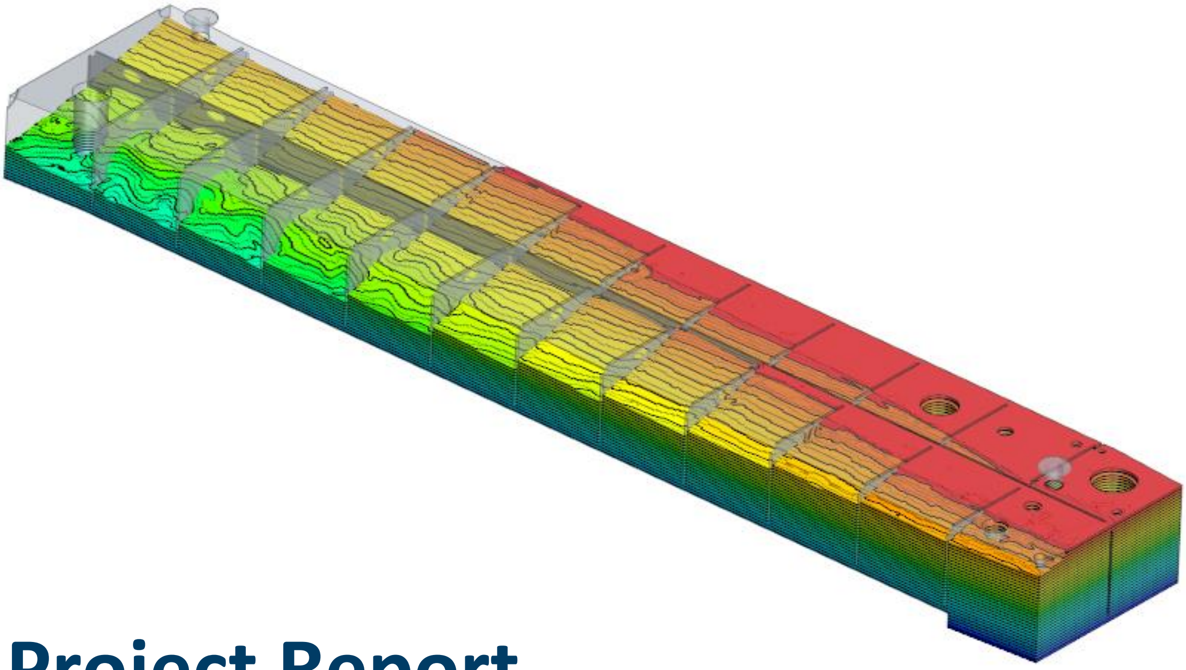

Project Report

Sloshing analysis of Viking Sky Oil Sump N. 05 STBD

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SUMMARY

This report contains computational fluid dynamics simulations of lubricating oil in Viking Sky Oil Sump N. 05 STBD. The dynamic criteria of SOLAS, Chapter II-1, Part C, Regulation 26.6 does not contain all the necessary information to define unambiguous test criteria and there is no approved method for its application. In the context of this report, the assumption is made that the design should sustain the roll and pitch amplitudes prescribed by SOLAS under any realistic motion pattern.

The simulations investigate how dynamic motions of the SOLAS criteria impact the oil level around the lube oil suction pipe. Results reveal that the suction pipe inlet area will be exposed to air for 4 seconds with the highest oil filling level recommended by the Engine Maker.

Additional simulations were run using recorded motion experienced by Viking Sky during the time of the accident. The results reveal a 20 cm oil level margin above the suction pipe inlet area for the highest oil filling level recommended by the Engine Maker. Estimated actual oil level results in exposed suction pipe inlet area around the same time as the ship experienced engine shutdown signals.

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1 Introduction

On 23 March 2019, Viking Sky suffered an engine failure off the coast of Norway. The Norwegian Safety Investigation Authority (NSIA) concluded in a preliminary report issued 12 November 2019 that the engines shut down as a result of the loss of lubricating oil pressure, due to low sump tank levels combined with pitching and rolling.

SOLAS, Chapter II-1, Part C Regulation 26.6 states:
“Main propulsion machinery and all auxiliary machinery essential to the propulsion and the safety of the ship shall, as fitted in the ship, be designed to operate when the ship is upright and when inclined at any angle of list up to and including 15' either way under static conditions and 22.5’ under dynamic conditions (rolling) either way and simultaneously inclined dynamically (pitching) 7.5’ by bow or stern.”

NSIA has found that the design of the lubrication oil tanks deviates significantly from the design recommended by the Engine Manufacturer, MAN, with respect to the minimum tank height. NSIA has therefore decided to investigate the tank design in view of the SOLAS regulation. The lubrication oil tank N. 05 STBD was identified by the shipyard, Fincantieri, to have the least margin for failure and was therefore selected for this study.

The primary goal of the simulations is to evaluate the likelihood of the lube oil suction pipe to be exposed to air if the Viking Sky would be subject to vessel motion as specified in the dynamic requirements of SOLAS, Chapter II-1, Part C Regulation 26.6 (i.e., 22,5 degrees roll and 7,5 degrees pitch simultaneously).

In addition, simulation cases that include the actual oil tank filling level and the recorded motion experienced by Viking Sky during the time of the accident are carried out. The purpose of these simulations is to evaluate the validity of the simulation model by comparing the results with the actual events as logged by the alarm system on board. Further, a simulation case combining the highest oil filling level recommended by the Engine Maker and the recorded vessel motion is carried out to evaluate if the oil suction pipe was likely to have been exposed to air under such conditions.

This report presents the computational fluid dynamics (CFD) simulation model, cases, and results of the Viking Sky Oil Sump N. 05 STBD performed by SINTEF Ocean AS (SO) at request by NSIA.

2 Simulation cases

2.1 SOLAS cases

Neither SO nor NSIA are aware of any approved method for the application of the relevant SOLAS requirements or the verification of compliance with them. In the absence of a supporting technical standard, the limited parameters included in the regulation are insufficient to define unambiguous test criteria (e.g., choice of roll and pitch periods, pattern, or duration). Therefore, NSIA decided to evaluate the tank design with the highest oil filling level recommended by the Engine Maker combined with the most unfavourable vessel motion, i.e., the dynamic conditions that maximise the potential for exposure of the oil suction pipe to air.

The initial simulation cases consist of imposing sinusoidal motion, in combinations of both pitch and roll, on the tank. Sinusoidal motion is a natural and realistic choice, being independent of specific sea states, ship geometries, loading conditions, and ship speeds. The SOLAS cases are structured to identify how pitch and roll motions influence the oil dynamics and to determine the worst-case scenario that the tank may theoretically be exposed to.

As the sinusoidal amplitude (7.5' pitching and 22.5' rolling) is determined by the SOLAS requirement, the parameters in the sinusoidal motions to be decided are the period and the phase difference between the pitch and roll motions (phase shift). The ship motion periods are a consequence of the sea state the ship is exposed to. To identify the characteristic periods of the ship, or Response Amplitude Operators (RAOs), SO has performed simulations using SO's software VERES (Vessel Response) based on a model of a similar cruise ship which has been scaled to match the characteristics of Viking Sky. From these simulations, two peak pitch periods of ~7 and ~13 seconds and one peak roll period of ~17 seconds were identified for the ship's response to waves. This correlates well with the seakeeping report performed by the Hamburg Ship Model Basin (HSVA) of hull #6236 for Viking Ocean Cruises with a natural roll period of 17.5 seconds and pitch RAO of 13.24 seconds. Note that the 7 seconds pitch period also corresponds to the sloshing period along the length of the tank assuming the bulkheads are not significantly affecting the sloshing natural period.

The case matrix for identification of the worst-case scenario by the SOLAS requirement is shown in Table 2-1. Note that the results presented in chapter 4.3 SOLAS cases are based on this case matrix structure. All these simulations have been conducted with an oil filling level of 55 cm (15 cm below tank top), corresponding to the highest oil filling level recommended by the Engine Maker.

Table 2-1: Case matrix for SOLAS requirement

Case nr.	Roll amplitude [deg]	Pitch amplitude [deg]	Period [s]	Phase shift [deg]	Comment
1	0	7.5	7	0	Only pitch, first pitch period
2	0	7.5	13	0	Only pitch, second pitch period
3	22.5	0	17.5	0	Only roll, roll period
4	0	7.5	17.5	0	Only pitch, roll period
5	22.5	7.5	17.5	0	Combined pitch and roll, roll period
6	22.5	7.5	20.125	0	Effect of varying period
7	22.5	7.5	18.375	0	Effect of varying period
8	22.5	7.5	16.625	0	Effect of varying period
9	22.5	7.5	14.875	0	Effect of varying period
10	22.5	7.5	17.5	45	Effect of phase difference
11	22.5	7.5	17.5	90	Effect of phase difference
12	22.5	7.5	17.5	135	Effect of phase difference
13	22.5	7.5	17.5	-45	Effect of phase difference
14	22.5	7.5	17.5	45	Worst-case condition with motion centre loading condition departure
15	22.5	7.5	17.5	45	Worst-case condition with motion centre loading condition arrival
16	22.5	7.5	17.5	45	Rerun of case 14 with oil properties @ 70 °C

The pitch and roll motions are presented with the same period as it results in the largest motions for the oil tank. Ships generally have very low damping in roll hence the roll motion is dominated by the natural roll period[1]. At sea conditions, the pitch motion period depends on the incoming wave period. The largest motion for the oil sump will then occur when the ship is excited by incoming wave periods matching the

---

[1] Lloyd, A R J M, *Seakeeping – Ship Behaviour in Rough Weather*, 1998

natural roll period. The incoming wave period depends on ship velocity, wave period and apparent wave direction.

2.2 Viking Sky motion cases

During the time of the Viking Sky accident, the ship pitch and roll motion data was captured by two sensors: ENIRAM Attitude Sensor aft and fore. The first automatic engine shutdown requests due to low oil pressure were recorded for DG4 and DG2 around 12:45:30 UTC. Therefore, a five-minute time window from 12:41:00 to 12:46:00 UTC was chosen to be simulated.

Three simulation cases have been conducted using the registered ship motion, as specified in Table 2-2. Surge, sway, yaw, and heave motions of the ship at the time of the accident, which all influence the oil dynamics in the tank, are not captured by any sensors and hence not present in the simulation.

Table 2-2: Viking Sky motion cases sensor and oil filling level

Case nr.	Sensor data used	Oil filling level	Comment
17	Aft	55 cm (15 cm below tank top)	Highest oil filling level recommended by the Engine Maker
18	Aft	32 cm (38 cm below tank top)	Actual filling level during incident
19	Forward	32 cm (38 cm below tank top)	Sensitivity study between sensors

3 Simulation model

The simulation model is a modification from the Star CCM+ simulation file "6236_OilSump5S.sim" provided by the shipyard. The simulation model contained the geometry of the oil sump and fluid properties. The CFD simulation utilises RANS k-ω SST turbulence and VOF multiphase models. Mesh and VOF settings have been modified to better capture the oil free surface and hence the sloshing. Time step size is adjusted so that the free surface convective courant number is for the most part below one. Both mesh and time step convergence tests have been run. The CFD software used is Star CCM+ v15.06.008-R8.

3.1 Tank geometry and configuration

The oil tank is positioned below the engine as illustrated in Figure 3-1. The oil tank is denoted as T-001 Lube oil service tank. The Dry oil pan, positioned between the engine and oil tank, collects oil from the engine and distributes oil to the oil tank through oil return pipes, denoted as 2111 and 2113. The oil is pumped back into the engine and auxiliary equipment by the Lube oil service pump through the oil suction pipe, denoted as 2121. A simplified illustration of the tank geometry and oil flow direction can be viewed in Figure 3-2. Tank geometry and main dimensions used in the simulations are shown in Figure 3-3 and Figure 3-4.

