Grzegorz Rutkowski
Akademia Morska w Gdyni

NUMERICAL ANALYSIS OF THE CONTACT FORCES GENERATED ON A „HILOAD DP1" PROTOTYPE ATTACHMENT SYSTEM AT CALM SEA

In this paper author describes the characteristics of a Hiload Technology installed on board „Hiload DP1" unit, known as the next-generation offshore loading solution (i.e. transferred buoy) for crude oil. The core technology was built up around the patented Remora Attachment System, which is similar to the Remora fish and equipped with a „suction cup", known as „a based attachment system", capable of transferring several thousand tons between the „Hiload DP1" unit and the connected object i.e. the bottom of a conventional tanker. In this paper author depicts the basic characteristics of a „Hiload DP1" prototype attachment system with the operational tests and the numerical analysis of a contact forces generated on such system at calm sea.

Keywords: *Hiload Technology, contact forces (static and dynamic), hydrostatic pressure, fiction forces, attachment system, offshore installations, DP systems.*

INTRODUCTION

As the oil and gas industry moves into deeper and deeper waters, the need for an efficient system to offload crude oil from FPSOs to tankers is steadily increasing. Traditionally, offloading of crude oil from FPSOs to tankers is carried out either in tandem configuration or via a remote Single Point Mooring (SPM) buoy solution. Tandem operations are normally carried out by use of specially built Dynamically Positioned (DP) tankers or with conventional tankers along with the use of several tugs in order to keep the tanker at a safe distance from the FPSO. Furthermore, oil transportation and trading are becoming more international, where oil companies tend to seek solutions that allow for conventional oil tankers to offload directly from FPSOs and transport the crude oil directly to the market.

The ideas behind the DP vessel is to use the features and experience gained from using purpose-built shuttle tankers in the North Sea and basically incorporate these on any conventional tanker during offloading operations. North Sea shuttle tankers are all equipped with dynamic positioning, specialized equipment for mooring and hose connection and extensive safety systems.

Unfortunately, most of the conventional tankers referred to are not equipped with any special means for offshore loading, other than mooring brackets on the bow and a hose handling crane amidships. All these tankers are therefore dependant on use of assisting vessels such as tugs and line handling boats for maneuvering, station keeping and cargo hose handling. For some field developments these vessels are likely to become a significant addition to the operation cost.

The new solution was found by the Norwegian company Remora AS [6]. This company along with Kongsberg Maritime Automation and Aibel Haugesund shipyard produced the first „Hiload DP1" unit in 2010. It was the first ship, unique in design, which allows us to use the innovative technology for loading and maneuvering conventional tanker having neither her on board, nor including any auxiliary systems, thrusters, DP system and/or additional tugs to control her movements.

This mobile system, nowadays known now as „Hiload DP1" unit, can run on any type of fields and is used for the safe and efficient transfer of oil from the FPSO to the tanker of every size or type. The Hiload is a financially effective, flexible and safe solution to transport the oil long haul to the refinery, with no need of a shuttle tanker. The design of the 2010 – built unit was inspired by the Remora fish – one of the world's most fascinating creatures, which employs suction to attach itself to the larger creatures such as sharks and whales. Teekay's new „Hiload DP1" unit is no different – it connects to any type of tanker keeping them in a safe distance from the production unit, when loading from offshore installations [3, 6, 7].

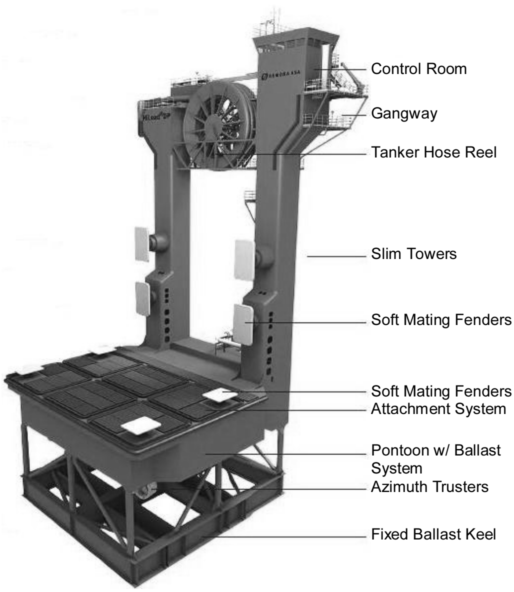

Fig. 1. The Hiload Technology built up around the patented Attachment System [4, 6]

