TRANSNAV
http://www.transnav.eu
the International Journal
on Marine Navigation
and Safety of Sea Transportation
Volume 8
Number 4
December 2014

DOI: 10.12716/1001.08.04.04

Numerical Analysis for the Dynamic Forces and Operational Risk Accomplished for a "Hiload DP1" Unit Docked to MT "Navion Anglia" at Sea Waves

G. Rutkowski
Gdynia Maritime University, Gdynia, Poland

ABSTRACT: In this paper author depicts the results of the sea trials of the operational test of a Hiload technology at sea waves with the numerical analysis for the dynamic forces and operational risk. The research was carried out on board MT "Navion Anglia" which was engaged in a towing operation through the Atlantic Ocean with a "Hiload DP1" prototype unit docked on her portside alongside, with different ship's draft and in different weather conditions. Additionally in this paper author presents the methods that can be used for estimating the safety factor SF against sliding and/or operational risk for the towing and/or manoeuvring operation with a "Hiload DP1" unit docked alongside at the open sea.

1 INTRODUCTION

In this paper the dynamic contact forces, generated between a "Hiload DP1" prototype attachment system [4], [7] and the bottom of the tanker hull at the open sea with waves, swell and/or current when the ships are freely moved in all six axis with pitch, roll, heave, surge, sway and the yow (see figure 1), will be depicted. In order to discuss the dynamic contact forces one needs to prepare some calculations for the different wave headings, distributed from 0° (head sea) to 180° (following sea). It is essential to remember that the forward transit speed of the tanker with a "Hiload DP1" unit docked alongside is assumed to be 4 knots (STW), with the transfer functions and phase angles included; the largest amplitude value in a rough sea at the open ocean should be expected.

In this study "Hiload DP1" prototype unit with the following ships particulars [5] will be used: Cyprus flag vessel, DNV 1A1 R Mobile Offshore Support Unit DYNPOS – AUTR, DP class 2 ship build in 2010, IMO= 8770950, call sign: 5BML2, Gross Tonnage (GRT)= 1697 GRT, Net tonnage (NRT)= 510, L.O.A.= 28.0 m, Breath= 27.0 m, Height from keel to top of mast= 58.5 m, Max operation draught= 42.0 m (Displacement (DWT)= 5544 MT), Minimum draught= 16.5 m (DWT = 4242 MT), 3 x caterpillar main engines each 3150 BHP, 3 x 550 kW Generators + 1 x 315 kW Emergency Generator, 3 off Azimuth Thrusters (Wartsila Lips) directly shafted to Diesel Combustion Engines and MT "Navion Anglia" with the following ships particulars [5]: Bahamas flag ship, DNV +1A1 Tanker for oil, Dynpos-AUTR, DP class 2 ship build in 1999, IMO 9204752, call sign: C6XC8, Gross Tonnage (GRT): 72.449, L.O.A.= 264.68 m, Breath = 42.50 m, Height from keel to top of mast= 50,0 m, maximum draught= 15,65 m, DWT= 152.809 MT, 2 x B&W main engines 10010 kW (13420 HP) each, Two Ulstein controllable pitch propeller 4 blades each, 2 x bow thrusters Brunvoll 2200 kW (2950 HP) each and 2 x stern thrusters Brunvoll 735 kW (990 HP) each.

