Time domain assessment of nonlinear coupled ship motions and sloshing in free surface tanks

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outline

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1. Motivation

1. Motivation

1. Liquid cargo and ART may significantly affect ship motions when in partially filled tanks.
2. Ship motions are crucial to establish ship operability (design marine operations) in a certain sea state (LNG transportation, drilling operations, fishing vessel operations, cargo transfer, etc...)
3. Dynamics is usually 6DOF and nonlinear when assessing operations in realistic scenarios

1. State-of-the-art (1/2)

1. TD commercial software for coupled sloshing and ship motions not available. BV HOMER is an exception of not clear scope.
2. FD linear approaches for internal & external dynamics available (Malenica et al., 2003, Kim&Shin, 2008): not able to model non-linear motion effects nor non-linear sloshing.
3. TD linear ship motions + non-linear sloshing (potential, NS+VOF)(Kim et al., 2007, Zhao et al., 2014, Bunnik&Veldman,2010): not able to model non-linear motion effects (roll damping, non-linear restoring, etc..)

1. State-of-the-art (2/2)

4. Nonlinear simplified 1DOF (Francescutto&Contento, 99, Hashimoto et al., 2012).
5. 6DOF nonlinear ship dynamics (nonlinear restoring) + U-tube-ART (Holden&Fossen, 2012).
6. 6DOF nonlinear ship dynamics (similar to H&F) + nonlinear FEM for internal flow (Mitra et al., 2012).
7. Nonlinearities associated with rigid body dynamics, interaction with the external flow, large amplitude motions, internal flow sloshing, maneuvering in waves, etc.... No tool available: let's work on it!

2. Simulation approach

SHIXDOF: nonlinear ship motion TD 6DOF

+

AQUAgpusph: SPH 3D gpu (internal flow)

2.1. Simulation approach SHIXDOF

1)"nonlinear SHIp motion simulation program with siX Degrees Of Freedom") (Bulian et al, 2012, 2013).

2)Simulation strategy is “blended” (or “hybrid”) : ship motions, maneuvering and propulsion sub-models are blended to solve the ship nonlinear rigid body dynamics in waves.

3)Rigid body dynamic solved using classical (manoeuvring-style) projection on ship-fixed reference system:

$$m \cdot \left[\begin{array}{l} \dot{\boldsymbol{u}}_O + \boldsymbol{\omega} \times \boldsymbol{u}_O + \\ + \dot{\boldsymbol{\omega}} \times \boldsymbol{x}_G + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \boldsymbol{x}_G) \end{array} \right] = \boldsymbol{F}_{ext}(t),$$

$$\begin{array}{l} \mathbf{I}_O \cdot \dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times (\mathbf{I}_O \cdot \boldsymbol{\omega}) + \\ m \cdot \boldsymbol{x}_G \times \dot{\boldsymbol{u}}_O + m \cdot \boldsymbol{x}_G \times (\boldsymbol{\omega} \times \boldsymbol{u}_O) \end{array} = \boldsymbol{M}_{ext,O}(t).$$

2.1. Simulation approach SHIXDOF

1) Diffraction forces from linear FD pre-calculations.
2) Froude-Krylov loads considered up to the instantaneous wetted surface of the hull. Nonlinear restoring.
3) Radiation terms via convolution integrals.
4) Linear maneuvering forces due to lift effects via derivatives-based approach (Clarke et al., 83)
5) Spatial variability of flow field in waves is accounted for in the maneuvering sub-model by an "equivalent surge-yaw-sway motion" relative to the water (Artyszuk, 2006)
6) Additional linear and nonlinear roll damping coefficients can be introduced for tuning purposes.
7) Other sub-models are available to represent the effect of other external actions, such as lifting surfaces, propellers, wind, elastic mooring lines, etc.

2.2. Simulation approach:

INTERNAL FLOWS

AQUAgpusph

1) New **free** SPH solver accelerated for GPUs (and heterogeneous platforms) with OpenCL (Cercos-Pita, 2015)
2) SPH is a meshless method to solve NS in complex free-surface flows, with fragmentation and breaking.
3) AQUAgpusph is Python extensible.
4) Weakly compressible approach used (explicit solver).

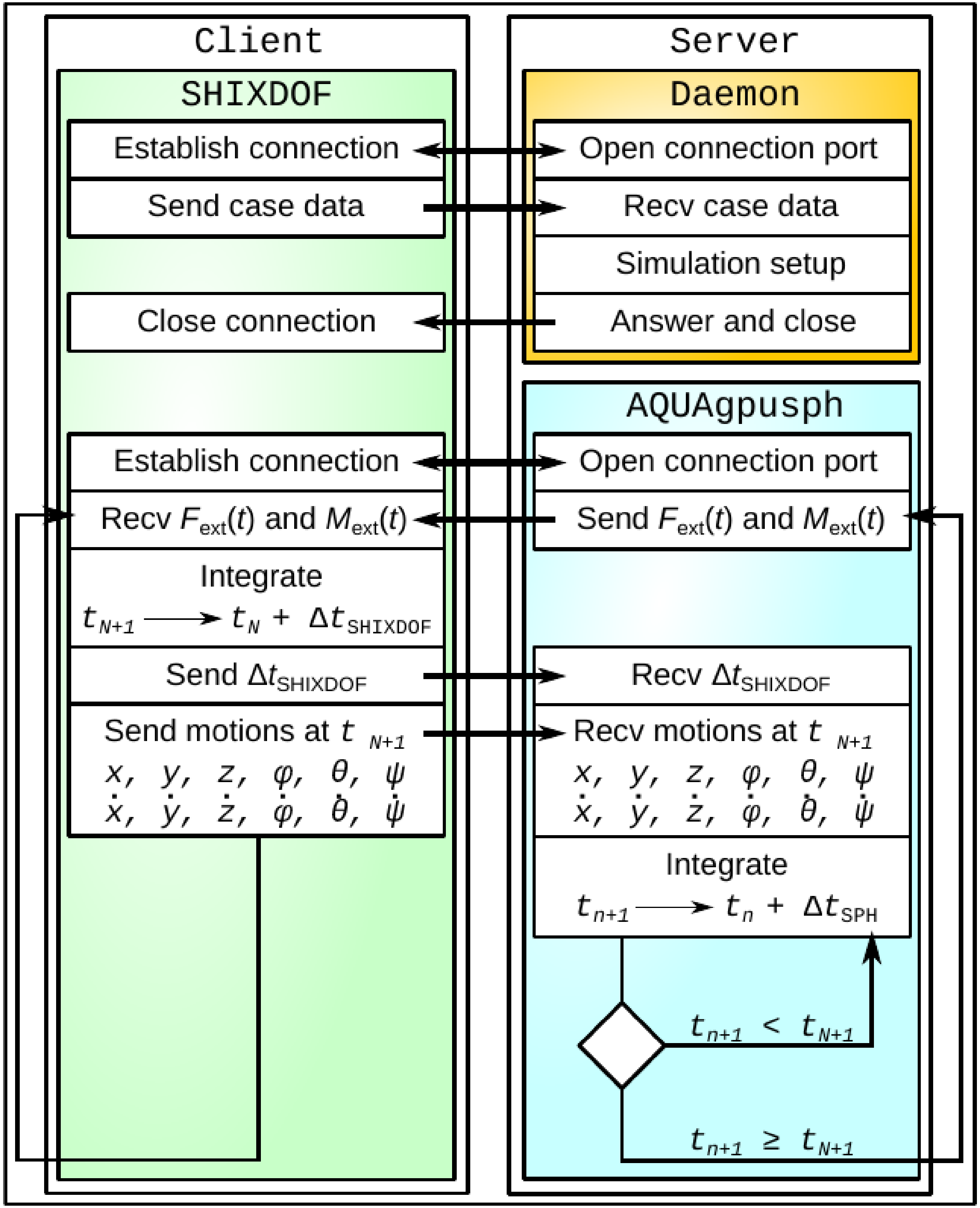
2.3. Simulation approach:

Coupling (explicit)

1) SHIXDOF + AQUAgpusph run in different computing facilities and communicate via ethernet, with tcp-ip protocol.

2) Several tanks can be run.

$$\Delta t_{\mathrm{SPH}} \ll \Delta t_{\mathrm{SHIXDOF}}$$



3. Application example (S60 with ART)

1) Freely available hull geometry (comparison purposes)
2) Experimental data regarding nonlinear roll motion available from previous campaigns.
3) Simulations carried out in regular beam waves with different tank lengths.

