

Numerical study on the rudder inflow behind the hull and the propeller in four quadrants

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3. Convergence study

4. Results and discussions

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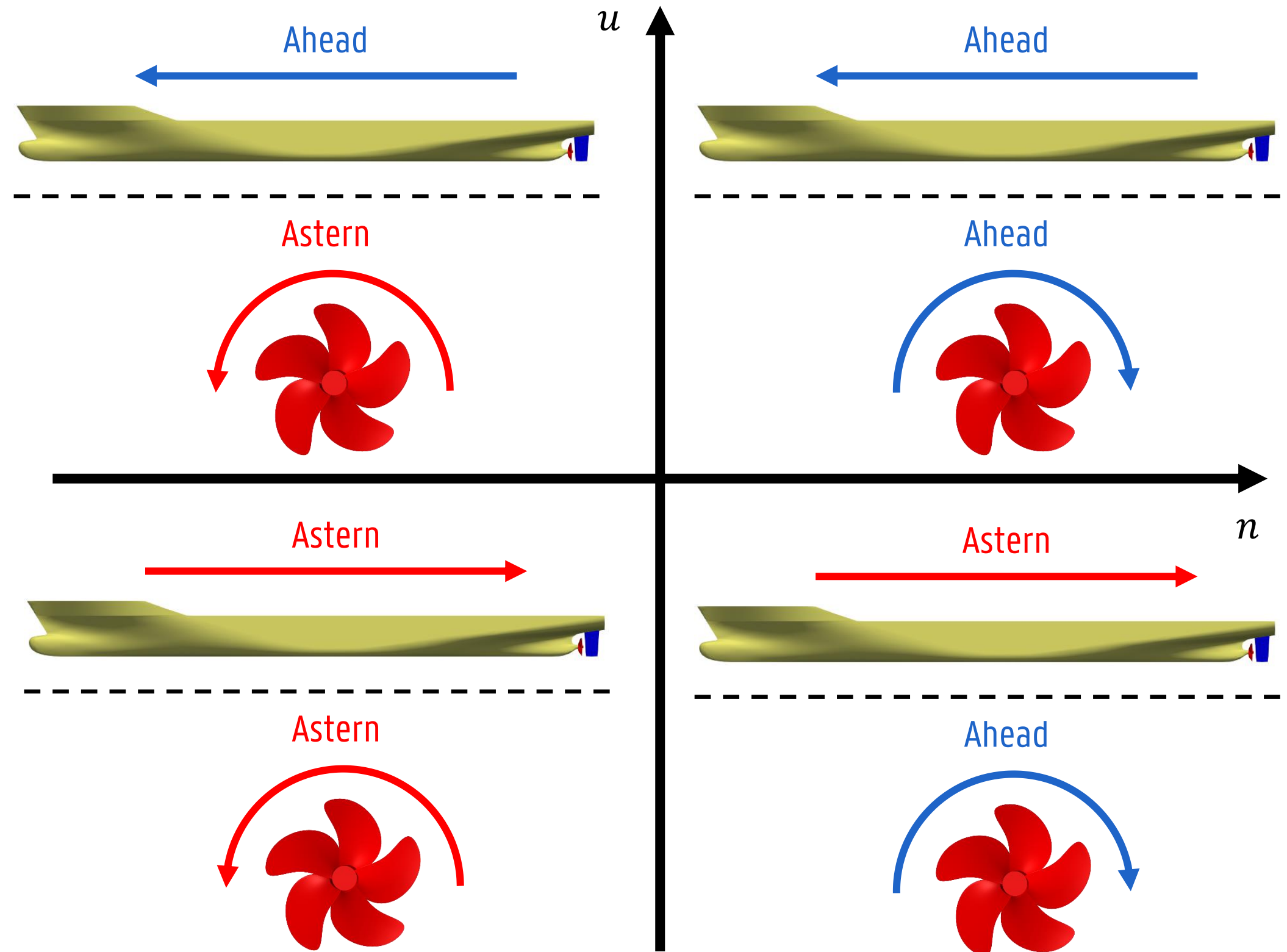
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1. Introduction

