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Smart Green Shipping Alliance Ltd.

CFD and velocity performance predictions for wind assisted ship technology

1 INTRODUCTION

The following report summarises a study in support of the design and evaluation of a collapsible wing sail technology on a bulk carrier ship hull form. A combination of computation fluid dynamic (CFD) and velocity performance prediction tools have been used to evaluate the concept at this early stage. A range of outputs have been supplied Humphreys Yacht Design (HYD) to aid the design process, of which this report only contains a partial selection.

The work was conducted broadly in accordance with Wolfson Unit Proposal No. 4814.

2 WORK PACKAGES

The project was broken down into a number of work packages:

- Aerodynamic CFD modelling of a single wing sail rig in isolation
- Aerodynamic CFD modelling of a single wing sail rig mounted upon a ship form
- Aerodynamic CFD modelling of a combination of wing sail rigs mounted upon a ship form
- Hydrodynamic CFD modelling of the ship hull form with appendages
- Velocity performance modelling

2.1 Wing Rigs

Unless otherwise stated, the same rig geometry was used for all simulations, as illustrated in Figure 1. The rig geometry comprises of a two wing elements; the main element (1), which rotates about a shaft connected to a tabernacle, and the second element (2), which is located behind the first element with a longitudinal gap of 0.091m, and which articulates about an axis within the tail of the main element. The axis of rotation for the second element lies 0.287m from the trailing edge of (i.e. within) the first element.

2.2 Computational Method

All simulations were conducted on the Iridis 5 supercomputer at the University of Southampton using the OpenFOAM CFD solver. Assumptions of the aerodynamic CFD model are as follows:

- Simulations were conducted using a steady Reynolds averaged Navier-Stokes (RANS) based steady-state solver
- Simulations were conducted at 1:1 scale, hence at the full scale Reynolds number.
- The air was specified as possessing a density of 1.224 kg/m^3 and kinematic viscosity 1.504m^2/s
- The inlet wind condition is specified as a power-law profile, representing the atmospheric boundary layer, with reference height 10m above sea level
- An unstructured hexahedral mesh was used to solve for the flow. The global mesh resolution was specified to capture the boundary layer over and turbulent wake behind the wing sails.
- Turbulence effects are accounted for using a kappa-omega (κ-ω) SST turbulence model

The hydrodynamic modelling of the ship hull is simulated using a Reynolds-averaged Navier-Stokes (RANS) based CFD solver using the volume of fluid (VoF) method to represent the free-surface interface. Further assumptions of the hydrodynamic CFD model are as follows:

- The hull is free to heave and trim under the action of hydrostatic and hydrodynamic forces
- The water is modelled as incompressible and turbulent
- The water is modelled as salt water at 15 ºC, including free-surface effects and wave-drag.
- The CFD mesh is optimised to capture the free-surface interaction with the hull and resultant wave-forms.

2.3 Aerodynamic CFD modelling of a single wing sail in isolation

A single wing sail was modelled on a flat surface at a combination of wind and flap angles, as can be seen in Figure 2, with results summarised in Table 2. This includes the overall forces and heel moment on the rig and with a broken down per item, i.e. each wing element and the tabernacle.

The separation between the trailing edge of element 1 and the leading edge of element 2 was then increased by 0.1 and 0.2m (i.e. to 0.191m and 0.291m respectively), and the results are presented in Table 3.

The results show that an apparent wind angle of approximately 18º and 20º of flap angle produces the highest lift contribution of the combinations tested.

The forces and moments from the simulations have also been used to predict the hinge moments of element 2 (about the rotational axes) presented in Table 5. These values have been compared to the moments resulting from an approximation of a force at a centre of pressure (CoP) 25% of the chord, which shows that the CoP is greater than 25% and therefore results in moments up to 18% greater than the 25% approximation approach.

2.4 Aerodynamic CFD modelling of a single wing on a ship form

The effect of mounting a single wing in a realistic use configuration was investigated by placing the sail rig on a representative Panamax bulk carrier geometry, which was provided in 3D CAD form by the client. The Panamax geometry possessed LOA of 225m, BOA of 32.9m and freeboard of 10.9m, and the wing axis was located 91.13m aft of the forward perpendicular, and 13.78m to starboard (Figure 3). The wing flap (i.e. element 2) angle was held constant at 20°.

The air flow over the vessel and rig geometry was simulated for a series of wind angles over the range 0° to 180° For each wind condition multiple simulations were conducted varying the wing angle, in order to determine the maximum drive force for each wind condition, and the angle of attack of the wing at which it occurs.

2.5 Aerodynamic CFD modelling of a combination of wing rigs on a ship form

The performance of a complete rig consisting of six wing sails (positions as agreed with HYD) was investigated for multiple wind angles using a two-stage process. During the first stage simulations were conducted of the ship mounted with the three windward wings only (i.e. if the wind is coming from port, only the wings on the port side will be simulated). All three wings were specified as possessing the same angle of rotation, and multiple simulations were conducted for each wind condition, varying the wing angle in order to obtain the maximum drive force. During the second stage a further series of simulations were conducted with the leeward wings also added to the model. The windward wings were specified as possessing the wing angle found to provide maximum drive force during stage 1, whilst the angle of the leeward wings was varied in order to determine the maximum drive force for the complete rig under these constraints.

Effectively this approach comprises a pragmatic optimisation process, based on the assumption that the leeward wings will exert less influence on the flow over the windward wings than vice versa.

2.6 Hydrodynamic CFD modelling of the ship hull form with appendages

The client supplied a geometry (Figure 3) of a candidate ship in 3D CAD form, which was simulated using the hydrodynamic CFD approach tools described in section 2.1. The canoe body and semi skeg rudder were modelled and no account of the propeller influence or other hull appendages and stern gear were modelled. The results of these simulations are included in Table 6.

The yaw moments (Mz) show that the virtual centre of pressure is relatively far forward at large leeway angles (angles of attack) for this single rudder ship form. The rudder shows effectiveness in moving the centre of pressure aft. It would be worth considering positioning the rigs as far forward as possible and to investigate alternative hydrodynamic means of moving the hydrodynamic centre of pressure aft. It must be borne in mind that that the simulations did not include the accelerated flow over the rudder from the propeller, which would contribute towards an aft ward shift in centre of pressure.

