

Unberthing simulations of a ship using a first-order lag model to take the hydrodynamic memory effect into account

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1. **Introduction**
2. **Studied ship**
 - Hull; flapped rudder; bow thruster
3. **Captive model tests**
4. **Calculation model of transient hydrodynamic forces**
 - Calculation of added mass during unberthing
 - Comparison of transient hydrodynamic forces in the calculations and experiments
5. **A first-order lag model to be taken into account**
6. **Unberthing simulations used for a first-order lag model**
7. **Concluding remarks**

Introduction

- When a ship moves laterally close to the bank, the additional hydrodynamic forces are caused by the bank effect acting on the ship hull.



- To advance such automatic navigating technology, it is necessary to predict the ship maneuvering motion during berthing/unberthing with high accuracy.

★We think that need for understanding and reasonably estimating methods to transient hydrodynamic forces acting on the ship hull.

Introduction

- Previous works on transient hydrodynamic forces.

1. For Experiments

- **Sadakane and Tsuruta (1993), Sadakane (1996);**
→ Measured transient hydrodynamic forces on a ship and observed the response delay from experiments.
- **Yoneda et al. (2018);**
→ Conducted captive model tests for unberthing with varying water depth, acceleration, and ship-bank distance.

2. For CFD

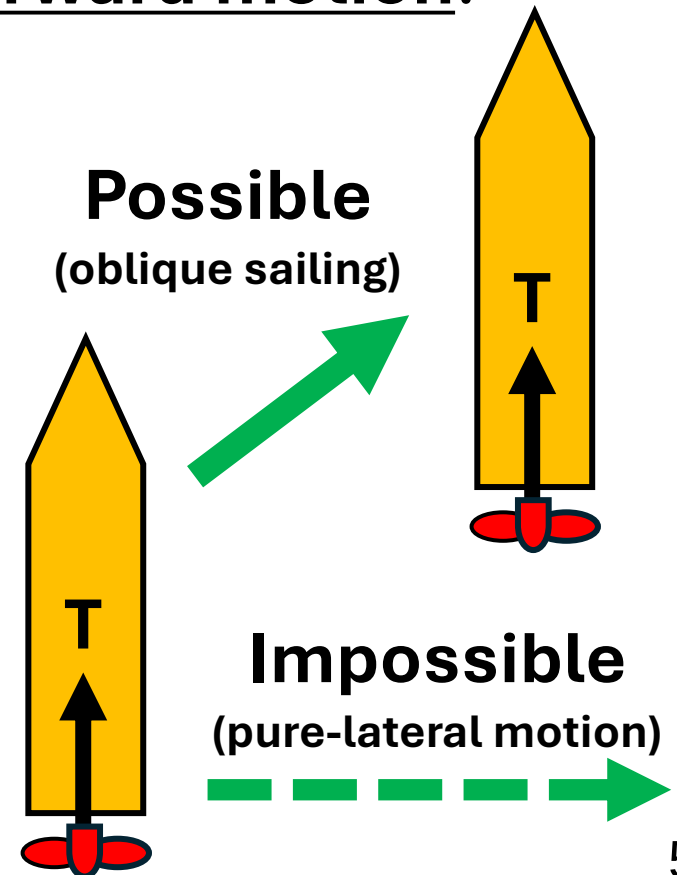
- **Lee et al. (2003), Shintani et al. (2020);**
→ The response delay for lateral moving is caused by shed vortices.

These works are focused on only pure-lateral motion.

Introduction

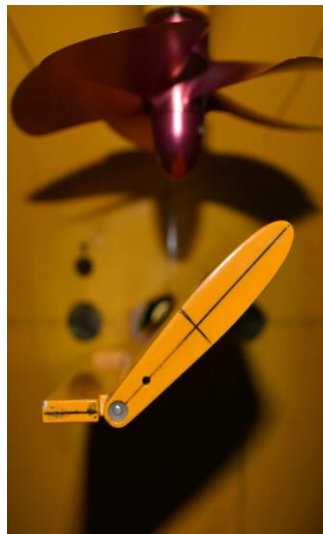
- The single-shaft ship cannot move pure-laterally without the assistance of tugs or bow and stern thrusters.
- The propeller thrust inducing forward motion.

1. Obtain transient hydrodynamic forces with various unberthing angles from the bank.
2. Attempted to approximate the response delay by using a first-order lag and a dead-time model, and incorporated the unberthing simulations.



Studied ship

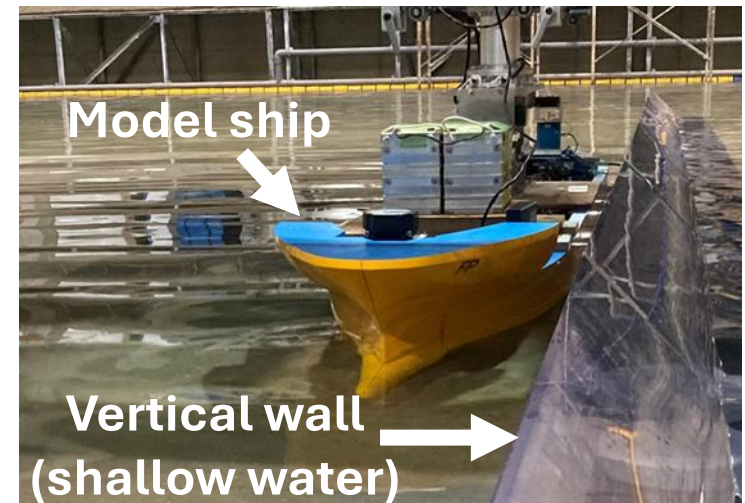
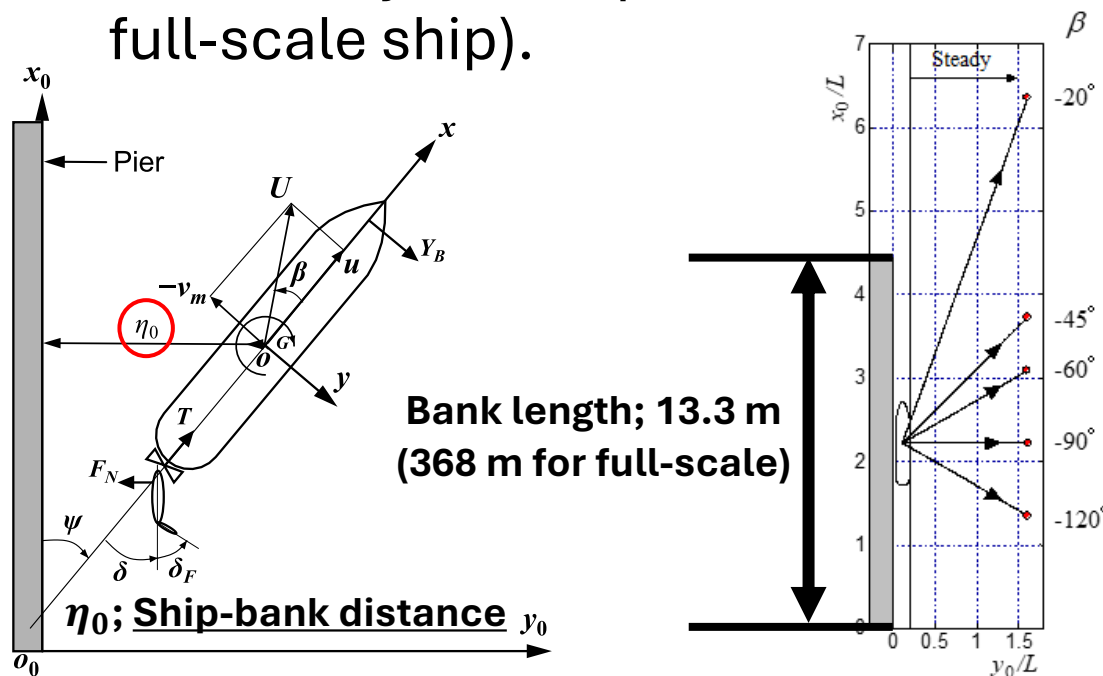
- Hull; flapped rudder; bow thruster.
- ✓ We selected the inland-type container ship called “Suzaku”.
- ✓ A 55.0 mm bow thruster model is attached at S.S. 9.43.
- ✓ The ship model has a flapped rudder.



