REPORT

EcoTrawl – CFD-analysis

Prepared for
ECO Trawls

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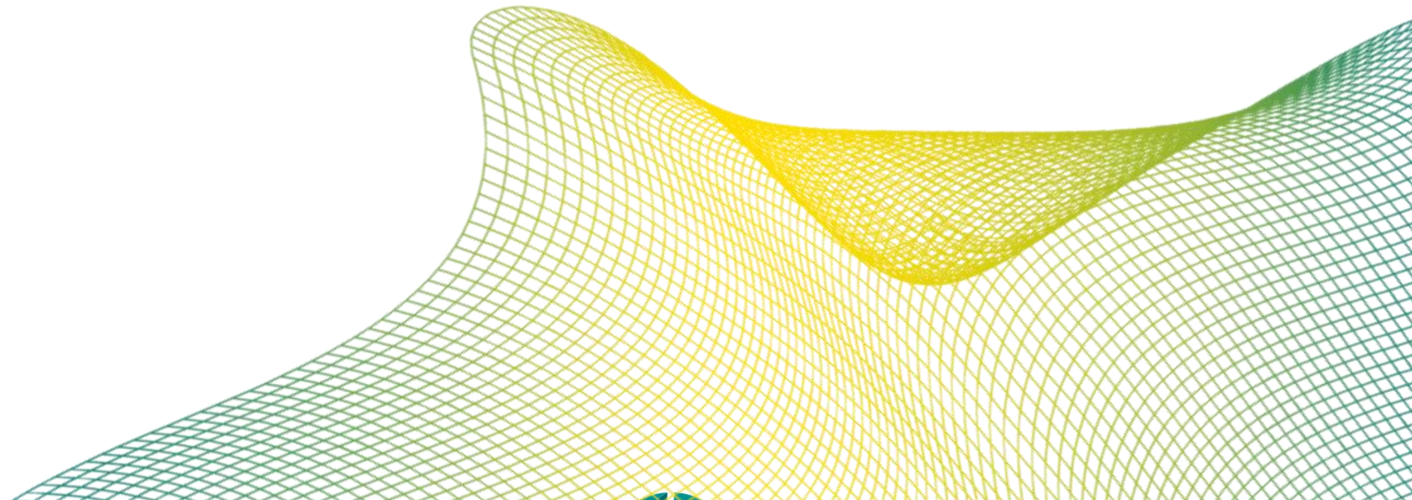

1. Contents

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1. Summary

The ECO Trawl, a self-propelled unit to replace conventional trawl doors, has been optimized with respect to efficiency under trawling conditions, using CFD-analysis. A parametric 3D cad-model was developed, using two contra-rotating propellers inside a duct. The propeller diameter, number of blades, blade area ratio and pitch could be varied.

For the chosen configuration hydrodynamic derivatives determined were through numerical Planar Motion Motions tests, in order to assess and controllability of the unit. The system show straight line stability for a moderately sized rudder.

A conventional trawl door was investigated under the same trawling conditions for comparison of necessary power. Power saving of 30 % during trawling can be expected.

2. Design basis

The chosen trawling speed was 4 knots.

Necessary thrust from each of the two EcoTrawl units is estimated to be 107781 N, which is half the drag of the trawl, plus the resistance of wire between the unit and the trawl, and finally half the resistance of the umbilical between the fishing vessel and the EcoTrawl unit.

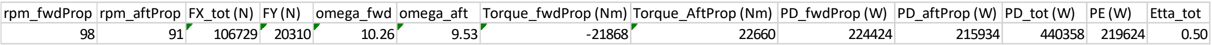
Necessary side force from each EcoTrawl unit was estimated to be 21556 N, in order maintain an angle of 11.31 degrees of the trawl wire relative to forward direction. For comparison, a conventional trawl door would need twice this side force to maintain the same angle.

It is assumed that external forces from the trawl wire and the drag on the umbilical from the fishing vessel, act through the center of gravity. This requires an appropriate mechanism.

Table 1. Characteristics of chosen configuration

Propellller diameter (m)	3.0
Number of blades	3
Blade area ratio, EAR	0.25
Volume (m^3)	8.57
Assumed mass properties	
Mass (kg)	8975
Centre of gravity at origin	
Radii of Gyration	[1.561 m, 1.391 m, 1.391 m]

Condition during trawling at 4 knots; drift angle 5.655 deg, reference condition for PMM tests



rpm_fwdProp	rpm_aftProp	FX_tot (N)	FY (N)	omega_fwd	omega_aft	Torque_fwdProp (Nm)	Torque_AftProp (Nm)	PD_fwdProp (W)	PD_aftProp (W)	PD_tot (W)	PE (W)	Etta_tot
98	91	106729	20310	10.26	9.53	-21868	22660	224424	215934	440358	219624	0.50