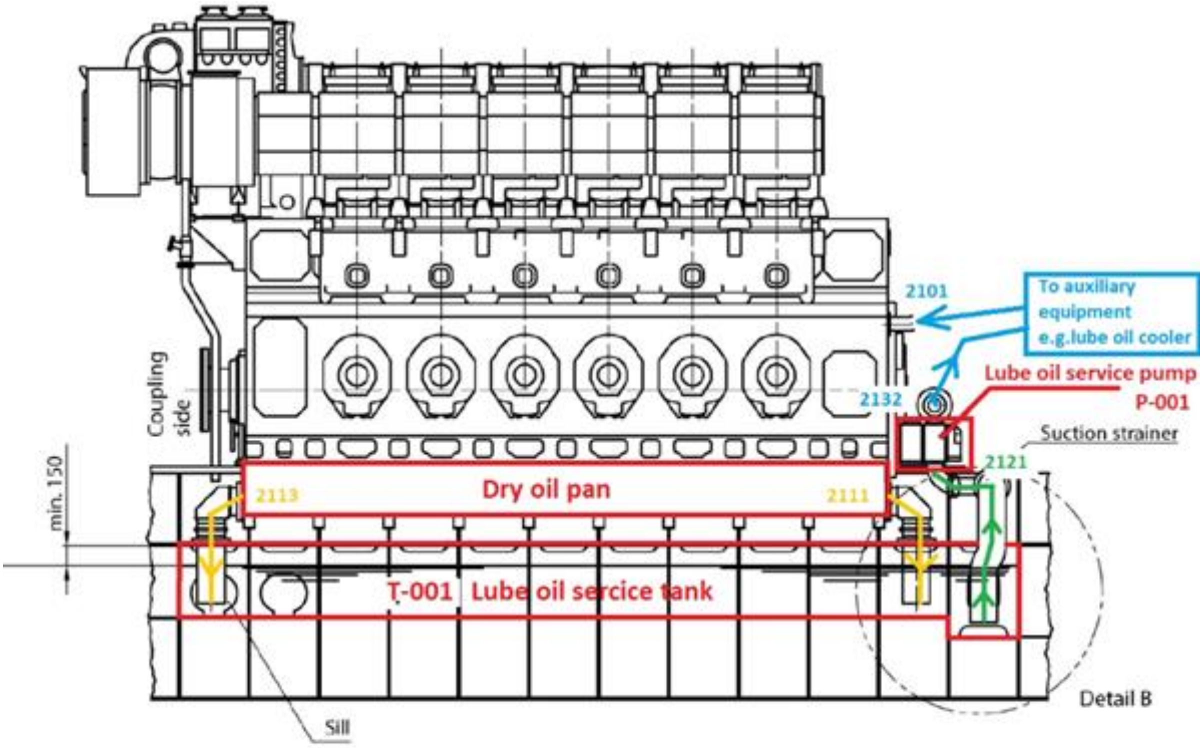

Figure 3-1: Engine and oil tank configuration

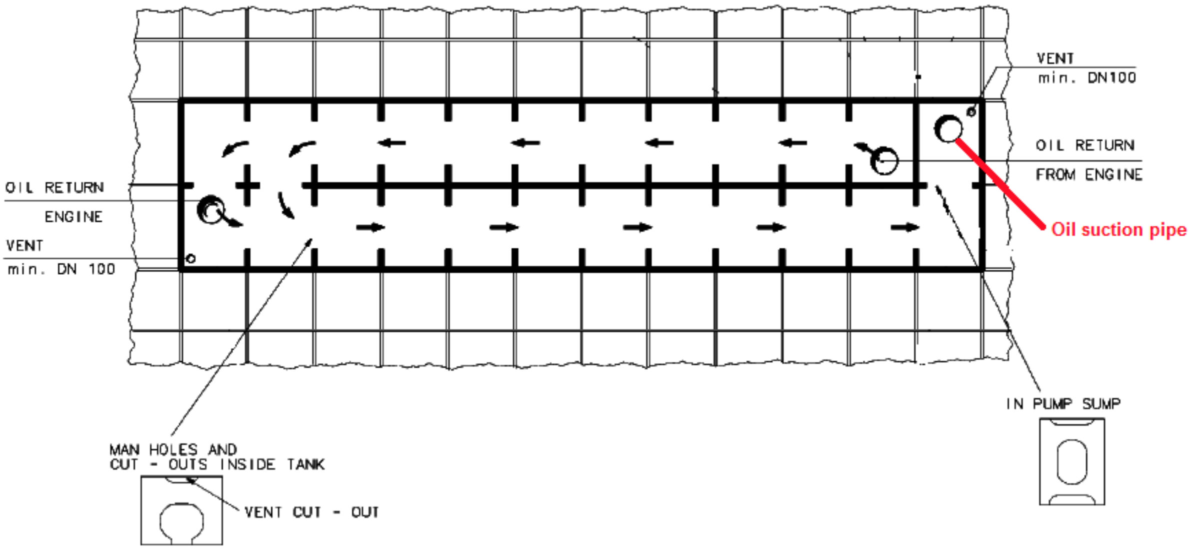

Figure 3-2: Top view of simplified oil tank. Tank lies along the length of the ship

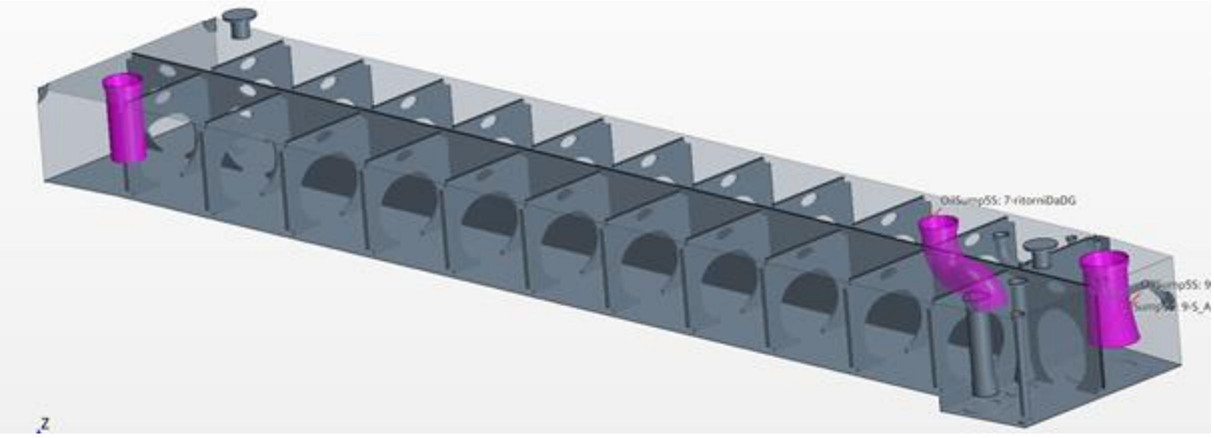

Figure 3-3: Oil tank simulation geometry. Oil return and suction pipes highlighted

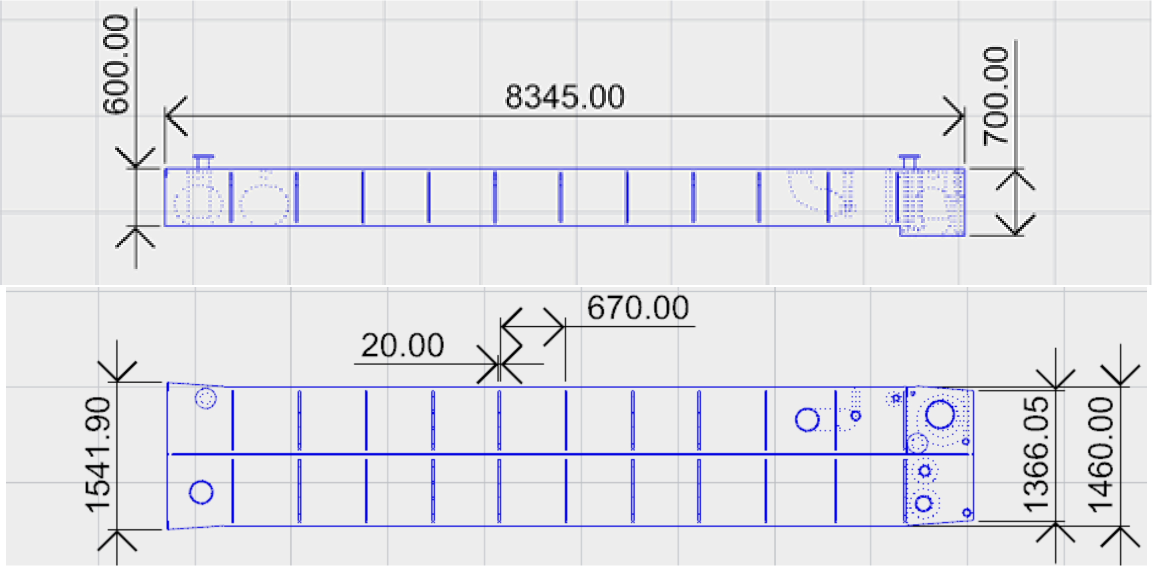

Figure 3-4: Oil tank geometry. Dimensions in mm

3.2 Tank position and centre of motion

The tank position and centre of motion are chosen according to the Viking Sky stability manual. The analysed tank is located on the starboard side. The tank position uses the centre of gravity (CoG) of the tank given a filling level of 55 cm as shown in Table 3-1. The centre of motion is chosen as the longitudinal centre of flotation (LCF) for the given loading condition. The motion centre will change as the ship experiences motion, but this cannot be estimated without referring to specific sea states, ship geometry, loading conditions, and ship speeds. Hence, the motion centre at a given loading condition is applied.

Two loading conditions of the ship have been used for the centre of motion which represents the largest changes in the motion centre; loading condition departure and arrival port as shown in Table 3-2. All positions refer to the stability manual where X = 0 at "frame 0" 1 meter in front of aft perpendicular (positive towards bow), Y = 0 at ship's centreline (positive towards starboard), and Z = 0 at keel (positive upwards).

Table 3-1: Oil tank CoG position at 55 cm oil filling level

Tank position	X [m]	Y [m]	Z [m]
CoG	51.84	(-)[2] 4.713	1.07

[2] Starboard direction is negative in the simulation model

Table 3-2: Motion centres SOLAS cases

Motion centre	X (LCF) [m]	Y [m]	Z (Draught) [m]
Departure	84.51	0	6.65
Arrival	86.49	0	6.26

During the time of the Viking Sky accident the draught was estimated to be 6.57 m resulting in a LCF at calm water of 85.05 m. Motion centre of the Viking Sky motion cases are using these values as shown in Table 3-3.

Table 3-3: Motion centre for Viking Sky motion cases

Motion centre	X (LCF) [m]	Y [m]	Z (Draught) [m]
Viking Sky motion cases	85.05	0	6.57

3.3 Simulation model parameters and functions

Oil parameters and functions in the simulation model are shown in Table 3-4. The oil density and viscosity are temperature dependent. The temperature distribution of the oil may not be uniform and can influence the results. The necessary information needed to take the temperature distribution into account, such as wall heat flux and oil heat conduction, was not part of the data material provided by the shipyard and hence not included in the simulations. Oil temperature has been measured to exit the engine at approximately 75 °C and expected to exit the oil tank in a temperature range of approximately 70-74 °C. Oil properties at 75 °C will primarily be used and a sensitivity case for oil properties at 70 °C will be presented in 4.3.5 Case nr. 14-16: Extremal loading conditions and viscous effect.

Table 3-4: Simulation model parameters and functions

Parameters/functions	Definition	Comment
Initial oil level	15 cm below tank top	Highest oil filling level recommended by the Engine Maker
Oil density	880 kg/m^3	M440 @ 75 °C
Oil kinematic viscosity	32 cSt (3.2E-5 m^2/s)	M440 @ 75 °C
Oil kinematic viscosity	40 cSt (4.0E-5 m^2/s)	M440 @ 70 °C, used as sensitivity check in SOLAS cases
Air density	1.18415 kg/m^3	Standard air @ 1 atm, 15 °C
Air dynamic viscosity	1.85508E-5 Pa-s	Standard air @ 1 atm, 15 °C
Pitch angle function (SOLAS cases)	$-\mathrm{A_{pitch}} \cdot \frac{\pi}{180} \cdot \sin\left(\frac{2\pi}{\mathrm{Period}} \cdot \mathrm{Time}\right)$	Negative sign corresponds to bow-up motion
Roll angle function (SOLAS cases)	$\mathrm{A_{pitch}} \cdot \frac{\pi}{180} \cdot \sin\left(\frac{2\pi}{\mathrm{Period}} \cdot \mathrm{Time} - \mathrm{Phase_{shift}} \cdot \frac{\pi}{180}\right)$	Positive sign corresponds to roll towards starboard motion

Time step (SOLAS cases)	Period/1000	Derived from time step sensitivity analysis
Maximum physical time (SOLAS cases)	Period · 20	Most cases converged between 10-15 periods

The trim (pitch) and list (roll) angles are derived from the onboard ENIRAM Attitude sensors for the Viking Sky motion cases. The data is defined with positive list as rolling towards starboard and positive trim as pitching bow up. The raw data is influenced by noise, probably resulting from hull flex and vibrations. A low pass filter has therefore been used to identify the noise frequency and has been filtered out. It was identified that the noise was primarily above 1 Hz frequency. A cut-off of 0.8 Hz has been used where all frequencies above 0.8 Hz are removed as illustrated in Figure 3-5. Comparison of the unfiltered and filtered sensor data for the 300 seconds time window are shown in Figure 3-6 to Figure 3-9.

