Heave plate hydrodynamics for offshore wind turbine applications

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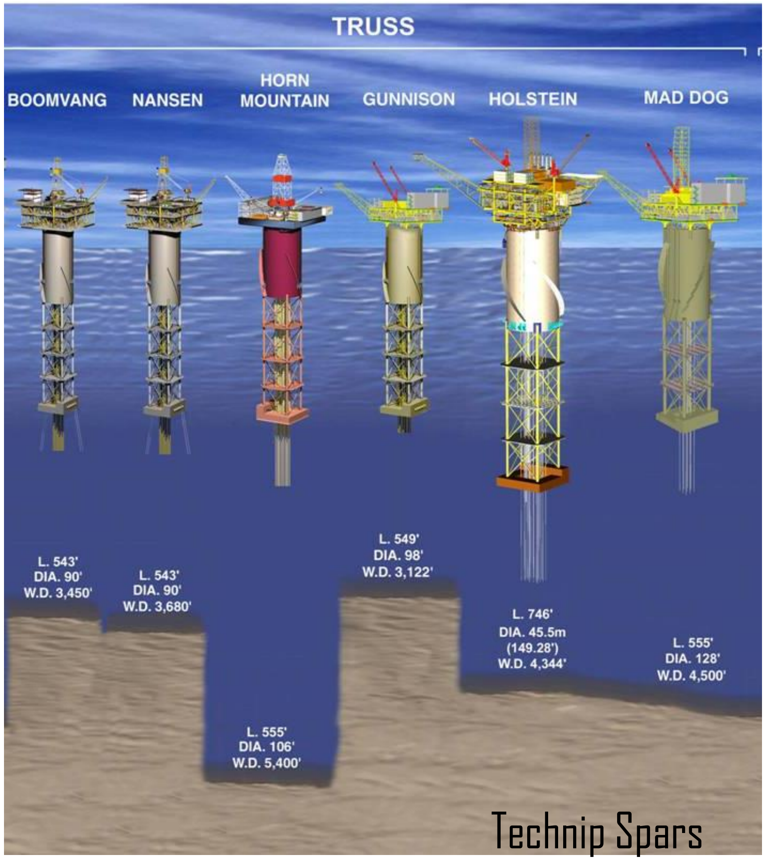
Outline

- Introduction
- Geometric configurations
  - Isolated heave plates
  - Heave plates attached to a column
- Issues common to both configurations
- Future Work

INTRODUCTION

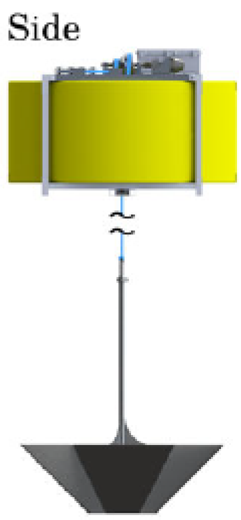
Heave plate application in offshore oil and gas production – spar platforms

- To limit vertical plane motion of platforms for supporting rigid risers
- To protect risers and mooring equipment (Tao & Cai, 2003)
- Heave plates work by:
  - increasing added mass and detuning the system.
  - Increasing damping due to vortex formation and shedding.
- Heave plates allow for a shallower draft (more economic) by decoupling the hull from wave excitation (Molin, 2001).

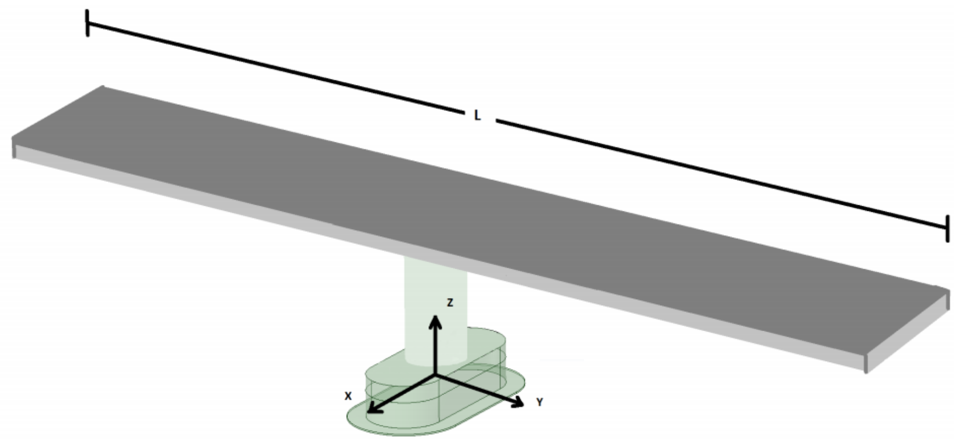


Other recent heave plate applications

- Wave Energy Converters
- Floating bridge stabilization



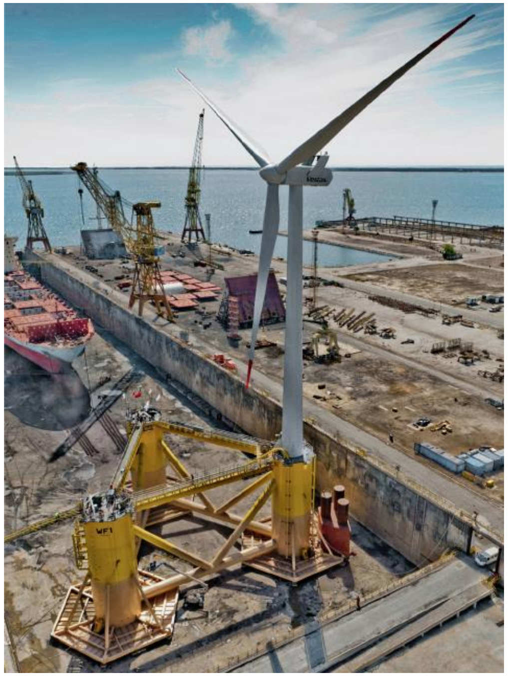
Side view of miniWEC
(Brown et al. 2017)



