Sloshing behaviour of liquid in prismatic LNG tanks and ship-tank coupled motion

Makoto Arai & Gustavo M. Karuka
Yokohama National University, Japan

YNU YOKOHAMA National University

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Introduction

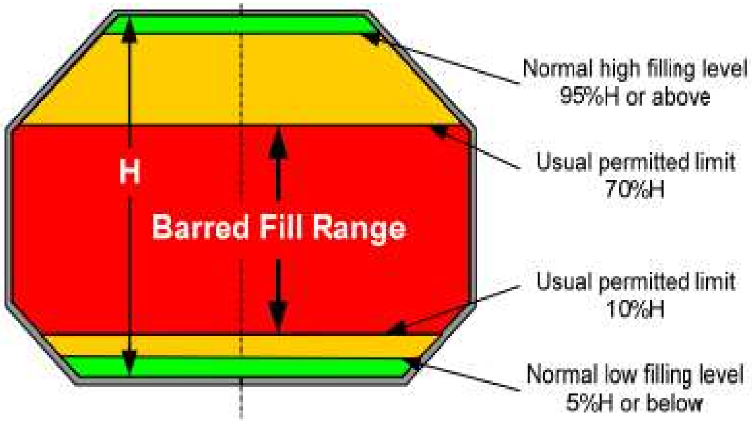
Remarkably good safety records in LNG transportation for about 50 years of LNG carriers' history.

However we must consider some new aspects which might affect the safety records of LNG fleets:

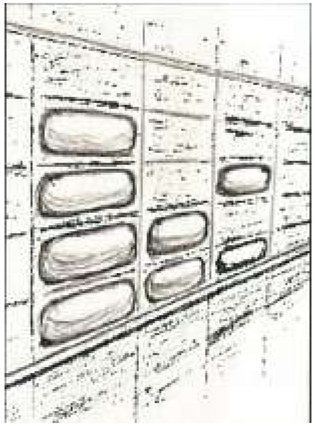
- Rapid growth of demand for LNG and increase of LNGCs worldwide
- Emergence of new voyage routes such as for transporting US shale gas through newly expanded Panama Canal, possible LNG transport from Russia to Asia using Arctic Ocean, etc.
- Large ships
- Operations in partially loaded condition such as those of FLNGs and their shuttle tankers, LNG as fuel for all type of ships, etc.

Sloshing in membrane tanks

Membrane type LNGC and cargo tank
(MHI Tech. Rev., 2007)

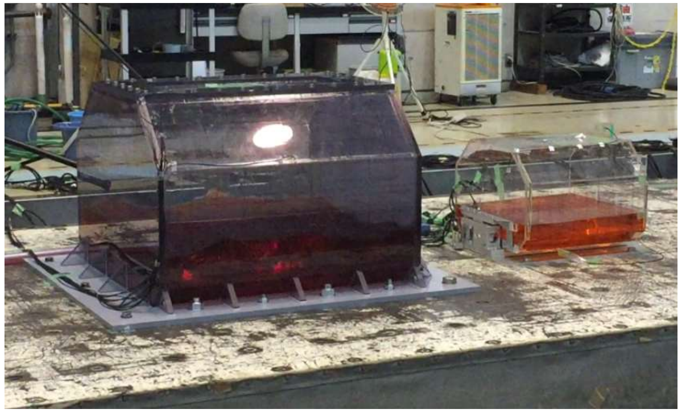


Fill range limitation

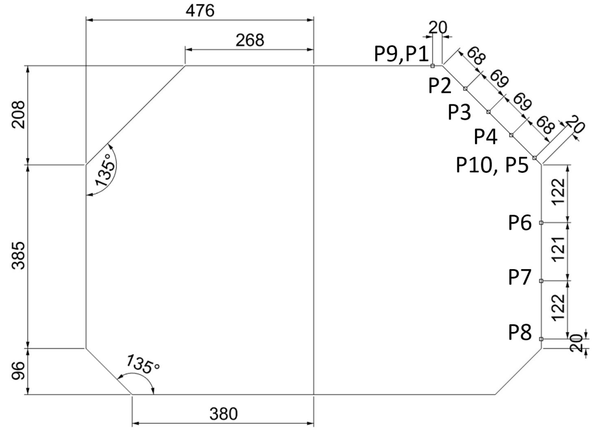


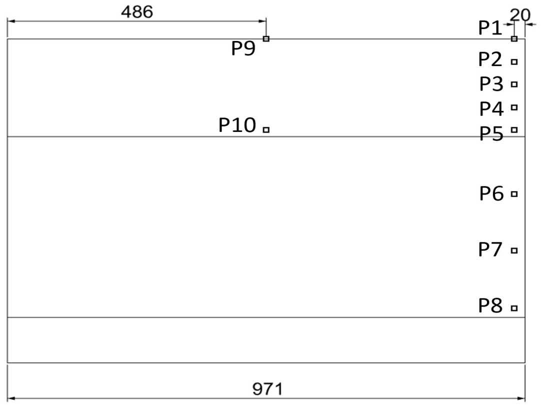
Example of damage due to sloshing（Lloyd’s register)

