KCS Wave Breaking

Background

Wave breaking commonly occurs in the bow and stern areas of a ship at sea and involves complex two-phase flow and unsteady hydrodynamic phenomena, which is challenging for both CFD simulations and physical understanding.

Several cases, such as DTMB 5415 and R/V Athena I, have been previously used for wave breaking studies and CFD validation. Olivieri et al. (2007) measured near- and far-field mean and RMS wave elevation and mean velocity under the breaking waves for the DTMB 5415, focusing on the bow and shoulder wave breaking. The results show a direct correlation between the regions with wave slopes greater than 17 degrees and the areas with large RMS variation in wave elevation. The R/V Athena I is a 50.3 m coastal patrol-boat built in 1969 and was converted to a research vessel in 1976. Model-scale mean elevations around the hull of R/V Athena I were measured by combining quantitative visualization (QViz) and finger probes in NSWCCD (Wilson et al, 2006). Fu et al. (2004, 2006) performed full-scale bow and stern wave measurement on the R/V Athena I using a laser-sheet visualization technique.

Unlike the previous investigations on DTMB 5415, which show quasi-steady bow plunger and spilling shoulder waves, more violent plunging type bow breaking waves were observed for the KRISO Container Ship (KCS) in the study by Wang et al. (2020) as part of the early investigations in the present study. The KCS wave breaking test case was designed to provide unsteady free surface validation data for high Froude number conditions. Moreover, when the ship is trimmed by the bow, the bow wave breaks more violently. Therefore, the KCS model with a 1° trim angle by bow was chosen for the EFD and CFD investigations. China Ship Scientific Research Center (CSSRC) has performed photo studies and flow field tests on the KCS at a high Froude number of 0.35. Forces, wave elevations, and velocities beneath the breaking surface were measured in the deep-water towing tank (Liu, et al. 2022). Both the mean and RMS wave elevations were available for the validation of the unsteady features of wave breaking.

References

[1] Fu, T. C., Karion, A., Rice, J. R., and Walker, D. C., "Experimental Study of the Bow Wave of the R/V Athena I", 25th Symposium on Naval Hydrodynamics, St. John's, Newfoundland and Labrador, Canada, 2004.

[2] Fu, T.C. and Fullerton, "Measurements of the Wave Field around the R/V Athena I", 26th Symposium on Naval Hydrodynamics, Rome, Italy, 2006.

[3] Liu, W., Wang, W., Qiu G., Wan D, Wang J., Wang, Z., and Stern, F., "KCS Unsteady Bow Wave Breaking Experiments for Physics and CFD Validation", 34th Symposium on Naval Hydrodynamics, Washington, D.C., June 2022.

[4] Olivieri, A., Pistani, F., Wilson, R., Campana, E., and Stern, F., Scars and Vortices Induced by Ship Bow Wave Breaking, *ASME J. Fluids Eng*, Vol. 129, Issue 11, pp. 1445–1459, November 2007.

[5] Wang, W., Qiu G., Wang J., and Wan D., "Experimental and Computational Investigations on KCS Wave Breaking with Trim and Sinkage Variation", Fourteenth ISOPE Pacific-Asia Offshore Mechanics Symposium, Dalian, China, pp.434–440, Nov. 2020.

[6] Wilson, R., Carrica, P. and Stern, F., URANS Simulations for High-Speed Transom-Stern Ship with Breaking Waves, *International Journal of CFD*, Vol. 20, No. 2, pp. 105–125, February 2006.

[7] Wilson, R.V., P.M. Carrica and F. Stern, Simulation of Ship Breaking Bow Waves and Induced Vortices and Scars, *International Journal for Numerical Methods in Fluids*, Vol. 54, 2007. doi: 10.1002/fld.1406.

EFD Overview and Uncertainties

Description

The EFD data of the KCS wave breaking is provided by CSSRC, including forces and moments, mean and RMS wave elevations, mean velocities beneath the free surface, as well as typical test photos and videos. The experiments were conducted with a 1/37.89 scaled KCS model in the deep-water towing tank of CSSRC, which is 474 m long, 14 m wide, and 7 m deep. Cylindrical studs were fitted at x/L_{PP} = 0.05 for turbulence stimulation. For all the tests, the ship model was towed with a fixed trim and sinkage (ship scale: T_A = 8.8 m / T_F = 12.8 m).

The reference coordinates shown in Fig. 2 are used for the geometry definition and the layout of the results for model tests and CFD simulations. They are fixed to the hull with the origin located at the intersection of the forward perpendicular and the undisturbed water plane. The X, Y, and Z axes are oriented in the directions of downstream, the starboard side of the hull, and upward, respectively.

The geometry file for the KCS model that has been converted to the test conditions and coordinate system, i.e., scaled to 1/37.89 and trimmed to 1° (with a precise value of 0.99635°) by the bow, is provided in the attachment. An overview of the KCS model for simulation is shown in Fig.1. The main particulars of the ship and model are given in Table 1.

For both experiments and CFD simulations, the center of gravity of the model should be set to the coordinates [2962.56 mm, 0 mm, 92.90 mm], i.e. [0.48805 L_{PP}, 0 L_{PP}, 0.01530 L_{PP}].

Table 1: Main particulars

Parameters	Symbol	Ship	Model
Scale factor	λ	1	37.89
Length between perpendiculars	L_{PP} (m)	230.0	6.0702
Length on waterline	L_{WL} (m)	224.616	5.9281
Breadth, moulded	B (m)	32.20	0.8498
Draught (F.P.)	T_F (m)	12.80	0.3378
Draught (Midship)	T_M (m)	10.80	0.2850
Draught (A.P.)	T_A (m)	8.80	0.2323
Displacement volume (w/o rudder)	∇ (m^3)	51071.1	0.9389
Displacement volume (with rudder)	∇ (m^3)	51101.3	0.9394
Wetted surface area (w/o rudder)	S (m^3)	9250.2	6.4432
Wetted surface area (with rudder)	S (m^3)	9246.3	6.4405

Fig.1: KCS model

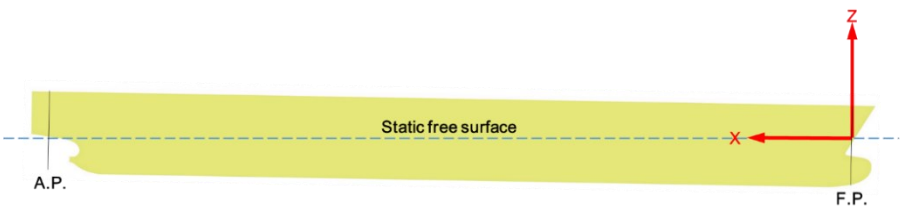


Fig. 2. Reference coordinate system

EFD results and uncertainties

The resistance, heave force, and pitch moment were measured with a 6-component load cell. The centers of gravity of the models were adjusted to the reference value of [2962.56 mm, 0 mm, 92.90 mm] to match the center of the load cell to ensure that the measured forces and moments are located at the center of gravity. The resistances and heave forces are positive in the X-axis and Z-axis directions, respectively, and the pitch moments are defined as positive according to the right-hand rule around the Y-axis. Uncertainties of the forces and moments were evaluated based on 9 repeated runs.

Table 2: Resistance, heave force, and pitch moment

Fr		$1000C_T$(-)	$1000C_L$(-)	$1000C_{MY}$(-)
0.35	Value	5.716	346.773	1.154
	$U(k=2)$	0.84%	0.25%	2.94%

The wave elevations were obtained through pointwise measurements of the free-surface elevation on a grid extending from the bow to about amidships. The time histories of wave elevation for more than 2000 points at the vertices of the regular grid shown in Fig.3 were collected. The transverse distance between the measurement points and the centerline plane extended from roughly 0.06 L_{PP} to 0.20 L_{PP}. The longitudinal and transverse spacings of each grid unit are Δx =41.7 mm (ab. 0.007 L_{PP}) and Δy =27.8 mm (ab. 0.004 L_{PP}), respectively. The wave elevations were measured by three servo-type wave probes with a sampling rate of 1000 Hz.