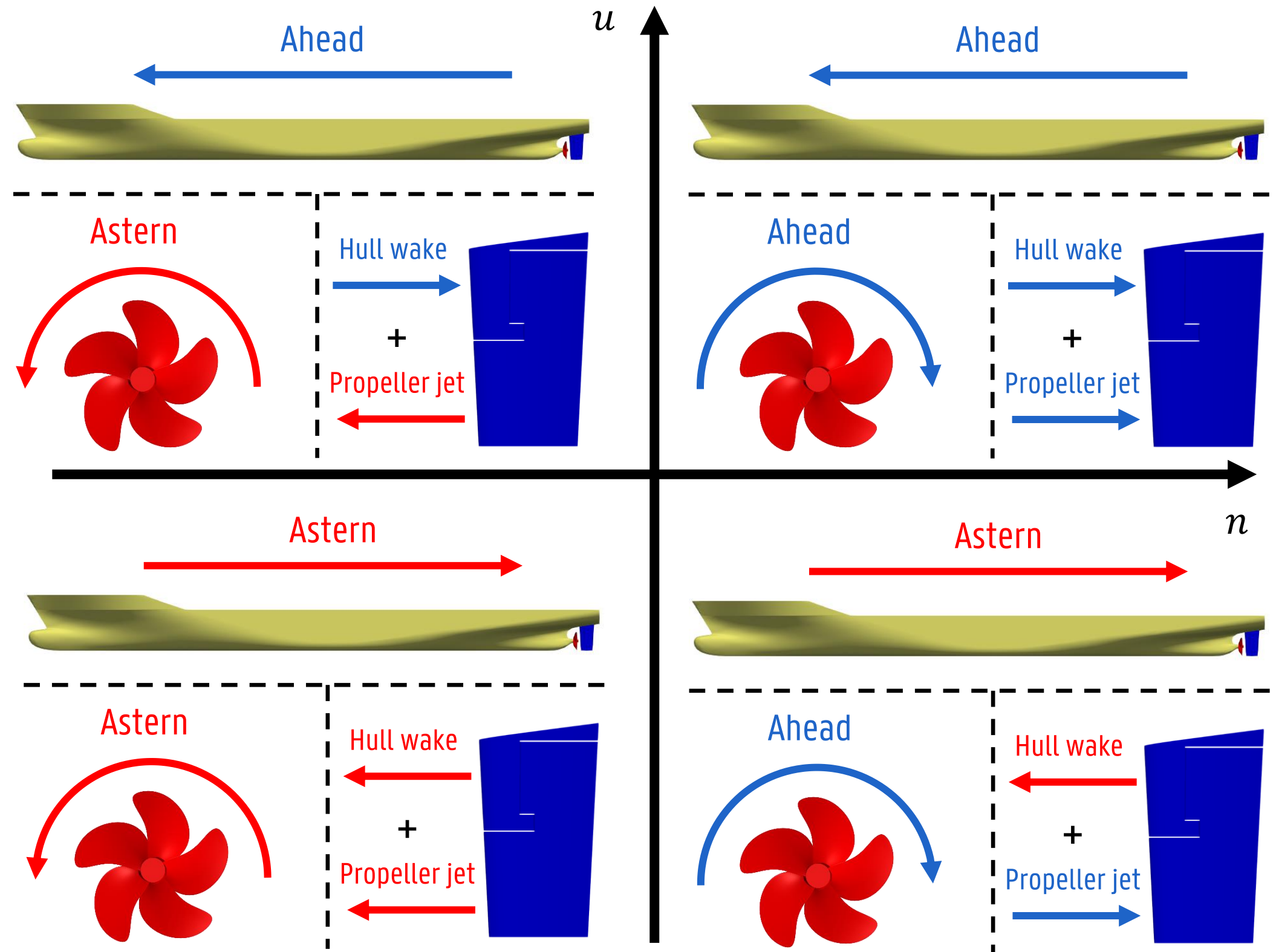
1. Introduction

- Four quadrants motion of the ship
 - Defined by signs of
 - Surge velocity u
 - Move ahead ($u > 0$)
 - Move astern ($u < 0$)
 - Propeller rate n
 - Rotate ahead ($n > 0$)
 - Rotate astern ($n < 0$)



1. Introduction

- Four quadrants motion of the ship
 - Rudder inflow
 - Hull wake
 - Propeller jet



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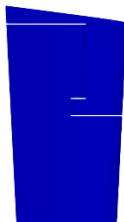
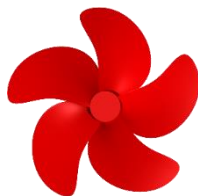
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2. Computation details

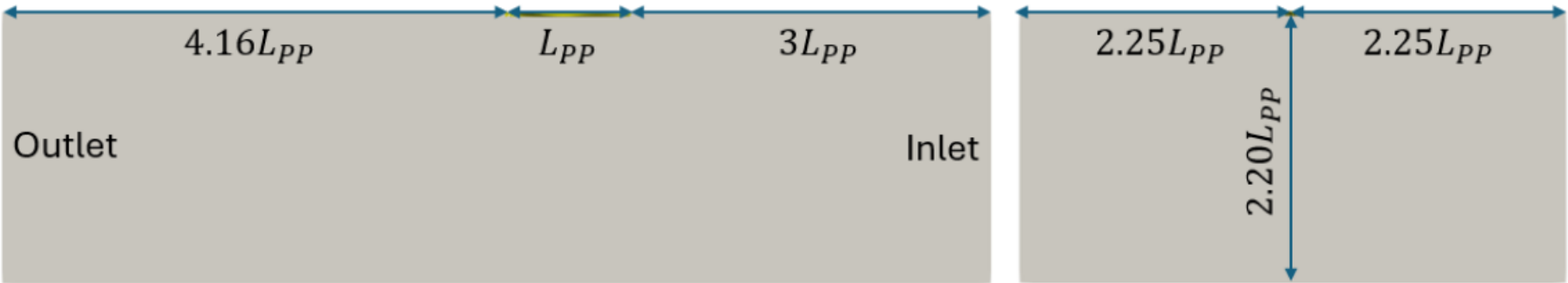
2. Computation details

— Geometrical information

KCS Hull		KP505 Propeller		Semi-balanced Rudder	
Particular	Value	Particular	Value	Particular	Value
L_{PP} (m)	7.278	D_P (m)	0.250	c_m (m)	0.174
B (m)	1.109	A_E/A_O (m)	0.448	Λ_G (m)	1.799
T (m)	0.342	$(P/D)_{0.7R}$ (-)	1.000	A_R (m ²)	0.054
λ (-)	1/31.6	λ (-)	1/31.6	λ (-)	1/31.6



— Domain size



2. Computation details

- Numerical method

Quadrant		Relative direction of hull wake and propeller jet	Numerical method
Q1	$u > 0, n > 0$	Same	RANS
Q2	$u > 0, n < 0$	Opposite	DDES
Q3	$u < 0, n < 0$	Same	RANS
Q4	$u < 0, n > 0$	Opposite	DDES

- Numerical setting

- Software
 - OpenFOAM v2206
- Numerical schemes
 - PIMPLE
 - 2nd order schemes with limiters

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3. Convergence study

- Convergence study on the bare hull

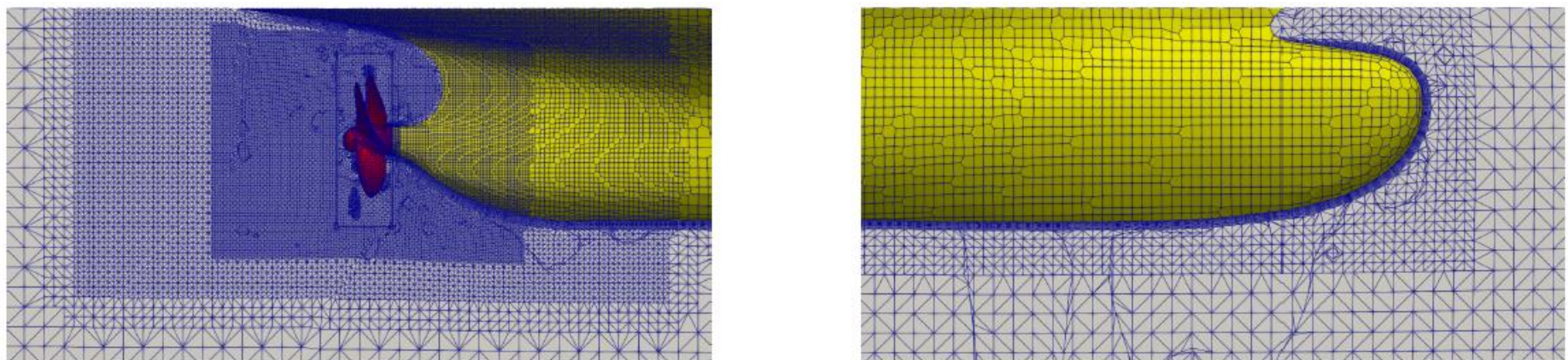
Mesh	Number of cells (—)	$C_V(-)$	$C_P(-)$	C_V Error (—)
Coarse	814 036	2.942×10^{-3}	2.741×10^{-4}	0.67%
Medium	1 882 360	2.928×10^{-3}	2.868×10^{-4}	1.52%
Fine	4 607 171	2.903×10^{-3}	2.069×10^{-4}	2.02%