2.7 Velocity Performance Prediction

In order to predict the performance of the vessel a multi-stage process was developed, consisting of the following steps:

1. Prediction of the vessel hydrodynamic resistance using Wolfson Unit Power Prediction Software in a ‘conventional’ motoring condition
2. Estimation of vessel aerodynamic windage
3. Selection of appropriate rig aerodynamic coefficients based on a combination of results from section 2.2-2.4
4. Creation of a hydrodynamic model including prediction of drag and sideforce due to heel and yaw, using item 1 and results from section 2.5

Items 1-4 were combined to create models suitable for processing in the WinDesign 4 Velocity Prediction Program (VPP) and spreadsheet based tools were used for further analysis and presentation of the results.

The following assumptions have been made:

1. A constant full load displacement condition was used for all the simulations
2. Reduction of rig performance due to siting on a ship geometry has been included, including the loss of lift and increase in drag
3. Longitudinal locating of the rigs and use of the vessel’s hydrodynamic lift generating appendages to maintain a steady course has been ignored
4. The impact of ship motions on the aerodynamic and hydrodynamic behaviour of the rigs have been ignored
5. No sea state margin has been applied
6. No account has been made for changes in efficiency of the existing propulsive system whilst in a wind assisted conditions

A 6 rig configuration has been used in this VPP study. The results are presented in terms of propulsion percentage power savings in Table 8. These show significant reductions in propulsive power result from the rigs’ wind assisted contribution.

Table 1 Candidate ship principal dimensions

Parameter	Units	
Displacement	tonnes	67,657
LOA	m	225.1
Beam max	m	32.8
Draft	m	10.0

Table 2 Results: Single rig in isolation

Air Speed	7.72	m/s
Air Density	1.23	kg/m3
Element 1 Area	200.14	m2
Element 2 Area	130.20	m2
Total Wing Area	330.33	m2

			Tabernacle			Wing Element 1			Wing Element 2					Complete Wing		
Wing Angle	Flap Angle		Fx	Fy	Fz	Fx	Fy	Fz	Fx	Fy	Fz	Heel Moment		Cl	Cd	L/D
(deg)	(deg)		(N)	(N)	(N)	(N)	(N)	(N)	(N)	(N)	(N)	(Nm)				
0	10		233.5	7.3	195.1	-17.7	3545.3	29.5	364.4	1652.9	16.7	-92874.4		0.43	0.03	14.99
2	10		238.6	39.8	203.2	32.6	5108.4	35.2	458.1	1841.9	26.9	-123230.5		0.58	0.04	14.16
4	10		251.1	78.7	217.4	111.4	6677.4	48.8	555.9	2009.4	40.2	-153029.7		0.72	0.06	13.02
6	10		284.6	63.7	196.0	237.3	8298.6	44.9	673.4	2212.2	51.0	-184057.0		0.87	0.08	11.54
8	10		300.3	75.7	183.4	394.2	9867.0	78.1	805.4	2376.0	60.7	-215027.1		1.02	0.10	10.21
10	10		303.7	106.5	184.8	576.4	11424.9	106.8	947.4	2585.1	68.3	-246618.3		1.16	0.13	9.19
12	10		315.5	122.7	182.6	790.3	12911.8	135.0	1096.1	2705.1	69.8	-276147.6		1.30	0.16	8.28
14	10		315.0	155.7	174.3	1030.6	14382.0	195.5	1260.8	2874.2	75.8	-306641.7		1.43	0.19	7.53
16	10		313.9	147.0	164.9	1310.6	15620.0	258.6	1428.9	2971.0	74.1	-333365.2		1.54	0.23	6.79
18	10		313.1	147.2	150.0	1618.0	16843.0	315.9	1601.5	3075.0	76.7	-359454.5		1.65	0.27	6.19
20	10		317.2	158.8	177.6	2120.8	12422.0	303.3	1741.2	2944.3	69.3	-283066.2		1.28	0.32	3.98
25	10		309.2	151.6	140.3	3460.7	10420.0	390.7	1870.8	2502.3	49.7	-248118.7		1.07	0.44	2.42
30	10		318.2	148.0	116.9	4117.4	9317.8	430.8	2162.9	2330.9	27.8	-219091.5		0.97	0.52	1.85
45	10		289.3	157.9	95.8	6647.0	7462.7	-24.1	3331.0	2251.4	-2.3	-167462.8		0.81	0.83	0.97
60	10		267.5	176.4	59.1	8267.4	5567.7	-24.6	4513.4	1650.2	-4.0	-125812.9		0.60	1.06	0.56
75	10		265.7	158.1	62.6	9002.5	3391.2	-20.8	5513.3	553.6	-6.2	-68588.8		0.33	1.20	0.27
90	10		270.6	127.5	90.7	8720.3	1111.2	-15.3	6069.1	-930.3	-7.3	-2812.1		0.02	1.23	0.01
8	0		0.0	0.0	0.0	201.5	5250.3	55.3	201.4	560.8	11.9	-103691.6		0.48	0.03	14.42
12	0		283.2	58.4	174.4	507.8	8464.8	99.6	303.7	924.2	27.6	-164779.9		0.78	0.07	11.57
14	0		295.5	78.0	177.7	704.6	9893.3	132.1	375.7	1123.8	34.6	-194272.1		0.91	0.09	10.20
18	0		290.1	122.9	170.0	1191.2	12762.4	213.0	550.1	1455.5	44.4	-252980.5		1.18	0.14	8.17
20	0		299.4	113.3	172.7	1681.3	10745.7	232.1	747.9	1678.6	41.6	-219367.9		1.03	0.20	5.11
25	0		328.9	139.1	182.1	2900.3	9637.3	299.9	1029.7	1988.9	50.0	-214117.2		0.97	0.33	2.96
30	0		312.8	132.8	136.3	3871.1	8836.7	389.2	1283.1	1920.9	31.8	-205878.4		0.89	0.43	2.09
8	20		310.1	179.6	205.2	485.7	14474.6	132.2	1985.3	4237.3	104.7	-329760.3		1.55	0.21	7.57
12	20		322.5	181.0	177.9	1009.7	17006.8	225.5	2420.0	4370.8	88.8	-383832.9		1.77	0.28	6.23
14	20		322.2	169.4	157.9	1293.8	17973.7	292.2	2640.8	4455.7	93.0	-406167.5		1.86	0.33	5.70
18	20		310.3	181.7	142.5	1960.4	20116.8	436.5	3032.5	4361.4	103.1	-449576.2		2.03	0.41	4.90
20	20		352.6	201.0	191.2	2477.2	13346.9	366.0	2976.7	3772.1	82.6	-322870.1		1.42	0.45	3.14
25	20		310.4	167.9	131.5	3709.6	10755.5	348.4	2896.6	2874.4	20.3	-252380.6		1.13	0.55	2.06
30	20		309.2	172.6	105.1	4285.1	9623.1	489.9	3041.2	2458.0	30.7	-229001.4		1.00	0.61	1.65
0	30		317.8	113.1	202.8	-169.1	11613.5	-14.8	2424.9	5671.3	87.8	-304192.9		1.43	0.19	7.66
6	30		321.8	175.1	197.2	318.3	14704.3	101.0	2978.6	5141.3	114.6	-351716.2		1.65	0.27	6.02
8	30		375.5	216.3	185.0	570.9	17687.7	136.2	3439.5	5761.5	126.4	-417868.0		1.95	0.33	5.85
10	30		314.2	166.7	170.6	708.3	15916.4	204.7	3182.1	4440.3	129.2	-367353.5		1.69	0.32	5.23
12	30		318.6	167.9	155.7	996.8	17304.6	283.5	3467.1	4531.3	137.3	-399442.3		1.81	0.37	4.89
14	30		309.6	166.4	146.0	1159.6	17451.7	328.2	3496.3	3952.0	143.1	-393303.4		1.78	0.39	4.60
18	30		347.8	205.1	162.2	2331.2	14893.0	370.8	3792.1	3784.5	125.3	-350851.4		1.55	0.51	3.05
20	30		334.1	177.7	137.4	2766.4	13198.4	340.7	3668.6	3266.9	61.9	-293404.6		1.37	0.53	2.56
25	30		355.7	160.7	110.9	4109.3	10845.9	402.8	3812.8	2777.8	33.2	-252822.2		1.13	0.66	1.72
30	30		312.7	183.0	85.0	5079.6	10666.7	496.2	4492.2	2770.4	21.2	-252706.0		1.12	0.79	1.40

