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Wind Influence on Ship Manoeuvrability – a Turning Circle Analysis

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ABSTRACT: Ship manoeuvrability is a wide term which consist of number of various parameters. Knowing the influence of these parameters on ship manoeuvrability is a first condition to ensure and maintain safe navigation. However, many of these parameters are external forces and, in some cases, cannot be calculated and prediction may be complicated. Analysing the influence of external forces can give as an insight into ship manoeuvrability when such external force occurs. The main purpose of this paper is to analyse the influence of wind on ship manoeuvrability. The best way to make such analysis is during turning circle because in this case wind acts in all 360°. Analysis is made using empirical equations and in situ with the real vessel. The results provide the better understanding of vessel trajectory and show that in some cases vessel may respond in unexpected manner.

1 INTRODUCTION

Safe manoeuvring implies knowing all characteristics which may influence ship behaviour. Ship manoeuvring is influenced by changeable and unchangeable forces. Changeable forces are mostly external forces of wind, waves, sea currents and interaction. Unchangeable forces are mostly ship dimensions and its manoeuvring system (engine, rudder, etc.). This paper analyses influence of wind force on ship manoeuvrability, more specific the influence of ship lateral wind force on ship above water areas. That wind force is pronounced on specific types of ships like cruise ships, Ro-Ro passenger ships, car carriers, container vessels, etc.

Similar analysis was conducted by other authors- Authors Seong-Gi.S., Mahbub M. [5] point out that the great importance of safe manoeuvring lies in knowing where pivot point is and author Kalinovcic H. [1] described different methods to assess ship manoeuvrability, standards and criteria for ship manoeuvrability. The effect of wind force is analysed by authors Pratama Putra M., Aisjah A.S. [4] where the wind effect was modelled, and wind disturbance changed initial actual heading yaw at different attack angles. Authors Ueno et al. proposed a simple method to estimate wind load coefficients. Using ship structural parameters and specific ship type give simple and reliable method for estimating wind loads. Author Zelazny K. [6] provides analysis of wind load on moving ship. This paper also analyses wind load coefficients which represent the unknown part of wind load.

2 WIND LOAD EFFECT ON SHIP MOTION

Wind force effect on ship motion can be observed through three basic situations: when wind force acts longitudinally towards the ship bow or stern and when the wind force act transverse in regard to ship centreline. Beside these three basic situations, wind force may act on ship from any other direction. Ship motion, regardless on wind force, depends on several different factors as:

- Above water surface and its layout (including deck cargo),
- Location of pivot point,
- Ship trim.

If the ratio of above and underwater surface is in order that above water area is greatly larger than underwater area, influence of wind force will be large. In case when ship underwater area is larger than above water area the influence of wind force will be smaller and in that case wind force has to act longer to overcome ship moment of inertia in order to archive ship drift.

Wind force effect depends on if the ship is carrying any deck cargo, such as containers, where fore and aft area ration may affect location of ship pivot point. That means if the ship pivot point is not in line with the wind force acting point the result is turning moment.

When the ship is not moving and is at even keel, the pivot point will be located near the ship gravity centre which is approximately around the midship. If the fore/aft above ship area is such that wind force acting point in in the line with the pivot point, the ship will position parallel with the wind force and there will be no turning momentum. In case that above water area is larger at stern/bow, the wind force acting point will be located closer to the stern/bow and there will be turning momentum.

However, if the ship is moving through the water, the pivot point will move towards the direction of moving. If the ship is moving forward the pivot point is also moving forward, approximately to the ¼ of the ship length from the bow. In that case if the wind force acting point is located on the stern the turning moment will turn ship bow toward the wind. If the ship is moving backward the pivot point will move toward the stern, approximately ¼ of the ship length from the stern. If the wind force acting point is on the bow the turning momentum will turn ship stern towards the wind.

Beside the turning momentum, the wind force will cause the ship heel angle. The turning and heeling momentum lever can be calculated using following expression [3]:

$$l_{w1} = \frac{P \cdot A \cdot Z}{1000 \cdot g \cdot \Delta}$$

where:
P – wind pressure (N/m^2),
A – lateral ship surface (m^2),
Z – vertical distance between surface point of gravity and underwater area centre of gravity (m),
Δ - displacement (t),
g – earth acceleration (9,81 m/s^2).

Wind pressure can be determined using following expression [3]:

$$P = C_{v(a)} \cdot \frac{1}{2} \cdot \rho_z \cdot Vr_v^2$$

where:
$C_{v(a)}$ – ship resistant coefficient. Its value depends on which angle wind acts on ship hull. For the Ro-Ro passenger ships its value is 0,85 for wind acting on lateral area and 0,95 for wind acting on frontal area [2].
ρ_z – air density (kg/m^3),
Vr_v – wind relative speed (m/s).

