Ship motion compensation platform for high payloads dynamic analysis and control

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Introduction: Pooltable on cruise ship

Two ship motion compensation platforms:

Ampelmann (personnel)

Bargemaster (~400 tonnes)

Offshore windturbine installation with Jack-up units

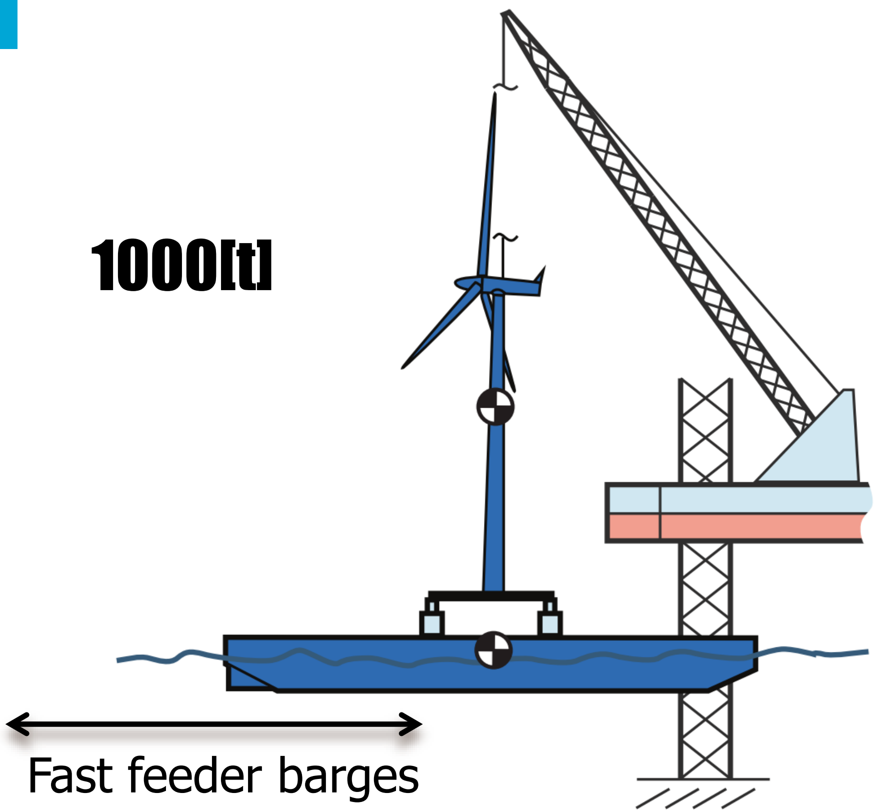
Present method

$

$

Goal: Complete windturbine installation from a floating unit

Motion stabilizing platform to extend operating limits



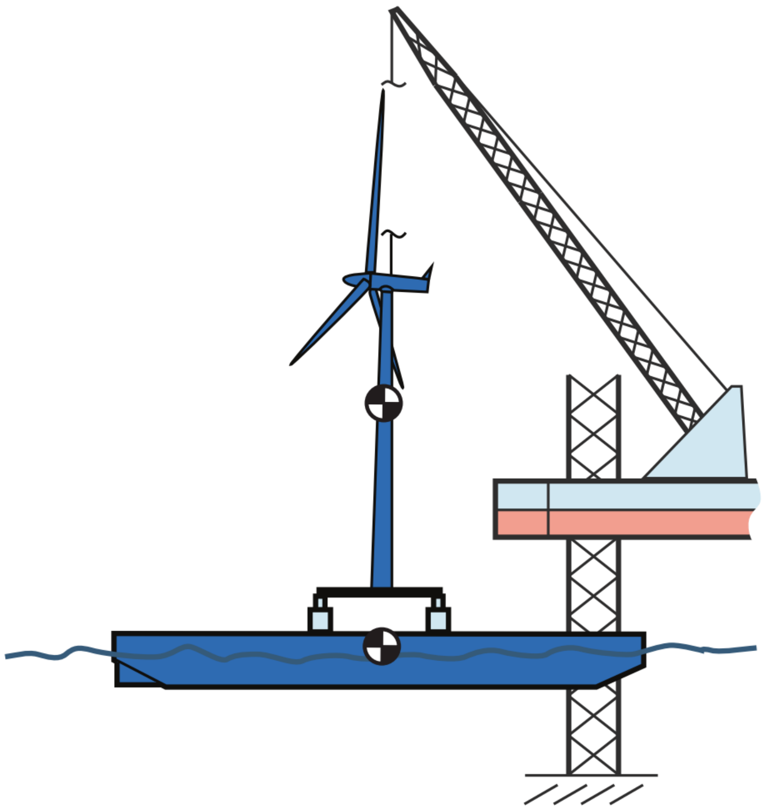
Small overview

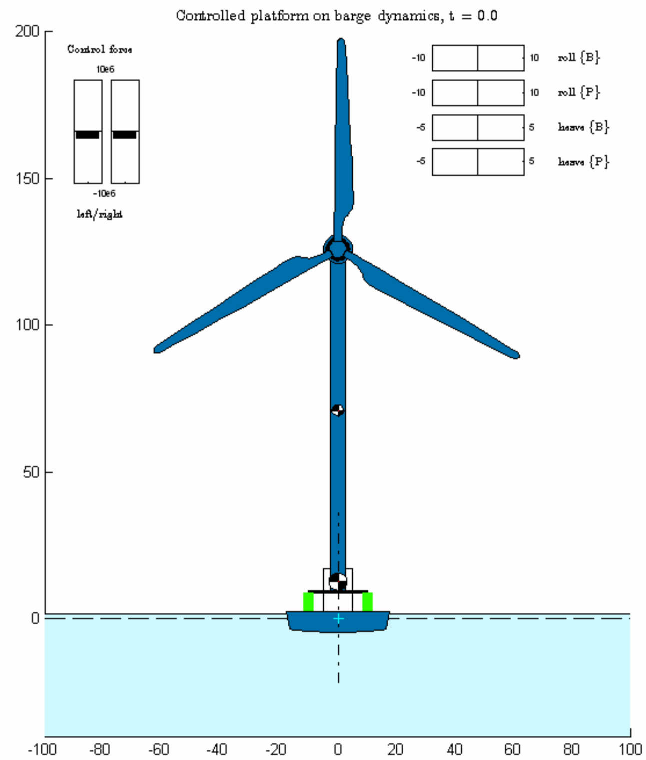
Preliminary 2D model

1. Analysis of Ampelmann scalemodel tests
2. 3D modeling of new mechanism on ship
3. Controlling the system

Goal: Complete windturbine installation from a floating unit

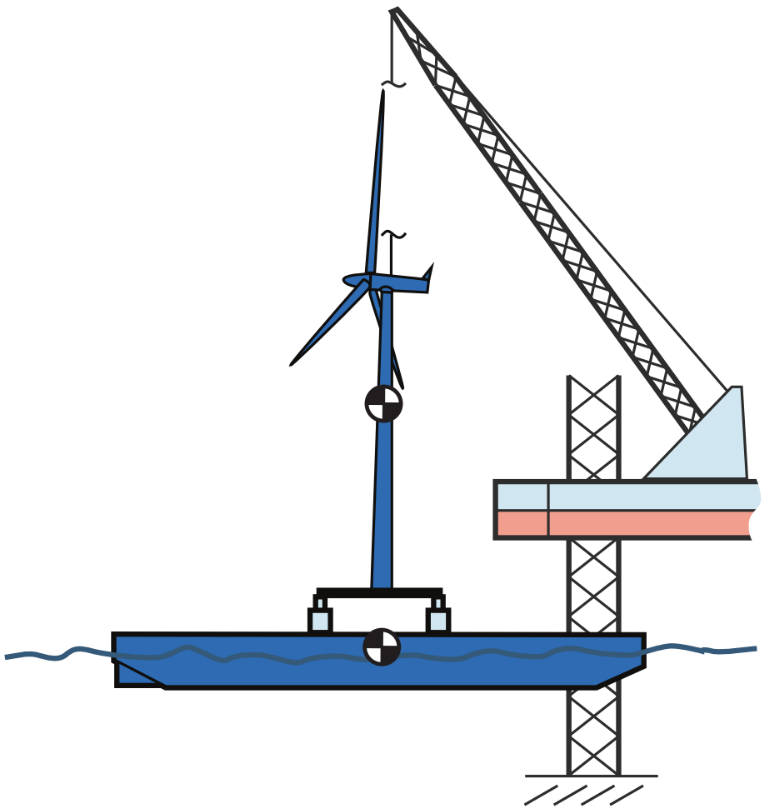
Preliminary 2D model showed feasibility …

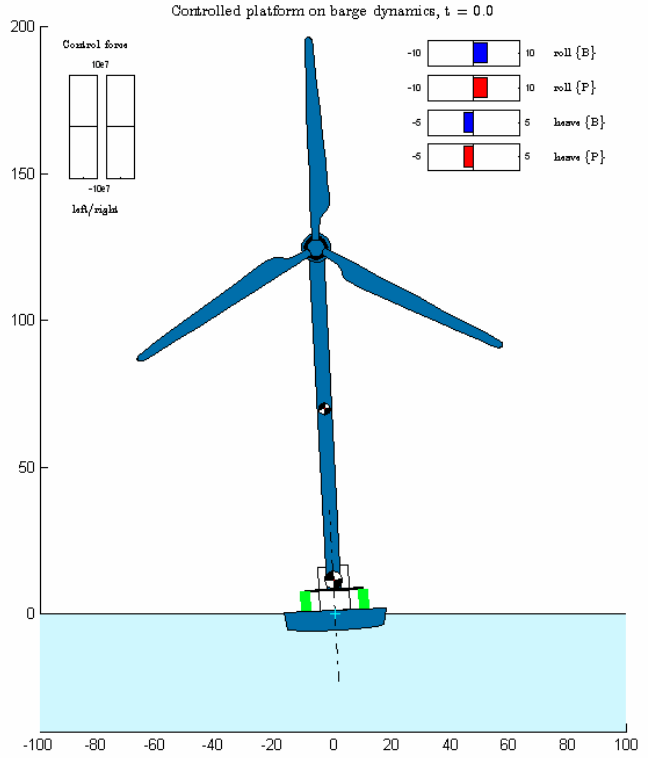




Goal: Complete windturbine installation from a floating unit

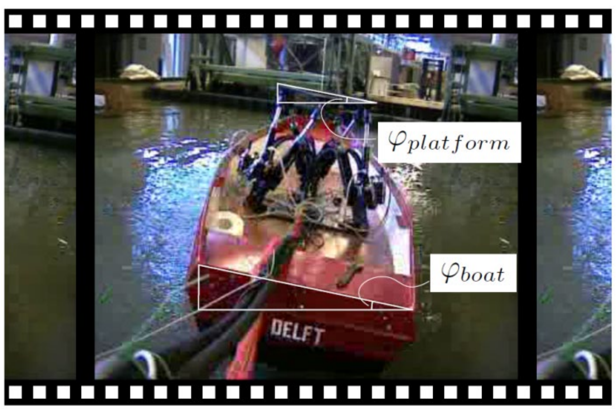
Preliminary 2D model showed feasibility but dynamic instability