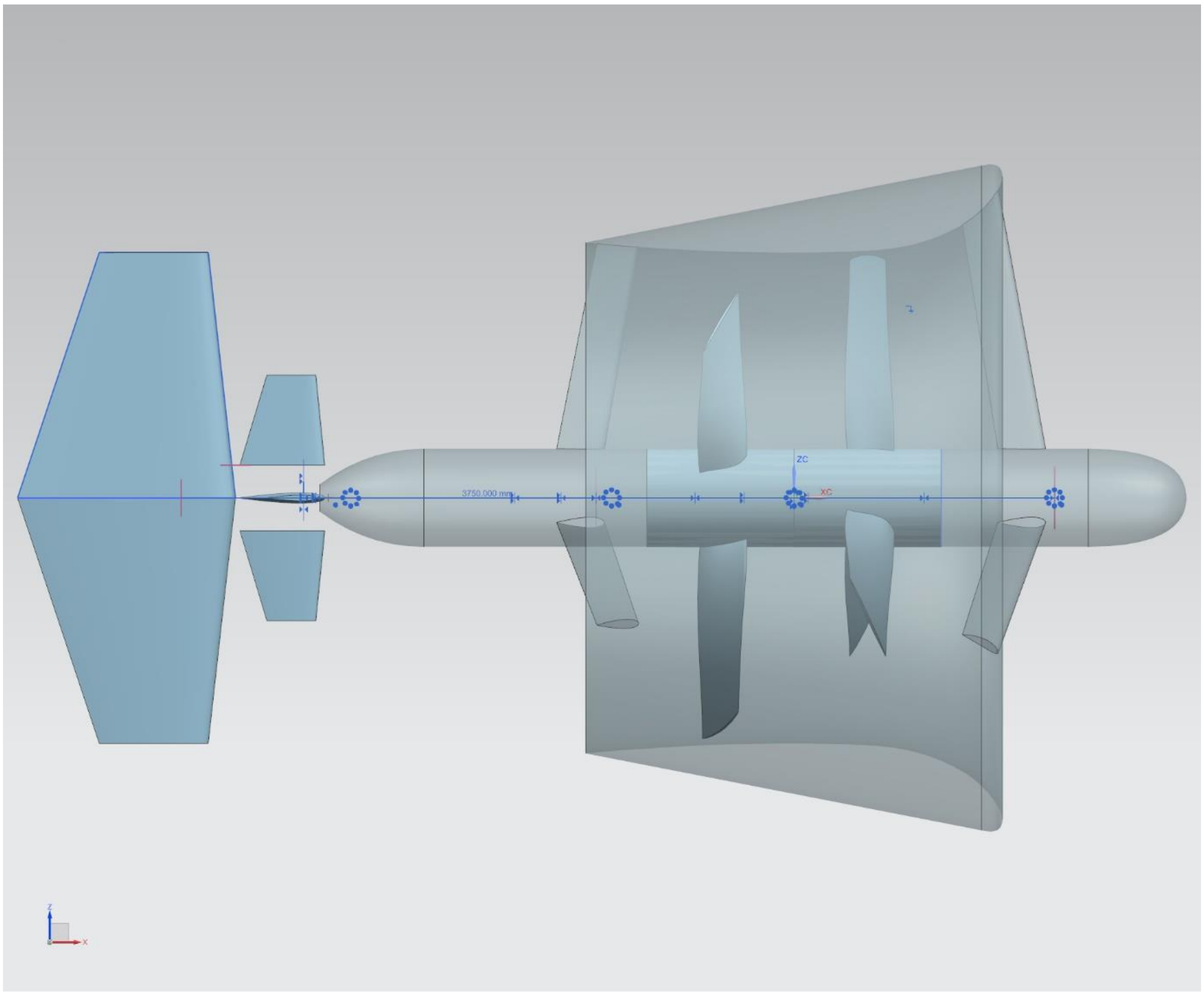


Figure 1. The ECO trawl unit, chosen configuration with respect to diameter and propellers. Necessary rudders will be smaller than indicated by the large rudder of 3m span, which has been shown to give straight line stability by a good margin. The centre of origin is between forward and aft propellers, z-axis positive up, x-axis positive forward along the center line.

3. Propeller test series

Two contra-rotating propellers inside a nozzle was chosen for the necessary thrust at trawling speed and minimizing the resulting roll moment from the propellers.

In order to cancel the roll moment from the propellers, the tests were run with a specified rate of revolutions of the forward propeller. The resulting torque of the forward propeller was applied on the aft propeller, giving typically rate of revolutions 9 % less than that of the forward propeller.

The Wageningen Ka series was used for propeller geometry. The duct was nozzle 19A. The propeller diameters were 0.99, and duct length 0.85, relative to the inner diameter of the duct. Standard NACA-profiles were used for the struts and control surfaces.

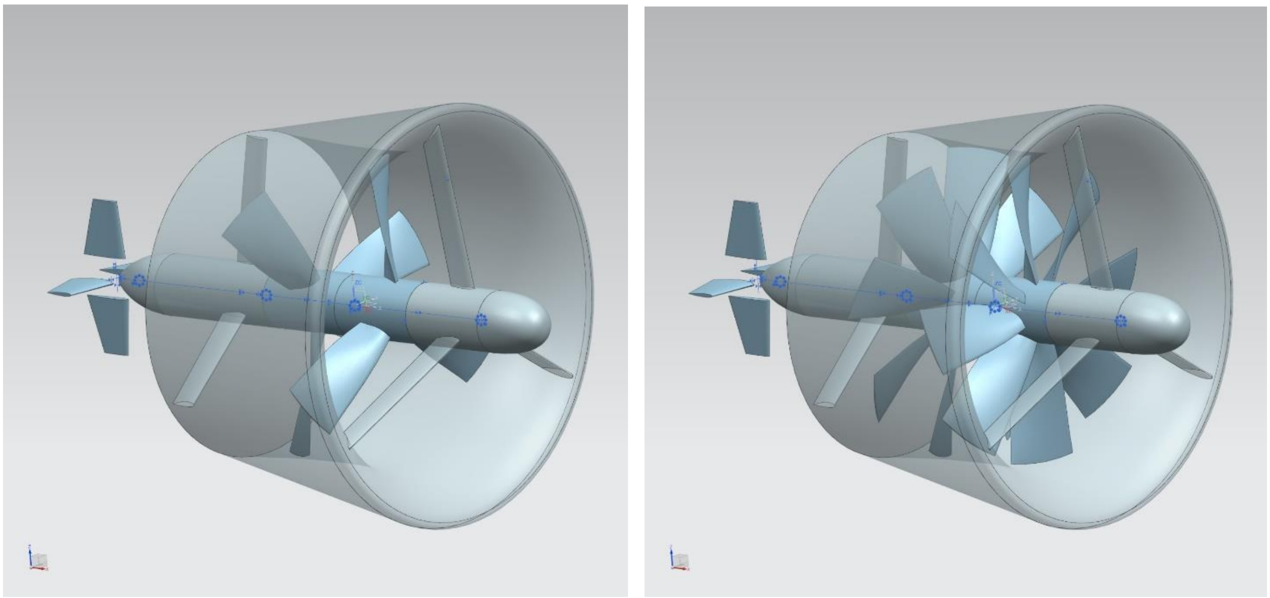


Figure 2. The ECO Trawl with three- and eight-bladed propellers.

For 3 m diameter (nozzle inner diameter) results from variation of number of propeller blades and blade area ratio are given in table 2 and figure 3. The rate of revolutions of the forward propeller was 100 rpm, and the pitch ratio of the propellers, P/D, were 1.25.

The efficiency, etta_tot, is defined by: $etta_{tot} = \frac{T_{tot}}{Q_{fwdProp}\ \omega_{fwdProp} + Q_{aftProp}\ \omega_{aftProp}}$

Ideal efficiencies based the on the nozzle inner diameter of 3 m, are included in the table for comparison. The best result was obtained for blade area ratio, EAR=0.25 and number of blades, z=3, with efficiency, etta_tot, equal to 0.50. The corresponding ideal efficiency is 0.51. Taking into account the outer dimeter of the nozzle, the ideal efficiency would be 0.61.