- Uncertainty estimation on the bare hull

	$C_V(-)$	$C_P(-)$
ϵ_{21}	-1.452×10^{-5}	1.273×10^{-5}
ϵ_{32}	-2.441×10^{-5}	2.009×10^{-5}
$\epsilon_{21}/\epsilon_{32}$	0.595	0.634
Convergence	Monotonic	Monotonic
p	2.030	1.811
$U_{G_{21}}$	1.482×10^{-3}	1.620×10^{-2}
$U_{G_{32}}$	2.730×10^{-3}	2.657×10^{-2}

3. Convergence study

— Time step independence study on the hull-propeller interaction case



$\Delta t(s)$	$\Delta \theta(^{\circ})$	$C_{T,DB}(-)$	$K_T(-)$	$10K_Q(-)$
1.462×10^{-4}	0.5	3.651×10^{-3}	0.174	0.368
2.060×10^{-4}	0.707	3.620×10^{-3}	0.173	0.362
2.924×10^{-4}	1.0	3.594×10^{-3}	0.172	0.362

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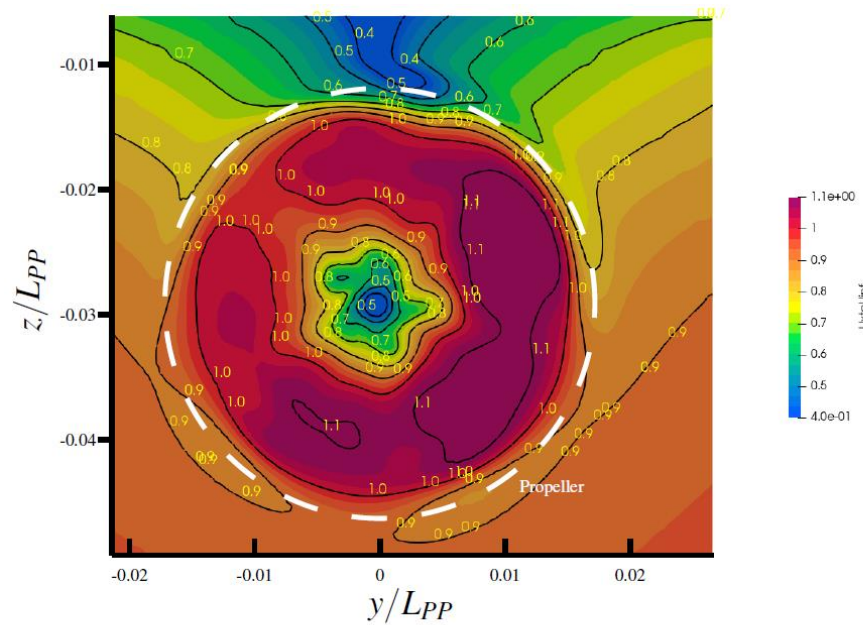
5. Conclusions

4. Results and discussions

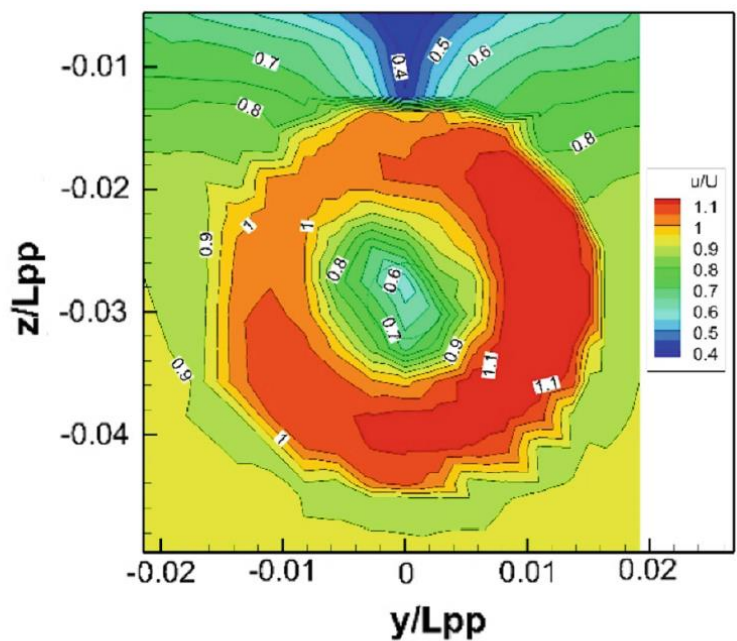
4. Results and discussions

- Validation in Q1
 - Double-body hull-propeller interaction
 - Propeller rate set to the experimental value^[1]
 - $n = 9.5 \text{ rps} = 570 \text{ rpm}$

	CFD		EFD		Error	
$C_{T,DB}(-)$	$KT(-)$	$10K_Q(-)$	$KT(-)$	$10K_Q(-)$	$KT(-)$	$10K_Q(-)$
3.566×10^{-3}	0.177	0.369	0.170	0.288	3.91%	28.09%



(a) CFD



(b) EFD, NMRI (Hino et al. 2021)

[1] Hino, Takanori, Frederick Stern, Lars Larsson, Michel Visonneau, Nobuyuki Hirata, and Jin Kim, eds., 2021. Numerical Ship Hydrodynamics: An Assessment of the Tokyo 2015 Workshop.