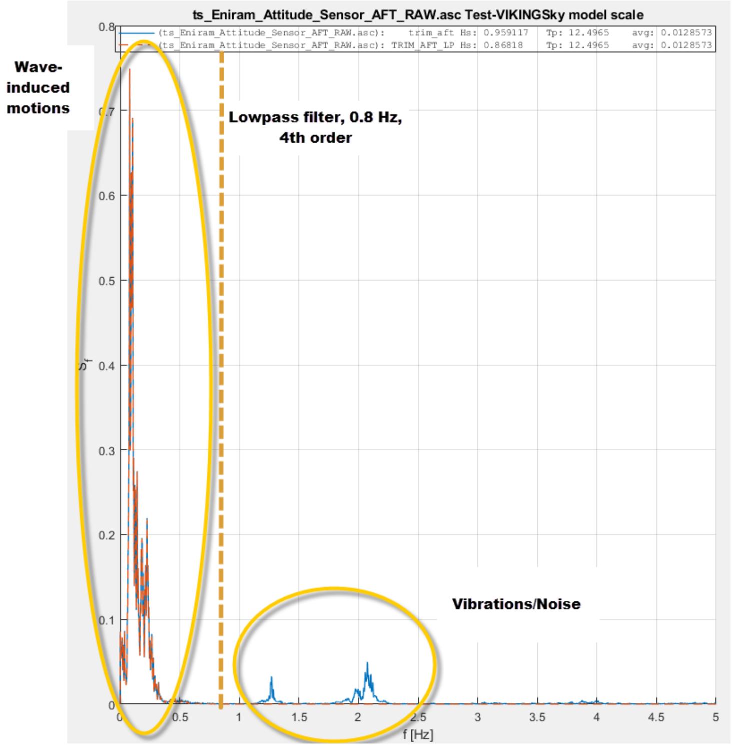

Figure 3-5: Lowpass filter of aft sensor

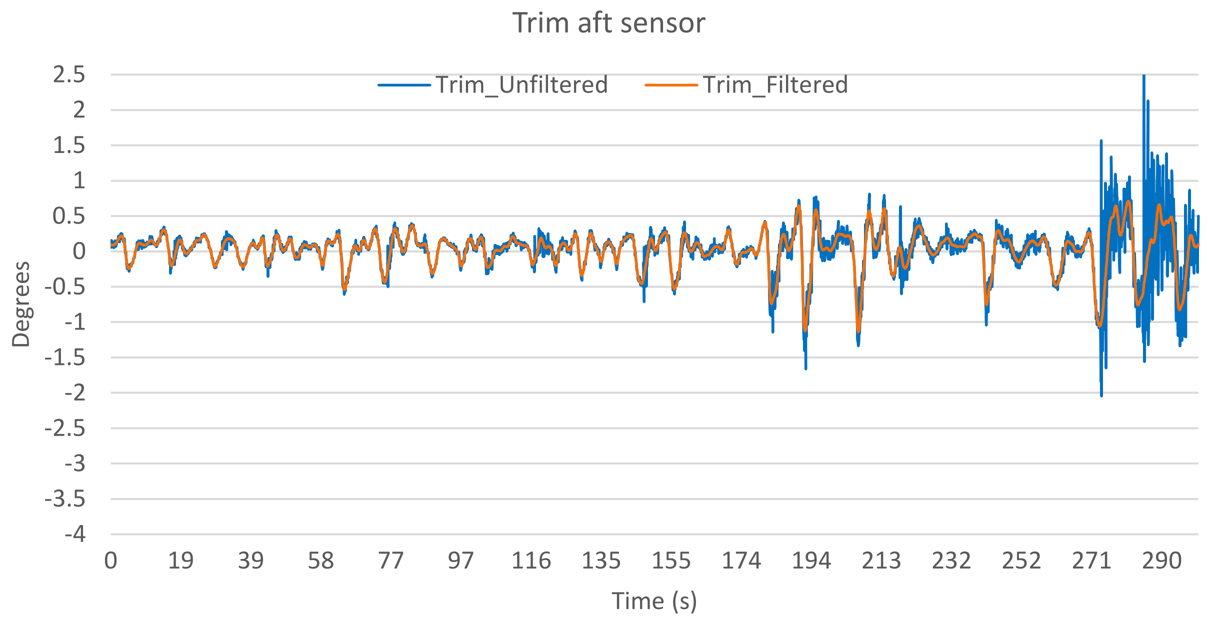

Figure 3-6: ENIRAM Attitude aft sensor unfiltered and filtered trim data

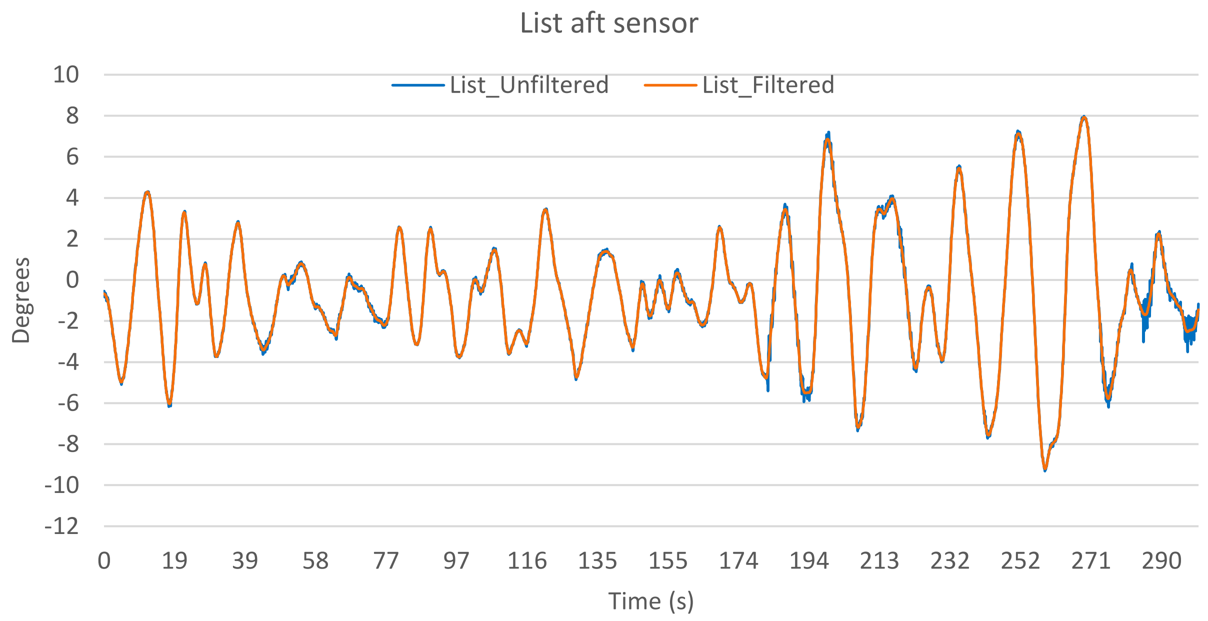

Figure 3-7: ENIRAM Attitude aft sensor unfiltered and filtered list data

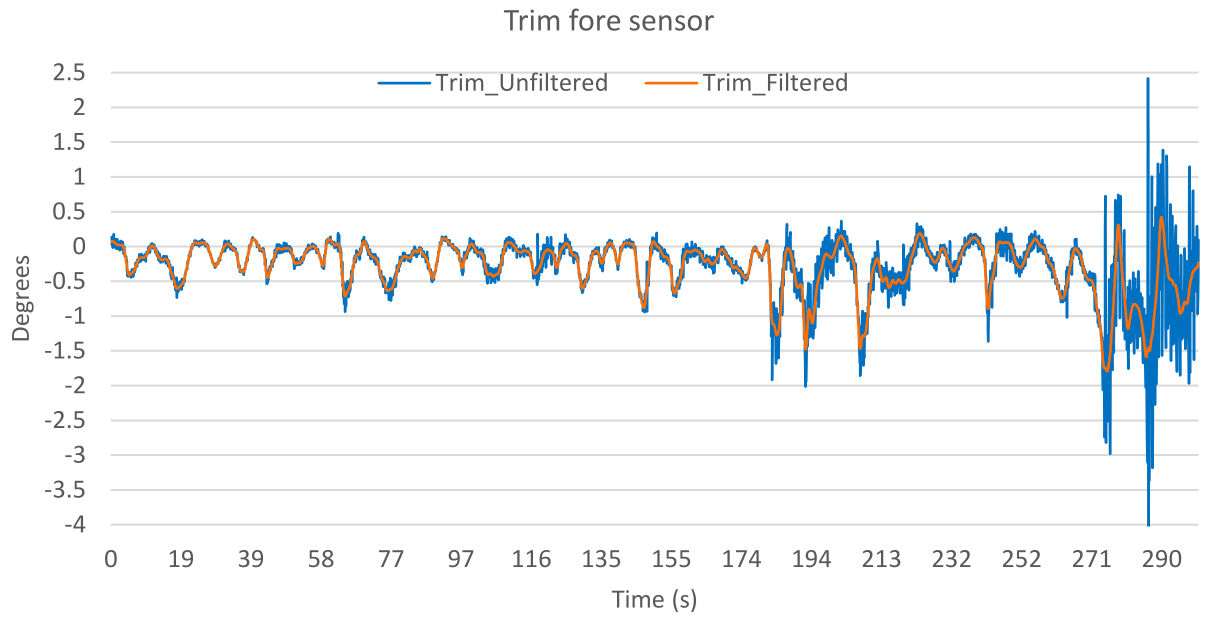

Figure 3-8: ENIRAM Attitude fore sensor unfiltered and filtered trim data

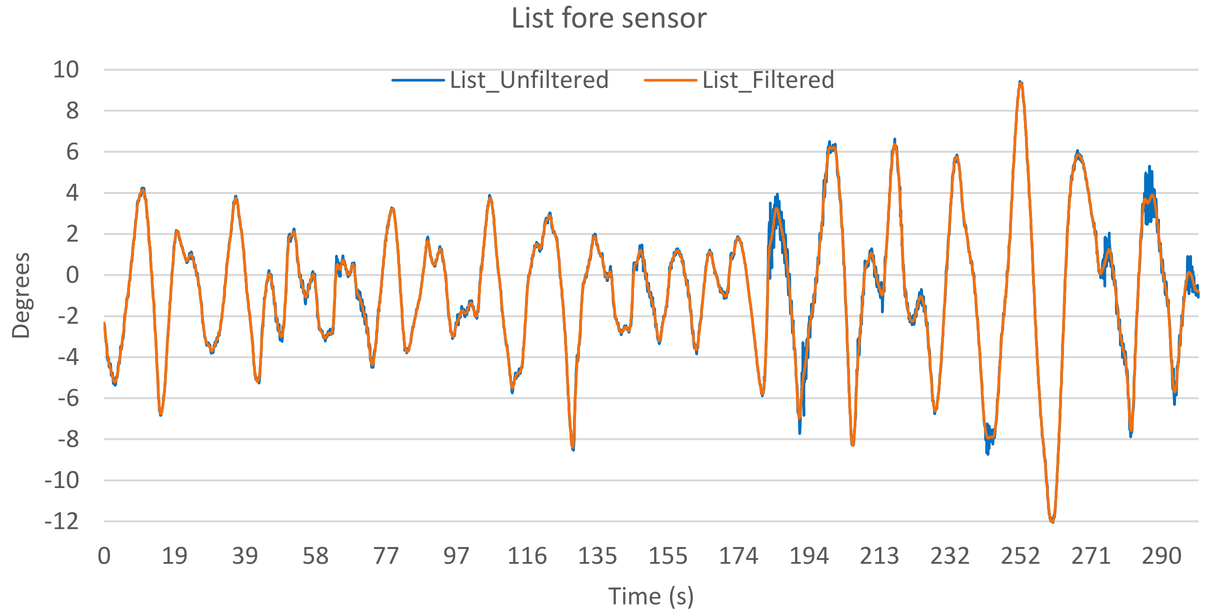

Figure 3-9: ENIRAM Attitude fore sensor unfiltered and filtered list data

From the filtered sensor data, a comparison is made to see how the recorded motions correspond to sinusoidal motion. The comparison is made where the recorded motions are largest from the aft sensor. Figure 3-10 shows the recorded list motion and sinusoidal motion with 17 s period and 7.5' amplitude. Figure 3-11 shows the recorded trim motion and sinusoidal motion with 10.5 s period and 0.7' amplitude. The recorded list motion corresponds quite well with sinusoidal motion while the recorded trim motion has more fluctuations from the sinusoidal motion. Note that the recorded list motion period is very similar to the natural roll period of 17.5 s.

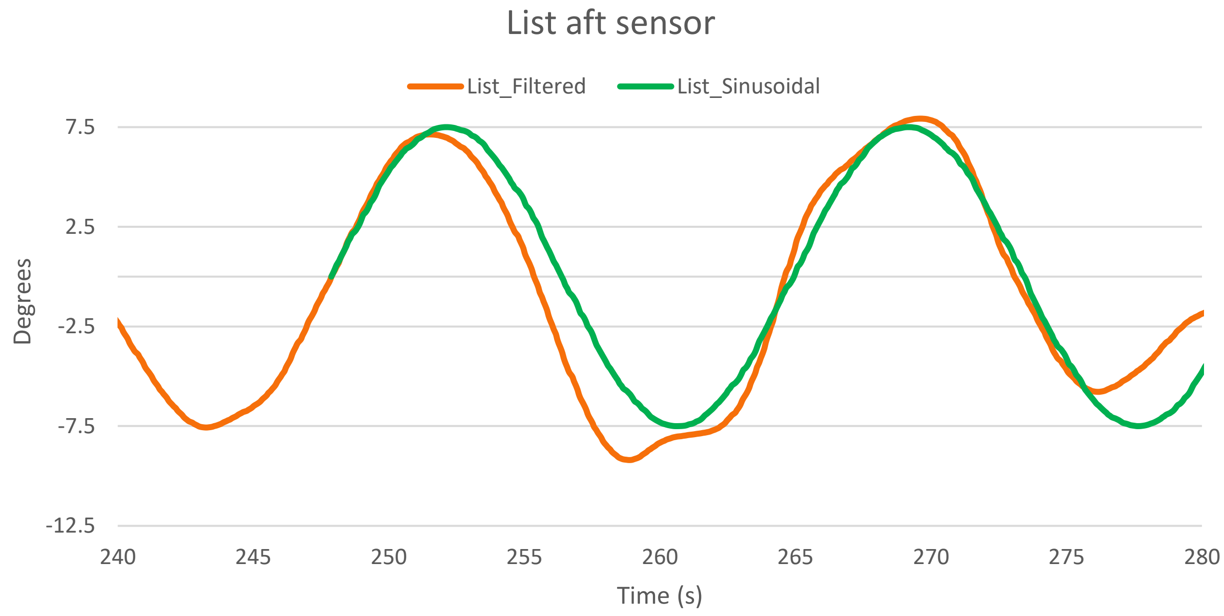

Figure 3-10: List aft sensor and sinusoidal motion

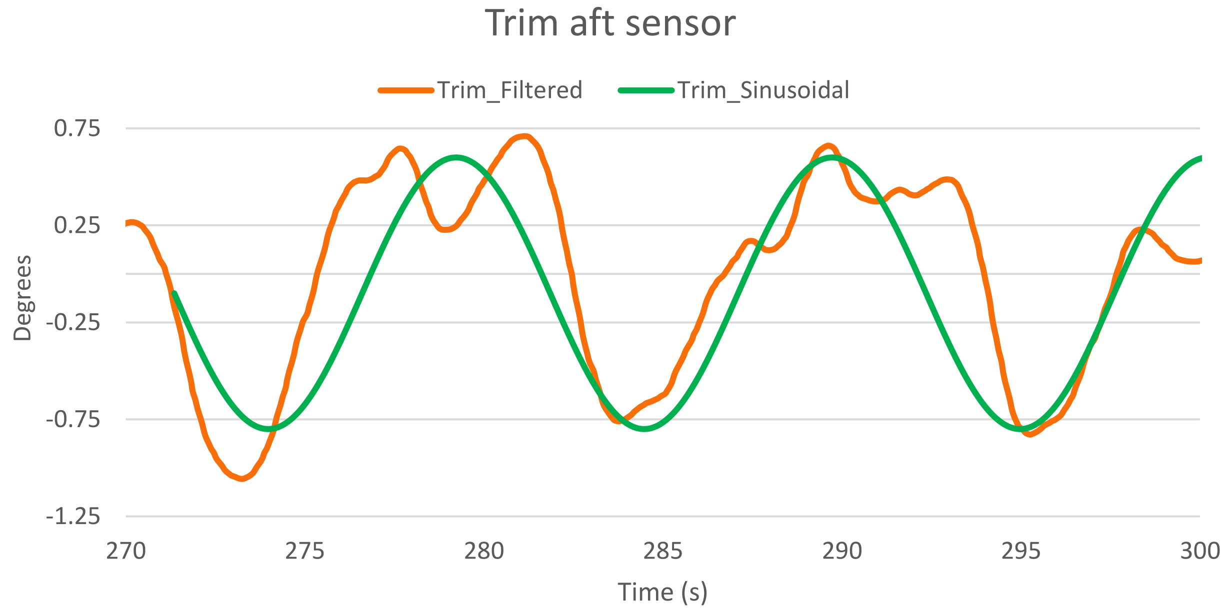

Figure 3-11: Trim aft sensor and sinusoidal motion

3.4 Oil tank circulation

The lube oil service pump is a positive displacement pump designed to pump a constant volumetric flow, specifically 141 m^3/h for this case. In the simulation model the suction pipe inlet has therefore been modelled as a mass flow outlet for the tank, where the mass flow is determined by Equation 3-1. Volume fractions are calculated on the suction pipe inlet area.