Although the first basic sea trials of this unique vessel (Fig. 1) were completed in 2011 off the coast of Norway, the first real life operational tests at the open sea started in 2013 when Teekay Offshore Partners L.P. owned the first prototype „Hiload DP1" unit and the Teekay Corporation agreed with Remora AS to take over full responsibility for the modifications, mobilization, transportation and other running costs before the commercial contract start-up of the Petrobras [6]. The utilization of the Hiload DP will enable the direct crude oil export from Brazil with the use of the conventional tankers. An important milestone was reached on August 11, 2013, when MT „Navion Anglia" (Teekay owned vessel) commenced her sea passage to Brazil with the first prototype of „Hiload DP1" unit safely docked at her port side alongside (Fig. 2).

Fig. 2. "Hiload DP1" unit docked to MT "Navion Anglia" during her sea voyage to Brazil in Q3 2013 (on the left) and during the sea trials tests carried out on Campos Basin Brazil in Q1 2014

1. HILOAD TECHNOLOGY DESCRIPTION

The „Hiload DP1" vessel is a complete self powered unit [3, 5], which has been designed and constructed according to DNV's Offshore Service Specifications, Standards and relevant Rules for Ships. It complies with the functional requirements for typical deepwater SPM. The vessel is designed to dock onto and keep any of the existing 2000 conventional tankers, from Aframax to VLCC size, safe on position during the typical 24 hours of offloading operations. The „Hiload DP1" unit is equipped with a dual redundant DP system configured to satisfy class notations equivalent to Dynamic Position Class 2 applications, whereas most of the DP equipment is located in the Pontoon. The general arrangement of the pontoon reflects the high level of redundancy implemented, whereas critical rooms and systems have been duplicated.

The „Hiload DP1" unit is equipped with three direct driven azimuth thrusters (2,350 kW each) and powered by individual diesel engines. Each of the three thrusters provides 50% of the required thruster force to keep a VLCC in position. Potential loss of one thruster is considered as a single point failure in a DP class 2 set up and will not affect the position keeping capability of the vessel. The DP vessel is therefore fully maneuverable with only two thrusters in operation.

In order to move the overall centre of gravity down below the centre of buoyancy and obtain the required stability margin, a large keel is implemented below the pontoon, where 1700 tons of fixed ballast have been installed in three separate ballast steel boxes. The keel arrangement ads a significant dampening effect of the combined set-up (DP vessel and tanker); it is designed to give high hydrodynamic dampening, thereby reducing overall roll and pitch motions during operations as well as in survival condition [5].

All contact forces between the DP vessel and the tanker are transferred by the fender system (Friction Attachment System) installed on top of the pontoon. The fender system basically consists of 6 cells each covered by high friction rubber elements and individually surrounded by a heavy duty compression seal. During contact with the tanker, the fender system will establish 6 independent and closed cells against the bottom of the tanker. The hydrostatic pressure acting on the bottom of the DP vessel will then be transferred to the tanker hull through the fender system. As a result, the attachment force on the fender system is increased and will vary as a function of the draught of the tanker. Since distributed loads are only replacing the hydrostatic pressure, it will only have limited impact on the local and global loads on the tanker. See also the figure 3 and 4 describing the function of friction attachment system before and after docking to the bottom of the hull of conventional tanker.