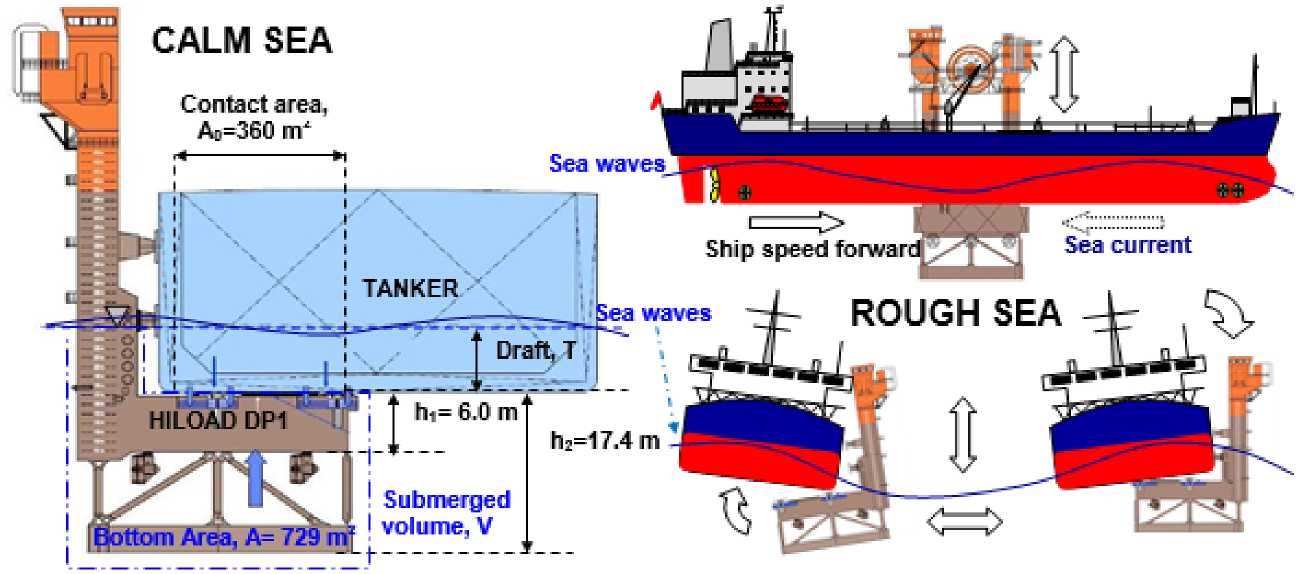

Figure 1.Function of the "Hiload DP1" friction attachment system after docking to the tanker at the calm sea (figure on the left) and on the rough sea (figure on the right) with pitch, roll, heave, surge, sway and the yow as an effect of wind waves, swell and/or sea current.

In this paper the results of the sea trials, accomplished at the operational tests, will be depicted. The tests were carried out in Q3 2013 on board MT"Navion Anglia" during her towing operation from Norway to Brazil through the big Atlantic Ocean with a "Hiload DP1" prototype unit docked on her portside alongside near amidships, with different ship's draft and different weather conditions. Additionally, we also are going to depict the real life operational tests results carried out offshore Brazil in 2014 on Campos Basin and/or Espirito Santo Basin Brazil.

We will try to present the methods that can be used for estimating the operational risk for towing and/or manoeuvring operation with a "Hiload DP1" unit docked alongside to the vessel at the open sea using the definition of a safety factor (SF) against sliding.

2 NUMERICAL ANALYSIS OF A CONTACT FORCE GENERATED ON A "HILOAD DP1" ATTACHMENT SYSTEM

In the calm water case (see on figure 1 on the left), Hiload DP is subjected to gravity and buoyancy forces in the vertical direction. The connection force between Hiload DP and the tanker bottom is given by the difference between the buoyancy force and the gravity force. It is also known that the buoyancy force of a floating body equals $\rho g V$, where ρ is the mass density of water and V is the submerged volume. This expression can be found by integrating the hydrostatic pressure over the submerged surface of the body. The same formula can be applied to "Hiload DP1" unit docked to MT "Navion Anglia" [4], [1]. In applying this formula we have implicitly assumed that the hydrostatic pressure also acts over the contact area, A_0. In reality the pressure is zero on A_0 (atmospheric pressure is treated as zero in this analysis, since it acts as an additional pressure on all surfaces). Hence, we need to subtract the hydrostatic force on A_0, which has been incorrectly included. If we denote forces acting upwards as positive, this force equals $-\rho g T A_0$. In such cases, taking into consideration all above, the corrected buoyancy force F_b can now be written as formula (1):

$$F_s = F_b - F_{grav} = \rho g V + \rho g T A_0 - mg \tag{1}$$

where:
F_s = the static contact force generated on Hiload DP attachment system, [N],
F_b = the force of buoyancy, [N],
F_{grav} = the gravity force (the weight of "Hiload DP1" unit), [N],
ρ = the mass density of water (for sea water ρ= 1025 kg/m3), [kg/m³],
g = the acceleration due to gravity (the gravity of Earth g=9.81 m/s²), [m/s²],
V = the volume of the object inserted into the fluid, [m³],
T = the draft of the vessel (the height) at which force acts on, [m],
A_0 = contact area in meter square with nil hydrostatic pressure (for "Hiload DP1" unit A_0=360 m² estimated from drawings [5]),[m²] .
m = the mass of object in kg, in our analyses the total mass of "Hiload DP1" unit equals 4674000 kg, [kg]

From equation (1) it is seen that the static connection force can be increased by reducing the mass of "Hiload DP1" unit, increasing the submerged volume of "Hiload DP1" ship, increasing the contact area or by increasing the draft of the tanker. However so far the sea waves, swell and all other dynamical forces were not considered in this analysis.

In the real life operation when the tanker with a "Hiload DP1" unit docked alongside is travelling in a seaway, they are both subjected to the wave induced forces, speed induced drag and inertia forces. Vertical drag forces on "Hiload DP1" unit are assumed to be small compared to the pressure forces and the inertia forces in the present study. In such cases for our simplified calculation the dynamic vertical contact force can be written as formula (2):

$$F_d = p_d A - m a_z \qquad (2)$$

where:

F_d = the dynamic vertical contact force, [N],

p_d = the hydrodynamic pressure acting on the horizontal bottom on "Hiload DP1" unit [Pa],

A = area in meter square on horizontal bottom (on "Hiload DP1" unit A= 729 m^2 as estimated value from drawings[5]: A= 27 m x 27 m= 729 m^2) [m^2],

m = the total mass of object, for "Hiload DP1" unit m= 4674000 kg, [kg]

a_z= the vertical acceleration of "Hiload DP1" unit [m/s^2].