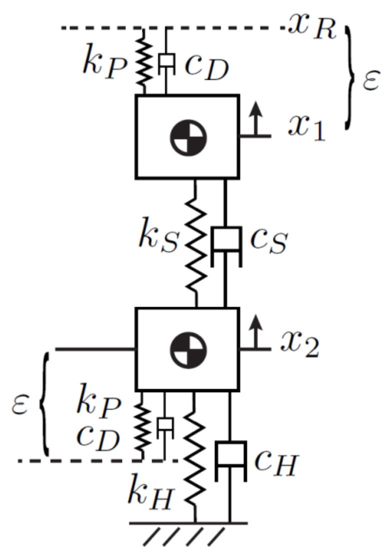


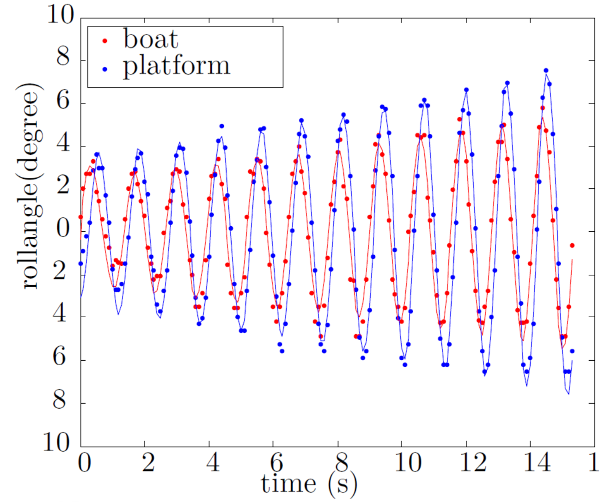


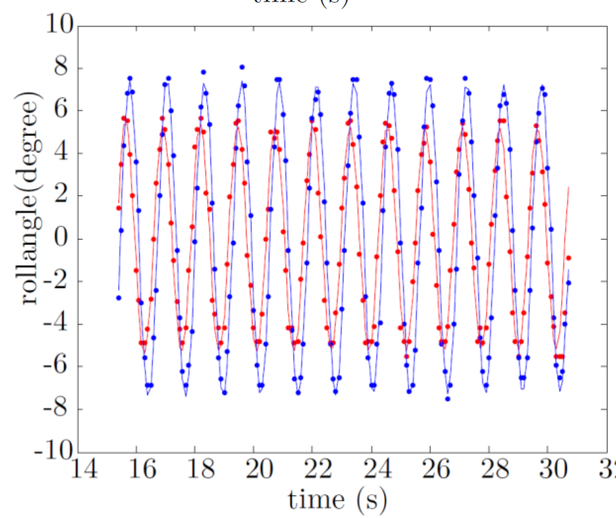
1. (In-)stability due to the quasistatic control?

Similar mass system: Ampelmann scale model tests



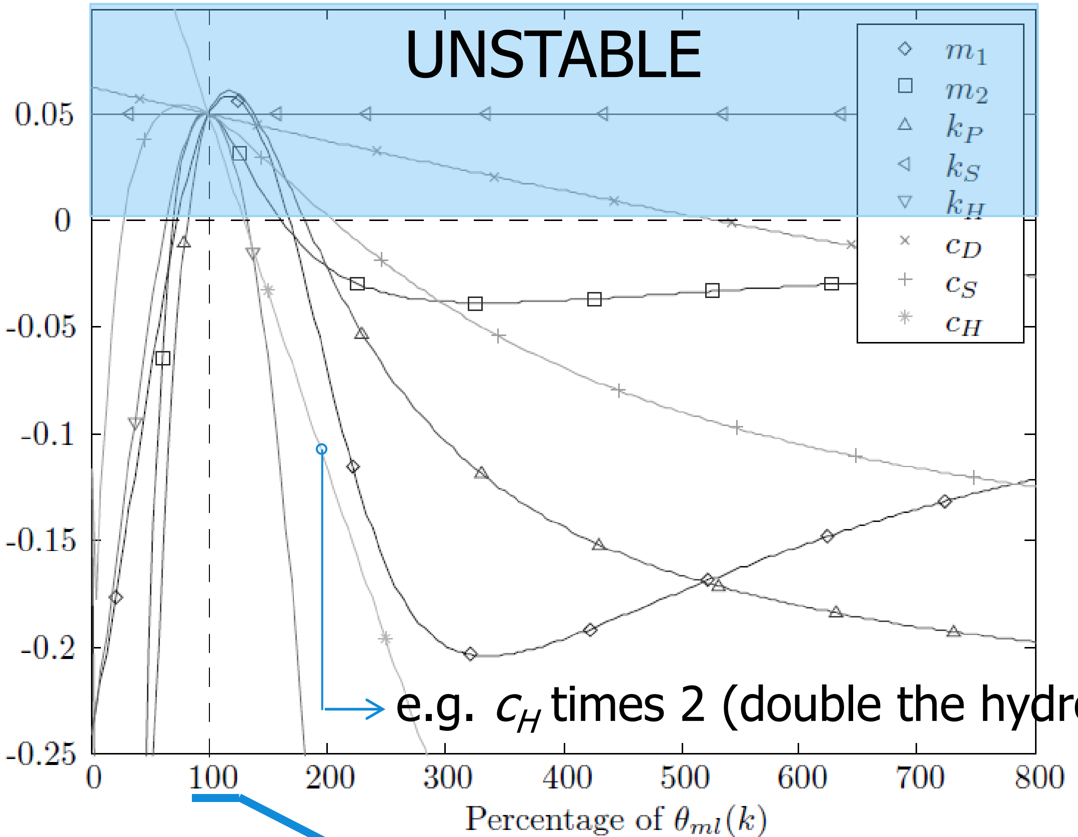


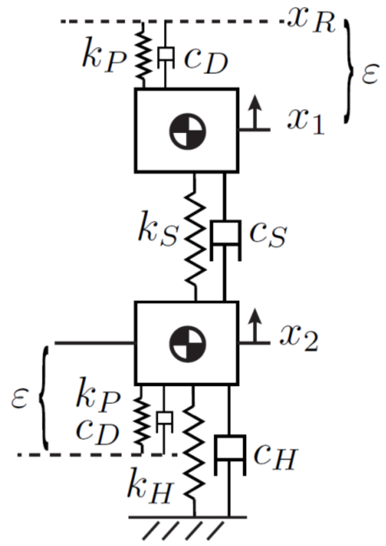




1. Stability of the fitted linear model

Maximum real part of eigenvalues of system matrix.
1 parameter varied around maximum likelihood estim.



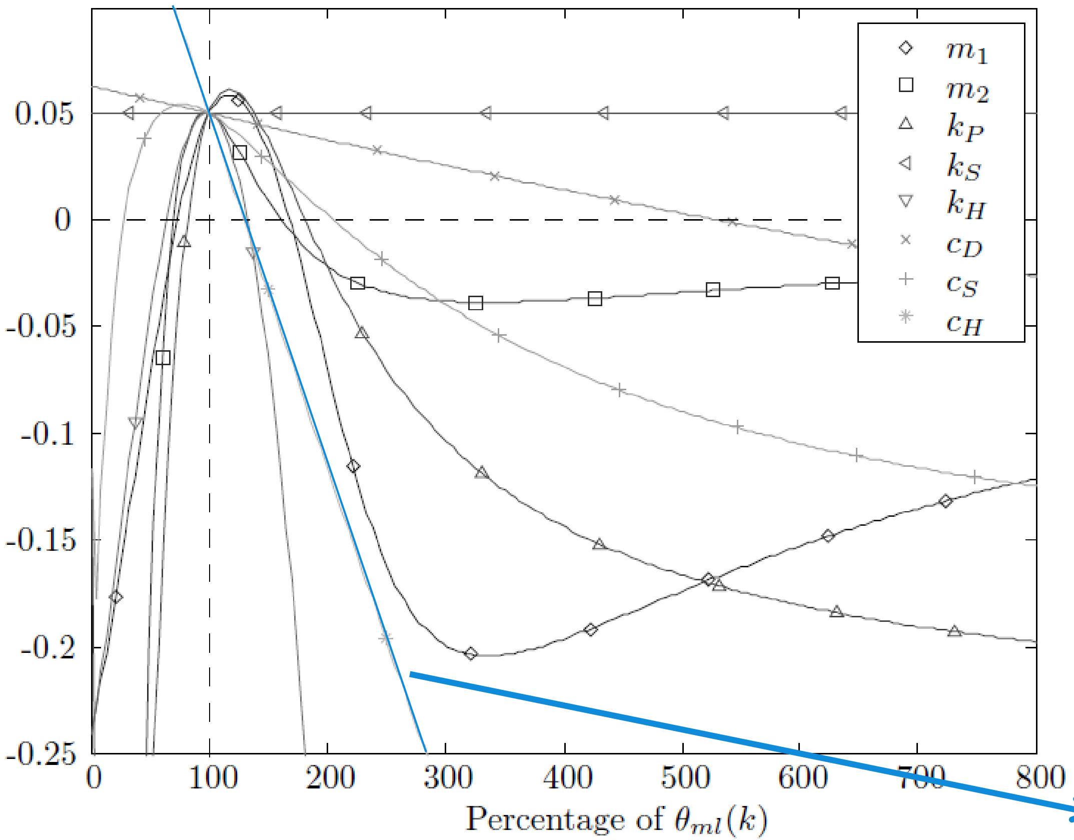


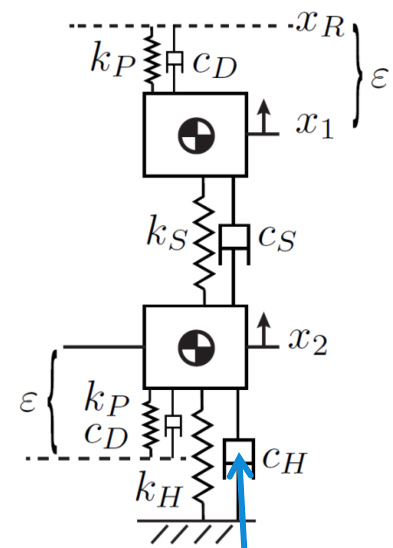
e.g. c_H times 2 (double the hydrodyn. damping) others identical