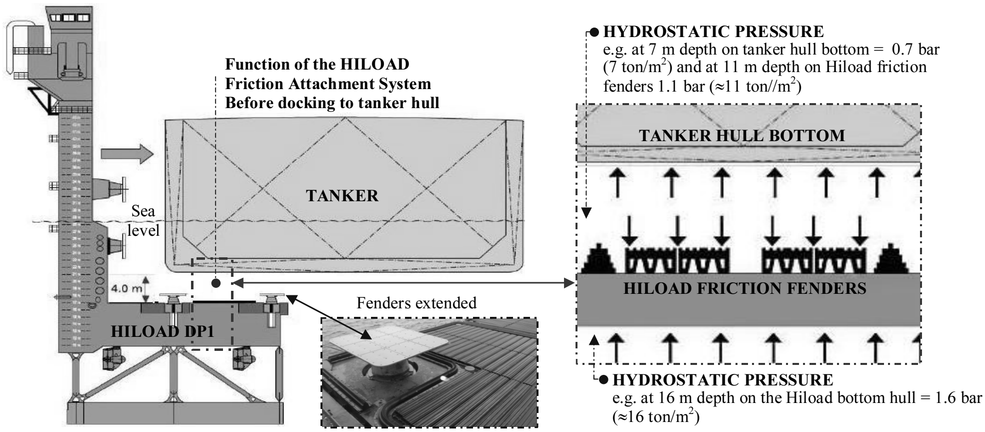

Fig. 3. Function of the „Hiload DP1" friction attachment system before docking to tanker vessel. Prepared on the bases of [2]

<u>„Hiload DP1" docking to the tanker operational steps [2] are as follows:</u>

1. Draught of tanker > 7 m. Draught of „Hiload DP1"= 28.4 m. „Hiload DP1" unit approaches slowly to conventional tanker on the port bow quarter (see Fig. 3).
2. Contact between Hiload fenders and conventional tanker.
3. Apply thruster force to side of tanker (Hiload will get some AFT Trim).
4. De-ballast 48 ton from Tank 1-P and 1-S (total 96 ton). All fenders in contact. Monitor Fender Forces. „Hiload DP1" draught = 26.8 m. Continue de-ballasting until totally 64 ton has been pumped out of Tank 1-P and 1-S (total 128 ton). Monitor Fender Forces.
5. De-ballast 50 ton from Tank 3-P, 3-S, 5-P and 5-S (totally 200 ton). Monitor pressure in the fenders, shall be evenly distributed.
6. Open Drain Valves for the Attachment System.

7. Retract all four (4) Pontoon Fenders simultaneously. Step 6 and 7 will be carried out simultaneously. Hiload DP will move up the remaining 300 mm and make contact with the tanker bottom. Attachment System is activated. Monitor level in tank 3 and 5 for leakage from Attachment System. Level to be kept at approx 50% filling. If needed lower down the gangway on tankers deck.

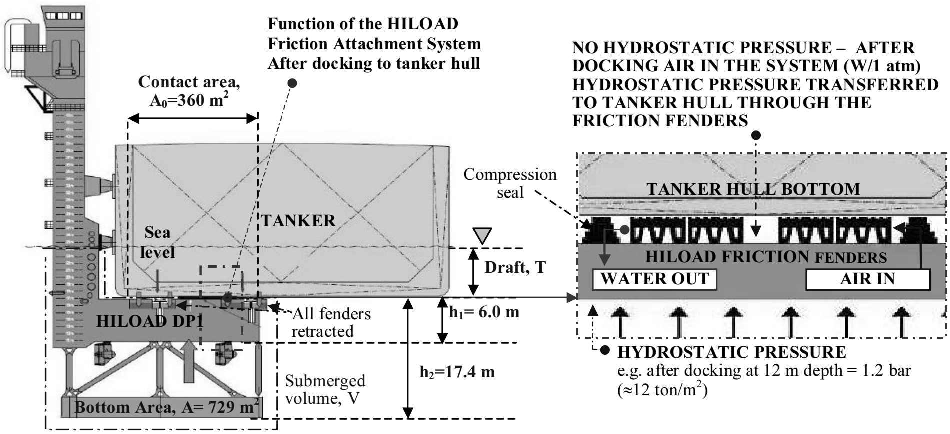

Fig. 4. Function of the „Hiload DP1" friction attachment system after docking to the bottom of the hull of conventional tanker. Prepared on the basis of [2]

Once the DP vessel is connected to the tanker, the DP vessel supports the tanker approach and maneuvering operations as well as the station keeping of the tanker during the entire offloading operation (typically 24 hours). The Hiload DP vessel's onboard crew comprises of three people: two DP operators and one marine engineer. The DP operators have visual contact with all critical areas of the operation at any given time, providing additional safety to the technically fully redundant system. A typical Field Layout with offloading from a spread moored FPSO is shown in figure 5. When not in use the DP vessel can either be parked onto the FPSO or kept floating away from the FPSO.