Bridge section with pontoon and heave plate
(Kleppa,2017)

Heave plate applications in offshore wind energy industry

- Offshore wind turbines require stable floating structures
- Stability can be augmented through the use of heave plates



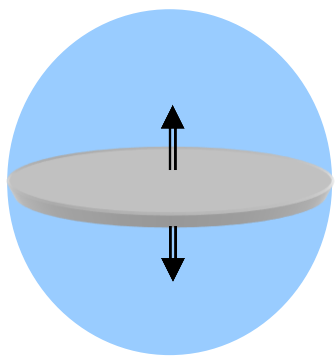
Close-up of a heave plate used on Principle Power's WindFloat platform; and platform assembly near Lisbon, Portugal; (Antonutti, et al. 2014)

Heave Plates and FOWT

- Hull is much lighter than oil and gas counterparts
- Shallower drafts of FOWTs can result in free surface effects and wave interaction with the heave plates
- Dynamic aerodynamic loading can affect hull pitch motion and effectiveness of heave plates
- Multiple plates located adjacent to each other.
- Numerical programs need hydrodynamic coefficients to represent heave plates in motion analysis of FOWT.

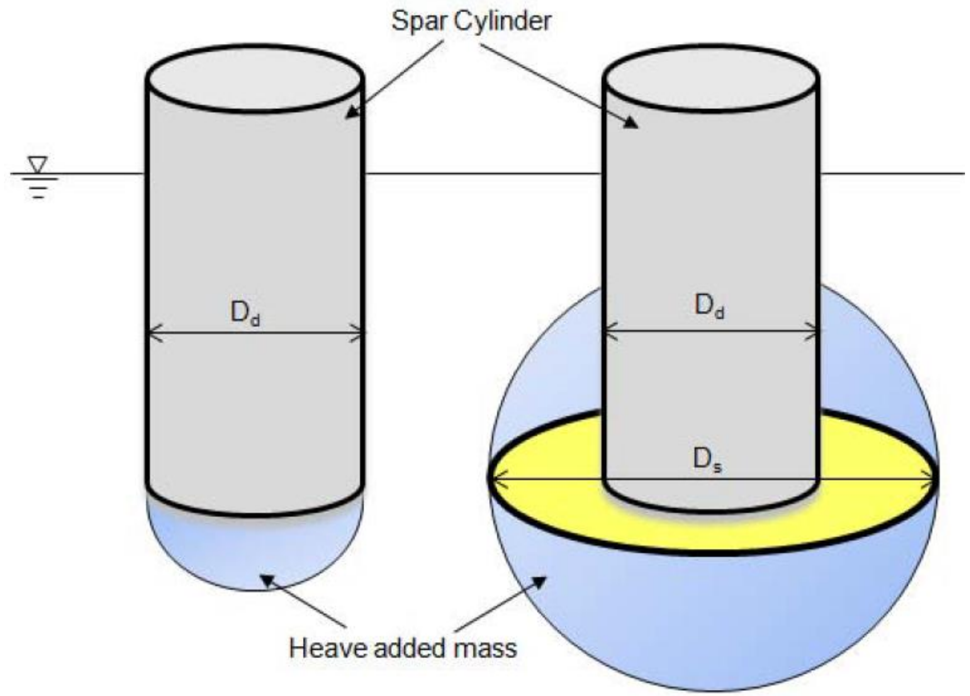
Added mass force

Increased inertial effect due to the acceleration of an additional volume of water along with the structure



$$\boxed{m_{a3} = \frac{1}{3}\rho D_{hp}^{3}}$$

Classical solution (Lamb, 1932)

