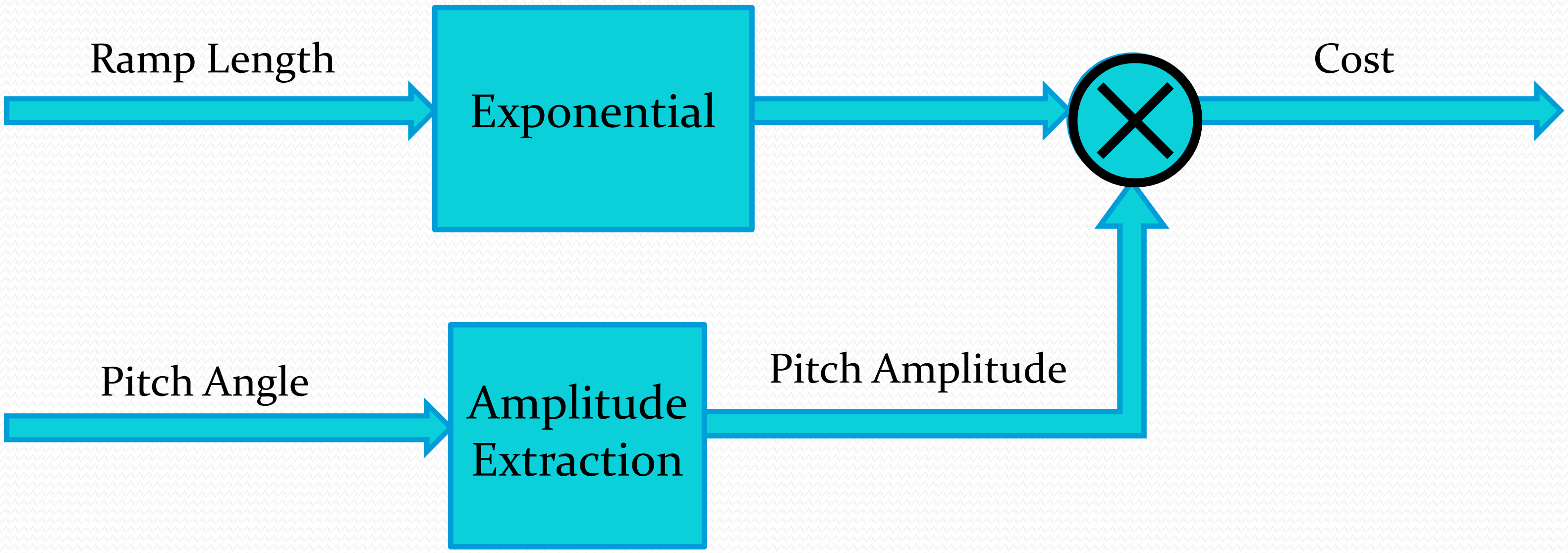
Optimization Cost/Penalty

Pitch amplitude and ramp length are penalized.

$$\text{Cost} = P_a \times 1.003^{R^2}$$

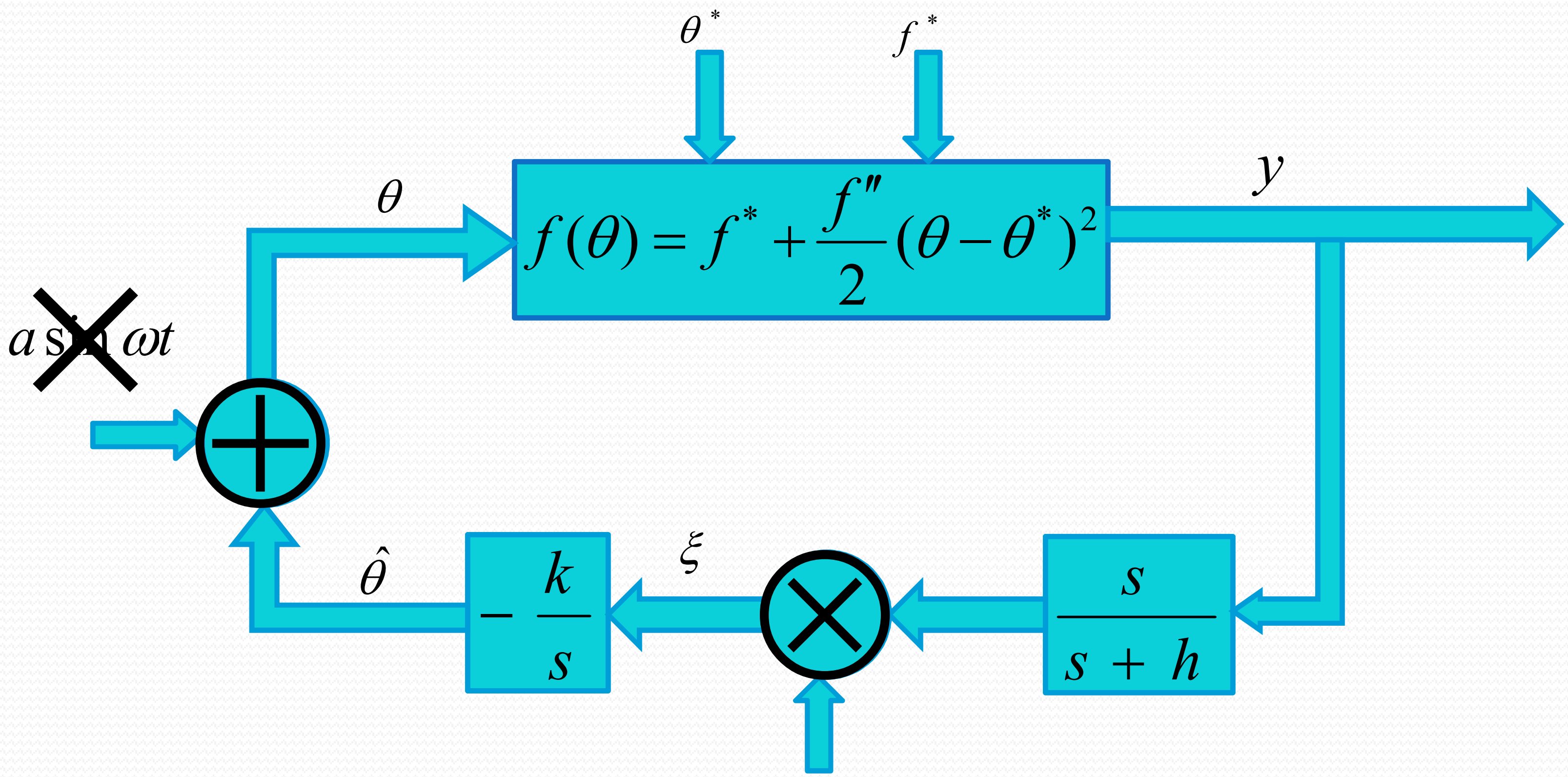
P_a =Pitch Amplitude

R =Ramp Length



Waves provide excitation for ES

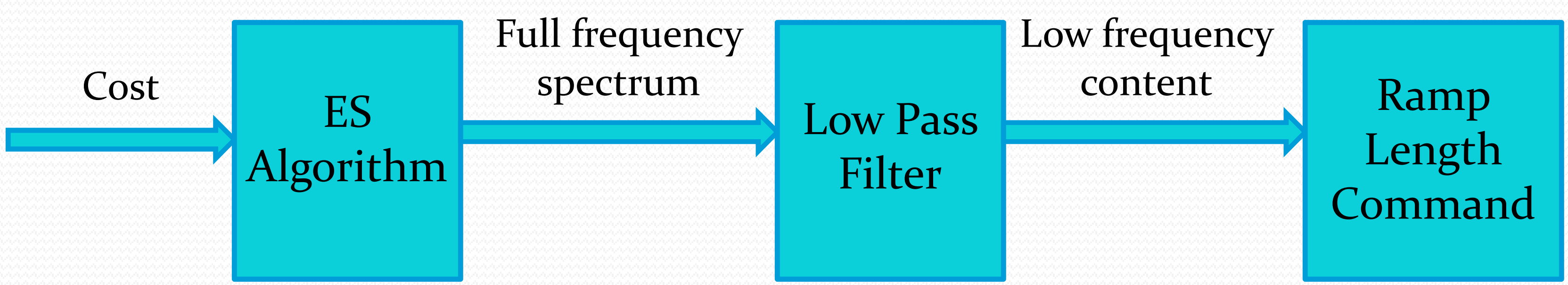
Normally sinusoidal excitation added in ES loop



"Pumping" of the ramp not needed!