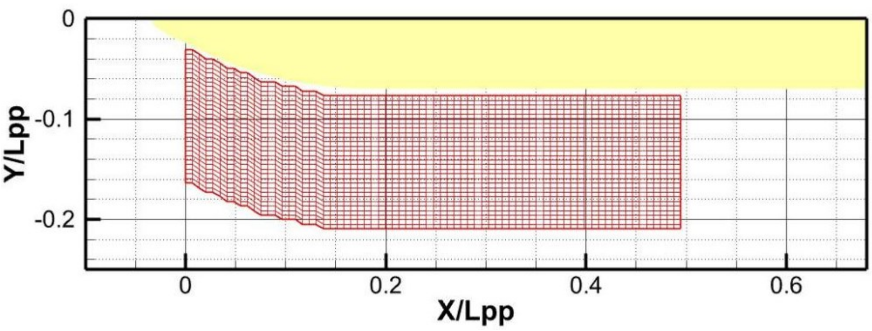


Fig. 3: Wave elevation measurement grids

Fig. 4: Photo of the KCS wave breaking

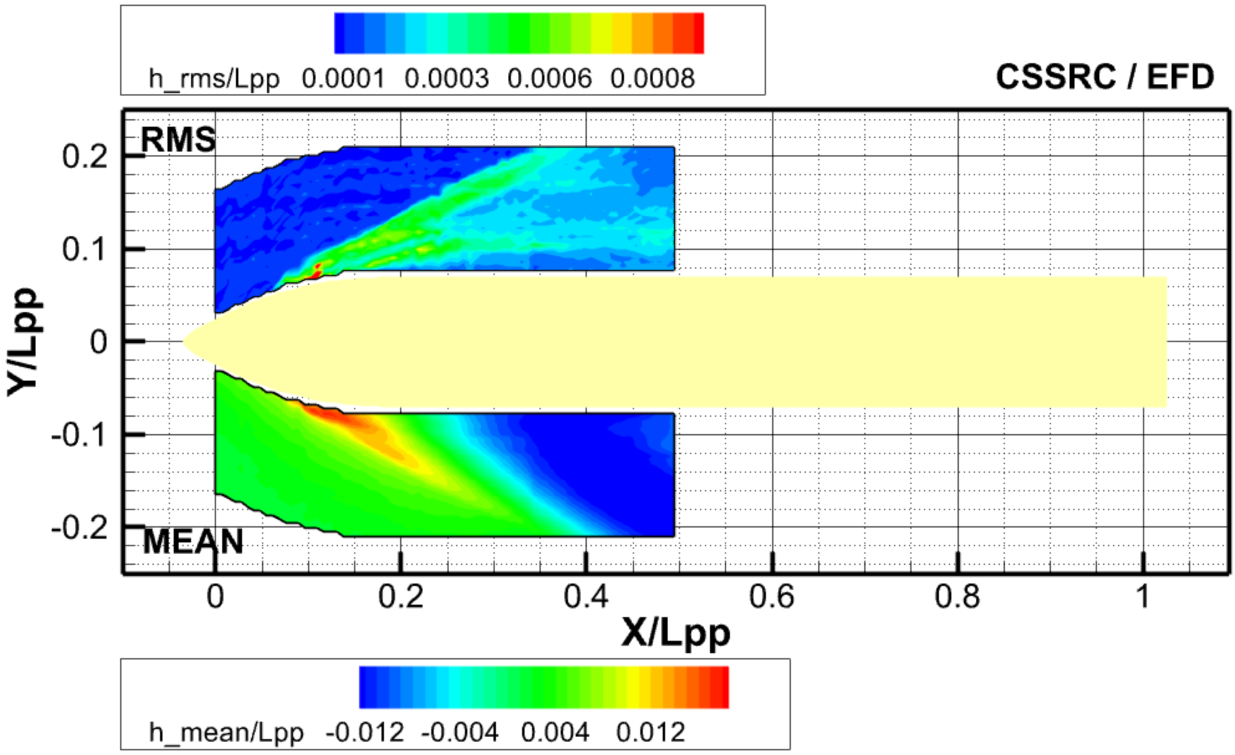


Fig. 5: Measured mean and RMS wave elevations

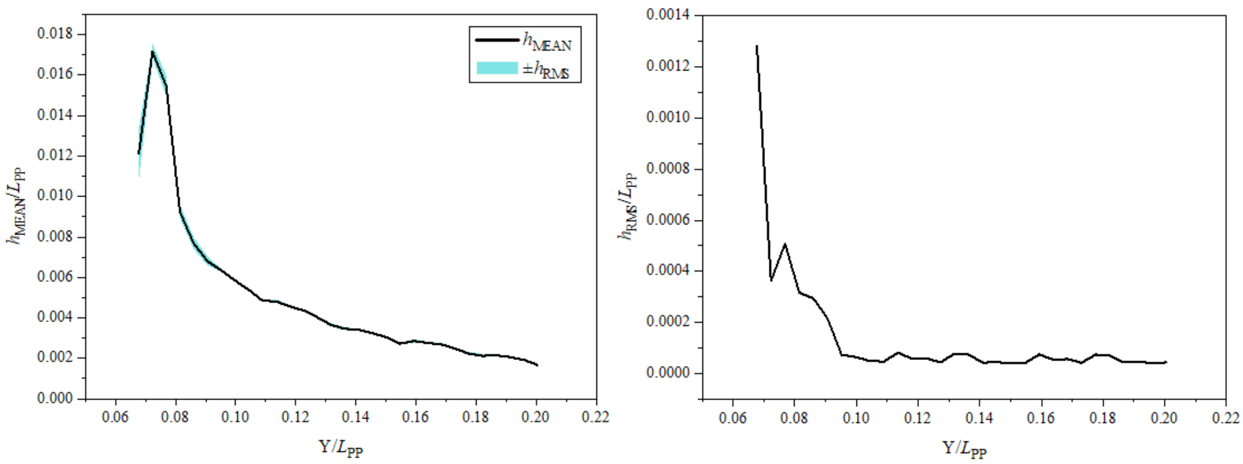


Fig. 6. Measured mean and RMS wave elevations (x/L_{PP} = 0.103)

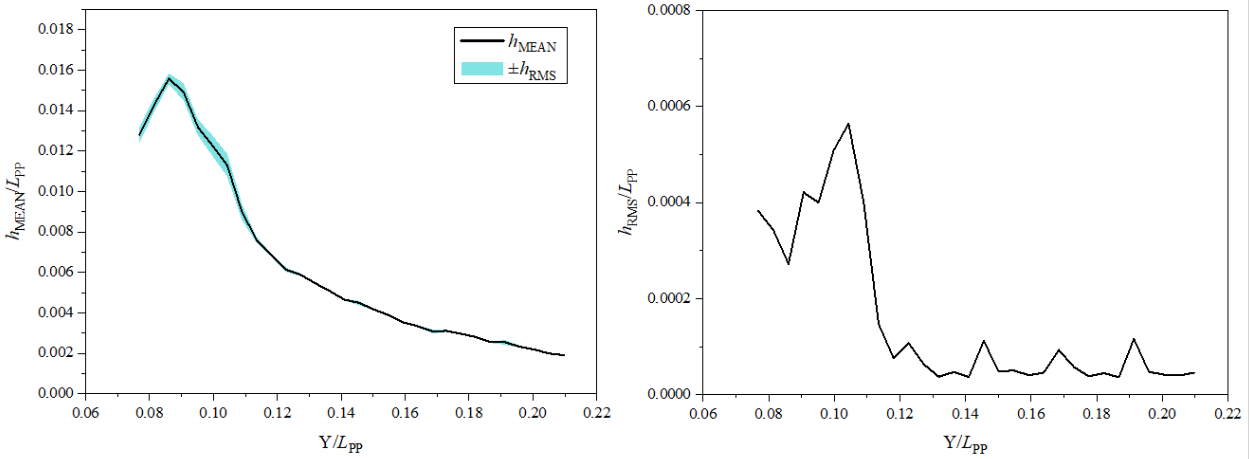


Fig. 7. Measured mean and RMS wave elevations (x/L_{PP} = 0.151)

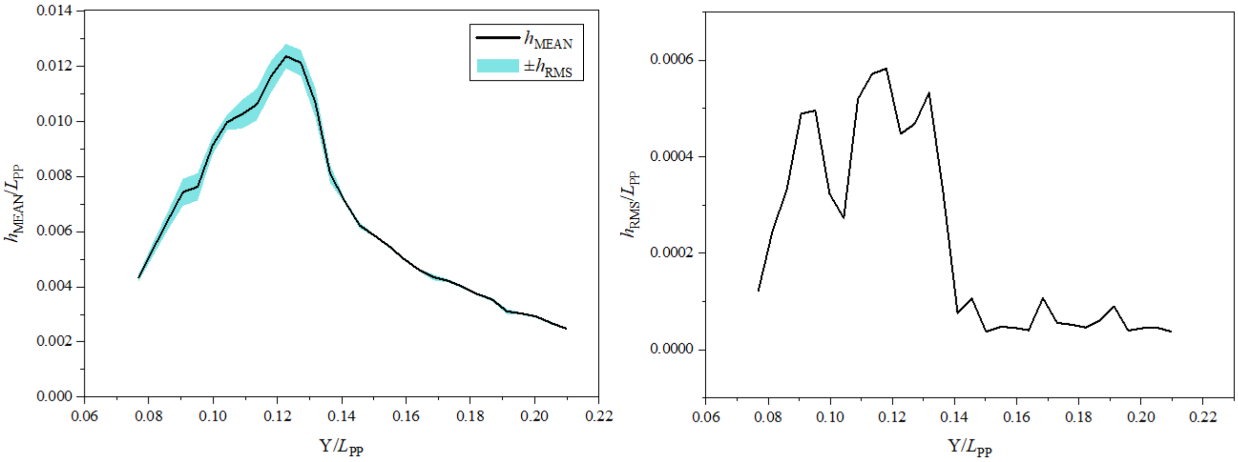


Fig. 8. Measured mean and RMS wave elevations (x/L_{PP} = 0.199)