Table 2. Variation of number of blades and blade area ratio.
D = 3 m, P/D = 1.25, rpm_fwdProp=100.

rpm_fwdProp	z	EAR	rpm_aftProp	Ct	Etta_I	Etta_tot	Thrust_tot (N)	Roll Moment (N)	Thrust_Nozzle (N)	Thrust_FwdProp (N)	Thrust_AftProp (N)	Torque_FwdProp (Nm)	Torque_AftProp (Nm)
100	3	0.25	-93.6	7.40	0.51	0.50	113552	2568	36050	39353	39094	-23250	23214
100	3	0.5	-94.5	6.72	0.53	0.49	103198	2687	32231	36075	35754	-21176	21179
100	3	0.75	-96.4	5.58	0.56	0.46	85661	2615	24561	31584	30217	-18673	18427
100	3	1	-97.4	4.65	0.59	0.38	71426	2525	16099	28638	27234	-19240	18572
100	4	0.25	-92.6	8.06	0.50	0.48	123823	2430	39503	42823	42396	-26247	26239
100	4	0.5	-93.6	7.66	0.51	0.48	117656	2466	37619	40576	40356	-24945	24887
100	4	0.75	-95.5	6.67	0.53	0.47	102392	2572	31666	36128	35344	-22031	21926
100	4	1	-97.4	5.68	0.56	0.43	87187	2777	24954	31819	31030	-19927	20020
100	5	0.25	-92.6	8.75	0.49	0.46	134313	2245	43130	46437	45566	-29507	29523
100	5	0.5	-92.6	8.34	0.49	0.47	127974	2172	41572	43807	43491	-27844	27844
100	5	0.75	-94.5	7.43	0.51	0.46	114017	2405	36431	39383	38982	-24898	24939
100	5	1	-95.5	6.48	0.54	0.45	99556	2574	30487	35275	34441	-22386	22474
100	6	0.25	-91.7	9.38	0.47	0.45	143958	1975	46105	49970	48714	-32870	32916
100	6	0.5	-93.6	8.86	0.48	0.45	136035	2070	44507	46414	45977	-30401	30452
100	6	0.75	-94.5	8.02	0.50	0.45	123194	2196	39837	42353	41795	-27635	27624
100	6	1	-94.5	7.14	0.52	0.44	109616	2309	34539	38402	37367	-25036	24989
100	7	0.25	-91.7	9.85	0.47	0.43	151214	1687	48335	52783	51039	-35829	35878
100	7	0.5	-92.6	9.33	0.47	0.44	143223	1983	47088	48864	48133	-33023	33044
100	7	0.75	-93.6	8.50	0.49	0.44	130558	2040	42498	44774	44074	-30079	30065
100	7	1	-94.5	7.65	0.51	0.43	117468	2204	37538	40768	39870	-27372	27377
100	8	0.25	-91.7	10.53	0.45	0.41	161741	1583	50929	56915	54792	-40011	40088
100	8	0.5	-92.6	9.77	0.47	0.43	149984	1913	49190	51416	50208	-35823	35852
100	8	0.75	-92.6	8.89	0.48	0.43	136447	1902	44655	46721	45890	-32334	32337
100	8	1	-93.6	8.06	0.50	0.42	123803	2065	39896	42788	41853	-29558	29589

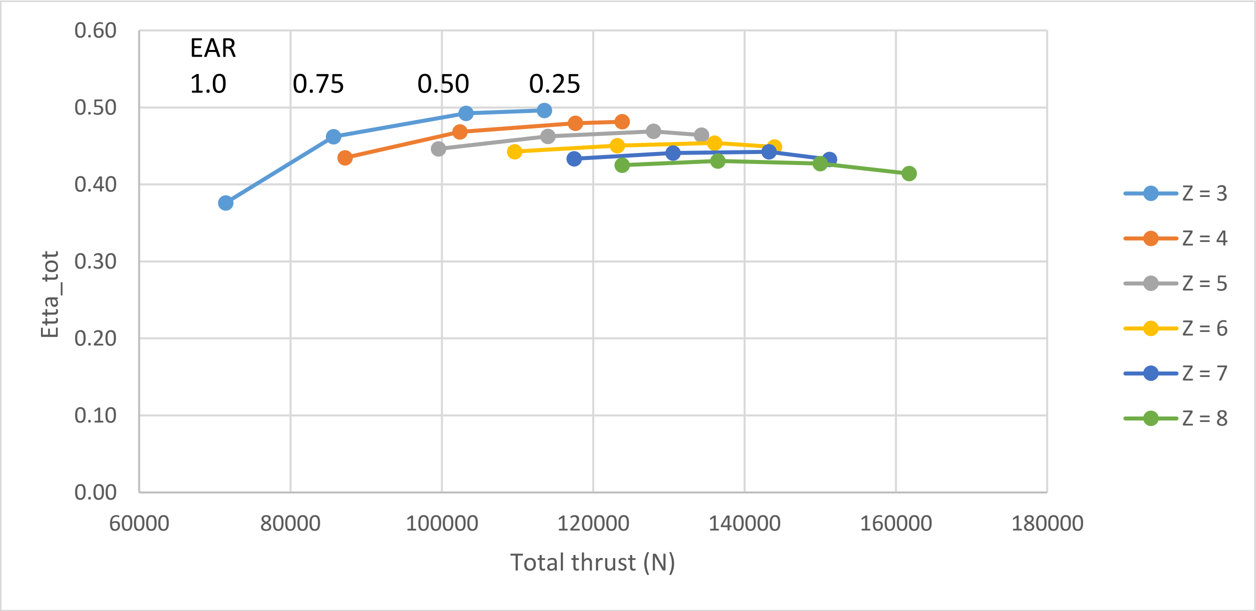


Figure 3. Variation of efficiency with number of blades (z) and blade area ratio (EAR).
D = 3 m, P/D = 1.25, rpm_fwdProp=100.

Results for the chosen configuration with z=3, EAR=0.25 and P/D=1.25 are given in table 3. At rpm_fwProp = 100 and rpm_aftProp=91.7, the total thrust equals the required thrust. For further optimization, different pitch ratios should be studied.

Thrust and torque coefficients are given in figure 4.

Table 3. Variation of rpm for z=3, D = 3 m, EAR=0.25 and P/D=1.25

rpm_fwdProp	rpm_aftProp	Ct	Etta_I	Etta_tot	Thrust_tot (N)	Roll Moment (N)	Thrust_Nozzle (N)	Thrust_FwdProp (N)	Thrust_AftProp (N)	Torque_FwdProp (Nm)	Torque_AftProp (Nm)	J	KT_tot	10*KQ_tot
90.0	-84.0	5.66	0.56	0.53	86867	1834	25609	31167	30901	-18505	18485	0.4573	0.4646	0.6595
92.0	-85.9	5.99	0.55	0.52	91930	1906	27574	32737	32451	-19411	19387	0.4473	0.4705	0.6620
94.0	-87.9	6.33	0.54	0.52	97145	1983	29612	34343	34046	-20338	20313	0.4378	0.4763	0.6644
96.0	-90.7	6.68	0.53	0.51	102498	2056	31725	35983	35669	-21284	21258	0.4287	0.4818	0.6666
98.0	-91.7	7.03	0.52	0.50	107997	2131	33913	37655	37333	-22248	22223	0.4200	0.4872	0.6687
100.0	-93.6	7.40	0.51	0.50	113631	2209	36173	39362	39024	-23233	23206	0.4116	0.4923	0.6706
102.0	-95.5	7.78	0.50	0.49	119409	2289	38509	41103	40751	-24237	24208	0.4035	0.4972	0.6724
104.0	-96.4	8.16	0.50	0.49	125333	2366	40914	42882	42516	-25263	25232	0.3957	0.5020	0.6742
106.0	-98.4	8.56	0.49	0.48	131394	2448	43402	44690	44307	-26305	26273	0.3883	0.5066	0.6757
108.0	-101.2	8.96	0.48	0.47	137600	2534	45959	46534	46139	-27368	27337	0.3811	0.5111	0.6773
110.0	-103.1	9.38	0.47	0.47	143947	2618	48592	48412	48001	-28451	28418	0.3741	0.5154	0.6787