Signal filtering

- Ramp length command filtered to eliminate wave frequency content
- Ramp extends smoothly

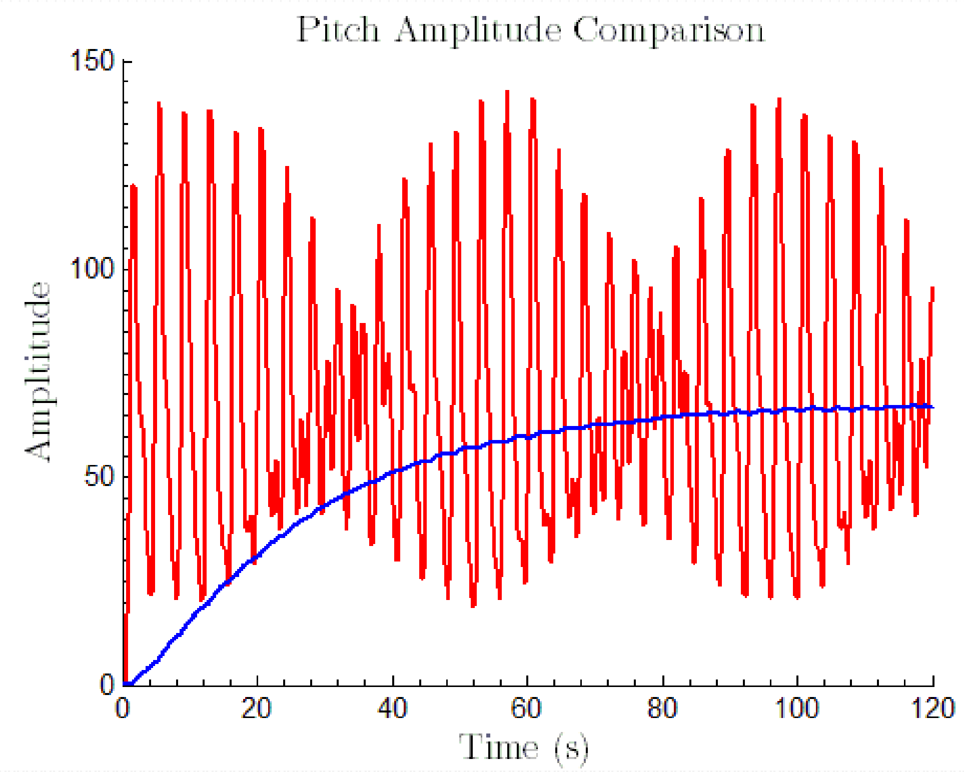


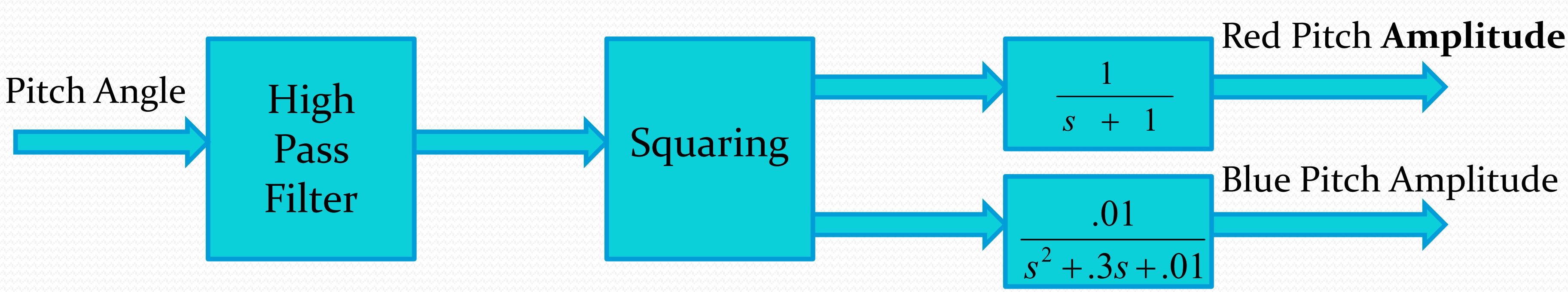
Mapping the cost in terms of ramp length and ship orientation

- Cost mapped to understand the global dependence on ramp length and ship heading
- Simulations run for ramp lengths from 5 to 20 meters and heading angle (w.r.t. waves) from 0 to 90 deg

Cost map

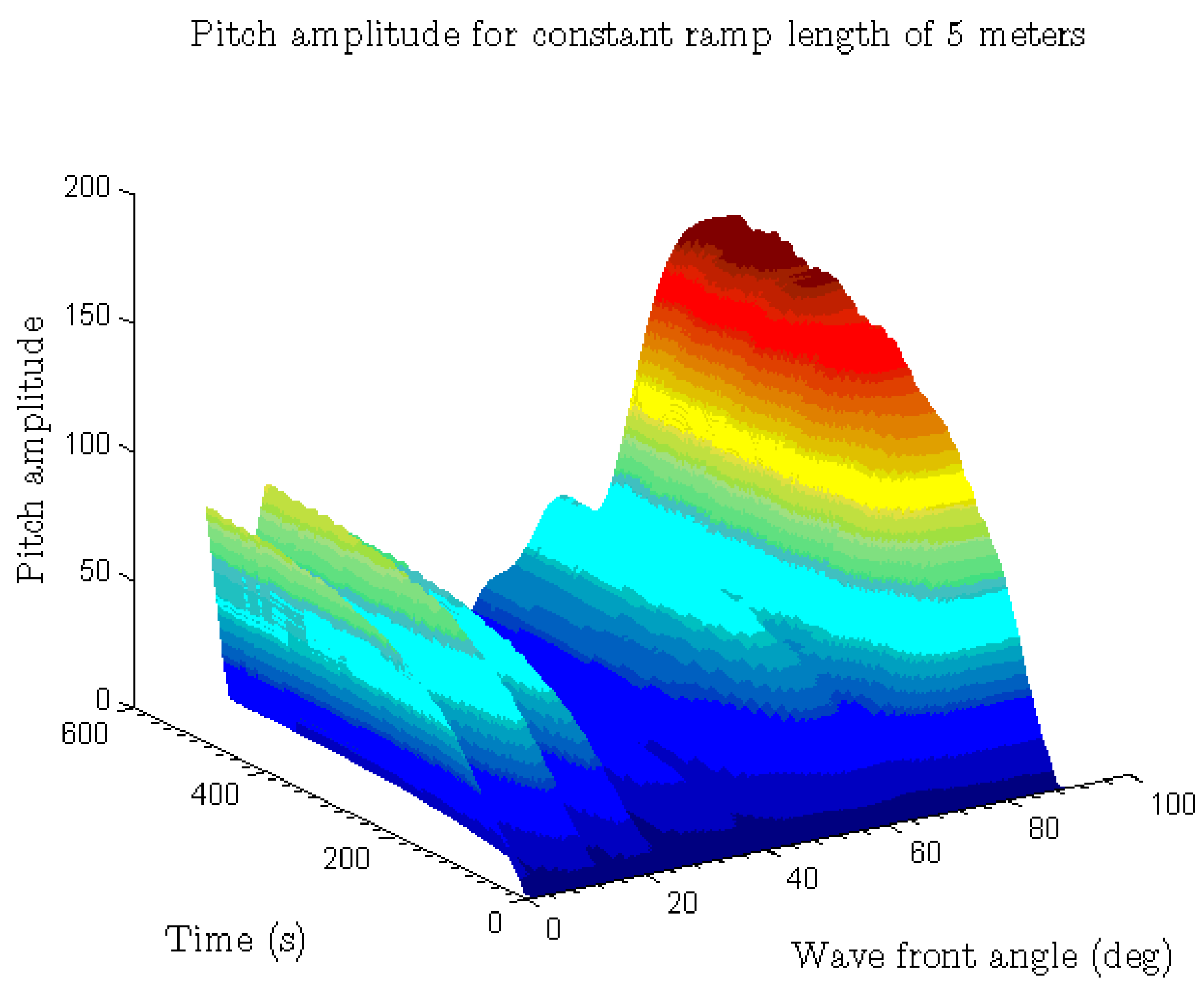
Map generated using 2^{nd} order filter to extract pitch amplitude without ES running