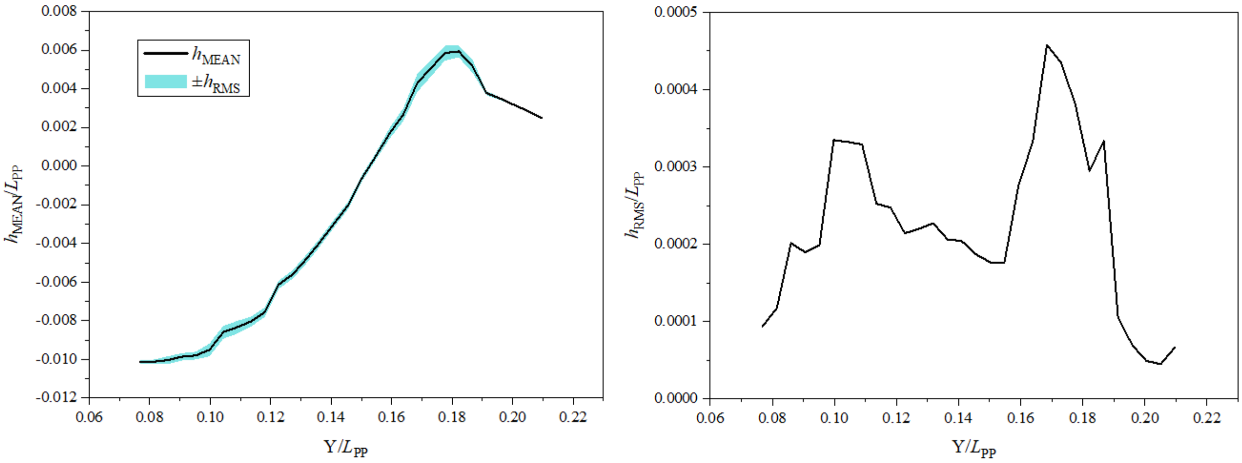


Fig. 9. Measured mean and RMS wave elevations (x/L_{PP} = 0.302)

The velocity field was measured with a five-hole pitot probe on the starboard side of the model at the locations of $x = 0.15L_{PP}$, $0.2L_{PP}$, and $0.3L_{PP}$. The X-axis is positive outward from the plane of the figures. The negative and positive vorticities are corresponding to clockwise and counterclockwise rotations, respectively.

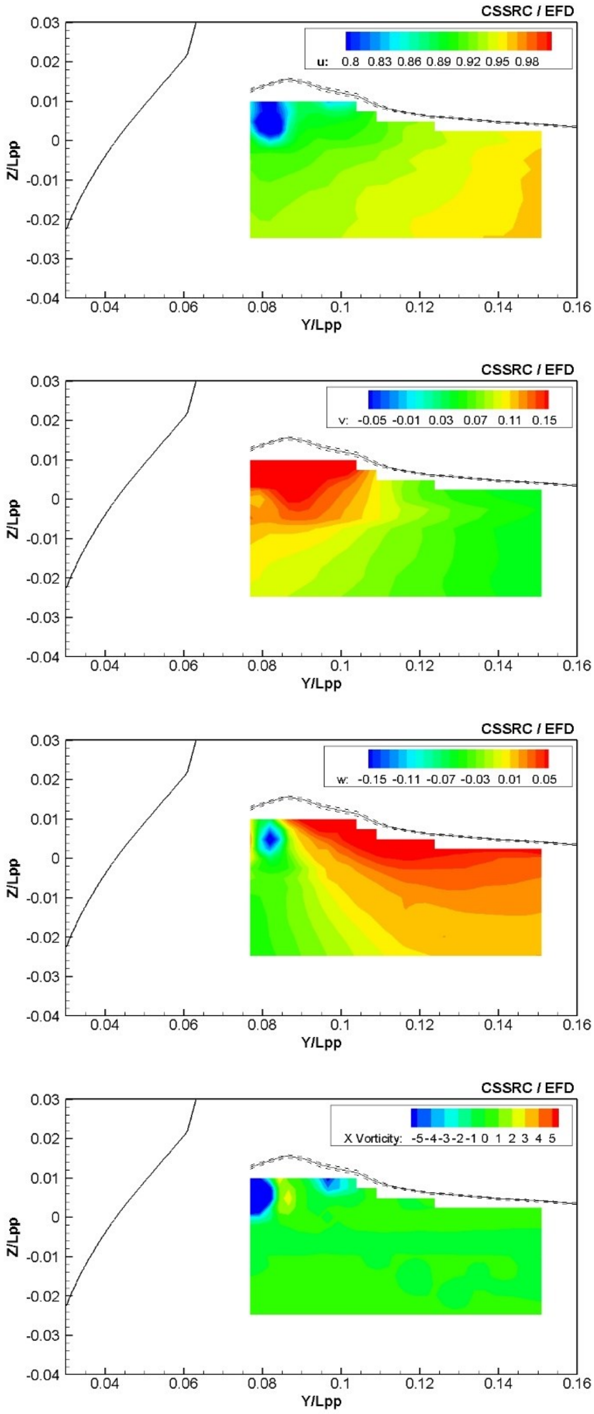


Fig. 10. Experimental results for velocities and axial vorticities at X/L_{PP}=0.151 (Measured mean wave elevation transverse cuts: solid lines, +/− rms: dashed line)

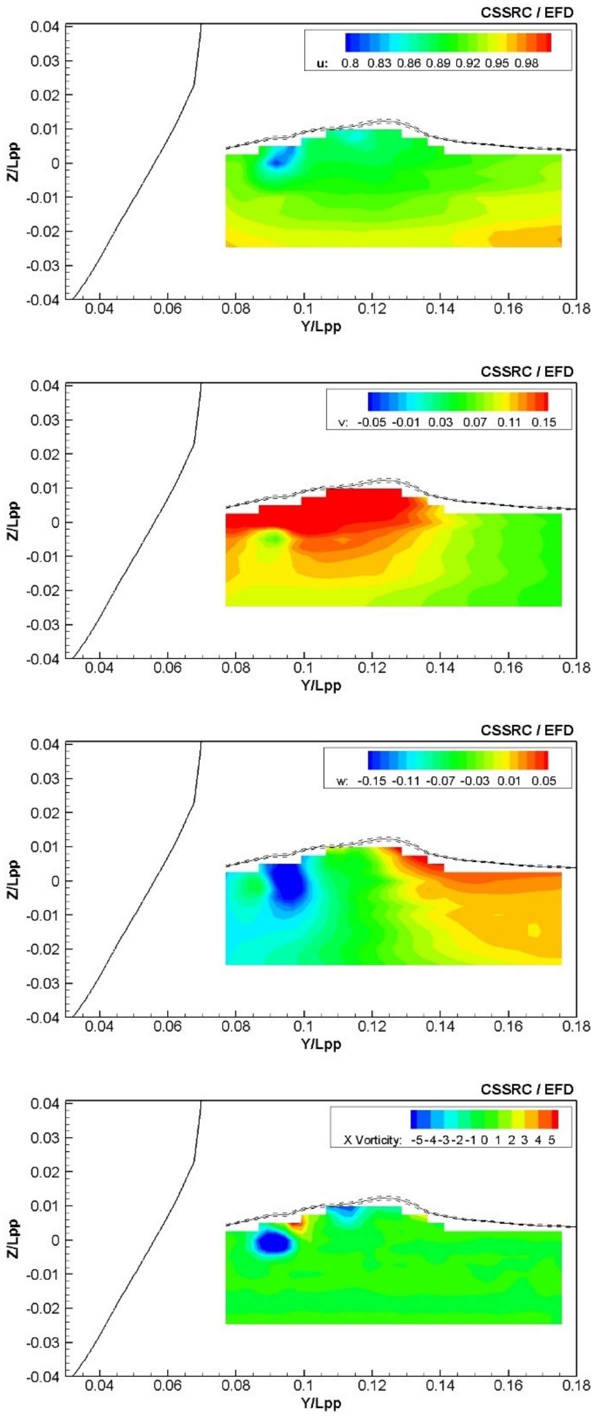


Fig. 11. Experimental results for velocities and axial vorticities at X/L_{PP}=0.199 (Measured mean wave elevation transverse cuts: solid lines, +/− rms: dashed line)