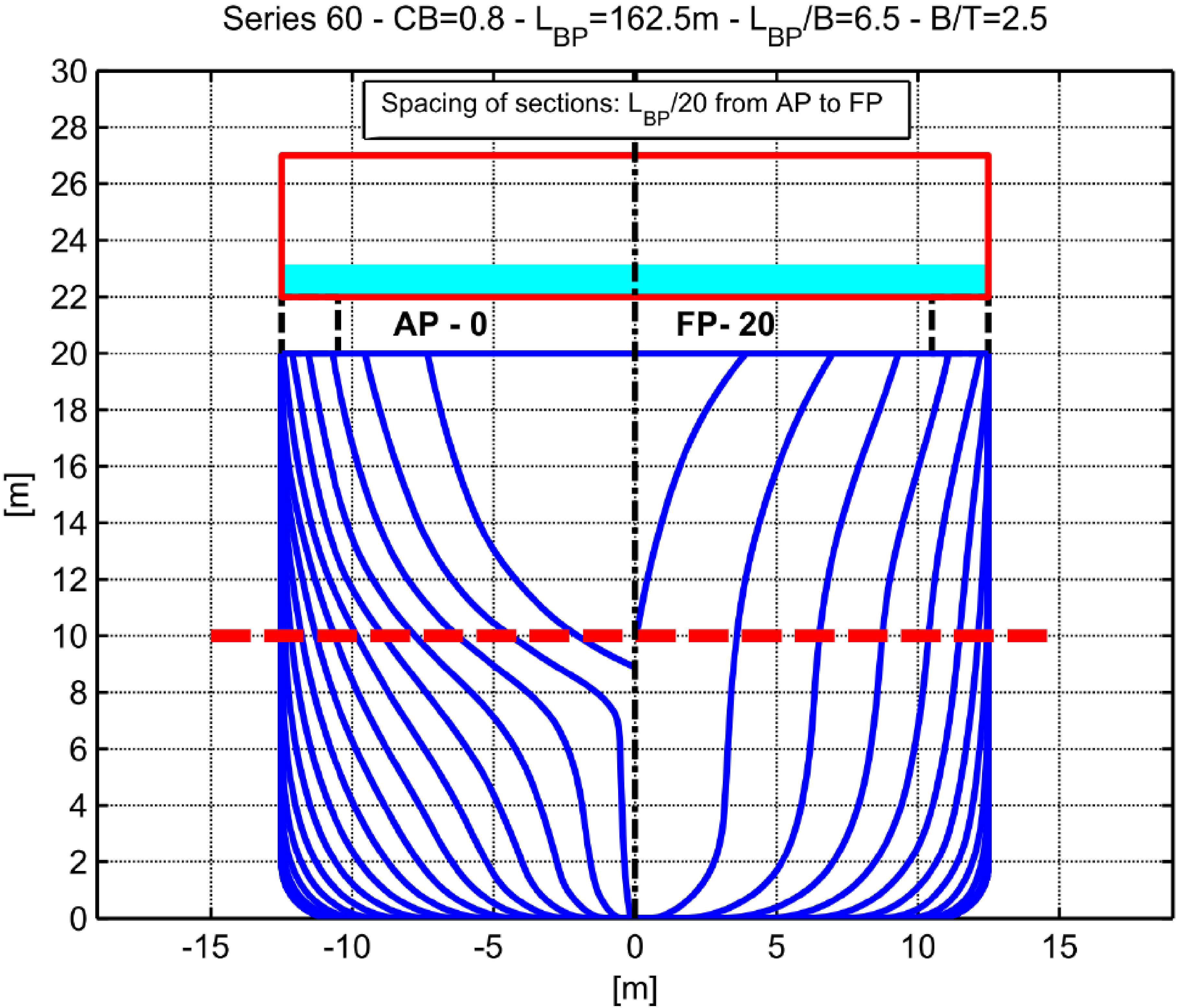
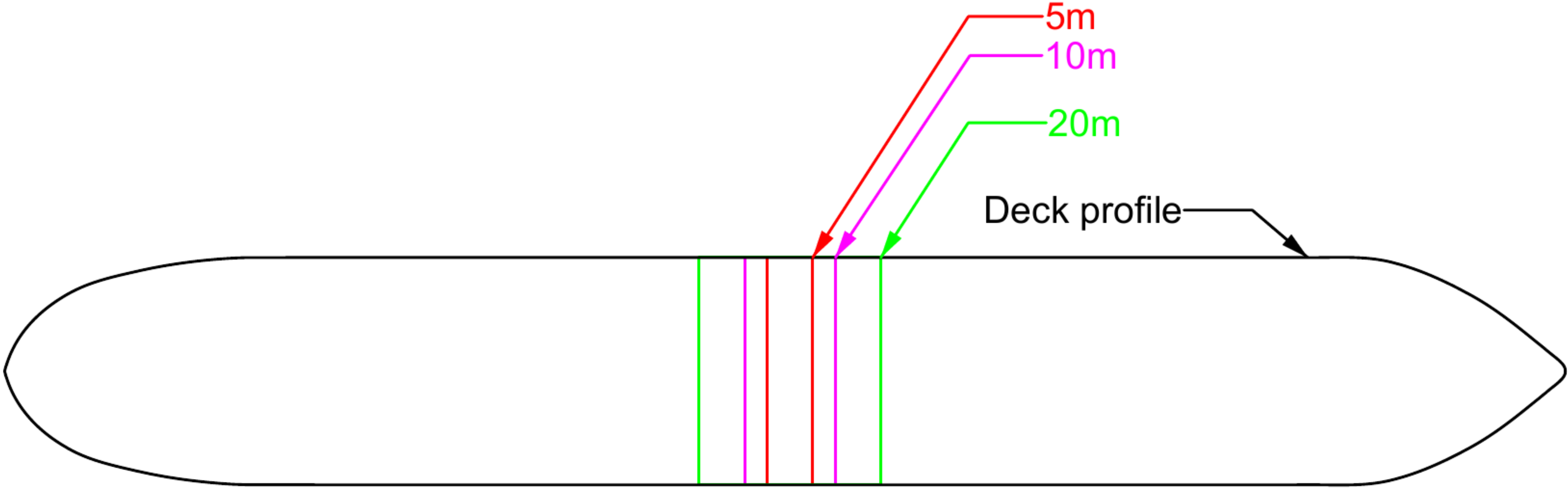

Series 60 - CB=0.8 - L$_{BP}$=162.5m - L$_{BP}$/B=6.5 - B/T=2.5
Spacing of sections: L$_{BP}$/20 from AP to FP
AP - 0
FP- 20
[m]
[m]
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
-15
-10
-5
0
5
10
15

Table 2: Characteristics of the tanks.