In practice, the dynamic pressure will not be uniform over the bottom (*A*), however in this project for our simplified analysis we can use the average value for such pressure checked at few different locations at the bottom of a "Hiload DP1" unit. The dynamic pressure p_d and the vertical acceleration a_z can be calculated with a ship motion analysis program using the linear strip theory module i.e. in VERES program [3], [1].

For "Hiload DP1" unit, the contact area with atmospheric pressure (A_0), does not cover the entire horizontal surface at this "deck" level. Hence, a part of this "deck" level is exposed to the hydrodynamic pressure and this should be accounted for in equation (2). If the area of this part is denoted A_t and the average dynamic pressure on this part is denoted p_{dt} ,a modified version of equation (2) becomes the following formula (3):

$$F_d = p_d A - p_{dt} A_t - m a_z \qquad (3)$$

where:

A_t = area in meter square on horizontal bottom A exposed to hydrodynamic pressure around contact area. For our calculation for "Hiload DP1" unit At= 329 m2 as the estimated area from drawings [5], [m2],

p_{dt} = the dynamic (hydrodynamic) pressure acting on the horizontal bottom part A_t, [Pa].

In the present analysis, the pressure pdt will be taken as the pressure underneath the tanker bottom in the area close to Hiload DP attachment system. For our analysis the average value of the hydrodynamic pressure will be depicted at 4 different locations immediately forward and aft of "Hiload DP1" unit. In reality, there will probably be significant pressure variations in the narrow gap between Hiload DP and the tanker bottom and the pressure in this gap is also expected to be quite different from the pressure on the part of "Hiload DP1" unit that extends outside the tanker hull (the part around the base of the towers). An accurate assessment of the dynamic pressure p_{dt} distribution over A_t area were therefore the part of the detailed analyses carried out by Marintek company [1] with VERES Ship motion analysis program [2].

In such cases, the linear frequency-domain strip theory module from the VERES program [3] will be used for further analyses, and the final results described on Marintek VERES simulator program research work [1] will be used for the simplified calculation. Finally taking into consideration the fact that in the study mentioned above [1] it was also noted that the correction introduced in equation (3) does not influence the results significantly and for our simplified calculation we can use the result obtained directly from equation (2) without any additional correction.

3 RESULTS OBTAINED IN VERES PROGRAM FROM A LINEAR STRIP THEORY MODULE

The linear strip theory module in VERES program is well suited for the analysis of the tanker motions at different forward speed. In a linear analysis it is implicitly assumed that there is a linear relation between the amplitude of all response quantities (motions, pressures, wave induced forces etc.) and the amplitude of the incidental waves which for ships with vertical sides in the waterline area is generally a valid assumption. In a linear frequency-domain analysis, the response of the ship in regular sinusoidal waves is calculated. This is repeated for a relevant range of wave frequencies, and the process is repeated for each relevant wave heading. This results in a set of *transfer functions (RAO)*, which relates the amplitude of each response to the amplitude of the incident waves and the phase of the response relative to the waves is also calculated. The responses of interest in the present study are the tanker motions, the vertical acceleration of "Hiload DP1" unit, the dynamic pressures on "Hiload DP1" and the relative wave elevation at the location of "Hiload DP1".

With reference to "Hiload DP1" unit the frame/truss structure underneath of "Hiload DP1" unit was not included in this analysis. It is assumed that the hydrodynamic pressure underneath the box-shaped part of Hiload DP gives rise to the most important vertical hydrodynamic force. Hence, for the purpose of such calculating the tanker/Hiload vertical motion and the dynamic pressure underneath "Hiload DP1" unit, "Hiload DP1" is modeled as a box underneath the tanker bottom. Since VERES requires port-starboard symmetry, the box extends from port to starboard side. In the ship's longitudinal direction, the box-length is 27 m.

When the relevant transfer functions have been calculated, they can be combined with a wave spectrum to establish the response spectrum and the standard deviation. The wave spectrum is defined by the significant wave height, *Hs*, and the peak period, *Tp*, of the waves.

An irregular sea state may be characterized by a standard wave spectrum such as the Pierson–Moskowitz, the JONSWAP (Joint North Sea Wave Project) wave spectrum or the two peaked Torsethaugen wave spectrum which are all available in the VERES Postprocessor [3].