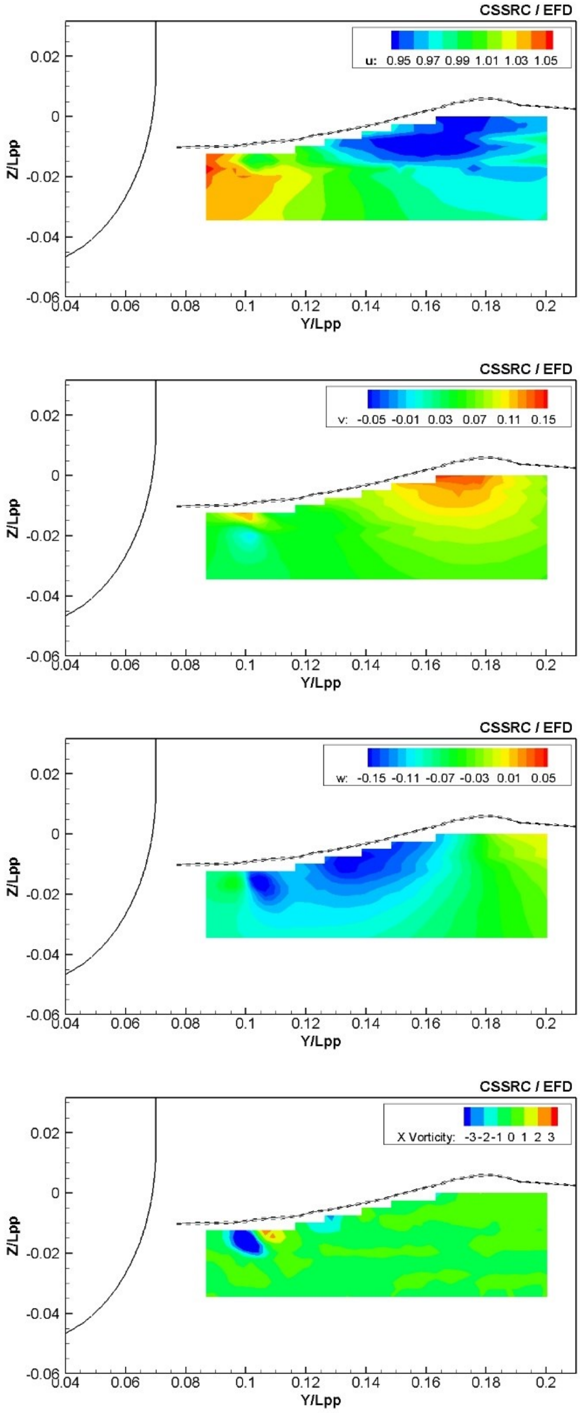


Fig. 12. Experimental results for velocities and axial vorticities at X/L_{PP}=0.302 (Measured mean wave elevation transverse cuts: solid lines, +/− rms: dashed line)

Validation Variables and Procedures

Resistance, heave force, and pitch moment.

- Time averaged non-dimensionalized resistance, heave force, and pitch moment will be compared to the EFD data.
- The complete time histories of the computed forces and moments are needed for low-frequency oscillation analysis.
- The moments need to be defined around the center of gravity.
- The resistances and heave forces are positive in the X-axis and Z-axis directions, respectively, and the pitch moments are defined as positive according to the right-hand rule around the Y-axis.
- The *Fr* and *Re* numbers need to be calculated using water density (ρ), ship speed (U_0), and length between perpendiculars (L_{PP}):

  $$Fr = \frac{U_0}{\sqrt{g \cdot L_{PP}}}, \qquad Re = \frac{U_0 \cdot L_{PP}}{\upsilon}$$

  where ***g*** is the gravitational acceleration and ***v*** is the kinematic viscosity.

- The total resistance coefficient C_{TM}, heave force coefficient C_L, and pitch moment coefficient C_{MY} need to be non-dimensionalized as following.

  $$C_T = \frac{R_T}{\frac{1}{2}\rho {U_0}^2 S}, \; C_L = \frac{F_Z}{\frac{1}{2}\rho {U_0}^2 S}, \; C_{MY} = \frac{M_Y}{\frac{1}{2}\rho {U_0}^2 S L_{PP}}$$

Mean and RMS wave elevation contours.

- The x, y coordinates and wave elevations need to be non-dimensionalized by the model length between perpendiculars L_{PP}.
- Mean and RMS values of wave elevation at a specific point are calculated as follows,

  $$h_{MEAN} = \frac{\sum_{i=1}^{n} h_i}{\mathrm{n}}, \; h_{RMS} = \sqrt{\frac{\sum_{i=1}^{n} (h_i - h_{MEAN})^2}{\mathrm{n}}}$$

  where h_i is the time series of wave elevation data and *n* is the total sampling number. Here, the RMS value of wave elevations is defined as the RMS of the wave fluctuations rather than the RMS of wave elevation time histories.

- The wave elevations need to be exported once the calculations have sufficiently converged, and it is recommended to monitor the wave calculations at typical locations on the free surface to ensure that the free surface is sufficiently stable.
- Both mean and RMS wave elevations need to be calculated on a fixed 2D grid. The reference approach is that the wave elevations are first extracted from the 3D solution files and then projected to a 2D Cartesian grid in the x - y plane. The wave elevations in terms of the z coordinates of the interface are interpolated to the 2D grid, and the mean and RMS are computed using the same method as the experiment.
- The presence of air cavities and water droplets in the breaking wave region introduces multiple air-water interface issues, which significantly affect the statistical values of wave elevations obtained at different interfaces, particularly the RMS values. Therefore, two methods for extracting the wave elevations from the top and bottom free surfaces are given below.

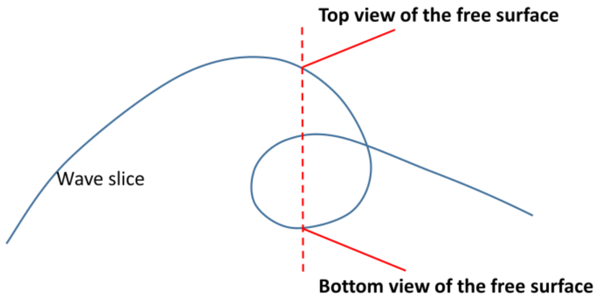


Fig. 13. Top and bottom wave elevation extraction method

- Previous studies have shown a low-frequency oscillation with a period of roughly 7s for forces and wave elevations in both EFD and CFD (shown in Fig.14), which can have a significant effect on the calculated RMS values. Therefore, the wave elevation data should be computed at least for two full cycles (with a total duration of no less than 14s).

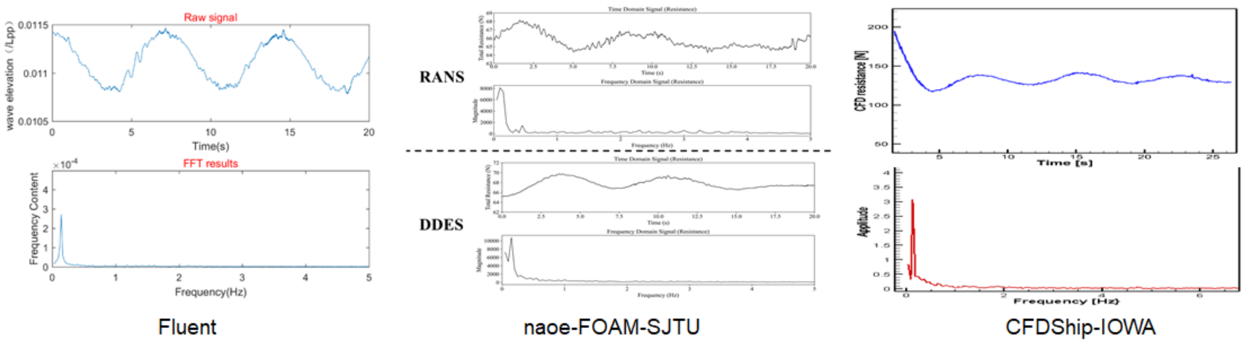


Fig. 14. Similar low-frequency oscillation of resistance from different CFD codes