$$\dot{\mathrm{m}} = \left(\mathbf{V}_{\mathbf{f,oil}} \cdot \boldsymbol{\rho}_{\mathbf{oil}} + \mathbf{V}_{\mathbf{f,air}} \cdot \boldsymbol{\rho}_{\mathbf{air}}\right) \cdot \mathbf{Q}$$

Equation 3-1: Outlet mass flow. $\dot{\mathrm{m}}$ $-$ **mass flow,** $\mathbf{V}_{\mathbf{f,oil}}$ $-$ **volume fraction oil,** $\boldsymbol{\rho}_{\mathbf{oil}}$ $-$ **density oil,** $\mathbf{V}_{\mathbf{f,air}}$ $-$ **volume fraction air,** $\boldsymbol{\rho}_{\mathbf{air}}$ $-$ **density air,** $\mathbf{Q}$ $-$ **volumetric flow**

The oil distribution into the oil tank through the oil return pipes is propelled by gravity from the dry oil pan above. It has therefore been decided to use stagnation inlets for the oil tank, where the total pressure is defined at the oil return pipes. The mass flow distribution through each oil return pipe is therefore determined by the oil pressure around the two oil return pipes which dynamically changes due to the motion. To maintain a constant oil volume in the tank, the fraction of oil and air flowing through the oil return pipes are the same as calculated at the oil suction pipe. The defined total pressure for the two oil return pipes is set equal as SO is unable to precisely model how the oil is distributed within the dry oil pan due to the motion. The entire circulation system would be required to be modelled to capture this distribution more accurately. The current setup distributes the oil into the oil tank as if the dry oil pan is unaffected by the motion. This simplification is assumed to be negligible as the hydrodynamic residence time, calculated as volumetric flow divided by tank volume, is on a far higher time scale than the motion periods. With volumetric flow of 141 m^3/h and oil volume of 5.4 m^3 results in a hydrodynamic residence time of 137.9 s while the motion periods are generally around 17.5 s. This means that the effect of motion has a far higher impact on the oil dynamics than the circulation.

It was quickly discovered in the project that simulations with both circulation and motions was difficult to perform. Two main problems were identified for which the simulation became unstable; (1) the oil return and suction pipe inlet areas were too large for the boundary conditions and (2) boundary conditions become unstable when a significant amount of air is sucked through the suction pipe. To solve the first issue the internal pipe geometry was modified to decrease the oil return and suction pipe inlet areas, as shown in Figure 3-12. The area at the entrance of the pipes (protruding into the tank) is defined so that the pipes maintain their wall thickness of 3.76 mm (DN200) and 4.19 mm (DN250) for the respective oil return and suction pipes. By retaining the wall thickness at the entrance of the pipes, the volumetric flow at the pipe entrances is maintained to not impact the fluid dynamics around the oil return and suction pipes.

Figure 3-12: Modified internal return and suction pipe geometry

The second issue, where a significant fraction of the suction pipe inlet area is exposed to air, could not be solved. While the circulation has less impact on the overall oil dynamics than the motion, it can have a local impact on the oil level close to the oil return and suction pipes. For the suction pipe, which is the primary focus of the analysis, the suction can either drive the oil in the rest of the tank faster towards the surrounding volume of the suction pipe or it can more quickly reduce the amount of oil in the surrounding volume.

To investigate the circulation effect on the oil level at the suction pipe, four different motion cases with similar setup as the SOLAS cases were defined where there is no air suction, as shown in Table 3-5. These cases are simulated with and without circulation and the oil level at the suction pipe is compared to each other. The results are presented in 4.2 Oil circulation cases.

Table 3-5: Oil circulation cases

Case nr.	Roll amplitude [deg]	Pitch amplitude [deg]	Period [s]	Phase [deg]
A	7.5	0	17.5	0
B	0	5.5	17.5	0
C	5.0	2.5	17.5	0
D	2.5	5.0	17.5	0

4 Results

The results are presented by measuring the average head of oil on a cylindrical section surrounding the oil suction pipe and the fraction of the suction pipe's inlet area covered by oil as shown in Figure 4-1. The measurements indicate bottom of tank at 0 cm, top of tank at 69.35 cm and suction pipe inlet area at 17.85 cm. Due to a small step in the bottom of the tank below the suction pipe, partially intersecting the cylinder section, there is an offset of 0.65 cm for the top of tank and suction pipe inlet area oil level in the measurements. Additional oil level measurements along two lines on both sides of the suction pipe, denoted Line probe 1 and 2 in Figure 4-1, has also been performed to validate the oil level measurements. Animations of the oil fraction in XZ and YZ planes and oil free surface elevation, along with graphs of the measured oil level on the two lines, have been provided to NSIA as supplement to this report.

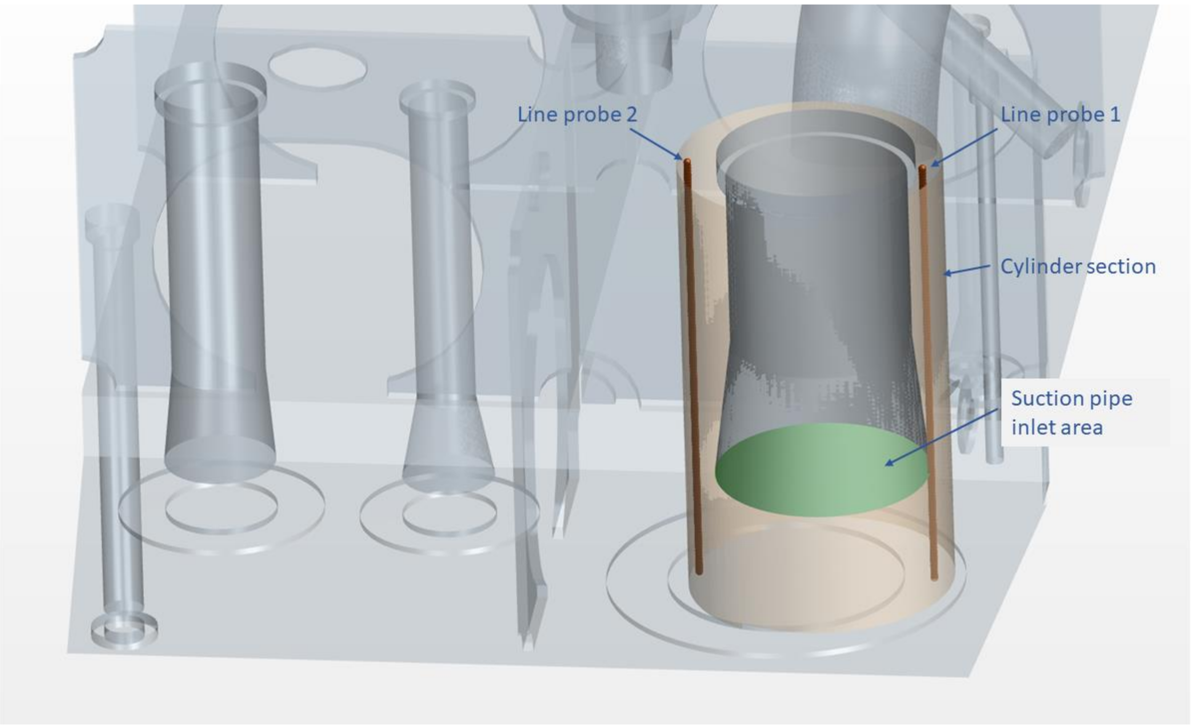

Figure 4-1: Results presentation

The oil fraction measurements on the suction pipe's inlet area will at times show that the area is not completely covered by oil even though it is submerged in oil. After the suction pipe inlet area is fully or nearly exposed to air and then fully submerged in oil, some air will be trapped underneath it which impacts the measurements. A small fraction of air is also at times mixed inside the oil giving the same impact. This effect is generally restricted to oil fraction measurements of 0.9, where it should be 1.

A periodic behaviour is reached for the oil circulation and SOLAS cases and hence only results from the last period will be presented. Viking Sky motion cases results will be presented with the full time-series.

4.1 Periodic convergence study

A periodic convergence study was performed on cases 5, 6 and 9 to validate the measurement errors between the converged periodic behaviour. Figure 4-2 and Figure 4-3 shows the oil level on the cylinder and oil fraction on the suction pipe inlet area for the mentioned cases for the 10th and 11th period.

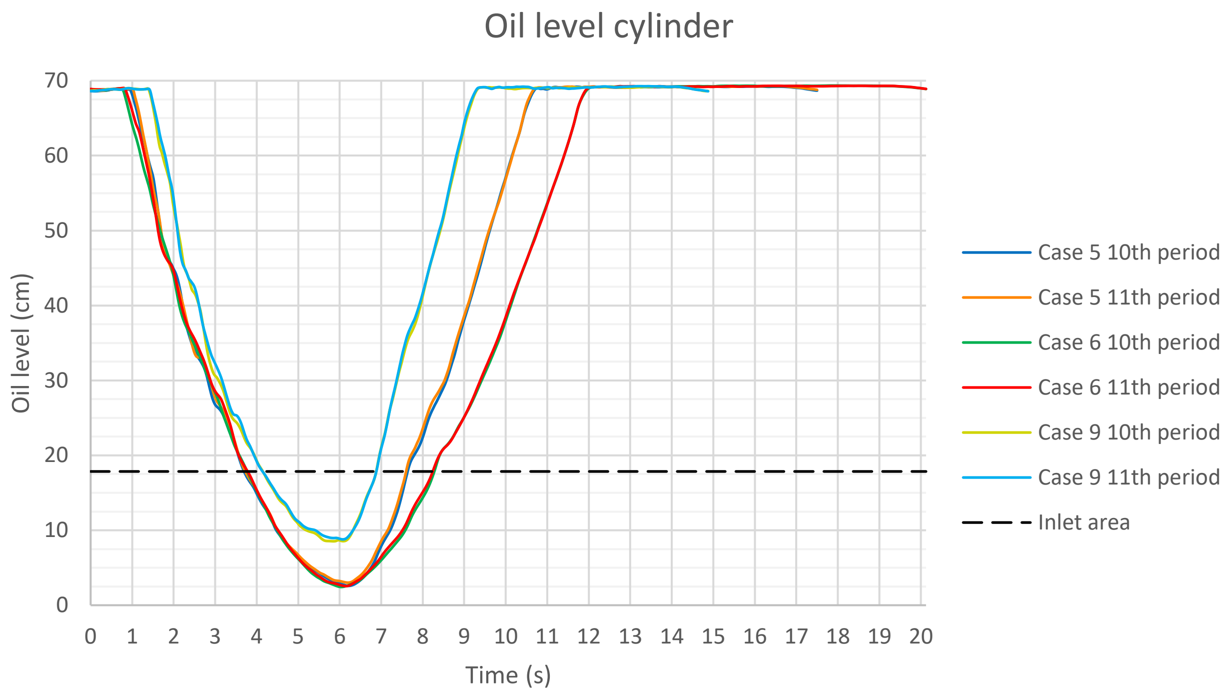

Figure 4-2: Oil level convergence study cases 5, 6 and 9

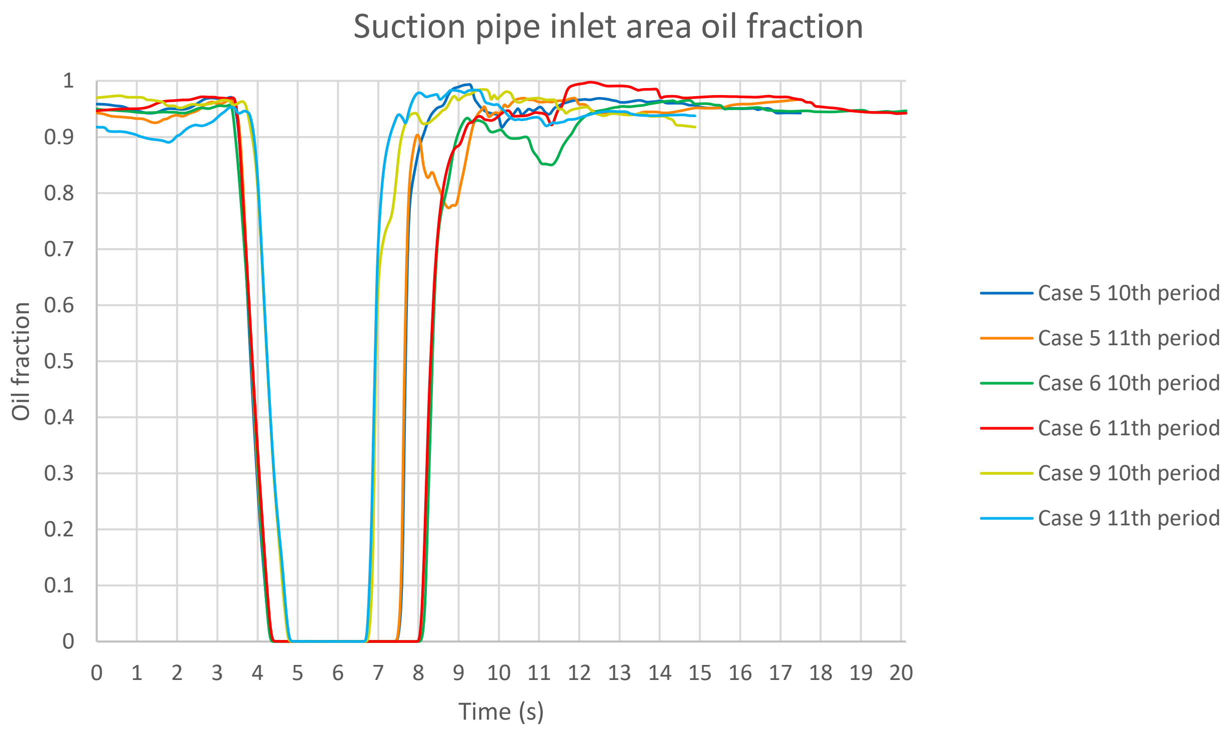

Figure 4-3: Oil fraction suction pipe inlet area convergence study cases 5, 6 and 9