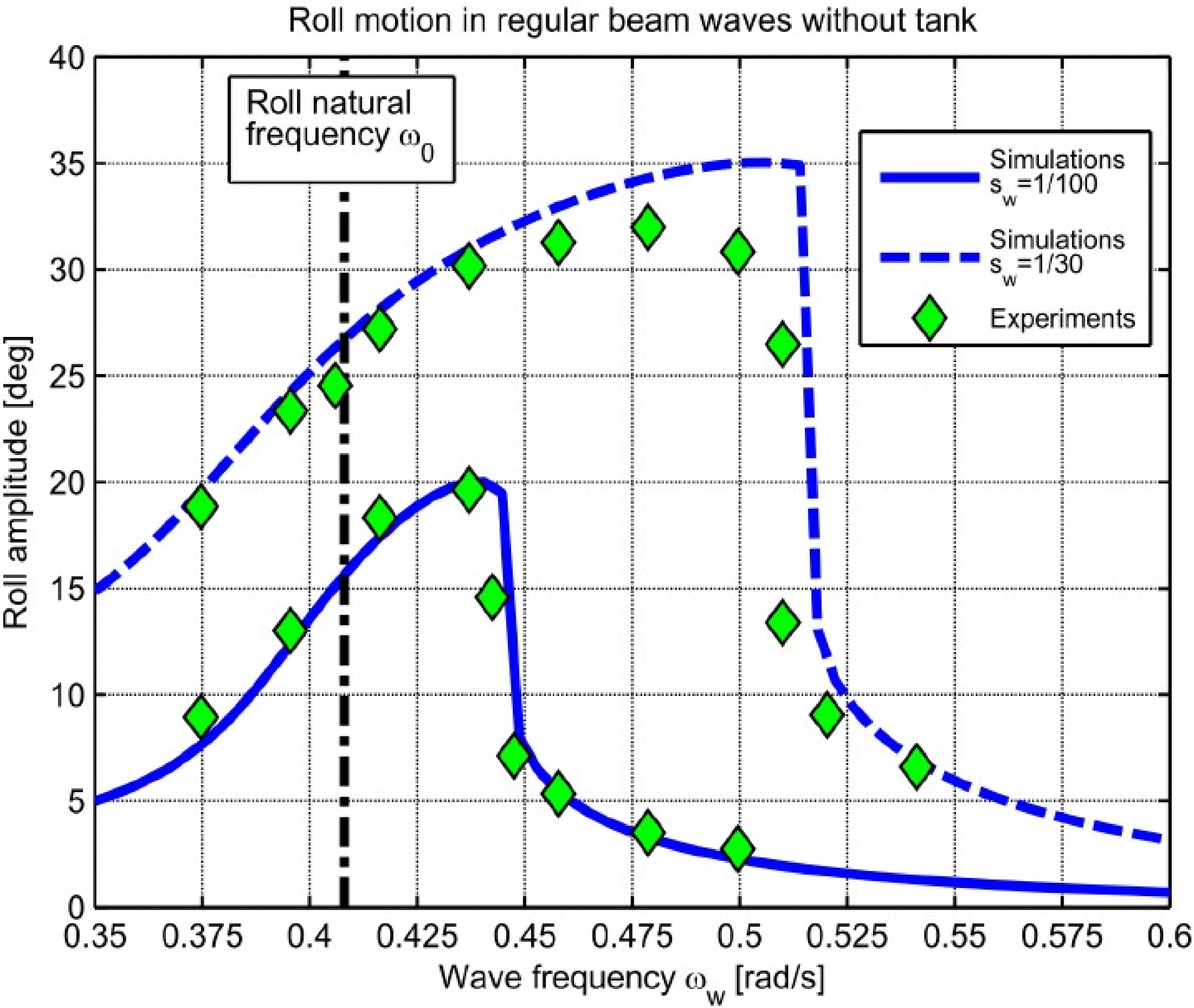
Longitudinal position of tank center	[m]	81.25 (amidships)
Width	[m]	25.0
Height of tank bottom from ship bottom	[m]	22.0
Height of tank	[m]	5.0
Fluid depth	[m]	1.08
First natural transversal sloshing frequency	[rad/s]	0.408
Longitudinal extent	[m]	5.0 , 10.0 , 20.0
Ratio between fluid mass in the tank and ship mass without tank	[%]	0.42 , 0.83 , 1.66


5m
10m
20m
Deck profile

Tuning of the 6-DOF ship motions code without tank

1) Hybrid nonlinear ship motions codes always require a certain tuning before using them for prediction purposes.

2) If roll is of concern, tuning roll damping is necessary using roll decay tests and/or roll response in waves (regular or irregular)


Roll motion in regular beam waves without tank
Roll natural frequency ω0
Simulations s_w=1/100
Simulations s_w=1/30
Experiments
Roll amplitude [deg]
Wave frequency ω_w [rad/s]
0
5
10
15
20
25
30
35
40
0.35
0.375
0.4
0.425
0.45
0.475
0.5
0.525
0.55
0.575
0.6

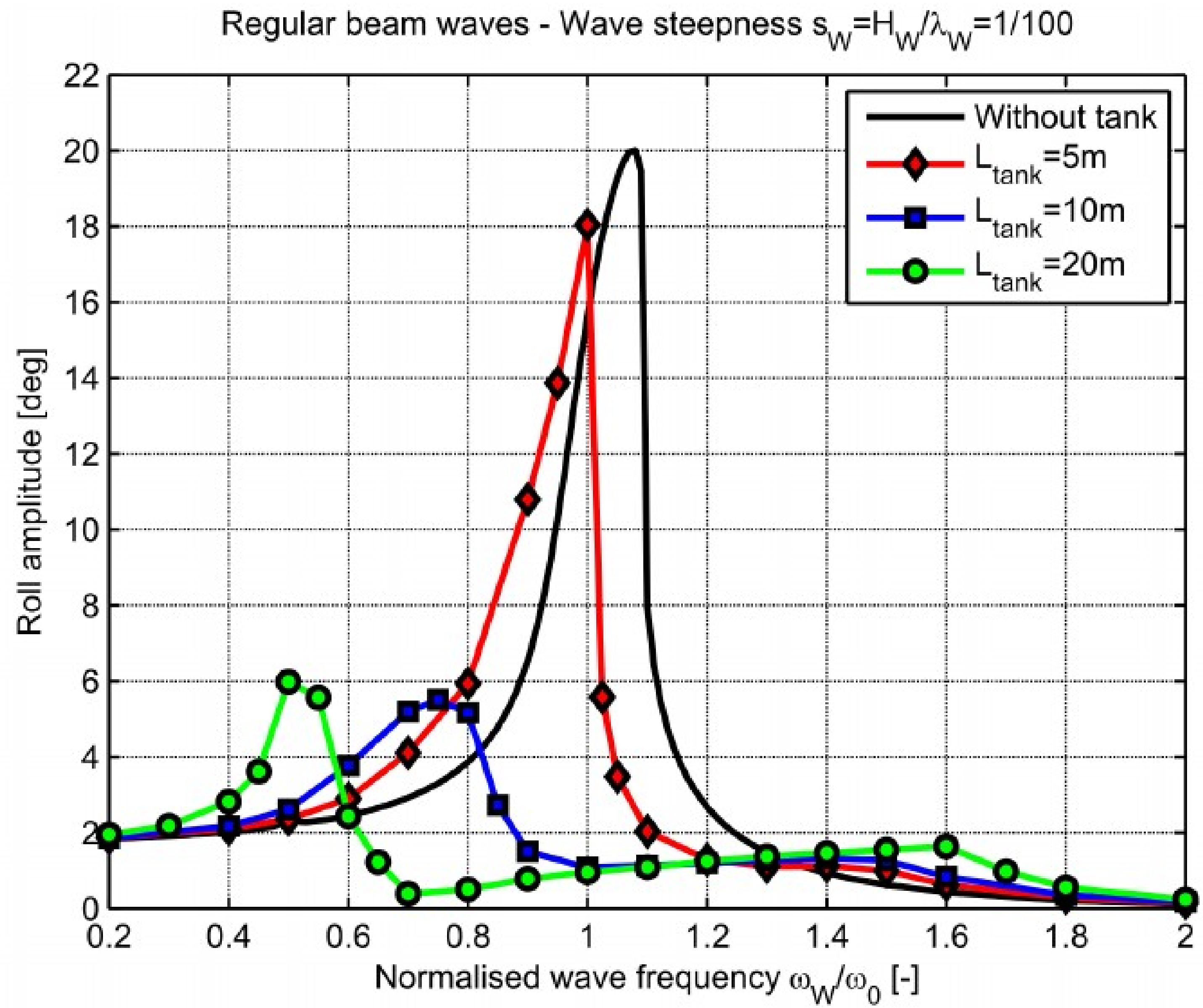
Validation of SPH code in angular motion TLD's

