Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2016, 47 (119), 66–73
ISSN 1733-8670 (Printed)
ISSN 2392-0378 (Online)
DOI: 10.17402/150

Received: 29.04.2016
Accepted: 17.09.2016
Published: 20.09.2016

A method for reserve determination of the static and dynamic list of liquefied natural gas carriers and its application to the dynamic under keel clearance system in the outer port in Świnoujście

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Key words: dynamic UKC, simulation methods, analytical methods, list, pressure transmitters, LNG carrier

Abstract

This paper presents a methodology for determining the components related to the heel of liquefied natural gas (LNG) carriers, excluding the heel of the vessel due to waves. The described method was applied to the description of under keel clearance of vessels approaching the outer port of Świnoujście. The method includes the determination of heel components caused by: draught reading errors, wind, current, tugboats and vessel maneuvers. Determination of the last component was carried out using a 2-stage method. In the first stage, simulation methods were used to identify the parameters of ship movement. In the second stage, the maximum heel of LNG carriers was calculated by analytical methods.

Introduction

The inspection of a vessel's draught, list and heel is the basis for their exploitation, especially in the areas where the under keel clearance is limited. With exception to navigational safety, these considerations are mainly economic. Knowledge of the available under keel clearance directly affects the amount of cargo that can be carried. Shallow water areas, in addition to those clearly safe to pass, are taken into consideration in the analysis of the possible vessel route. It hould be noted, however, that "shallow water" is a relative term, largely dependent on the size of the vessel which navigates within such areas. The shallow waters, which are known as restricted water areas, include, among others, harbors, dredged fairways, straits, and river or sea channels (Nowicki, 1999).

The following different sources of data are taken into consideration to determine a vessel's under keel clearance:

1. Width and available depth of the waterway;
2. Density of water;
3. Tides value;
4. Vessel LOA and breadth;
5. Vessel draught and displacement;
6. Vessel squat;
7. Weather conditions: wave height, wind speed and direction.

As mentioned above, there are many different variables which must be accounted for to calculate the vessel's under keel clearance. It is very important to determine them with high accuracy, especially the value of vessel draught, list and heel. Presently, these variables are identified with the use of numerous different methods. To provide safe navigation and proper economical exploitation, it is necessary to have the ability to correctly assess their accuracy.

Systems and methods of vessel draught identification and their accuracy level

Measurements of vessel draught and list are among the most important pieces of information during navigation. On their basis, the stability of the vessel is determined. Nowadays, the readings of vessel draught can be carried out from several separate and independent sources such as:

- Draught marks located on the vessel's hull;
- Cargo loading program;
- Submersible pressure transmitters.

Due to the nature of draught accuracy, the readouts of measuring equipment are continuous. Comparison of draught value readouts from draught marks and cargo loading program is the most popular method of operation. These readings are considered as the most reliable.