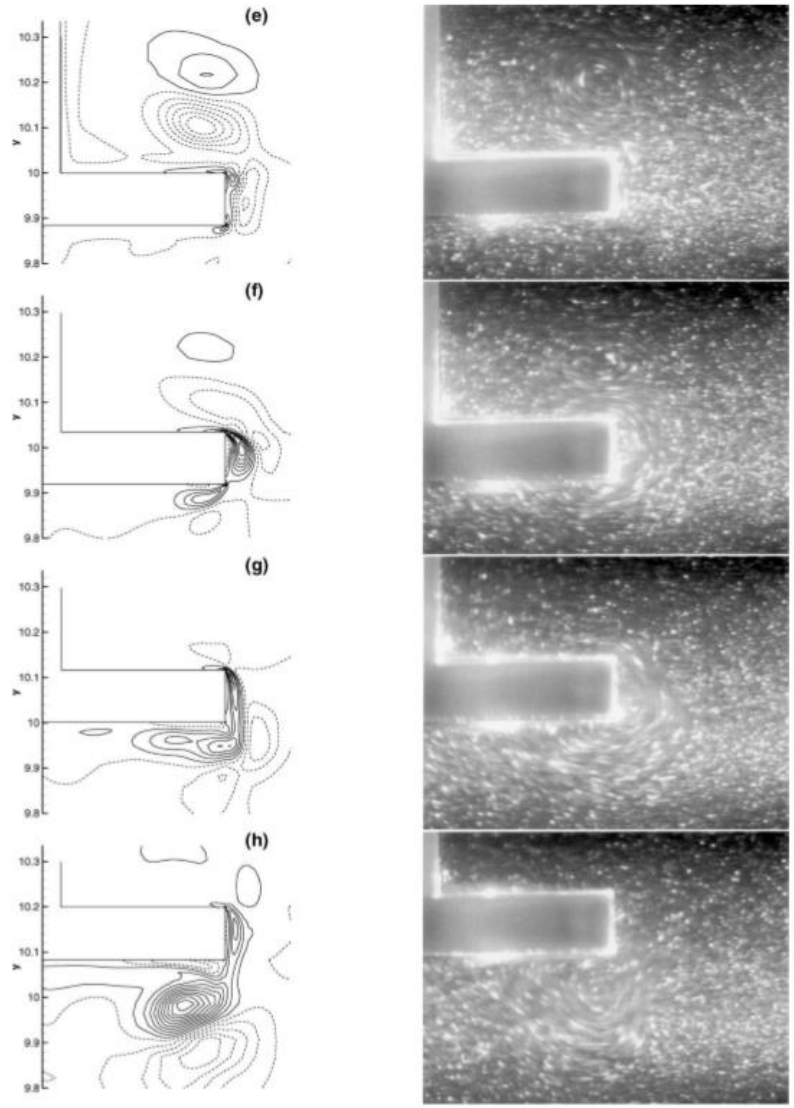


Added mass of a cylinder and cylinder with heave plate; (Sudhakar & Nallayarasu, 2011)

Damping force

Damping forces created by:

- Friction along the walls (small)
- Vortex shedding off the edges
- Wave radiation (small)



Vortex shedding and PIV (Tao & Thiagarajan, 2003)

Data Collection

Reviewed 66 papers from 1958 to present

Papers included 24 Experimental, 26 Numerical and 15 combined

Experiments and numerical analysis included

- free decay tests
- forced oscillations
- regular and irregular waves
- complex wind and wave loading

ISOLATED HEAVE PLATE

Key variables

Heave amplitude and frequency of motion are represented by

- Keulegan Carpenter number

$$KC = \frac{2\pi A}{D_{hp}}$$

- Frequency parameter

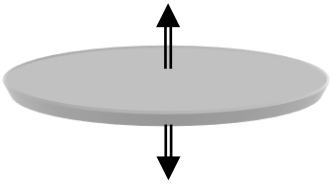
$$\beta = \frac{D_{hp}^2 f}{\upsilon}$$

A - amplitude

D - diameter

f - frequency

υ - kinematic viscosity



Dimensionless hydrodynamic coefficients

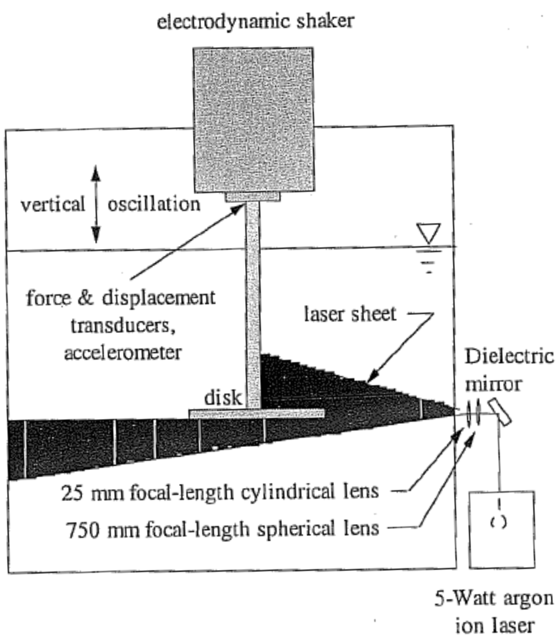
- Added mass coefficient

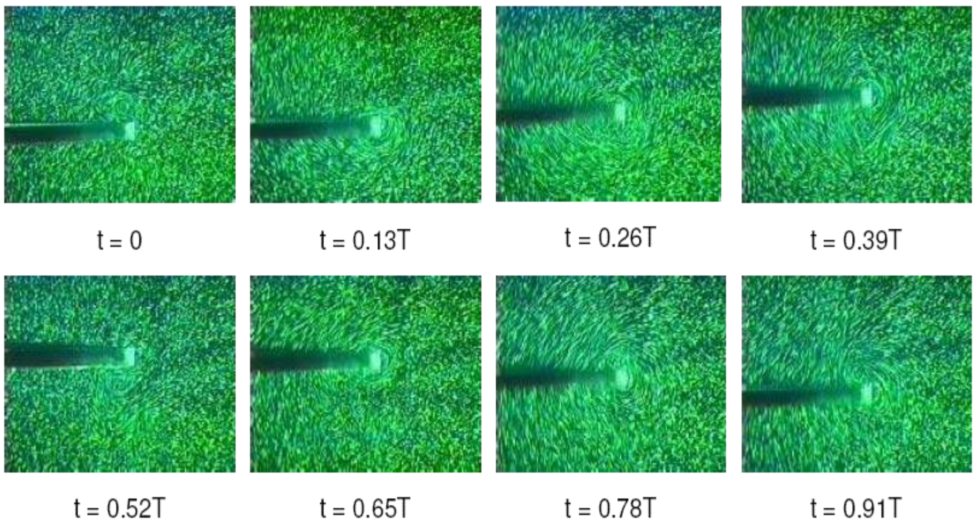
$$\boxed{C_a \text{ or } A' = \frac{A_{33}}{\frac{1}{3}\rho D_{hp}^3}}$$