	Model	Full-scale
L [m]	3.000	83.00
B [m]	0.488	13.5
d [m]	0.1376	3.8
∇ [m ³]	0.1486	3146
$\overline{GM}$ [m]	0.0329	0.91
C_b	0.7369	
Dp [m]	0.101	2.80
Z	5	

Captive model tests

- The vertical bank model was placed on the bottom of a square tank in shallow water; **the transient hydrodynamic forces were measured (only bare hull condition).**
- The water depth (h) is in two conditions; **$h/d = 1.5$ and 1.2 .**
- The absolute value of the unberthing angle from the bank (drift angle β) varied between $-20^\circ \sim -120^\circ$.
- The steady-state speed was set to 0.170 m/s (1.7 knots for the full-scale ship).



Captive model tests

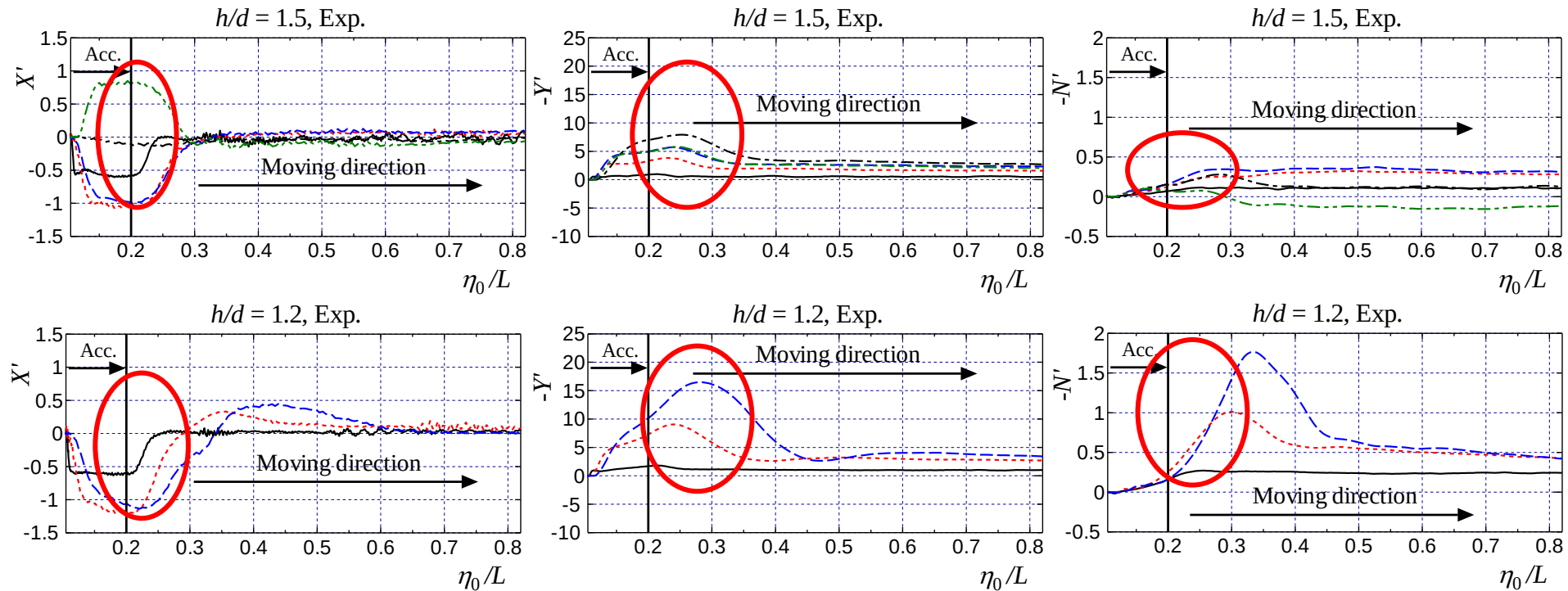
- Video of the captive model tests (at unberthing).



Captive model tests

- Measurement results for the transient hull forces.

$\text{—} \beta = -20^\circ$
 $\text{---} \beta = -45^\circ$
 $\text{---} \beta = -60^\circ$
 $\text{---} \beta = -90^\circ$
 $\text{---} \beta = -120^\circ$



- ✓ Even at steady-state speed ($\eta_0/L > 0.2$), **the transient hull forces continue to change.**
- ✓ Transient hydrodynamic forces have appeared in the response delay.
- ✓ The water depth becomes shallower, the effect becomes larger.

Calculation model of transient hydrodynamic forces

- Compare the experimental results with the theoretical value of transient hydrodynamic forces including the bank effect.

✓ The equation of ship motion is expressed as:

$$\left. \begin{aligned}
 (m + m_{11})\dot{u} - (m + m_{22})v_m r - m x_G r^2 &+ m_{12}\dot{v}_m + m_{13}\dot{r} - m_{23}r^2 = F_x \\
 (m + m_{22})\dot{v}_m + (m + m_{11})ur + m x_G \dot{r} &+ m_{21}\dot{u} + m_{23}\dot{r} = F_y \\
 (I_{zz} + m_{33} + m x_G^2)\dot{r} + m x_G(\dot{v}_m + ur) &+ m_{31}\dot{u} + m_{32}(\dot{v}_m + ur) = M_z
 \end{aligned} \right\} \begin{array}{l} \leftarrow \text{Surge(1)} \\ \leftarrow \text{Sway(2)} \\ \leftarrow \text{Yaw(3)} \end{array}$$

Ordinally equation of motion

Close to the bank (vary with η_0)

m_{kj} : k ; the added mass/moment, j ; ship motions for each directions.