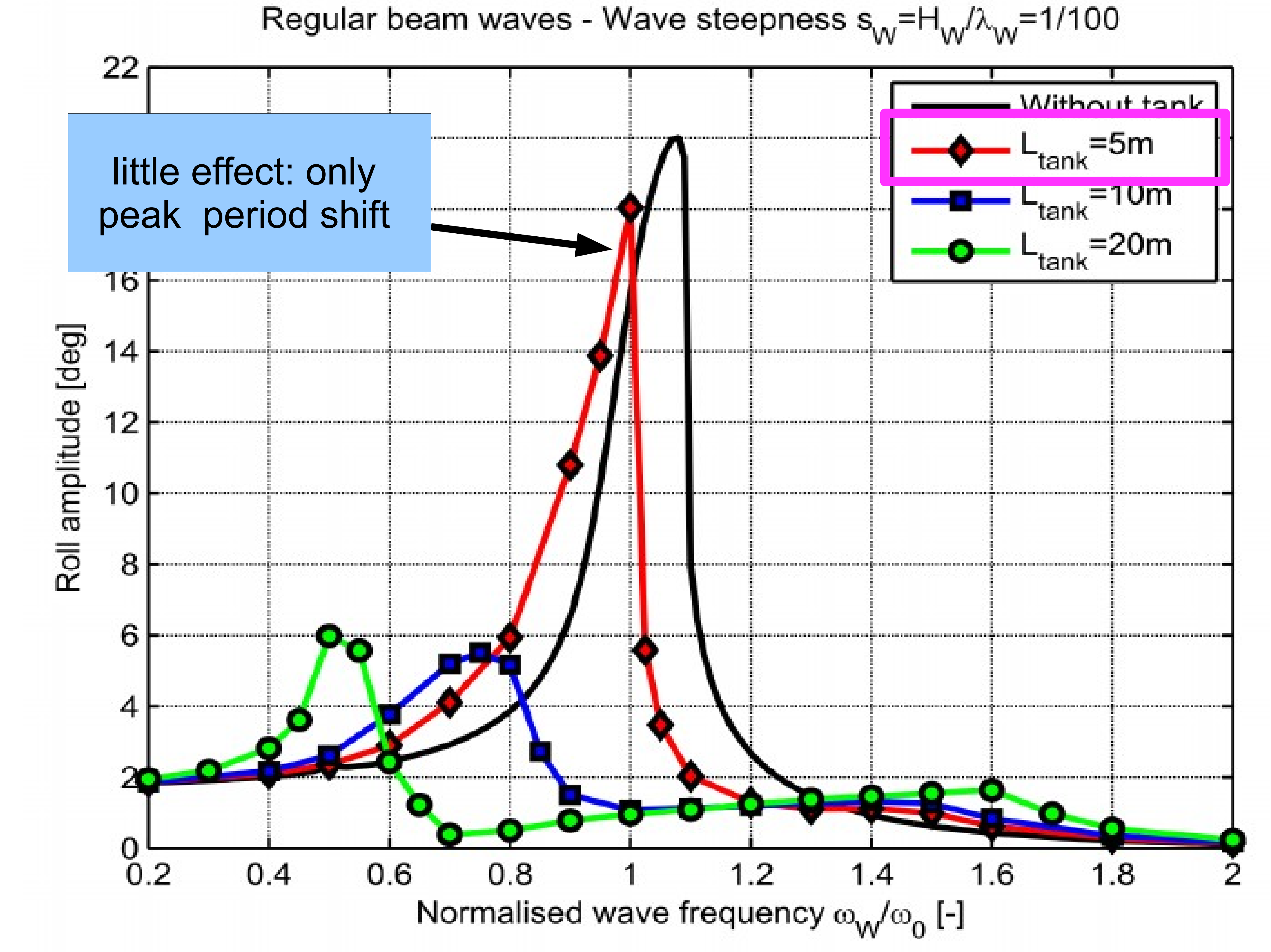
previously published papers:
Bulian et al, 2010, Bouscasse et al, 2014a,b

Roll in coupled simulations in beam regular waves

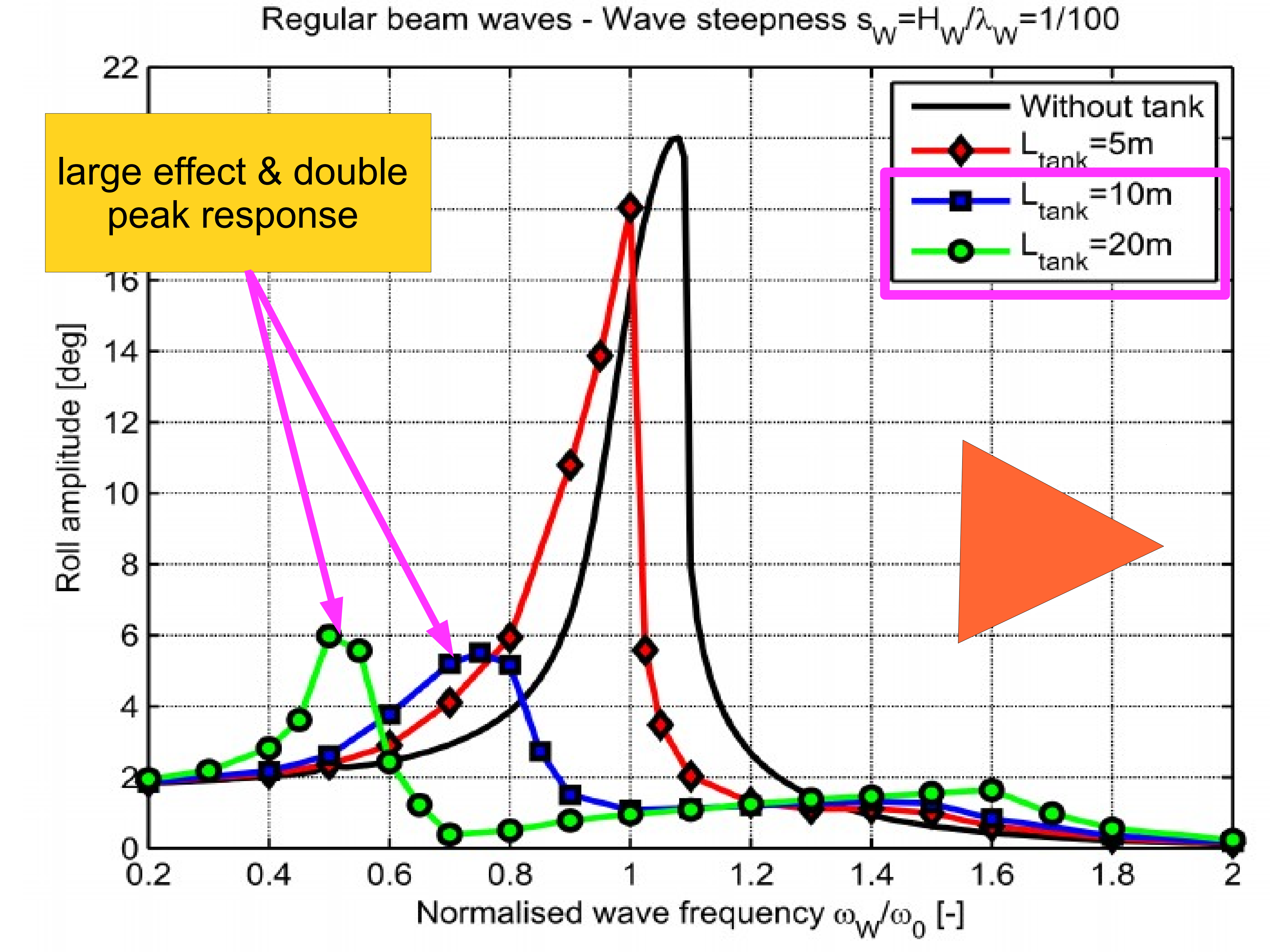
zero forward speed, mild seas (sw=1/100)