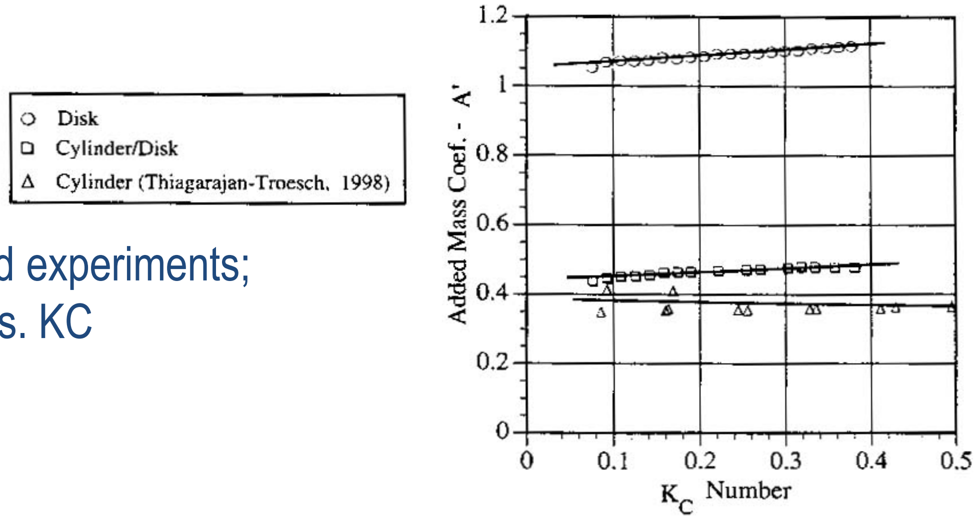
- Damping coefficient

$$\boxed{C_b \text{ or } B' = \frac{B_{33}}{\frac{1}{3}\rho\omega D_{hp}^3}}$$

Flow features around an isolated disk

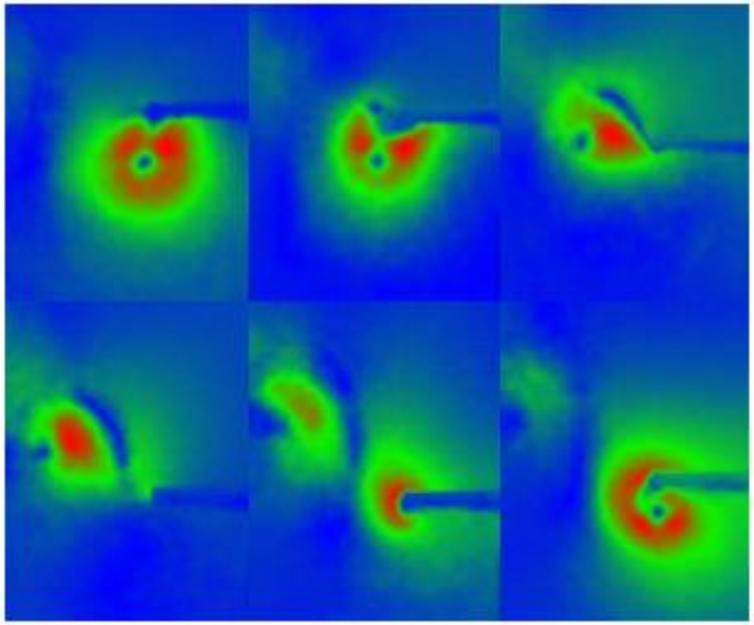


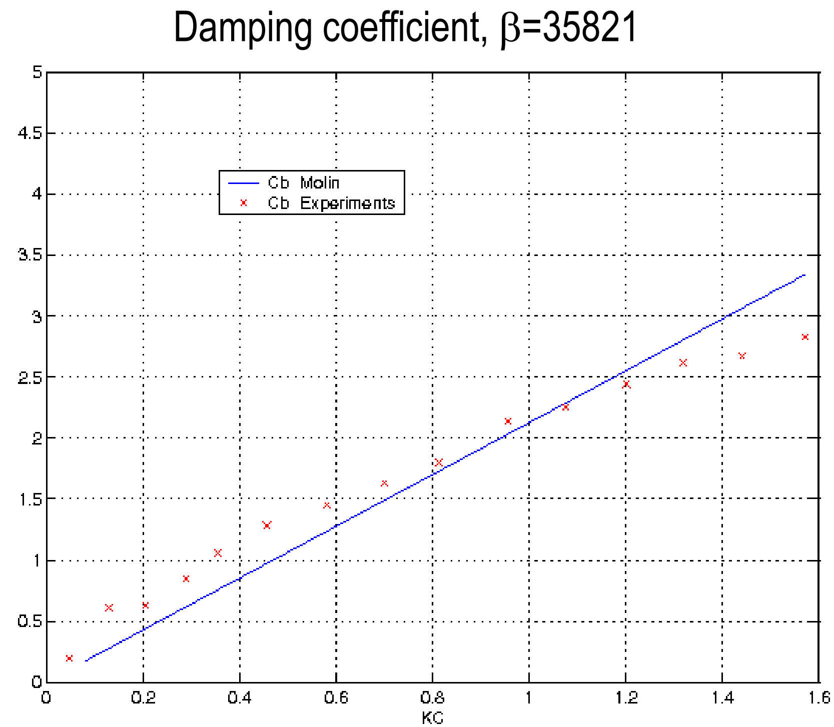




Particle Image Velocimetry setup and experiments;
Results for added mass coefficient vs. KC
(Lake et al. 2000)

Damping coefficients of isolated plates





Particle Image Velocimetry experiments; Results for damping coefficient vs. KC (Sireta et al. 2008) (Molin, 2001)

HEAVE PLATES ATTACHED TO A COLUMN

Added mass coefficient definition

C_a = ratio of added mass to displaced mass of the structure

$$C_a = \frac{A_{33}}{\rho\left(\frac{\pi}{4}D_{hp}^2 t_{hp} + \frac{\pi}{4}D_c^2 T_C\right)}$$