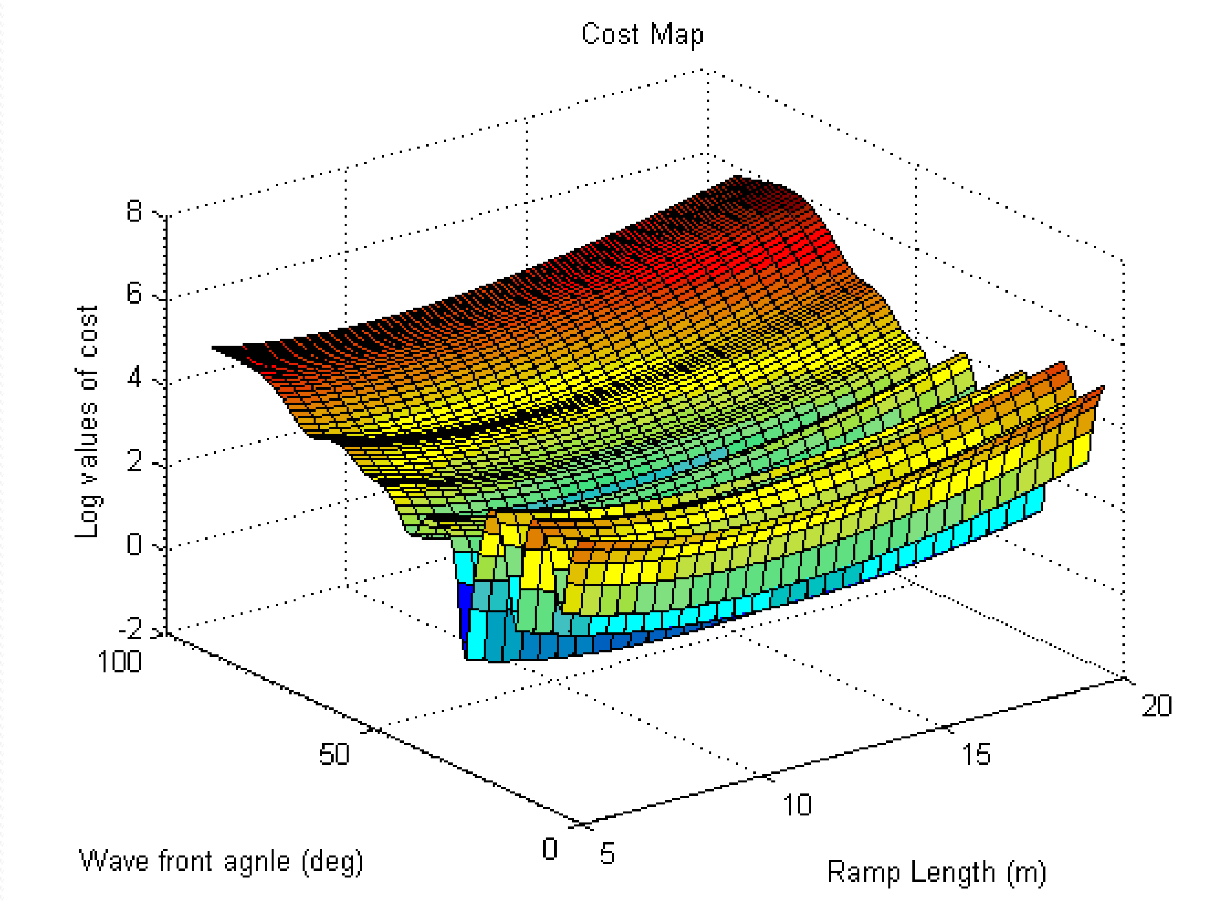
Cost map

Pitch amplitude extraction with 2nd order filter for a range of heading angles



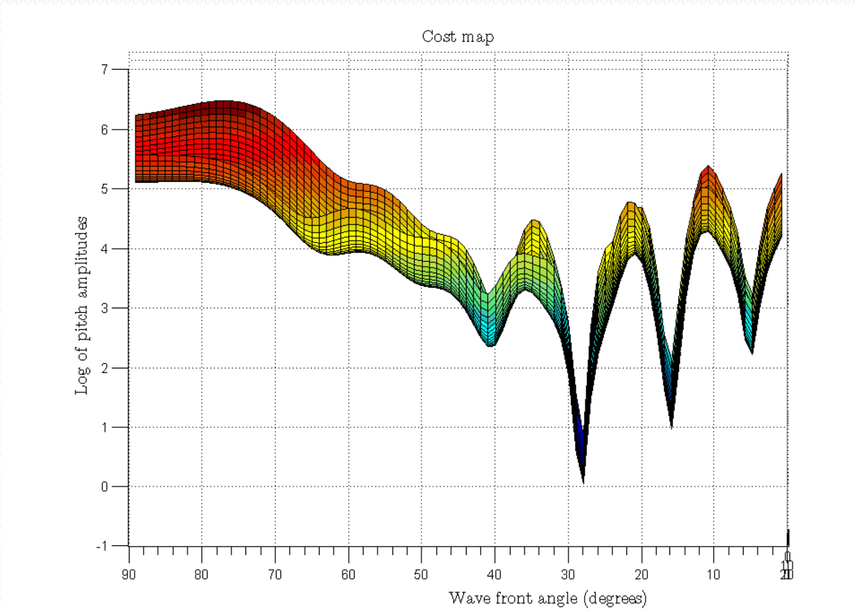
Cost map

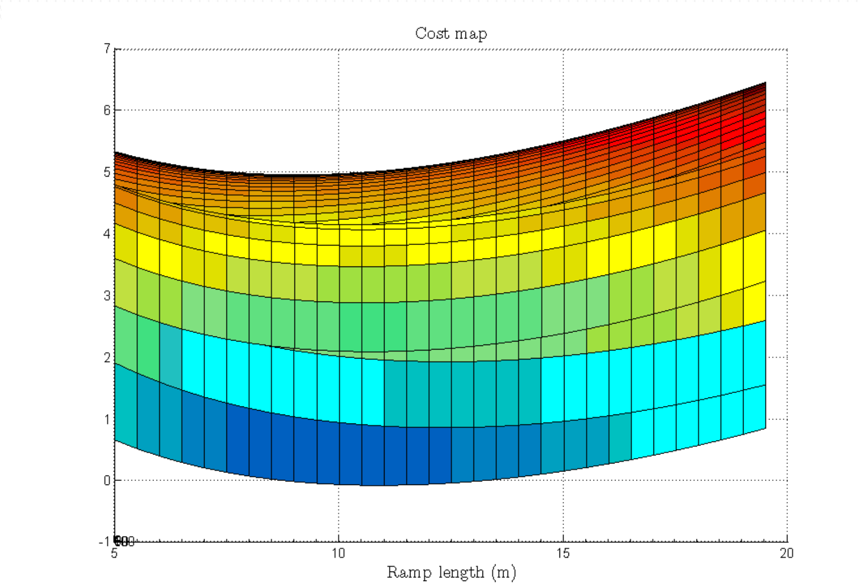
- The final amplitude value was taken from each simulation, multiplied by ramp penalty, and then plotted in a log scale graph