Model tests at MTI Yokohama Lab



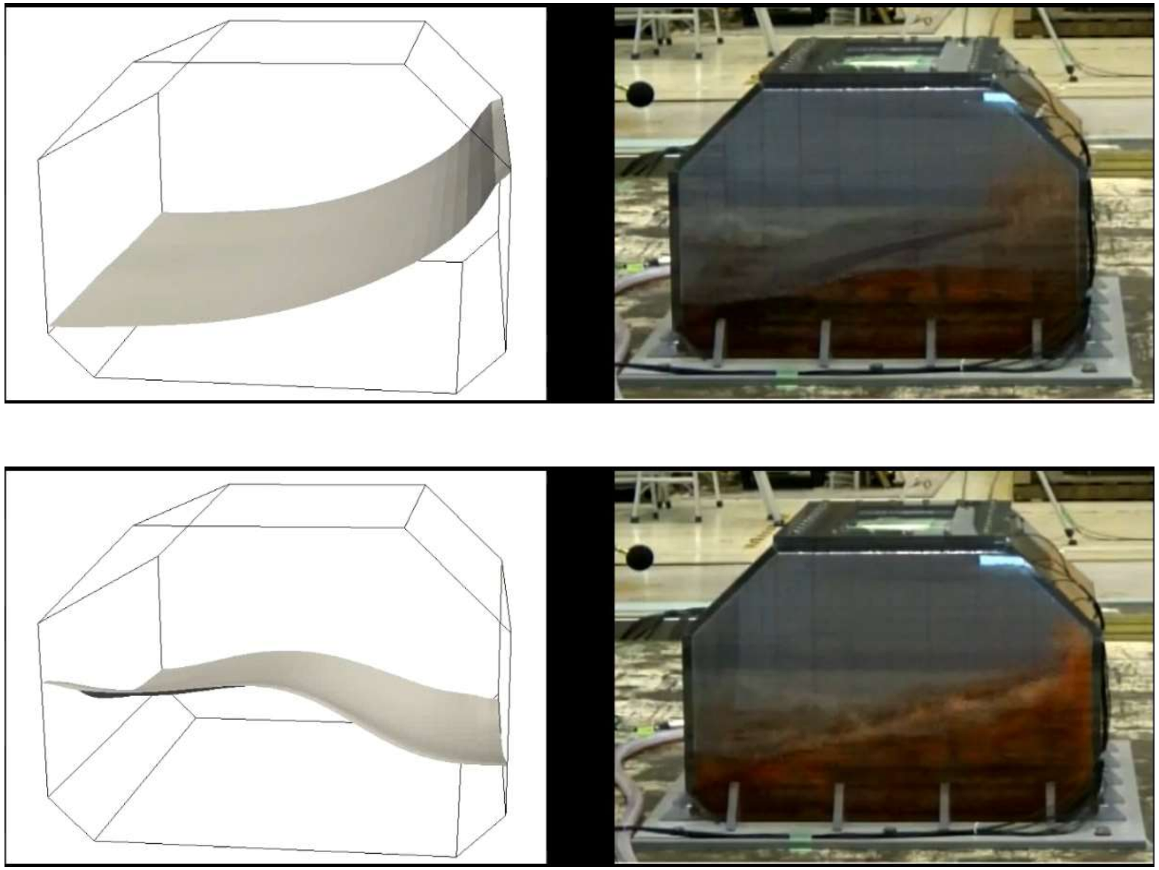
Model tanks on moving table





- Pressure: 10 points
- Hydrodynamic forces to the tank: 2 directions
- Scale: 1/40
- Length x Breadth x Depth: 971mm x 952mm x 689mm

Comparison of liquid motion in the tank (30% , amp.=2cm, 90deg., f=0.71Hz)



Sloshing

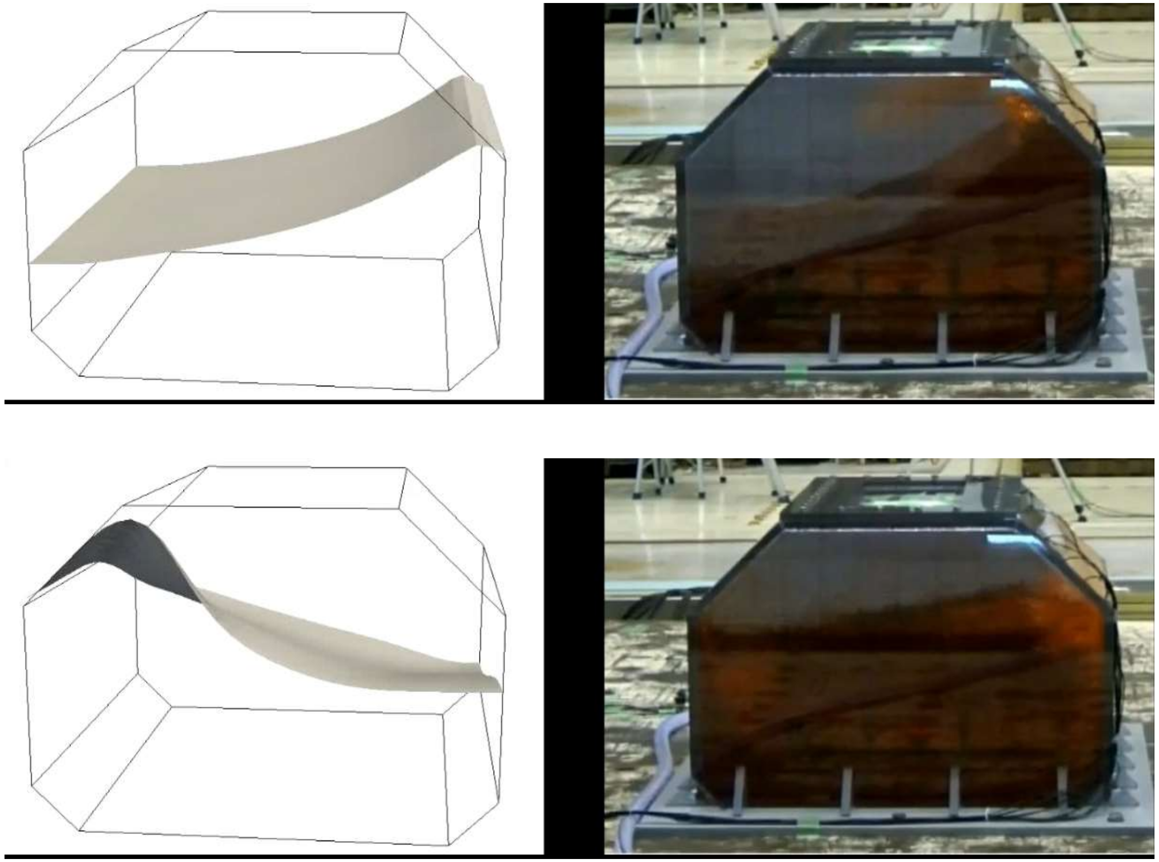
Swirling

Numerical simulation

Experiment

Comparison of liquid motion in the tank

(50% , amp.=2cm, 90deg., f=0.804Hz)



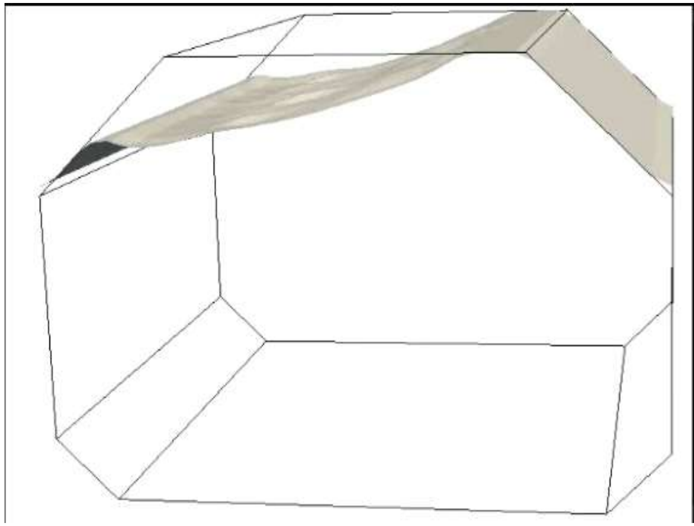
Sloshing

Swirling

Numerical simulation

Experiment

Comparison of liquid motion in the tank
(90% , amp.=2cm, 90deg., f=0.95Hz)