4. Results and discussions

- Vortex structures in four quadrants

- Q1

- Velocity acceleration

- Q2

- Chaotic vortices

- Dominant flow shifts

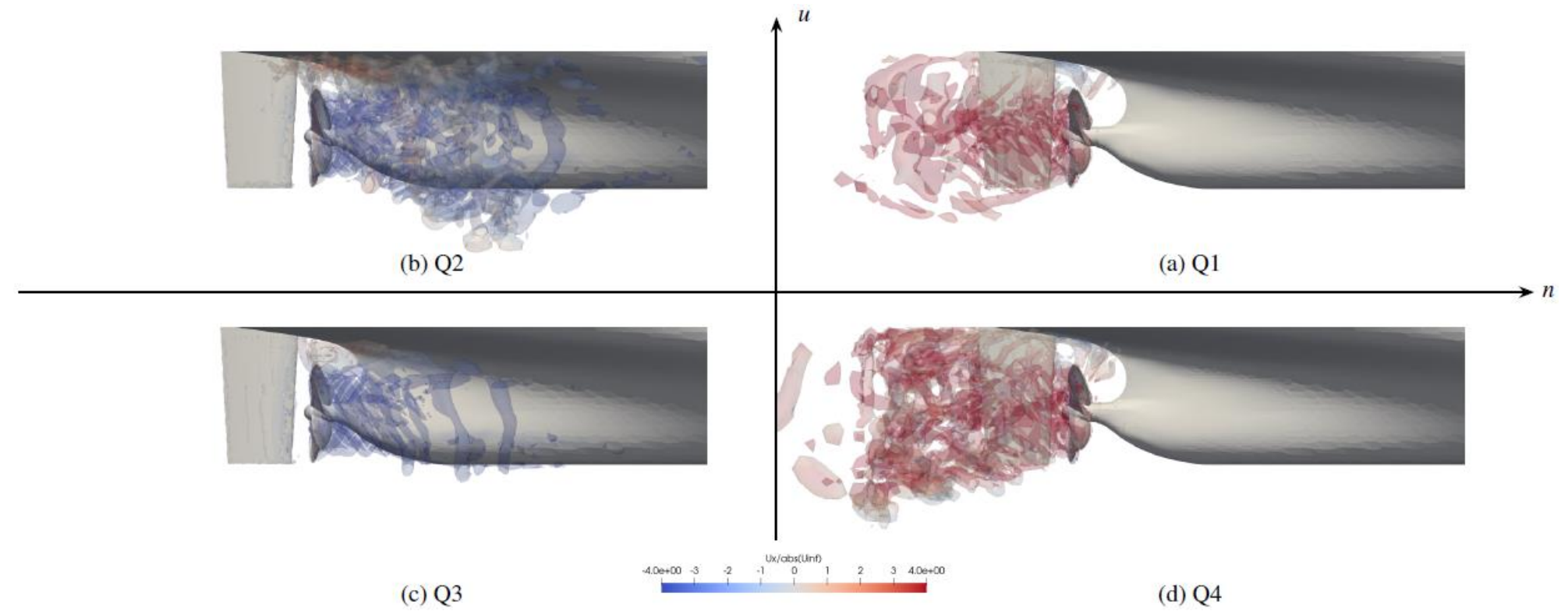
- Q3

- Reverse acceleration

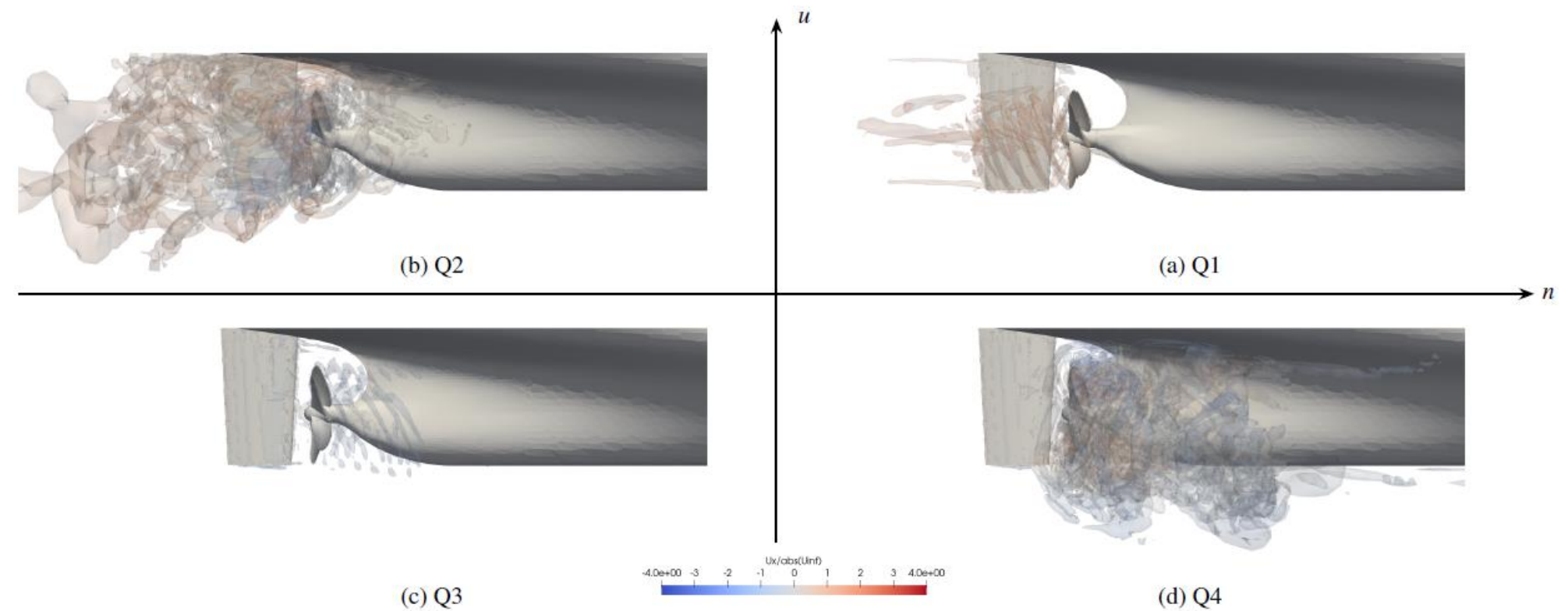
- Rudder positioned in astern flow

- Q4

- Similar dominant flow shift as Q2



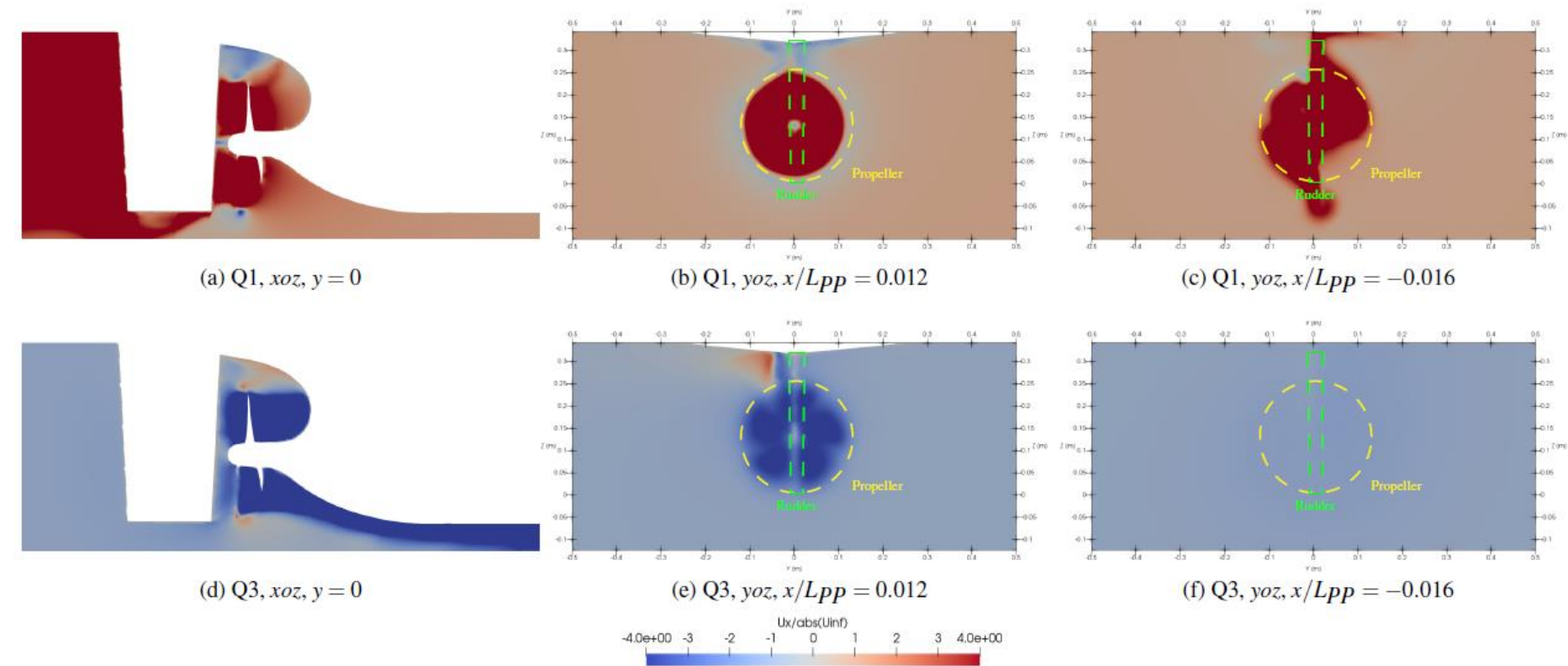
$$|Fr| = 0.028, |n| = 9.5 \text{ rps}, Q' = 4$$