900 s real time simulations

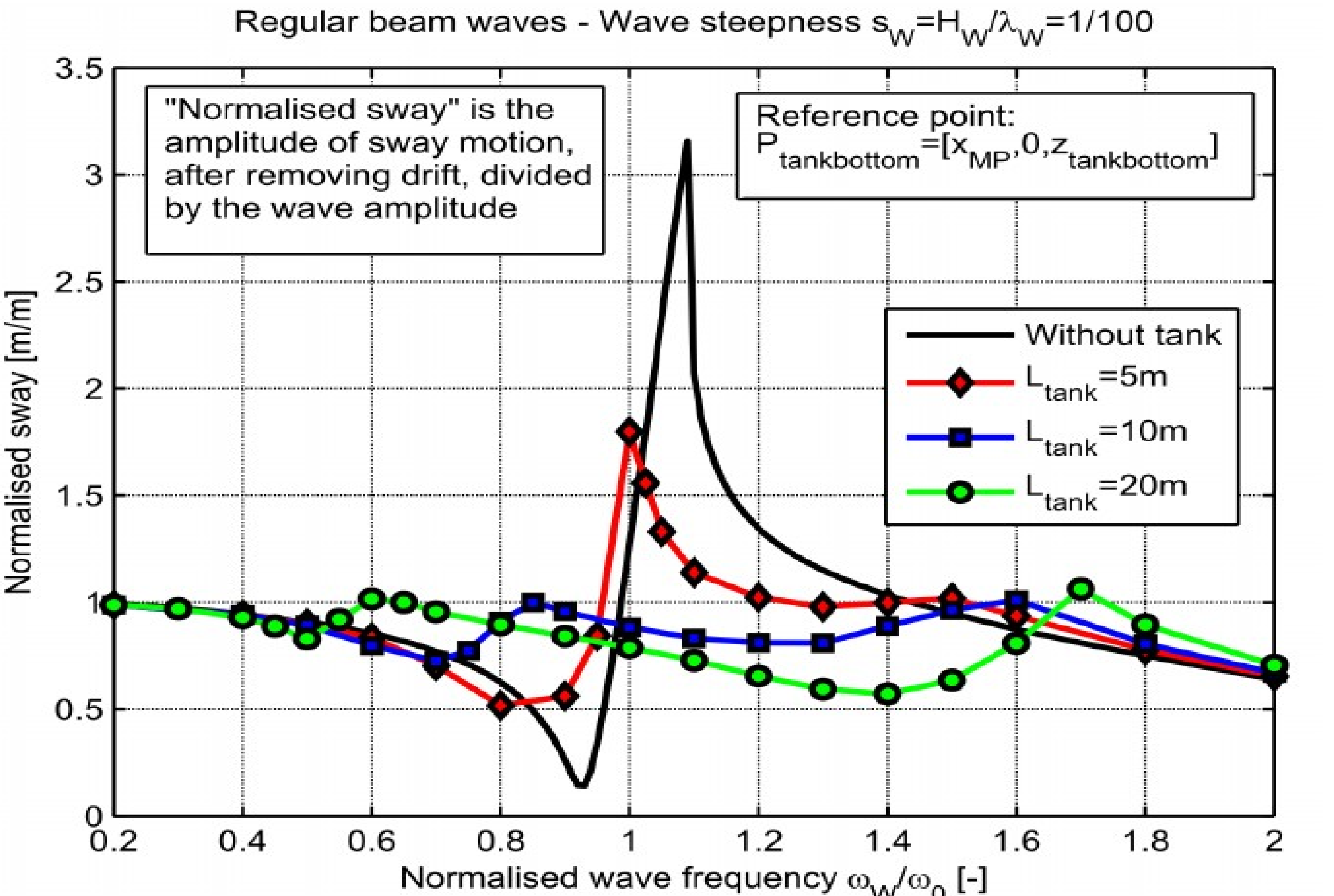




Regular beam waves - Wave steepness $s_W=H_W/\lambda_W=1/100$
little effect: only peak period shift
Without tank
L_{tank}=5m
L_{tank}=10m
L_{tank}=20m
Roll amplitude [deg]
Normalised wave frequency ω_W/ω_0 [-]
0
2
4
6
8
10
12
14
16
22
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