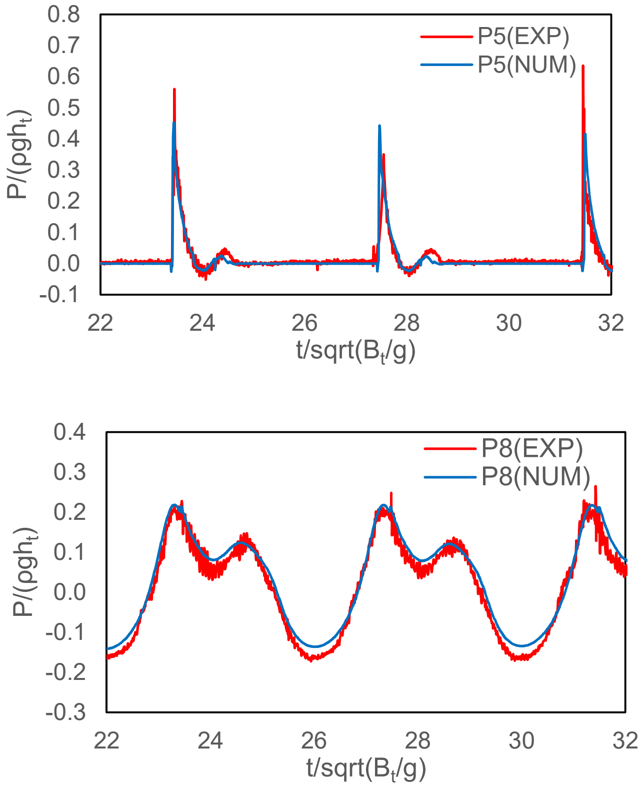


Numerical simulation

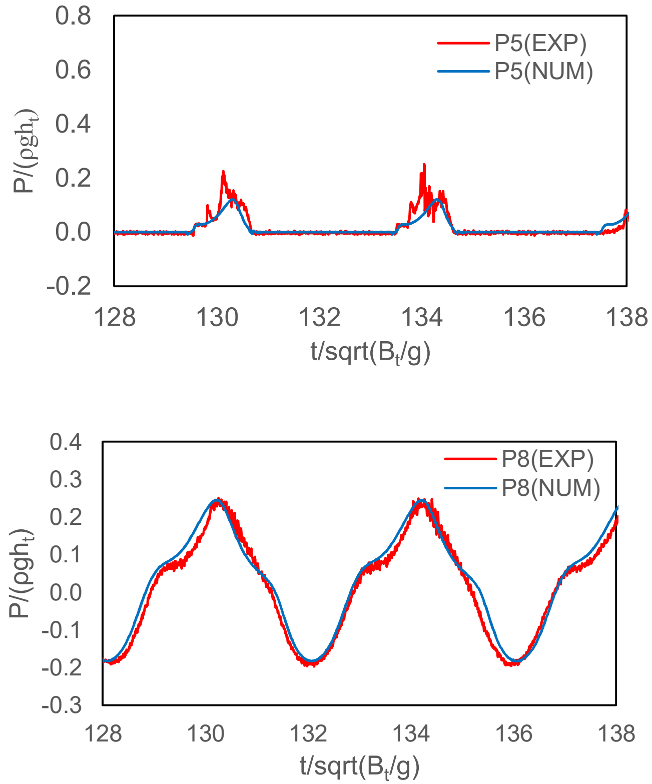
Experiment

Only sloshing was observed

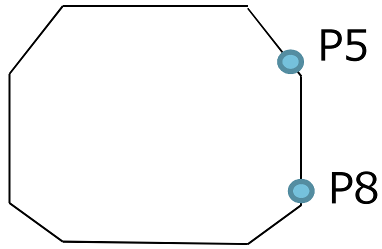
Comparison between measured and computed pressures



Sloshing phase

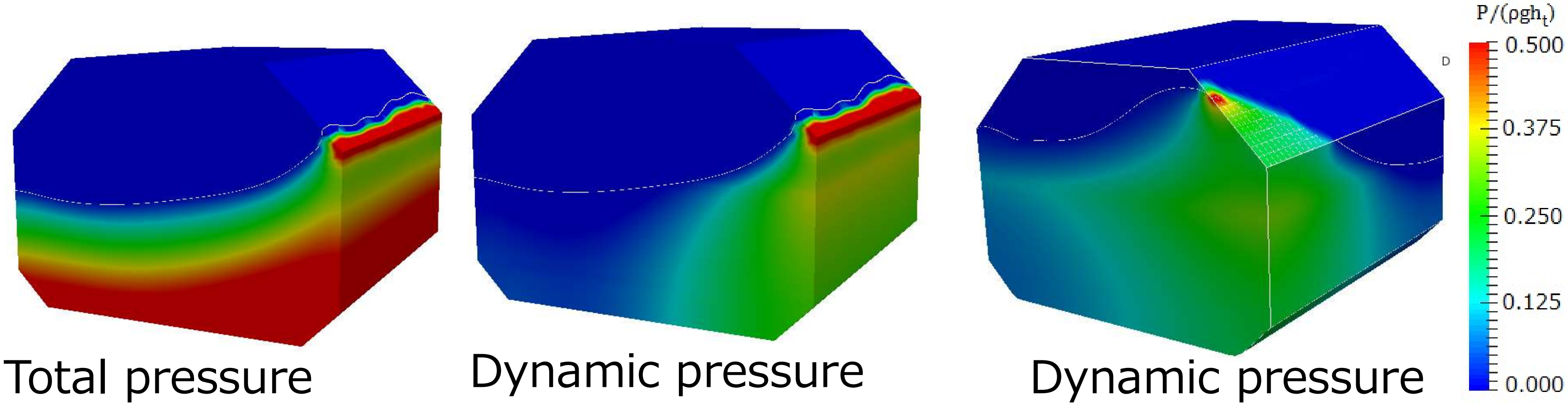


Swirling phase



(50% , amp.=2cm, 90deg., f=0.804Hz)

Snapshots of pressure distribution in the tank (50%filling, excitation at resonant frequency)



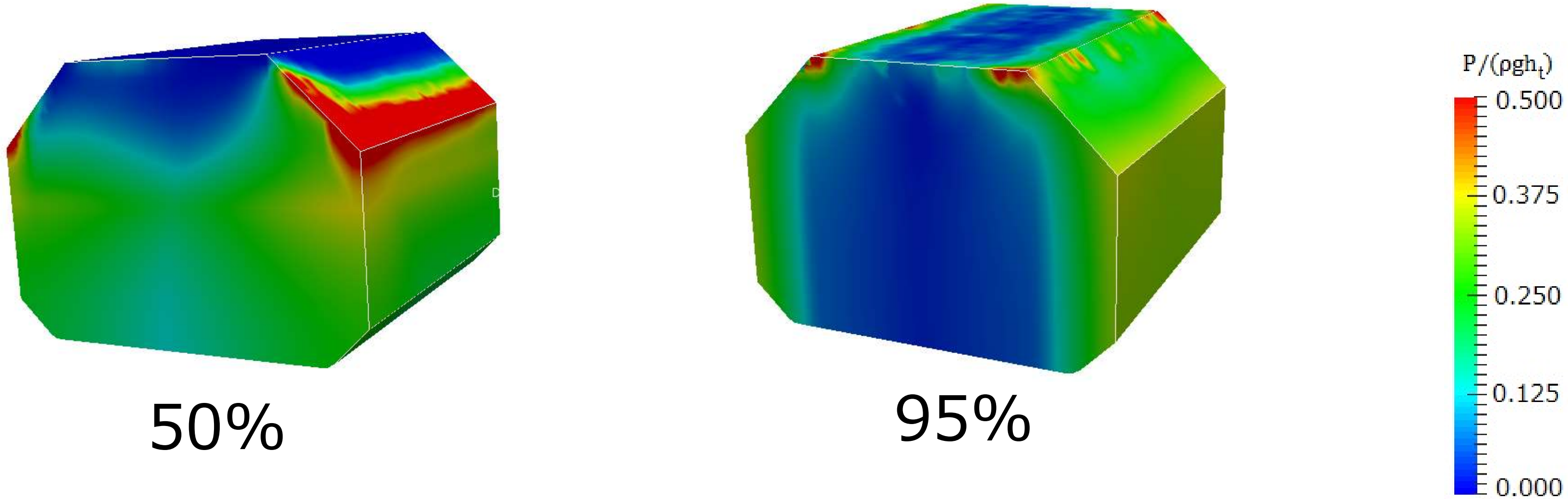
Total pressure in sloshing phase

Dynamic pressure in sloshing phase

Dynamic pressure in swirling phase

(Dynamic pressure) = (Total pressure) – (Static pressure at T=0)