All parameters as in fit of first 15 seconds

1. Stability of the fitted linear model

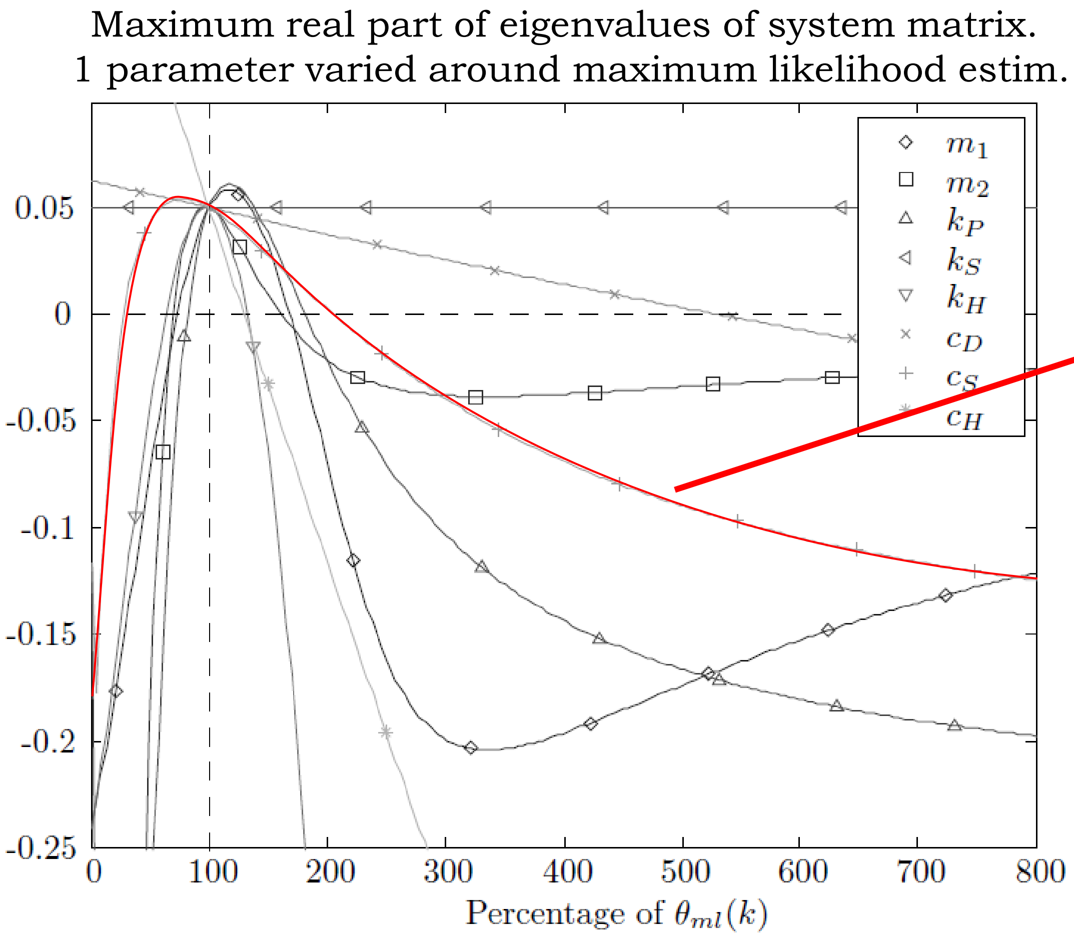
Maximum real part of eigenvalues of system matrix.
1 parameter varied around maximum likelihood estim.

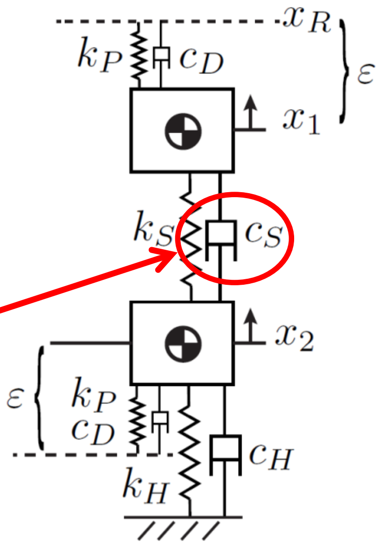




- Adding hydro-damping stabilizes

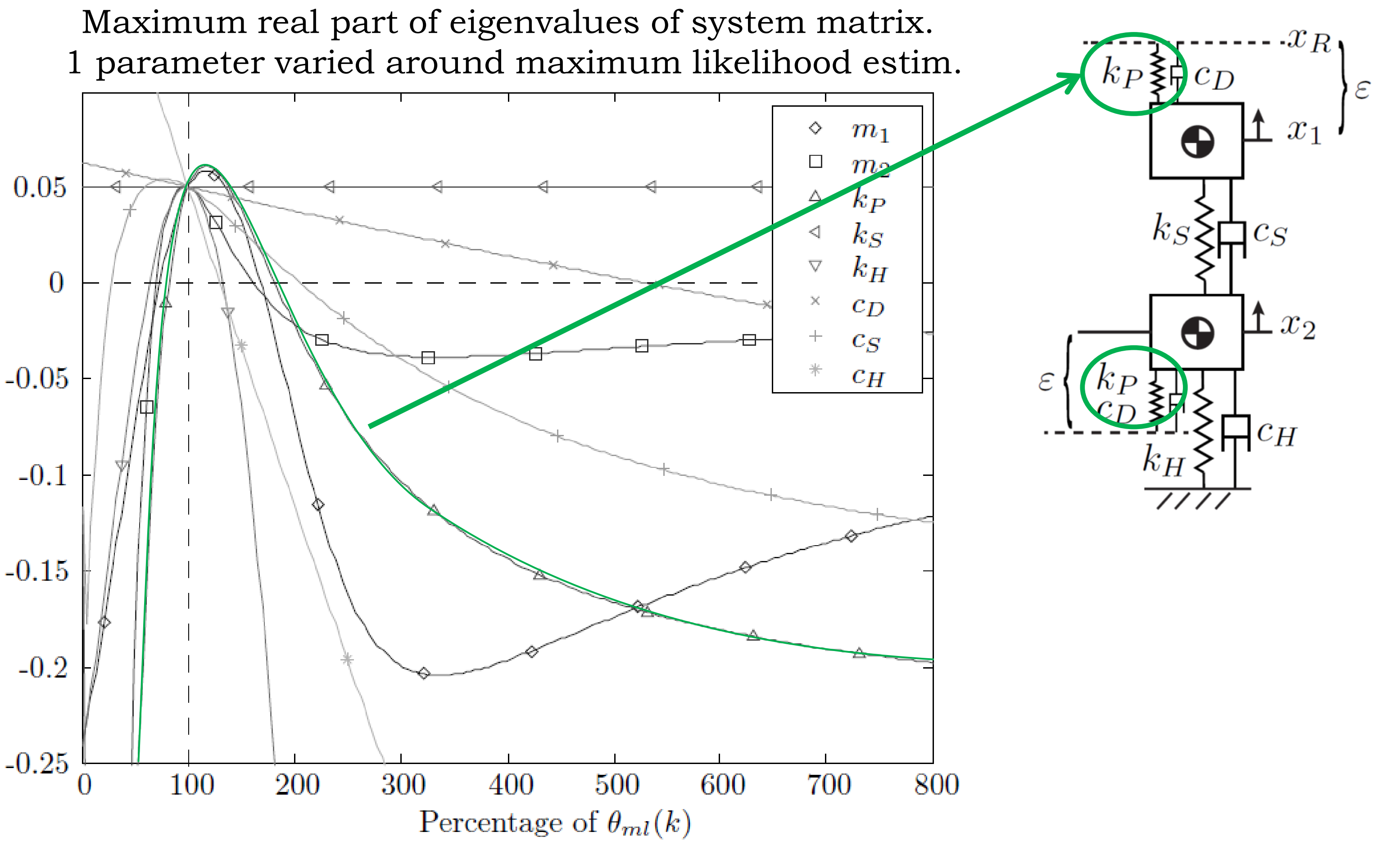
1. Stability of the fitted linear model





- The damping on opposite movements is a destabilizing factor, possible unmodeled nonlinearities

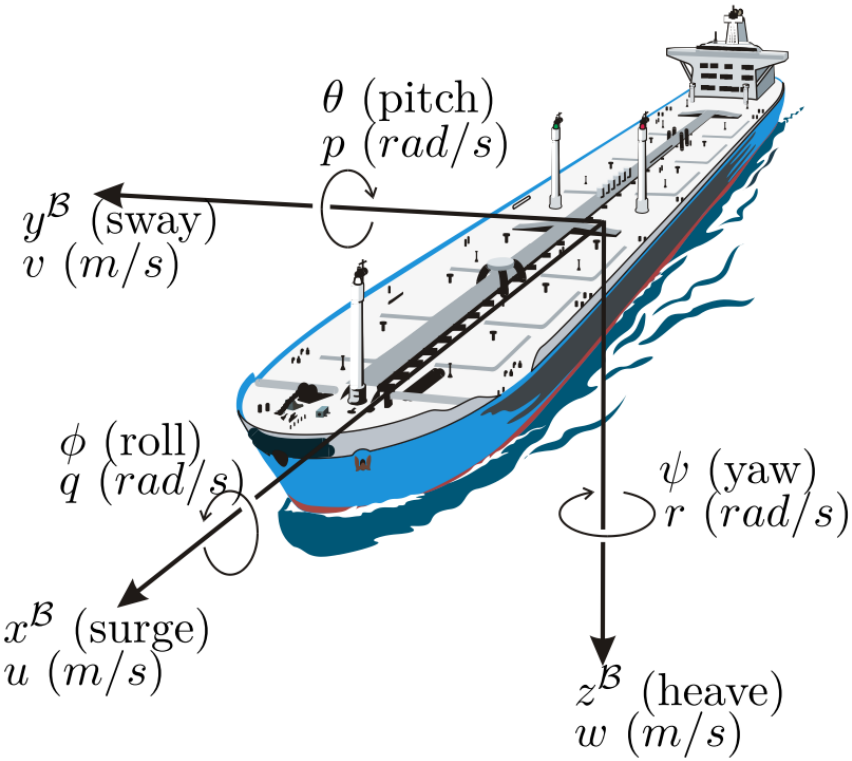
1. Stability of the fitted linear model



- The proportional control has stable and unstable settings

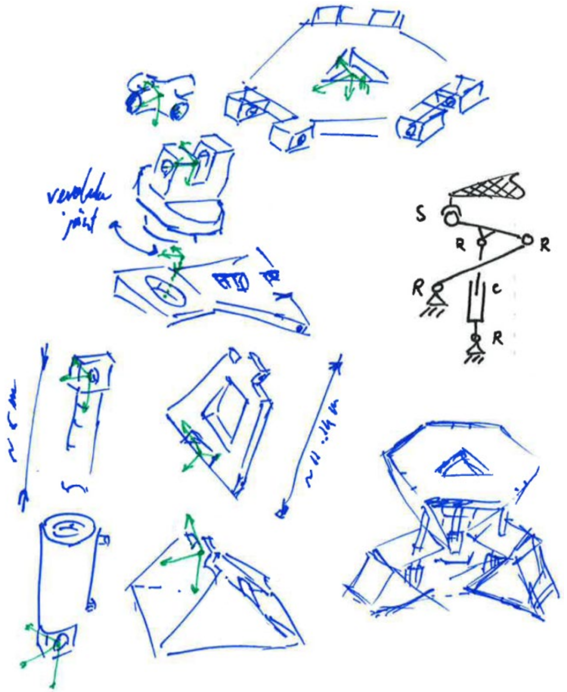
2. 3D modeling - ship movements

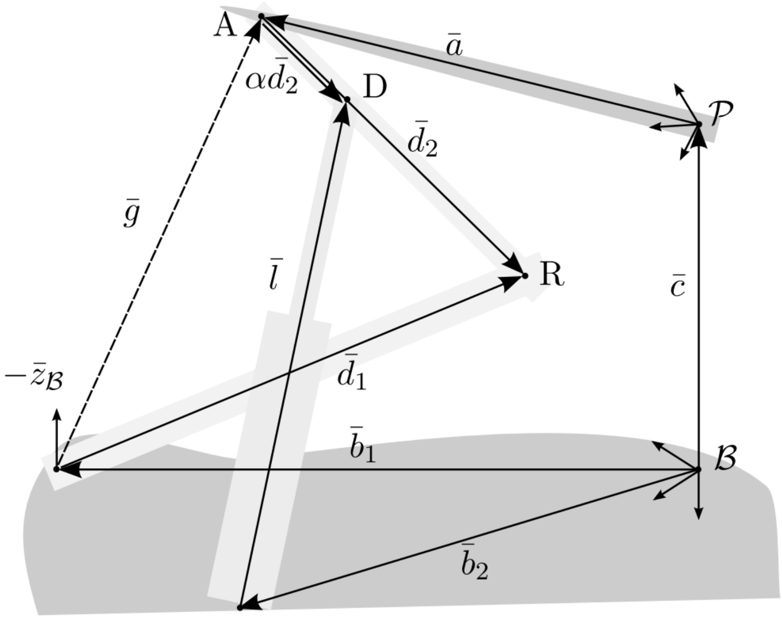
- Accelerations due to planar movements surge, sway and yaw are smaller than due to off planar movements
- Platform should compensate heave, roll and pitch