Draught marks

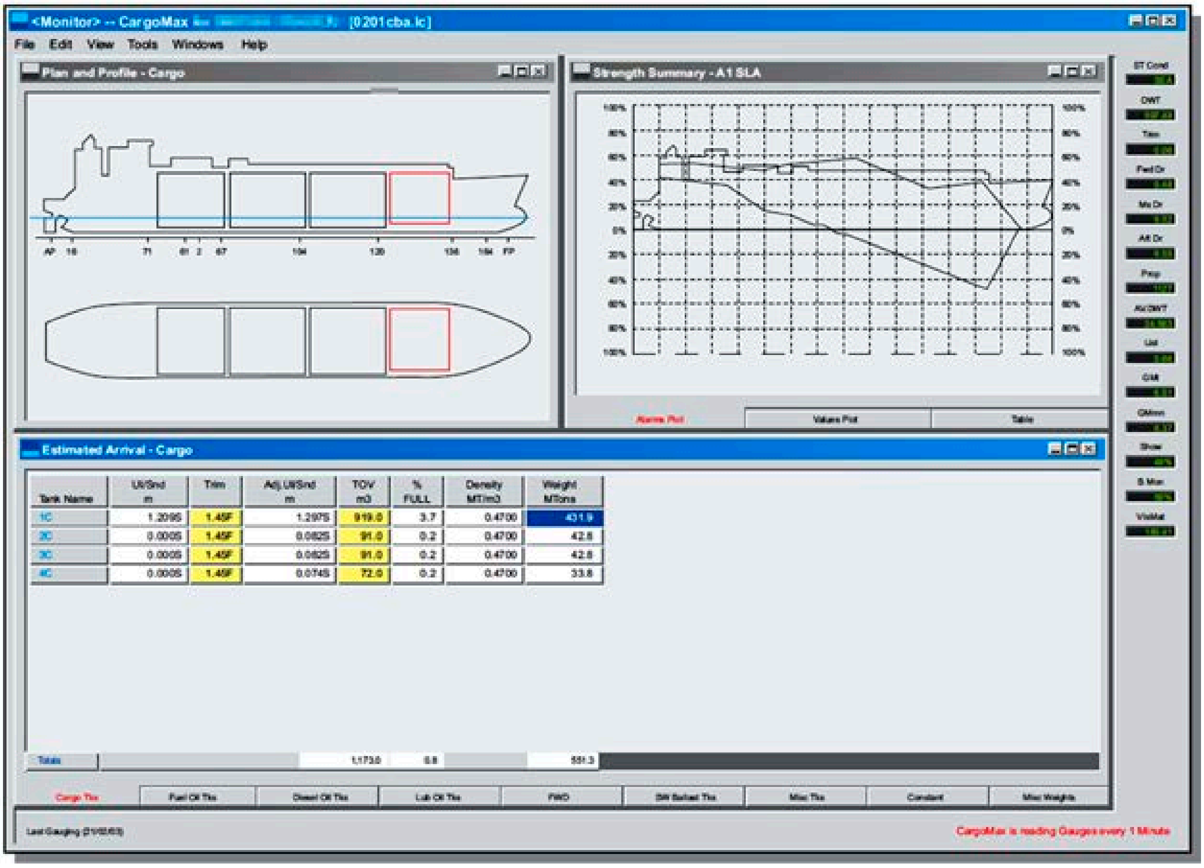
The accuracy of draught identification depends on officer experience and sea state at the moment of reading. Although it is the oldest method, it is still recognized as the one of the most accurate, giving the real value of vessel draught.

Cargo loading software

Cargo loading software (Figure 1), after its accreditation by classifiers, is the main source of vessel draught and list readouts and of the basis of its results the stability of the vessel is determined. Properly calibrated cargo loading software allows to term the parameters with an accuracy of less than 1 cm. The accuracy level depends on the quality of data transmitted from the radar sensor located in the tank. Possible errors, which can occur in radar sensors used in tanks of LNG carriers, are verified with the use of onboard measurement equipment (Whessoe gauge).

Pressure transmitters

The values of vessel draught and list are obtained from measure points and lines, located on the submerged, bow and stern parts of the hull, and also symmetrically on both sides at midship. The readout is inaccurate, with an error up to 5 cm at the beginning that increases over time. There are Different pressure transmitters with diverse accuracy are available on the market. Table 1 presents a selection



Tank Name	Ult/Snd m	Trim	Adj.Ult/Snd m	TOV m3	% FULL	Density MT/m3	Weight MTons
1C	1.2095	1.45F	1.2975	919.0	3.7	0.4700	431.9
2C	0.0005	1.45F	0.0825	91.0	0.2	0.4700	42.8
3C	0.0005	1.45F	0.0825	91.0	0.2	0.4700	42.8
4C	0.0005	1.45F	0.0745	72.0	0.2	0.4700	33.8
Totals				1,173.0	0.8		551.3

Last Gauging (21/02/03)

CargoMax is reading Gauges every 1 Minute

Figure 1. Screenshot of Kongsberg CargoMax (cargo loading software), showing the values of vessel draught and list

of the products most commonly installed on LNG carriers, along with their relative narrow measure error.