Beside turning moment wind force may case following effects:

- Speed increment, if the ship is moving downwind,
- Speed decrement, if the ship is moving upwind,
- Drift angle, if the wind force acts lateral to the centreline. Drift angle is angle between the ship heading and course over ground.

3 WIND FORCE CALCULATION

Influence of the wind force, acting on the above water ship surfaces, will depend on wind speed and attack angle. In most cases the greatest impact wind has at angles between 60° - 120° in regard to ship centreline.

In order to archive correct lateral above water surface ship side view plan can be used. Ship side plan silhouette is then divided in 1 meter height parts (Figure 1). That enables easier calculation of each part square surface area, where imperfections at bow or stern are negligible and to include different wind effect at different heights.

For the purpose of this paper in research Ro-Ro passenger ship Dubrovnik was used (Table 2). Using ship side plan lateral surface was calculated and specific wind impact at different height was calculated using dimensionless coefficients obtained from Schoeneich research.

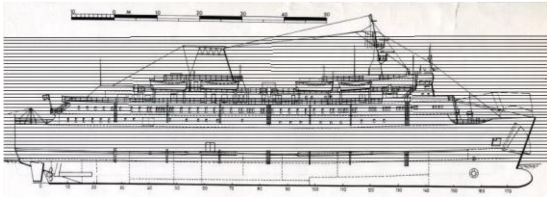

Figure 1. Ship side view plan division into 1 meter height parts to calculate longitudinal area (Source: authors)

Calculation process is shown in Table 1, where the used wind speed is 20 knots (10 m/s), air pressure 1013 hPa and 0 °C air temperature. In Table 1 following abbreviations were used:

1. *Ah (m^2)* – dissected part of ship side plan lateral area (1 meter in height · LOA),
2. *h(m)* – height from ship bottom to dissected part centre of gravity,
3. *Ah·h (m^3)* – represent momentum of each dissected area,
4. *P_{mid} (N/m^2)* – wind pressure median,
5. *M_{VVL} (Nm)* – wind momentum at each dissected area and total sum of this column is wind lateral momentum (obtained by multiplication of *Ah·h* and *P_{mid}*),

Table 1. Wind force and momentum effect calculation (Source: authors)

Height above water line	Ah (m^2)	h (m)	$Ah \times h$ (m^3)	$Psred$ (N/m^2)	Mv_{VL} (Nm)	Fv (N)
0-1m	118,5	0,5	59,25	17,75	1051,69	2103,38
1-2m	119,0	1,5	178,5	26,91	4803,44	3202,29
2-3m	119,5	2,5	298,75	33,09	9885,64	3954,26
3-4m	119,8	3,5	419,3	37,91	15895,66	4541,62
4-5m	120,2	4,5	540,9	42,13	22788,12	5064,03
5-6m	120,5	5,5	662,75	45,93	30440,11	5534,57
6-7m	120,9	6,5	785,85	49,30	38742,41	5960,37
7-8m	121,1	7,5	908,25	52,28	47483,31	6331,11
8-9m	112,5	8,5	956,25	54,88	52479,00	6174,00
9-10m	103,0	9,5	978,5	57,12	55891,92	5883,36
10-11m	100,0	10,5	1050	59,01	61960,50	5901,00
11-12m	92,0	11,5	1058	60,64	64157,12	5578,88
12-13m	91,0	12,5	1137,5	62,09	70627,38	5650,19
13-14m	86,0	13,5	1161	58,72	68173,92	5049,92
14-15m	85,0	14,5	1232,5	64,65	79681,13	5495,25
15-16m	82,0	15,5	1271	65,80	83631,80	5395,60
16-17m	64,0	16,5	1056	66,89	70635,84	4280,96
17-18m	57,0	17,5	997,5	67,91	67740,23	3870,87
18-19m	26,5	18,5	490,25	68,88	33768,42	1825,32
19-20m	21,0	19,5	409,5	69,79	28579,01	1465,59
20-21m	11,5	20,5	235,75	65,42	15422,77	752,33
21-22m	8,8	21,5	189,2	71,47	13522,12	628,94
22-23m	8	22,5	180	72,23	13001,40	577,84
23-24m	3,5	23,5	82,25	72,96	6000,96	255,36
24-25m	2	24,5	49	73,65	3608,85	147,30
25-26m	0,8	25,5	20,4	74,30	1515,72	59,44
26-27m	0,7	26,5	18,55	74,92	1389,77	52,44
27-28m	0,5	27,5	13,75	75,51	1038,26	37,75
28-29m	0,35	28,5	9,975	76,08	758,90	26,63
29-30m	0,2	29,5	5,9	76,63	452,12	15,33
ΣA_h=1915,85		$\Sigma A_h \cdot h$=16456,33		ΣMv_{VL}=965127,52		ΣF_v=95815,93

6. Fv (N) – wind force at each dissected part and total sum of this column is wind lateral force (obtained by multiplication of Ah and P_{mid}).