- All coupling terms of the added mass appear because **the symmetric flow field around the ship is broken.**

Right side terms;

$$\left. \begin{aligned}
 F_x &= F_{H1} + F_{B1} + F_{P1} + F_{R1} + F_{BT1} \\
 F_y &= F_{H2} + F_{B2} + F_{P2} + F_{R2} + F_{BT2} \\
 M_z &= F_{H3} + F_{B3} + F_{P3} + F_{R3} + F_{BT3}
 \end{aligned} \right\} \begin{array}{l} F_{Hi} : \text{Hull forces} \\ F_{Bi} : \text{Additional forces owing to bank effect} \\ F_{Pi} : \text{Propeller forces} \\ F_{Ri} : \text{Rudder forces} \\ F_{BTi} : \text{Bow thruster forces} \end{array}$$

Calculation model of transient hydrodynamic forces

✓ The bank effect term is expressed as:

$$\left. \begin{aligned} F_{B1} &\cong m_{11y}u|v_m| + m_{12y}v_m^2 + D_{11}^{(1)}u|u|/2 \\ F_{B2} &\cong m_{21y}uv_m + m_{22y}v_m|v_m| + D_{11}^{(2)}u^2/2 \\ F_{B3} &\cong m_{31y}uv_m + m_{32y}v_m|v_m| + D_{11}^{(3)}u|u|/2 \end{aligned} \right\} \begin{array}{l} m_{k jy} : \text{Added mass derivatives} \\ \quad \quad \quad \text{(derivatives with respect to } y_0) \\ D_{11}^{(i)} : \text{Additional force owing to bank} \\ \quad \quad \quad \text{(obtained from the tank tests)} \end{array}$$

➤ Since $\dot{r} = r = 0$ in the captive model tests, and conducted the bare hull condition; **propeller, rudder, bow thruster were not considered.**

➡ The values measured in the captive model tests (X, Y, N) are expressed as:

$$\left. \begin{aligned} X &= F_{H1} + F_{B1} - (m + m_{11})\dot{u} - m_{12}\dot{v}_m \\ Y &= F_{H2} + F_{B2} - m_{21}\dot{u} - (m + m_{22})\dot{v}_m \\ N &= F_{H3} + F_{B3} - m_{31}\dot{u} - (mx_G + m_{32})\dot{v}_m \end{aligned} \right\} \leftarrow \text{Include inertial forces associated with acceleration.}$$

Vary with the distance to bank η_0

Using the previous data for Okuda et al. (2024)

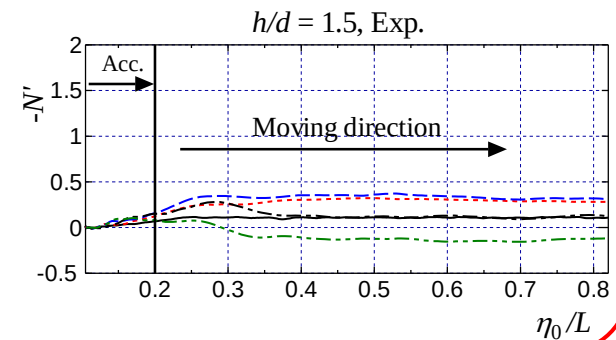
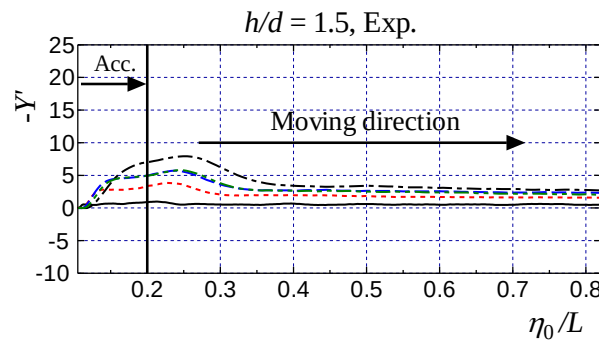
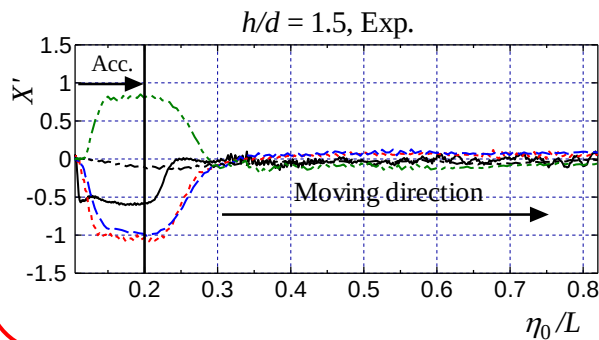
Calculation model of transient hydrodynamic forces

- Comparison of transient hydrodynamic forces in the calculations and experiments.

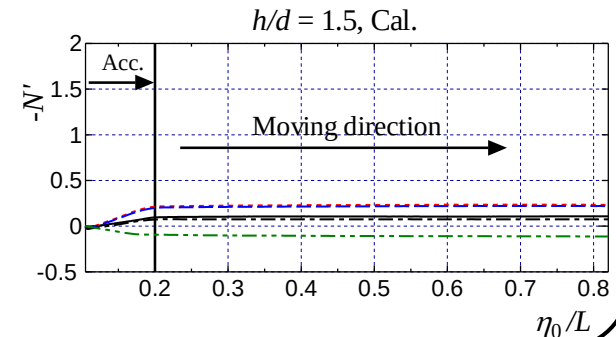
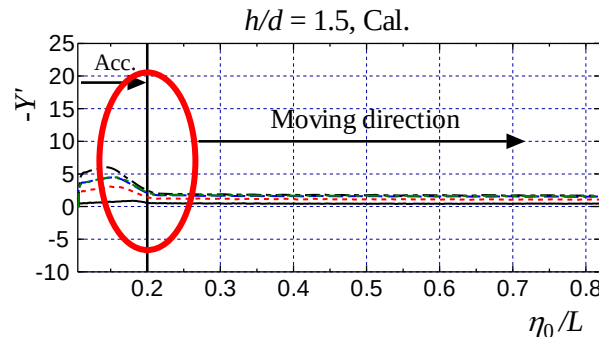
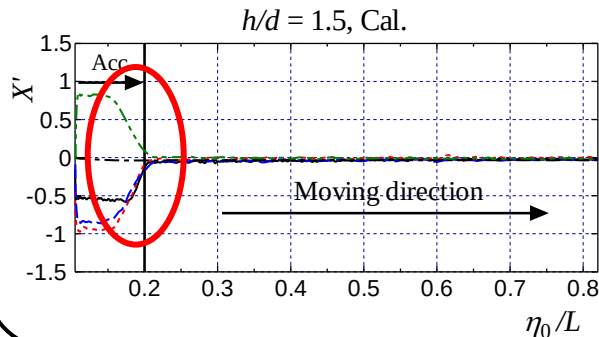
➤ In case of $h/d = 1.5$;

$\beta = -20^\circ$ $\beta = -45^\circ$ $\beta = -60^\circ$
 $\beta = -90^\circ$ $\beta = -120^\circ$