The significant discrepancy between the periods appears for the oil fraction before and after the suction pipe inlet area is exposed to air. This discrepancy is caused by air trapped underneath the suction pipe inlet area and air being mixed inside the oil. At the beginning of the trough, when the suction pipe inlet area is beginning to be exposed to air, the results are consistent from oil fraction 0.9 and below. At the end of the trough, when the exposed suction pipe inlet area is becoming submerged in oil, the results are similar until the oil fraction reaches 0.7. The oil level measurement is similar for the entire periods. The general discrepancy for the oil level measurements between the periods are at 0.5 cm and the fully exposed suction pipe inlet area time between the periods are at 0.1 s.

4.2 Oil circulation cases

Oil level measurements for the Oil circulation cases are shown in Figure 4-4 to Figure 4-7. Oil fraction on the suction pipe inlet area is not presented as it is always submerged in oil. Simulations with circulation is denoted as Flow and those without as Closed.

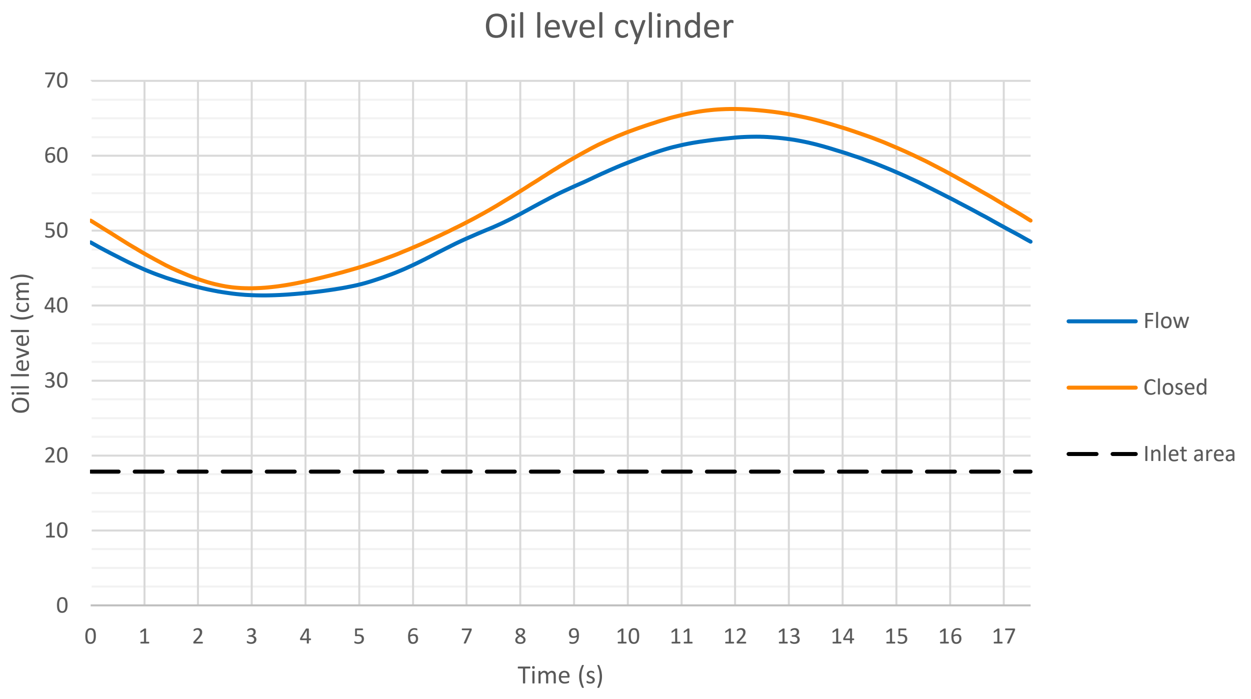

Figure 4-4: Oil level Oil circulation case A

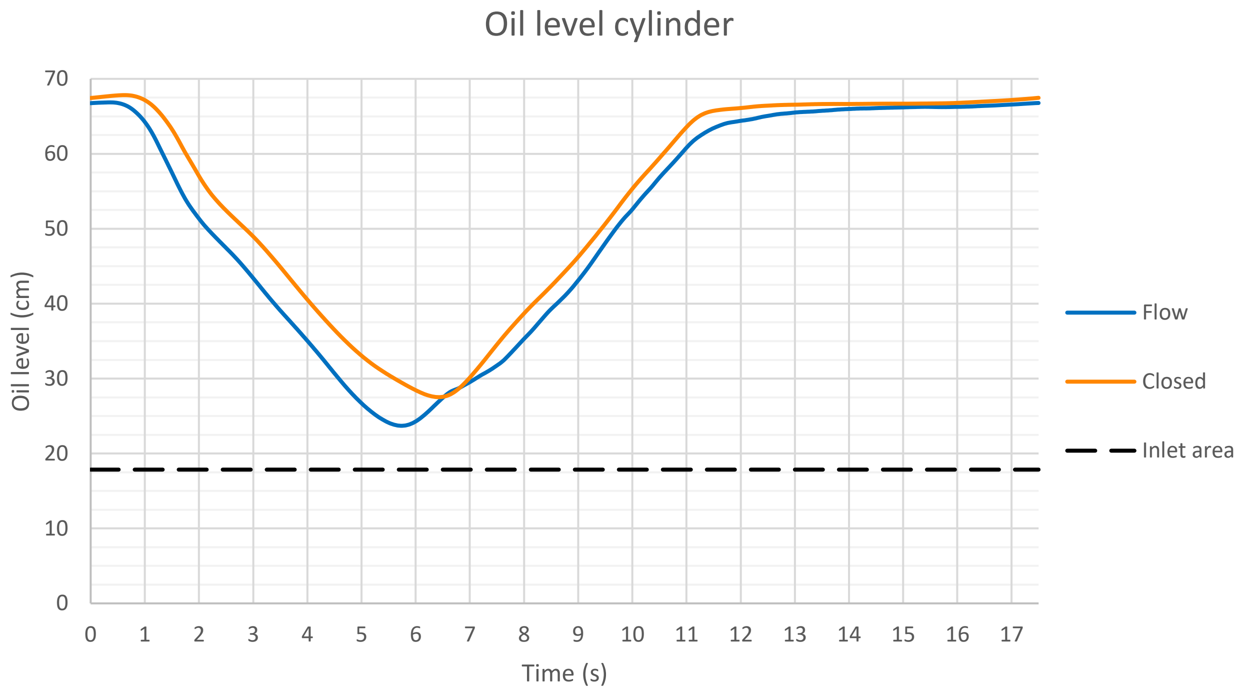

Figure 4-5: Oil level Oil circulation case B

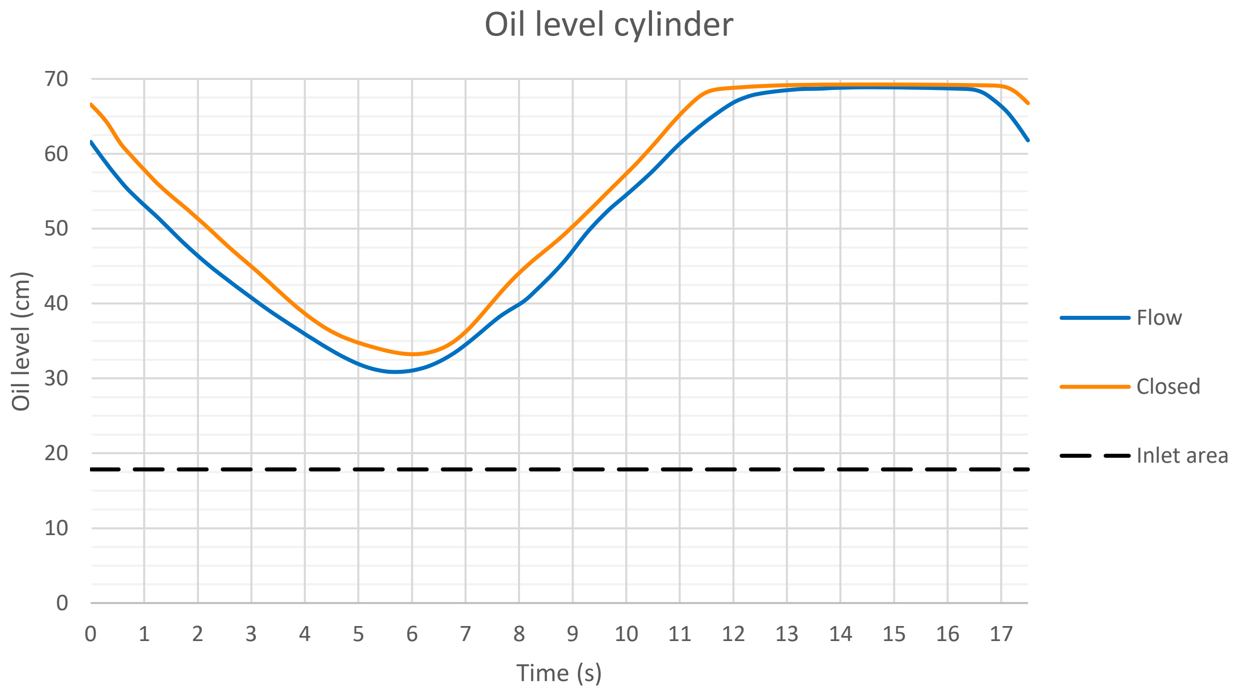

Figure 4-6: Oil level Oil circulation case C

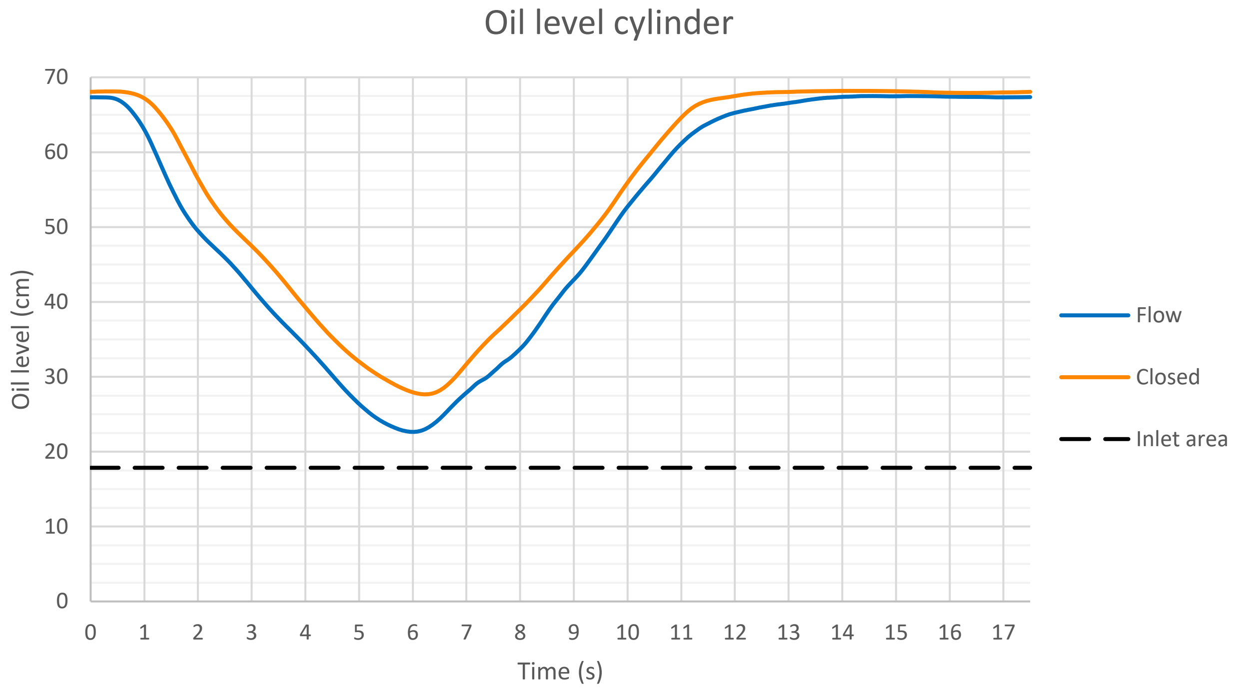

Figure 4-7: Oil level Oil circulation case D

From these results it is shown that the oil level is on average 2.7 cm higher for the cases without circulation compared to those with circulation. In the oil level trough, taken from 0 to 6 s in case A and 2 to 10 s in cases B-D, the averaged oil level difference varies between 1.7 to 4.8 cm. The difference increases with lower oil level. There is only one instance where the oil level without circulation is below the one with circulation, shown in Figure 4-5: Oil level Oil circulation case B. This is a result from the circulation causing a slight shift of the bottom oil level trough where the oil level is increasing for the circulation case while at the same time the oil level is at the lowest without circulation.