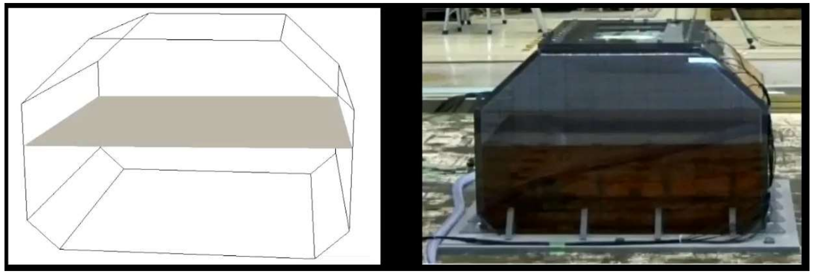
Maximum dynamic pressure in the whole simulation

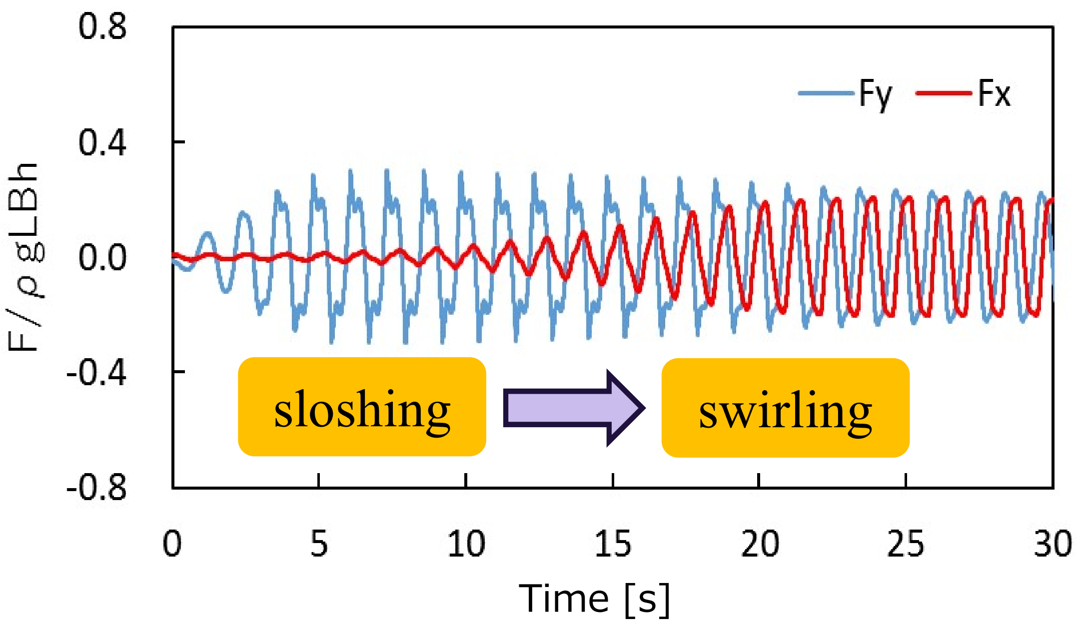


- In case of middle fill levels (30% to 70%), the lower part of the top chamfers suffer the highest pressure, and when swirling occurs its effect is observed on the edges of the top chamfers.
- In case of high fill levels, high pressure occurs at the intersections between top chamfers and tank ceiling.

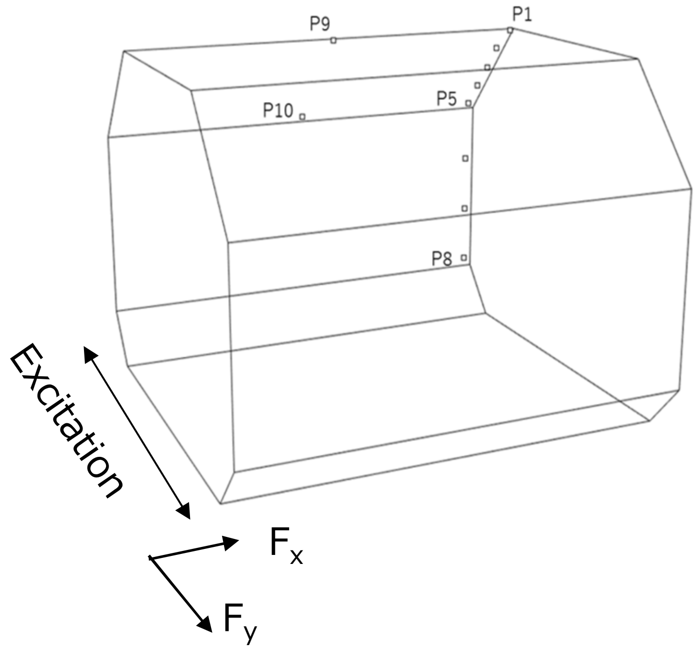
Swirling

In some test cases, 2-dimensional sloshing motion occurs in the beginning of the test but it transfers to swirling motion later.