Experiments



Calculations



Cannot capture the response delay and the peak values are different. 12

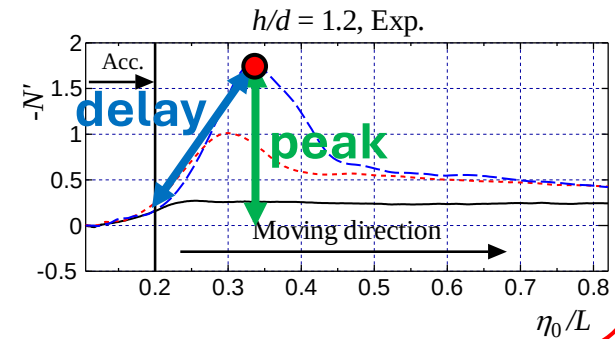
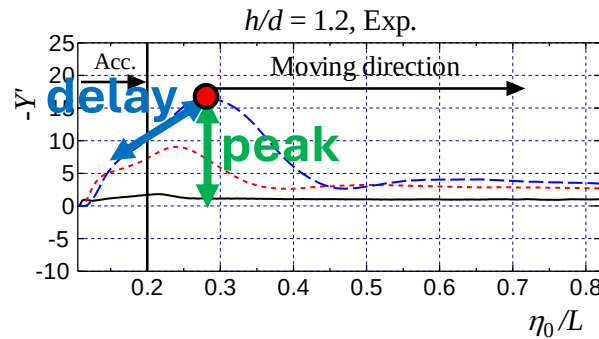
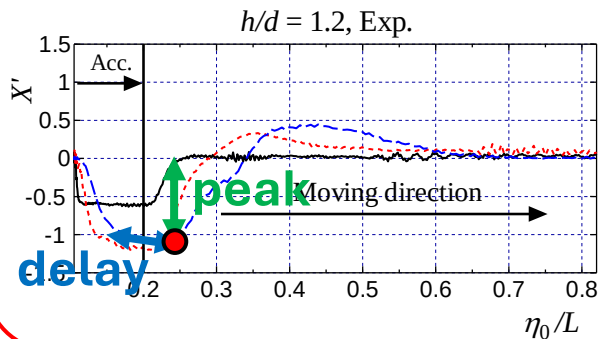
Calculation model of transient hydrodynamic forces

- Comparison of transient hydrodynamic forces in the calculations and experiments.

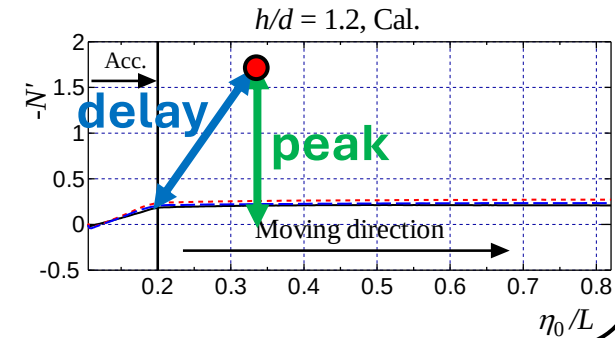
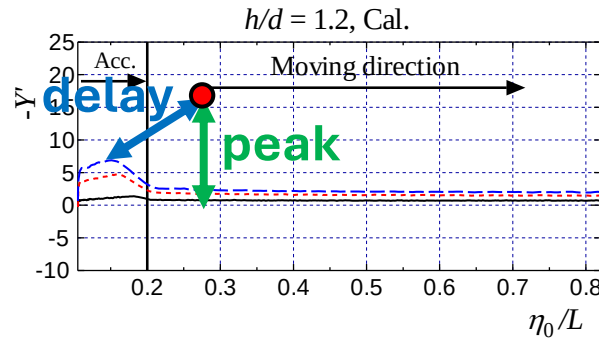
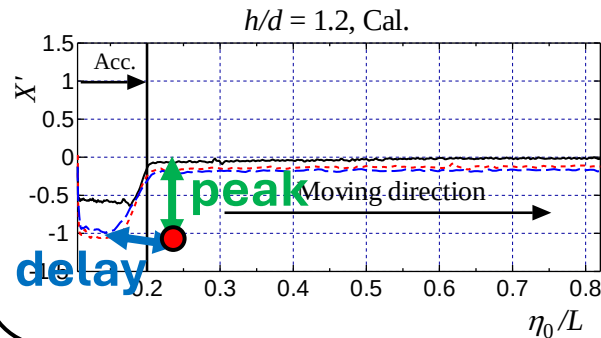
➤ In case of $h/d = 1.2$;

— $\beta = -20^\circ$ - - - $\beta = -45^\circ$ - - - $\beta = -60^\circ$

Experiments



Calculations

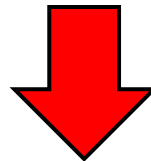


The memory effect at unberthing cannot be ignored??

A first-order lag model to be taken into account

➤ Summary to this point

- Experimental values were observed for the response delay owing to the memory effect, the same as in the previous study.
- The theoretical calculation includes bank effects that cannot capture the experimental transient hydrodynamic forces.
- The quasi-stationary assumptions for the hydrodynamic forces cannot be used in unberthing simulations.



- ✓ We adopted a first-order lag and dead-time model.
- ✓ Attempt to approximate the response delay of the hydrodynamic forces during acceleration!

A first-order lag model to be taken into account

- A first-order lag model with dead-time.
- ✓ The differential equation is expressed as:

$$a(t) + T_1 \frac{da(t)}{dt} = K_1 b(t - L_1)$$

K_1 : System gain
 T_1 : Time constant
 L_1 : Dead-time
 Called “**first-order lag parameters**”

~Discretization~

$$a(k_d) = -c_1 a(k_d - 1) + c_2 b(k_d - t_d - 1)$$

Output:
Hull forces considering the response delay.

Input: Transient hull forces

$$\left. \begin{aligned} X &= F_{H1} + F_{B1} - (m + m_{11})\dot{u} - m_{12}\dot{v}_m \\ Y &= F_{H2} + F_{B2} - m_{21}\dot{u} - (m + m_{22})\dot{v}_m \\ N &= F_{H3} + F_{B3} - m_{31}\dot{u} - (mx_G + m_{32})\dot{v}_m \end{aligned} \right\}$$

$$c_1 = -\frac{T_1}{T_s + T_1}, c_2 = \frac{K_1 T_s}{T_s + T_1}, t_d = \frac{L_1}{T_s}$$

A first-order lag model to be taken into account

- Determined the first-order lag parameters.

1. **Determine K_1** : The peak value of the transient hydrodynamic forces in the calculation results should match that in the captive model tests.
2. **Determine T_1 & L_1** : The response delay in the calculation results should match that in the captive model tests.