Table 3 Results: Gap study

Air Speed	7.72	m/s
Air Density	1.23	kg/m3
Element 1 Area	200.14	m2
Element 2 Area	130.20	m2
Total Wing Area	330.33	m2

				Tabernacle			Wing Element 1			Wing Element 2					Complete Wing		
Wing Angle	Flap Angle	Gap		Fx	Fy	Fz	Fx	Fy	Fz	Fx	Fy	Fz	Heel Moment		Cl	Cd	L/D
(deg)	(deg)			(N)	(N)	(N)	(N)	(N)	(N)	(N)	(N)	(N)	(Nm)				
8	0	+0.1m		301.5	84.3	191.3	368.5	9574.5	71.4	828.9	2801.3	59.2	-216819.4		1.03	0.10	10.34
12	0	+0.1m		323.7	138.5	179.6	755.8	12713.6	131.6	1148.3	3181.1	66.0	-279242.6		1.32	0.16	8.35
14	0	+0.1m		330.9	157.1	186.3	979.1	14149.5	182.0	1322.0	3382.2	74.0	-309488.1		1.46	0.19	7.62
18	0	+0.1m		312.3	162.5	158.1	1559.0	16688.9	298.9	1700.7	3612.7	70.6	-364761.9		1.69	0.27	6.23
20	0	+0.1m		319.7	158.8	182.9	2233.9	11421.9	268.2	1678.0	2838.9	66.6	-259189.2		1.18	0.32	3.65
25	0	+0.1m		336.3	193.2	185.2	3265.9	10834.0	358.7	2039.5	2881.3	45.8	-251332.8		1.14	0.44	2.59
30	0	+0.1m		308.4	162.7	127.1	4024.1	9243.9	455.0	2178.5	2471.2	36.1	-224393.0		0.97	0.51	1.89
8	0	+0.2m		283.5	106.5	207.0	352.2	9258.5	65.7	831.5	3070.3	52.2	-216033.4		1.02	0.10	10.42
12	0	+0.2m		303.1	125.5	173.8	716.0	12287.6	138.2	1188.7	3457.7	66.8	-278036.9		1.31	0.16	8.27
14	0	+0.2m		300.6	122.0	164.8	936.6	13335.9	197.7	1355.1	3534.9	75.0			1.40	0.19	7.36
18	0	+0.2m		319.0	166.4	186.7	1643.1	12373.1	224.5	1624.1	3153.2	61.7	-273698.2		1.29	0.27	4.75
20	0	+0.2m		320.5	132.0	167.9	2092.0	12207.3	304.8	1725.2	3025.6	51.0	-283891.8		1.26	0.32	3.99
25	0	+0.2m		337.6	169.6	186.2	3264.2	10351.5	334.1	1986.2	2765.8	43.1	-239835.7		1.09	0.44	2.50
30	0	+0.2m		336.8	162.5	136.9	4028.3	8829.9	414.4	2164.2	2452.1	34.7	-215468.4		0.94	0.51	1.82

Table 4 Results: Single ship mounted rig

Datum (for moments): mast centre at deck level (z=10.718m)

Wind Speed	15	knots	
Air Density	1.225	kg/m3	
Flap Angle	20	deg	
B.L Ref. Height	10	m	

Fx = drive (negative Fx=positive drive)
Fy = sideforce
Fz = vertical force

Mx = roll moment
My = pitch moment
Mz = yaw moment

Wind Angle	Wing AoA	Wing Positi	Tabernacle			Wing E1			Wing E2			Wing E1+E2					
(deg)	(deg)		Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Mx (Nm)	My (Nm)	Mz (Nm)
0	6	Leeward	230	128	128	376	13256	31	1884	4443	103	2260	17699	134	-3.1E+05	4.2E+04	4.4E+04
0	10	Leeward	215	146	91	853	16362	105	2343	4649	96	3196	21011	201	-3.8E+05	6.0E+04	4.8E+04
0	14	Leeward	223	191	89	1437	19516	224	2779	4728	105	4216	24244	330	-4.3E+05	8.0E+04	5.2E+04
0	16	Leeward	229	163	85	1885	17076	280	2900	4393	107	4785	21469	386	-4.1E+05	9.1E+04	4.9E+04
0	18	Leeward	291	185	143	2332	14427	277	2912	3875	94	5244	18302	371	-3.4E+05	9.8E+04	4.5E+04
0	20	Leeward	262	162	134	2708	11215	306	3020	3749	59	5728	14964	364	-2.7E+05	1.0E+05	4.4E+04
0	22	Leeward	263	162	128	3192	11349	333	3018	3347	47	6209	14696	380	-2.7E+05	1.1E+05	4.3E+04