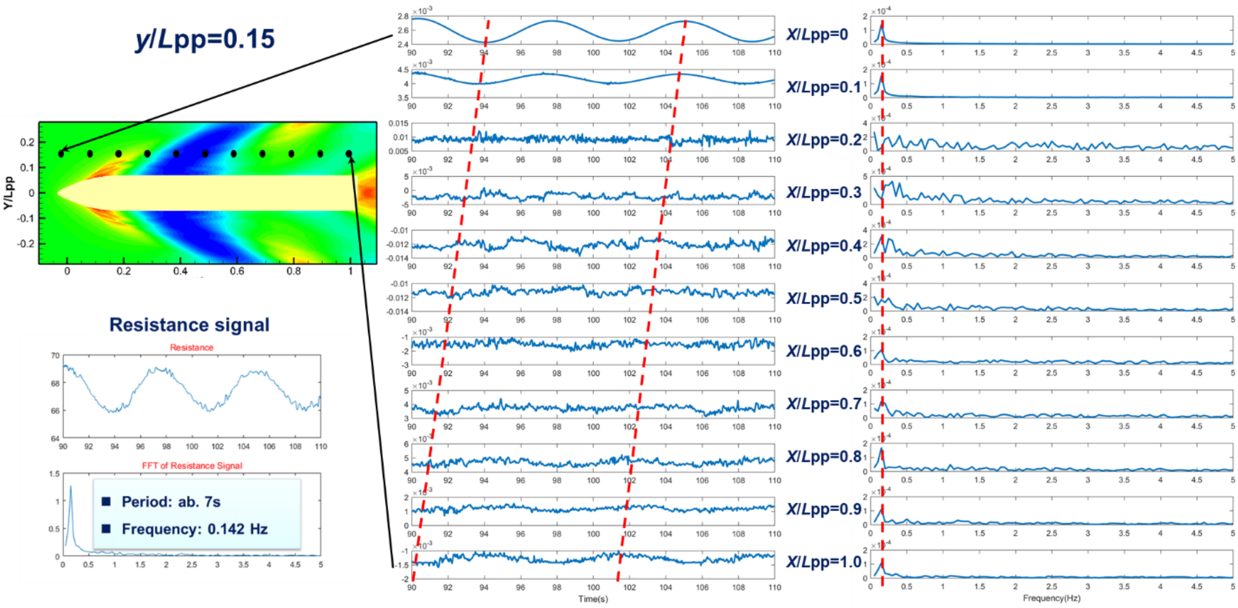


Fig. 15. Correlation between resistance and wave elevations at $y/L_{PP}=0.15$

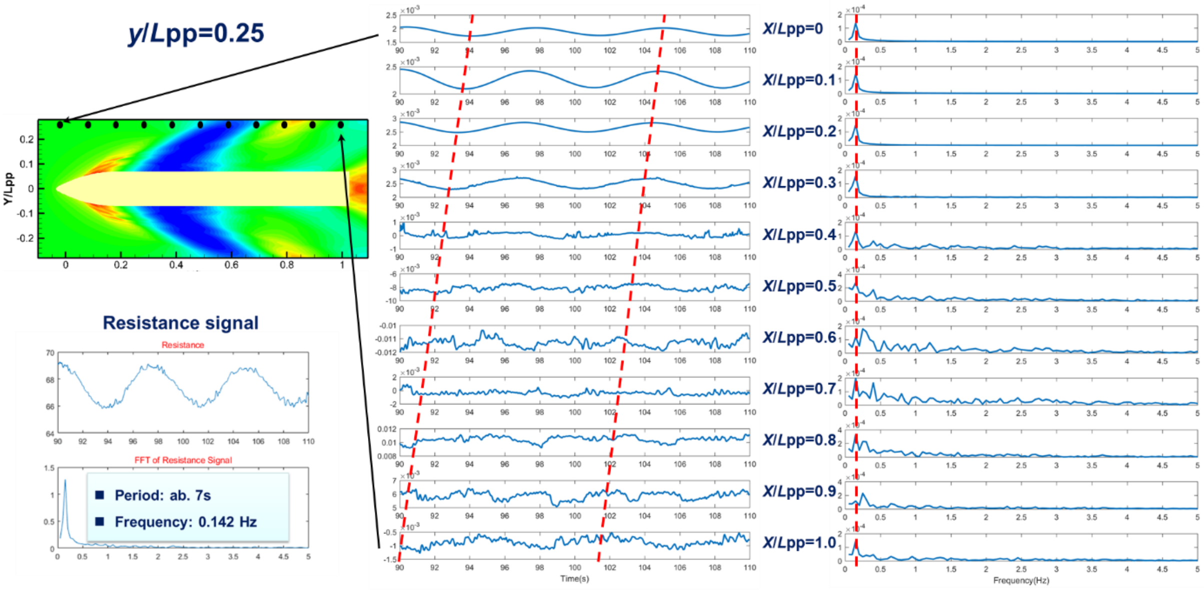


Fig. 16. Correlation between resistance and wave elevations at y/L_{PP}=0.25

Mean and RMS wave cuts, time histories.

- Mean and RMS wave cuts at x/LPP =0.103, 0.151, 0.199, 0.302 need to be provided
- Time histories of wave elevations at the following points in Table 3 need to be provided for frequency analysis and comparison.
- Similar to the wave contours, it is recommended to export both the top and bottom views of the wave cuts.

Table 3: Locations for time histories and the corresponding FFTs

Label	x/L_{PP}	y/L_{PP}
P1	0.103	0.0677
P2	0.103	0.0723
P3	0.103	0.0769
P4	0.103	0.0814
P5	0.103	0.0860
P6	0.103	0.0906

3D air tubes and vortical structures

- 3D perspective view of the air tubes
- Slice cuts at x/L_{PP} =0.065, 0.084, 0.103, and 0.124 with locations at wave crest, jet, and plunging point for wave breaking oscillations, FFT of wave elevation at these points.
- For the detailed method of vortical structure analysis, a guidance document is provided as attached.

Mean u, v, w, and axial vorticity

- *u*, *v*, *w* need to be made non-dim with the towing velocity *U*.
- *u*, *v*, *w* and axial vorticity are recommended to be calculated using time-averaged values, if not available, instantaneous values may be used instead.
- *u*, *v*, *w* and axial vorticity need to be exported at the starboard side of the model.

CFD Setup

- KCS model as provided in the IGES file (with a scale ratio of 37.89, has been rotated to the initial trim and converted to the reference coordinate system in Fig 2)
- Center of gravity for the ship model: [x/L_{PP}=-0.48805/L_{PP}=0, x/L_{PP}=-0.01530
- With rudder, without propeller
- Calm water condition
- Fixed to the initial sinkage and trim
- L_{PP}=6.0702m, Fr=0.35, V_M=2.700m/s
- g = 9.7946 m/s^2
- Water temperature = 15℃, water density = 999.1026kg/m^3, water viscosity = 1.1386×10^{-6} m^2/s
- All the variables should be exported from the same simulation with the same time-averaging window.

Submission Instructions and Format

The computed results should be put into folders 2.12-1~2.12-5 as shown in the example package, and the root folder should be named as [Institute Name]-[Solver Name]. For example, if your institute is CSSRC and solver is FLUENTv18.2, identifier should be CSSRC-FLUENTv18.2. Then the complete folder structure needs to be zipped for submission.

Resistance, heave force, and pitch moment

- The computed results here should be submitted in xlsx format.
- The computed time-averaged non-dimensionalized resistance, heave force, and pitch moment need to be put in the table of excel sheet 'Mean Value' of '2.12-1.xlsx' in folder 2.12-1.
- The computed time-averaged non-dimensionalized resistance, heave force, and pitch moment need to put in the table of excel sheet 'Time histories' of '2.12-1.xlsx' in folder 2.12-1.

Table / Figure#	**Items**	**EFD Data**		**Submission Instruction**	
		Data file	**Image**	**Data files**	**Sample + Tecplot layout file**
2.12-1	Resistance, heave force, and pitch moment	Refer to sample file for detail		<common> Filename: 2.12-1.xlsx	See in the attached folder "package-2024-11-08/2.12-1/".

Table 4: Examples of non-dimensionalized forces and moments

Parameters		**EFD**	**CFD**
1000C_T	Value	5.716	
	U(k=2)	0.84%	
1000C_L	Value	346.773	
	U(k=2)	0.25%	
1000C_{MY}	Value	1.154	
	U(k=2)	2.94%	

Table 5: Examples of time histories of forces and moments

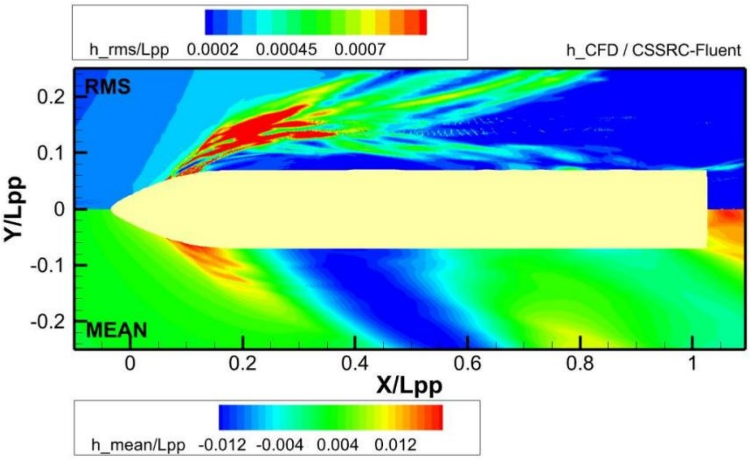
CFD			
t(s)	$1000C_T$	$1000C_L$	$1000C_{MY}$

Mean and RMS wave elevation contours.