➤ **For example...**

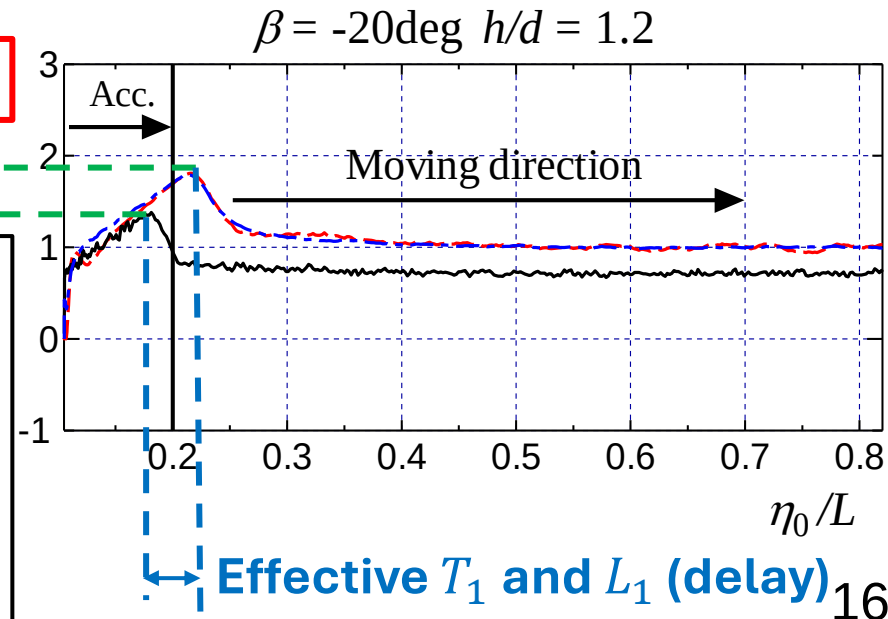
— Cal. (original) - - - Cal. (1st lag) - - - Exp.

Dealing with both the peak and the delay!

Note;

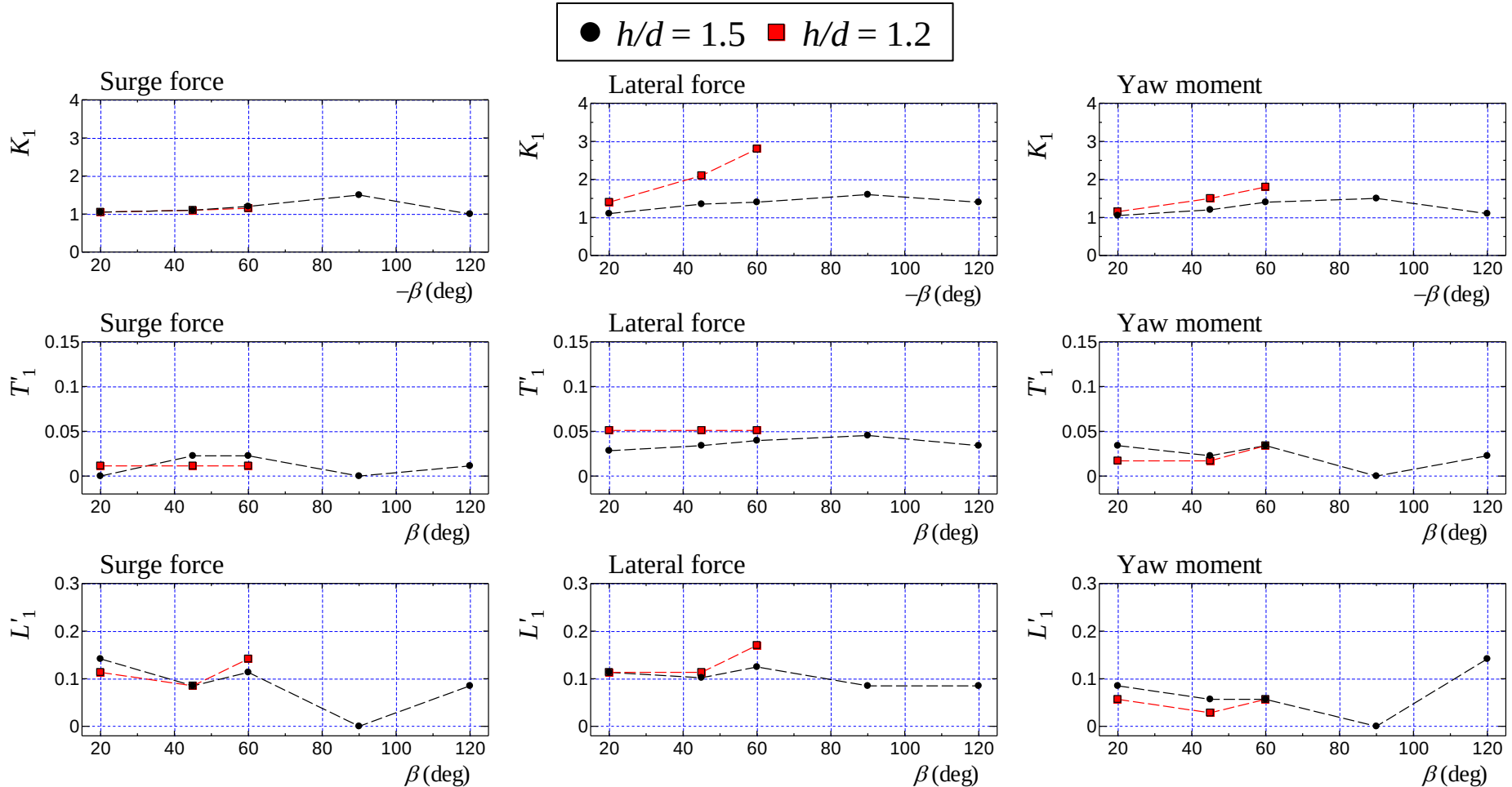
Effective K_1 (peak)

- Determine the first-order lag parameters to fit the experimental transient forces.
- The parameters are different for each X, Y, N .
- Obtain the parameters for each drift angle and interpolate.



A first-order lag model to be taken into account

- Estimated results of the parameters.
(T_1 and L_1 are divided by L/U_0 for nondimensionalization.)