Wind Angle	Wing AoA	Wing Positi	Tabernacle			Wing E1			Wing E2			Wing E1+E2					
(deg)	(deg)		Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Mx (Nm)	My (Nm)	Mz (Nm)
30	6	Leeward	77	132	106	-8503	13894	105	-626	5072	97	-9129	18966	201	-3.5E+05	-1.6E+05	4.7E+04
30	10	Leeward	40	155	91	-9682	16645	242	-310	5398	108	-9991	22044	350	-4.1E+05	-1.8E+05	5.1E+04
30	14	Leeward	85	148	78	-7696	15555	370	158	5200	110	-7538	20756	481	-4.1E+05	-1.5E+05	4.9E+04
30	16	Leeward	95	172	88	-5341	12766	323	411	5122	97	-4930	17888	420	-3.5E+05	-9.9E+04	4.7E+04
30	18	Leeward	99	184	84	-4407	12522	339	572	4596	74	-3835	17118	413	-3.2E+05	-7.4E+04	4.5E+04
30	20	Leeward	102	200	78	-3788	12280	388	756	4797	65	-3032	17076	453	-3.2E+05	-6.2E+04	4.6E+04
30	22	Leeward	79	209	71	-3232	12061	459	927	4952	57	-2305	17014	517	-3.2E+05	-4.9E+04	4.7E+04

Wind Angle	Wing AoA	Wing Positi	Tabernacle			Wing E1			Wing E2			Wing E1+E2					
(deg)	(deg)		Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Mx (Nm)	My (Nm)	Mz (Nm)
45	6	Leeward	-31	84	99	-12223	11374	196	-1866	4610	100	-14089	15985	296	-3.1E+05	-2.6E+05	4.6E+04
45	10	Leeward	-53	98	105	-13917	13595	290	-1645	4963	111	-15562	18558	400	-3.6E+05	-2.9E+05	4.9E+04
45	14	Leeward	-88	94	98	-15090	15490	425	-1292	5074	120	-16381	20563	545	-4.0E+05	-3.1E+05	5.0E+04
45	16	Leeward	19	135	103	-7372	10251	204	-799	4691	48	-8171	14942	252	-2.7E+05	-1.5E+05	4.5E+04
45	18	Leeward	0	145	102	-6777	9989	218	-712	4908	41	-7489	14897	259	-2.7E+05	-1.3E+05	4.6E+04
45	20	Leeward	29	154	97	-6038	10257	276	-448	4805	36	-6486	15062	312	-2.7E+05	-1.2E+05	4.6E+04
45	22	Leeward	6	172	100	-5785	10669	351	-317	5003	29	-6103	15671	380	-2.8E+05	-1.1E+05	4.8E+04

Wind Angle	Wing AoA	Wing Positi	Tabernacle			Wing E1			Wing E2			Wing E1+E2					
(deg)	(deg)		Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Mx (Nm)	My (Nm)	Mz (Nm)
60	6	Leeward	54	-38	105	-10587	5992	286	-2488	3388	125	-13075	9380	411	-2.0E+05	-2.8E+05	3.8E+04
60	10	Leeward	38	-40	97	-12227	7416	414	-2369	3695	135	-14596	11111	549	-2.4E+05	-3.1E+05	4.0E+04
60	14	Leeward	7	-36	82	-13981	9002	570	-2179	3914	146	-16159	12917	715	-2.7E+05	-3.4E+05	4.1E+04
60	16	Leeward	16	-34	81	-8890	6724	451	-1778	3801	86	-10668	10525	538	-2.1E+05	-2.2E+05	3.7E+04
60	18	Leeward	20	-20	78	-8822	7330	453	-1498	3716	47	-10320	11046	501	-2.2E+05	-2.0E+05	3.7E+04
60	20	Leeward	-10	11	51	-8950	8197	454	-1517	4088	-10	-10467	12285	444	-2.3E+05	-2.0E+05	4.2E+04
60	22	Leeward	5	22	56	-8124	8269	433	-1441	4273	-5	-9565	12543	428	-2.3E+05	-1.8E+05	4.3E+04

Wind Angle	Wing AoA	Wing Positi	Tabernacle			Wing E1			Wing E2			Wing E1+E2					
(deg)	(deg)		Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Mx (Nm)	My (Nm)	Mz (Nm)
90	6	Windward	38	11	173	-9487	662	147	-3625	1608	93	-13112	2269	241	-4.3E+04	-2.6E+05	3.5E+04
90	10	Windward	40	12	167	-11926	1104	245	-3725	1978	81	-15651	3082	326	-5.9E+04	-3.1E+05	3.8E+04
90	14	Windward	80	2	169	-14340	1665	383	-3721	2344	104	-18062	4009	488	-7.7E+04	-3.5E+05	4.1E+04
90	16	Windward	69	6	163	-15166	1906	446	-3836	2563	112	-19002	4469	558	-8.6E+04	-3.7E+05	4.2E+04
90	18	Windward	62	19	170	-16211	2248	496	-3855	2756	115	-20066	5004	610	-9.6E+04	-3.9E+05	4.4E+04
90	20	Windward	120	7	184	-17261	2609	591	-3888	2955	134	-21149	5564	725	-1.1E+05	-4.1E+05	4.5E+04
90	22	Windward	137	17	195	-12543	3074	439	-3287	2929	86	-15829	6003	524	-1.1E+05	-2.9E+05	4.1E+04

Wind Angle	Wing AoA	Wing Positi	Tabernacle			Wing E1			Wing E2			Wing E1+E2					
(deg)	(deg)		Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Mx (Nm)	My (Nm)	Mz (Nm)
90	6	Leeward	-4	-10	117	-9207	404	197	-3450	1525	134	-12657	1929	331	-4.1E+04	-2.7E+05	3.3E+04
90	10	Leeward	-8	-9	118	-11570	842	308	-3661	1908	110	-15231	2751	418	-5.9E+04	-3.3E+05	3.7E+04
90	14	Leeward	-12	-7	115	-13856	1372	448	-3759	2291	124	-17615	3662	572	-7.8E+04	-3.8E+05	4.0E+04
90	16	Leeward	-18	-7	112	-15183	1693	535	-3759	2491	133	-18941	4184	669	-8.9E+04	-4.0E+05	4.1E+04
90	18	Leeward	-19	-8	111	-15961	1999	616	-3684	2627	136	-19646	4626	752	-9.9E+04	-4.2E+05	4.2E+04
90	20	Leeward	-20	-7	108	-10835	2351	487	-3501	2791	85	-14337	5142	572	-1.0E+05	-2.9E+05	4.0E+04
90	22	Leeward	-24	-5	107	-11287	2837	526	-3141	2823	75	-14427	5661	601	-1.1E+05	-2.9E+05	3.9E+04