Table 1. Summary of accuracy level of selected pressure transmitters

Manufacturer	Product	Accuracy	Source
Vega	VEGAWELL52	< 0.1% FR	VEGA Grieshaber KG (2015)
Kongsberg	GT403	< 0.25% FR	Kongsberg Maritime AS (2009)
Besi	PESS	< 0.2% FR	BESI Armaturen GmbH & Co KG (2000)
A.P.I. Marine	UPT	0.2% FR	A.P.I. Marine ApS (2009)
Yokogawa	EJA120E	±0.2%	Yokogawa Electric Corporation (2015)
Validyne	DR800	±0.1% FR	Validyne Engineering (2015)

FR – full range [psi]

Systems and methods of vessel list identification

Vessel list, similar to the vessel draught, can be identified with the use of different methods, as below:

- Draught marks located at vessel midship;
- Inclinometer;
- Mathematical pendulum;
- Cargo loading software;
- Pressure transmitters.

Draught defined on the basis of marks located at the midship

The readout from draught marks, located at the midship, is considered to be one of the most reliable measures; however, for determining the vessel list or heel, it has a disadvantage. To identify the values, it is necessary to take the draught readouts from both sides of the hull at the same time. Due to that inconvenience the method is mainly used while vessel is in the shipyard or alongside. These readouts are compared with values obtained from other appliances available onboard.

Clinometer

This method is the most popular since it offers the fastest way to identify the vessel list and its stability (Figure 2). Because of its sensitivity, the device is mostly used during harbor loading operations. On the other hand, to get proper readouts of vessel list out of the port, calm sea conditions are necessary. During LNG carrier loading operations, due to the many different external factors that can falsify readouts of list, the position of the vessel must be checked continuously. The external factors include waves caused by vessels passing nearby and slack of mooring lines.

Figure 2. Selected clinometers used onboard of LNG carrier (Sea shop, 2016; West Sea Company, 2016)

The mathematical pendulum is a very popular alternative to the clinometer in monitoring and comparing the vessel list. Its principle of operation is the same as the clinometer.

Pressure transmitters and cargo loading software

Pressure transmitters and cargo loading software are used in similar ways as in draught measurements (Figure 3).

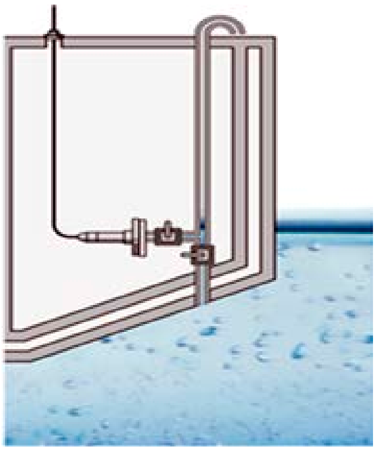


Figure 3. Typical application scheme of a pressure transmitter (Vega, 2016)

Reserve of constant list of LNG carrier (Δ7)

LNG carriers are equipped with auto-measurement systems of vessel list and/or heel (inclinometers), which offer the possibility of conducting fast and easy readouts. Compensation of constant list is achieved with the use of the vessel ballast system.

The list correction should also include:

- Constant list $\Delta 7_s$;
- Heel caused by wind $\Delta 7_w$;
- Heel caused by current $\Delta 7_p$;
- Heel caused by vessel turning $\Delta 7_z$;
- Heel caused by tugs $\Delta 7_h$.

The factors mentioned above should be taken into consideration in the future when modeling list. The correction models should also include the real states of external environmental conditions, because they represent 25% of the total reserve amount.

Constant list $\Delta 7_s$

The maximum reserve of constant list will not exceed 5 cm if the pressure transmitters, with maximum inaccuracy of 5 cm, are located at vessel midship.

Heel caused by wind $\Delta 7_w$

An accurate description of the environmental forces and moments is important in vessel simulators that are produced for human operators (Fossen, 2011).

To calculate the vessel heel caused by the wind, it is necessary to determine the lateral windage area, with the height of center point of the wind influence, direction and value of wind force. The following methods can be applied:

1) accurate method based on vessel stability data, including its righting lever curves GZ = $f(\varphi)$ for a given loading condition;
2) approximate method for minor vessel heel, where the location of its center of gravity, KG, must be known.

This paper presents calculations for a loaded LNG carrier with the use of the accurate method, since all necessary stability parameters are known.

The wind force F_w affecting the vessel at a height d_h, measured from the water surface, is shown in Figure 4. The wind force lever arm, d_w, is calculated for the axis of rotation located between the center of gravity, KG, and the center of buoyancy, KF (which is 0.5 T). Based on vessel stability data and performed calculations, the correction of vessel heel caused by wind was determined (Table 2).