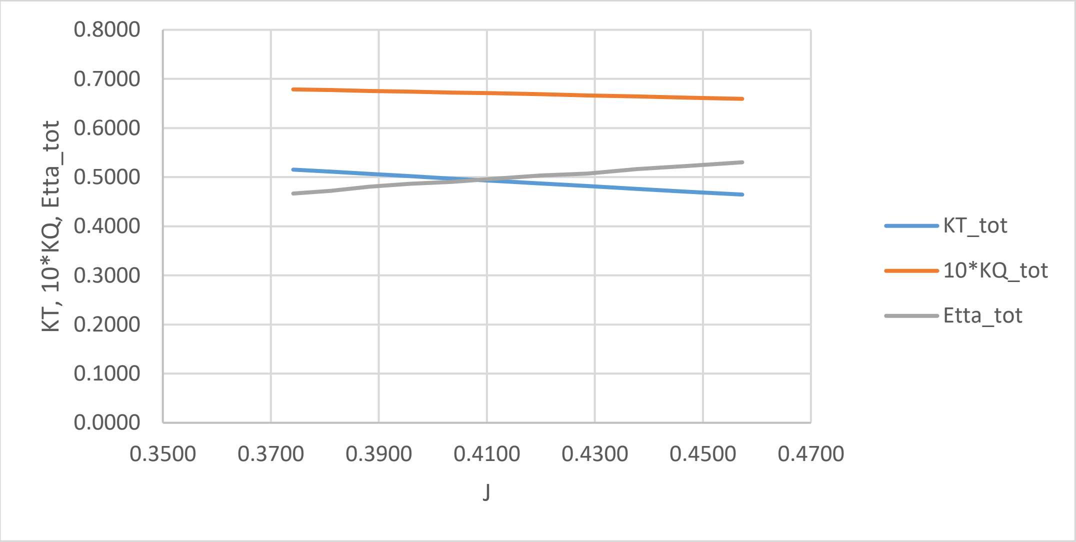


Figure 4. Propeller coefficients (based on rpm_fwdprop) for the ECO Trawl unit for z=3, D = 3 m, EAR=0.25 and P/D=1.25.

4. Maneuvering coeffecients

CFD-analysis with forced sway and yaw motion, equivalent to PMM tests, were carried out in order to find the manuevering coefficients of the EcoTrawl unit, and to assess whether it is stable and controllable when operating in trawling condition. The optimum configuration, with z=3 and EAR=0.25, from the propeller test series was investigated.

Forward speed was constant 2.06 m/s. This was first done at a drift angle of 5.655 degrees, for necessary side force, with the propellers rotating at 98 and 91 rpm respectively, ref. table 1. The control surfaces were removed. Fourier analysis of hull forces and moments, with resulting manuevering coefficients are given in table 4. The idea was to calculate the necessary rudder area and position from lifting line theory, to achieve straight line stability.

For verification a second set of tests were carried at zero drift angle, with and without rudder, see table 5. The 3 m span rudder shown in figure 1 was used. The propellers were represented by actuator discs with corresponding thrust from the condition above.

Motion in a plane defined by positions of the EcoTrawl unit relative to the trawl is considered. For reference, see [1] and [2].

The ITTC (International Towing Tank Conference) standard notation has been used.

The general linear manuevering model is given by:

$$\mathrm{m}\dot{\mathrm{u}}=\mathrm{X}_{\dot{\mathrm{u}}}\mathrm{u}$$

$$m(\dot{v}+ur+\dot{r}x_G\,)=Y_{\dot{v}}\dot{v}\;+\;\;Y_{\dot{r}}\dot{r}\;+Y_v v+Y_r r+Y_\delta\delta \quad (1)$$

$$I_{zz}\dot{r}+mx_G(\dot{v}+ur)=\;N_{\dot{v}}\dot{v}\;+N_{\dot{r}}\dot{r}\;+N_v v+N_r r+N_\delta\delta$$

here $\dot{\mathrm{u}}=0$ and $\delta=0$

External sway force and yaw moment becomes:

$$Y\,=(m-Y_{\dot{v}})\dot{v}\;+(mx_G-\;\;Y_{\dot{r}})\dot{r}-Y_v v+(mu-Y_r)r \quad (2)$$

$$N\,=\left(mx_G-N_{\dot{v}}\right)\dot{v}+(I_{zz}-N_{\dot{r}})\dot{r}-N_v v+(mx_G u-N_r)r$$

By assuming that CG is in the origin we get

$$Y\,=(m-Y_{\dot{v}})\dot{v}\;-Y_{\dot{r}}\dot{r}-Y_v v+(mu-Y_r)r \quad (3)$$

$$N\,=-N_{\dot{v}}\dot{v}+(I_{zz}-N_{\dot{r}})\dot{r}-N_v v-N_r r$$

Furthermore, the mass and moment of inertia was zero in the cfd-analysis with force sway and yaw motion. Hence, the external forces become:

$$Y\,=-Y_{\dot{v}}\dot{v}\;-Y_{\dot{r}}\dot{r}-Y_v v-Y_r r \quad (4)$$

$$N\,=-N_{\dot{v}}\dot{v}-N_{\dot{r}}\dot{r}-N_v v-N_r r$$

The resulting sway force and yaw moment on the hull from the flow due to pressure and shear forces are:

$$Y_H = Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_v v + Y_r r \quad (5)$$

$$N_H = N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} + N_v v + N_r r$$

Pure sway

$$Y_H = Y_{\dot{v}}\dot{v} + Y_v v \quad (6)$$

$$N_H = N_{\dot{v}}\dot{v} + N_v v$$

Pure yaw

$$Y_H = Y_{\dot{r}}\dot{r} + Y_r r \quad (7)$$

$$N_H = N_{\dot{r}}\dot{r} + N_r r$$

The sway and yaw motion are given by

Sway motion:

$$y = a_0 \sin \omega t \quad (8)$$

$$\dot{y} = v = a_0 \omega cos\omega t$$

$$\ddot{y} = \dot{v} = -a_0 \omega^2 sin\omega t$$

Yaw motion:

$$\varphi = \varphi_0 \cos \omega t\,,\ y = a_0 \sin \omega t \quad (9)$$

$$\dot{\varphi} = r = -\varphi_0 \omega sin\omega t$$

$$\ddot{\varphi} = \dot{r} = -\varphi_0 \omega^2 cos\omega t$$

with

$$\varphi_0 = \frac{a_0 \omega}{U}$$

The yaw motion is a combination of sway and yaw in the global system, which gives zero sway velocity in the hull coordinate system, ie pure yaw.