Example of force histories generated by liquid motion

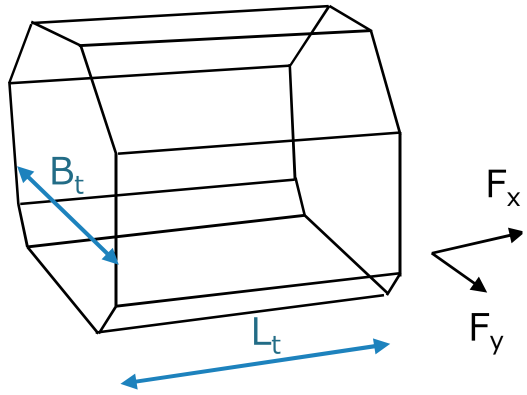


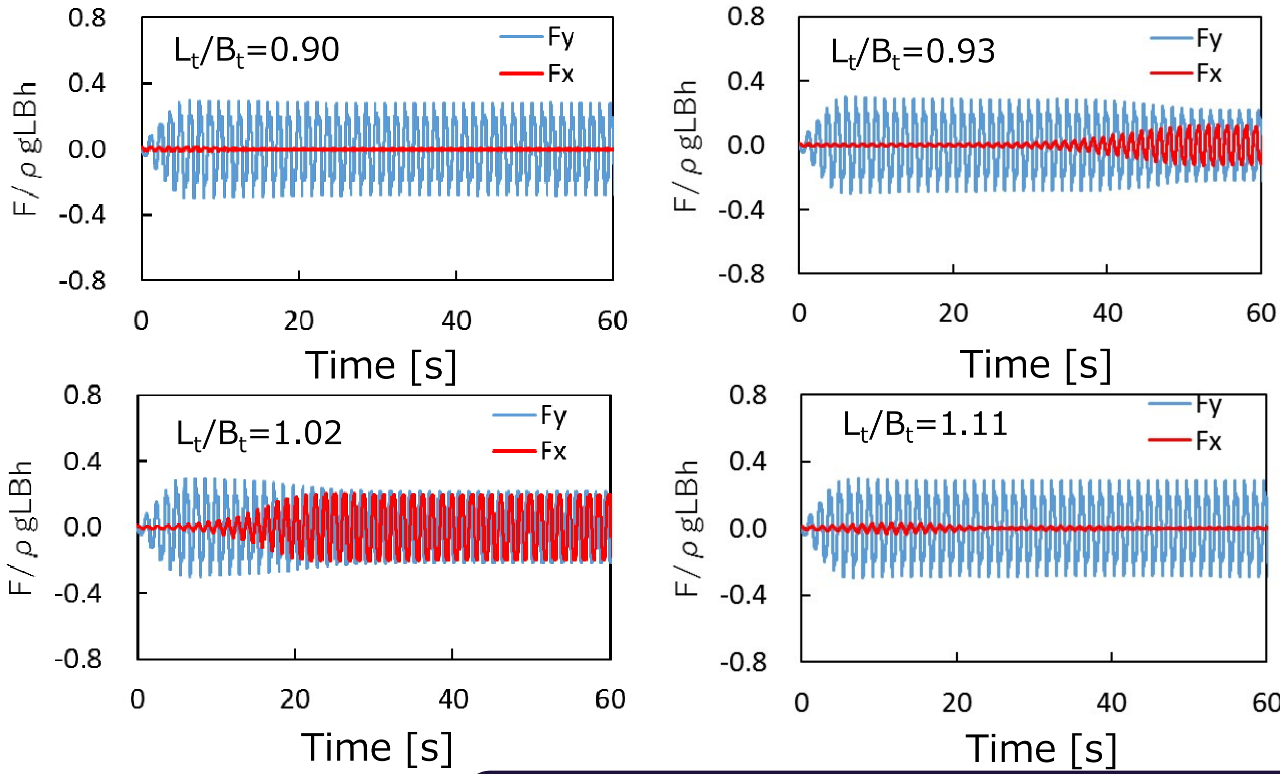
Note: In numerical computation, small initial disturbance is necessary to generate swirling motion.

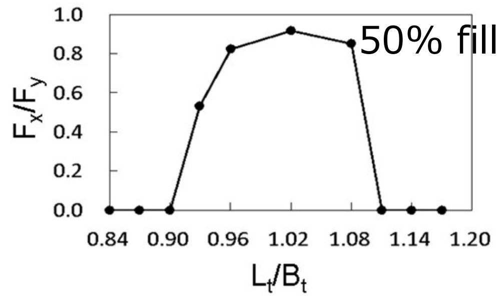
Condition for swirling generation

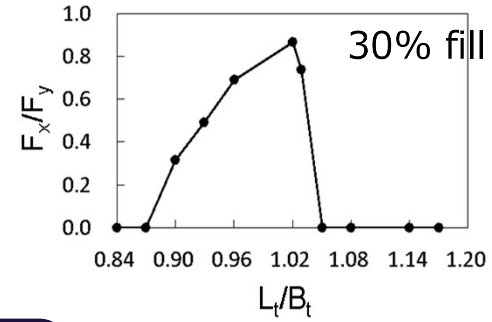
Computed force histories for different L_t /B_t ratio
(Fill level: 50%, excitation: tank liquid natural frequency)

L_t: tank length, B_t: tank breadth





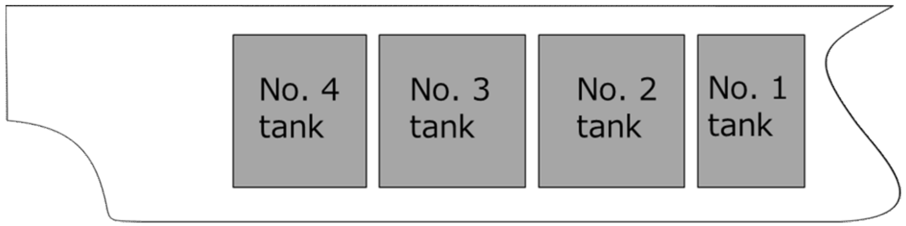




Swirling occurs when fill level=30%～60% and L_t/B_t=0.9～1.1

Actual ships' tank dimensions

Condition of swirling occurrence: L_t/B_t=0.9～1.1



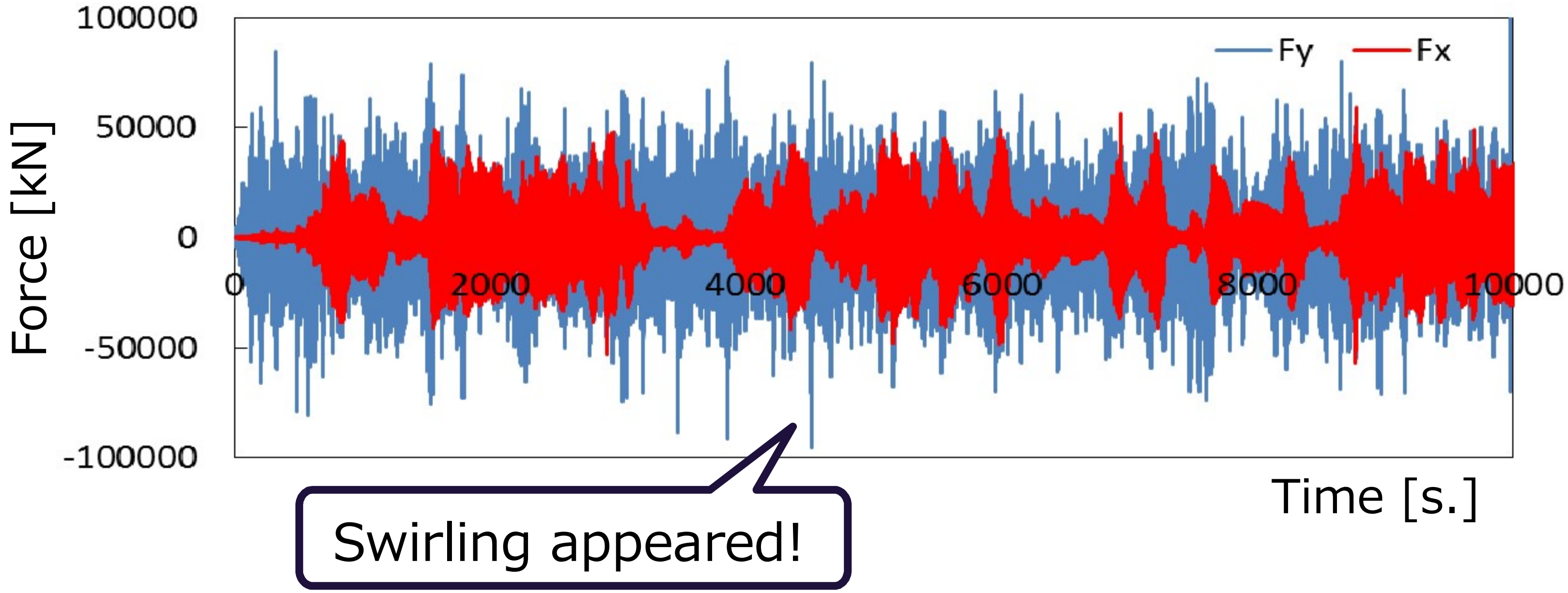
Ship	NO.4 Tank			No.3 Tank			No.2 Tank			No.1 Tank		
	Lt(m)	Bt(m)	Lt/Bt	Lt(m)	Bt(m)	Lt/Bt	Lt(m)	Bt(m)	Lt/Bt	Lt(m)	Bt(m)	Lt/Bt
1	46.05	42.65	1.080	46.05	42.65	1.080	46.05	42.65	1.080	31.09	36.53	0.851
2	46.05	40.31	1.142	46.05	40.31	1.142	46.05	40.31	1.142	35.50	36.80	0.965
3	49.60	49.90	0.994	49.60	49.90	0.994	49.60	49.90	0.994	39.87	40.57	0.983
4	47.07	41.63	1.131	47.07	41.63	1.131	47.07	41.63	1.131	33.81	32.11	1.053
5	38.28	37.81	1.012	43.58	37.81	1.153	43.89	37.81	1.161	Wedge Shape		
6	40.00	37.81	1.058	44.75	37.81	1.184	44.75	37.81	1.183	31.45	33.75	0.932

From 14 LNG carriers, 6 vessels have tanks with $0.9<L_t/B_t<1.1$.
There is a possibility that swirling occurs when these vessels operate in partial load condition.