Cost map

Side views of cost plots show optimal values of ramp length and orientation



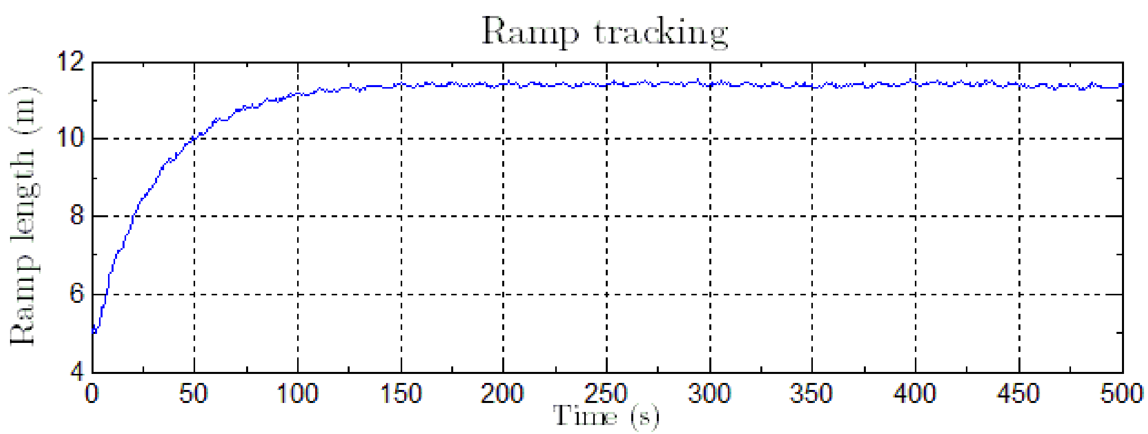


Optimal ramp length achieved between 11-12 meters

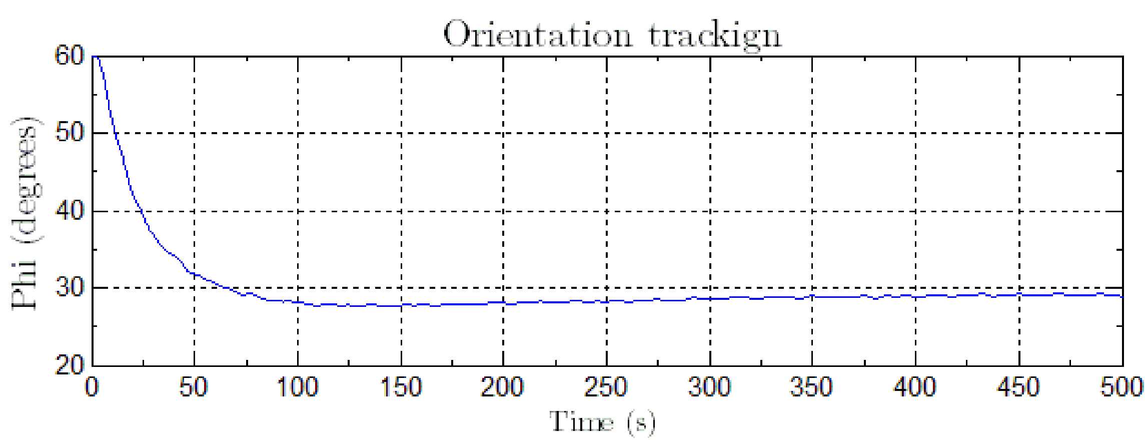
Optimal wave front achieved at just under 30 degrees

Test results with ES

ES tested on highly non-optimal initial conditions of ramp length and heading



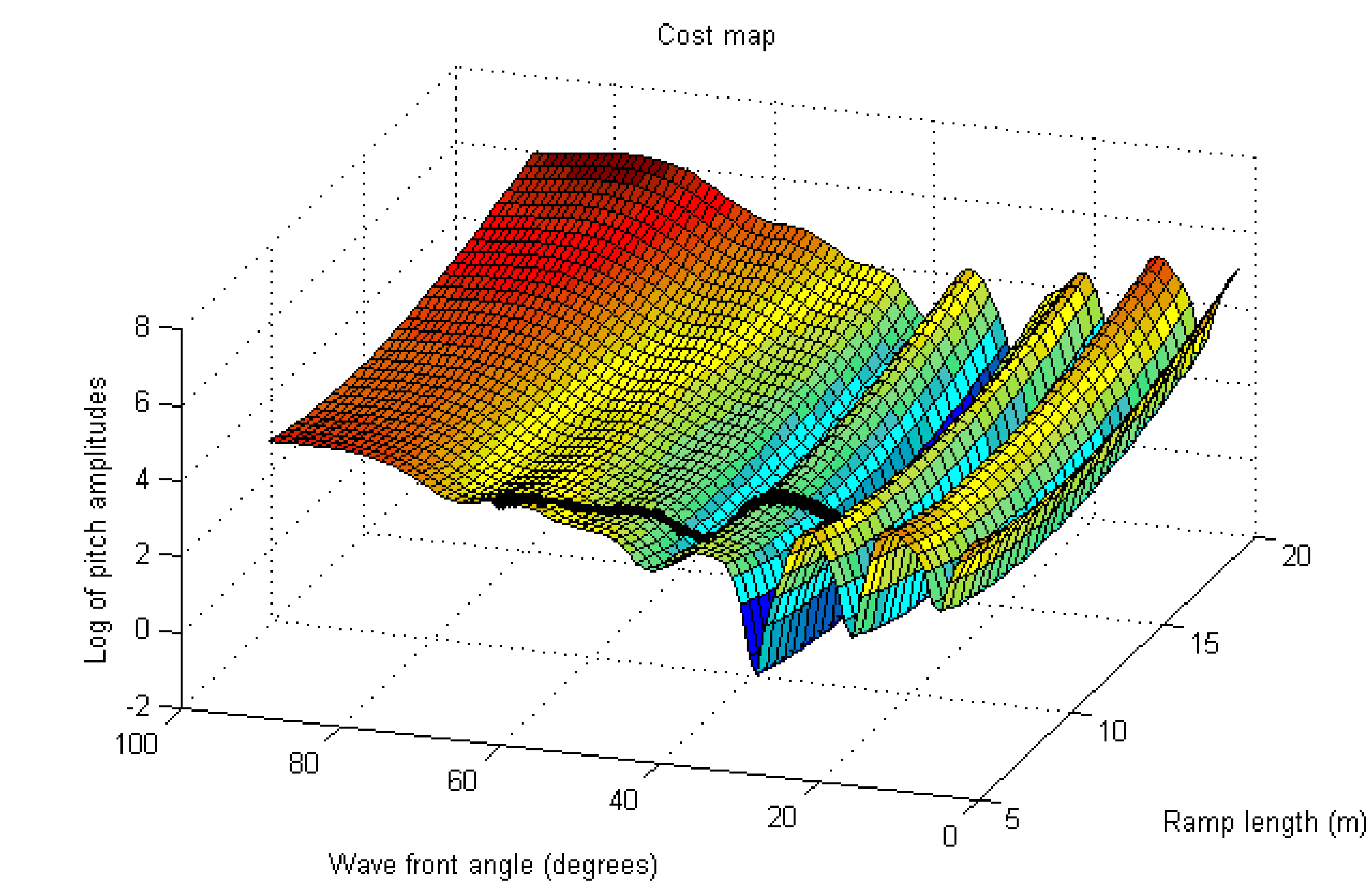
ES extends ramp length to 11.5 meters



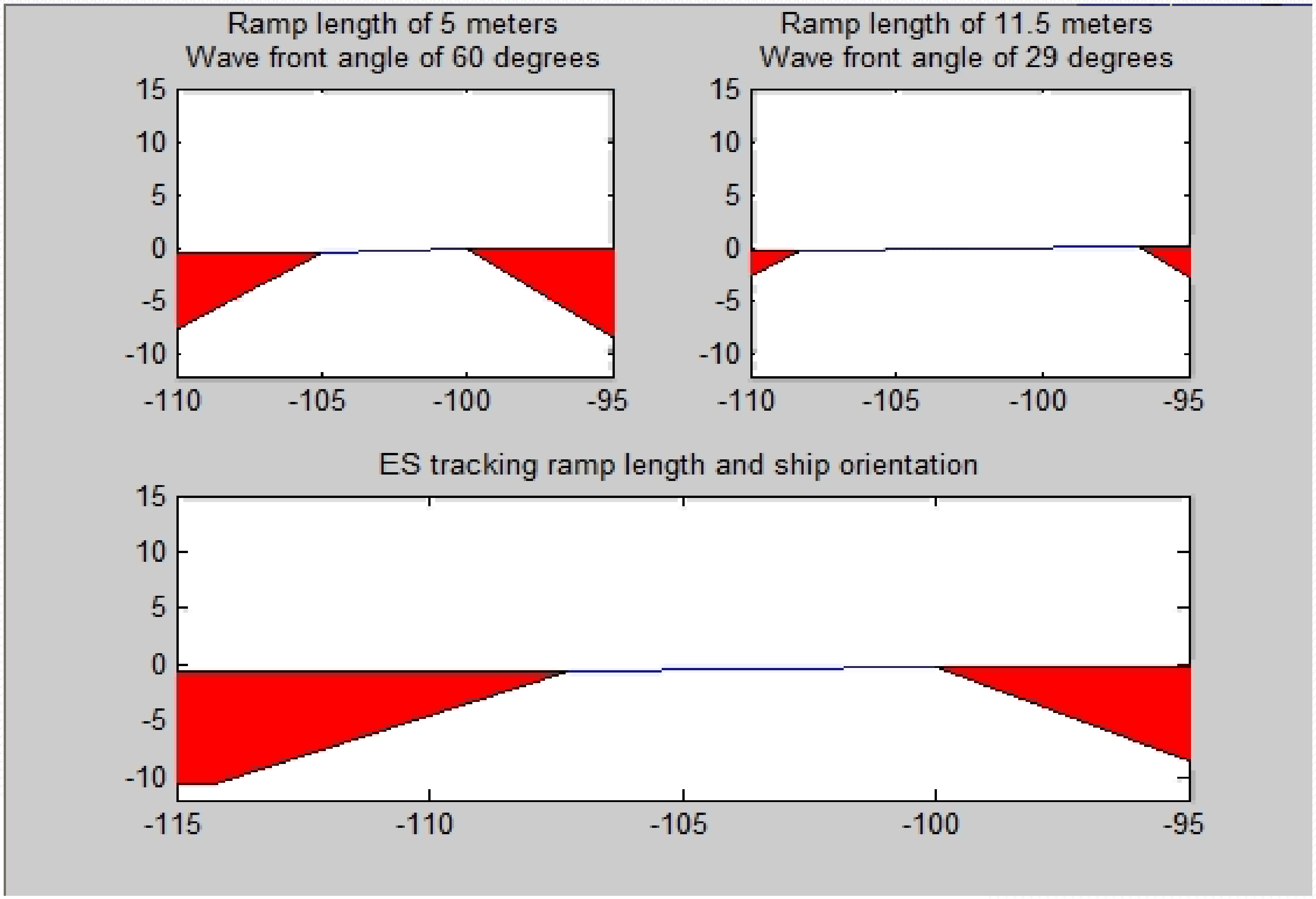
ES orients ship slightly past 29 degrees then returns