The wave spectrum expresses the distribution of wave energy (which is proportional to the wave amplitude squared) for different wave frequencies. The standard spectra are suitable for different types of irregular sea [3] and different ocean areas:

The JONSWAP spectrum is assumed to be especially suitable for the North Sea, and does not represent a fully developed sea. It has a peakedness parameter γ, which determines the concentration of the spectrum about the peak frequency and usually is set to 3.3.

The Pierson–Moskowitz spectrum is suitable for a fully developed sea, i.e. a sea state where the wind has been blowing long enough over a sufficiently open stretch of water, so that the high frequency waves have reached equilibrium. At this point, the waves are breaking slightly. In the part of the spectrum where the frequency is greater than the peak frequency ($\omega > \omega_p$), the energy distribution is proportional with ω^{-5}. For a given significant wave height and peak period, the Pierson–Moskowitz spectrum is identical with the Bretschneider, ISSC and ITTC spectrum models. The Pierson–Moskowitz spectrum appears for $\gamma = 1$ in the JONSWAP formulation.

The Torsethaugen spectrum is a two peaked spectrum which includes both wind generated sea and swell. An option is included to enable long crested swell from a direction different from the principal wave direction (direction of the wind generated waves).

According DNV Classification Notes 30.5, the spectral density function for the JONSWAP (Joint North Sea Wave Project) spectrum can be written as:

$$S_\varsigma(\omega_0) = \alpha g^2 \omega_0^{-5} e^{-\frac{5}{4}\left(\frac{\omega_p}{\omega_0}\right)^4} \gamma^{e^{-\frac{1}{2}\left(\frac{\omega_0-\omega_p}{\sigma\omega_p}\right)^2}} \tag{4}$$

where the wave spectrum parameters are:
α = Spectral parameter (generalized Phillips' constant),
g = acceleration of gravity, g=9.81 m/s^2,
ω_0 = Wave frequency [rad/sec],
ω_p = Peak frequency, $\omega_p = 2\pi/Tp$,
γ = Peakedness parameter,
σ = Spectral width parameter, $\sigma = 0.07$ for $\omega_0 < \omega_p$ and $\sigma = 0.09$ for $\omega_0 > \omega_p$

The Pierson–Moskowitz spectrum appears for $\gamma = 1$. The spectral parameter α is computed as:

$$\alpha = \frac{5}{16}\frac{H_s^2\omega_p^4}{g^2}\left(1-0.287\ln\gamma\right) = 5.061\frac{H_s^2}{T_p^4}(1-0.287\ln\gamma) \tag{5}$$

where H_s is the significant wave height. A standard value of the peakedness parameter γ is 3.3. However, a more correct approach is to relate the peakedness parameter to the significant wave height and the peak period:

$$\gamma = \begin{cases} 5 & \text{for} \quad T_p/\sqrt{H_s} \le 3.6 \\ e^{5.75-1.15T_p/\sqrt{H_s}} & \text{for} \quad 3.6 < T_p/\sqrt{H_s} < 5 \\ 1 & \text{for} \quad T_p/\sqrt{H_s} \ge 5 \end{cases} \tag{6}$$

In the VERES Postprocessor, you can choose either to specify the peakedness parameter γ directly, or the γ value can be calculated from (6) based on the significant wave height and peak period.

In a linear analysis, the probability distribution of the response amplitudes in a given storm will be given by the Rayleigh distribution. The Rayleigh distribution is defined by the standard deviation of the response, and for a given peak period, the standard deviation is proportional with the significant wave height. Hence, it is sufficient to calculate the standard deviation for H_s=1 for all relevant peak periods and wave directions in order to derive extreme values for higher sea-states.

In our simplified calculations for the irregular waves, a JONSWAP wave spectrum with peakness parameter $\gamma = 3.3$ was used. The forces on the ship have been found by integration of the pressure distribution on the submerged hull. The bilge keels were included in the VERES model. For roll motions, viscous damping forces due to bilge keels and skin friction were included and the wave amplitude of 2.5 m was used when these nonlinear damping forces were calculated [1]. All other parameters from formula (4) to (6) were obtained in VERES program as average value adequate for North Sea and Atlantic Ocean.

The results from the irregular waves were generally presented in terms of standard deviations, σ. The standard deviation is dependent on the significant wave-height, the period (in [1] the peak period is used) of the waves, and the wave direction. In the present linear analysis, the response amplitudes follow the Rayleigh distribution, and the standard deviation of any response will vary linearly with the significant wave-height. Hence, the results will be presented for a unit significant wave-height. In such case, the extreme values were estimated directly from the standard deviation. Some relevant relationships were as follows: significant value of the response amplitude= $2^*\sigma$; expected largest response amplitude in a sea-state ≈ $4^*\sigma$ and extreme value of the response amplitude with one percent probability of exceedence ≈ $5^*\sigma$ (approximately).