Forces and moments are expressed in a local coordinate system following the sway and yaw motion, ie offset from hull fixed coordinate system by the drift angle. The coefficients are obtained by separating the part of the force and moment in phase with the motion and the part out of phase, through Fourier analysis.

For pure sway the hull forces become:

$$Y_H = Y_{\dot{v}}(-a_0\omega^2 sin\omega t) + Y_v a_0 \omega cos\omega t \quad (10)$$

$$N_H = N_{\dot{v}}(-a_0\omega^2 sin\omega t) + N_v a_0 \omega cos\omega t$$

and the manuevering coefficients are given by:

$$Y_{\dot{v}} = -\frac{Y_{H\,in\,phase}}{a_0\omega^2},\ N_{\dot{v}} = -\frac{N_{H\,in\,phase}}{a_0\omega^2} \quad (11)$$

$$Y_v = \frac{Y_{H\,out\,of\,phase}}{a_0\omega}, \qquad N_v = \frac{N_{H\,out\,of\,phase}}{a_0\omega}$$

Similarly for pure yaw:

$$Y_H = Y_{\dot{r}}(-\varphi_0\omega^2 cos\omega t) + Y_r(-\varphi_0\omega sin\omega t) \quad (12)$$

$$N_H = N_{\dot{r}}(-\varphi_0\omega^2 cos\omega t) + N_r(-\varphi_0\omega sin\omega t)$$

$$Y_{\dot{r}} = -\frac{Y_{H\,in\,phase}}{\varphi_0\omega^2},\ N_{\dot{r}} = -\frac{N_{H\,in\,phase}}{\varphi_0\omega^2} \quad (13)$$

$$Y_r = -\frac{Y_{H\,out\,of\,phase}}{\varphi_0\omega}, \qquad N_r = -\frac{N_{H\,out\,of\,phase}}{\varphi_0\omega}$$

Table 4. Manuevering coefficients from tests with running propellers at drift angle 5.655 deg.

PURE SWAY											
		Sway velocity (m/s)					**Sway acceleration (m/s^2)**				
		fSwayVel(x) = a0 + a1*cos(x*w) + b1*sin(x*w)					fSwayAcc(x) = a0 + a1*cos(x*w) + b1*sin(x*w)				
Period (s)	**Ω**	**a0**	**a1**		**b1**		**a0**	**a1**		**b1**	
2.000	3.142	0.000	0.785		0.000		0.000	0.013		-2.467	
4.000	1.571	0.000	0.393		0.000		0.000	0.002		-0.617	
6.000	1.047	0.000	0.262		0.000		0.000	0.000		-0.274	
8.000	0.785	0.000	0.196		0.000		0.000	0.000		-0.154	
		Sway force, FY (N)					**Yaw moment, MZ (Nm)**				
		fMZ(x) = a0 + a1*cos(x*w) + b1*sin(x*w)					fMZ(x) = a0 + a1*cos(x*w) + b1*sin(x*w)				
Sway amp (m)	**Yaw amp (rad)**	**a0**	**a1 (out of phase)**	**Y_v**	**b1 (in phase)**	**Y_vdot**	**a0**	**a1 (out of phase)**	**N_v**	**b1 (in phase)**	N_vdot
0.250	0.000	20080	-40580	-51668	55870	-22647	11690	-45040	-57347	2102	-852
0.250	0.000	20030	-19560	-49809	14540	-23573	11590	-22980	-58518	501	-812
0.250	0.000	19970	-13100	-50038	6482	-23640	11500	-15340	-58594	196	-716
0.250	0.000	19940	-9879	-50326	3602	-23359	11460	-11490	-58533	83	-540
			Y_v =	**-50460**	**Y_vdot =**	**-23305**		**N_v =**	**-58248**	**N_vdot =**	**-730**
PURE YAW											
		Yaw velocity (rad/s)					**Yaw acceleration (rad/s^2)**				
		fYawVel(x) = a0 + a1*cos(x*w) + b1*sin(x*w)					fYawAcc(x) = a0 + a1*cos(x*w) + b1*sin(x*w)				
Period (s)	**Ω**	**a0**	**a1**		**b1**		**a0**	**a1**		**b1**	
2.000	3.142	0.000	0.000		-1.144		0.000	-3.595		-0.019	
4.000	1.571	0.000	0.000		-0.296		0.000	-0.465		-0.001	
6.000	1.047	0.000	0.000		-0.132		0.000	-0.139		0.000	
8.000	0.785	0.000	0.000		-0.075		0.000	-0.059		0.000	
		Sway force, FY (N)					**Yaw moment, MZ (Nm)**				
		fMZ(x) = a0 + a1*cos(x*w) + b1*sin(x*w)					fMZ(x) = a0 + a1*cos(x*w) + b1*sin(x*w)				
Sway amp (m)	**Yaw amp (rad)**	**a0**	**a1 (in phase)**	**Y_rdot**	**b1 (out of phase)**	**Y_r**	**a0**	**a1 (in phase)**	**N_rdot**	**b1 (out of phase)**	N_r
0.250	0.382	22330	11930	-3318	-108700	-95017	10820	55900	-15549	100100	-87500
0.250	0.191	20140	2452	-5275	-27950	-94458	11520	7531	-16203	23280	-78675
0.250	0.127	20010	1021	-7367	-12640	-95468	11430	2113	-15245	10190	-76964
0.250	0.095	19960	496	-8454	-7192	-96369	11410	857	-14611	5688	-76216
			Y_rdot =	**-6104**	**Y_r =**	**-95328**		**N_rdot =**	**-15402**	**N_r =**	**-79839**

Table 5. Manuevering coefficients from tests with actuator disc and zero drift angle.