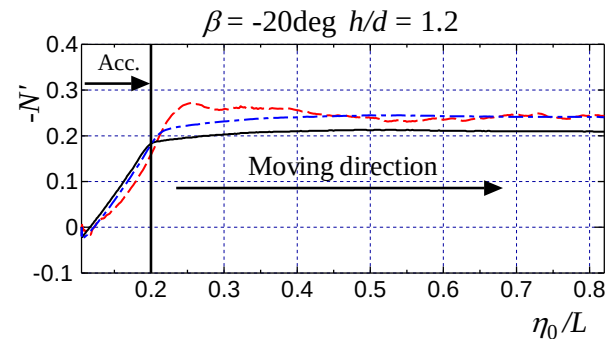
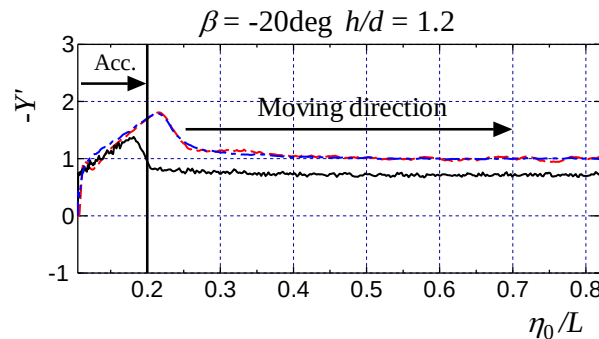
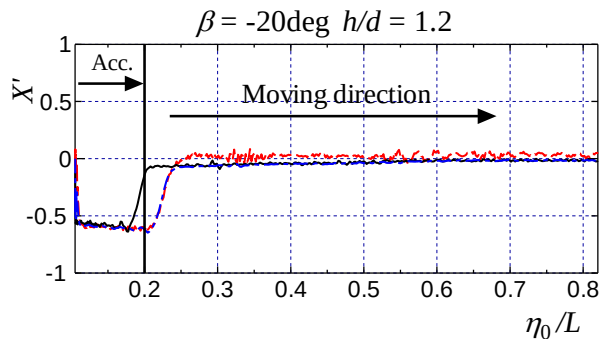
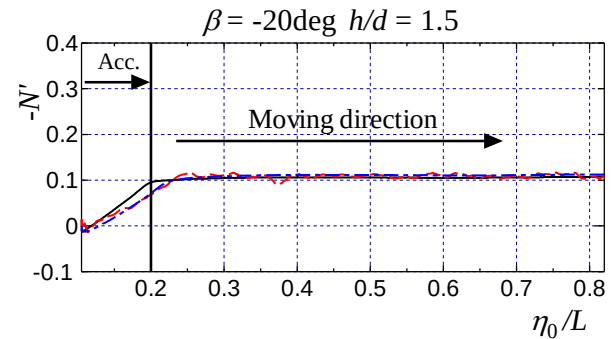
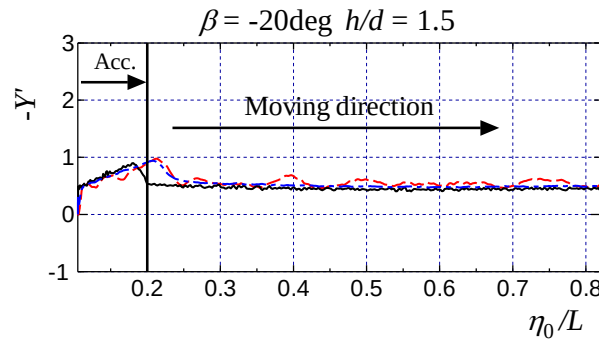
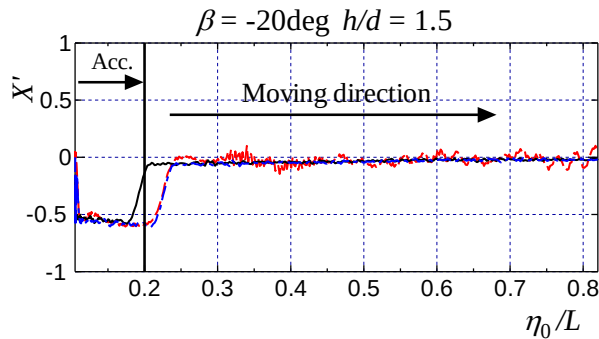
K_1 is greatly affected by the difference in the drift angles.

A first-order lag model to be taken into account

- Calculation results of the transient hydrodynamic forces.

➤ In case of $\beta = -20$ deg;

— Cal. (original) - - - Cal. (1st lag) - - - Exp.



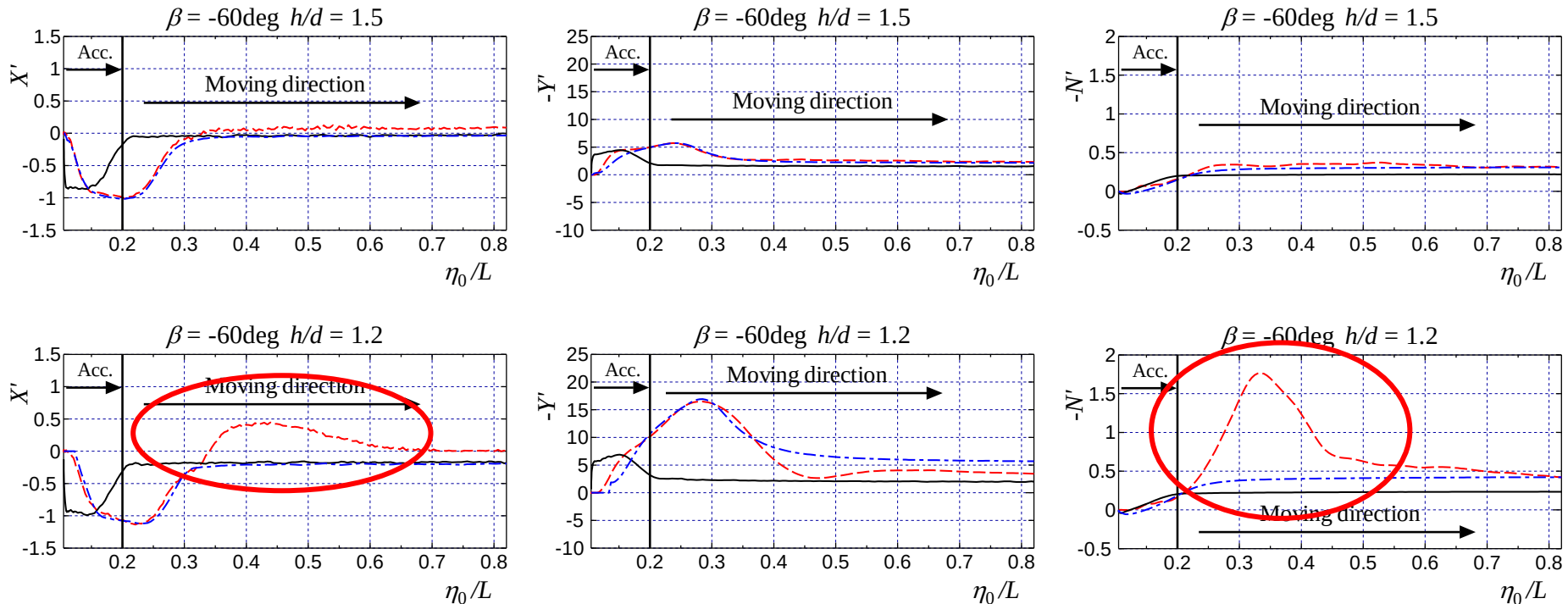
✓ In case the drift angle is relatively small, introducing the first-order lag model improved the accuracy of the estimation!

A first-order lag model to be taken into account

- Calculation results of the transient hydrodynamic forces.

➤ In case of $\beta = -60$ deg;