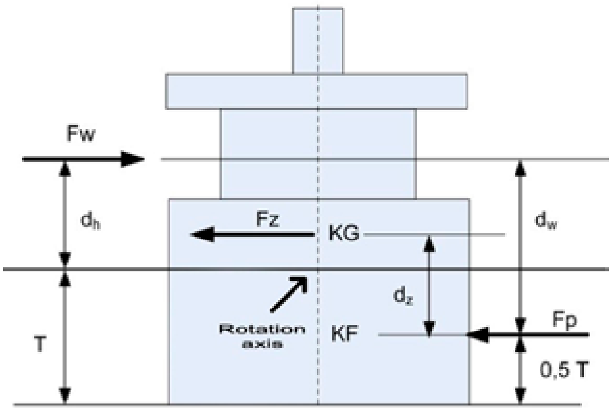


Figure 4. Parameters used in calculation of vessel heel caused by wind

Table 2. Correction of LNG Qflex list caused by wind

Symbol	Value	Unit	Parameter
L_{pp}	300	m	length overall
B	50	m	breadth
T	12.5	m	draught
D	145200	T	displacement
KF	6.25	m	axis of rotation 0.5T = KF
d_h	13	m	height of center point of the wind influence counted from water surface
d_w	19.25	m	wind heeling arm from point of rotation (KF)
KG	17	m	center of gravity point
GM	5.3	m	intact metacentric height
d_z	10.75	m	distance counted from KG to KF
v_w	10	m/s	wind speed
ρ_p	1.226	kg/m^3	air density
ρ_w	1000	kg/m^3	water density
P_{w1}	4300	m^2	lateral windage area
C_{w1}	1.1	–	wind resistance factor of the hull
P_{w2}	2200	m^2	lateral windage area of tanks
C_{w2}	0.7	–	wind resistance factor of the tanks
P_{w3}	1000	m^2	lateral windage area of superstructure
C_{w3}	1	–	wind resistance factor of the superstructure
P_{ws}	7500	m^2	total lateral windage area
F_w	445651	N	wind force
F_w	45.4	T	wind force expressed in tones
M_w	874.493	Tm	wind heeling moment
sin(φ)	0.00113	–	sinus of heeling angle GZ = GM·sin(φ) for minor φ = 0 to 6 deg
φ	0.07	deg	constant vessel heel caused by wind
φ_d	0.13	deg	dynamic vessel heel
$\Delta 7_w$	0.06	m	correction of vessel heel caused by wind

The following formulas were used to calculate the correction of vessel heel caused by wind $\Delta 7_w$.

Wind heeling arm d_w:

$$d_w = (T - \text{KF}) + d_h \ [\text{m}] \tag{1}$$

Distance d_z, measured from KG to KF:

$$d_z = d_w - \text{KF} \ [\text{m}] \tag{2}$$

Wind force F_w (according to windage areas shown in Figure 5):

$$F_w = 0.5\left(\left(P_{w1}C_{w1}\right)+\left(P_{w2}C_{w2}\right)+\left(P_{w3}C_{w3}\right)\right)\cdot \rho_p \cdot v_w^2 \ [\text{N}] \tag{3}$$

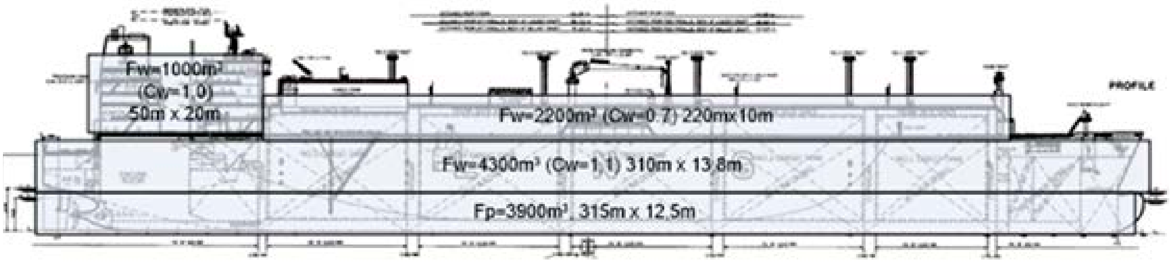


Figure 5. Lateral windage areas and wind resistance factors of Q-Flex type LNG carrier applied to calculations