PURE SWAY											
		Sway velocity (m/s)					**Sway acceleration (m/s^2)**				
		fSwayVel(x) = a0 + a1*cos(x*w) + b1*sin(x*w)					fSwayAcc(x) = a0 + a1*cos(x*w) + b1*sin(x*w)				
Period (s)	**Ω**	**a0**	**a1**		**b1**		**a0**	**a1**		**b1**	
8.000	0.785	0.000	0.196		0.000		0.000	0.000		-0.154	
		Sway force, FY (N)					**Yaw moment, MZ (Nm)**				
		fMZ(x) = a0 + a1*cos(x*w) + b1*sin(x*w)					fMZ(x) = a0 + a1*cos(x*w) + b1*sin(x*w)				
Sway amp (m)	**Yaw amp (rad)**	**a0**	**a1 (out of phase)**	**Y_v**	**b1 (in phase)**	**Y_vdot**	**a0**	**a1 (out of phase)**	**N_v**	**b1 (in phase)**	N_vdot
No rudder											
0.250	0.000	46	-10160	-51758	2991	-19397	-189	-15090	-76872	694	-4501
With rudder											
0.250	0.000	-48	-12100	-61640	6296	-40830	55	-7812	-39796	-11160	72374
PURE YAW											
		Yaw velocity (rad/s)					**Yaw acceleration (rad/s^2)**				
		fYawVel(x) = a0 + a1*cos(x*w) + b1*sin(x*w)					fYawAcc(x) = a0 + a1*cos(x*w) + b1*sin(x*w)				
Period (s)	**Ω**	**a0**	**a1**		**b1**		**a0**	**a1**		**b1**	
8.000	0.785	0.000	0.000		-0.075		0.000	-0.059		0.000	
		Sway force, FY (N)					**Yaw moment, MZ (Nm)**				
		fMZ(x) = a0 + a1*cos(x*w) + b1*sin(x*w)					fMZ(x) = a0 + a1*cos(x*w) + b1*sin(x*w)				
Sway amp (m)	**Yaw amp (rad)**	**a0**	**a1 (in phase)**	**Y_rdot**	**b1 (out of phase)**	**Y_r**	**a0**	**a1 (in phase)**	**N_rdot**	**b1 (out of phase)**	**N_r**
No rudder											
0.250	0.095	-40	614.8	**-10487.888**	-6795	**-91049.176**	29	1293	**-22057.318**	2899	**-38844.969**
With rudder											
0.250	0.095	-39	6846	**-116786.080**	-16060	**-215194.962**	43	964	**-16446.605**	37980	**-508910.626**

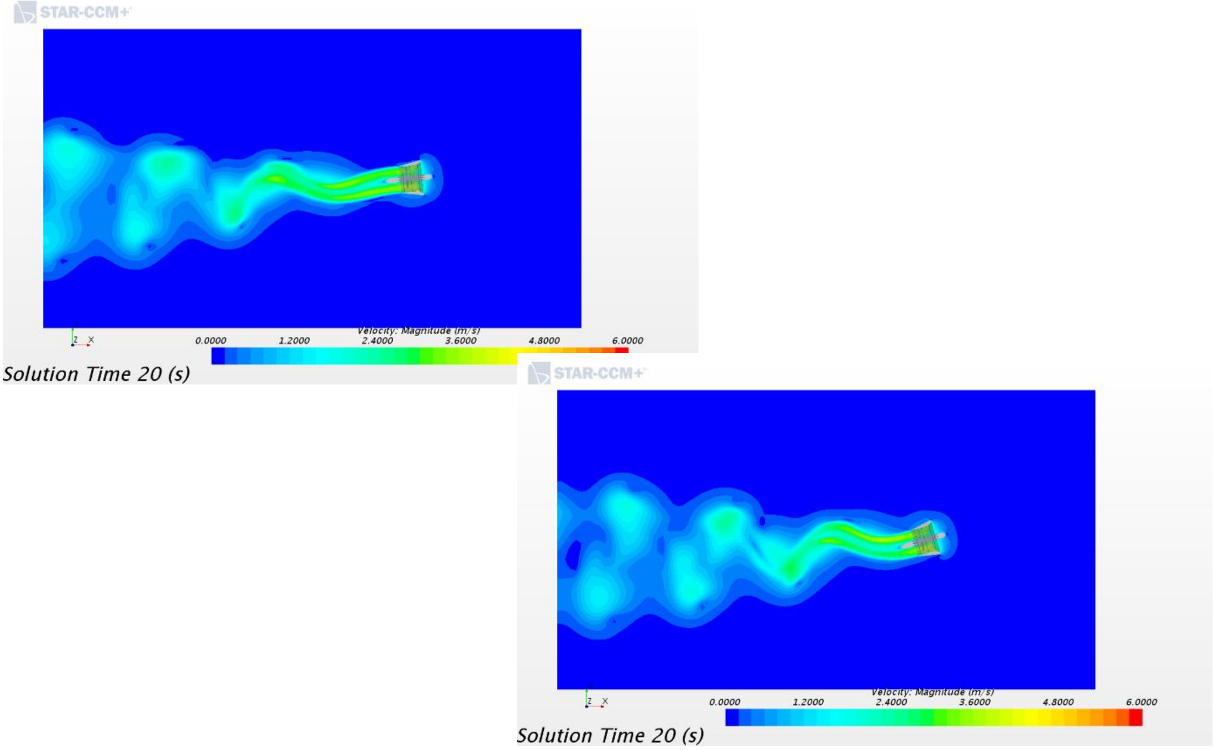


Figure 5.Tests with running propellers at drift angle 5.655 deg. Pure sway top left, pure yaw bottom right, T=4 s.

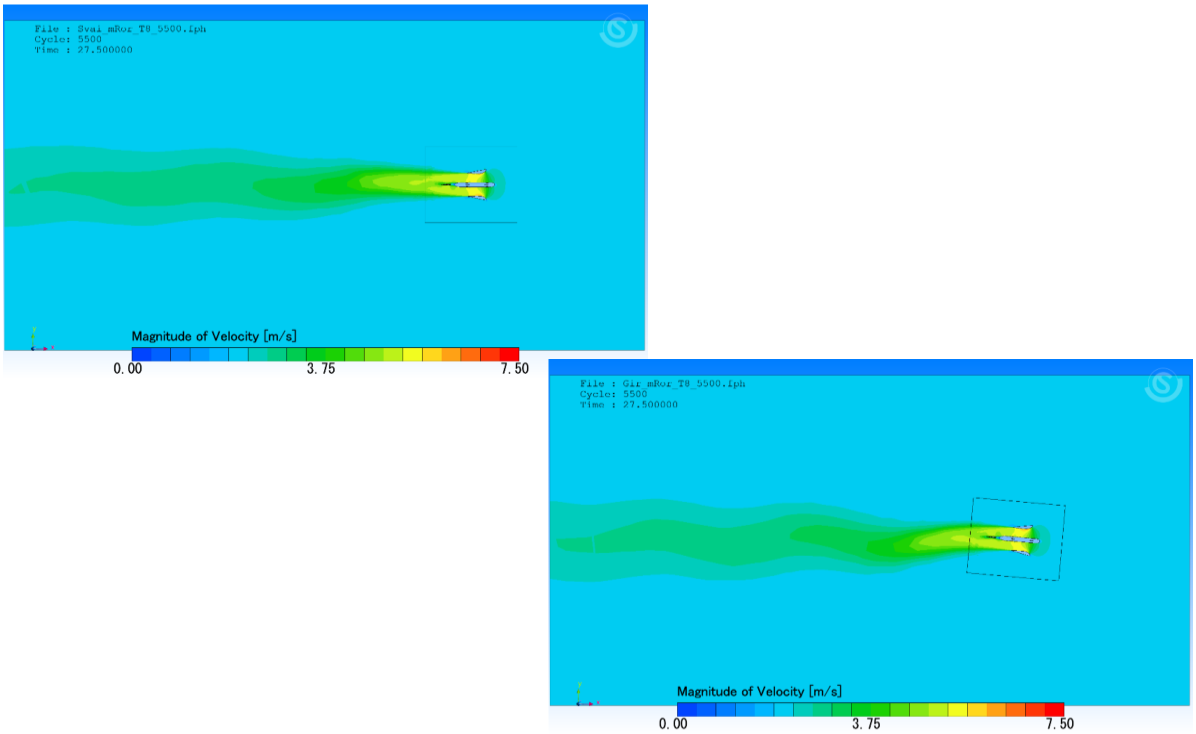


Figure 6. Tests with actuator disc and rudder at zero drift angle. Pure sway top left, pure yaw bottom right, T=8 s