- The computed results here should be submitted in png format.
- Identifier in the Figure should be [Institute Name]/[Solver Name].

Table / Figure#	**Items**	**EFD Data**		**Submission Instruction**	
		Data file	**Image**	**Image files**	**Sample + Tecplot layout file**
2.12-2	Mean and RMS wave elevations	Refer to sample file for detail		<common> Axis: $-0.1 < x/L_{PP} < 1.1$. $-0.25 < z/L_{PP} < 0.25$ Aspect ratio = 1:1 <contour> Filename: wave-elevation_2-12-2.png Top half: RMS wave elevation Bottom half: mean wave elevations Contour style: flood Contour levels and intervals: Mean: -0.012~0.018 (interval 0.001) RMS: 0.00005~0.0009 (interval 0.00005) <rectangular box> Range: $0.0877 < y/L_{PP} < 0.151$, $-0.025 < z/L_{PP} < 0.01$ Line thickness (%): 0.2	See in the attached folder "package-2024-11-08/2.12-2/".

- Image examples:



Mean and RMS wave cuts, time histories.

- The computed results here should be submitted in xlsx format.
- The wave cuts for different slices should be placed in the corresponding excel sheet of '2.12-3-wave cuts.xlsx' in folder 2.12-3.
- The time histories of wave elevations at six typical points should be placed in the excel sheet of '2.12-3-wave time histories.xlsx' in folder 2.12-3
- The wave cuts and time histories in the top view are recommended to be submitted and that in the bottom view are optional.

Table / Figure#	Items	EFD Data		Submission Instruction	
		Data file	Image	Data files	Sample + Tecplot layout file
2.12-3	Mean and RMS wave elevations	Refer to sample file for detail		<common> Filename of wave cuts: 2.12-3-wave cuts.xlsx Filename of time histories of wave elevations: 2.12-3-wave time histories.xlsx	See in the attached folder "package-2024-11-08/2.12-3/".

Table 6: Examples of Mean and RMS wave cuts

X/L_{pp}	Y/L_{pp}	MEAN wave elevations ($/L_{pp}$)	RMS wave elevations ($/L_{pp}$)	X/L_{pp}	Y/L_{pp}	MEAN wave elevations ($/L_{pp}$) Top Free surface	RMS wave elevations ($/L_{pp}$) Top Free surface	MEAN wave elevations ($/L_{pp}$) Bottom Free surface	RMS wave elevations ($/L_{pp}$) Bottom Free surface
0.1030	0.0677	0.012119	0.001281						
0.1030	0.0723	0.017170	0.000363						
0.1030	0.0769	0.015460	0.000508						
0.1030	0.0814	0.009222	0.000317						
0.1030	0.0860	0.007672	0.000296						
0.1030	0.0906	0.006799	0.000217						
0.1030	0.0952	0.006348	0.000075						
0.1030	0.0998	0.005847	0.000066						
0.1030	0.1043	0.005383	0.000051						
0.1030	0.1089	0.004849	0.000049						
0.1030	0.1135	0.004810	0.000083						
0.1030	0.1181	0.004560	0.000059						
0.1030	0.1227	0.004358	0.000061						
0.1030	0.1272	0.004017	0.000045						
0.1030	0.1318	0.003644	0.000080						
0.1030	0.1364	0.003455	0.000076						
0.1030	0.1410	0.003404	0.000045						
0.1030	0.1456	0.003247	0.000046						
0.1030	0.1501	0.003038	0.000042						
0.1030	0.1547	0.002727	0.000043						
0.1030	0.1593	0.002856	0.000076						
0.1030	0.1639	0.002755	0.000056						
0.1030	0.1685	0.002686	0.000058						
0.1030	0.1730	0.002480	0.000044						
0.1030	0.1776	0.002228	0.000076						
0.1030	0.1822	0.002124	0.000073						
0.1030	0.1868	0.002144	0.000045						
0.1030	0.1914	0.002064	0.000047						
0.1030	0.1959	0.001921	0.000043						
0.1030	0.2005	0.001676	0.000045						

Table 7: Examples of wave time histories

X/L_{pp}	Y/L_{pp}	t(s)	wave elevations ($/L_{pp}$) Top view of free	wave elevations ($/L_{pp}$) Bottom view of free surface
0.0103	0.0677			
0.0103	0.0677			
0.0103	0.0677			
0.0103	0.0677			
0.0103	0.0677			
0.0103	0.0677			
0.0103	0.0677			
0.0103	0.0677			
0.0103	0.0677			
0.0103	0.0677			
0.0103	0.0677			
0.0103	0.0677			
0.0103	0.0677			

3D air tubes and vortical structures

- The computed results here should be submitted in PNG format.
- The submitted image files need to be placed in folder '2.12-4'

Table / Figure#	Items	EFD Data		Submission Instruction	
		Data file	**Image**	**Image files**	**Sample + Tecplot layout file**
2.12-4-1	Air tube iso-surface	not available		<Iso surface > Perspective view: spherical angles of ψ = 60, θ = 240, and α = 0. Color: Cyan; Translucency: 50% Axis: -1.4< x/L_{PP} < 3.0 -1.6< y/L_{PP} < 1.55 -1.6< z/L_{PP} < 0.5 Filename: Air-Tube-Iso-Surface.png	See in the attached folder " package-2024-11-08/2.12-4/" .
2.12-4-2	Slice cuts			<contour lines> 3 points chosen for each slice: air tube (or crest), jet, and plunging point. Filename: X-0065Cut.png X-0084Cut.png X-0103Cut.png X-0122Cut.png	
2.12-4-3	FFT of WB points			Filename: WB_crest.png WB_jet.png WB_plunge.png	
2.12-4-4	Vortical structures			<image filename> IsoOmegaR_Front_view: front_view_vortex_isoOmegaR.png IsoOmegaR_Top_view: top_view_vortex_isoOmegaR.png IsoOmegaR_Perspective_view: perspective_view_vortex_ isoOmegaR.png IsoQ_Front_view: front_view_vortex_isoQ.png IsoQ_Top_view: top_view_vortex_isoQ.png IsoQ_Perspective_view: perspective_view_vortex_isoQ.png <contour> Contour style: flood Contour levels and intervals: X_vorticity: -5~5 (interval 0.1)	

- Image examples:

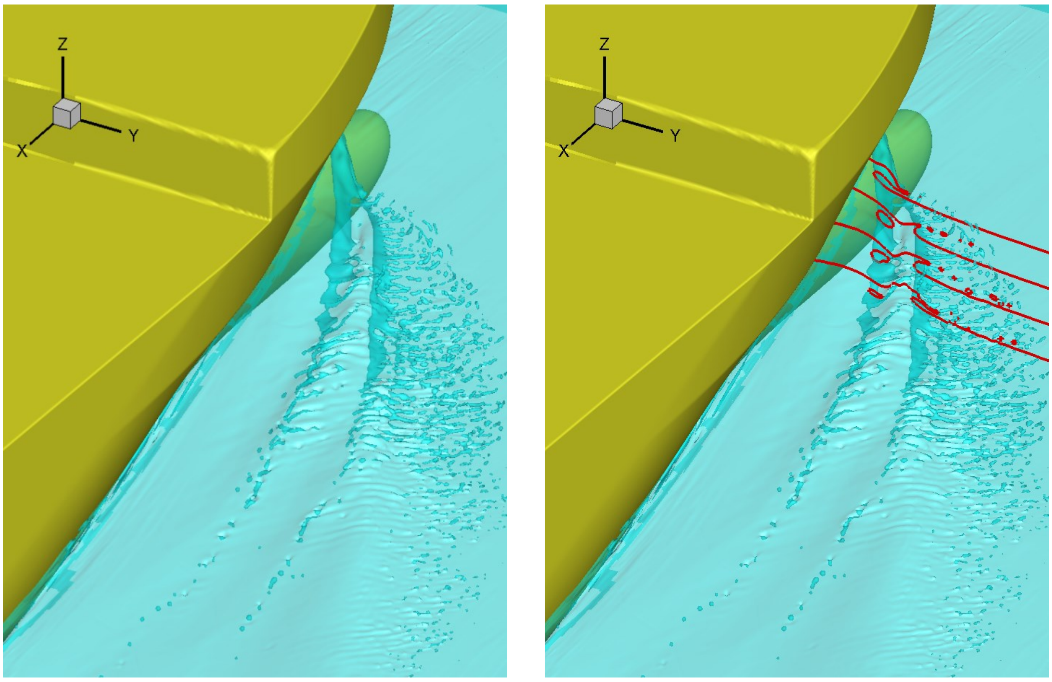


Fig. 17. Examples of Air tube iso-surface

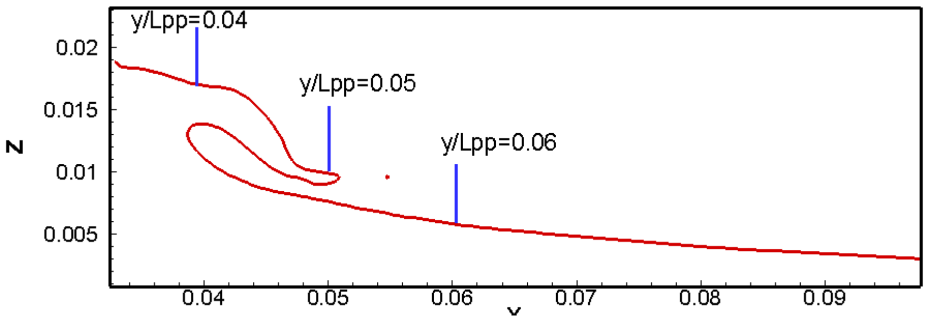


Fig. 18. Examples of slice cut at x/Lpp=0.065.