Test results with ES

Trajectory shown with solid black line



Ramp and Heading Tuning Video



Pros and Cons

- Method will work for different sea states and craft configurations
- Wave induced motion provides perturbation needed by ES without perturbation via actuated quantities
- Requires extensible ramp
- Possible settling in local minima instead of global minima

Different Configurations

- Other configurations such as port to starboard considered
- Ramp extension in this direction more difficult to control

Passive Control:
Emulating Automotive Suspension With Springs and Dampers

Using shock absorber-like design to reduce oscillations in pitch and other angles

Passive Control

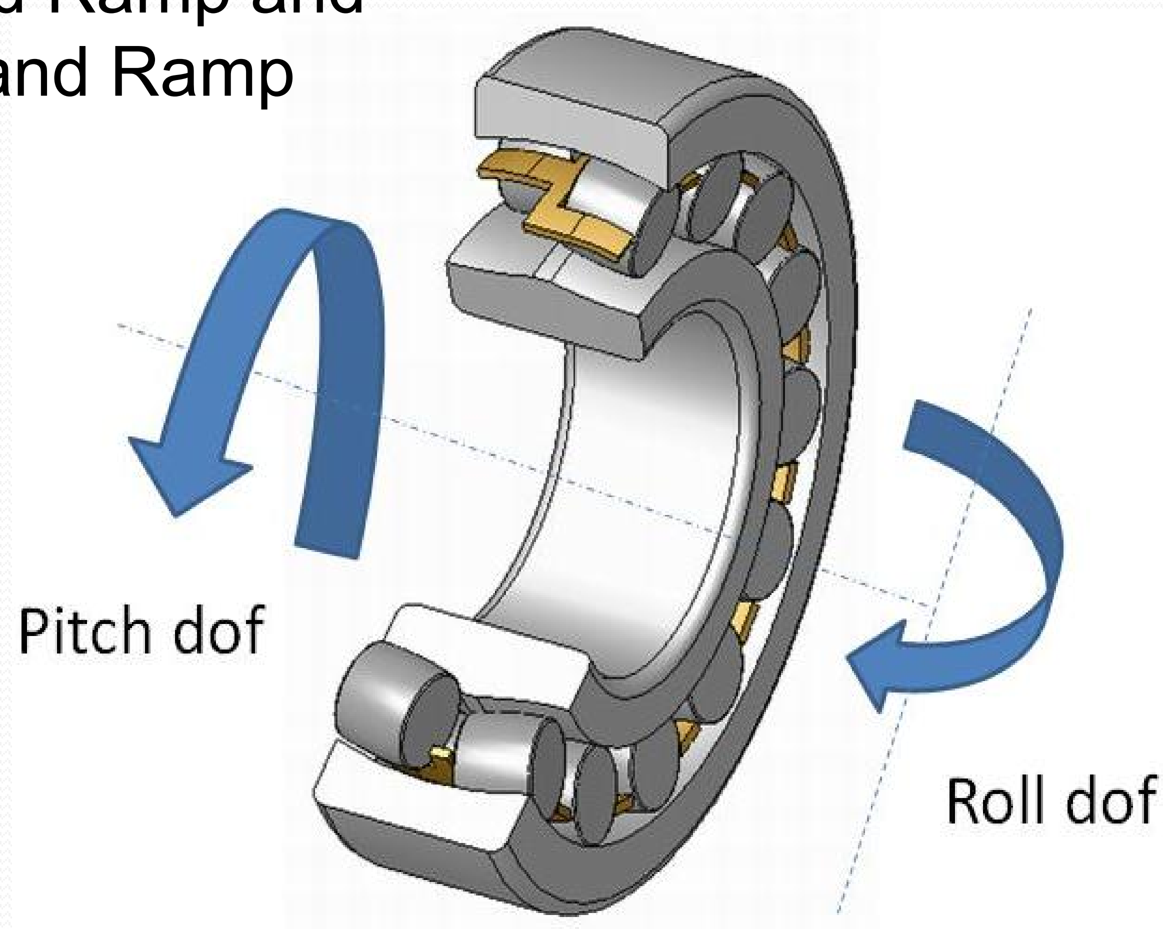
- No actuators, sensors, or feedback laws employed

- Basic parameters in simulations:
  - ramp length = 10 meters
  - wave front angle = 45 degrees

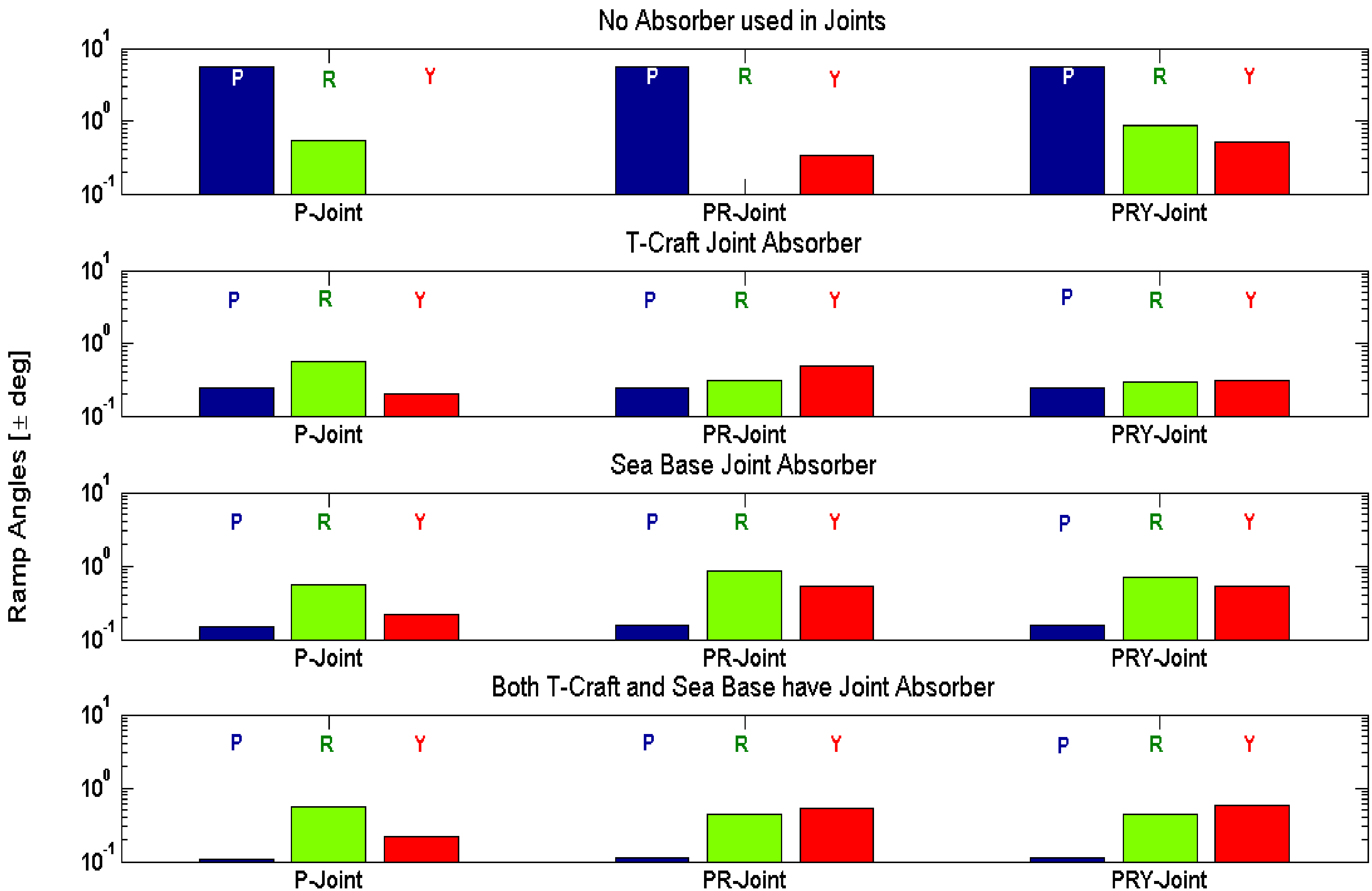
- Joint types considered:
  - Pitch (P) Joint
  - Pitch-Roll (PR) Joint
  - Pitch-Roll-Yaw (PRY) Joint