2. 3D modeling - platform mechanism

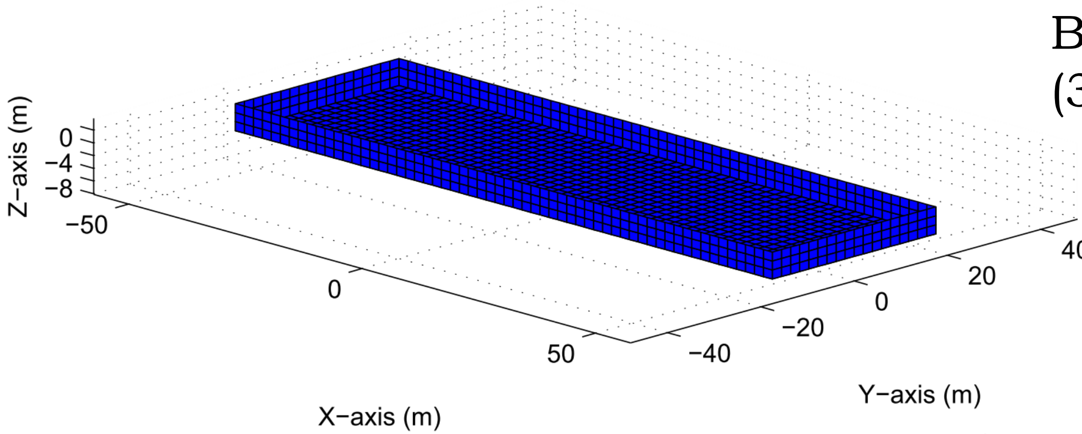
- New mechanism for a 3 degree of freedom platform
- Planar movements are constrained by 3 Sarrus type linkages
- Force vs. Reach variable via α



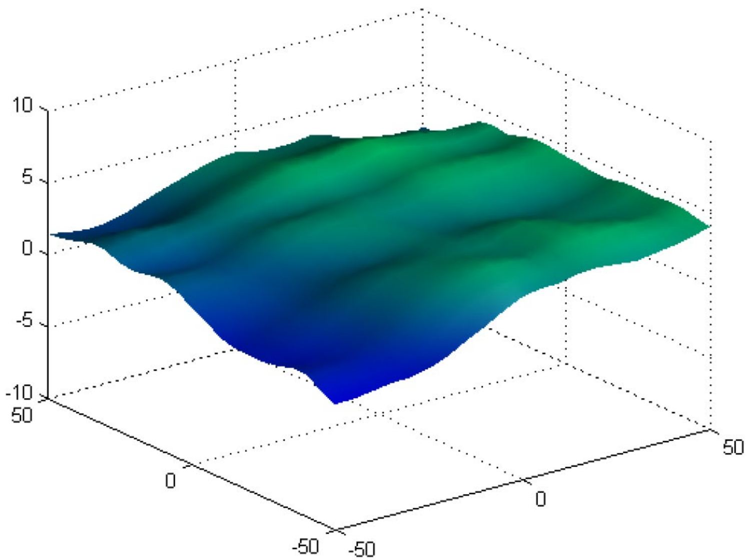


Vectorial representation of the planar linkage system of one leg.

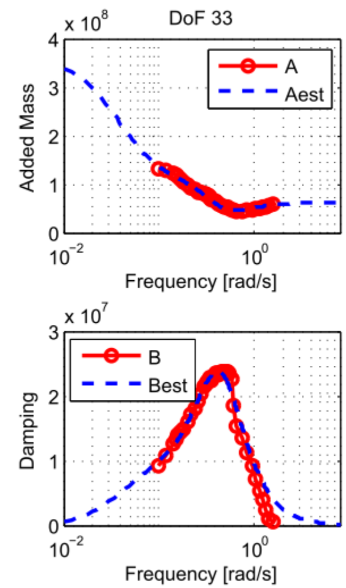
2. 3D modeling - hydrodynamics



Barge panel model (35x115m)



External wave field realization

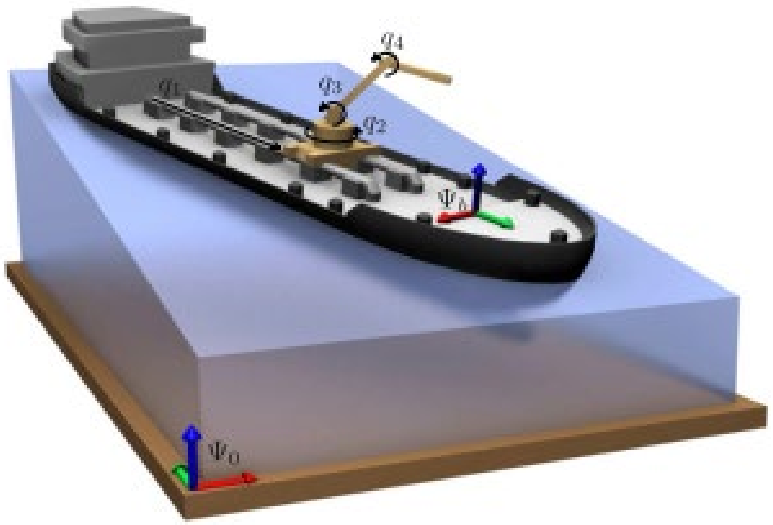


State-Space approx. of wave radiation terms

TU Delft

2. 3D modeling - vessel+platform

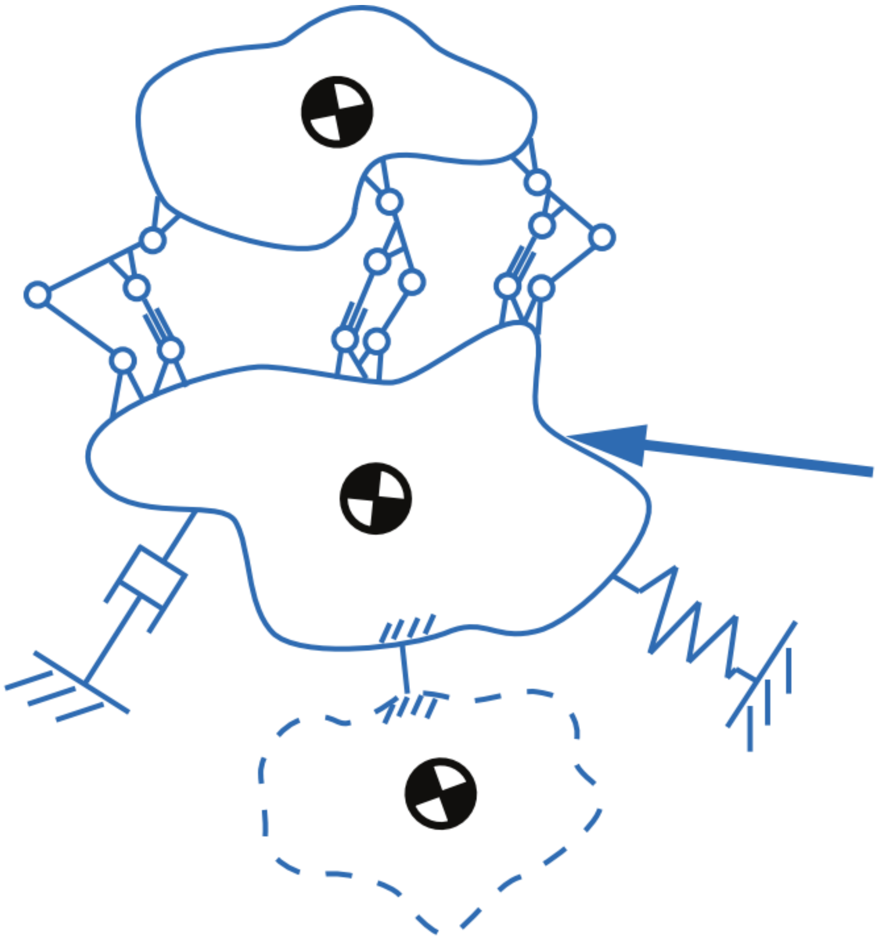
- Lagrangian dynamics (body fixed)
- Extension of serial robot on ship to parallel robots