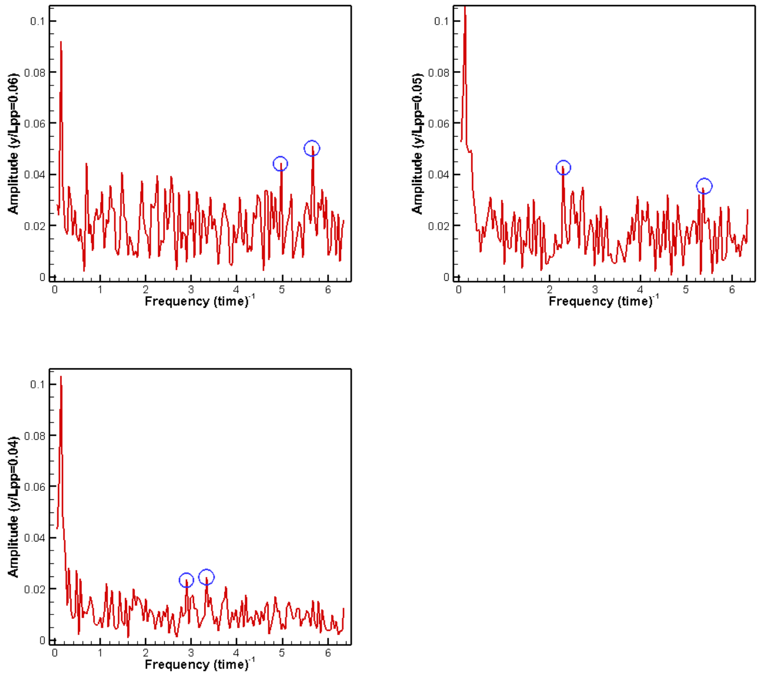
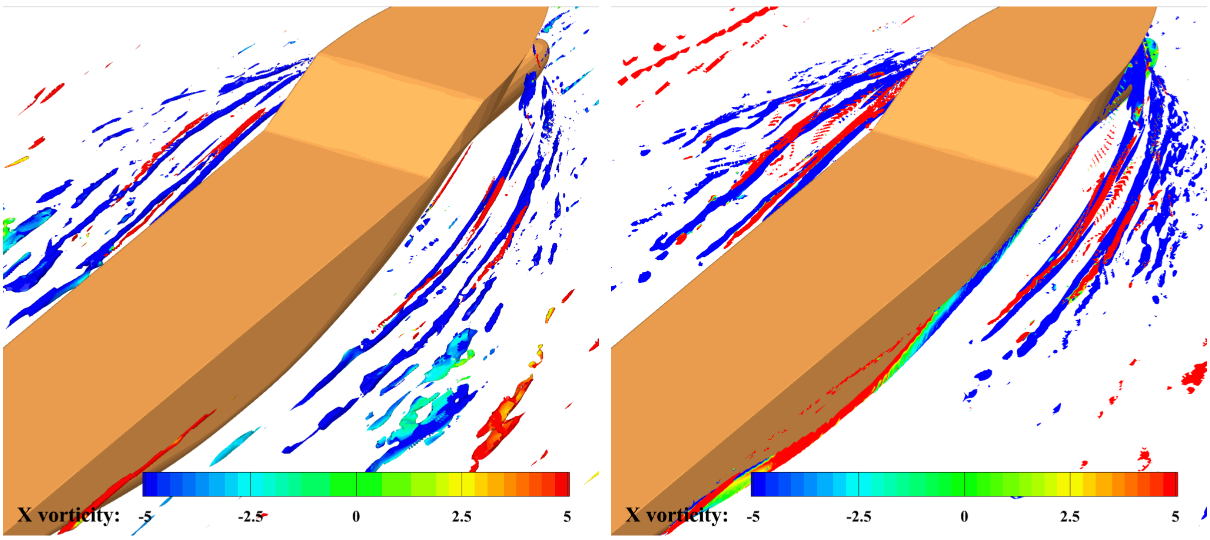


Fig. 19. Examples of FFT of WB points: wave crest, jet, and plunging point.



(a) IsoSurface OmegaR=0.65 *(b) IsoSurface Q=20*

Fig. 20. Examples of vortex structures under perspective view

u, v, w, and axial vorticity

- The computed results here should be submitted in PNG format.
- The submitted image files need to be placed in folder '2.12-5'
- Identifier in the Figure should be [Institute Name] / [Solver Name].
- All figures should be in colorful using the color map of "small rainbow".

<table>
<tr><th rowspan="2">Table / Figure#</th><th rowspan="2">Items</th><th colspan="2">EFD Data</th><th colspan="2">Submission Instruction</th></tr>
<tr><th>Data file</th><th>Image</th><th>Image files</th><th>Sample + Tecplot layout file</th></tr>
<tr><td>2.12-5-1</td><td>u, v, w, and axial vorticity at x/L_{PP}=0.151</td><td colspan="2" rowspan="2">Refer to sample file for detail</td><td><image filename>
Axial velocity: X0151_u_2-12-5.png
Transverse velocity: [X0151_v_2-12-5.png
Vertical velocity: X0151_w_2-12-5.png

Axial vorticity: X0151_VORT-X_2-12-5.png

<common>
Axis:
$0.03 < Y/L_{PP} < 0.16$
$-0.04 < Z/L_{PP} < 0.03$
Aspect ratio = 1:1

<contour>
Contour style: flood
Contour levels and intervals:
u: 0.9~1.1 (interval 0.01)
v: -0.05~0.15 (interval 0.01)
w: -0.15~0.05 (interval 0.01)
Axial vorticity: -5.0~5.0 (interval 1.0)

<rectangular box>
Range: $0.0877 < y/L_{PP} < 0.151$, $-0.025 < z/L_{PP} < 0.01$
Line thickness (%): 0.4</td><td rowspan="2">See in the attached folder “package-2024-11-08/2.12-5/” .</td></tr>
<tr><td>2.12-5-2</td><td>u, v, w, and axial vorticity at x/L_{PP}=0.199</td><td><image filename>
Axial velocity: X0199_u_2-12-5.png
Transverse velocity: X0199_v_2-12-5.png
Vertical velocity: X0199_w_2-12-5.png
Axial vorticity: X0199_VORT-X_2-12-5.png

<common>
Axis:
$0.03 < Y/L_{PP} < 0.18$
$-0.04 < Z/L_{PP} < 0.04$
Aspect ratio = 1:1

<contour>
Contour style: flood
Contour levels and intervals:
u: 0.9~1.1 (interval 0.01)
v: -0.05~0.15 (interval 0.01)
w: -0.15~0.05 (interval 0.01)
Axial vorticity: -5.0~5.0 (interval 1.0)</td></tr>
</table>

			<rectangular box> Range: 0.077 < y/L_{PP} < 0.176, -0.025 < z/L_{PP} < 0.01 Line thickness (%): 0.4	
2.12-5-3	u, v, w, and axial vorticity at x/L_{PP}=0.302		<image filename> Axial velocity: X0302_u_2-12-5.png Transverse velocity: X0302_v_2-12-5.png Vertical velocity: X0302_w_2-12-5.png Axial vorticity: X0302_VORT-X_2-12-5.png <common> Axis: 0.04 < Y/L_{PP} < 0.21 −0.06 < Z/L_{PP} < 0.03 Aspect ratio = 1:1 <contour> Contour style: flood Contour levels and intervals: u: 0.9~1.1 (interval 0.01) v: -0.05~0.15 (interval 0.01) w: -0.15~0.05 (interval 0.01) Axial vorticity: -3.0~3.0 (interval 1.0) <rectangular box> Range: 0.087 < y/L_{PP} < 0.2, -0.035 < z/L_{PP} < 0 Line thickness (%): 0.4	