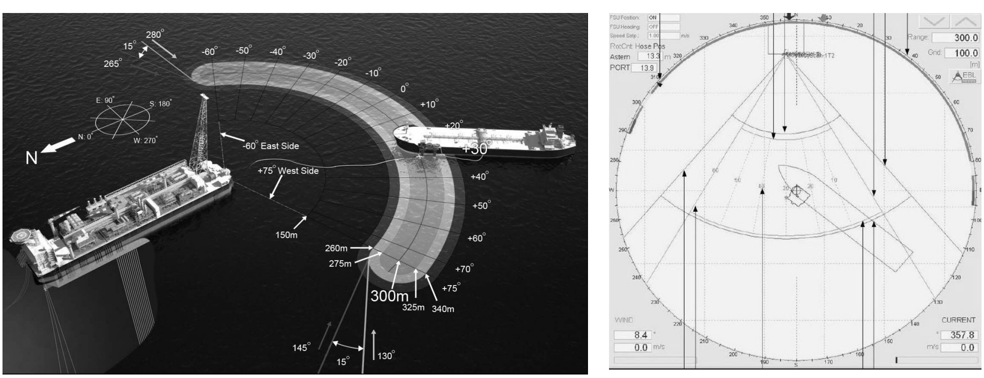

Fig. 5. Typical field layout with offloading sectors from a spread moored FPSO designated for Hiload DP init. Prepared on the basis of [2] and [6]

Hiload undocking from tanker operational steps [2] are as follows:

1. If needed secure the gangway between Hiload and tankers deck. Fill Tank 3 and 5 slowly to 80% filling (28 cm to top of tank, vent pipe is 20 × 20 cm). Drain valves for Attachment System still open.
2. Extend all pontoon fenders. Rubber compressed 720 mm. Cylinder 320 mm from upper position. No fender signal as fender is not in upper position. Pressure 160 bar = 64 ton each fender.
3. Apply thruster force towards side of the tanker. Close all 12 drain valves for Attachment System and simultaneously open all 6 „open to sea" valves for Attachment System (6"). Attachment system will be released. Fenders will push Hiload DP 0.6 m down. Still 25 ton pressure on each fender as Tank 3 and 5 is not completely filled.
4. Fill Tank 3 and 5 to 100% filling. Monitor decreasing fender pressure. Open all 12 drain valves for Attachment System to ensure 100% filling of tank 3 and 5.
5. Fill 64 ton in Tank 1-P and 1-S (total 128 ton). Draught of Hiload DP will be = 29.8 m. AFT Trim due to thruster force will occur.
6. Depart from the tanker. Some forward trim due to thrusters force will occur.

In the next chapter we are going to study the static contact force generated between Hiload DP attachment system and the bottom of the tanker in a seaway.

In this study we are going to use „Hiload DP1" unit with the following ships particulars [5]: Cyprus flag vessel, DNV 1A1 R Mobile Offshore Support Unit DYNPOS – AUTR, DP class 2 ship build in 2010, IMO = 8 770 950, 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 × caterpillar main engines each 3150 BHP, 3 × 550 kW Generators + 1 × 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 × B&W main engines 10 010 kW (13 420 HP) each, Two Ulstein controllable pitch propeller 4 blades each, 2 x bow thrusters Brunvoll 2200 kW (2950 HP) each and 2 × stern thrusters Brunvoll 735 kW (990 HP) each.

2. STATIC ANALYSIS OF THE CONTACT FORCES GENERATED ON A „HILOAD DP1" ATTACHMENT SYSTEM

In the calm water case, Hiload DP is subjected to gravity and buoyancy forces in the vertical direction [1, 2]. The connection force between Hiload DP and the tanker bottom is given by the difference between the buoyancy force and the gravity force:

$$F_s = F_b - F_{grav} \tag{1}$$

where:

- F_s – the static contact force generated on „Hiload DP1" „attachment system" in Newton [N],
- F_b – the force of buoyancy in Newton [N],
- F_{grav} – the gravity force in Newton [N],

The gravity force $\boldsymbol{F_{grav}}$ can be written:

$$F_{grav} = mg \tag{2}$$

Where:

- m – the mass of object in kg, in our analyses we are going to use the total mass of „Hiload DP1" unit equal to 4 674 000 kg [kg],
- g – the acceleration due to gravity, the gravity of Earth $g = 9.81$ m/s^2 [m/s^2].