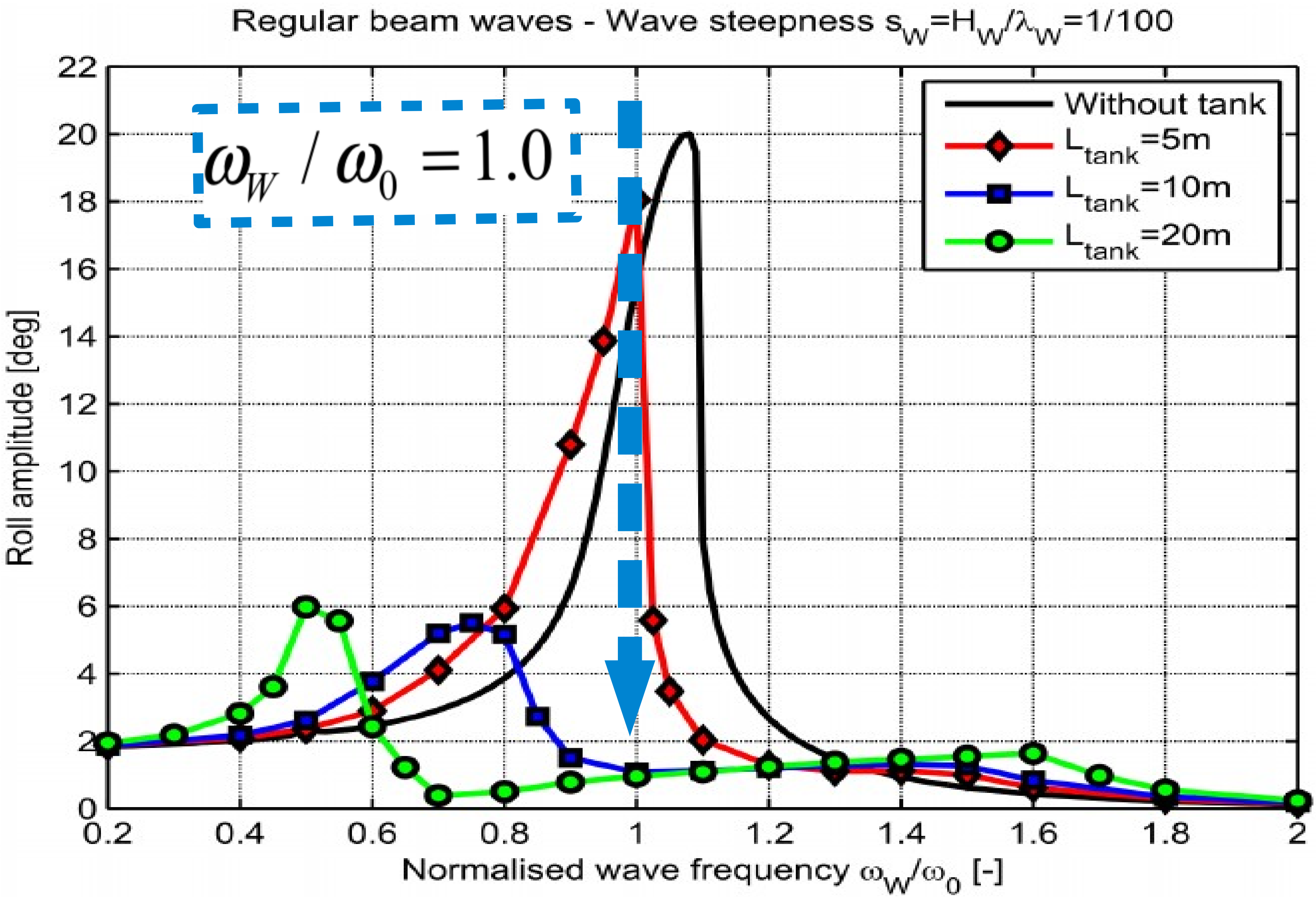


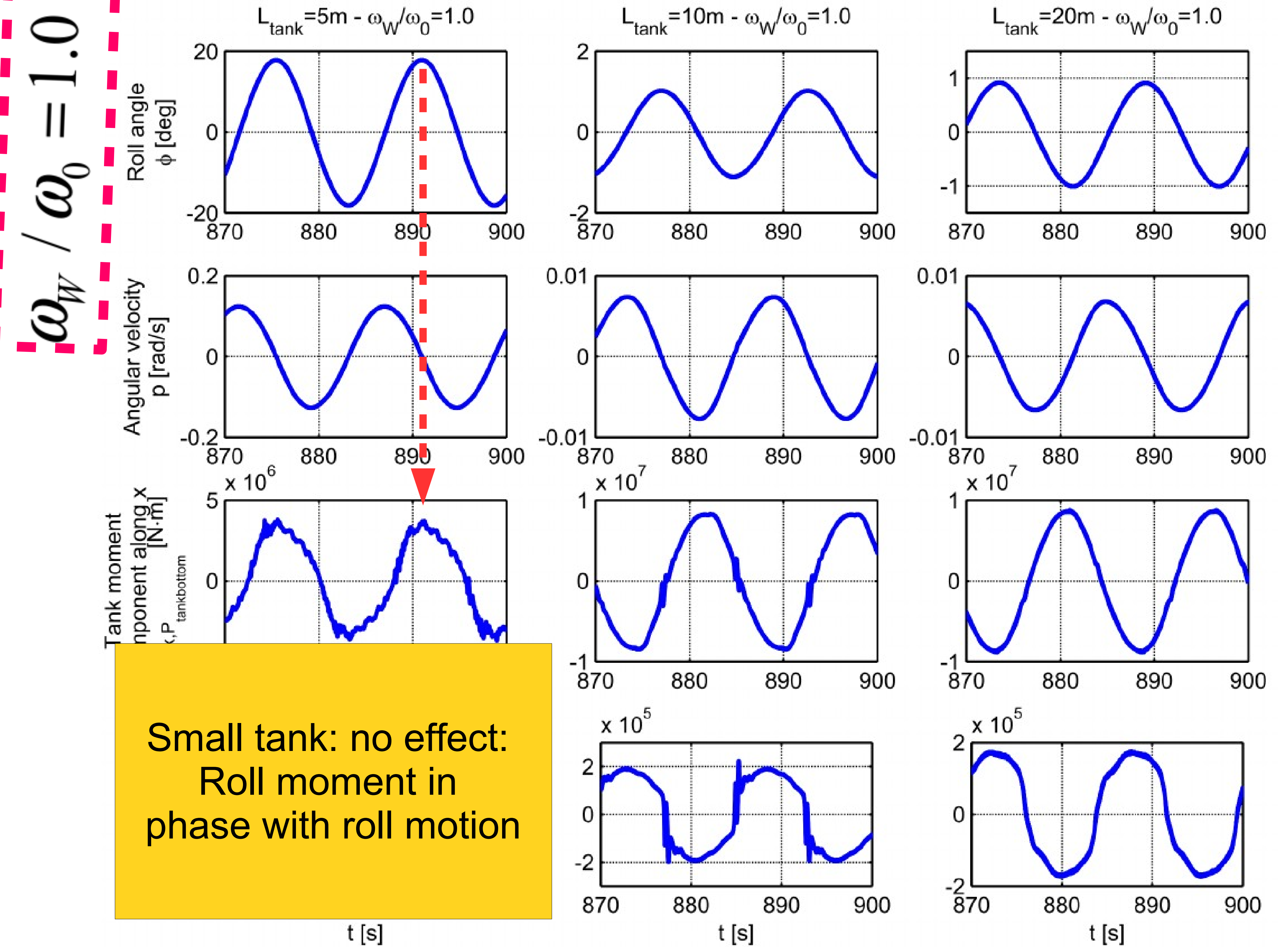
Regular beam waves - Wave steepness $s_W=H_W/\lambda_W=1/100$
large effect & double peak response
Without tank
L_{tank}=5m
L_{tank}=10m
L_{tank}=20m
Roll amplitude [deg]
Normalised wave frequency ω_W/ω_0 [-]
0
2
4
6
8
10
12
14
16
22
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2



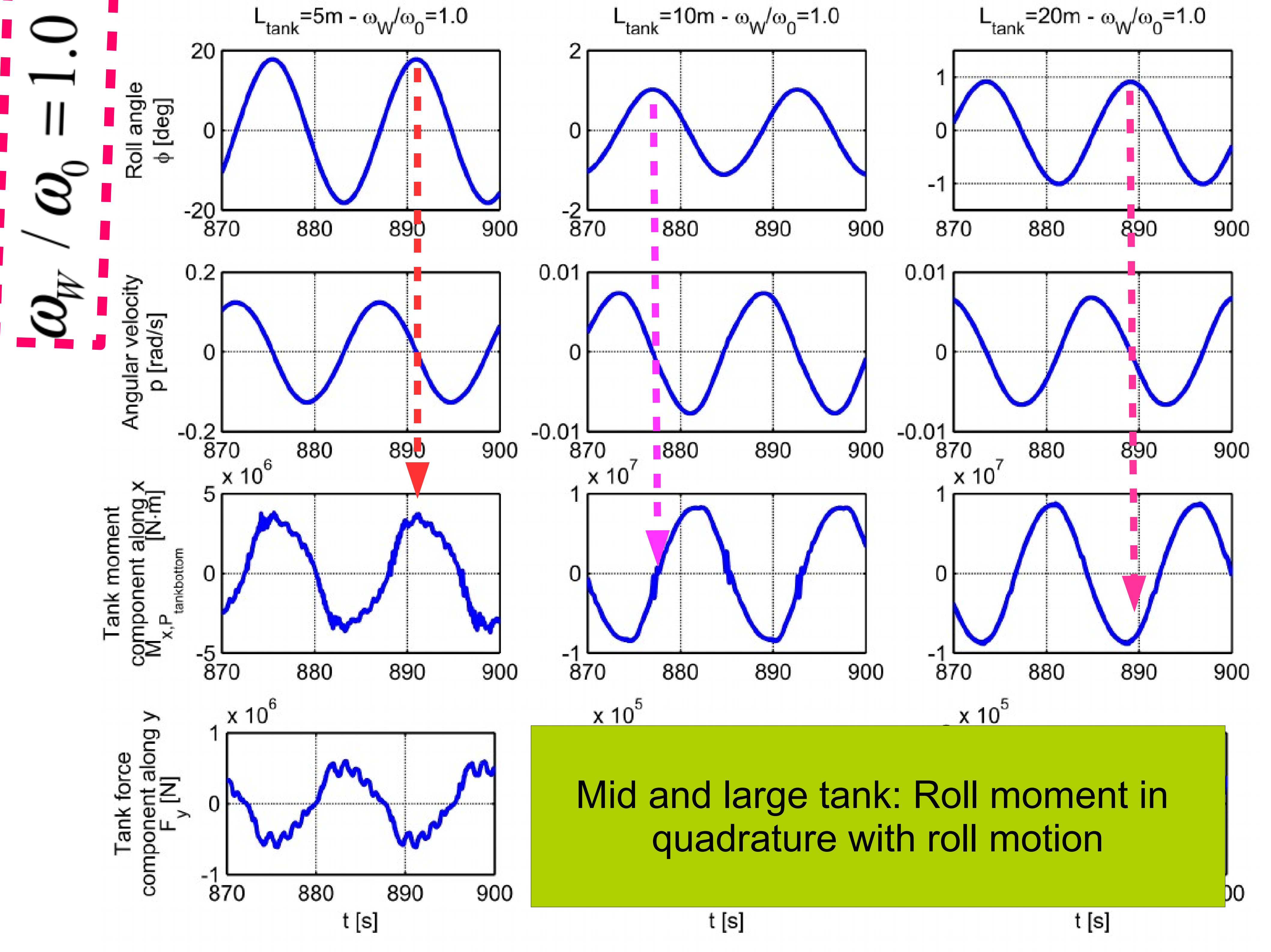
large variation in sway at the tank position due to large variations in roll