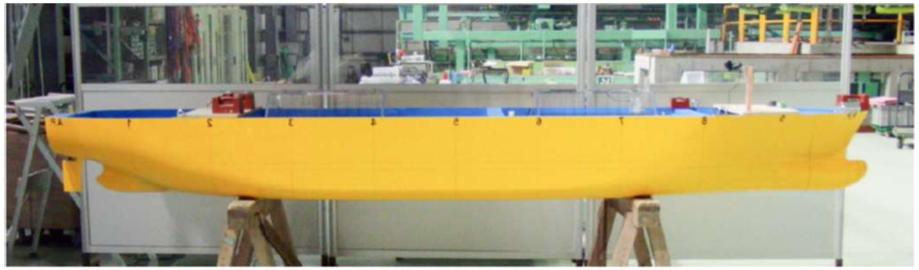
Does swirling really occur in actual irregular seaways?

Model tank was excited on a moving table with irregular sway motions.

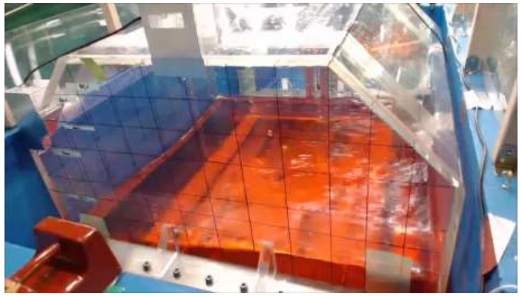
Test No.	Type of excitation	Liquid level	Significant wave height	Average wave period	Duration of test in actual scale
54	Sway	50 %	5.93 m	9.58 sec.	10,000 s.≈ 2.8 hrs



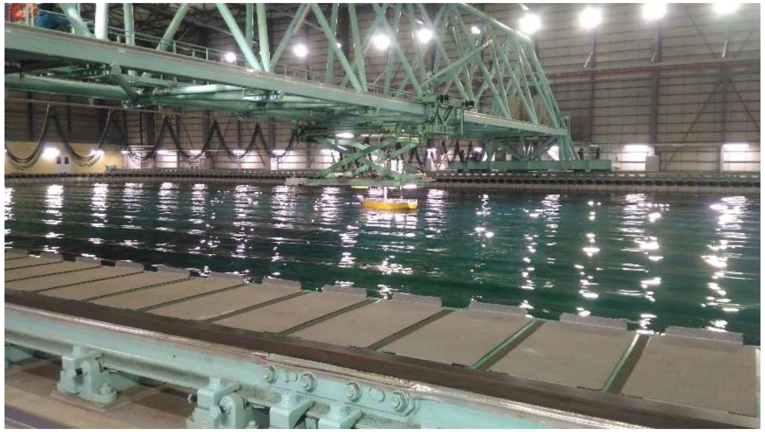
Membrane tank sloshing tests at model basin



LNG carrier model (L=4.0m)



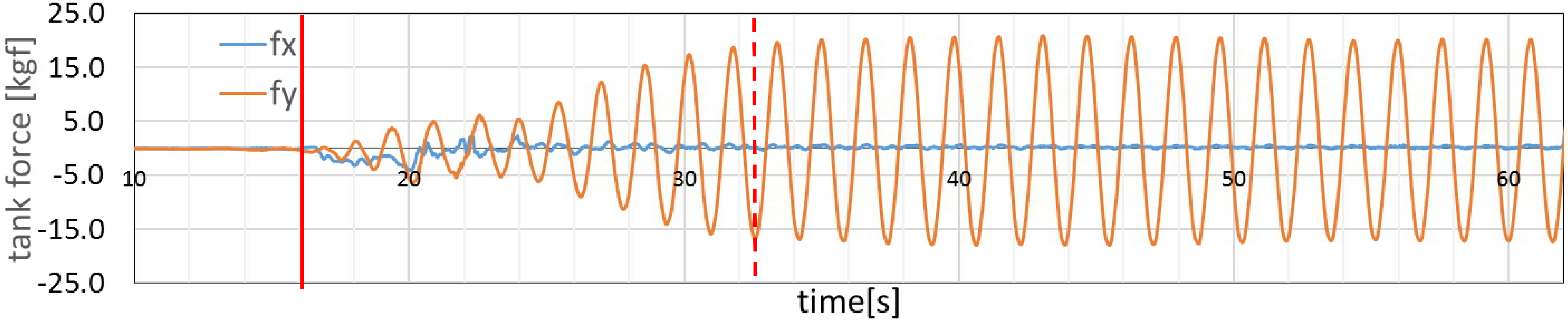
Acrylic tank



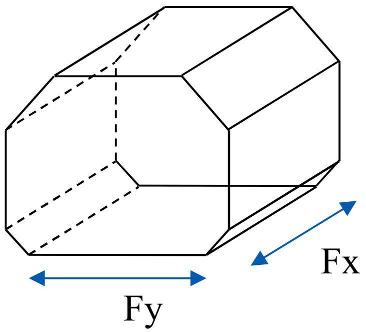
Actual Sea Model Basin,
National Maritime research Institute

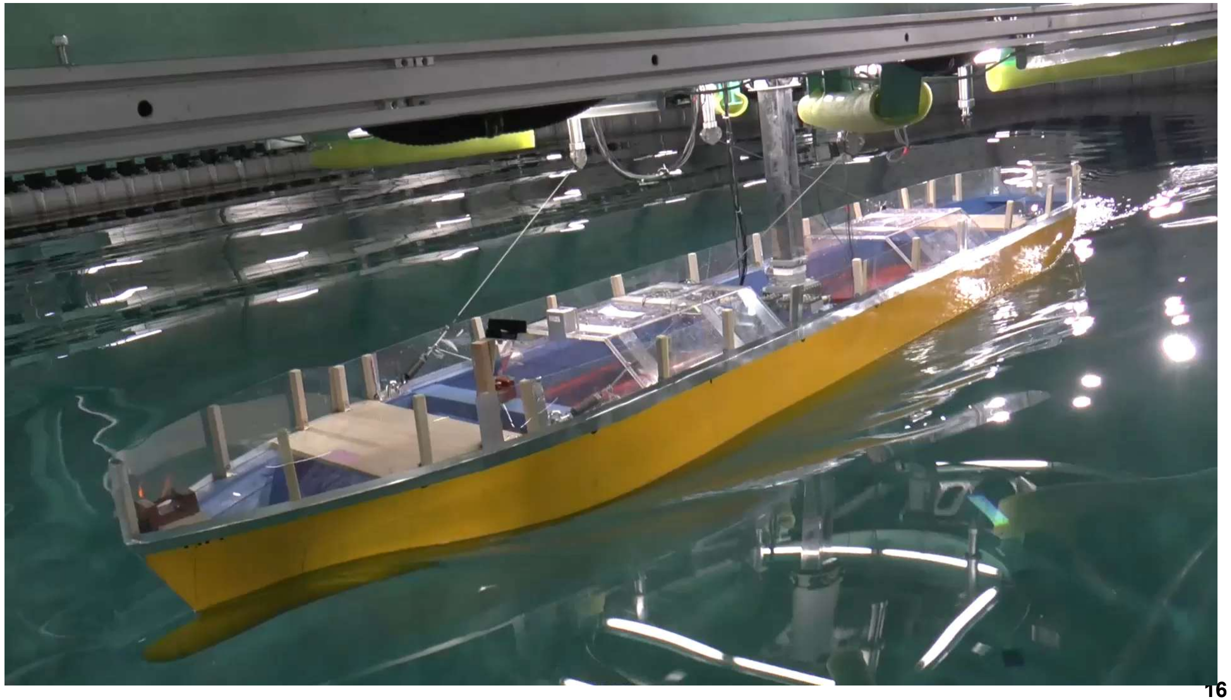
Measured items: Ship motions, Liquid motion in tanks,
Tank forces (F_x, F_y), Pressures, …