D_c – Column diameter

T_c – column draft

t_{hp} – heave plate thickness

Damping ratio vs. drag coefficient

- Linear vs. quadratic damping representation

$$F_{3d}(t) = B_{33} v_{rel}(t) \qquad\qquad F_{3d} = C_d \frac{1}{8} \rho \pi D^2 v_{rel} |v_{rel}|$$

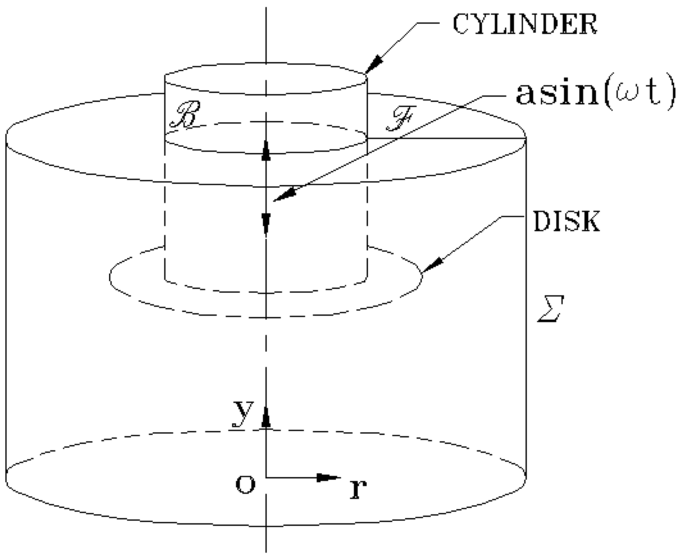
- By equivalent linearization

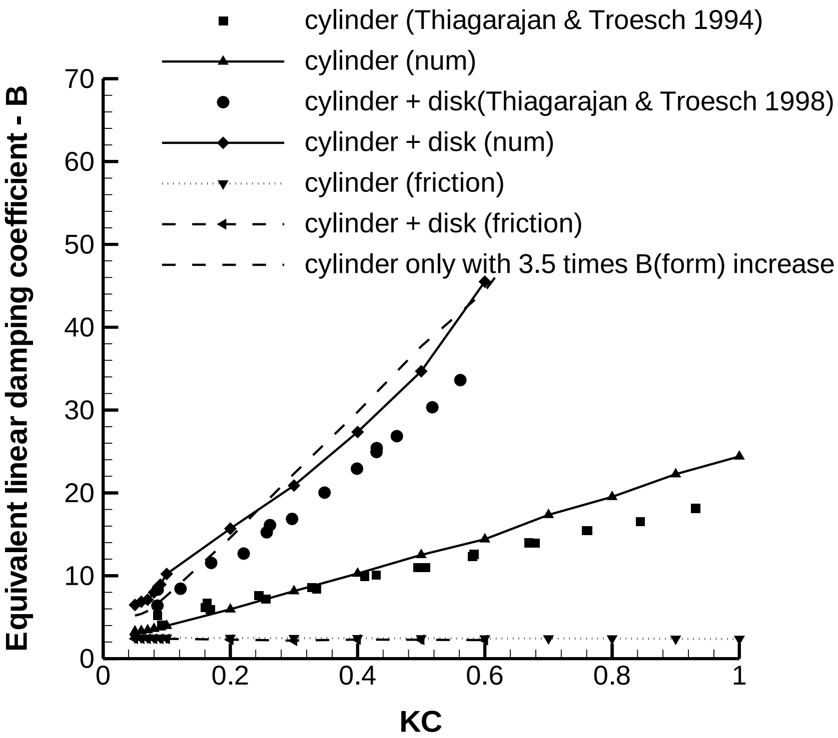
$$B_{33} = \frac{1}{3} \mu \, \beta \, D \, KC \, C_d$$

- Damping Ratio:

$$Z = \frac{\text{system damping}}{\text{critical damping}} = \frac{1}{3\pi^2} \frac{C_d}{C_m} \frac{D_{hp}^2 D_c}{(D_c^2 T + D_{hp}^2 t_{hp})} KC$$