Pitch-Roll Joint Example

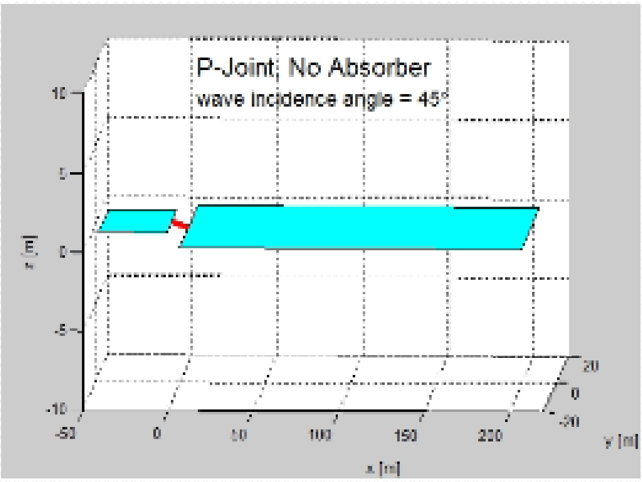
Between T-Craft and Ramp and
between SeaBase and Ramp

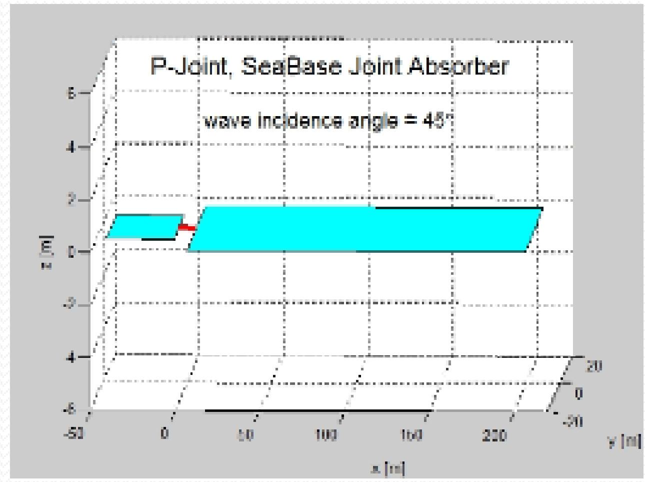


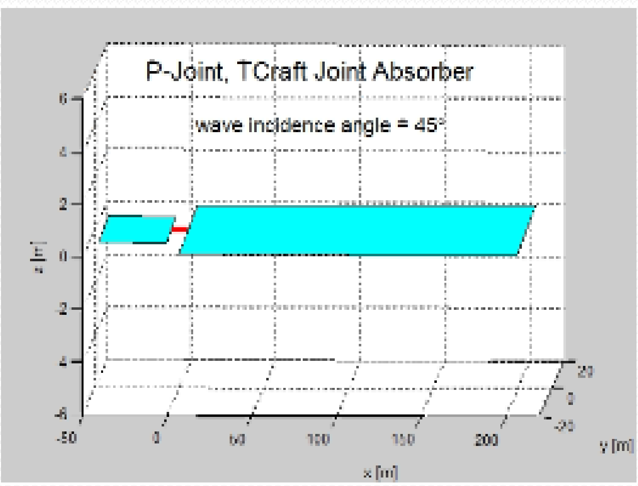
Test Results: Ramp Angle Amplitudes

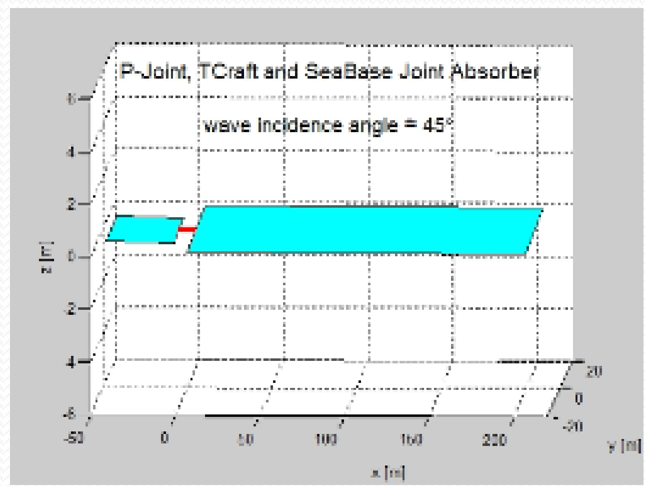


Results: P-Joint





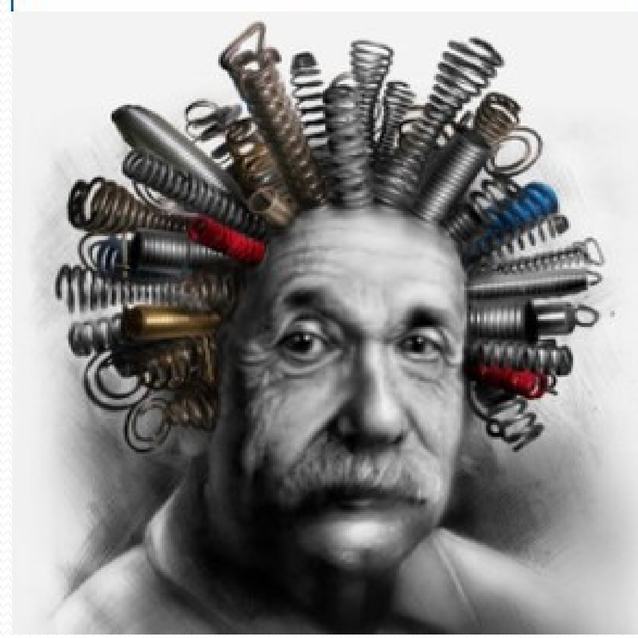




Weight and Cost

Damper

- Vendor : EFDYN , www.efdyn.com
- damping rate = $4x10^3$ Nm/rad/s
- Mass = 17 kg
- Cost = $4,400 each



Spring

- Vendor : MW Industries
- Spring rate =$5x10^9$ Nm/rad
- Mass = 160 kg

Tunable Dampers

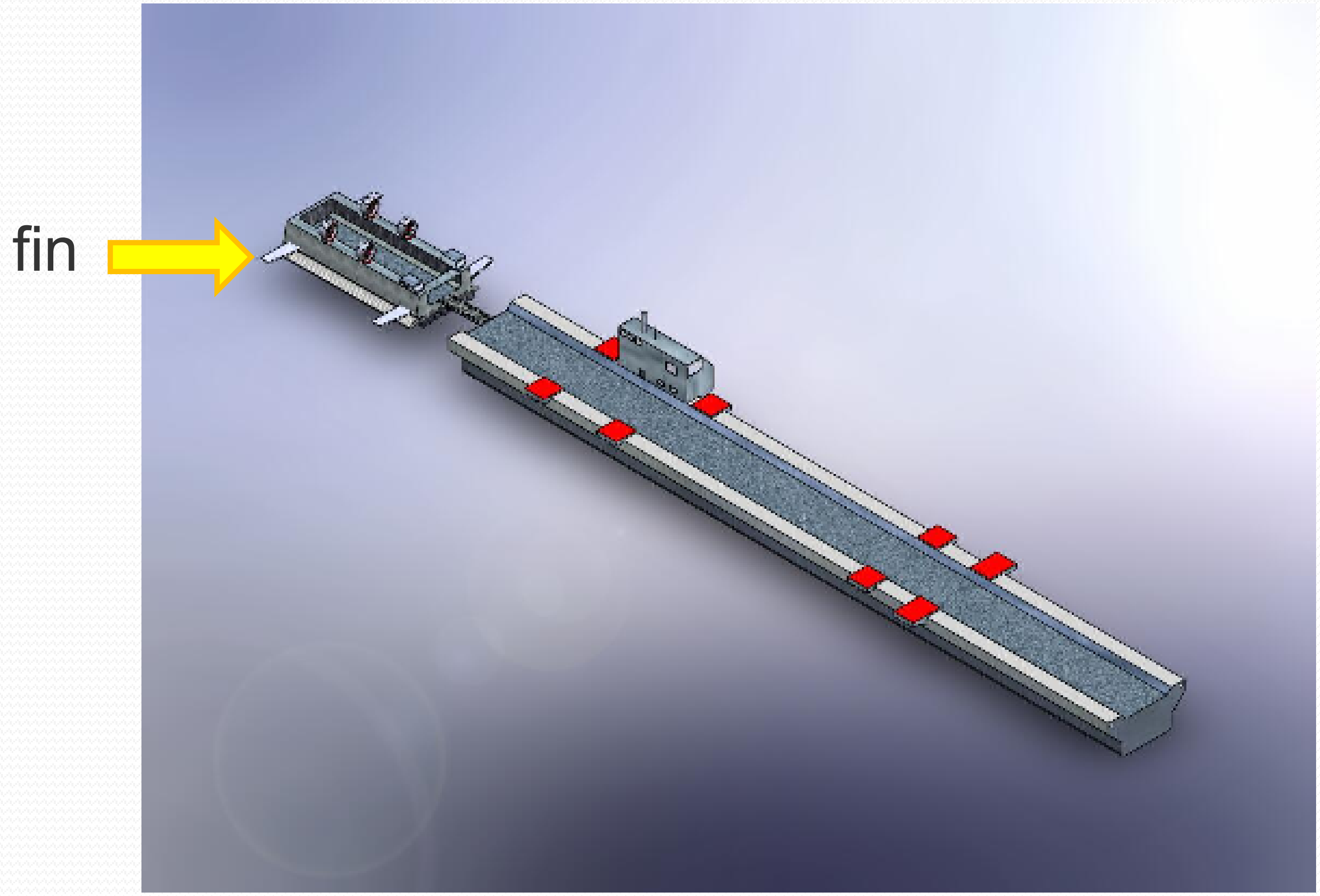
- Magnetorheological
- Vehicles: MillenWorks Light Utility Vehicle, US Army Stryker, Humvee, Cadillac models (DTS, XLR, SRX), Corvette, Buick Lucerne, Ferrari, Acura MDX, etc.