Wind Angle	Wing AoA	Wing Positi	Tabernacle			Wing E1			Wing E2			Wing E1+E2					
(deg)	(deg)		Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Mx (Nm)	My (Nm)	Mz (Nm)
135	6	Leeward	-207	-20	206	-6042	-4852	-27	-4035	-1575	79	-10077	-6428	53	1.2E+05	-1.9E+05	3.9E+04
135	10	Leeward	-235	-28	226	-8917	-6687	15	-4630	-1448	102	-13548	-8136	117	1.5E+05	-2.5E+05	4.5E+04
135	14	Leeward	-286	-35	260	-11998	-8471	92	-5376	-1325	87	-17374	-9797	179	1.8E+05	-3.3E+05	5.1E+04
135	16	Leeward	-285	-31	271	-13477	-9234	140	-5600	-1163	85	-19077	-10398	225	2.0E+05	-3.6E+05	5.3E+04
135	18	Leeward	-313	-35	275	-14818	-9850	211	-5883	-1054	95	-20701	-10904	306	2.1E+05	-3.9E+05	5.6E+04
135	20	Leeward	-315	-38	276	-16156	-10422	289	-5981	-822	101	-22137	-11244	389	2.1E+05	-4.2E+05	5.7E+04
135	22	Leeward	-326	-29	282	-17427	-10941	357	-6232	-685	98	-23659	-11627	455	2.2E+05	-4.5E+05	5.9E+04
135	24	Leeward	-288	-20	263	-13725	-7742	354	-5257	-137	98	-18982	-7878	452	1.5E+05	-3.7E+05	4.9E+04

Wind Angle	Wing AoA	Wing Positi	Tabernacle			Wing E1			Wing E2			Wing E1+E2					
(deg)	(deg)		Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Fx (N)	Fy(N)	Fz (N)	Mx (Nm)	My (Nm)	Mz (Nm)
180	80	Leeward	-206	-11	111	-5571	82	-26	-4942	705	-13	-10513	786	-39	-1.5E+04	-1.9E+05	4.9E+04
180	90	Leeward	-206	-23	99	-6258	-872	-37	-4832	-99	-14	-11090	-971	-51	1.7E+04	-2.0E+05	4.9E+04
180	100	Leeward	-209	-37	90	-6676	-2034	-42	-4484	-842	-14	-11160	-2876	-56	5.0E+04	-2.0E+05	4.7E+04
180	110	Leeward	-207	-44	80	-6697	-3247	-39	-3893	-1427	-13	-10590	-4674	-52	8.1E+04	-1.9E+05	4.4E+04

Table 5 Results: Selected hinge moments

						CFD Results		Hinge moment estimate		
Wing and wind conditions						(element 2)		(assuming 1/4 chord CoP)		
Mount	AWA	AOA	Wing Angle	Flap Angle		Mz Hinge		Mz Hinge	Error	Approx CoP
	(deg)	(deg)	(deg)	(deg)		(Nm)		(Nm)		
Flat Plate	0	12	12	10		4.65E+03		3.89E+03	-16.33%	29.1%
Flat Plate	0	18	18	10		5.68E+03		4.62E+03	-18.77%	29.7%
Hull	90	20	70	20		7.84E+03		6.50E+03	-17.10%	29.3%
Hull	45	14	31	20		8.53E+03		6.96E+03	-18.42%	29.6%

Table 6 Results: Hydrodynamic

High Resolution										Low Resolution			
RUN	LWL	Density	Speed	Yaw	Rudder	Fx	Fy	Fz		RunID	Fy	Mz	Lever
	m	kg/m^3	knots	deg	deg	kN	kN	kN			kN	kN.m	%LWL
RUN001	225.113	1026	10	0	0	391	2	567535		RUN001LR	-95.9772	-215.014	9.95
RUN002	225.113	1026	12	0	0	508	-3	565176		RUN002LR	-128.748	-243.838	8.41
RUN003	225.113	1026	12	3	0	578	368	564985		RUN003LR	4018.312	54335.18	60.07
RUN004	225.113	1026	12	6	0	621	781	565261		RUN004LR	8561.384	98400.55	51.06
RUN005	225.113	1026	12	9	0	824	1419	563161		RUN005LR	16350.17	158153.7	42.97
RUN006	225.113	1026	12	6	3	625	855	564569		RUN006LR	9400.642	89453.65	42.27
RUN007	225.113	1026	12	6	6	641	939	565265		RUN007LR	10157.16	83216.64	36.39
												forward of midships	

Table 7 Results: Multiple rigs on ship form

Apparent Wind Angle	Angle of Attack (for windward rigs)	Angle of Attack (for leeward rigs)	Flap Angle		Drive Force	Side Force	Drive Force Coefficient	Side Force Coefficient	Drag Coefficient	Lift Coefficient
Wind Angle	AoA(W)	AoA(L)	Beta	RunID	all_F1	all_F2	Cx	Cy	Cd	Cl
deg	deg	deg	deg		kN	kN				
30	18	14	20	run_1401A	-42.714	137.477	-0.5249	1.6895	0.3901	1.7256
30	18	16	20	run_1401	-42.989	141.946	-0.5283	1.7444	0.4147	1.7748
30	18	18	20	run_1402	-36.767	135.724	-0.4518	1.6679	0.4427	1.6704
30	18	20	20	run_1403	-33.160	131.885	-0.4075	1.6207	0.4575	1.6074
45	18	14	20	run_1404A	-64.001	111.786	-0.7865	1.3737	0.4152	1.5275
45	18	16	20	run_1404	-66.784	112.784	-0.8207	1.3860	0.3997	1.5604
45	18	18	20	run_1405	-61.226	111.872	-0.7524	1.3748	0.4401	1.5042
45	18	20	20	run_1406	-61.360	115.605	-0.7541	1.4207	0.4714	1.5378
60	18	16	20	run_1407	-108.000	105.815	-1.3272	1.3004	0.4625	1.7996
60	18	18	20	run_1408	-108.858	108.552	-1.3378	1.3340	0.4864	1.8255
60	18	20	20	run_1409	-103.288	109.428	-1.2693	1.3448	0.5299	1.7716
90	22	20	20	run_1410	-135.433	46.365	-1.6643	0.5698	0.5698	1.6643
90	22	22	20	run_1411	-139.335	47.864	-1.7123	0.5882	0.5882	1.7123
90	22	24	20	run_1412	-130.728	48.926	-1.6065	0.6013	0.6013	1.6065
135	20	16	20							
135	20	18	20	run_1413	-113.255	-48.768	-1.3918	-0.5993	0.5604	1.4079
135	20	20	20	run_1414	-108.846	-45.272	-1.3376	-0.5563	0.5524	1.3392
135	20	22	20	run_1415	-108.818	-44.562	-1.3373	-0.5476	0.5584	1.3328
135	55	55	20	run_1416	-55.236	18.412	-0.6788	0.2263	0.6400	0.3200
135	45	45	20	run_1417	-55.084	8.944	-0.6769	0.1099	0.5564	0.4009
135	35	35	20	run_1418	-74.893	-15.371	-0.9204	-0.1889	0.5172	0.7844