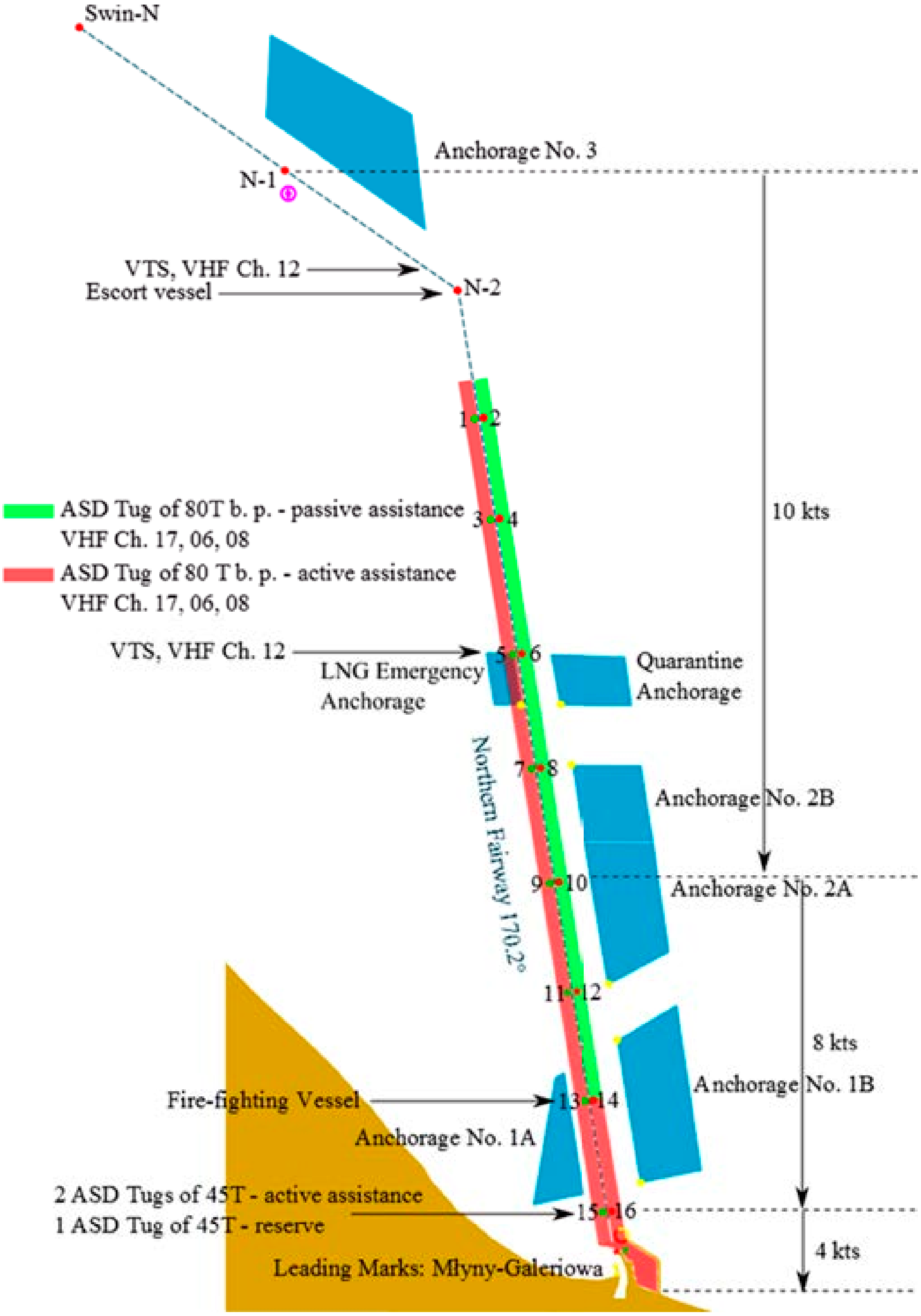


Figure 6. LNG carrier fairway to Outer Port of Świnoujście (Artyszuk, 2015)

$$F_w = 0.5\sum\left(P_{wn}C_{wn}\right)\cdot \rho_p \cdot v_w^2 \text{ [N]} \tag{4}$$