FORCES AND MOTIONS FOR SPECIFIC CASES

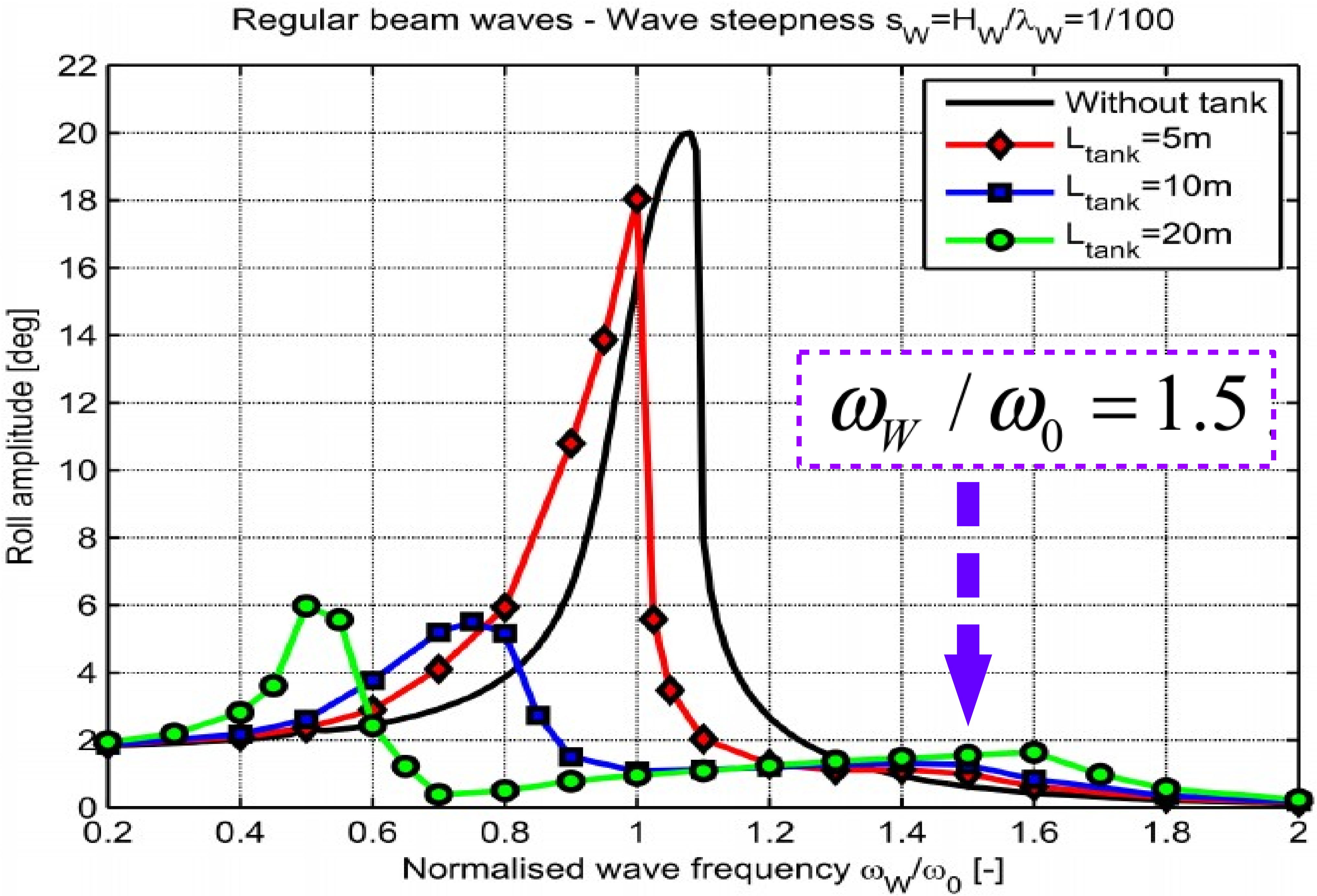




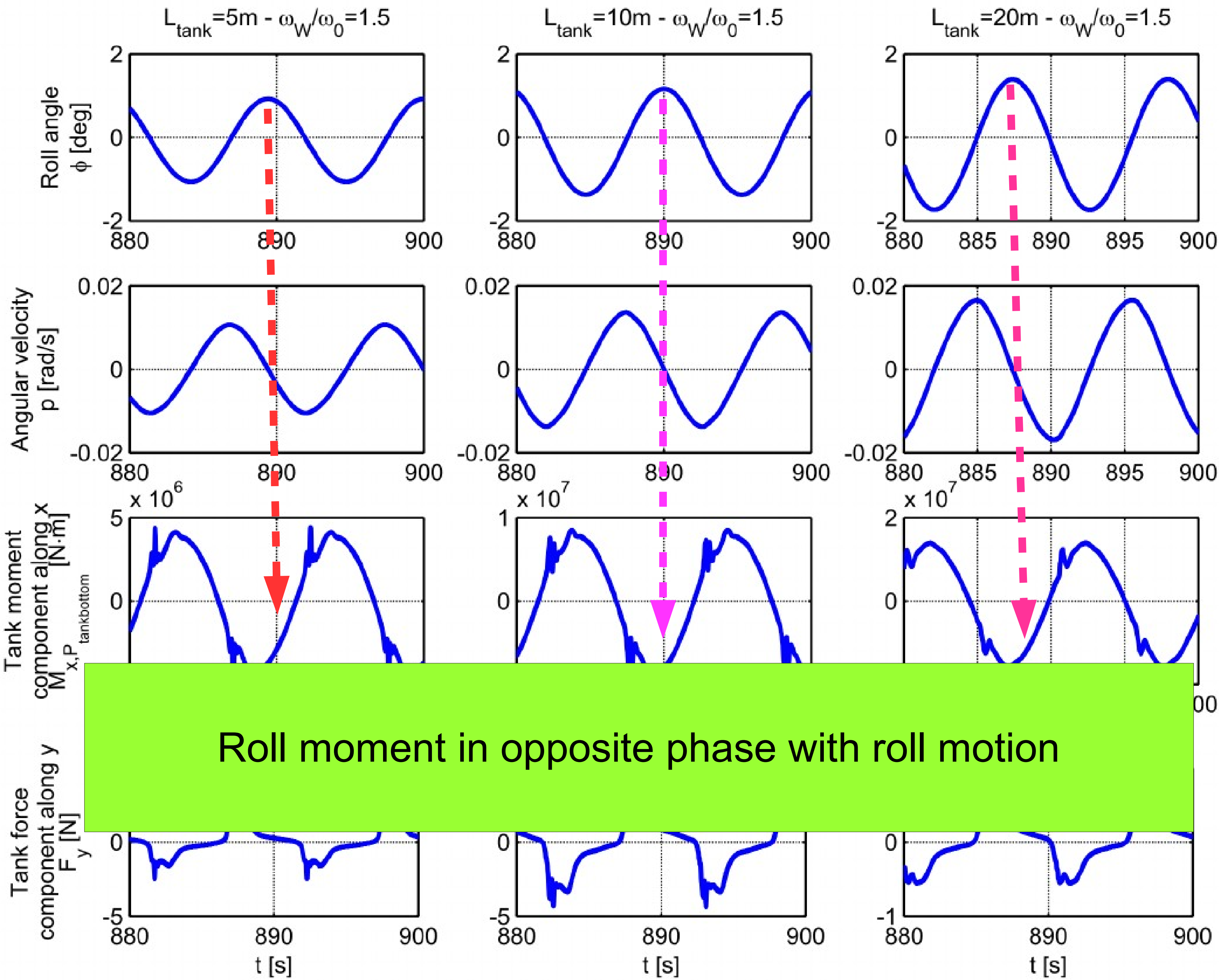
$\omega_W / \omega_0 = 1.0$
L_{tank}=5m - ω_W/ω_0=1.0
L_{tank}=10m - ω_W/ω_0=1.0
L_{tank}=20m - ω_W/ω_0=1.0
Roll angle ϕ [deg]
Angular velocity p [rad/s]
Tank moment component along x [N·m]
x 10^6
x 10^7
x 10^5
t [s]
Small tank: no effect:
Roll moment in
phase with roll motion