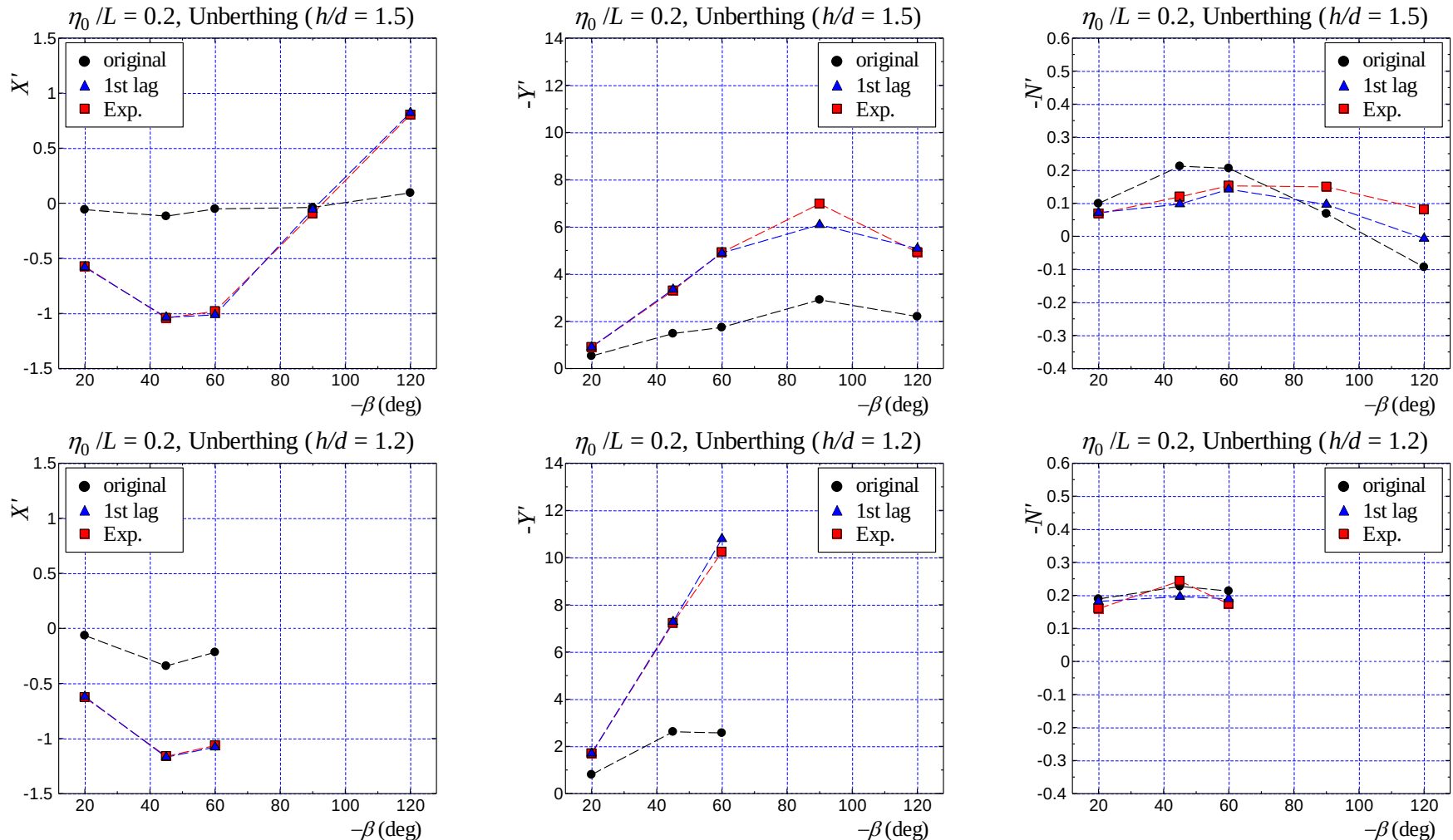
— Cal. (original) - - - Cal. (1st lag) - - - Exp.



- ✓ As the absolute value of the drift angle increases, it becomes difficult to capture the complex behavior of hydrodynamic forces.

A first-order lag model to be taken into account

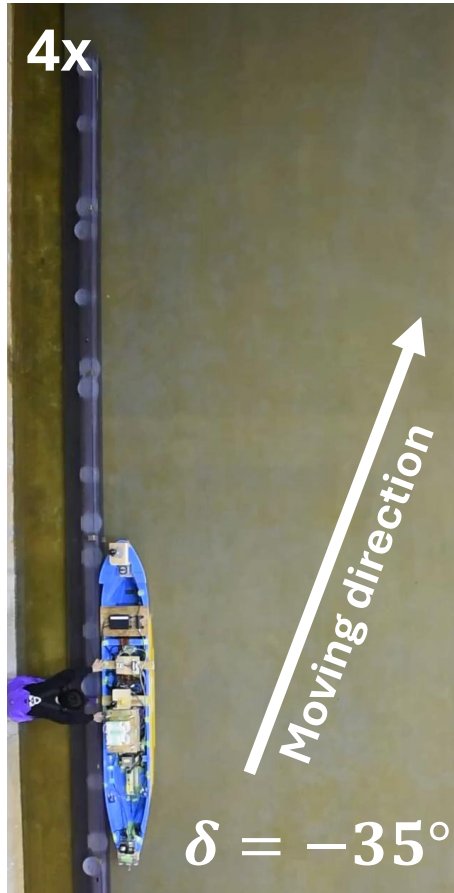
- Comparison of the hull forces versus β at $\eta_0/L = 0.2$.



The estimation accuracy of the hull force improved! ₂₀

Unberthing simulations used for a first-order lag model

- Simulation scenario.