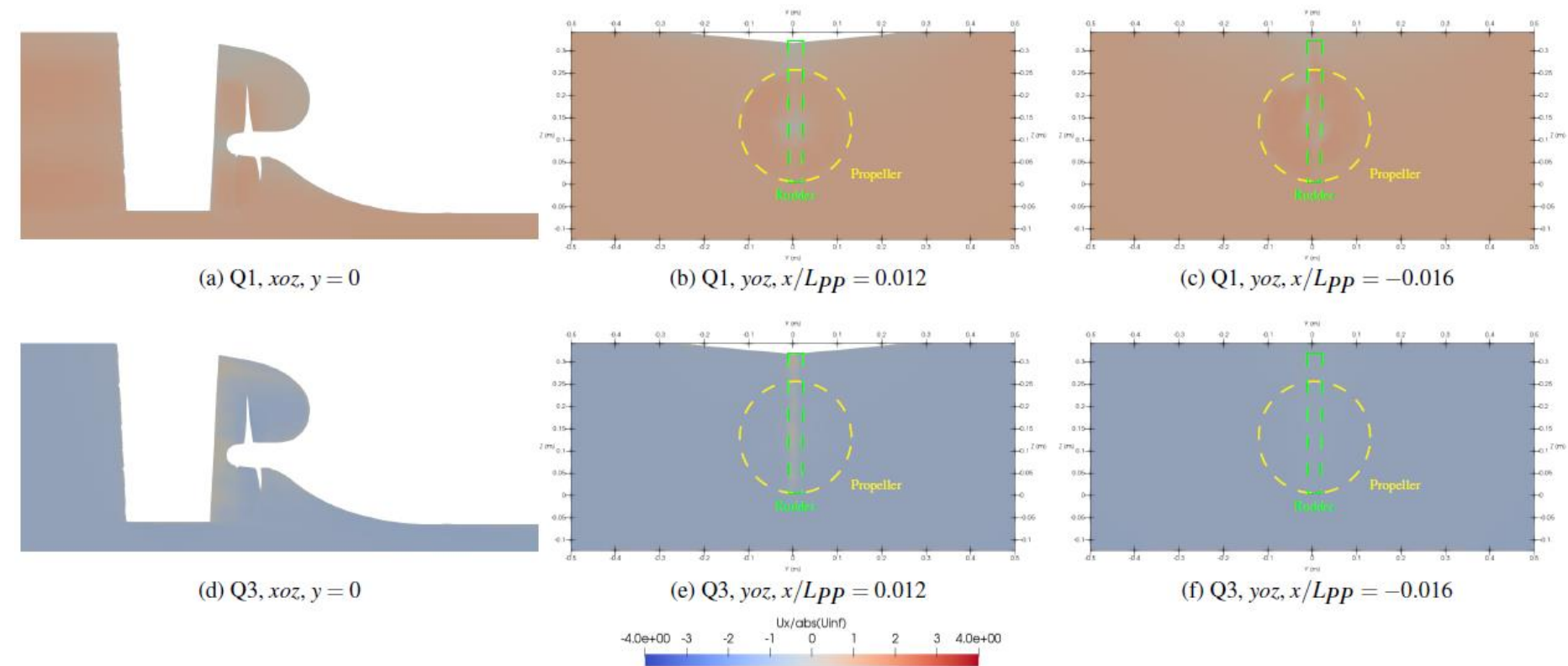
$$|Fr| = 0.26, |n| = 9.5 \text{ rps}, Q' = 4$$

4. Results and discussions

- Axial velocity
 - Q1
 - Accelerated upstream inflow to rudder
 - Q3
 - Flow accelerated towards hull
 - Most rudder area not in propeller jet