Shock absorber (right) and
Suspension strut (left)
Delphi Corporation

Active Control:
Using Lateral Fins on the T-Craft

Exploiting hydrodynamic forces in **underway** cargo transfer to control ramp motion by controlling T-craft pitch

Active Control: basic idea



T-craft controlled in pitch to reduce movement of ramp

Key question

How big must the fins be to achieve desired effect on ramp pitch?

Bow-to-stern or side-to side configuration

Bow-to-stern:

- Small changes to pitch angle of T-Craft result in larger changes in height of the bow in bow-to-stern config. With side-to-side configuration, T-craft has to roll a lot.
- More space for fins available

Side-to-side configuration:

- When ships are sailing into the wave fronts, they will move simultaneously
- Perhaps water tanks (in existing configuration where water is moved side-to-side) can be used to control roll

Ship Dynamics Model (simplified)

- Potential energy

$$V_\rho = \sum_i \left\{ \frac{1}{6} \rho g w_i l_i^{\,3} \theta_i^{\,2} + \frac{1}{2} w_i l_i z_i \rho g (z_i + (-1)^i \theta_i l_i) \right\}$$

- Kinetic energy

$$T = \frac{1}{2} \nu^T \underbrace{Y^T \breve{M} Y}_{M} \nu \qquad \nu = \dot{q} = \begin{bmatrix} \dot{x}_i & \dot{z}_i & \dot{\theta}_i & \dot{z}_i & \dot{\theta}_i \end{bmatrix}^T$$

- Hamiltonian equations of motion

$$\dot{p} = -\frac{\partial H}{\partial q} \qquad H = p \cdot \dot{q} - T + V = T + V$$

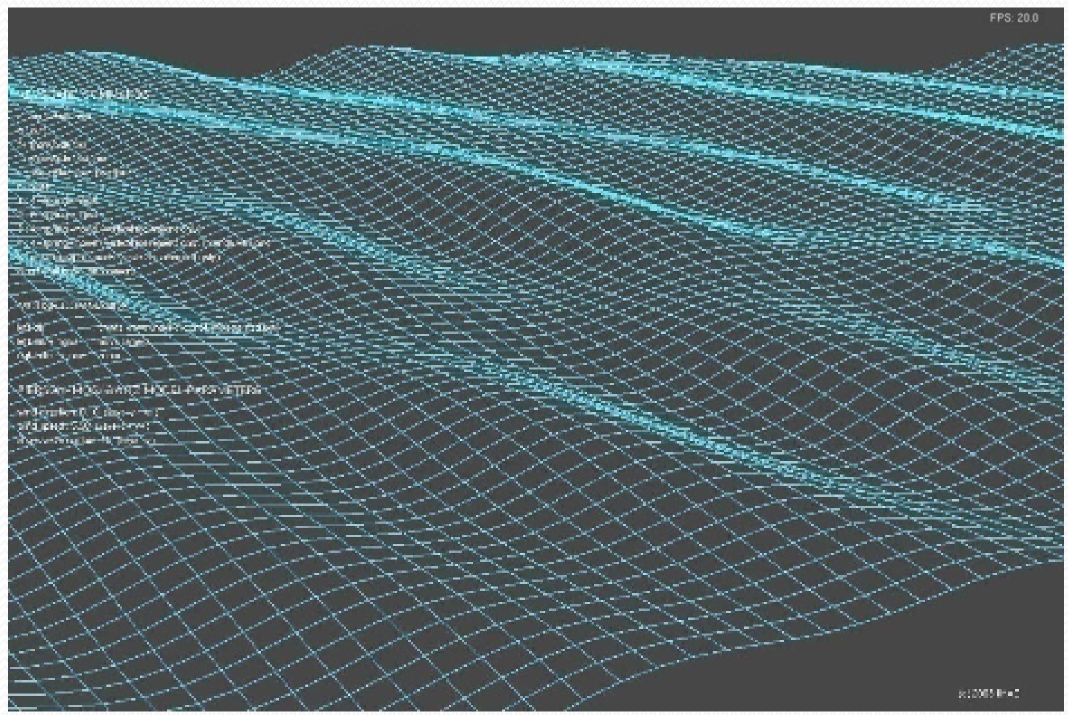
$$\dot{q} = \frac{\partial H}{\partial p}$$

Waves model

- Linear approx. of Pierson-Moskowitz spectrum via 4th order filter forced by white noise

$$h(s) = \frac{K_w s^2}{\left(s^2 + 2\lambda\omega_0 s + \omega_0^2\right)^2}$$

- Response Amplitude Operators



Control

Dynamics are linearized

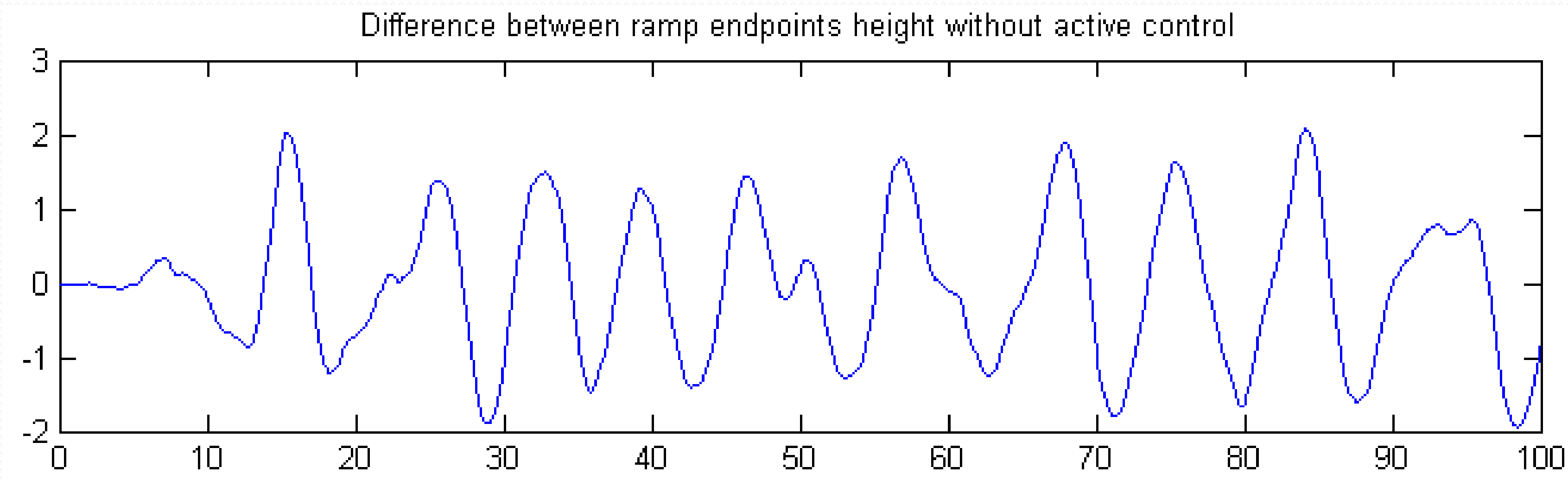
- Linear Quadratic Optimal control
- Intuitive tuning (cost defined in terms of ramp pitch)