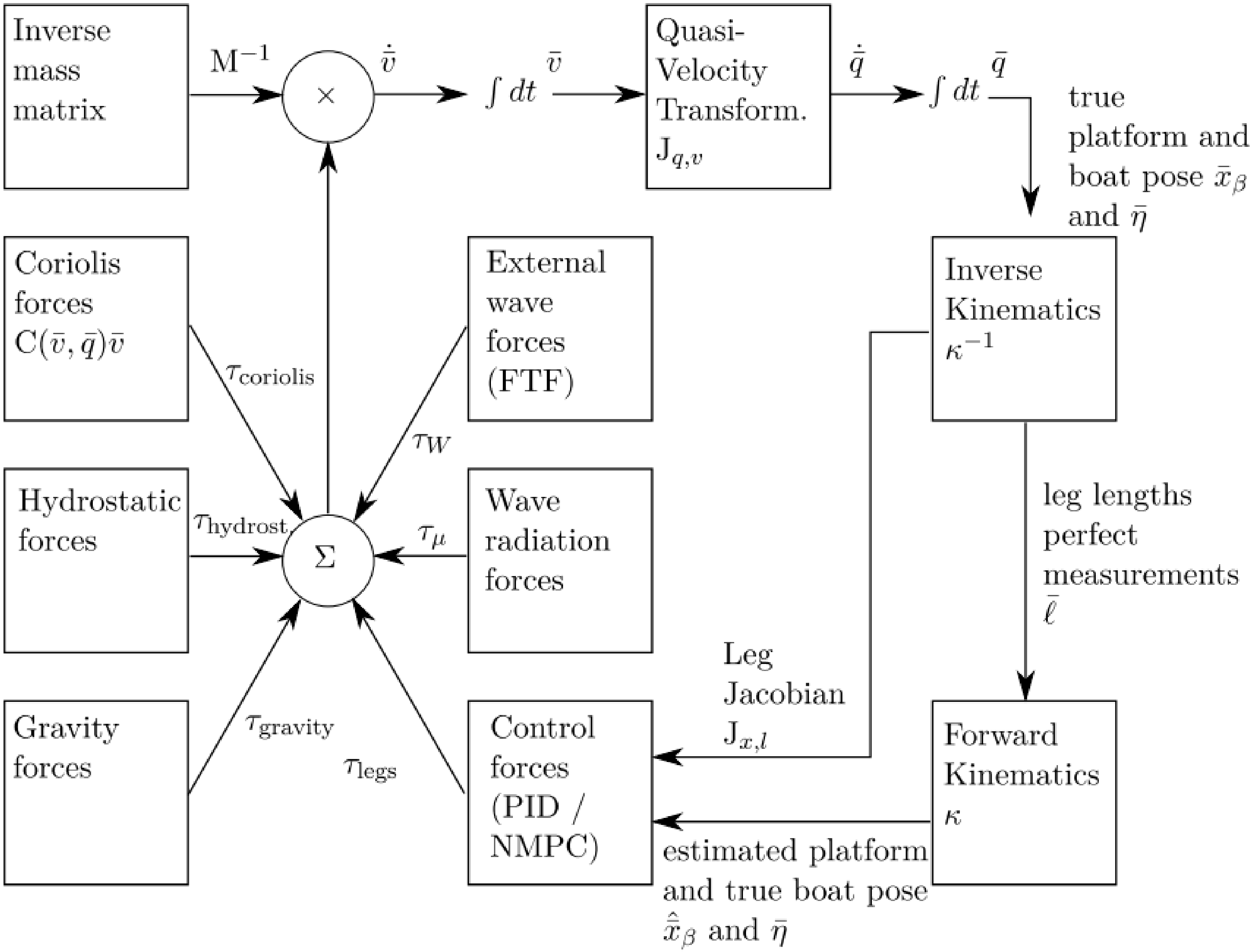
2. 3D modeling - total dynamics

- Nonlinear kinematics
- Coriolis terms
- Pose dep. mass matrix

- External waveloads
- Hydrostatics
- Hydrodynamics
  - Wave radiation
  - Added mass/damping



2. 3D modeling - total dynamics



3. Controllers - Naïve Quasistatic vs. Model Based

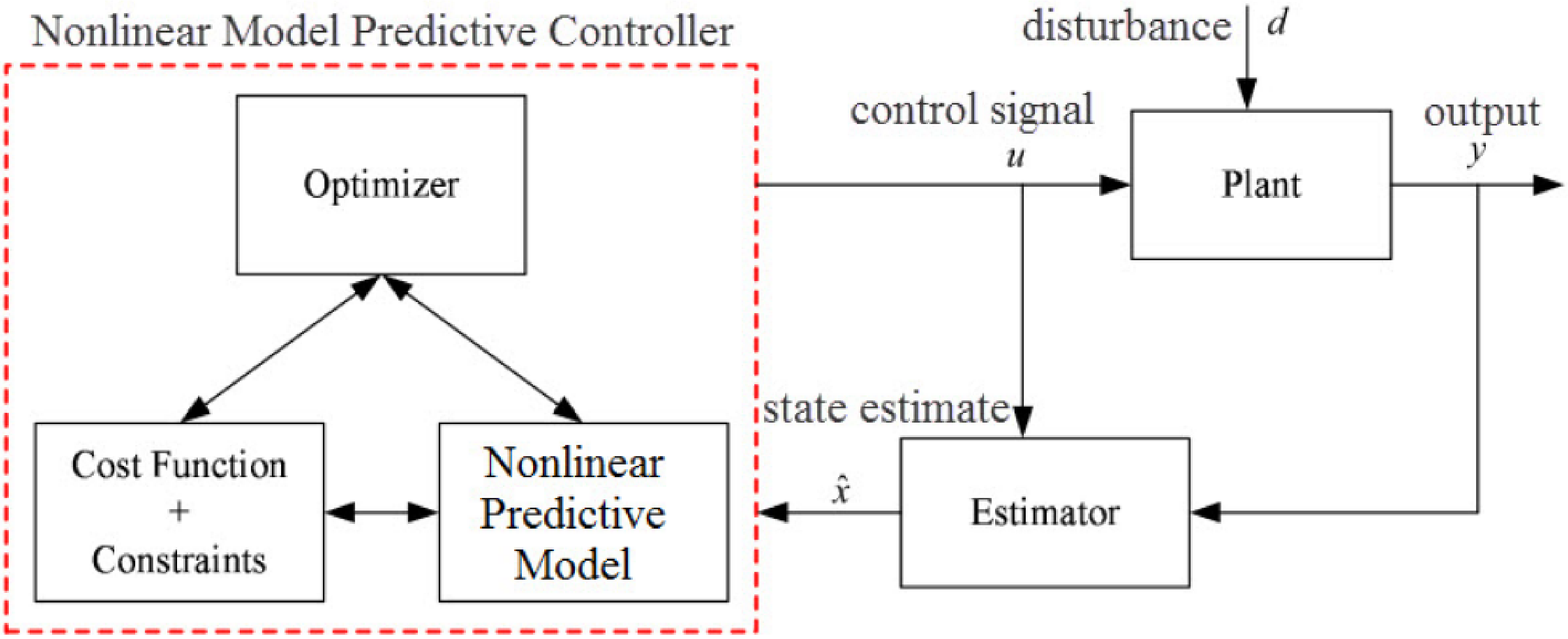
Quasistatic:

- Calculate leg length error assuming fixed boat position
- 2 Proportional-Integral-Derivative (PID) controllers
    - On mean error
    - On asymmetric errors

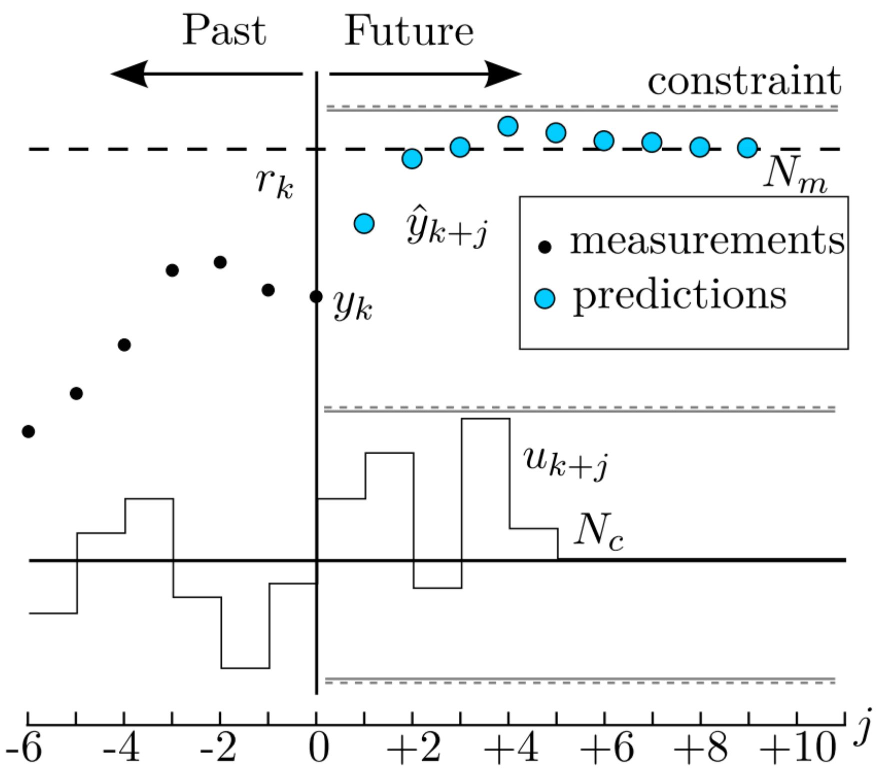
Model Based:

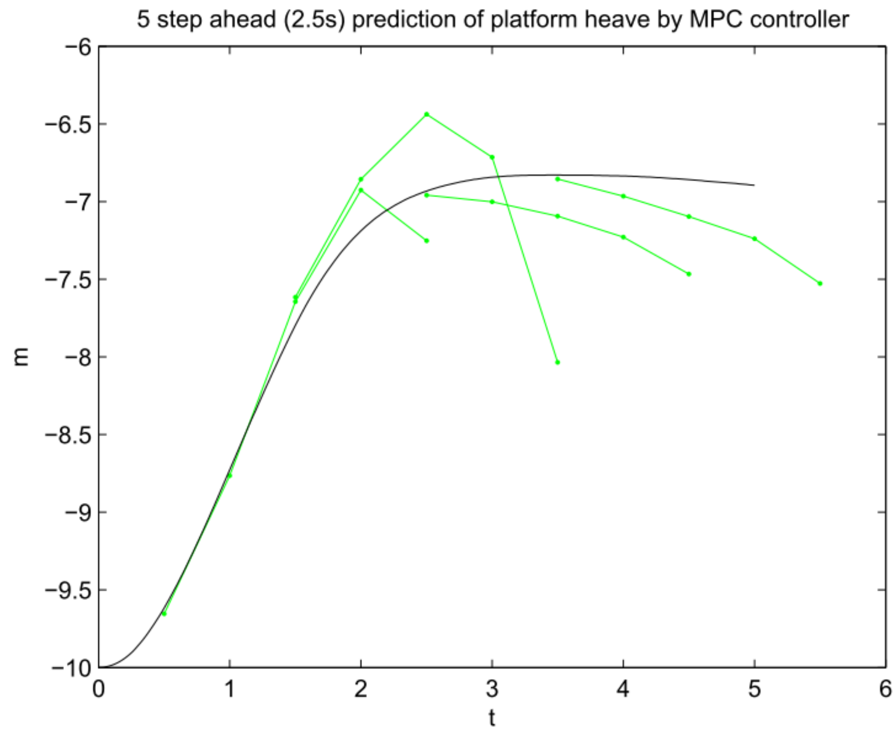
- Nonlinear Model Predictive Control

3. Control - Nonlinear Model Predictive Control

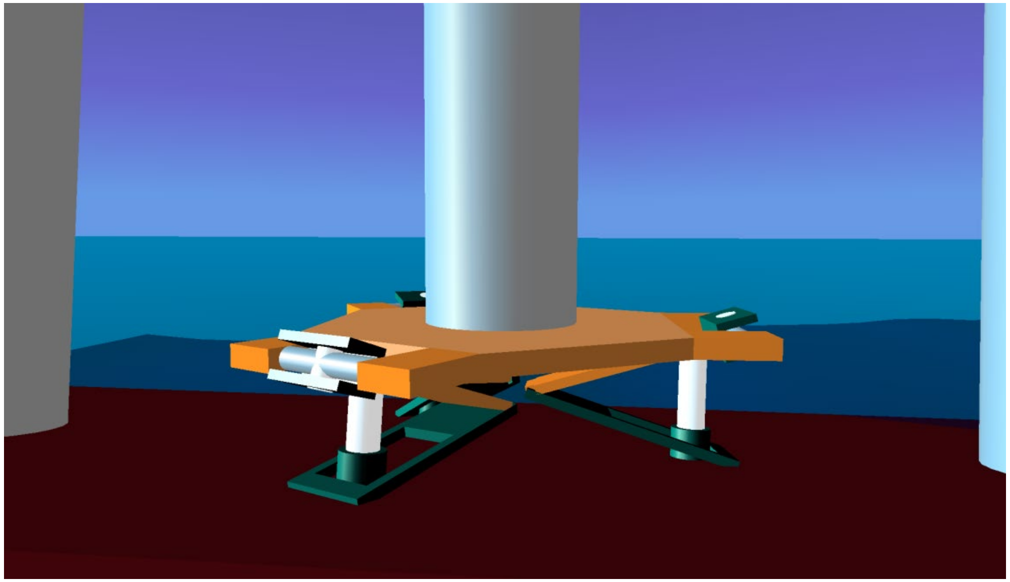


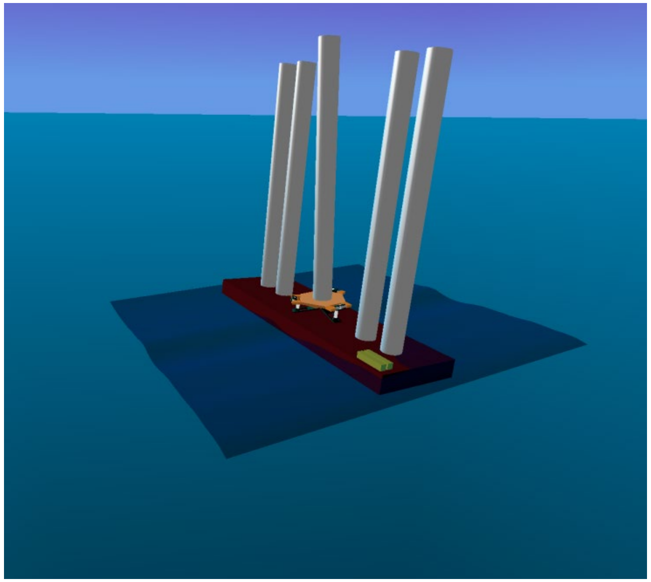
3. Control - Nonlinear Model Predictive Control



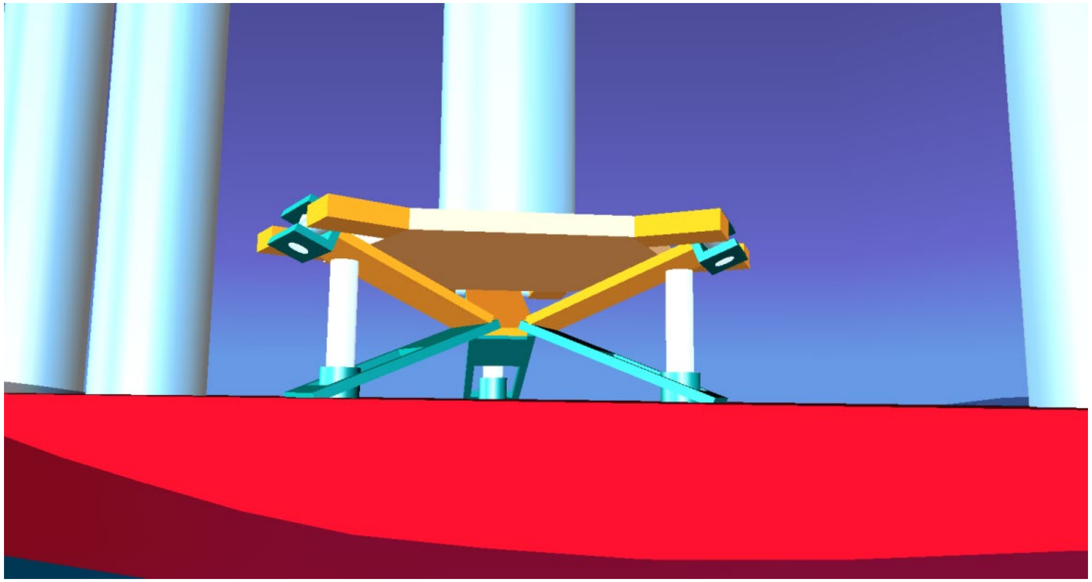


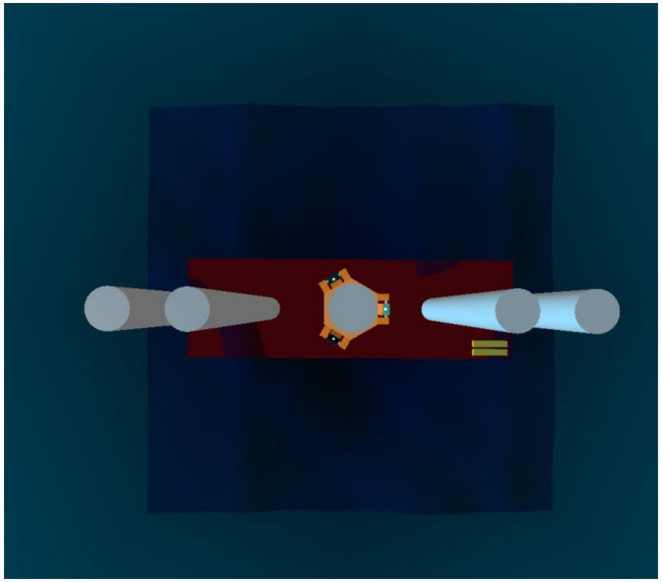
Visualizations





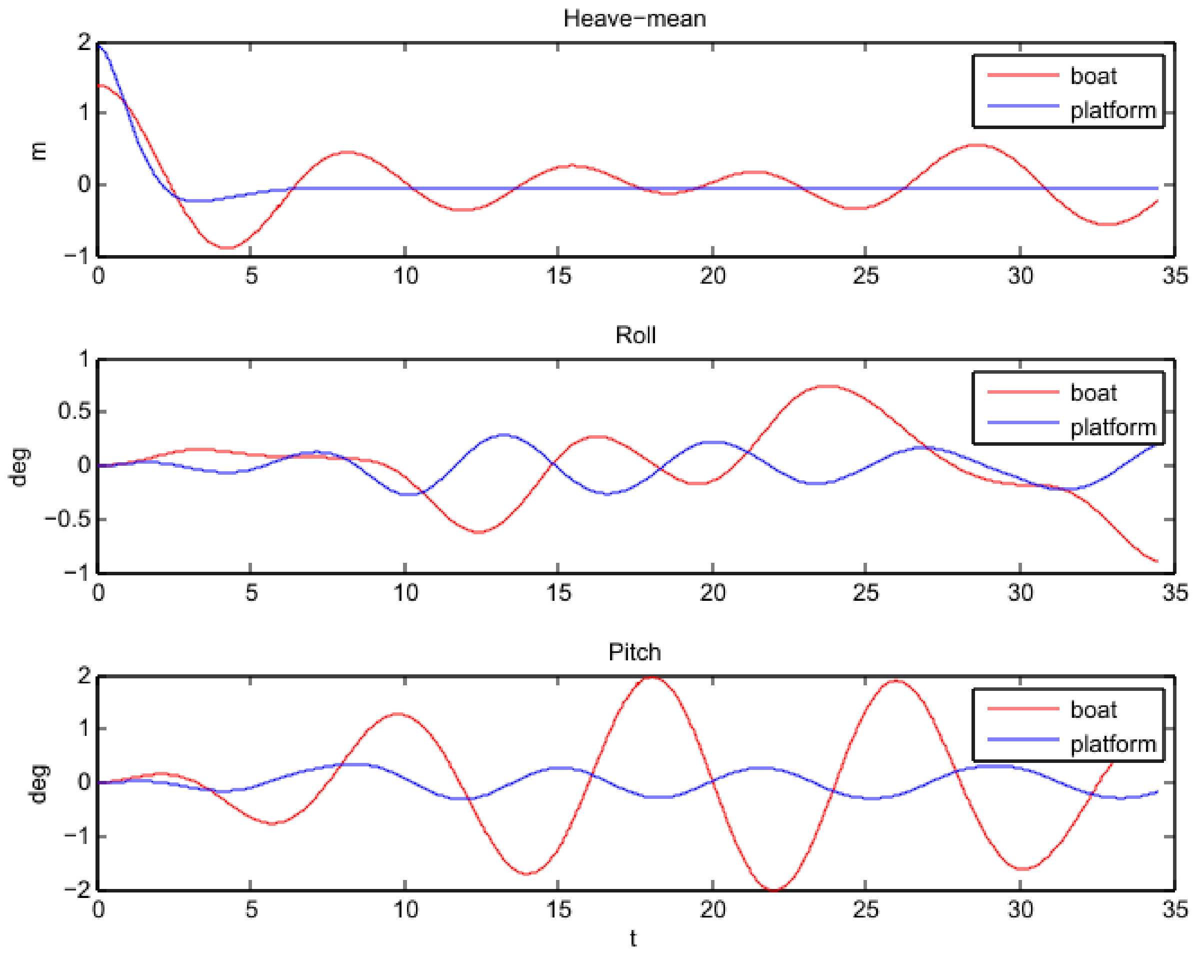
Visualizations





Heave-Roll-Pitch in storm conditions

Head sea, seastate Hs=4m T1=6.5s.



Energy usage in disturbance rejection

Milder sea

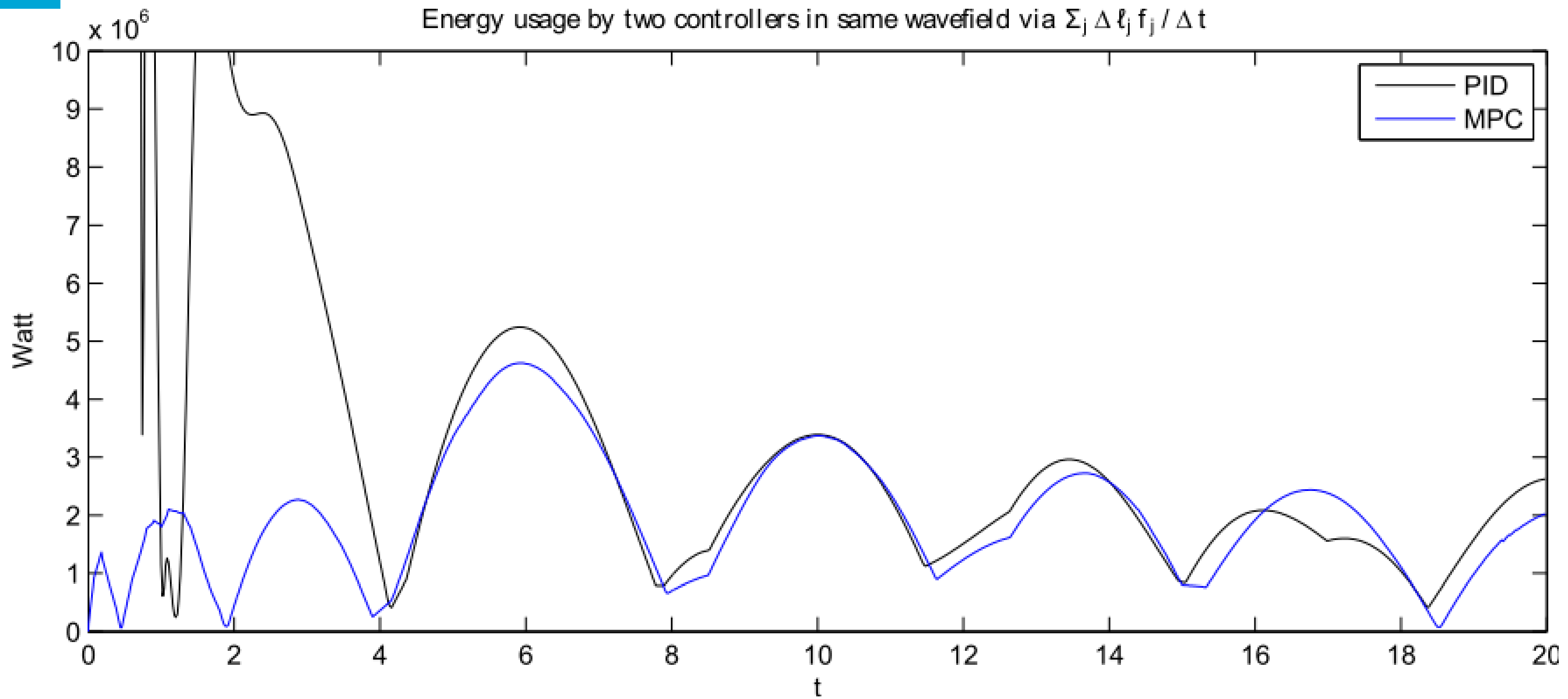
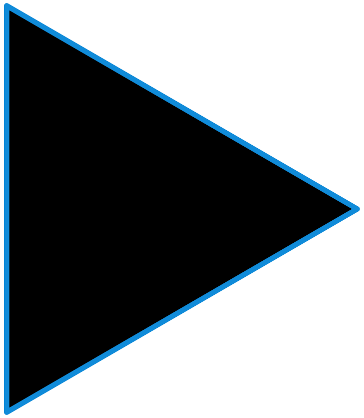