Damping coefficients of deeply submerged plates





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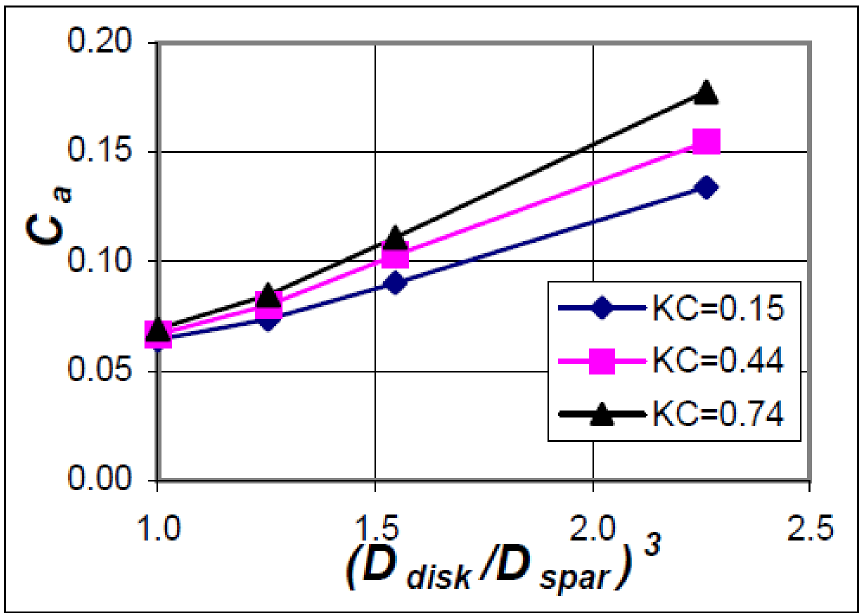
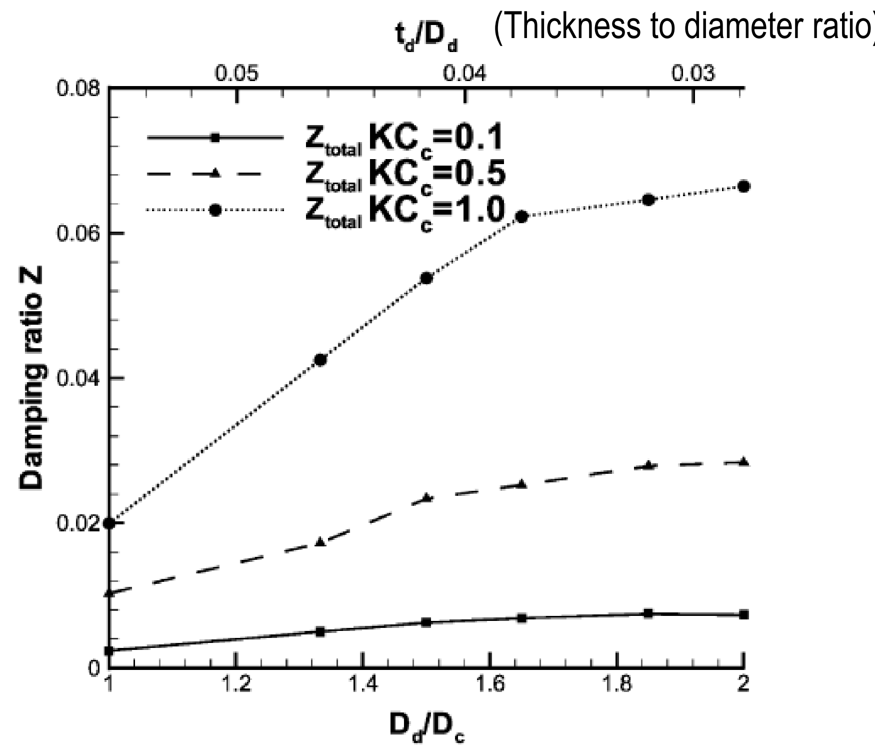
Data Trends: Size (Diameter Ratio)

Added mass increases with Diameter ratio

Damping increases with diameter ratio to an optimum 1.2-1.3 (Sudhaker and Nallayarasu 2011) or 1.2-1.4 (Subbulakshmi, Sundaravadivelu 2016)



Added mass coefficient vs. Diameter Ratio (Thiagarajan, Datta, Ran, Tao & Halkyard, 2002)

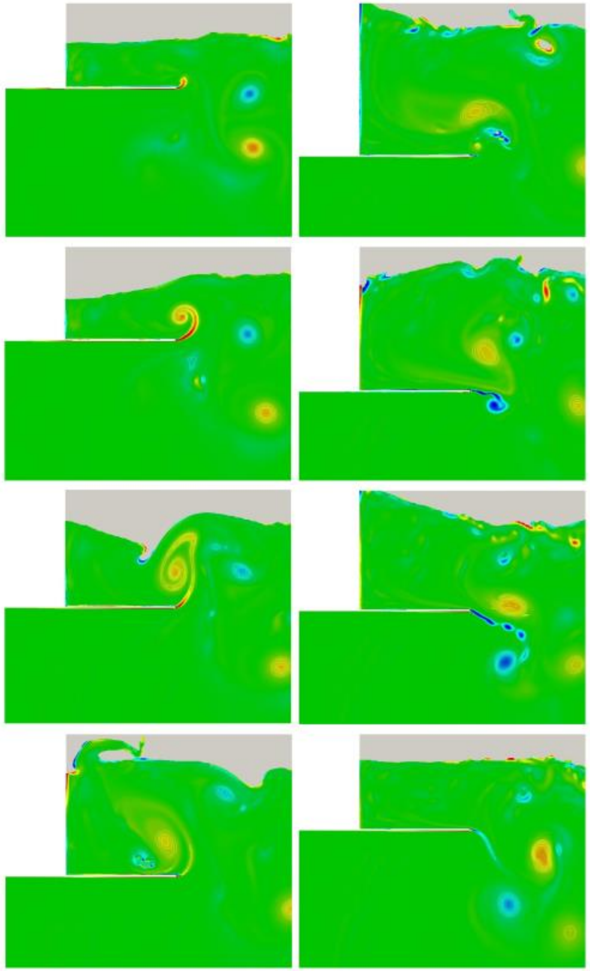


Damping ratio vs. Diameter Ratio (From: Tao & Cai, 2003)

ISSUES COMMON TO BOTH CONFIGURATIONS

Proximity to the free surface

- At a constant frequency (fixed β), the added mass and damping coefficients increase with KC and with decreasing distance to free surface.
- Good agreement between numerics and experiments.