The horizontal wave drift force generated on a vertical wall of "Hiload DP1" unit attached to MT "Navion Anglia" can be also computed in VERES program from the following equation :

$$F_w = 2\rho g\xi S e^{kz}\sin(\omega t) \tag{7}$$

where:
F$_w$= horizontal wave drift force generated on a vertical wall of Hiload DP unit [N],
ξ = wave amplitude [m],
ω = wave frequency [Hz],
S = vertical area [m^2],.
k = wave number: k=2π/λ [radians/m] ,
z = immersion [m],

In this study the horizontal wave drift forces (F_w) have been obtained using the VERES program for "Hiload DP1" unit docked to the tanker at the amidships area with tanker draft 8 m and 10 m and with correction for immersion due to corresponding amplitudes of the relative motion in regular waves with amplitudes of 2.5m and 5m. For wave amplitude ξ= 2.5 m the horizontal wave drift forces were considered as 5.55 MN for the tanker draft T= 8 m and to 5.05 MN for tanker draft 10 m. For wave amplitude ξ= 5.0 m the horizontal wave drift forces were estimated accordingly as 11.1 MN for the tanker draft T= 8 m and to 10.1 MN for tanker draft 10 m (see table 1).

Table 1. Estimation of the horizontal wave drift forces obtained in VERES program for "Hiload DP1" unit docked to similar vessel (Vigdis Knutsen – 120 000 DWT) as MT "Navion Anglia"

Tanker draft T [m]	Wave amplitude $\xi = 2.5$ m	Wave amplitude $\xi = 5.0$ m
8 m	*5.55 MN*	*11.1 MN*
10 m	*5.05 MN*	*10.1 MN*

The dynamic vertical contact force per unit wave-height has been obtained in VERES program and the expected maximum dynamic contact force per unit Hs was accounted as around 2.4 MN for head waves (0° heading) and the wave peak period around 5s.

4 OPERATIONAL RISK ANALYSIS AND SAFETY FACTOR SF AGAINST SLIDING

During the transit voyage, the "Hiload DP1" was affected by drag forces generated by the water flow around its submerged part. It was also a prerequisite for the safe transit operation that the friction force, F_f, between "Hiload DP1" unit and the MT "Navion Anglia" bottom remains larger than the summarized drag and wave induced horizontal forces, F_t, otherwise "Hiload DP1" unit can start sliding relative to the tanker hull. In such cases, with all the above the safety factor taken into consideration, *SF*, against sliding can be implemented and defined as:

$$\mathrm{SF} = \frac{\mathrm{F_f}}{\mathrm{F_t}} \tag{8}$$

where:
SF = Safety Factor against sliding,
F$_f$ = Friction force between "Hiload DP1" unit and tanker bottom, [N].
F$_t$ = Inducted horizontal forces effected on "Hiload DP1" unit, [N].

The friction force equals the contact vertical force times multiplied by the friction coefficient, μ. The contact vertical force is the sum of the static and the dynamic contact forces as describe in figure (11):

$$\mathrm{F_f} = (\mathrm{F_s} - \mathrm{F_d})\mu \tag{9}$$

where:
F$_s$ = the static contact force generated by "Hiload DP1" unit in Newton,[N],
F$_d$ = the dynamic vertical contact force generated on "Hiload DP1" unit specify in Newton,[N]
μ = the friction coefficient (in our analysis with "Hiload DP1" unit equals μ=0.6).

The critical situation is when the dynamic contact force is negative. Hence, we can write:

$$\mathrm{SF} = \frac{(\mathrm{F_s} - \mathrm{F_d})\mu}{\mathrm{F_t}} \tag{10}$$

In such cases for a given safety factor we get the following requirement to the dynamic contact force:

$$\mathrm{F_d} < \mathrm{F_s} - \frac{\mathrm{SF} \cdot \mathrm{F_t}}{\mu} \tag{11}$$

When the transfer function for F_d has been calculated, we can use formula (11) to evaluate the maximum allowable significant wave height for a given safety factor and a given peak period.

5 DISCUSSION OF THE RESULTS AND SUMMARY REPORT

The tanker mt "Navion Anglia" is used in the present study with the following conditions: medium ballast condition (T_1= 8m), full ballast condition (T_2= 10m), partly loaded (T_3=12 m) and fully loaded condition (T_4=15 m). The main particulars of this ship are given in Table 2.

The radia of inertia have been estimated based on the author experience from the similar ships. The MT "Navion Anglia" is equipped with 0.5 meter wide bilge keels, which extend from approximately 25% to 75% of the ship length from AP.