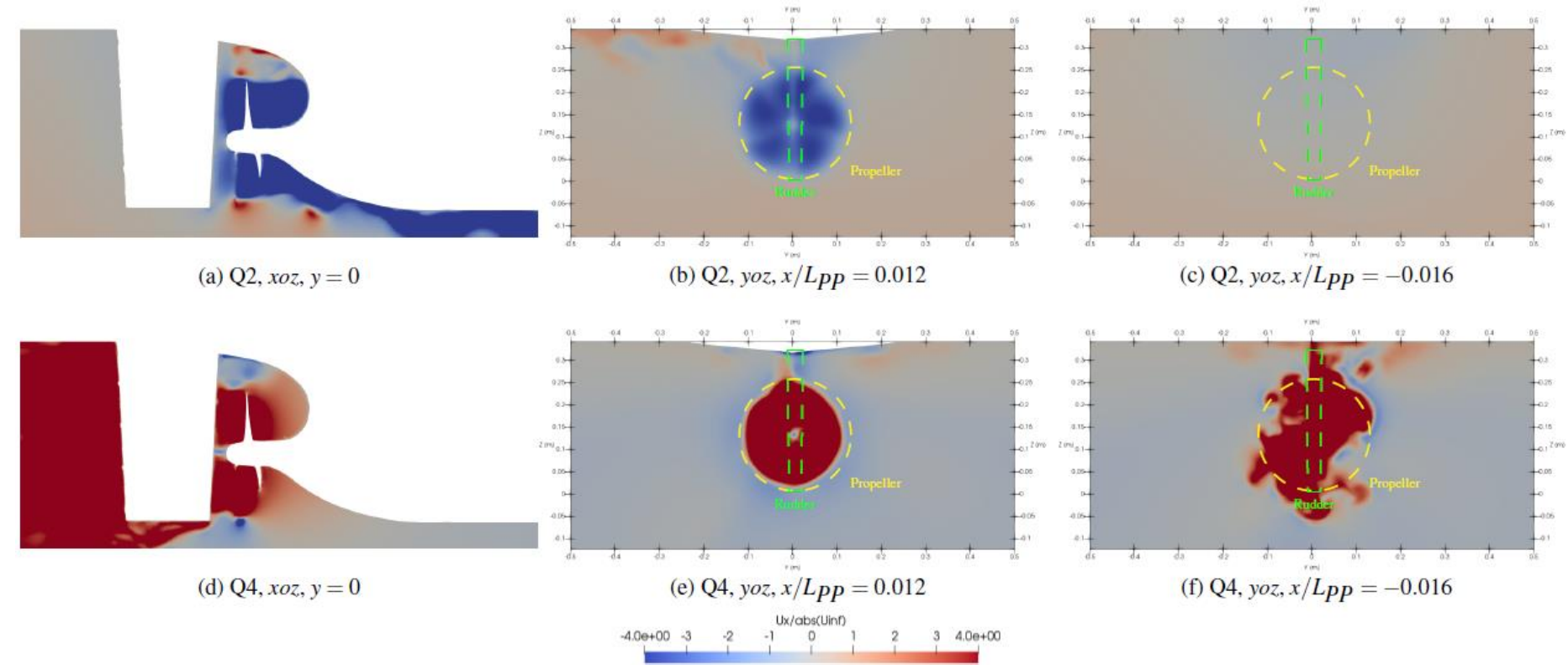
$$|Fr| = 0.028$$



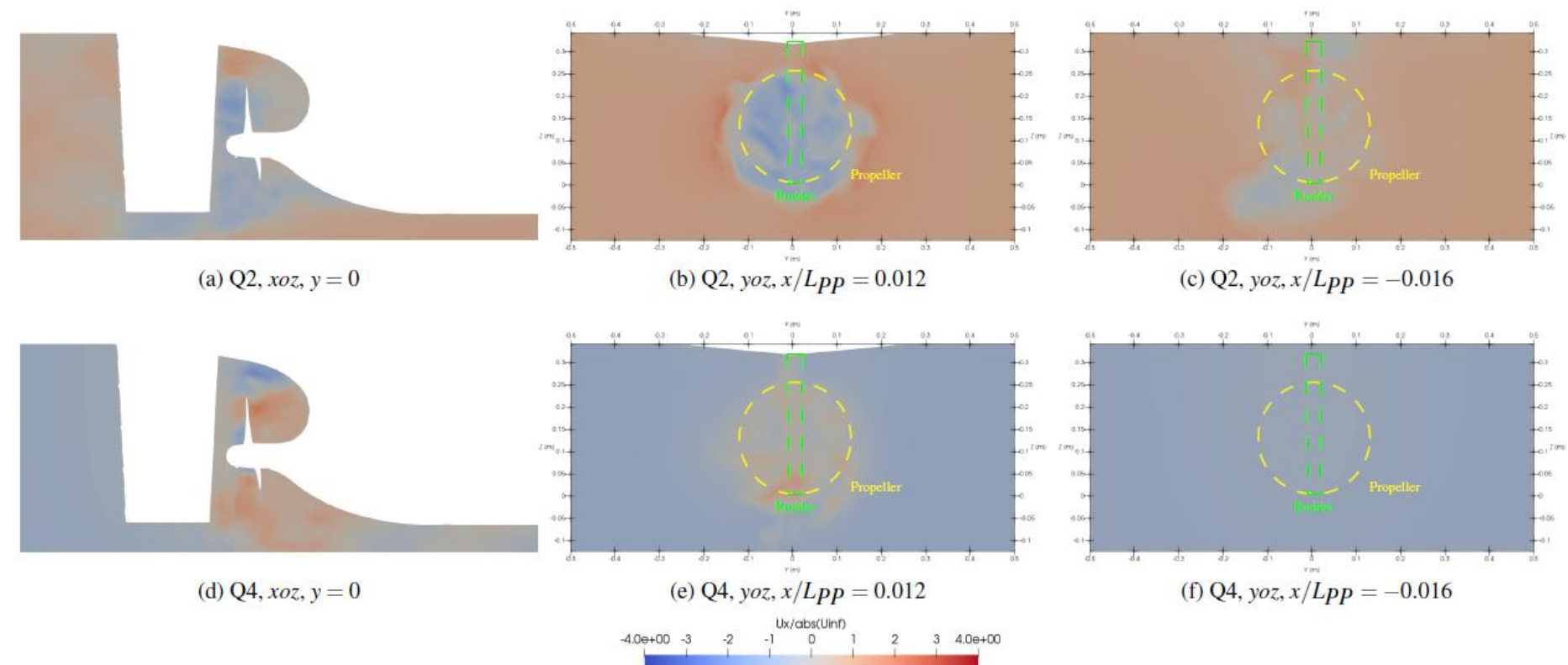
$$|Fr| = 0.26$$

4. Results and discussions

- Axial velocity
 - Overall rudder inflow direction changes with dominant flow
 - Q2
 - Larger hull wake impact on rudder for high velocity
 - Q4
 - Larger propeller jet impact on rudder for low velocity