From Table 1 additional data following data were obtained:

1. $\Sigma A_h \cdot h$ – total above water surface momentum (m3),
2. ΣA_h – total above water lateral surface (m3),
3. ΣMv_{VL} – wind lateral momentum (Nm),
4. ΣF_v - wind lateral force (N).

Beside before mentioned data, additional data is calculated:

1. h_{lat} - Lateral above water surface centre of gravity (m):

$$h_{lat} = \frac{\sum A_h \cdot h}{\sum A_h} = \frac{16456,33}{1915,85} = 8,59\ m$$

2. h_{wind} – centre of gravity of acting wind force (m):

$$h_{wind} = \frac{\sum Mv_{VL}}{\sum F_v} = \frac{965127,52}{95815,93} = 10,07\ m$$

3. P_{mid} – average wind fore pressure (N/m^2):

$$P_{mid} = \frac{\sum F_v}{\sum A_h} = \frac{95815,93}{1915,85} = 50,01\ N/m^2$$

4. Analysis of wind influence on ship manoeuvrability

In order to gather reliable data for this research Ro-Pax ship Dubrovnik was used. The Ro-Pax ship Dubrovnik data is shown in Table 2.

Table 2. Ro-Pax ship Dubrovnik technical data

Ship name	Dubrovnik
Year built	1979
Summer deadweight	1310
LOA	122 m
LBP	116 m
Breadth	18.83 m
Draught	4,8 m
Max. speed	21 knots
Number and type of propellers	2 controllable pitch propellers
Number of rudders	2
Passenger capacity	1200
Cars capacity:	300

The experiment consisted of making turning circles (over port and starboard side) on two different conditions. First experiment was conduced 21 nautical mile out of port Ancona and second experiment in Croatian territorial waters 1,5 nautical mile off coast. Ship instruments were used to collect data such as ship speed (speedometer for ship speed through water and GPS for speed over ground), ECDIS for plotting ship position and anemometer for wind speed and direction. To analyse influence of wind following conditions had to be met: sea state bellow 1 of Beaufort scale, sea current under 0.5 knot and wind speed of 20 knots. That conditions were obtained on second experiment position where experiment took place. First experiment was conducted on conditions where wind, sea current speed were 0 knots and sea were calm, to obtain control data.

Both experiments were made in following order and procedure. First, ship speed and curse had to be constant and stabilised. Then, rudder was turned full to port/starboard (35°) until full circle was made. For every phase of turning circle ship speed and time was recoded as well as turning circle data such as advance (AD), tactical diameter (TD) and transfer (TR).

First experiment took place at 20. December 2018 in the morning and recorded data is shown in Table 3 and Figure 2.

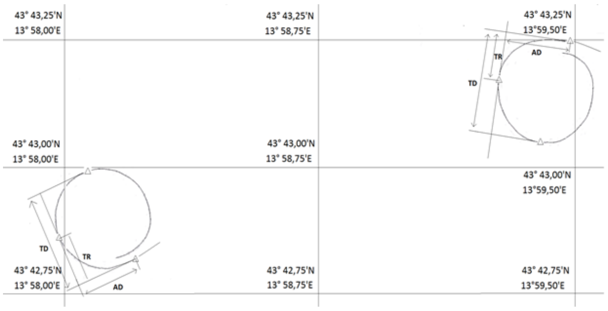

Figure 2. Turning circle first experiment recorded trajectory

In theory turning circle over port or starboard side should be the same. However, in this experiment minor differences were recorded. For example, turning circle over port side have advance shorter for 3,7 %, transfer smaller for 2,7 % and tactical diameter shorter for 8,6 %. Also, total time needed for making turning circle over port side is faster for 9,6 seconds than over starboard side. Those differences are minor and are result in differences in port and starboard engine.

Second experiment was conduced on 26. December 2018 when required conditions were met. At site recorded wind speed was 20 knots (10 m/s) from NNE, sea state was 1 and there was no sea current. Recorded data is shown in Table 4 and Figure 3.