The relevant properties of Hiload DP used in the present analysis are as follow: total mass m= 4674000 kg, mass displacement ϱV= 4972141 kg for tanker draft T= 8 m, 5074259 kg for T= 10 m and 5176376 kg for T=12 m, contact area A_0= 360 m^2 (estimated from the drawings [5] of "Hiload DP1" attachment system), exposed area around contact area A_f= 329 m^2, area of "Hiload DP1" bottom A= 27m x 27m = 729 m, maximum drag force at water flow speed of 5 knots F_{t1}= 1.5 MN for 8 m draft, F_{t2}=1.6 MN for 10m draft and, F_{t3} = 1.7 MN for 12 m draft and F_{t4}= 1.8 MN for 15 m draft. In this analysis we used friction coefficient μ=0.6.

The static contact force can be calculated using equation (1) and the safety factor in calm water can be calculated from equation (10) by setting F_d=0 (see results in Table 3).

It is clearly stated from table 3, that according to a safety factor SF in calm water (without dynamic forces) accounted for the tanker vessel proceeding with 4 knots speed forward, 1 knot current and 20 m/s wind and with draft i.e. 12 m the static force generated on a Hiload attachment system is 17.1 times bigger than the force F_t from resistance (drag) due to speed, ocean current and wind and will increase with ship's draft. Since the estimated tanker resistance (including effect of 1 knot ocean current) is 1.7 MN, the safety factor is 17.1 in this case. This evaluation was done without considering the wave induced horizontal force.

Table 2: Main particulars and mass properties of the MT "Navion Anglia"" during her towing operation through the Atlantic Ocean with a "Hiload DP1" unit docked on port side alongside.

Ship particulars: Loa= 264.68 m; Depth molded D= 22.07m; Breadth molded B= 42.5 m; Lpp= 256.96 m; Summer deadweight= 126 749 tons;	Tanker draft T [m]			
	8	10	12	15
Deadweight [tons]	*46 770*	*68 652*	*87 751*	120 337
VCG – vertical center of gravity (from baseline - BL) [m]	*12.37*	*9.65*	*10.22*	10.74
LCG – longitudinal center of gravity (from aft perpendicular – AP) [m]	*134.88*	*134.09*	*132.30*	131.28
Displacement in condition [tons]	*73 245*	*95 127*	*114 227*	146 812
Roll radius of inertia [m]	*17.0*	*17.0*	*17.0*	17.0
Pitch radius of inertia [m]	*62.9*	*62.9*	*63.0*	63.0
Yaw radius of inertia [m]	*62.9*	*62.9*	*63.0*	63.0

Table 3: The static forces and safety factor accounted for "Hiload DP1" unit docked on port side alongside to MT "Navion Anglia" with different draft in calm sea condition.

Parameter	Tanker draft T [m]				Unit
	8 m	10 m	12 m	15 m	
Buoyancy ($\rho g V$)	*48.8*	*49.8*	*50.8*	*52.3*	MN
Weight ($F_{grav}= mg$)	*45.9*	*45.9*	*45.9*	*45.9*	MN
Net buoyancy = Buoyancy – Weight	*2.9*	*3.9*	*4.9*	*6.4*	MN
Correction due to contact area ($\rho g T A_0$)	*29.0*	*36.2*	*43.4*	*54.3*	MN
Static contact force (F_s) as per formula (1)	*31.9*	*40.1*	*48.4*	*60.7*	MN
Friction force F_f as per formula (9)	*19.1*	*24.1*	*29.0*	*36.4*	MN
Resistance (drag) due to speed, ocean current and wind (F_t)	*1.5*	*1.6*	*1.7*	*1.85*	MN
Safety factor SF in calm water, at 4 knots forward speed, 1 knot current and 20m/s wind (as per formula (12))	12.7	15.1	17.1	19.7	

Table 4: The safety factor SF value accounted for different draft of the tanker T and different sea waves Hs condition. In this analysis there were used ships particulars for "Hiload DP1" unit attached to MT "Navion Anglia" at the amidships. Some dynamic forces were accounted in VERES program using the model of similar tanker for significant wave heights Hs= 2,5 m and 5 m [1]. The other factors were accounted using formula (10) with fixed statistical data and linear interpolation for horizontal wave drift force.

T [m]	F_s [N]	F_t [N]	Significant Wave Height Hs [m]															
			0,5	1,0	1,5	2,0	2,5	3,0	3,5	4,0	4,5	5,0	5,5	6,0	6,5	7,0	7,5	8,0
8	*31.9*	*1.50*	7.06	4.76	3.52	2.74	2.20	1.82	1.52	1.29	1.10	0.95	0.82	0.71	0.61	0.53	0.46	0.40
9	*36,0*	*1.55*	8.00	5.49	4.11	3.23	2.63	2.18	1.85	1.58	1.36	1.19	1.04	0.91	0.80	0.70	0.62	0.54
10	*40,1*	*1.60*	8.94	6.25	4.73	3.76	3.08	2.58	2.19	1.89	1.64	1.44	1.27	1.12	1.00	0.89	0.79	0.71
11	*44,2*	*1.65*	9.89	7.03	5.38	4.31	3.55	3.00	2.57	2.23	1.95	1.72	1.52	1.36	1.21	1.09	0.98	0.88
12	*48,4*	*1.70*	10.85	7.84	6.07	4.90	4.07	3.45	2.97	2.59	2.28	2.02	1.80	1.62	1.45	1.31	1.19	1.08
13	*52,5*	*1.75*	11.79	8.66	6.78	5.51	4.61	3.93	3.41	2.98	2.64	2.35	2.10	1.89	1.71	1.55	1.41	1.29
14	*56,6*	*1.80*	12.74	9.51	7.52	6.17	5.19	4.45	3.87	3.41	3.02	2.70	2.43	2.20	2.00	1.82	1.66	1.52
15	*60,7*	*1.85*	13.68	10.38	8.30	6.87	5.81	5.01	4.38	3.87	3.45	3.09	2.79	2.53	2.31	2.11	1.93	1.78