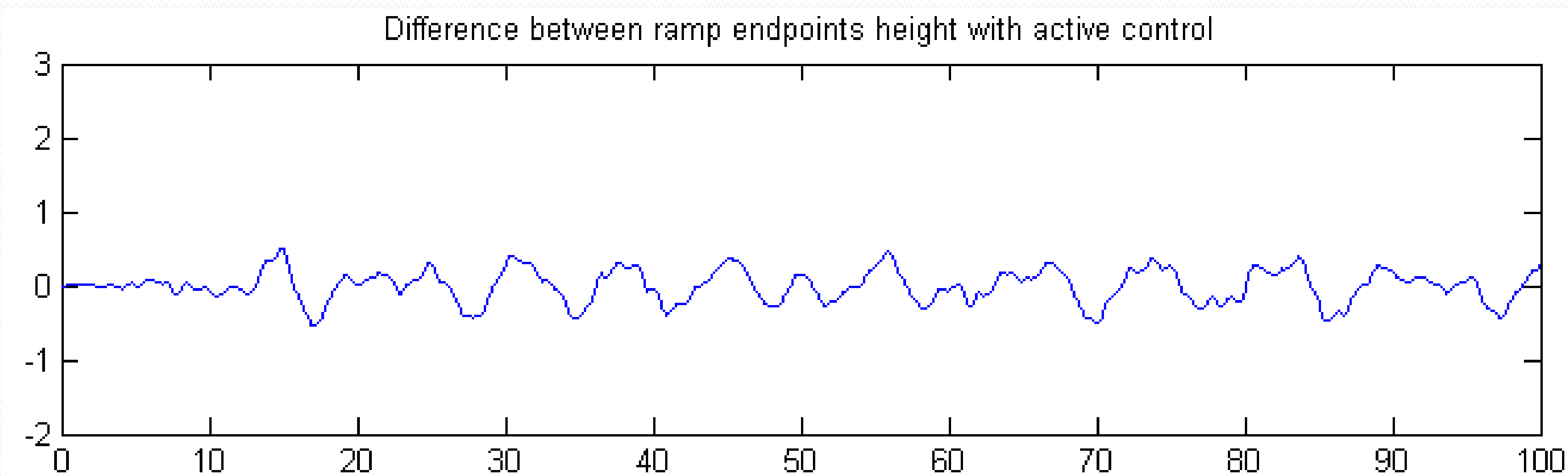
Results

- In seastate 4 (waves 2.5 m) for a ship that is 60 meter long and 10 meter wide, a force of about 3 MN is required to produce good attenuation of wave effects

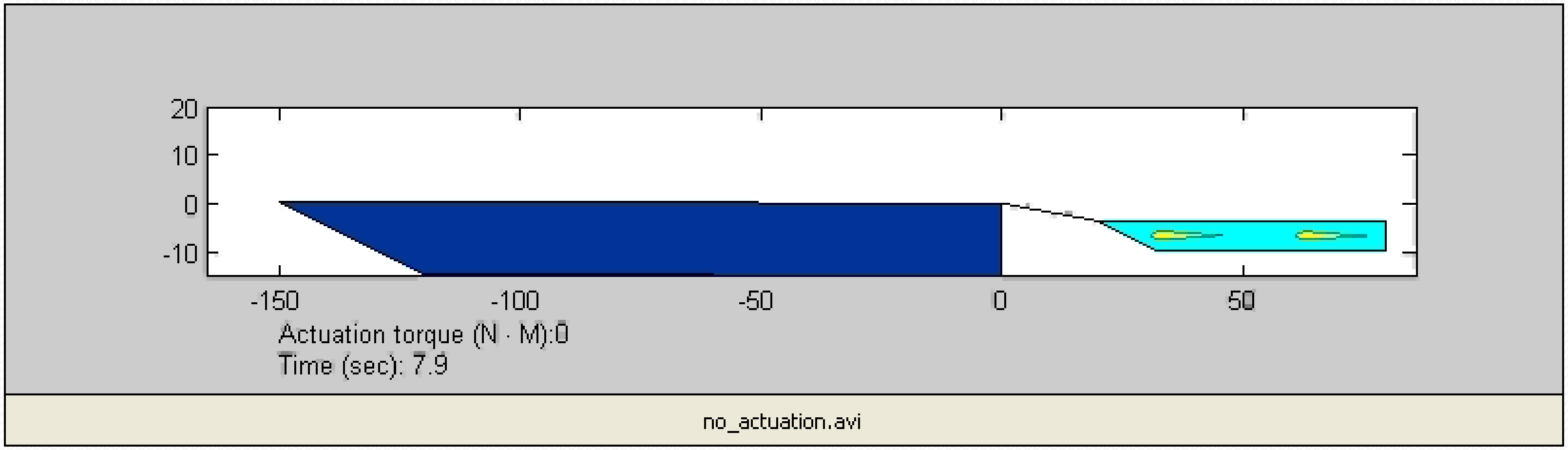
- At 7 m/s (14 kt) surge speed, the force of 3 MN can be delivered by fins with total area of 110 m^2, can be given by **four 7x4 m fins**

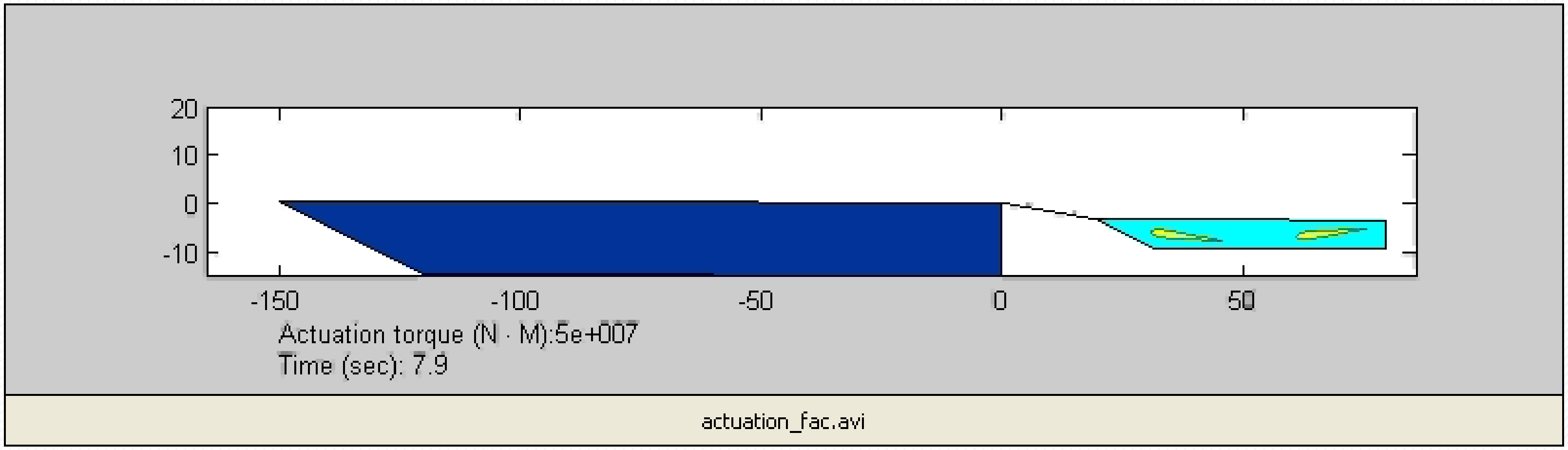
Results


Difference between ramp endpoints height without active control
3
2
1
0
-1
-2
0
10
20
30
40
50
60
70
80
90
100


Difference between ramp endpoints height with active control
3
2
1
0
-1
-2
0
10
20
30
40
50
60
70
80
90
100

Results


20
10
0
-10
-150
-100
-50
0
50
Actuation torque (N · M):0
Time (sec): 7.9
no_actuation.avi


20
10
0
-10
-150
-100
-50
0
50
Actuation torque (N · M):5e+007
Time (sec): 7.9
actuation_fac.avi

Future Work

- Extend the tests of tuning of heading, ramp length, and joint absorbers to SAIC's LAMP code
- Develop a wave observer (using heave etc. sensing)
- Compensate for lag in fin actuators
- Model side-to-side configuration with water tank actuation
- Collaborate in developing an experimental model and in its testing