Table 8: % Predicted Power Savings

If value is greater than 100%, then a greater ship speed will be possible (greyed out areas represent where numerical convergence issues occurred but in all cases the percentage savings would be in excess of 100%, i.e. free sailing)

Ship Speed = 6 knots

True Wind Angle (degrees)	True Wind Speed (knots)											
	6	7	8	9	10	12	14	16	20	25	30	35
80			7.8	13.0	17.7	27.7	39.3	51.3	74.1	93.7		
90			14.7	20.3	26.3	40.4	57.1	75.3	113.4	127.0		
100	6.6	12.7	18.3	24.6	31.6	48.3	68.1	90.3	123.7			
110	8.4	14.0	19.7	25.9	33.0	51.0	72.5	97.2	120.8			
120	8.2	13.5	18.7	24.9	31.9	49.4	70.1	94.2	122.6			
135	4.3	10.4	15.2	20.2	25.3	38.5	55.6	75.9	119.1	115.8		
150		0.5	8.1	12.3	16.6	27.0	41.3	59.0	103.5	120.2		
160				7.1	11.9	21.3	33.6	49.3	90.0	126.7		
170				1.1	7.7	16.9	27.4	41.2	77.5	121.2		
180					4.0	13.7	22.9	34.5	67.0	116.9		

Ship Speed = 8 knots

True Wind Angle (degrees)	True Wind Speed (knots)											
	6	7	8	9	10	12	14	16	20	25	30	35
80					4.2	12.7	19.6	27.4	44.5	66.2	84.1	96.7
90			0.5	7.4	11.9	19.9	29.2	39.9	65.1	101.1	117.8	120.3
100			6.3	11.2	15.1	24.2	34.6	47.4	77.6	117.7	144.4	
110		1.3	8.0	12.5	16.3	25.5	36.6	50.3	82.9	119.3	154.4	
120		1.1	8.0	12.0	15.6	24.5	35.3	48.7	80.4	119.1	152.3	
135			3.5	8.7	12.4	19.5	27.9	38.0	64.5	107.3	116.6	
150					4.5	12.0	18.3	26.7	49.0	87.2	121.6	140.7
160						6.8	13.7	20.9	40.4	74.7	115.7	113.7
170						0.2	10.0	16.4	33.5	64.2	104.5	116.3
180							6.6	13.4	28.0	55.0	90.6	121.9

Ship Speed = 10 knots

True Wind Angle (degrees)	True Wind Speed (knots)											
	6	7	8	9	10	12	14	16	20	25	30	35
80						2.0	10.0	15.6	27.9	44.9	64.3	79.2
90					0.4	10.3	16.8	23.6	40.5	65.9	94.8	122.7
100					6.4	13.8	20.7	28.8	47.7	78.4	111.4	121.0
110				3.0	8.2	14.9	21.8	30.6	50.8	83.9	120.7	115.1
120				3.1	8.1	14.2	20.9	29.3	49.0	81.3	116.7	117.9
135					3.8	11.3	16.8	22.8	38.5	65.1	99.4	123.7
150						2.2	9.7	14.6	27.0	49.5	79.5	112.3
160							3.0	10.0	21.0	41.1	67.8	101.2
170								5.4	16.8	34.2	58.2	87.6
180								0.3	13.7	28.5	49.3	75.9

Ship Speed = 12 knots

True Wind Angle (degrees)	True Wind Speed (knots)											
	6	7	8	9	10	12	14	16	20	25	30	35
80							0.3	9.1	18.4	32.1	49.9	64.2
90						1.2	10.3	15.0	28.2	49.3	73.0	99.2
100						7.8	13.3	19.4	32.6	56.7	86.8	115.6
110						9.6	14.2	20.9	34.2	60.5	92.9	120.0
120						9.5	13.7	19.8	33.0	58.4	90.0	118.4
135						4.7	11.2	15.1	27.2	47.1	72.3	103.2
150							0.6	9.4	16.9	31.6	54.1	81.7
160									12.5	26.2	45.4	69.8
170									9.1	21.0	36.2	58.3
180									4.9	16.5	30.1	50.3

Ship Speed = 14 knots

True Wind Angle (degrees)	True Wind Speed (knots)											
	6	7	8	9	10	12	14	16	20	25	30	35
80								1.8	12.2	24.0	37.8	51.3
90							4.2	9.9	20.7	36.6	54.5	74.9
100							8.4	13.3	24.7	43.0	63.6	89.4
110						3.8	9.9	14.7	25.8	44.7	67.3	95.7
120						4.0	9.8	14.0	25.0	43.4	65.3	92.6
135							6.9	10.9	20.8	34.7	51.8	74.2
150								3.1	11.7	22.8	38.3	56.7
160									7.1	17.7	30.0	46.4
170										12.9	23.8	39.2
180										9.6	20.1	33.7