Ex.1: Encounter wave period ≈ Natural period of ship’s roll motion



Beam sea (90°),
H_w = 5.5 m,
50% loading





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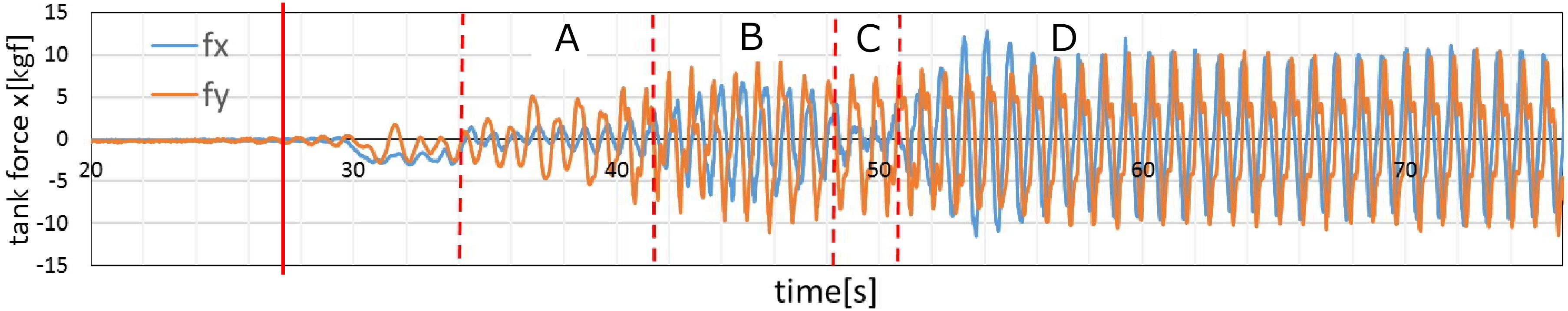
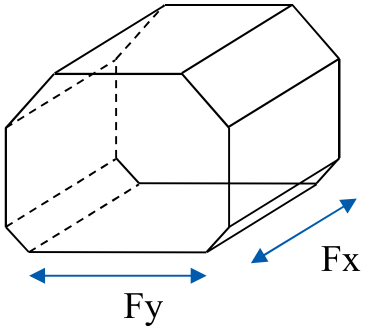
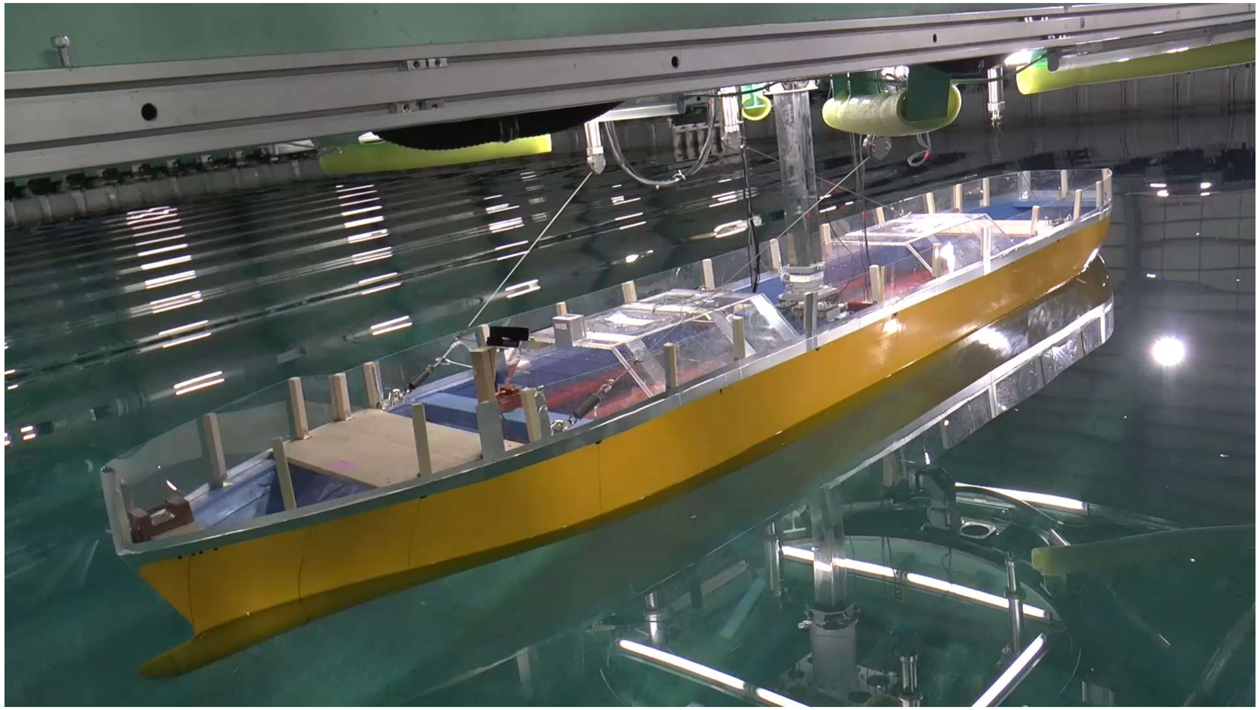
Ex.2: Encounter wave period ≈ Natural period of liquid motion



A:Sloshing→B:Swirling(Unticlockwise)→C:Transition→D:Swirling(Clockwise)

Beam sea (90°),
H_w = 5.5 m,
50% loading





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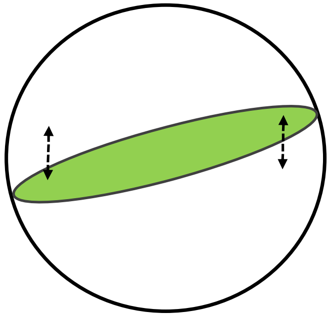
Conclusions

1. The global fluid motion and dynamic pressures obtained by our numerical sloshing simulation agree well with experimental data, which confirms the suitability of the numerical tool to represent the phenomena.
2. For middle to low filling levels, swirling occurs if the tank length to breadth ratio is near 1.0. On the other hand swirling does not appear in high filling conditions, i.e., 70% or more filling levels. We also confirmed that swirling in membrane tanks can occur in the actual irregular seaways.
3. In partially loaded conditions, very complicated liquid motion in the tank is generated when the encounter wave period is near the natural period of the tank liquid motion. For other encounter periods, the liquid motion in the tank is almost two dimensional and the wave inside the tank is generated almost parallel to the tank walls.