Figure 4-18: Comparison of the power required by the platform.

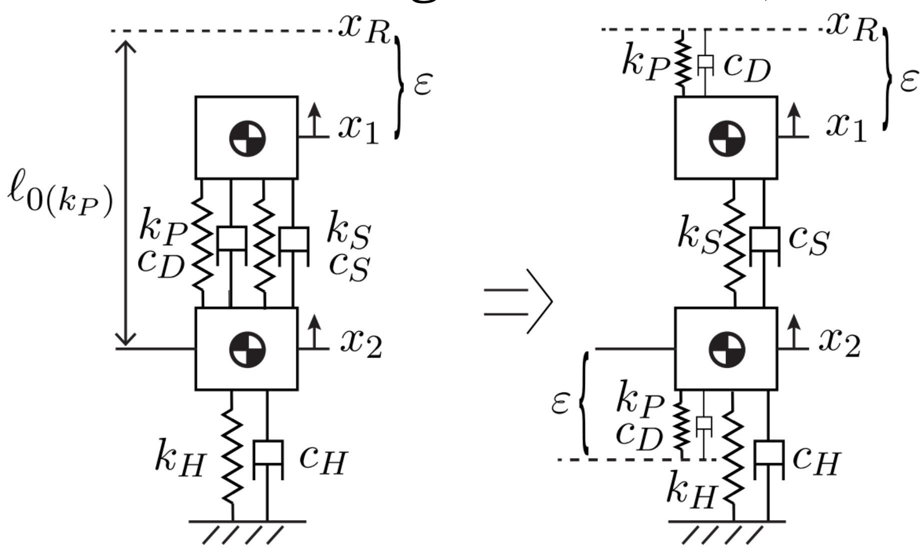
Conclusions

- The scalemodel roll instability can be reproduced by a linear model with quasistatic control and influential parameters can be recognized.
- The coupled ship - parallel platform dynamics are derived and he new platform can compensate the ship movements.
- MPC is shown to be a successful candidate for control, requires less power than PID in disturbance rejection and is less hard to tune and to stabilize.



Thank you. Questions?

#1: Second degree model fit, technique



$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \ddot{\mathbf{x}} = \begin{bmatrix} -(c_S + c_D) & c_S \\ (c_S + c_D) & -(c_S + c_H) \end{bmatrix} \dot{\mathbf{x}} + \begin{bmatrix} -(k_S + k_P) & k_S \\ (k_S + k_P) & -(k_S + k_H) \end{bmatrix} \mathbf{x} + \begin{bmatrix} c_D \\ -c_D \end{bmatrix} \dot{x}_R + \begin{bmatrix} k_P \\ -k_P \end{bmatrix} x_R \tag{3-8}$$

Or for with a non changing reference of zero ($x_R = 0$)[1]

$$\ddot{\mathbf{x}} = \begin{bmatrix} -\frac{(c_D+c_S)}{m_1} & \frac{c_S}{m_1} \\ \frac{(c_D+c_S)}{m_2} & -\frac{(c_H+c_S)}{m_2} \end{bmatrix} \dot{\mathbf{x}} + \begin{bmatrix} -\frac{(k_P+k_S)}{m_1} & \frac{k_S}{m_1} \\ \frac{(k_P+k_S)}{m_2} & -\frac{(k_H+k_S)}{m_2} \end{bmatrix} \mathbf{x}$$

$$SSR = \sum_{1}^{N} (\mathrm{y} - \hat{\mathrm{y}})^T (\mathrm{y} - \hat{\mathrm{y}})$$

Fitting technique:

$$A_s = \begin{bmatrix} C & K \\ I & \underline{0} \end{bmatrix} \quad \hat{\mathrm{y}}(t) = e^{A_s t}\mathbf{x_0}$$

$$\min_{\mathbf{x_0}, C, K} SSR$$

#1b: Second degree model fit, results

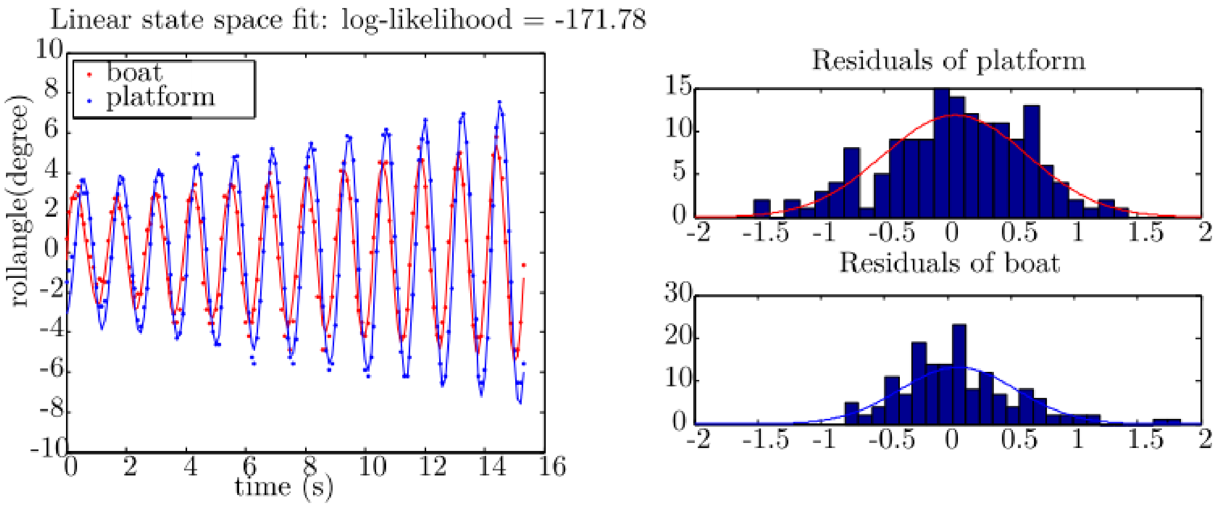


Figure 3-8: Fit for the first 15 seconds using the parametric physical model. $m_1 = 20kg$ and the first half of the dataset is used so $t = 0..T/2$. The dots are the measured data points and the full line is the estimated model.

$\dot{\phi}_{p0}$	23.25	(4.77)	$\dot{\phi}_{b0}$	−1.64	(−0.76)
ϕ_{p0}	−0.37	(−0.71)	ϕ_{b0}	−3.09	(−10.01)
m_1	20.00	(fixed)	m_2	72.97	(275.16)
k_P	755.63	(54.57)	k_S	0.00	(0.01)
k_H	2068.72	(164.39)	c_D	3.37	(1.40)
c_S	63.00	(43.21)	c_H	35.39	(18.46)
σ	0.74	(16.85)			

Table 3-3: Physical parameterized fit of first 15 seconds with $\log \mathcal{L} = -171.78$.

#2: Kinematics – leg joint velocity Jacobian construction

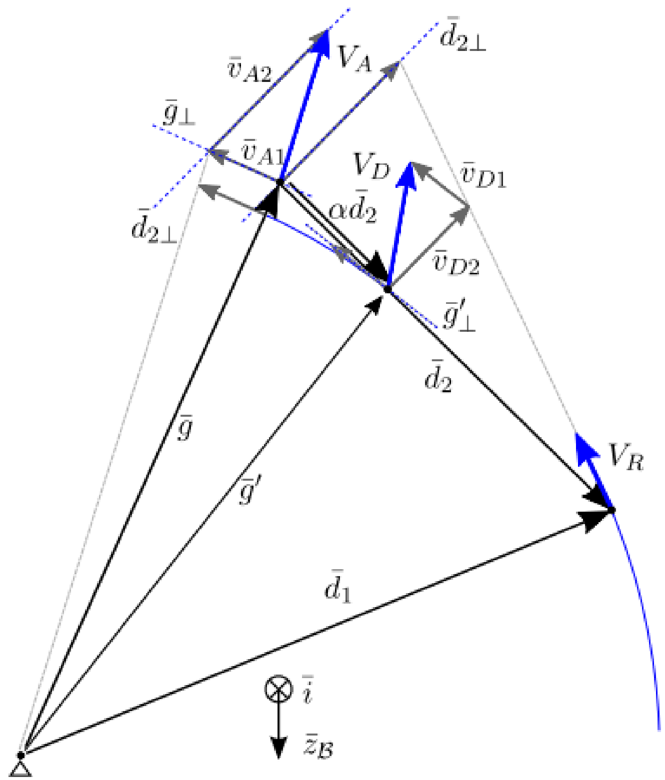
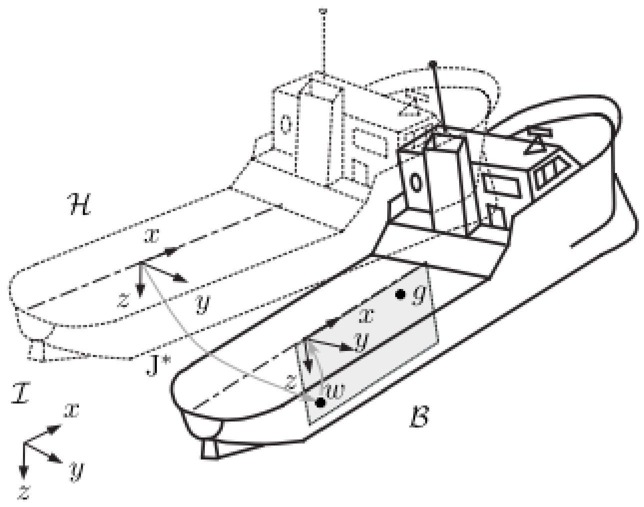


Figure 4-6: Velocity of joints in planar linkage system. The linkage is connected to the platform in A and to the hydraulics in D. The vectors $\bar{d}_1$ and $\bar{d}_2$ form the parallel mechanism of the linkage, and the auxiliary vectors $\bar{g}$ and $\bar{g}'$ are used in calculation and represent no parts. The main strategy of the velocity transformation is to decompose velocity vector V_A in two independent directions that represent the two rotations around the revolute joints at the floor and in R.