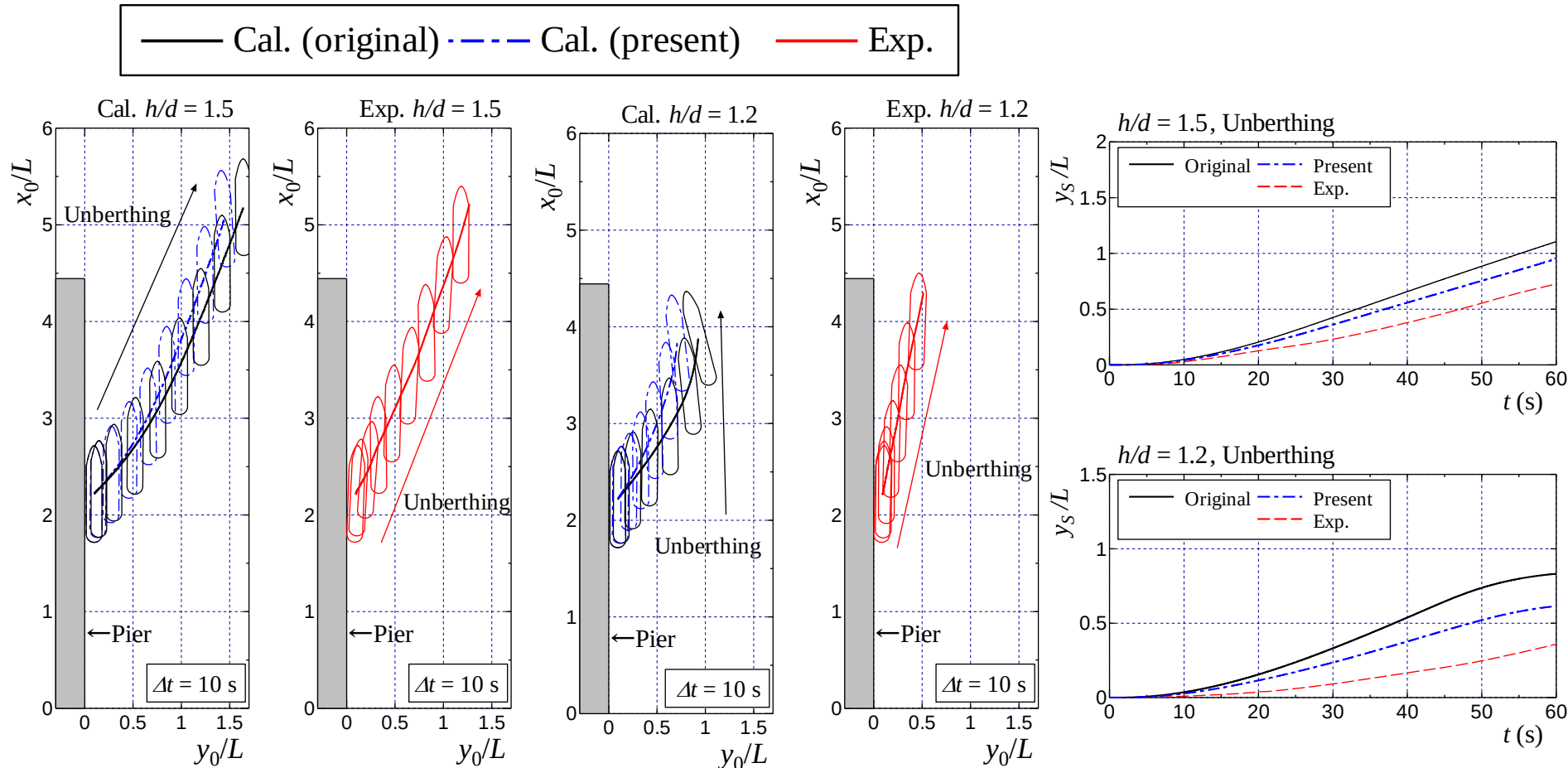


- ✓ Propeller rev.;
5.8 rps for the model scale.
(Main engine output; Dead Slow)
- ✓ Rudder angle;
-35 deg (The bow being port turning)
- ✓ B/T control model;
Presented by Okuda et al. (2024).
Max; 0.31 kgf (6.5 tons for full-scale)
- ✓ Water depth;
 $h/d = 1.5$ and 1.2 (2 conditions).

- Conducted two simulations;
- ✓ Cal. (original); Exclude the bank effect and the response delay.
- ✓ Cal. (present); Include the bank effect and the response delay.

Unberthing simulations used for a first-order lag model

- Trajectories.

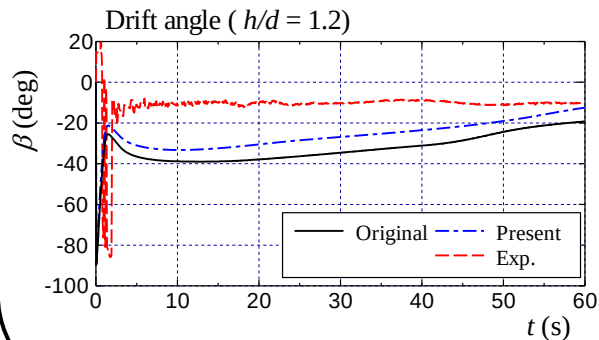
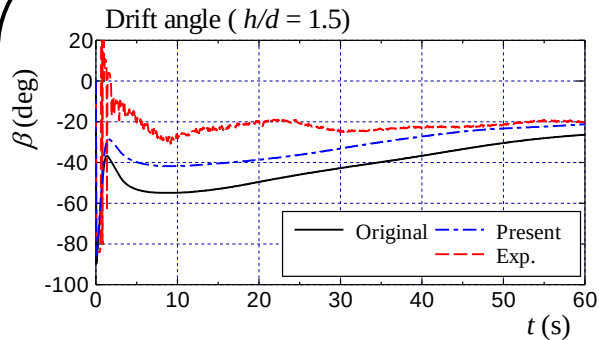


- The Present trajectory is closer to the free-running model test results.
- However, the simulation accuracy of $h/d = 1.2$ has room for improvement.

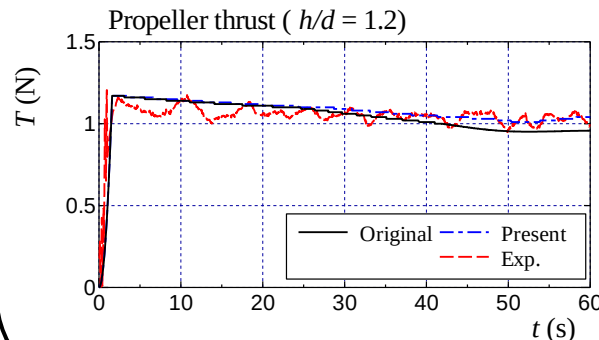
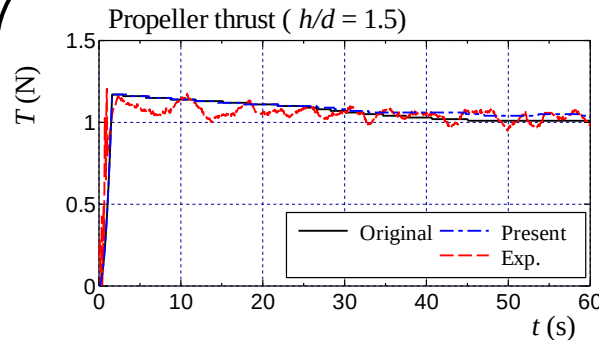
Unberthing simulations used for a first-order lag model

- Time histories.

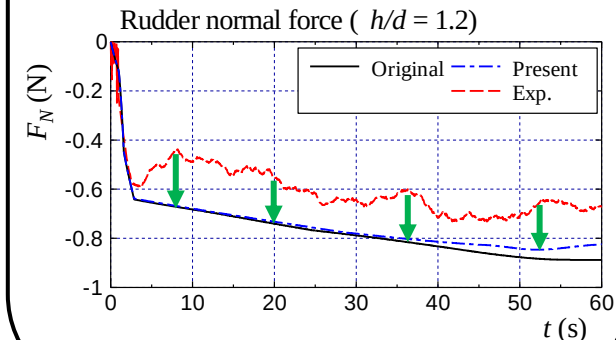
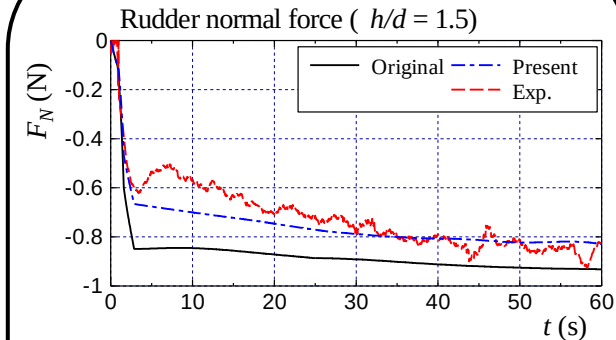
Drift angle



Propeller thrust



Rudder force



- Especially in $h/d = 1.5$, the simulation accuracy improved for time histories.
 - F_N with $h/d = 1.2$ has room for improvement in estimate accuracy.
- The complex transient hydrodynamic forces may act on the rudder.

Concluding remarks

1. This study focuses on the transient hydrodynamic forces during the unberthing of a single-shaft ship, and conducted captive model tests.
2. The hull forces were calculated considering the bank effect and compared with the experimental results.



As results...

- The response delay of the hydrodynamic force due to the memory effect becomes significant in shallow water.
- **The original mathematical model cannot produce a response delay in the transient hull forces.**



Introduce the first-order lag model

- **It can capture the transient hydrodynamic forces and improve the unberthing simulation accuracy.**
- Note, however, that this is an approximate method.

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Thank you!