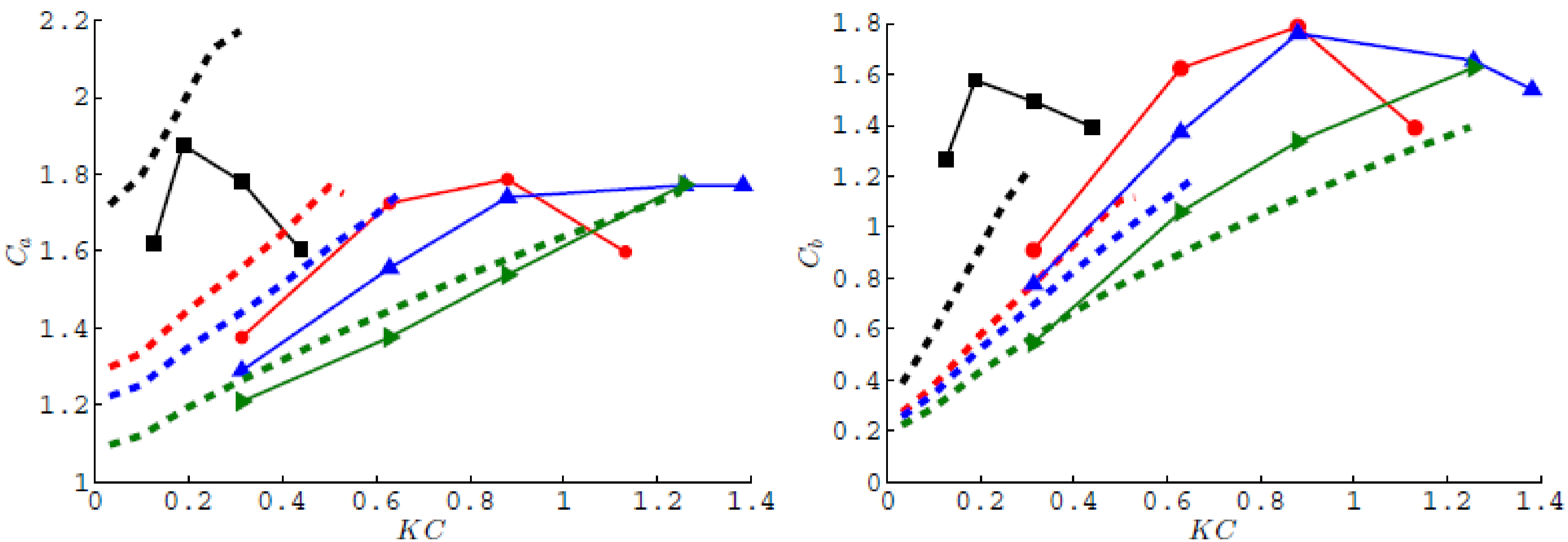


Vortex generation around disk at KC = 0.65 and submergence of 0.5 radius. Blue is negative and red is positive vorticity magnitude. (Mendoza et al. 2014)

Data Trends: Proximity To Free Surface

Drag Coefficient greatly effected by the free surface (An & Faltinsen, 2013)

Larger vortices observed when heave plate oscillates closer to the free surface (Garrido-Mendoza et al., 2014)



Added mass and damping coefficients at different submergences (h/r_d; $r_d = \frac{D_{hp}}{2}$) (Garrido-Mendoza, et al., 2014)

ONGOING WORK

Added mass coefficient definition

- Offshore oil and gas platforms
  - C_a = ratio of added mass to displaced mass of the structure

$$C_a = \frac{A_{33}}{\rho\left(\frac{\pi}{4}D_{hp}^2 t_{hp} + \frac{\pi}{4}D_c^2 T_C\right)}$$

- Floating offshore wind turbines (e.g. FAST)
  - C_a defined for top and bottom part of the plate:

$$C_{a_t} = \frac{A_{33_t}}{\frac{1}{12}\rho\pi\left(D_{hp}^3 - D_c^3\right)} \qquad C_{a_b} = \frac{A_{33_b}}{\frac{1}{12}\rho\pi D^3}$$

$$\frac{A_{33_t}}{A_{33}} = ? \qquad \frac{A_{33_b}}{A_{33}} = ?$$

We assume:

$$C_{a_t} = C_{a_b} = C_a$$

Drag coefficient definition

Assuming the drag force is equally split between top and bottom surfaces:

$$C_{d_b} = \frac{B_{33}}{\frac{2}{3}\rho D_{hp}^2 \omega A}$$

$$C_{d_t} = \frac{B_{33}}{\frac{1}{3}\rho D_{hp}^2 \omega A (2 - R^2)}$$

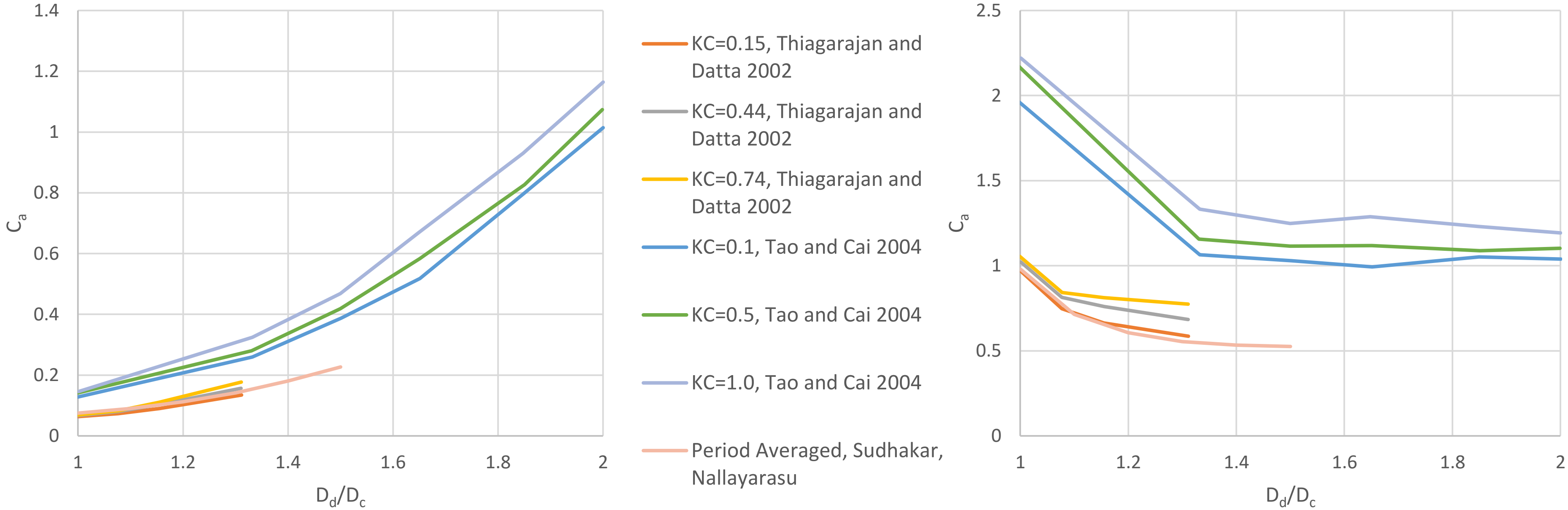
$$R = \frac{D_c}{D_{hp}}$$

Coefficients in FAST format

Splitting into top and bottom surfaces produces counter-intuitive results:

$$C_a = \frac{A_{33}}{\rho\left(\frac{\pi}{4}D_{hp}^2 t_{hp} + \frac{\pi}{4}D_c^2 T_C\right)}$$

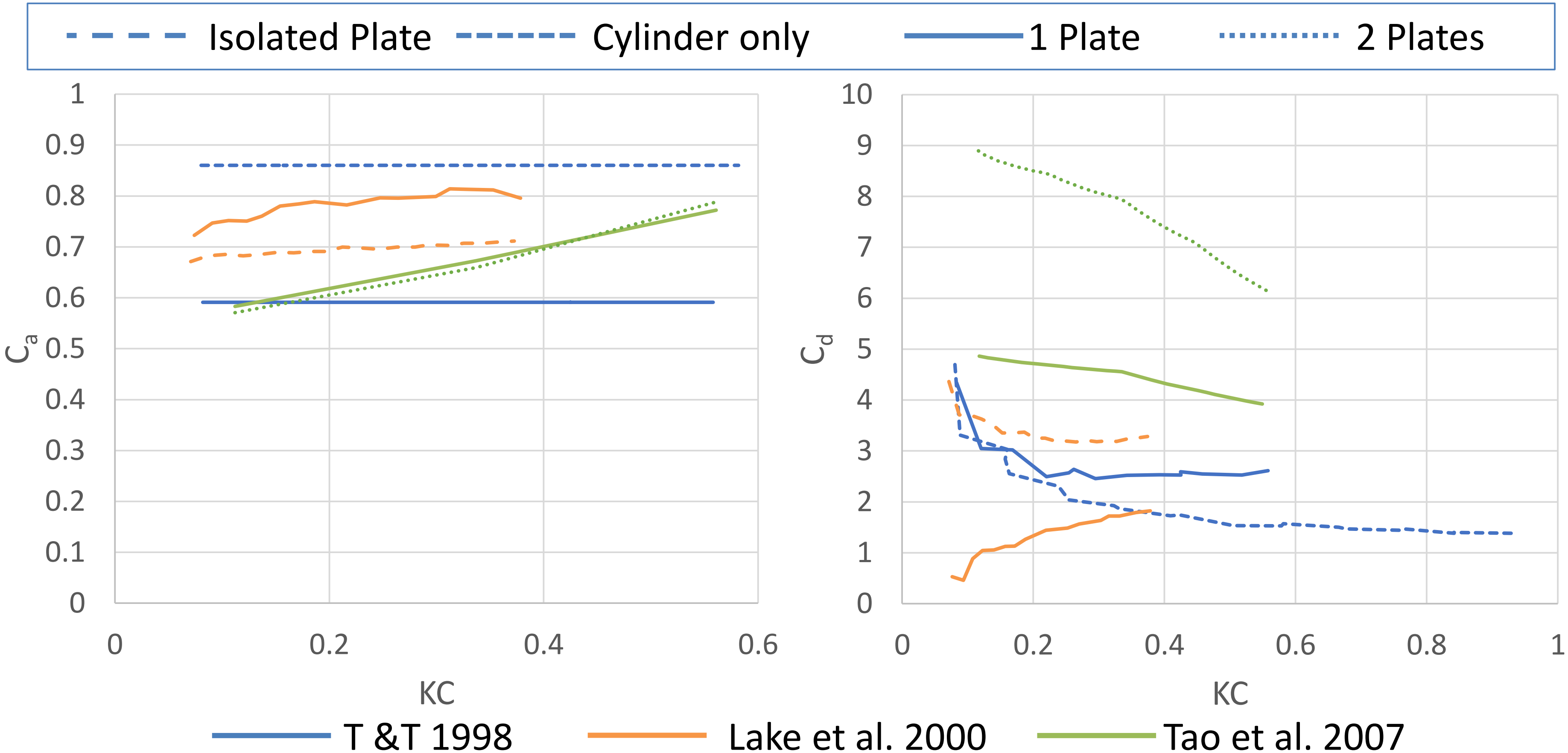
$$C_a = \frac{A_{33}}{\frac{1}{12}\rho\pi\left(2D_{hp}^3 - D_c^3\right)}$$



The new added mass coefficient decreases as the heave plate becomes relatively larger ($R = \frac{D_c}{D_{hp}}$ decreases) despite the actual added mass increasing.

Comparison of Heave Plate Quantity

Analysis of a Cylinder with 0, 1, and 2 heave plates (separated on cylinder by $0.375D_{hp}$) as well as an isolated heave plate with no cylinder:



Additional Heave plates increase the drag coefficient, but have less impact on added mass

Ongoing Work

- Use data trend lines to develop coefficients for top and bottom parts of a plate
- UMass small scale and PIV experiments to support NREL testing campaign as part of OC6.

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