It is also well known that the buoyancy force of a floating body equals ρgV, 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 in Figure 4. 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 $-\rho gTA_0$. The corrected buoyancy force F_b can now be written:

$$F_b = \rho gV + \rho gTA_0 \tag{3}$$

where:

- F_b – the force of buoyancy in Newton [N],
- ρ – the mass density of water (for sea water $\rho = 1025$ kg/m^3) [kg/m^3],
- g – the acceleration due to gravity (the gravity of Earth $g = 9.81$ m/s^2) [m/s^2],
- V – the volume of the object inserted into the fluid [m^3],
- T – the draft of the vessel and/or the draft of the attachment system (the height at which force acts taken from the surface to tanker bottom) [m],
- A_0 – contact area in meter square with nil hydrostatic pressure (for „Hiload DP1" unit $A_0 = 360$ m^2 estimated from drawings) [m^2].

The expression for the static contact force can now be written:

$$F_s = F_b - F_{grav} = \rho gV + \rho gTA_0 - mg \tag{4}$$

From equation (4) 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. Taking into consideration the following parameters estimated for a „Hiload DP1" unit (m = 4 674 000 kg, $A_0 = 360$ m^2), which is attached to the tanker vessel with different draft (T) in calm sea condition we can estimate the value of the static contact forces (using formula (4)) and compare all of these values with the weight of „Hiload DP1" unit. The factor (F_s/F_{grav}) will present the effectiveness of the attachments system in a stable sea condition. To see the result look at table 1 attached below:

Table 1. Static contact forces accounted for „Hiload DP1" unit docked to MT „Navion Anglia" with different draft and good weather condition at the calm sea

Tanker Draft T [m]	Submerged volume of „Hiload DP1": V [m^3]	Force of buoyancy as per (3): F_b [N]	Static contact force as per (4): F_s [N]	Gravity force (weight of „Hiload DP1") as per (2): F_{grav} [N]	F_s/F_{grav}
8	4851	77 735 825	31 883 885	45 851 940	0.70
9	4901	81 856 602	36 004 662	45 851 940	0.79
10	4950	85 977 379	40 125 439	45 851 940	0.88
11	5000	90 098 156	44 246 216	45 851 940	0.96
12	5050	94 218 933	48 366 993	45 851 940	1.05
13	5100	98 339 710	52 487 770	45 851 940	1.14
14	5149	102 460 487	56 608 547	45 851 940	1.23
15	5200	106 581 264	60 729 324	45 851 940	1.32

3. RESULT OF THE NUMERICAL ANALYSIS AT CALM SEA

The tanker MT „Navion Anglia" is used in the present study with the following conditions: medium ballast condition (T_1 = 8 m), full ballast condition (T_2 = 10 m), 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:

Table 2. Main particulars and mass properties of the MT „Navion Anglia" with „Hiload DP1" unit docked on port side alongside

Ship particulars: Loa = 264.68 m; Depth molded D = 22.07 m; Breadth 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

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. With reference to „Hiload DP1" unit the frame/truss structure underneath of „Hiload DP1" unit were 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 modelled as a box underneath the tanker bottom. In the ship's longitudinal direction, the box-length is 27 m. The distance from the bottom of the tanker to the bottom of the box is 6 m (see Fig. 4).

The relevant properties of Hiload DP used in the present analysis are as follow: total mass m = 4 674 000 kg, mass displacement ρV = 4 972 141 kg for tanker draft T = 8 m, 5 0742 59 kg for T = 10 m and 5 176 376 kg for T = 12 m, contact area A_0 = 360 m^2 (estimated from drawings of „Hiload DP1" attachment system), exposed area around contact area A_t = 329 m^2, area of „Hiload DP1" bottom A = 27 m × 27 m = 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 10 m 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 (4) and the safety factor in calm water can be calculated from equation (12) by setting F_d = 0. The results are presented in Table 3.

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

Parameter	Tanker draft T [m]				Unit
	8 m	10 m	12 m	15 m	
Buoyancy (ρgV)	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 (ρgTA_0)	29.0	36.2	43.4	54.3	MN
Static contact force (F_s) as per formula (4)	31.9	40.1	48.4	60.7	MN
Friction force $F_f = (F_s - F_d)\mu$ where F_d = 0 and μ = 0.6	19.1	24.1	29.0	36.4	MN
Resistance (drag) due to speed, ocean current and wind (F_t) from VERES simulator program	1.5	1.6	1.7	1.85	MN
Safety factor SF in calm water, at 4 knots forward speed, 1 knot current and 20 m/s wind as per formula: SF = *Ff/Ft*	***12.7***	***15.1***	***17.1***	***19.7***	

4. SUMMARY REPORT

From Table 3 one can clearly state that according to safety factor SF in the calm water (without dynamic forces) accounted for tanker vessel proceeding with 4 knots speed forward, 1 knot current and 20 m/s wind and with draft i.e. 10 m the static force generated on Hiload attachment system is 15.1 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 1.6 MN, the safety factor is 15.1 in this case. This evaluation was done without taken into account the wave induced horizontal force.