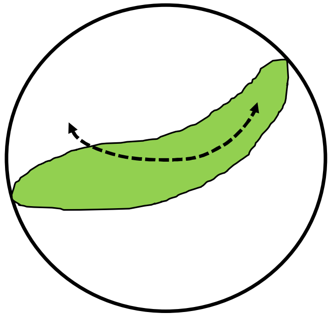
Part of this research was carried out as ClassNK's Joint R&D with industries and Academic Partners Project. We are planning to publish full research results including ship-slosh coupling analysis in the near future.

Thank you very much for your kind attention!

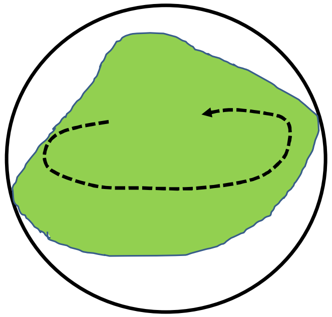
2. Types of the liquid motion



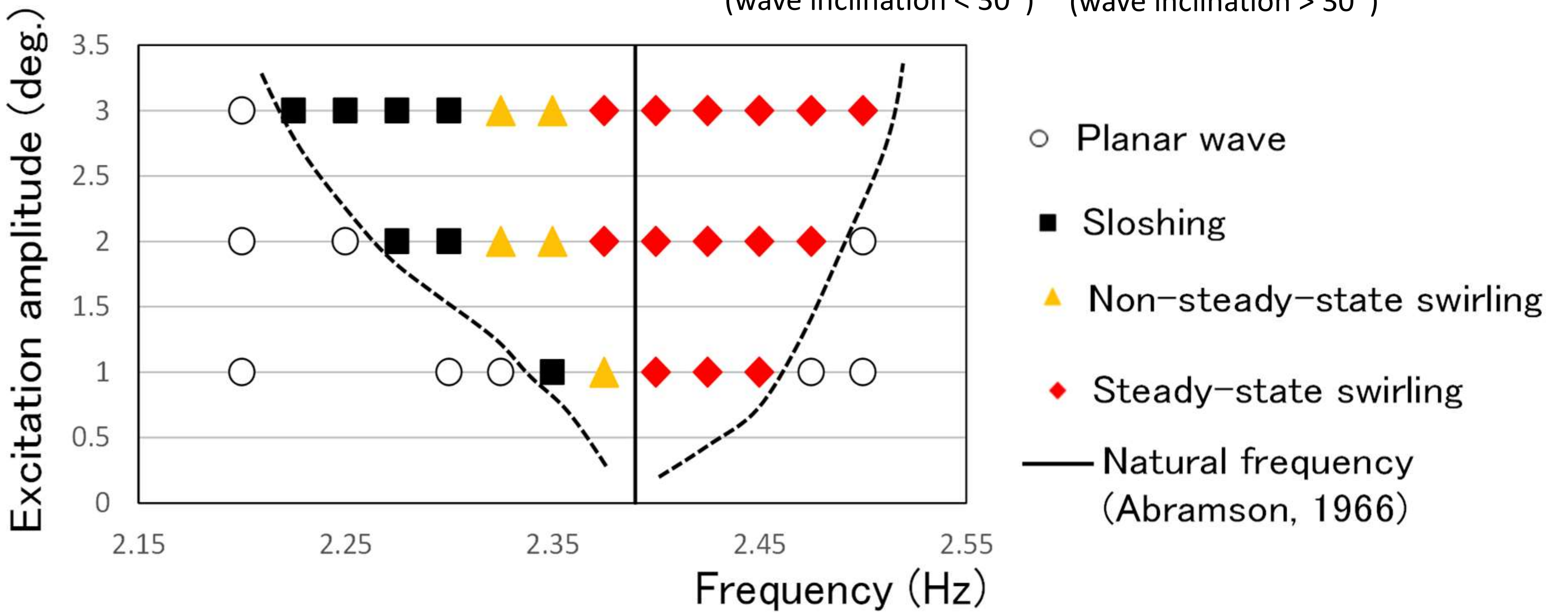
Planar wave
(wave inclination < 30˚)



Sloshing
(wave inclination > 30˚)



Swirling



Behavior of the liquid motion in the spherical tank (filling ratio: 70%)

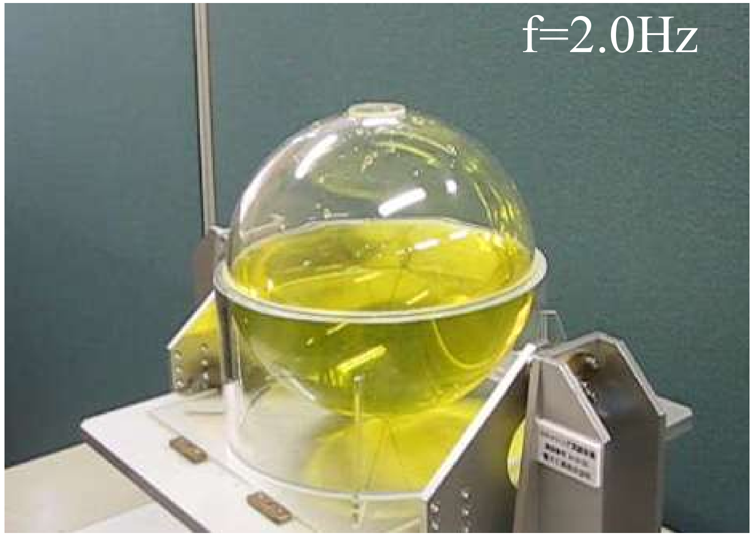
Arai, et al., PRADS2016

3. Observed liquid motions

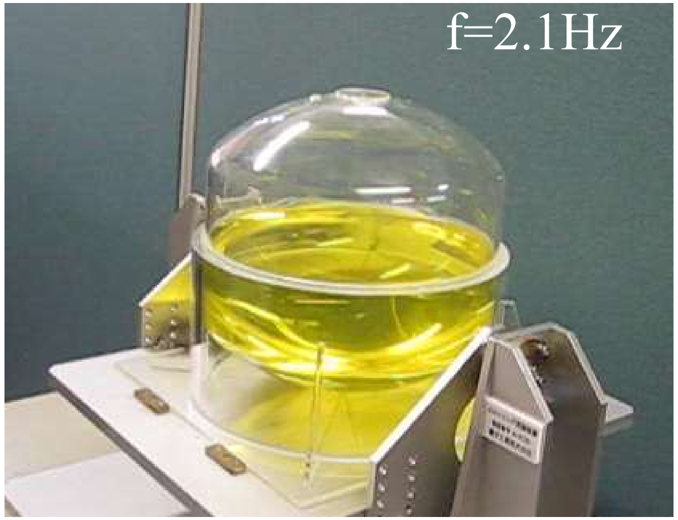
Spherical tk.

Stretched sphere tk.

Steady-state swirling



Non-steady -state swirling



$h/D = 0.50,\ \theta = 3^{\circ}$