Wind heeling moment M_w:

$$M_w = F_w \cdot d_w \text{ [Tm]} \tag{5}$$

Sinus of heeling angle $\sin(\varphi)$:

$$\sin(\varphi) = \frac{M_w}{\text{GM} \cdot D} \tag{6}$$

Dynamic vessel heel φ_d:

$$\varphi_d = 2\,\varphi \tag{7}$$

Correction of vessel heel caused by wind $\Delta 7_w$:

$$\Delta 7_w = \frac{B \cdot \sin(\varphi_d)}{2} \tag{8}$$

The calculated value of vessel heel caused by wind is only 0.13 deg, which gives the correction Δ7 on the level of 0.06 m. According to stability documentation in that particular loading condition, the vessel list obtained for wind speed of 28 m/s is calculated at 1.3 deg.

Vessel heel caused by current $\Delta 7_p$

The vessel heel caused by current occurs only when a strong current rapidly affects the LNG carrier from the side. This comes when the vessel drift remains unstable (still changing). In practice, such conditions occur when the vessel passes the junction of channels, river estuaries and the like. Moreover, it should be noted that the torque caused by current takes on the minimum value. This is because the current force, F_p, affects the hull on the level of the axis of vessel rotation, i.e. in the vicinity of the center of buoyancy, KF, and is therefore negligible.

Vessel heel caused by vessel turning $\Delta 7_z$

The calculations described in this paper were carried out on the basis of simulation trials, which assumed the safe entry of the LNG Qflex carrier into the outer port of Świnoujście (Figure 6). The simulation was performed in the worst weather conditions allowing entrance in the port.

Turning at speed could be executed by using the rudder. When moving ahead, the ship rotates around the pivot point located in the front part of the ship (MacElrevey, 2004).

The standard deviation of the statistical sample S, which contained the rudder angles recorded during vessel pass from buoys 9–10 to 13–14, was calculated using following formula:

$$S = \sqrt{\frac{\sum\left(X - \bar{X}\right)^2}{n-1}} \tag{9}$$

where:

X – consecutive number of samples;

$\bar{X}$ – arithmetic average;

n – total number of samples.

With the use of formula (9), the following was calculated:

$$S = 2.3\ [°]$$

$$S(0.95) = 4.6\ [°]$$

The standard deviation calculated for rudder angles with a level of confidence of 95%, can be defined as the interval (Figure 7):

$$S(0.95) = (-7, -2)\ [°]$$

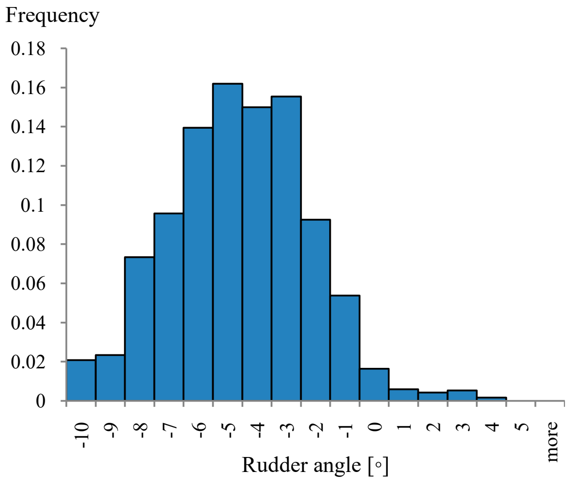


Figure 7. Rudder angle histogram for LNG Qflex carrier passing Świnoujście fairway from buoys 9–10 to 13–14

To determine the turning circle radius of the LNG Qflex carrier, it was necessary to carry out a simulation experiment, which assumed trials of starboard side, 180 deg turning, performed for selected rudder angles, with a start speed of 6 knots, using the tactical diameter of turning circle D_t (Table 3 and Figure 8).