It can be concluded that the simulations without circulation are conservative, i.e., that the suction pipe inlet area would be exposed to air earlier if the effect of the circulation had been taken into account. As the difference in oil level increases with lower oil levels, an oil level of 0 to 5 cm is further denoted as "dangerous low oil level" where there is a chance that the suction pipe opening may be exposed to air. This definition is only relevant for 4.4 Viking Sky motion cases.

4.3 SOLAS cases

The SOLAS cases results are divided into the below subsections to reflect the procedure used to identify the worst-case scenario by the SOLAS criteria.

4.3.1 Case nr. 1-3: Natural roll period and pitch RAOs

The natural roll period and pitch RAOs are used as motion periods to connect the SOLAS criteria to the specific ship. Before combining the rolling and pitching motion they are first examined separately to identify which case is the most severe. At a certain sea-state, maximum pitching motion can occur at the natural roll period while the same does not apply for maximum roll motion at pitch RAOs. The results for case nr. 1-3 are shown in Figure 4-8 and Figure 4-9. Note that the horizontal axis is denoted as Time/Period due to different periods. The periods of Cases 1, 2 and 3, respectively, is 7 s, 13 s and 17.5 s. Cases 1 and 2 are simulations of pure pitch motions, while Case 3 is pure roll motion.

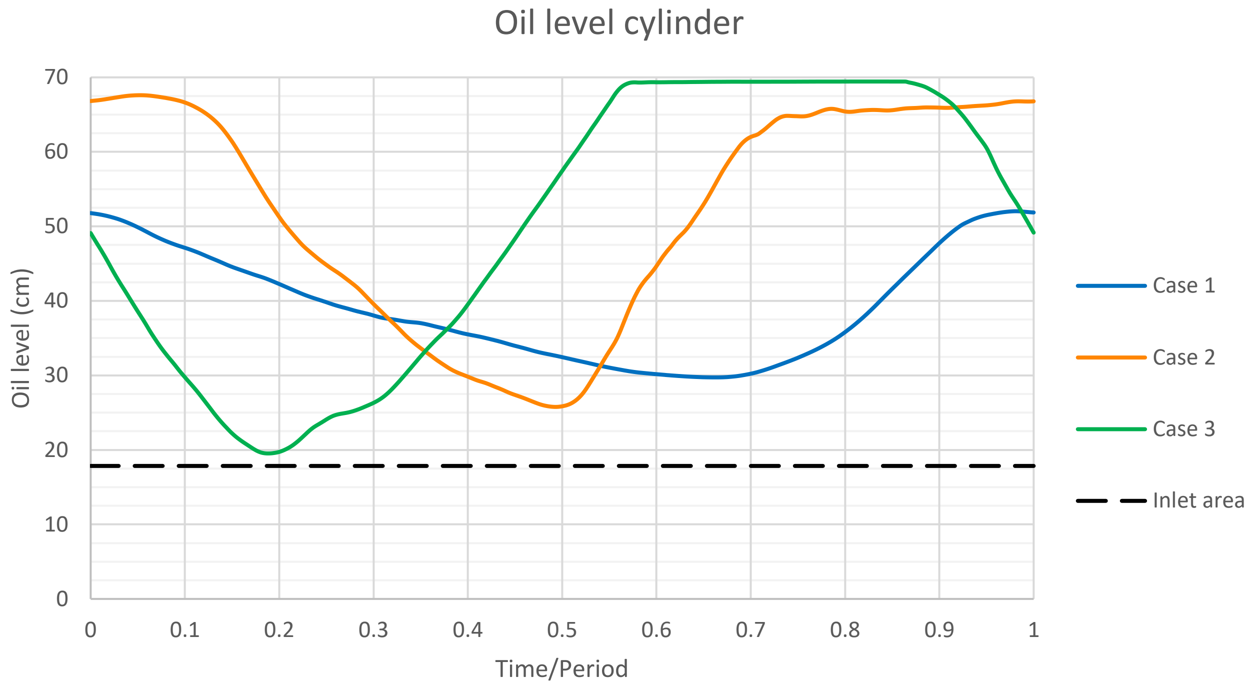

Figure 4-8: Oil level SOLAS cases 1-3.

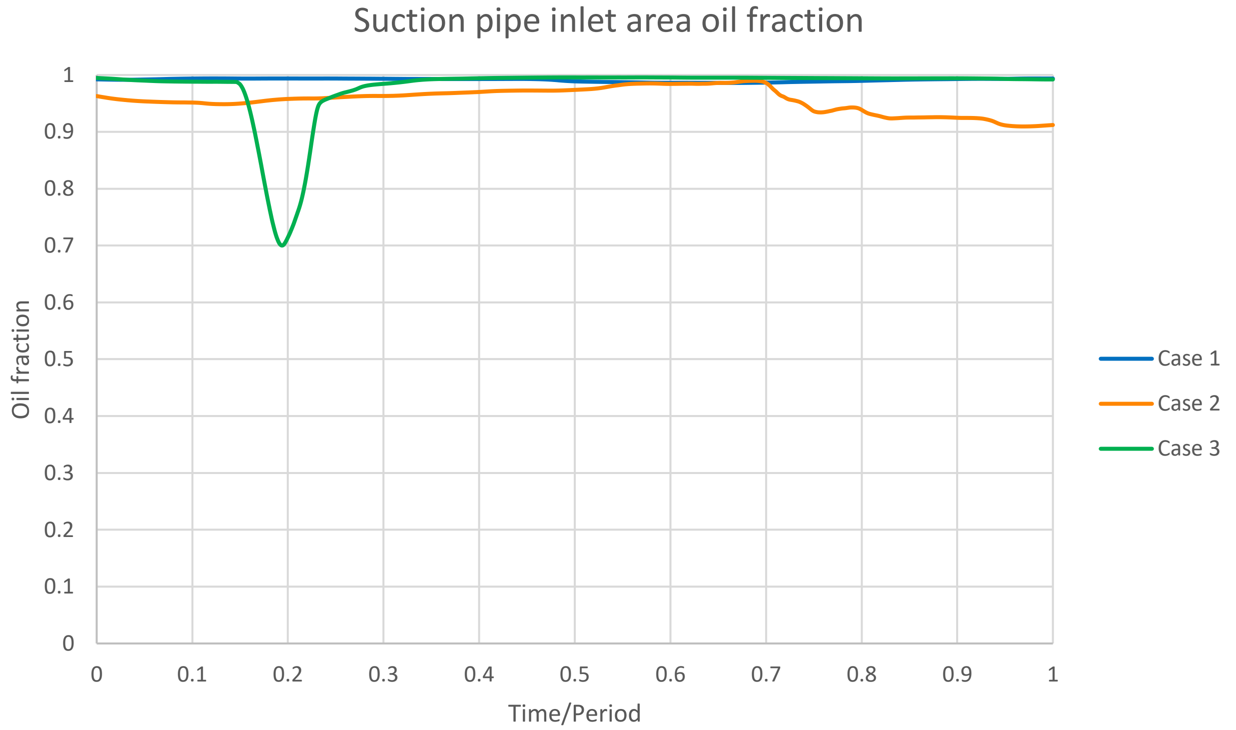

Figure 4-9: Oil fraction suction pipe inlet area SOLAS cases 1-3

It is evident that the smallest pitch period, case 1, has the smallest effect on the oil level. The roll period, case 3, has the lowest oil level and shows partial exposed suction pipe inlet area. Case 2 also shows small partial exposed suction pipe inlet area, but this is due to the mixed air in the oil. Note that case 3 has longer period than the other two cases meaning that the time of low oil level is longer. 17.5 s period was therefore chosen to pursue further.

4.3.2 Case nr. 4-5: Combined pitch and roll motion

The pitch amplitude without roll amplitude at the natural roll period is used in case 4 to see its effect compared to the previous cases before both roll and pitch amplitudes are combined in case 5. Results are presented in Figure 4-10 and Figure 4-11. The figures also include results from case 2 and 3 to show the result tendencies. Note that the horizontal axis is denoted as Time/Period due to different periods.

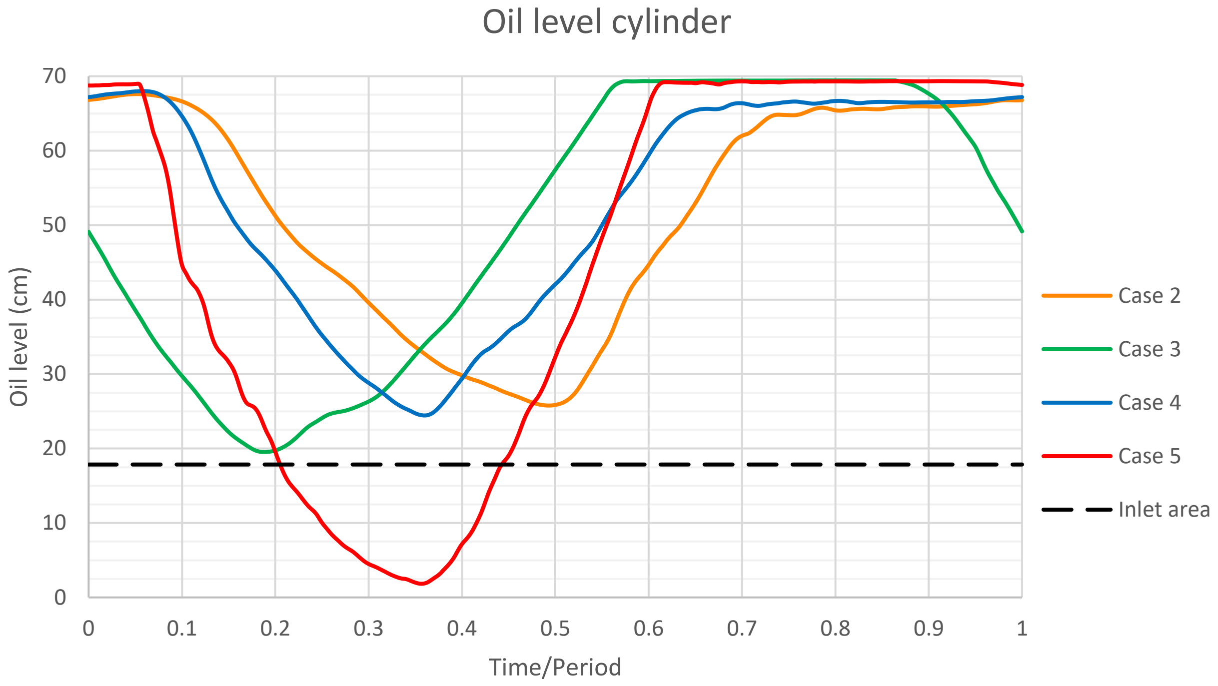

Figure 4-10: Oil level SOLAS cases 2-5

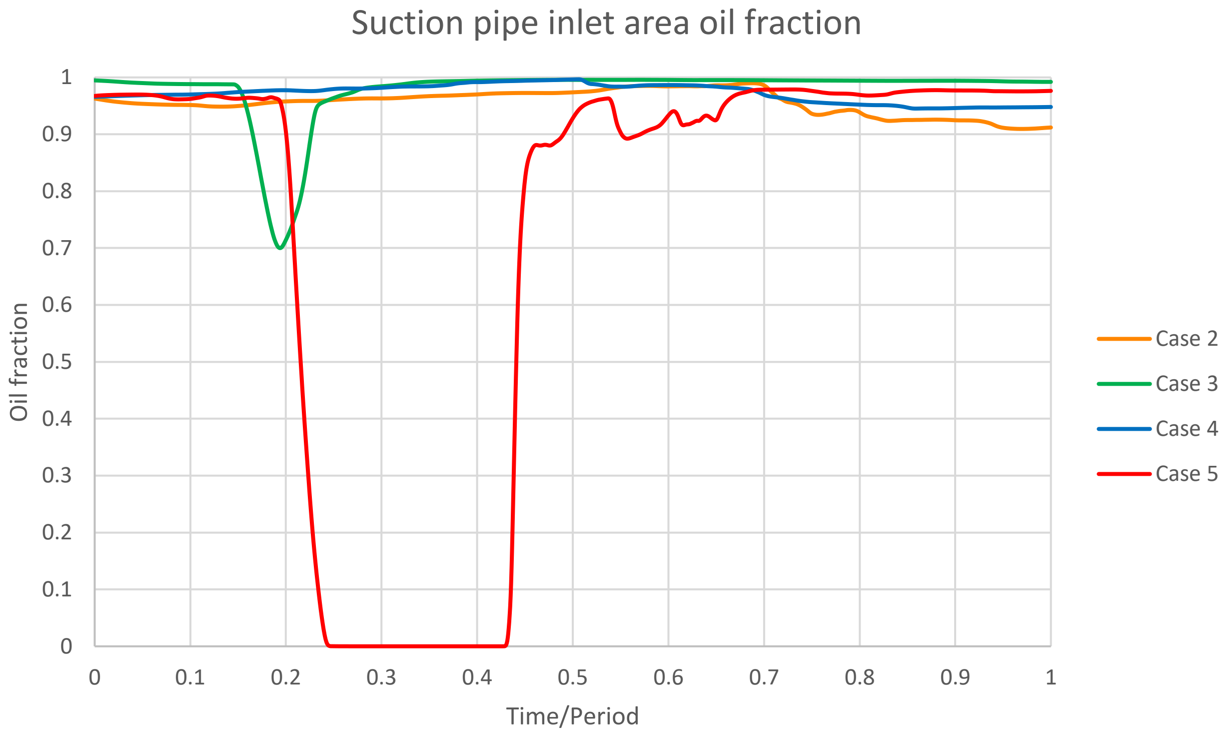

Figure 4-11: Oil fraction suction pipe inlet area SOLAS cases 2-5

Case 4 has very close results to case 2 indicating that the oil level affected by pitch motion is close to a convergence between or around 13 to 17.5 s. Case 5 has completely exposed suction pipe inlet area with the combined pitch and roll motion over a time of 3.1 seconds. Note that the bottom trough of case 3 and 4 occurs at different times and the bottom trough of case 5 is between that of case 3 and 4. Phase variation between roll and pitch motions are therefore expected to impact the results.