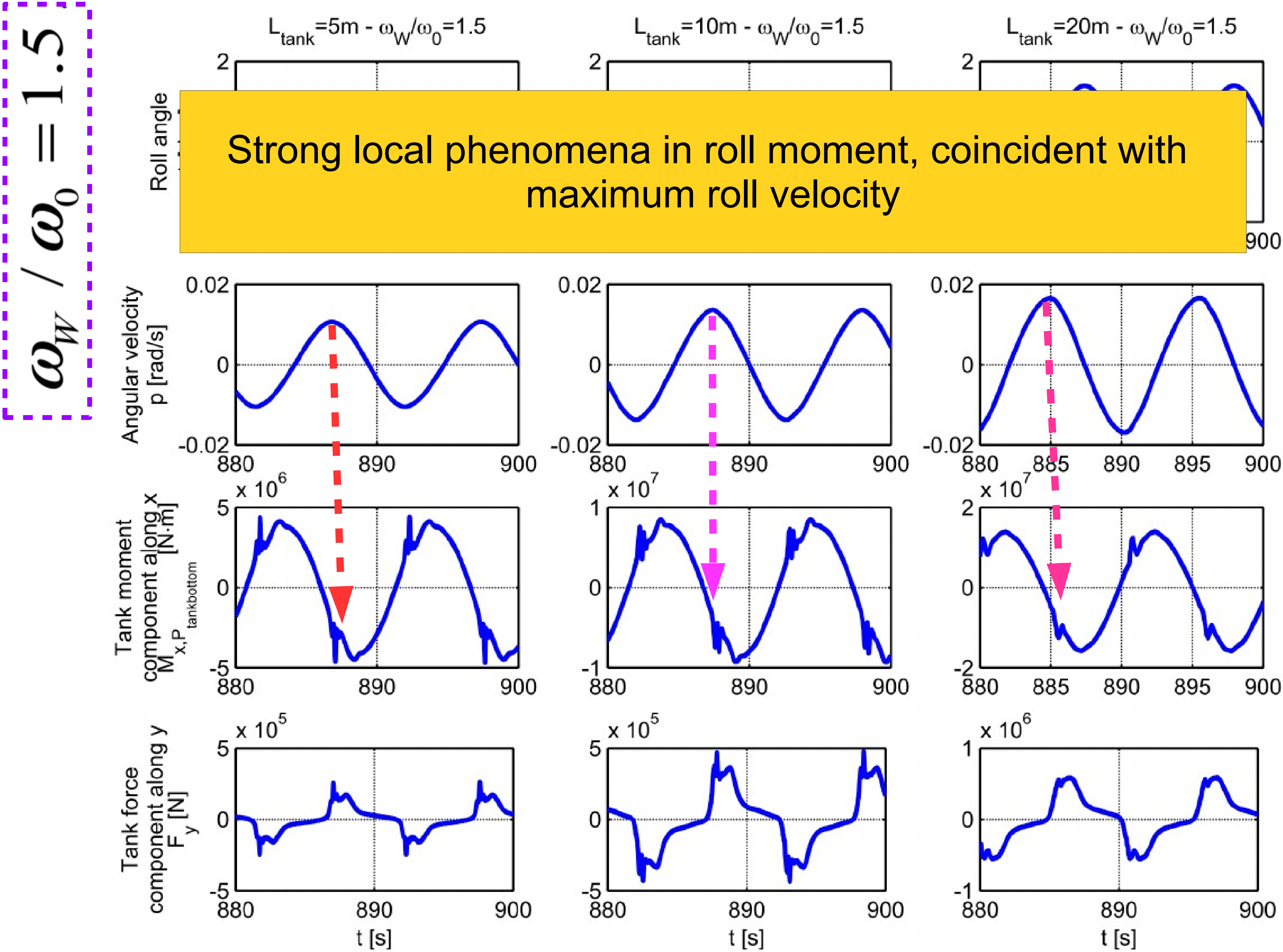

ωW / ω0 = 1.0
Ltank=5m - ωW/ω0=1.0
Ltank=10m - ωW/ω0=1.0
Ltank=20m - ωW/ω0=1.0
Roll angle
φ [deg]
Angular velocity
p [rad/s]
Tank moment
component along x
Mx,Ptankbottom [N·m]
Tank force
component along y
Fy [N]
x 10^6
x 10^7
x 10^5
t [s]
Mid and large tank: Roll moment in quadrature with roll motion

FORCES AND MOTIONS FOR SPECIFIC CASES



$\omega_W / \omega_0 = 1.5$





$\omega_W / \omega_0 = 1.5$
Strong local phenomena in roll moment, coincident with maximum roll velocity
Ltank=5m - ωW/ω0=1.5
Ltank=10m - ωW/ω0=1.5
Ltank=20m - ωW/ω0=1.5
Roll angle
Angular velocity p [rad/s]
Tank moment component along x Mx,Ptankbottom [N·m]
Tank force component along y Fy [N]
x 10^6
x 10^7
x 10^5
t [s]

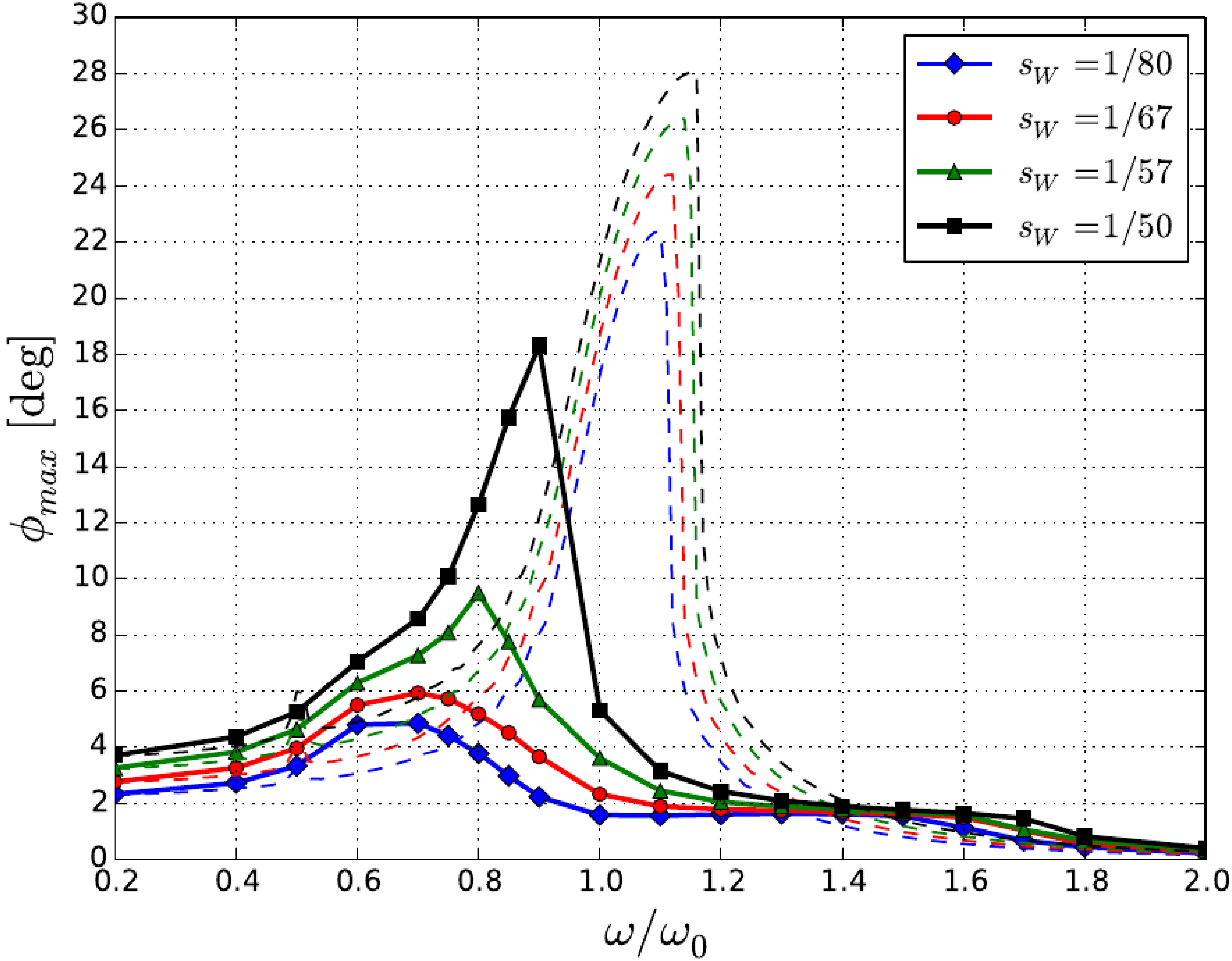
Final Remarks 1/2

1) A time domain approach intended to address the coupled system of ship motions and flow in internal tanks has been presented.
2) A blended (hybrid) nonlinear 6-DOF ship motions simulation code has been coupled with an SPH solver for the internal tanks
3) They run in different facilities and communicate under tcp-ip protocol

Final Remarks 2/2

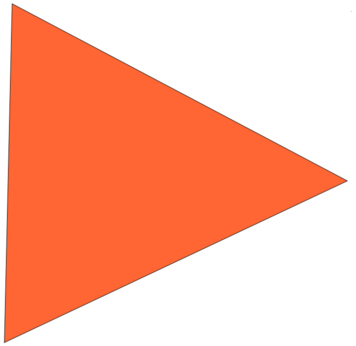
1) An application for a Series-60 hull, with ART alternatives (different length), has been presented.
2) Simulations have been carried out at zero forward speed in beam regular waves of constant steepness.
3) Small tank shows little effect while two largest dramatically dampen roll motion.
4) Nonlinearities in forces and moment time histories are noticeable.

FUTURE WORK: HOW ARE RESULTS AFFECTED WHEN WAVE FORCING IS INCREASED (STEEPER WAVES)?



FUTURE WORK: HOW ARE RESULTS AFFECTED WHEN WAVE FORCING IS INCREASED (STEEPER WAVES)?

EXAMPLE: sw 1/50



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