Figure 1 Example of individual rig

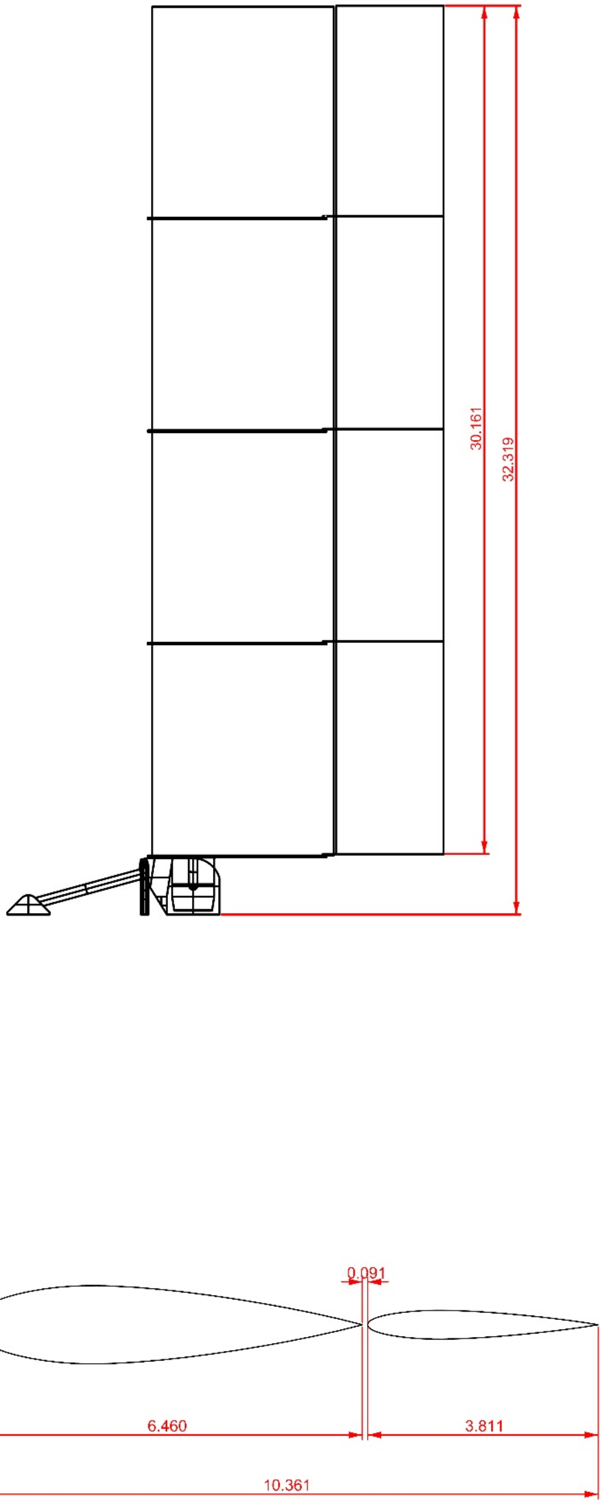


Figure 2 Single wing arrangement on flat surface: velocity slice presentation

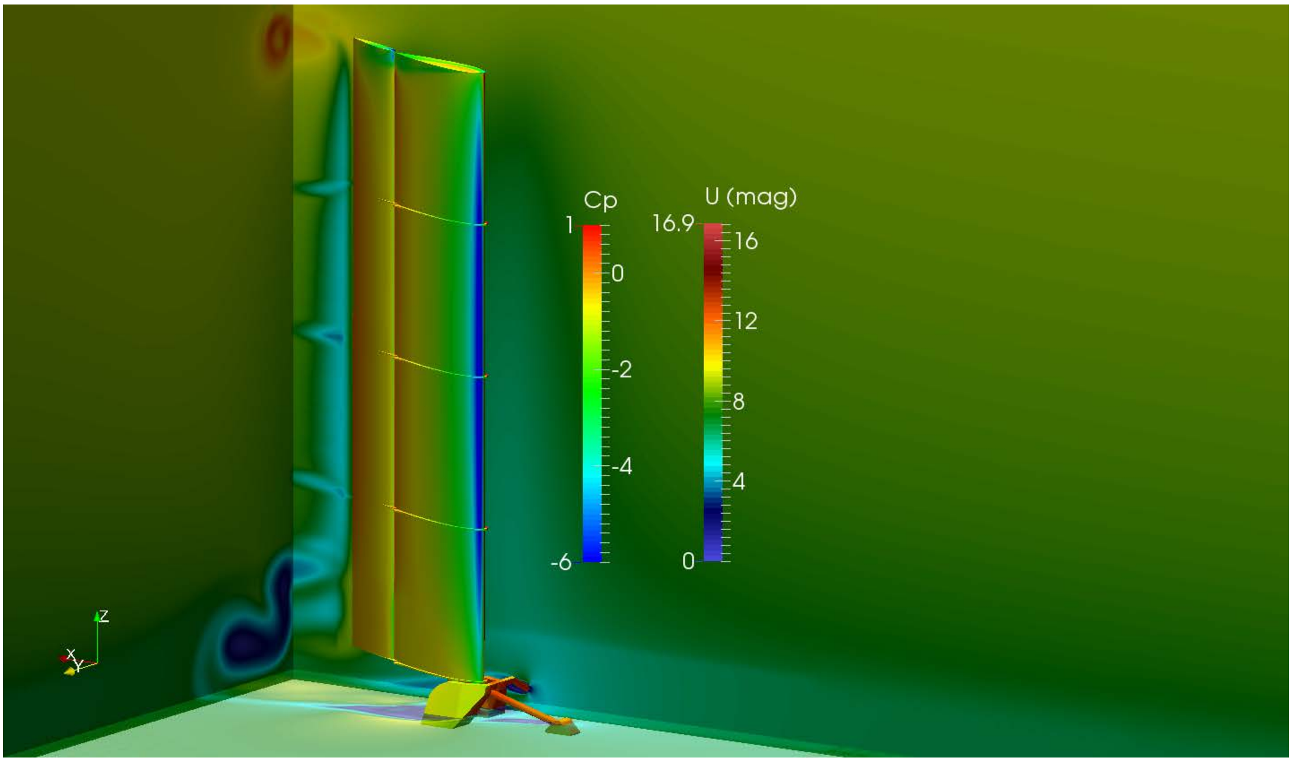


Figure 3 Illustration of single wing mounted on the Panamax geometry

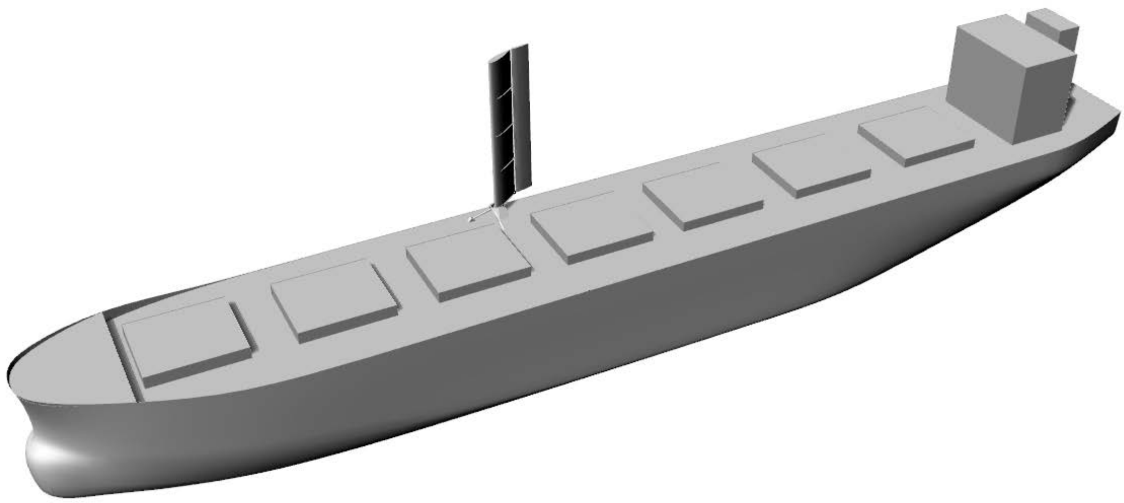