4.3.3 Case nr. 6-9: Period variation

Before phase variation is pursued, the effect of period variation is investigated to assess how periods deviating from the natural roll period impact the results. Four period variations were simulated, and their results are shown in Figure 4-12 and Figure 4-13 along with case 5 as reference. Note that the horizontal axis is denoted as Time (s) to better indicate the variation in the results.

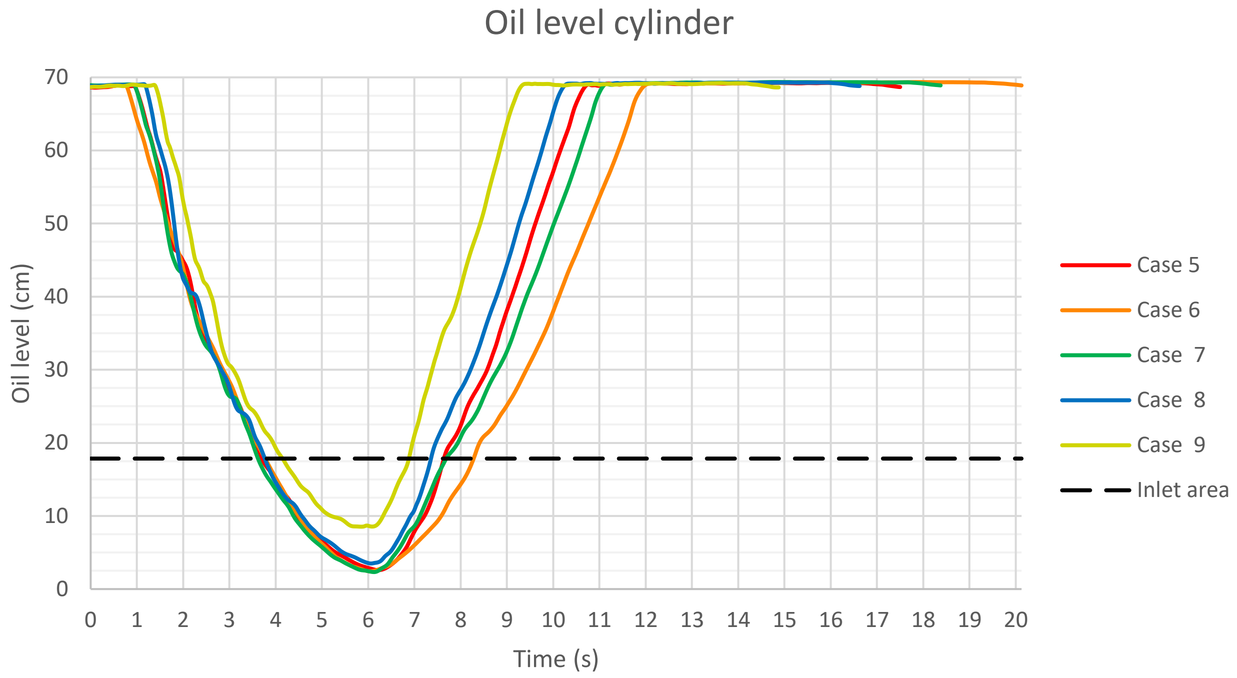

Figure 4-12: Oil level SOLAS cases 5-9

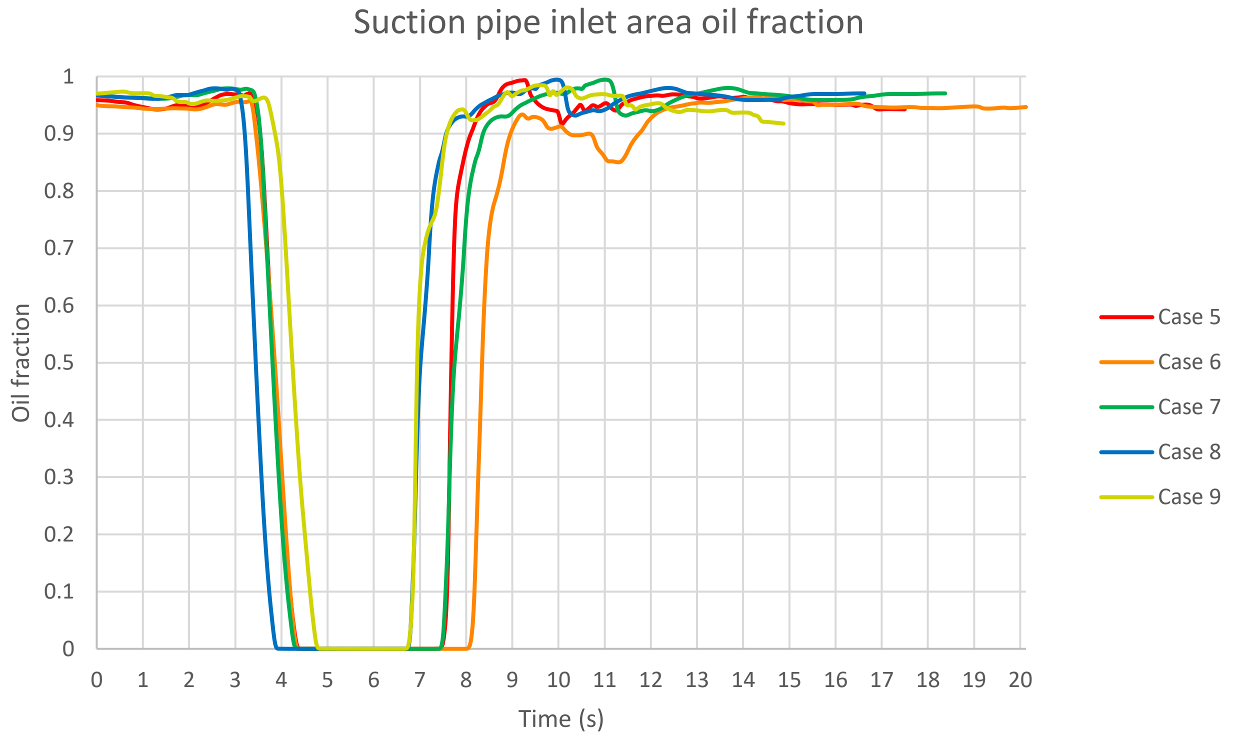

Figure 4-13: Oil fraction suction pipe inlet area SOLAS cases 5-9

It is evident that decreasing the period, case 8 and 9, also decreases the time the suction pipe inlet area is exposed to air. A small increase in period, case 7, has negligible difference to case 5. Case 6, however, has an increase of 0.6 s for fully exposed suction pipe inlet area. As the difference is not that large and that case 6 has a period of 20.125 s, quite far away from the natural roll period, the period of 17.5 s was chosen to pursue further as it better corresponds to the ship's realistic motion.

4.3.4 Case nr. 10-13: Phase variation

Positive phase in these cases indicates a "delay" in the roll motion. As demonstrated in Figure 4-10, the roll motion results in an oil level bottom trough earlier than the pitch motion cases and delaying the roll motion will synchronize the troughs. Results of the four phase variation results are shown in Figure 4-14 and Figure 4-15 along with case 5 as reference. Horizontal axis is denoted as Time (s) as all periods are the same.

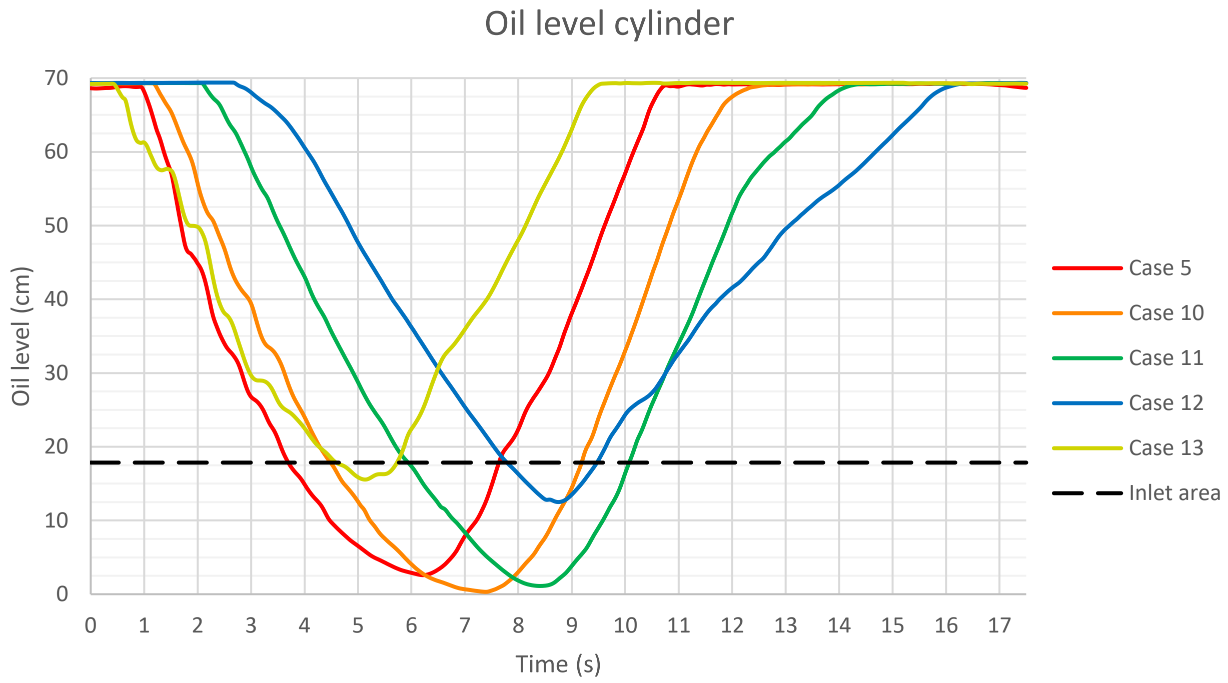

Figure 4-14: Oil level SOLAS cases 5 and 10-13

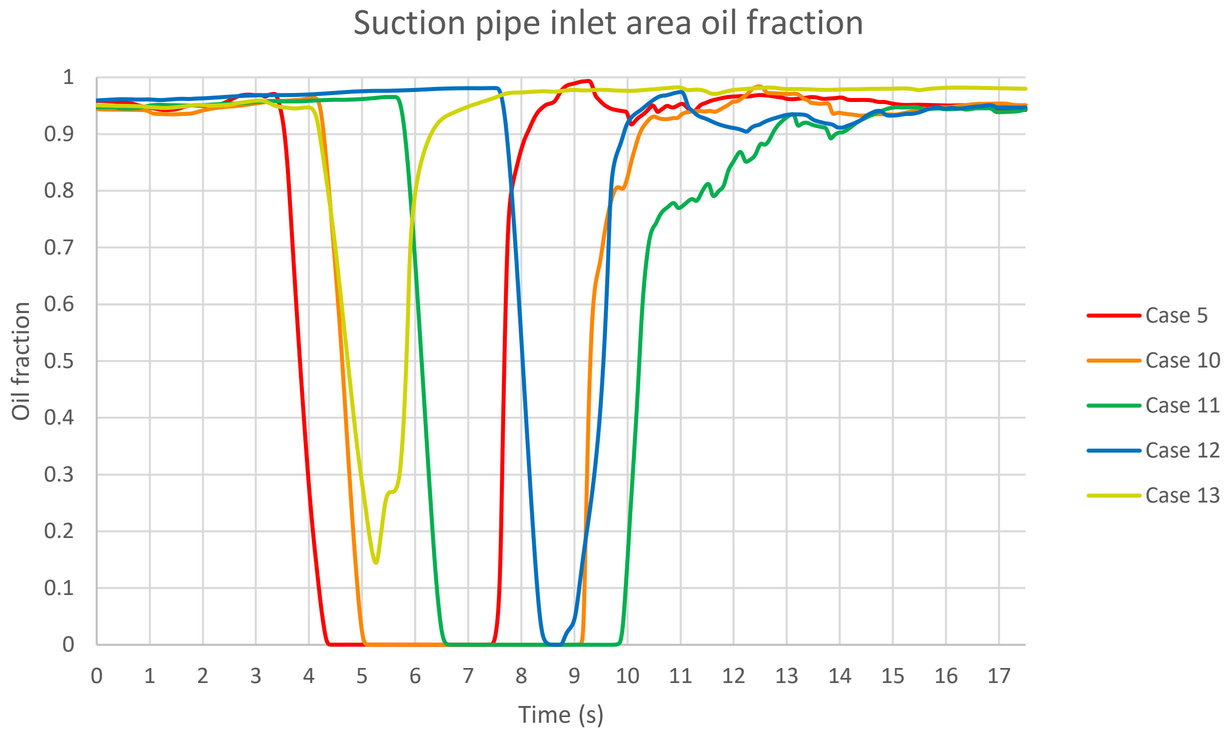

Figure 4-15: Oil fraction suction pipe inlet area SOLAS cases 5 and 10-13

Case 12 and 13, phase difference of respective 135' and -45', has a clear decreased time of low oil level and exposed suction pipe inlet area. Case 5 and 11, phase difference of 0' and 90', are about the same where the suction pipe inlet area is completely exposed to air for 3.1 seconds. Case 10, phase difference of 45', has a clear increased time of low oil level and exposed suction pipe inlet area. The suction pipe inlet area is now completely exposed to air for 4 seconds. As case 10 has a phase difference right between case 5 and 11, where the results are quite similar, it is reasonably assumed that case 10, phase difference of 45' and 17.5 s period, is the worst-case scenario in the SOLAS cases.