#3: Hydrodynamics – rad forces



Cummins eqn. in hydrodyn. ref. frame:

$$(\mathrm{M}_{\mathrm{RB}}^{\mathcal{H}} + \mathrm{A}_{\infty})\ddot{\bar{\xi}}^{\mathcal{H}} + \int_{-\infty}^{t} \mathrm{K}(t-t')\dot{\bar{\xi}}^{\mathcal{H}}(t)dt' + \mathrm{G}\bar{\xi}^{\mathcal{H}} = \bar{\tau}^{\mathcal{H}}$$

With the retardation function $\mathrm{K}(t) = \frac{2}{\pi}\int_0^\infty \mathrm{B}(\omega)\cos(\omega t)d\omega$.

Retardation forces (vector):

$$\bar{\mu}^{\mathcal{B}} = \int_0^t \mathrm{K}(t-t')\bar{\nu}(t)dt'$$
$$= \int_0^t \left[\frac{2}{\pi}\int_0^\infty (\mathrm{J}^{*T}\mathrm{B}(\omega)\mathrm{J}^*)\cos(\omega(t-t'))d\omega\right]\bar{\nu}(t)dt'$$

State space approx. per radiation component (scalar):

$$\dot{\bar{\chi}} = \mathrm{A}_{rad}\bar{\chi} + \mathrm{B}_{rad}\bar{\nu}$$
$$\mu^{\mathcal{B}} \approx \hat{\mu}^{\mathcal{B}} = \mathrm{C}_{rad}\bar{\chi}$$

Known values via hydrodynamic code (WAMIT):

$$\bar{\tau}_{rad}^{\mathcal{B}} = \mathrm{A}_c^{\mathcal{B}}(j\omega)\bar{\nu}^{\mathcal{B}} = \left[\frac{\mathrm{J}^{*T}\mathrm{B}(j\omega)\mathrm{J}^*}{j\omega} + \mathrm{J}^{*T}\mathrm{A}(j\omega)\mathrm{J}^*\right]\bar{\nu}^{\mathcal{H}}$$

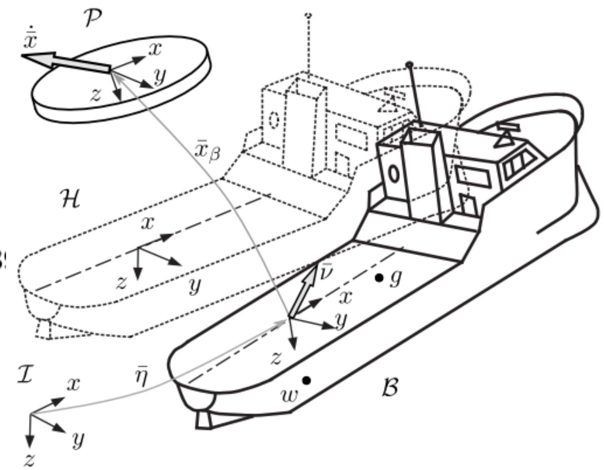
Approx. model: (Gauss-Newton iter)

$$\hat{\tau}_{rad_{kl}}^{\mathcal{B}}(s) = \left[\mathrm{A}_{\infty_{kl}}s + \frac{\mathrm{P}_{kl}(s)}{\mathrm{Q}_{kl}(s)}\right]\nu_l(s)$$

#4a: Dynamics – Pose dep. mass matrix

The kinetic energy of the platform is now found using the platform rigid body inertia matrix $\mathrm{M}_{RBp} \in \mathbb{R}^{6\times 6}$ with the reduction matrices H from Eq. (4-34) and the velocity of the platform with respect to the inertial frame expressed in the platform frame $\mathcal{P}$ ($\bar{V}_{0p}^{\mathcal{P}}$) as:

$$
\begin{aligned}
\mathcal{K}_{\text{platform}} &= \frac{1}{2}(\bar{V}_{0p}^{\mathcal{P}})^T \mathrm{M}_{RBp} \bar{V}_{0p}^{\mathcal{P}} \\
\text{(Relative velocity)} &= \frac{1}{2}(\bar{V}_{0b}^{\mathcal{P}} + \bar{V}_{bp}^{\mathcal{P}})^T \mathrm{M}_{RBp} (\bar{V}_{0b}^{\mathcal{P}} + \bar{V}_{bp}^{\mathcal{P}}) \\
\text{(ref. frame transf.)} &= \frac{1}{2}(\bar{V}_{0b}^{\mathcal{B}} + \bar{V}_{bp}^{\mathcal{B}})^T \mathrm{Ad}_{\mathcal{BP}}^T \mathrm{M}_{RBp} \mathrm{Ad}_{\mathcal{BP}} (\bar{V}_{0b}^{\mathcal{B}} + \bar{V}_{bp}^{\mathcal{B}}) \\
\text{(notation)} &= \frac{1}{2}(\bar{\nu} + \mathrm{H}\dot{\bar{x}})^T \mathrm{Ad}_{\mathcal{BP}}^T \mathrm{M}_{RBp} \mathrm{Ad}_{\mathcal{BP}} (\bar{\nu} + \mathrm{H}\dot{\bar{x}}) \\
&= \frac{1}{2}(\bar{\nu}^T + \dot{\bar{x}}^T \mathrm{H}^T) \mathrm{Ad}_{\mathcal{BP}}^T \mathrm{M}_{RBp} \mathrm{Ad}_{\mathcal{BP}} (\bar{\nu} + \mathrm{H}\dot{\bar{x}}) \\
\text{(expand)} &= \frac{1}{2}\bar{\nu}^T \underbrace{\mathrm{Ad}_{\mathcal{BP}}^T \mathrm{M}_{RBp} \mathrm{Ad}_{\mathcal{BP}}}_{\mathrm{M}_{vv}} \bar{\nu} + \bar{\nu}^T \underbrace{\mathrm{Ad}_{\mathcal{BP}}^T \mathrm{M}_{RBp} \mathrm{Ad}_{\mathcal{BP}} \mathrm{H}}_{\mathrm{M}_{vc}} \dot{\bar{x}} \\
&\quad + \frac{1}{2}\dot{\bar{x}}^T \underbrace{\mathrm{H}^T \mathrm{Ad}_{\mathcal{BP}}^T \mathrm{M}_{RBp} \mathrm{Ad}_{\mathcal{BP}} \mathrm{H}}_{\mathrm{M}_{cc}} \dot{\bar{x}}
\end{aligned}
\qquad (4\text{-}3
$$



Where we've recognised the velocity of the ship expressed in the ship frame (only heave, roll and pitch) as $\bar{V}_{0b}^{\mathcal{B}} = \mathrm{H}^T \bar{\nu}$ and the velocity of the platform relative to the ship expressed in $\mathcal{B}$ as $\bar{V}_{bp}^{\mathcal{B}} = \dot{\bar{x}}$. Now the total mass matrix for the platform dynamics becomes:

$$
\mathrm{M}_p = \begin{bmatrix} \mathrm{M}_{cc} & \mathrm{M}_{vc} \\ \mathrm{M}_{vc}^T & \mathrm{M}_{vv} \end{bmatrix} = \begin{bmatrix} \mathrm{H}^T \\ \mathrm{I}_{6\times 6} \end{bmatrix} \mathrm{M}_{vv} \begin{bmatrix} \mathrm{H} & \mathrm{I}_{6\times 6} \end{bmatrix} \in \mathbb{R}^{9\times 9} \qquad (4\text{-}40)
$$

And the kinetic energy and massmatrix for the ship are found by the rigid body mass plus the infinite period added mass in the body frame (Eq. (4-32)):

$$
\begin{aligned}
\mathcal{K}_{\text{ship}} &= \frac{1}{2}\bar{V}_{0b}^{\mathcal{B}^T} \mathrm{M}_s \bar{V}_{0b}^{\mathcal{B}} \\
&= \frac{1}{2}\bar{\nu}^T \mathrm{M}_s \bar{\nu}
\end{aligned}
\qquad (4\text{-}41)
$$

The total mass matrix is now (platform) pose dependent

#4b: Dynamics - Lagrange

Now using the velocity transform coupling the position variables to the quasi-velocities defined as:

(body fixed general velocities) $\bar{v} = \mathrm{S}(\bar{q})\dot{\bar{q}}$ (euler angle rates) (4-44)

Gives the Lagrangian $\tilde{L}$ expressed in the derivative of the position variables $(\bar{q})$:

$$
\begin{aligned}
\tilde{L}(\bar{q}, \bar{v}) &= \frac{1}{2}\dot{\bar{q}}^T \mathrm{S}^T(\bar{q})\mathrm{M}(\bar{q})\mathrm{S}(\bar{q})\dot{\bar{q}} - \mathcal{U}(\bar{q}) \\
\frac{\partial \tilde{L}}{\partial \bar{v}} &= \mathrm{S}^T(\bar{q})\frac{\partial L}{\partial \bar{v}} \\
\frac{d}{dt}\left(\frac{\partial \tilde{L}}{\partial \bar{v}}\right) &= \dot{\mathrm{S}}(\bar{q})\frac{\partial L}{\partial \bar{v}} + \mathrm{S}^T(\bar{q})\frac{d}{dt}\left(\frac{\partial L}{\partial \bar{v}}\right) \\
\frac{\partial \tilde{L}}{\partial \bar{q}} &= \frac{\partial L}{\partial \bar{q}} + \frac{\partial^T(\mathrm{S}(\bar{q})\dot{\bar{q}})}{\partial \bar{q}}\frac{\partial L}{\partial \bar{v}}
\end{aligned}
\tag{4-45}
$$

Now Lagrange's equations are found as:

$$
\frac{d}{dt}\left(\frac{\partial \tilde{L}}{\partial \bar{v}}\right) - \frac{\partial \tilde{L}}{\partial \bar{q}} = \mathrm{S}^T\tau \tag{4-46}
$$

$$
\begin{aligned}
\mathrm{M}(\bar{q})\dot{\bar{v}} + \underbrace{\dot{\mathrm{M}}(\bar{q})\bar{v} - \mathrm{S}^{-T}(\bar{q})\frac{1}{2}\frac{\partial^T \mathrm{M}(\bar{q})\bar{v}}{\partial \bar{q}}\bar{v}}_{\text{Multibody Coriolis terms}} \\
+ \underbrace{\mathrm{S}^{-T}(\bar{q})\left(\dot{\mathrm{S}}^T(\bar{q}) - \frac{\partial^T(\mathrm{S}(\bar{q})\dot{\bar{q}})}{\partial \bar{q}}\right)\mathrm{M}(\bar{q})\bar{v}}_{\text{Coriolis terms identical to single body case}} + \mathrm{S}^{-T}(\bar{q})\frac{\partial \mathcal{U}(\bar{q})}{\partial \bar{q}} = \tau
\end{aligned}
\tag{4-47}
$$