Table 3. Radius of turning circle R determination

Rudder angle	λ_1 [deg]	λ_2 [deg]	D_t [deg]	D_t [Mm]	R [m]
5°	14.2612	14.4426	0.1814	10.9	10079
10°	14.2612	14.3491	0.0879	5.3	4882
15°	14.2612	14.3242	0.0629	3.8	3497
20°	14.2612	14.3096	0.0483	2.9	2686
25°	14.2612	14.3004	0.0392	2.4	2177
30°	14.2612	14.2941	0.0329	2.0	1827
35°	14.2612	14.2898	0.0285	1.7	1586

The tactical diameter, D_t, and radius, R, of turning circle were calculated using the following formulas:

$$D_t = \lambda_2 - \lambda_1\ [°] \tag{10}$$

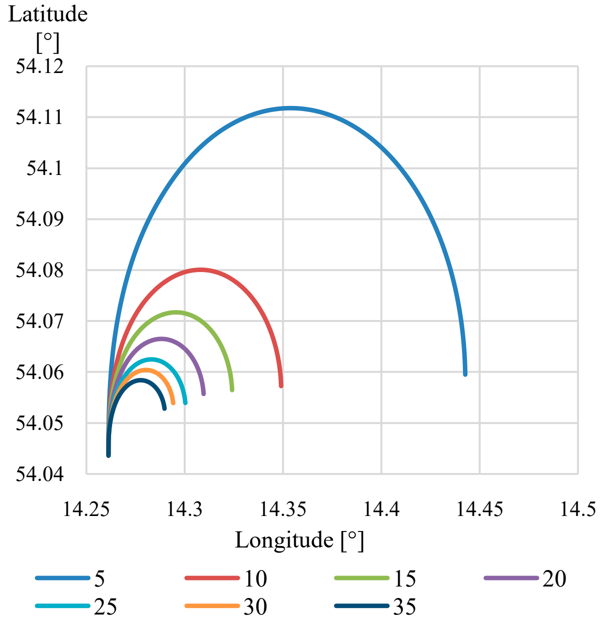


Figure 8. Diameter of tactical turning circle achieved from simulation passages of LNG Qflex with rudder angle interval from 5 to 35 deg

$$R = \frac{D_t}{2}\ [\text{m}] \tag{11}$$

The vessel does not turn hard while entering the port; however, soft corrections of heading can cause the heel of such a large vessel.

The centrifugal force, F_z, appearing while the vessel turns, acts on the KG level and takes on the value of:

$$F_z = \frac{Mv^2}{R}\ [\text{m}] \tag{12}$$

where:

M – mass of vessel with water that accompanies;

v – vessel speed while turning;

R – radius of turning circle

or, with the alternative method:

$$\tan\varphi = \frac{v^2 \cdot \text{FG}}{g \cdot R \cdot \text{GM}}\ [\text{m}] \tag{13}$$

where:

FG – distance between vessel center of gravity and center of buoyancy (d_z parameter);

GM – intact metacentric height;

R – radius of turning circle.

In practice, the vessel heel is lower, because the contrary inclined rudder counterbalances its value (about 20%).

If we assume that the vessel makes minor corrections of heading using its rudder up to 10 deg (Table 4), the correction of vessel heel caused by its turning can be calculated with following formulas.

Heeling moment M_z:

$$M_z = F_z \cdot d_z\ [\text{Tm}] \tag{14}$$

Determination of vessel heel φ:

$$\sin(\varphi) = \frac{M_z}{\text{GM} \cdot D} \tag{15}$$

Or, by an alternative method (Derret, 1999):

$$\tan\varphi = \frac{V^2 \cdot d_z}{R \cdot \text{GM} \cdot g}\ [\text{m}] \tag{16}$$

Correction of vessel heel caused by its turning $\Delta 7_z$:

$$\Delta 7_z = \frac{B \cdot \sin(\varphi)}{2} \tag{17}$$

Table 4. Correction of LNG Qflex vessel list caused by her turning

Rudder angle	del	deg	**5**	**10**	**15**	**20**	**25**	**30**	**35**
mass of vessel with water that accompanies	M	m^3	145200	145200	145200	145200	145200	145200	145200
turning circle radius	R	m	5979	2963	2167	1704	1648	1204	1065
start speed	V	m/s	3.3	3.3	3.3	3.3	3.3	3.3	3.3
centrifugal force	F_z	T	264.46	533.65	729.68	927.95	959.48	1313.3	1484.7
intact metacentric height	GM	m	5.3	5.3	5.3	5.3	5.3	5.3	5.3
vessel breadth	B	m	50	50	50	50	50	50	50
distance between vessel centre of gravity and centre of buoyancy	d_z	m	10.75	10.75	10.75	10.75	10.75	10.75	10.75
Heeling moment	M_z	Tm	2843	5737	7844	9975	10314	14118	15960
	$\sin(\varphi)$		0.00369	0.0074	0.0101	0.0129	0.0134	0.0183	0.0207
gravity	g	m/s^2	9.81	9.81	9.81	9.81	9.81	9.81	9.81
vessel heel	φ	deg	**0.21**	**0.42**	**0.58**	**0.74**	**0.76**	**1.05**	**1.18**
correction		m	**0.09**	**0.18**	**0.25**	**0.32**	**0.33**	**0.45**	**0.51**
	or:								
	$\tan(\varphi)$		0.00037	0.0007	0.0010	0.0013	0.0013	0.0018	0.0021
vessel heel	φ	deg	**0.02**	**0.04**	**0.05**	**0.07**	**0.08**	**0.10**	**0.12**
correction of vessel heel caused by her turning	$\Delta 7_z$	m	**0.00**	**0.01**	**0.02**	**0.03**	**0.03**	**0.04**	**0.05**

Vessel heel caused by tugs $\Delta 7_h$

In the calculations it has been assumed that the vessel heel is caused by thrust of two tugs (emergency situation), which pull the LNG Qflex in a 45 deg direction with respect to the vessel centerline.

Table 5. Vessel heel caused by tugs

U	200	T	tugs pull force
k	45	deg	towing line direction
F_h	141.42	T	lateral force made by tug
h_h	26	m	height of application of the tugs force measured from keel
d_{fh}	19.75	m	distance from point of application to center of buoyancy
M_h	2793.07	Tm	Heeling moment
$\sin(\varphi)$	0.0036		vessel heel
φ	0.21	deg	vessel heel
$\boldsymbol{\Delta 7_h}$	**0.09**	**m**	**correction of vessel heel caused by tugs**

The following algorithm was used to determine the value of correction of vessel heel caused by tugs $\Delta 7_h$ (Table 5).

Value of lateral force made by tugs F_h:

$$F_h = \sin(k)\cdot U \ \text{[T]} \tag{18}$$

Distance from point of application to center of buoyancy d_{fh}:

$$d_{fh} = h_h - \text{KF} \ \text{[m]} \tag{19}$$

Heeling moment M_h:

$$M_h = F_h \cdot d_{fh} \ \text{[Tm]} \tag{20}$$

Vessel heel caused by tugs:

$$\sin(\varphi) = \frac{M_h}{\text{GM} \cdot D} \tag{21}$$

Correction of vessel heel caused by tugs $\Delta 7_h$:

$$\Delta 7_h = \frac{B \cdot \sin(\varphi)}{2} \ \text{[m]} \tag{22}$$

Summary of all corrections of LNG Qflex list – $\Delta 7$

The total correction of vessel list $\Delta 7$ can be defined as the sum value of all partial corrections:

$$\Delta 7 = \Delta 7_s + \Delta 7_w + \Delta 7_p + \Delta 7_z + \Delta 7_h \tag{23}$$

Conclusions

The paper describes methods of vessel draught, list and heel determination. The total correction of vessel list $\Delta 7$ for an LNG Q-flex type carrier was calculated considering the worst weather conditions that still allow entrance to the outer port of Świnoujście and resulted in the value of 0.36 m. It is known that the experience of crew members has a direct impact on the amount of cargo that can be carried, as they know how to operate the deep draught vessel. The essence is that knowing the technological limits of equipment used to indicate the level of draught and list or heel is fundamental.

Basic calculations of vessel stability are very important to determine the draught, list and heel with the use of traditional methods. The following parameters have to be taken into consideration to calculate the value of total list, including heel components: draught readouts errors, influence of wind, current and tugboats, and heel caused by the vessel turning.

Systematic inspection and calibration of the modern measuring devices must be conducted to maintain a high accuracy of vessel draught, list and heel readouts. Additionally, to decrease the possibility of grounding, local regulations in the field of extra value of under keel clearance are implemented by ship owners. The additional UKC is expanded by so called "margin of safety", added to the previously calculated UKC.

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