The safety factor is higher for a deeper tanker draft. Increase of the vessel draft should be considered as the most effective way to increase the safety factor in all conditions including the critical weather conditions.

All statements mentioned before have been also confirmed during sea trials carried out in Norway on Kristiansand bay in Q3 2013 at the calm sea condition and offshore Brazil in 2014, when „Hiload DP1" unit was docked to MT „Navion Anglia" in good weather condition. From sea trials at calm sea it was noted that Hiload DP attachment system is a very effective and time reserving system. All docking and/or undocking operations can be arranged very fast (usually within about 20 to 30 minutes window) without any additional work and/or preparation of mooring line and/or another mooring equipment.

At the calm sea „Hiload DP1" unit was able to move the tanker in each direction and without any problem and/or assistance from mother ship was able to proceed forward with speed about 2 to 3 knots towing our vessel. In this case MT „Navion Anglia" kept all her thrusters switched off and main engine on standby mode. Similar test were confirm offshore Brazil at calm sea on Campos Basin in 2014.

During real life operation carried out at calm sea at the open ocean some influence for mother ship with a small vibration on „Hiload DP1" unit was noted when sailing with the opposite current. Ocean current direction was assumed to be most critical when opposite to the vessel forward motion. The total water flow velocity relative to the tanker surface was assumed to always be: 4 knots (forward speed) + 1 knot (ocean current speed) = 5 knots SOG (Speed Over Ground). Before the sea passage through Atlantic Ocean „Hiload DP1" attachment system was tested in Norway [1] with MT „Navion Anglia" in two locations: amidships in distance about 132 m from AP m (0.5 Lpp) and forward in location about 198 m from AP (0.75 Lpp). During the sea trials a better heading control and Rate of Turn (ROT) control when „Hiload DP1" unit was docked forward were noted. Simultaneously when „Hiload DP1" unit was docked amidships a better side movements control was noted.

According to the numerical analysis carried out above, the safety factor is almost the same for both considered locations of a „Hiload DP1" unit. However for the transit voyage through Atlantic Ocean it was recommended to position the „Hiload DP1" unit at the amidships in order to decrease variation of the dynamical forces.

Due to limited place in this paper sea waves, swell and all other dynamical forces were not considered in this analysis. However more details regarding numerical analysis of Hiload technology and operational risk can be found in [1] and [4].

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ANALIZA NUMERYCZNA SIŁ KONTAKTOWYCH GENEROWANYCH W NOWATORSKIM SYSTEMIE DOKOWANIA STATKU „HILOAD DP1" NA WODZIE SPOKOJNEJ

Streszczenie

W niniejszym artykule przedstawiono krótką charakterystykę nowatorskiej technologii Hiload zastosowanej na prototypie statku nowej generacji „Hiload DP1". Technologia ta opiera się na opatentowanym przez firmę Remora SA systemie „przyssawek dennych" (Remora Attachment System), który umożliwia sprawne dokowanie statku do burty (dna) innych jednostek morskich, umożliwiając jednostkom konwencjonalnym ich odholowanie do punktów zbornych i/lub dynamiczne ich pozycjonowanie w wyznaczonym obszarze operacyjnym, wspomagając ich operacje ładunkowe w sektorze off-shore. Istota działania systemu jest przy tym tożsama z systemem przyssawek skórnych stosowanym przez ryby remora. W artykule skupiono się na analizie numerycznej sił kontaktowych statycznych, wygenerowanych w systemie „przyssawek dennych" statku „Hiload DP1" na wodzie spokojnej.

Słowa kluczowe: *technologia Hiload, siły kontaktowe (statyczne i dynamiczne), ciśnienie hydrostatyczne, siły tarcia, system dokowania, instalacje offshore, systemy dynamicznego pozycjonowania.*