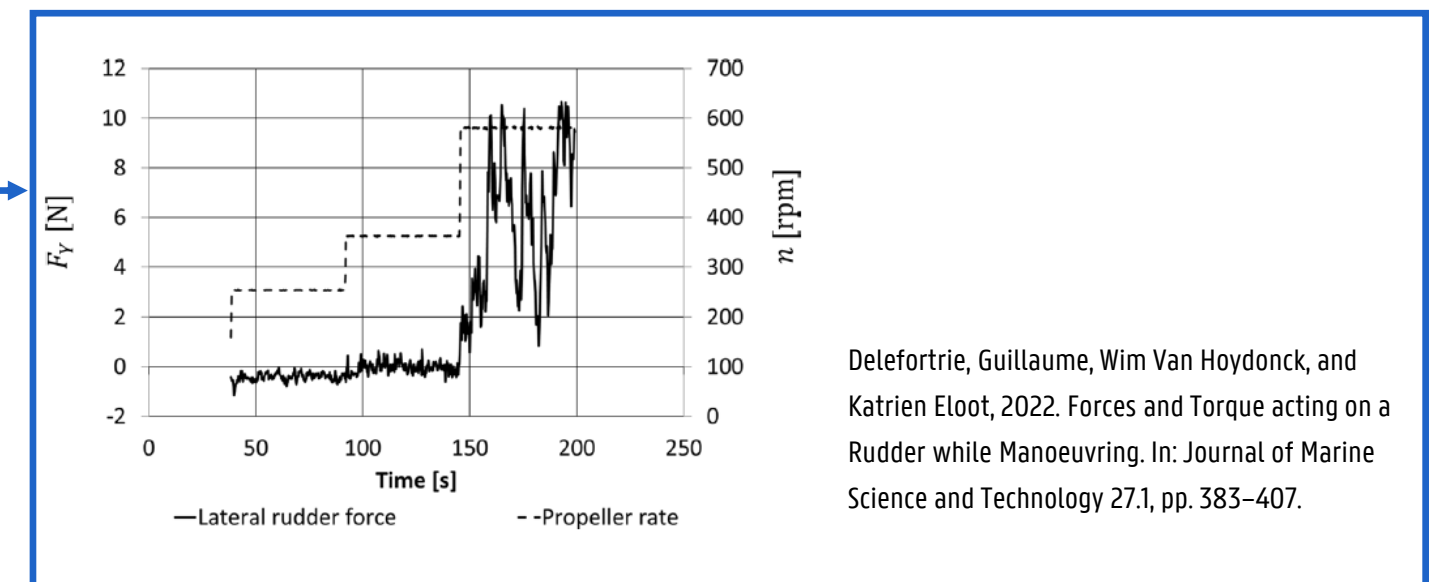
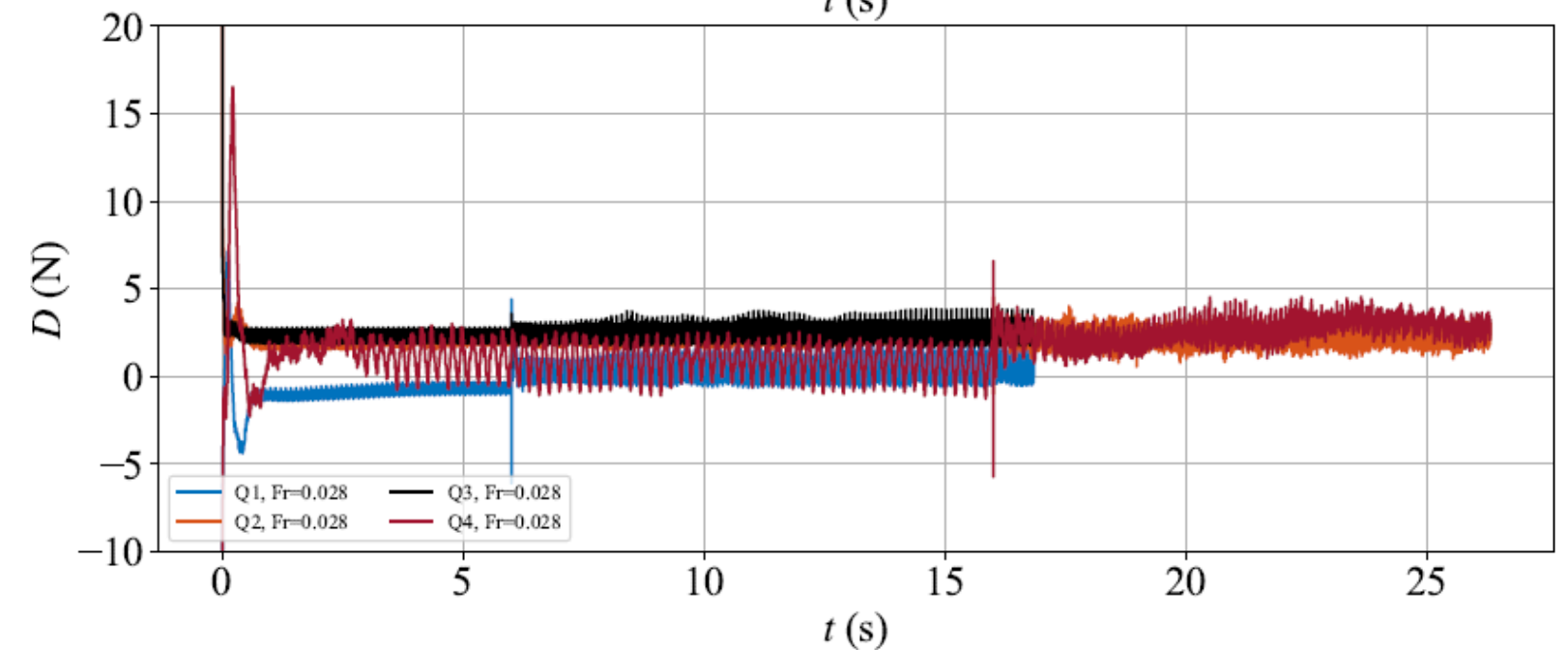
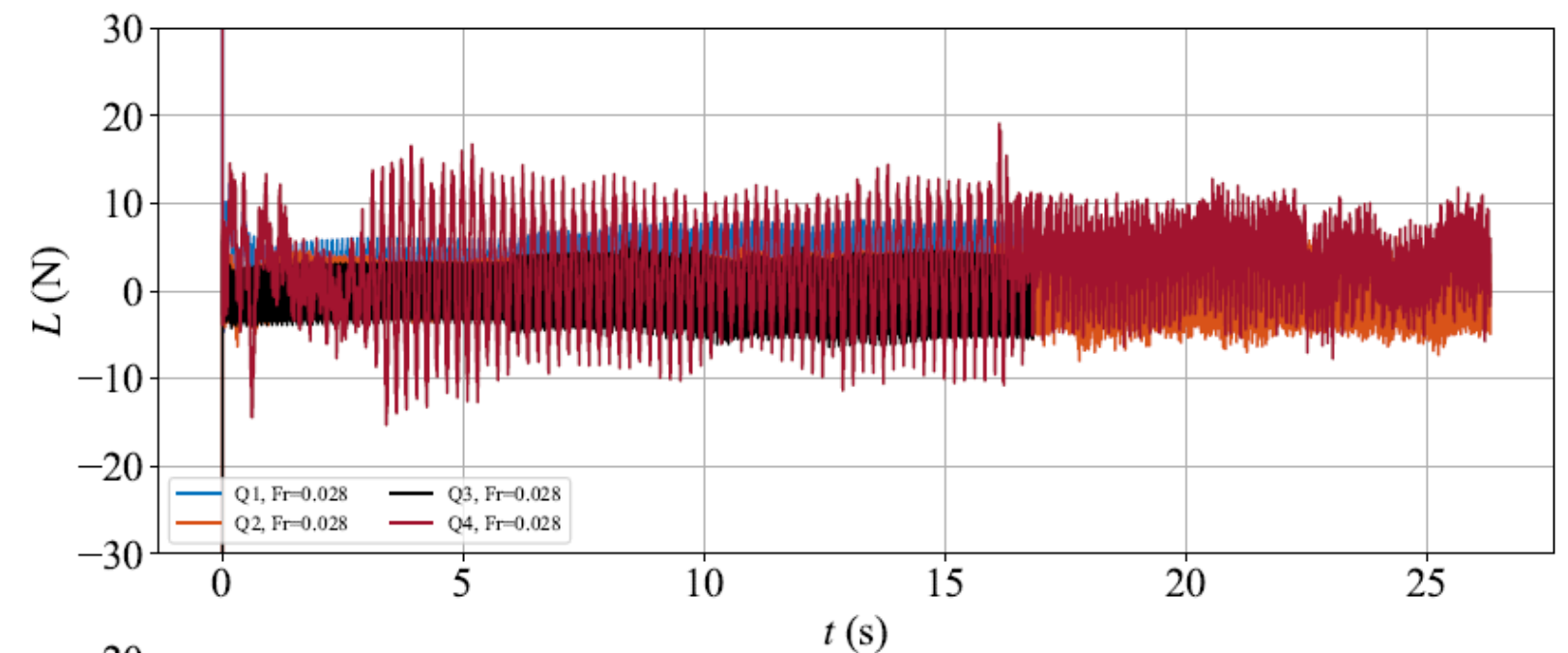
$$|Fr| = 0.028$$