5. Dynamic stability

A vessel that maintains a straight course after a disturbance with the rudder(s) fixed at zero angle, is said to have straight line stability. This is strictly not necessary. However, the vessel will need to have directional stability in order to be controllable. This means that the vessel, through use of the rudder(s), is able to maintain the original direction after a disturbance.

A vessel with straight line stability does also have directional stability.

From (1)

$$(m - Y_{\dot{v}})\dot{v} + (mx_G - Y_{\dot{r}})\dot{r} - Y_v v + (mu - Y_r)r = Y_\delta \delta \quad (14)$$

$$(mx_G - N_{\dot{v}})\dot{v} + (I_{zz} - N_{\dot{r}})\dot{r} - N_v v + (mx_G u - N_r)r = N_\delta \delta$$

The instantaneous rudder angle is expressed by $\delta = k_1 r + k_2 \varphi$, where φ is the course deviation and *r* the yaw rate.

The sway dependence in (14) can be removed by combining the sway and yaw equations resulting in one higher order differential equation for yaw. For stick fixed, $\delta = 0$, we get a homogeneous second order equation:

$$(AD^2 + BD + C)r = 0,\ with\ D = \frac{d}{dt} \quad (15)$$

$$A = (N_{\dot{r}} - I_{zz})(Y_{\dot{v}} - m) - (Y_{\dot{r}} - mx_G)(N_{\dot{v}} - mx_G)$$

$$B = (N_{\dot{r}} - I_{zz})Y_v + (N_r - mx_G u)(Y_{\dot{v}} - m) - (Y_{\dot{r}} - mx_G)N_v - (Y_r - mu)(N_{\dot{v}} - mx_G)$$

$$C = (N_r - mx_G u)Y_v - (Y_r - mu)N_v$$

With the solution

$$r = C_{r_1} e^{\sigma_1} t + C_{r_2} e^{\sigma_2} t$$

$$\sigma_{1,2} = \frac{1}{2}\left(-\frac{B}{A} \pm \sqrt{\left(\frac{B}{A}\right)^2 - 4\frac{C}{A}}\right)$$

The real parts of $\sigma_{1,2}$ have to be negative for disturbance to die out with time. It can be shown that they are negative for $C > 0$, or:

$$l_v \equiv \frac{N_v}{Y_v} < \frac{N_{r-} mx_G u}{Y_r - mu} \equiv l_r$$

This means that straight line stability is obtained when the point of application of yaw force is forward of the point of application of sway force.

Results are given in table 6. Estimated effect of rudders are also included. Lifting line theory with elliptic lift distribution has been used to estimate effect on damping. Added mass of a corresponding cylinder has used for correction of acceleration terms. The effect increased speed in propeller slipstream was on lift was not considered.

Table 6. Straight line stability

Point of application sway and yaw forces (m)	$l_v \equiv \frac{N_v}{Y_v}$	$\frac{N_{r-}mx_Gu}{Y_r - mu} \equiv l_r$
Running propellers at drift angle 5.655 deg, no rudder	1.154	0.701
Running propellers at drift angle 5.655 deg, *Estimated effect of 3 m span / 1 m chord rudder, at 3.75 m aft of CG*	0.268	1.274
Running propellers at drift angle 5.655 deg, *Estimated effect of 1.5 m span / 1 m chord rudder, at 3.0 m aft of CG*	0.851	0.862
Actuator disc, zero drift angle, no rudder	1.485	0.355
Actuator disc, zero drift angle, 3 m span rudder at 3.75 m aft of CG, ref. fig 1.	0.646	2.178

Without rudder the EcoTrawl unit is unstable. The tested 3 m span rudder is more than adequate for straight line stability. The estimated effect of 1.5 m span rudder indicate that this is sufficient for straight line stability.

6. Conventional trawl door

Lift and drag with angle of attack are given in table 7 and figure 7 for a conventional trawl door at 4 knots. Figure 8 show the flow at 20 degrees angle of attack.

The trawl door had a span of 5 m and a chord of 2m. To achieve the necessary 2*21556 N side force, the projected area has scaled by 1.2755, i.e. the scaled span equals 5.65m and the scaled chord equals 2.26 m.

Table 7. Drag and lift (side force) of a conventional trawl door at 4 knots.

angle of attack (deg)	Drag (N)	Lift (N)	Drag_scaled (N)	Lift_scaled (N)
0.0	1.80E+03	1.41E+04	2.30E+03	1.80E+04
2.5	2.24E+03	1.62E+04	2.86E+03	2.07E+04
5.0	2.92E+03	1.95E+04	3.73E+03	2.49E+04
7.5	3.63E+03	2.21E+04	4.63E+03	2.82E+04
10.0	4.44E+03	2.48E+04	5.66E+03	3.17E+04
12.5	5.34E+03	2.75E+04	6.81E+03	3.51E+04
14.0	5.88E+03	2.89E+04	7.50E+03	3.69E+04
14.5	6.03E+03	2.93E+04	7.70E+03	3.74E+04
15.0	6.28E+03	2.99E+04	8.00E+03	3.82E+04
15.5	6.46E+03	3.04E+04	8.24E+03	3.87E+04
16.0	6.65E+03	3.08E+04	8.49E+03	3.93E+04
17.5	7.23E+03	3.21E+04	9.22E+03	4.09E+04
18.5	7.61E+03	3.29E+04	9.71E+03	4.19E+04
19.0	7.74E+03	3.30E+04	9.87E+03	4.20E+04
19.5	7.96E+03	3.33E+04	1.02E+04	4.25E+04
20.0	8.22E+03	3.38E+04	1.05E+04	4.32E+04
20.5	8.23E+03	3.35E+04	1.05E+04	4.27E+04
21.0	8.17E+03	3.25E+04	1.04E+04	4.15E+04
21.5	8.19E+03	3.14E+04	1.04E+04	4.00E+04
22.5	8.40E+03	3.09E+04	1.07E+04	3.94E+04
25.0	8.83E+03	2.85E+04	1.13E+04	3.64E+04