- Image examples

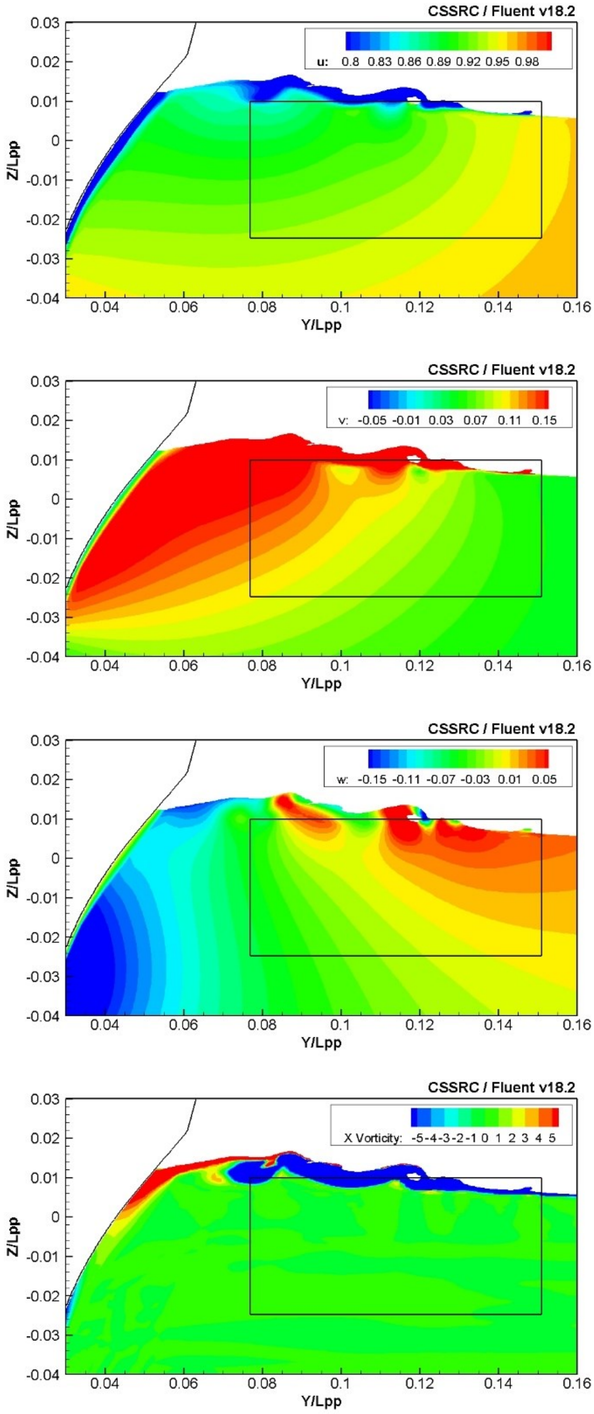


Fig. 21. *Examples of submitted CFD results for velocities and axial vorticities at* X/L_{PP}*=0.151*

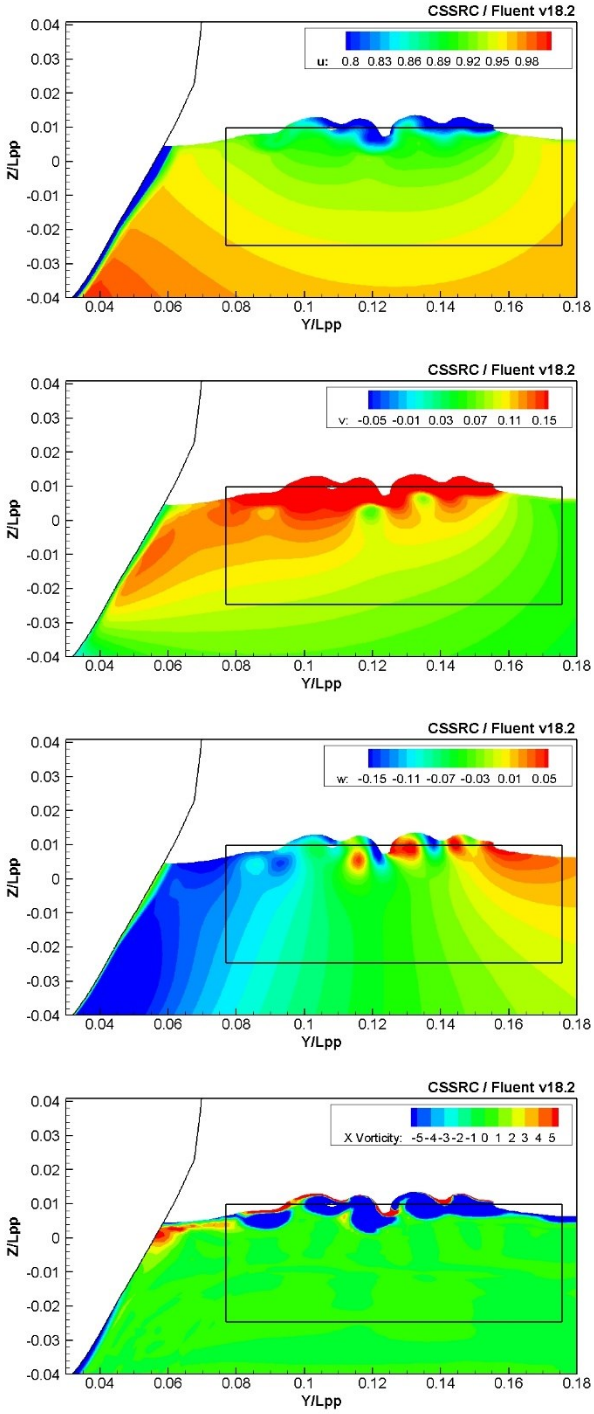


Fig. 22. *Examples of submitted CFD results for velocities and axial vorticities at* $X/L_{PP}=0.199$

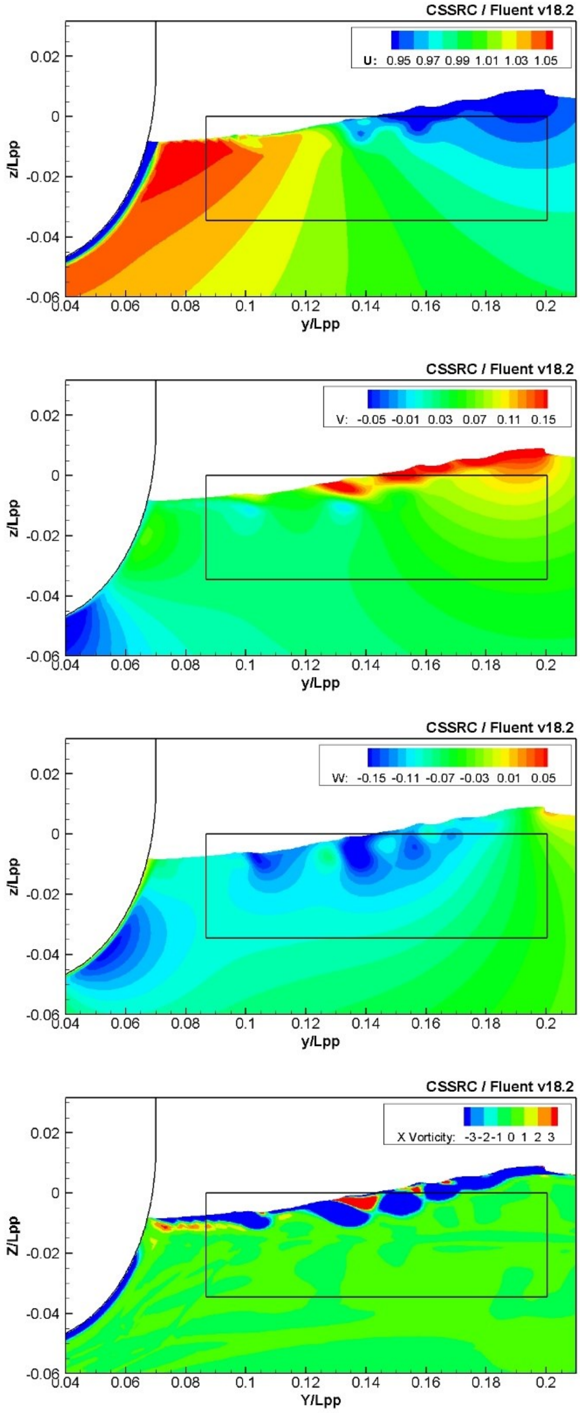


Fig. 23. *Examples of submitted CFD results for velocities and axial vorticities at* $X/L_{PP}=0.302$

Document Revisions

- 2024-11-13: Initial version for the website