$$|Fr| = 0.26$$

4. Results and discussions

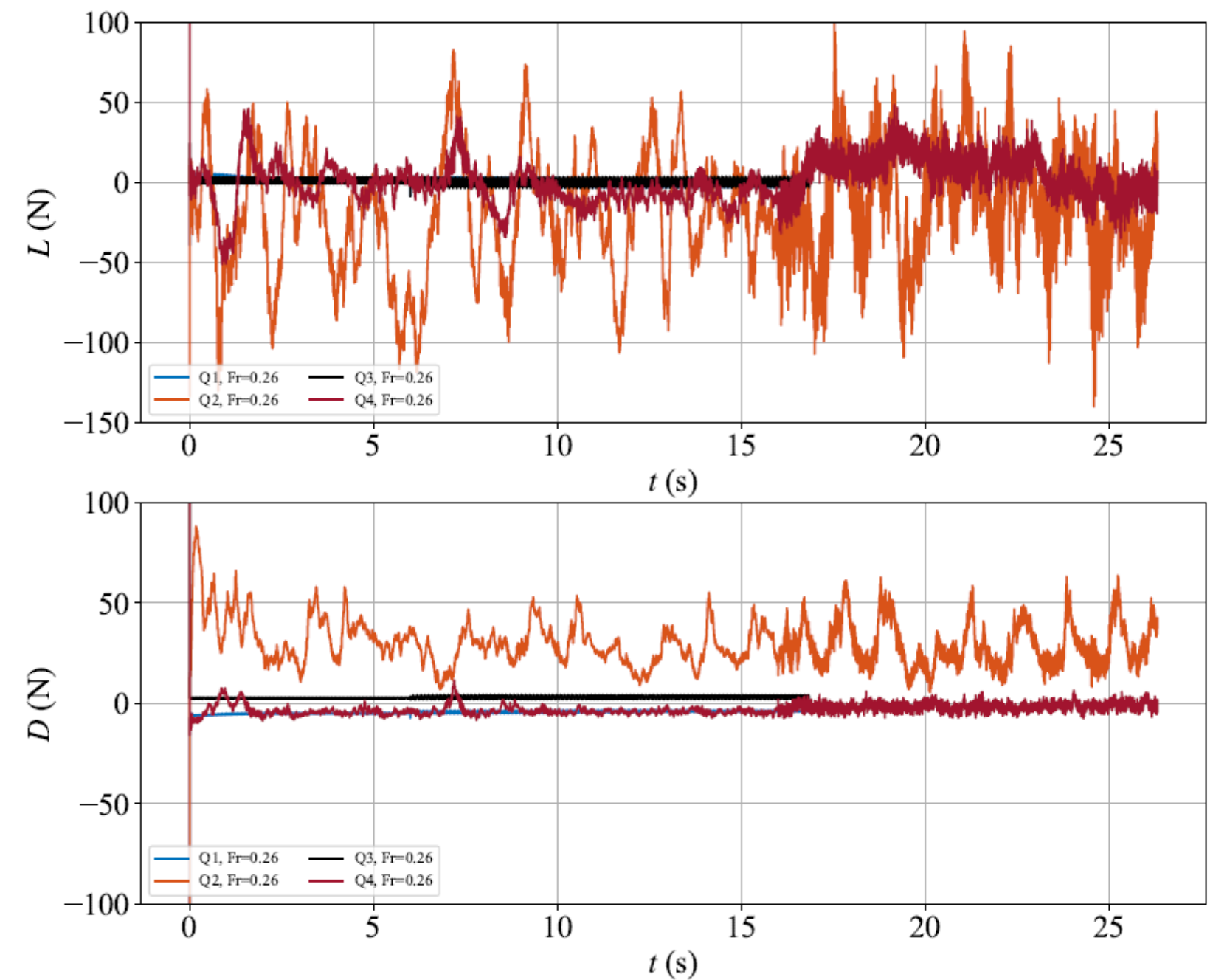
- Time history of rudder force
 - $|Fr| = 0.028, \delta = 0^\circ$
 - Q1
 - Positive drag due to strong swirl components
 - Q2
 - Higher positive drag than Q1 because of the propeller jet acceleration
 - Q3
 - Lift close to 0
 - Drag direction the same as astern inflow
 - Q4
 - Large lift oscillation which coincides with the model test of another ship



Delefortrie, Guillaume, Wim Van Hoydonck, and Katrien Eloot, 2022. Forces and Torque acting on a Rudder while Manoeuvring. In: Journal of Marine Science and Technology 27.1, pp. 383–407.

4. Results and discussions

- Time history of rudder force
 - $|Fr| = 0.26, \delta = 0^\circ$
 - Q1
 - Averaged lift closer to 0 than low velocity case
 - Q2
 - More severe fluctuations of lift and drag
 - Q3
 - Rudder positioned in astern flow and lift close to 0
 - Q4
 - More stable time histories than Q2 since the uniform inflow dominant



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5. Conclusions

- As the uniform inflow and the propeller jet
 - Along the same direction
 - Rudder inflow
 - Q1
 - Accelerated inflow to the rudder
 - More significant acceleration under heavy loading
 - Q3
 - Propeller jet evolves towards hull
 - Rudder force
 - Small-scale oscillations, indicating relatively stable inflow conditions

5. Conclusions

- As the uniform inflow and the propeller jet
 - Along opposite directions
 - Rudder inflow
 - Q2 and Q4
 - The dominant flow can switch
 - Unstable vortex structures
 - Rudder force
 - More oscillations than Q1 and Q3
 - the lateral force oscillations are more significant for
 - The inflow-dominant case in Q2
 - The jet-dominant condition in Q4

Thank you for your listening!

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