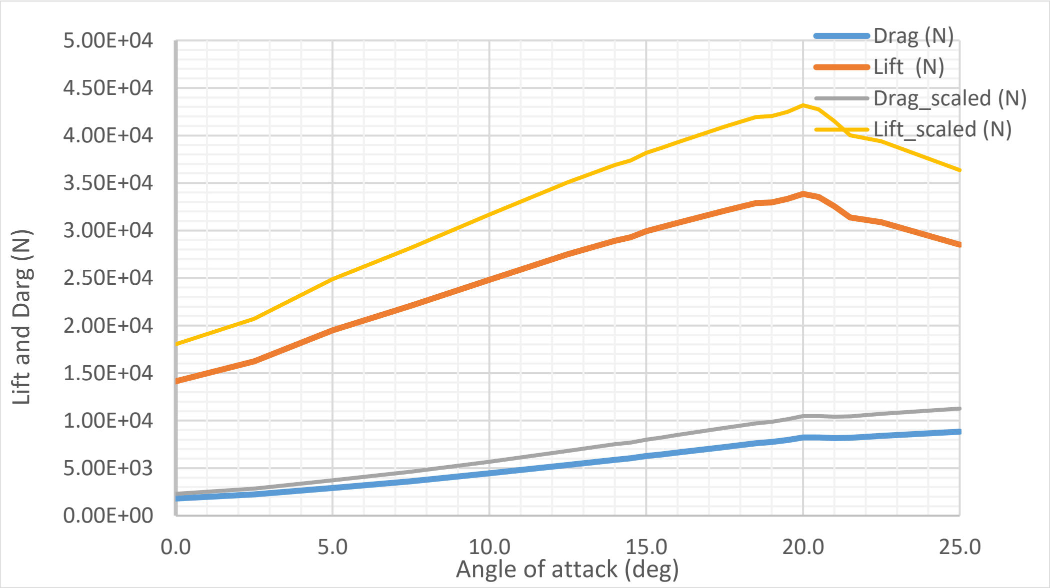


Figure 7.. Drag and lift (side force) of a conventional trawl door at 4 knots.

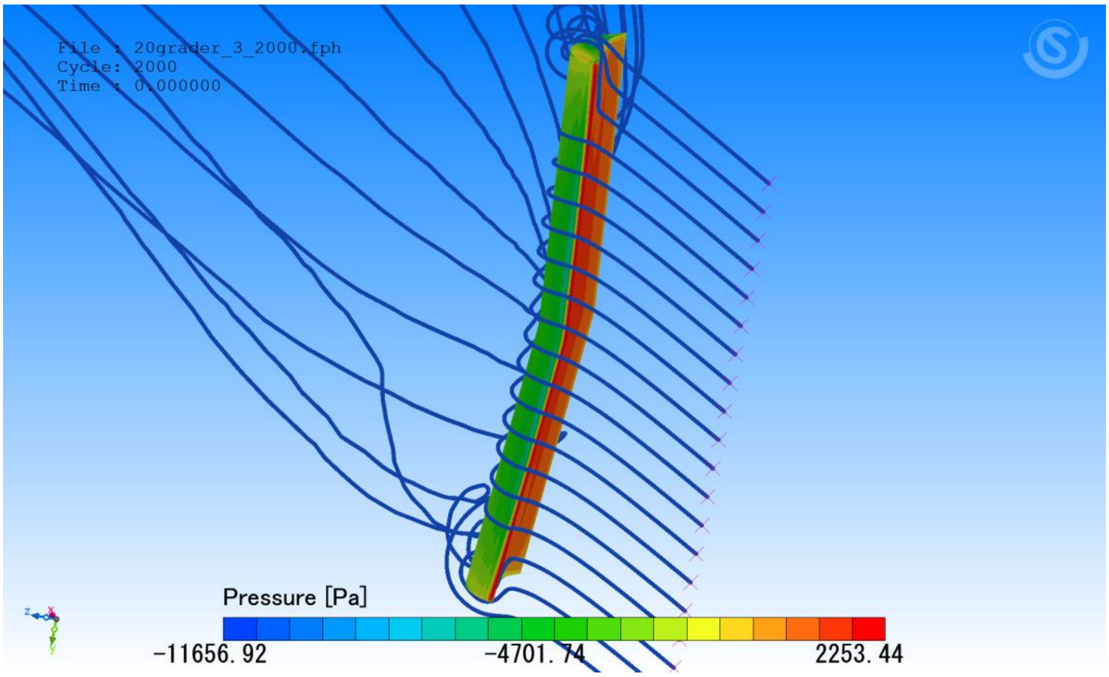


Figure 8. Conventional trawl door at 20 degrees angle of attack.

7. Comparison of necessary power during trawling

Comparisons of necessary power during trawling have been made between the use of EcoTrawl units and conventional trawl doors for trawl speed 4 knots. The comparisons are made with and without the effect of the estimated resistance of the fishing vessel and the umbilical / wire between the fishing vessel and EcoTrawl / trawl door. For simplicity ideal efficiency of propeller has been assumed for the fishing vessel.

Conventional trawling

Drag:

Drag of 2 trawl doors: 2*10484 = 20968 (N)

Total drag of trawl and wire 2*107781 = 215562 (N)

Estimated hull resistance 40000 (N)

Drag_total1 = 276530 (N)

Drag_total2= 236530 (N)

Effective power:

PE1 = 569037 (W)

PE2 = 486726 (W)

Ideal efficiency for 3 m diameter propeller of fishing vessel:

Etta_i1 = 0.374

Etta_i2 = 0.398

Delivered power:

PD1_conv = 1521489 (W) = 1521 (kW)

PD2_convc = 1222930 (W) = 1223 (kW)

EcoTrawl

Delivered power 2*EcoTrawl, ref. table 1   2*441000 (W) = 882 (kW) = PD2_EcoTrawl

Fishing vessel

Estimated hull resistance	40000 (N)
Effective power	82311 (W)
Ideal efficiency for 3 m diameter propeller of fishing vessel	Etta_i = 0.69
Delivered power	119291 (W)

PD1_EcoTrawl = 1001 (kW)

PD2_EcoTrawl = 882 (kW)

Power comparison

PD1_EcoTrawl / PD1_conv = 1001/1521 = 0.66

PD2_EcoTrawl / PD2_conv = 882/1223 = 0.72

8. Conclusions

- By using a combination of speed and torque control, the contra rotating propellers the heel moment on the EcoTrawl is eliminated.
- Straight line stability is achieved with a rudder of moderate size.
- A power saving of about 30 % can be expected during trawling when using the EcoTrawl units instead of conventional trawl doors.

Suggested further work:

- Development and testing of control algorithm and a full 6 degree of maneuvering model.
- Include effect of forces from trawl wire and umbilical
- Further propeller optimization