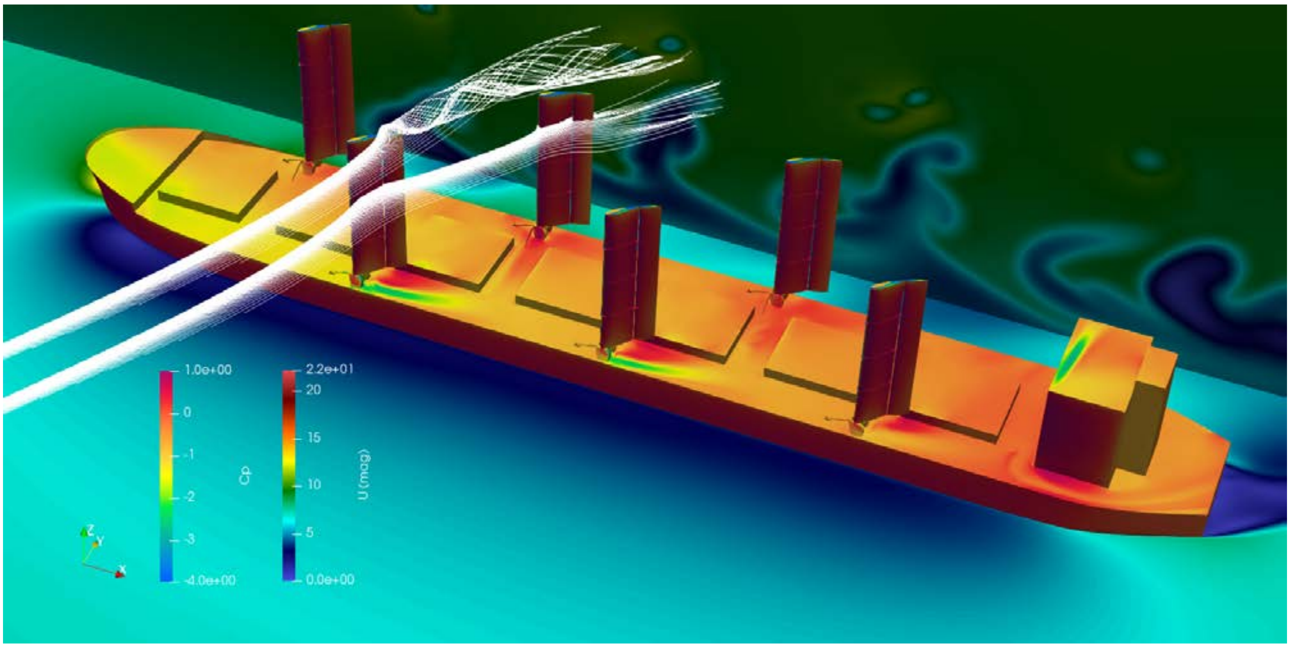


Figure 4 Illustration of the complete rig with six sails mounted on the ship geometry at 15 knots wind speed and 60° wind angle, showing the view from both port and starboard



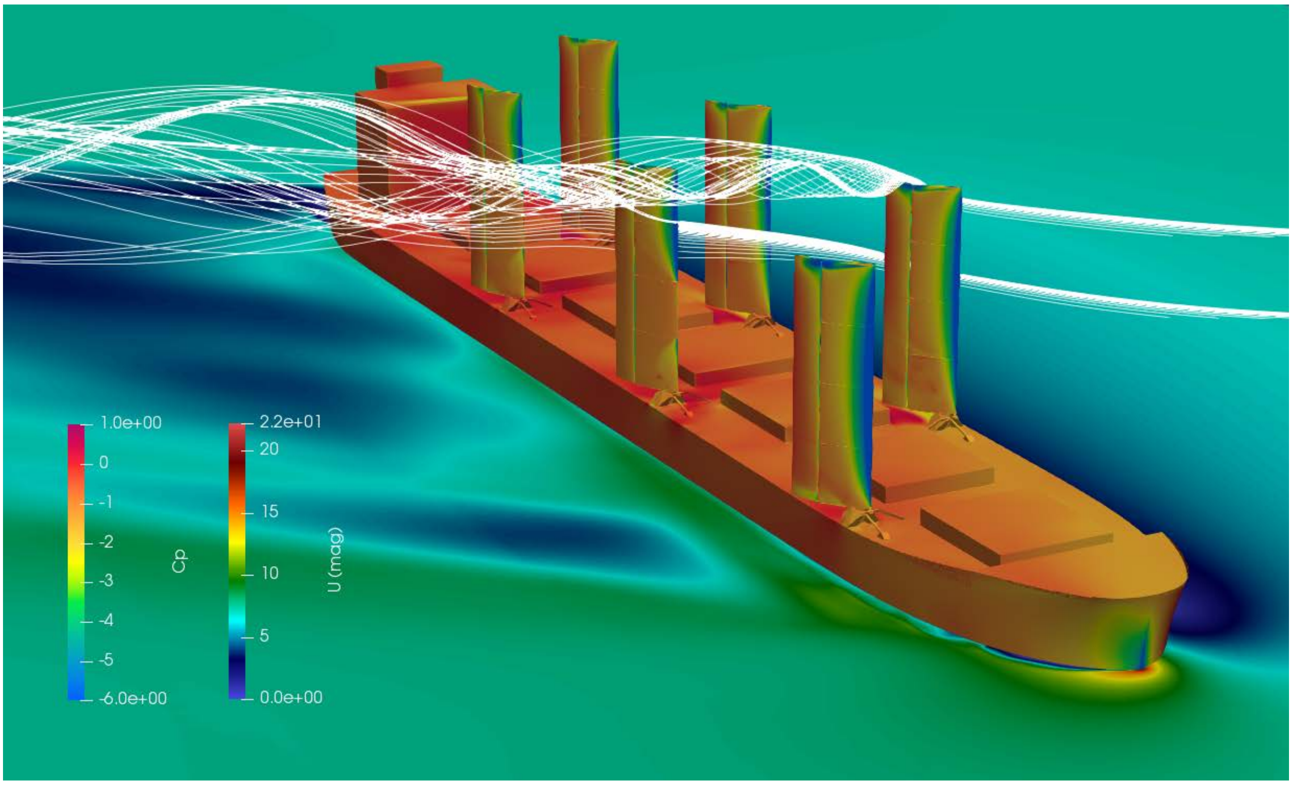


Figure 5 Figure 6 Client supplied ship hull form as viewed from below