However if we take into consideration all dynamical forces (i.e. vertical and horizontal wave drift forces) the results obtained above are not adequate anymore.

With reference i.e. to the horizontal wave drift forces (F_w) for this simplified study we can use the results obtained from VERES program and research analyses [1], where for wave amplitude ξ= 2.5 m the horizontal wave drift forces were considered as 5.55 MN for the tanker draft T= 8 m and to 5.05 MN for tanker draft 10 m. For wave amplitude ξ= 5.0 m the horizontal wave drift forces were estimated accordingly as 11.1 MN for the tanker draft T= 8 m and to 10.1 MN for tanker draft 10 m (see table 1).

The dynamic vertical contact force per unit waveheight has been also obtained in VERES program and the expected maximum dynamic contact force per unit *Hs* was accounted as around 2.4 MN for head waves (0° heading) and the wave peak period around 5s [1].

It means that for *Hs*= 5 m the expected maximum dynamic contact force can be considered as: F_d= 2.4 x 5 = 12.0 MN. Additionally it means that for static contact force F_s =40.1 MN (accounted for tanker draft T=10 m – see table 3 or 4), the expected smallest contact force becomes around 40.1 – 12.0 = 28.1 MN, which gives a friction force F_f of 16.9 MN. Since the estimated tanker resistance (including effect of 1 knot ocean current) is 1.6 MN, the safety factor from formula (10) is 10.5 in this case (see formula (12)).

$$SF = \frac{(F_s - F_d)\mu}{F_t} = \frac{(40.1 - 12.0)\cdot 0.6}{1.6} = 10.5 \qquad (12)$$

Unfortunately this evaluation was done without taken into consideration the wave induced horizontal force. When we take into account such dynamic horizontal wave drift force F_w of 10.1 MN for tanker draft T=10 m and wave amplitude ξ= 5.0 m (see table 1) the result of SF will decrease up to value only around 1.44 (see formula 13):

$$SF = \frac{(F_s - F_d)\mu}{F_t + F_{td}} = \frac{(40.1 - 12.0)\cdot 0.6}{1.6 + 10.1} = 1.44 \qquad (13)$$

In table 4 for the example there are some safety factors accounted for a different draft of MT "Navion Anglia" with "Hiload DP1" unit docked on port side alongside near amidships are proceeding at the open sea with different sea conditions with different significant waves heights *Hs*.

6 CONCLUSIONS

As a result of this study the following conclusion has been noted:

- For vessel similar in size as mt "Navion Anglia" (summer deadweight= 126 749 tons) maneuvering with a "Hiload DP1" unit docked on portside alongside near amidships area, (where the sea fastening of HiLoad DP No.1 unit was done by utilizing a special and integrated Friction Attachment System fitted on board the vessel), with speed forward 4 knots, in a significant wave-height of 5.0 m, the calculated safety factors in the range from 0.95 (for draft 8 m) to 3.09 (for draft 15 m) have been obtained, depending on the tanker draft and Hiload DP location (see table 4).
- From Table 4 it is clearly visible that safety factor SF against sliding is bigger for the smaller significant wave heights and dipper tanker drafts (area marked in green color).
- Taking into consideration the fact, that in all cases the safety factor is higher for a deeper tanker draft - increase of the vessel draft should be always considered as the most effective way to increase the safety factor in the critical weather conditions.
- Additionally according to the formula (10) it also clearly stated that the safety factor is almost the same for both considered locations of a "Hiload DP1" unit (forward location =0.75 Lpp or amidships area= 0.5 Lpp). However if we take into consideration the expected vibration due to waves, swell and/or current it is recommended to position the "Hiload DP1" unit around amidships area on mother ship. The transit voyage of a mother ship with a "Hiload DP1" unit docked near amidships can decrease variation of the dynamic forces. For the mother ship it was also noted that a better heading control is achieved with a Hiload docked near amidships area in comparison with a "Hiload DP1" unit docked forward of mother ship.
- When the mother ship was using the Autopilot in a seaways during towing operation, it was also noted, that with "Hiload DP1" unit docked forward the consumption of HFO of mother ship was a little higher than comparing with a "Hiload DP1" unit docked near the amidships area. The reason for this is most probably the fact, that with Hiload DP unit docked forward for mother ship it was a bigger problem to keep the steady course over the ground (COG) and our Autopilot usually kept the rudder in fixed position turned to the starboard side up to about 8°to 12°with Hiload docked near amidships area and about 12°to 15°with Hiload docked forward.
- The dynamic vertical contact force per unit wave-height was the largest for sea-states with the wave peak period around 5s. In these sea-states, the expected maximum dynamic contact force per unit Hs is around 2.4 MN for head waves (0° heading). The value 2.4 MN for dynamic vertical force was confirmed via VERES simulator program [1] and used later for our simplified calculation of SF described in Table 4.
- Taking into consideration the previous point it means that for Hs= 5 m the expected maximum dynamic contact force can be considered as: Fd= 2.4 x 5 = 12.0 MN. It means also that for static contact force Fs =40.1 MN (accounted for tanker draft T=10 m – see table 3 or 4), the expected smallest contact force becomes around 40.1 – 12.0 = 28.1 MN, which gives a friction force Ff of 16.9 MN. Since the estimated tanker resistance (including effect of 1 knot ocean current) is 1.6 MN, the safety factor from formula (10) is 10.5 in this case. However when we take into account dynamic horizontal wave drift force Fw of 10.1 MN for tanker draft T=10 m and wave amplitude ξ= 5.0 m (see table 1) the result of SF will decrease to approximately 1.44 (formula 13):
- During the voyage through the Atlantic Ocean the current direction was assumed to be the most critical when opposite to the vessel forward motion. In such cases to reduce vibration on "Hiload DP1" unit and increase the safety factor (SF) for towing arrangement on mother ship we reduced the speed forward to maximum SOG= 5 knots with Speed through the water STW= 4 knots. The total water flow velocity relative to the tanker surface was assumed to be always: 4 knots (forward speed STW) + 1 knot (ocean current speed) = 5 knots (Speed Over Ground SOG).
- Wind-generated head or following waves (causing relatively large horizontal wave forces) combined with swell from aside (causing roll motions and relatively large dynamic pressure variation underneath Hiload DP and roll-induced inertia forces) were considered as the most critical conditions when: λ> ½ Lpp for wind waves and swell coming from the forward direction ± 20° to the port and starboard side of mother ship and for wind waves and swell coming from shipside when λ> ½ B. The maximum vibration on "Hiload DP1" unit were noted from sea waves coming from the port bow on the relative direction about 45° on the port side from mother ship's heading (waves coming directly between "Hiload DP1" unit and Navion Anglia hull). The best solution in such cases was the reduction the speed through the water to approximately 2 knots and COG adjustment to ± 20° on the port or starboard side.
- In head waves when the vertical dynamical contact force is the minimum (wave hollow) - the wave induced horizontal drift force was acting forwards and they were therefore be reduced by the drag (resistance) forces acting backwards. A critical situation appeared in the following sea where the drag forces and the horizontal forces were working in the same direction and the dynamic vertical contact force is at the lowest level.
- The relative motion per unit wave-height (for Hs = 1.0 m) was largest for the sea states with peak period (Tp) in the range 9 – 10 s in stern oblique waves (heading 135°). In these sea states, the standard deviation per unit Hs was 0.28 m. Hence, if Hs = 5 m, the standard deviation was 0.28 x 5= 1.5 m, and one would expect the largest relative

motion amplitudes to be close to 6 m. The relative motions for the Fwd location of the Hiload DP were in general slightly lower in longer waves.

REFERENCES

[1] Hermundstad O.A.: Numerical Analysis of Hiload DP in Waves. MARINTEK report no. 530785.00.01. Trondheim 2011.

[2] Hiload Joint Operations Manual Rev. 7 dated February 2014 generated by Teekay for Petrobras Fields P-47 and P-57.

[3] MARINTEK Report No. 609660, SHIPX Vessel Responses (VERES) Ship Motions and Global Loads Users' Manual, 2004-12-21.

[4] Rutkowski G., Hiload technology and numerical analysis of contact forces generated on "Hiload DP1" prototype attachment system at calm sea, Gdynia, 2014.

[5] Teekay internal documentation: ships particulars and drawings for MT "Navion Anglia" and Hiload DP,1 dated: 2013-2014.

[6] Transportation manual for the transport of Hiload DP no.1 from Kristiansand, Norway to Offshore location at Rio de Janeiro, Brazil - being docked onto a transportation vessel. Teekay internal document No. 1280-KA-O-00001, Rev. B, dated 12.07.2013.

[7] http://www.remora.no.

[8] http://www.teekay.com