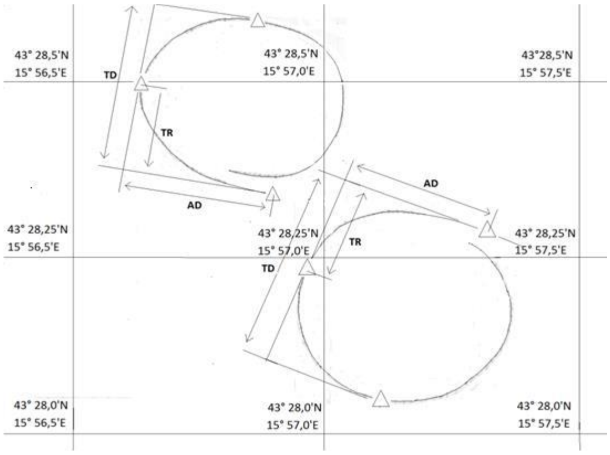

Figure 3. Turning circle second experiment recorded trajectory

As in the second experiment wind direction was NNE starting course was approximately NNW, so the wind was acting lateral at the beginning of the turning circle. Turning circle over port side was down wind so the tactical diameter is larger for 54 meters, as well as advance which is larger for 68,52 meters and transfer which is larger for 24 meters. Total time for turning circle over port side is longer for 24 second than turning circle over starboard side. To analyse wind influence data from both experiments were compared (Table 5).

It can be seen from Table 5, that downwind turning circle is a lot greater than upwind turning circle as well as time needed. One of the reasons is that this is a ship with quite large above water area and small displacement where drift is pronounced. Recorded data was compared with ship Trials report which were conducted by Verolme Cork Dockyard in January 1979. At the time of trials wind was 6-7 Beaufort from SW. Sea state was moderate with sweel. These conditions are approximate to our experiment. Data from trials turning circles are shown in table 6.

Table 3. Turning circle first experiment recorded data

Turning side	Rudder angle	engine RPM	Starting course	ΔKp 90° (s)	ΔKp 180° (s)	ΔKp 270° (s)	ΔKp 360° (s)	AD (m)	TR (m)	TD (m)
Port	35°	250 rpm	292°	55,5	78,2	122,8	147,8	351,88	194,46	346,32
Stbd	35°	250 rpm	240°	55,5	89,5	125,6	157,4	364,84	199,64	375,96

Table 4. Turning circle second experiment recorded data

Turning side	Rudder angle	engine RPM	Starting course	ΔKp 90° (s)	ΔKp 180° (s)	ΔKp 270° (s)	ΔKp 360° (s)	AD (m)	TR (m)	TD (m)
Port	35°	250 rpm	292°	84,3	136,1	184,3	233,5	590,78	266,68	498,19
Stbd	35°	250 rpm	283°	72,0	115,8	160,7	209,5	522,26	242,61	444,48

Table 5. Differences in turning circle between first and second experiment

Turning side	ΔKp 90° (s)	ΔKp 180° (s)	ΔKp 270° (s)	ΔKp 360° (s)	AD (m)	TR (m)	TD (m)
Port	+51,9%	+74,0%	+50,1%	+58,0%	+67,9%	+37,1%	+43,9%
Stbd	+29,7%	+29,4%	+27,9%	+33,1%	+43,1%	+21,5%	+18,2%

Table 6. Trial run turning circle data

Turning side	Rudder angle	engine RPM	Starting course	ΔKp 90° (s)	ΔKp 180° (s)	ΔKp 270° (s)	ΔKp 360° (s)	AD (m)	TR (m)	TD (m)
Port	35°	24.3	080	54	113	178	233	250	245	500
Stbd	35°	17.95	085	63	120	170	237	325	180	350

It can be seen that starboard circle was done with lower starting speed and upwind, while port circle was done downwind. Since the port turning circle is downwind that larger starting speed can be ascribed to that phenomena. Data from table 6 shows that this vessel is prone to drifting and that effect is pronounced with larger wind speeds.

4 CONCLUSION

This paper analyses in situ the wind influence on ship manoeuvring. For the purpose of experiment and to comply with safety standards ship turning circle was analysed. The experiment had to be executed on appropriate conditions, one with no wind and sea influence and one with wind speed of 20 knots and minimal sea state.

The results show that this type of ship, Ro-Ro passenger, is due to larger above water surface accelerated downwind and deaccelerated upwind. Also, lateral wind will cause significant ship drifting. Data analyses show that turning circle is greater than one without external forces and that influence should be considered when making turning circle. That drift should be also considered when making turning up to 180°.

Since the safe ship manoeuvring implies knowing all ship manoeuvring features this type of experiments should be conducted on other ship types. That data enables safer ship manoeuvring in conditions where navigational dangers are close to fairway or when manoeuvring in port.

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