4.3.5 Case nr. 14-16: Extremal loading conditions and viscous effect

The worst-case scenario identified in the previous cases are now applied to the extremal loading conditions, cases 14 and 15, to investigate how the change in motion centre affects the results. Case 16 is a rerun of case 14 with kinematic viscosity of 40 cSt. Results are presented in Figure 4-16 and Figure 4-17. The results are almost identical, indicating that the SOLAS cases are not sensitive to change of the motion centre within the realistic range of the ship's loading conditions. The change in viscosity does not alter the results either indicating that the results are not sensitive to viscosity change within the temperature range of 70-75 °C.

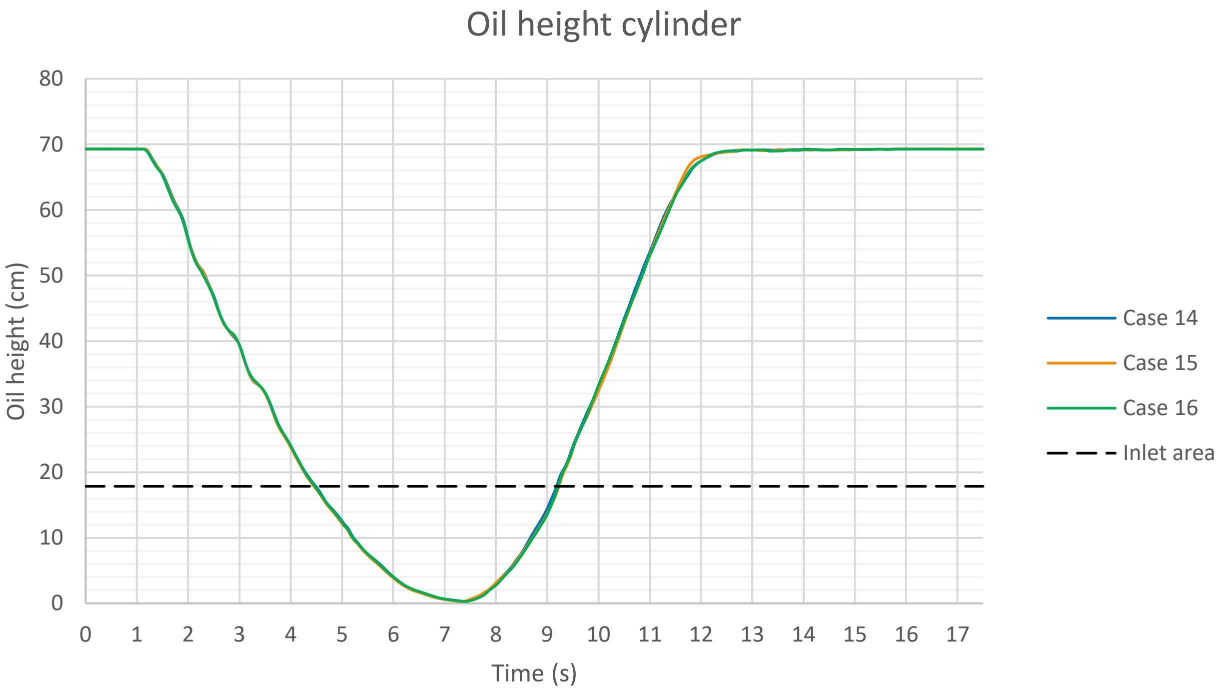

Figure 4-16: Oil level SOLAS cases 14-16

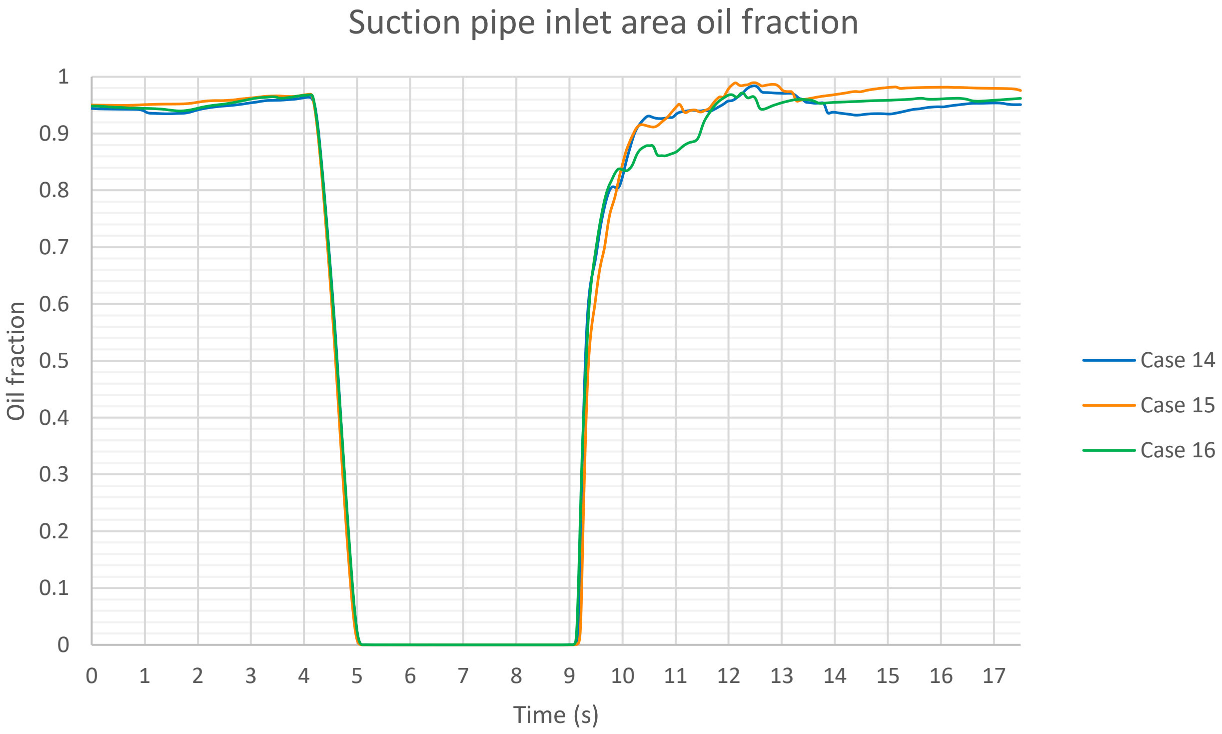

Figure 4-17: Oil fraction suction pipe inlet area SOLAS cases 14-16

4.4 Viking Sky motion cases

The Viking Sky motions cases are independent of the SOLAS cases and their primary purpose is to evaluate the validity of the simulation model by comparing the results with the actual events as logged by the alarm system on board. Additionally, a simulation case combining the highest oil filling level recommended by the Engine Maker and the recorded vessel motion is carried out to evaluate if the oil suction pipe is likely to be exposed to air under such conditions.

There are in total three cases (17-19) where case 17 is using the aft sensor data at recommended filling level of 55 cm (15 cm below tank top), case 18 using the same sensor with estimated actual filling level of 32 cm (38cm below tank top) and case 19 using the fore sensor with estimated actual filling level. The simulations are using roll and pitch data over a 300 s time window recorded between UTC 12:41:00 to 12:46:00 on the date of the accident. The first automatic engine shutdown requests due to low oil pressure were recorded for DG4 and DG2 around UTC 12:45:30. The results are presented in Figure 4-18 and Figure 4-19.

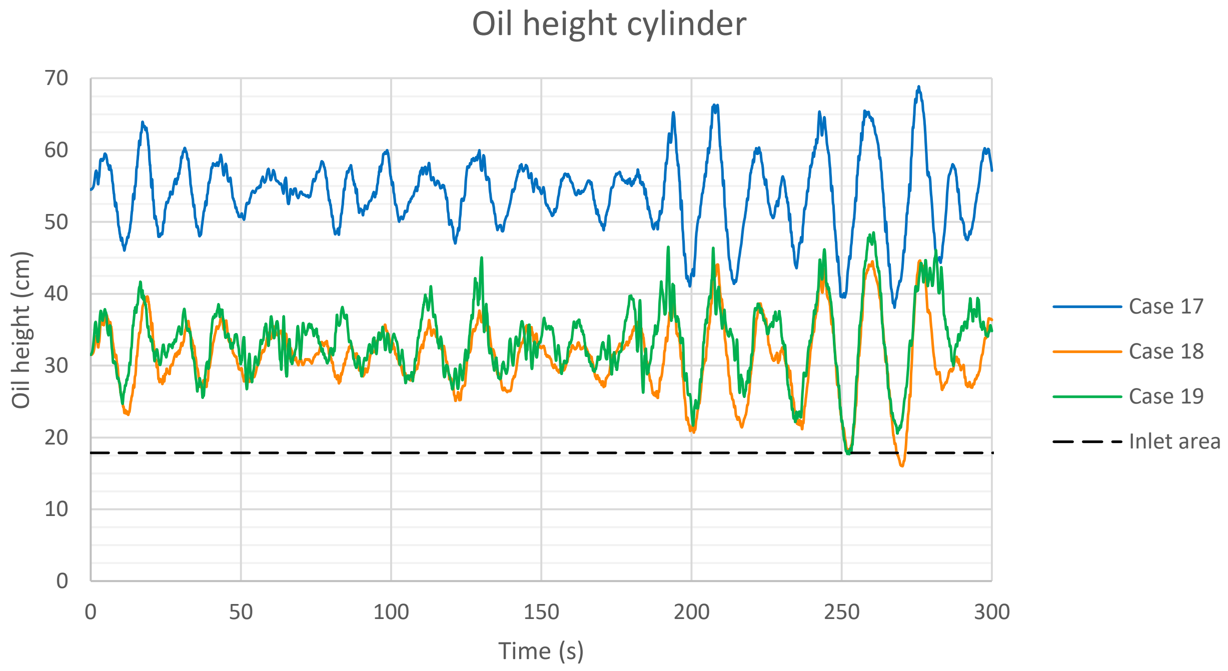

Figure 4-18: Oil level Viking Sky motion cases 17-19

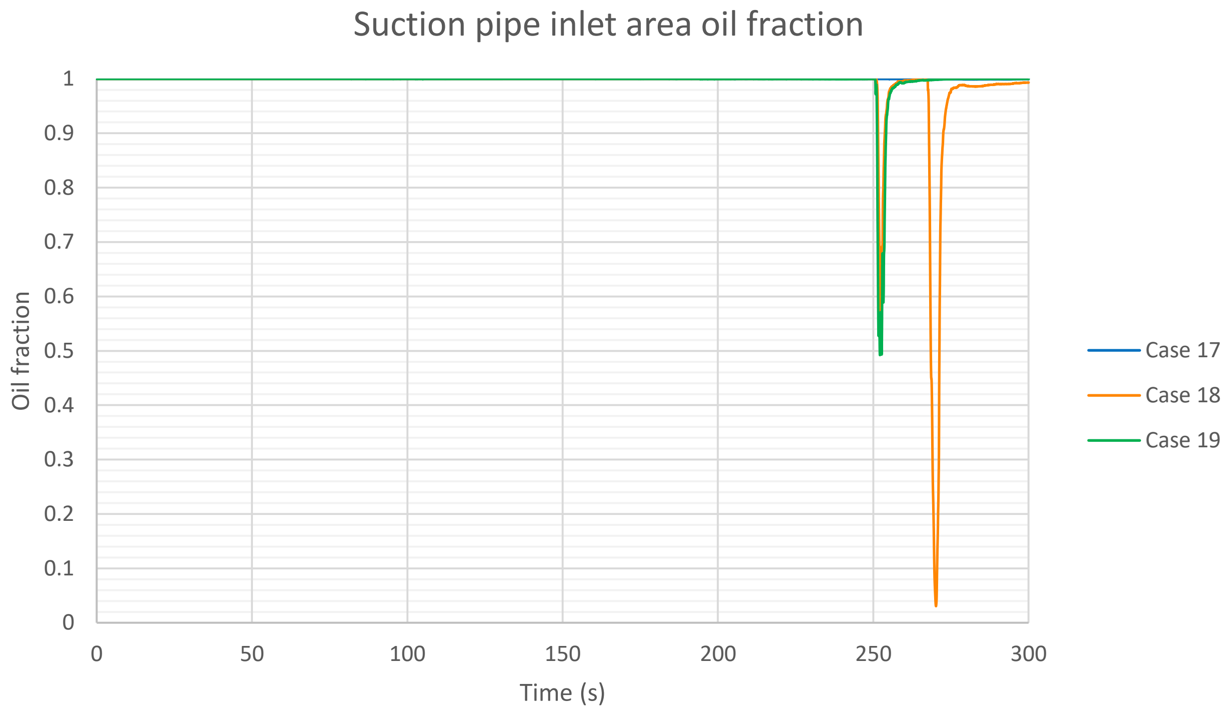

Figure 4-19: Oil fraction suction pipe inlet area Viking Sky motion cases 17-19

Case 18 has a quite constant offset from case 17 in its oil level while case 19 has some small deviance due to the different sensor data. The suction pipe inlet area is completely covered in oil at all times for case 17 and its lowest oil level is 20 cm above the bottom of the oil pipe. Case 18 and 19 have partial exposed suction pipe inlet spikes in the interval 251-274 s, UTC 12:45:11-12:45:34, which is in good agreement with the reported ship engine errors. Figure 4-20 better illustrates the oil fraction for this interval. Both case 18 and 19 have ~3 s partial exposed suction pipe inlet area at 253 s (UTC 12:45:13) and case 18 with a larger interval of ~4.4 s at 270 s (UTC 12:45:30). Dangerous low oil level, where there may be air suction, can also be identified at 201 s, 217 s and 234 s (respective UTC 12:44:21, 12:44:37 and 12:44:54) for case 18 and the same but excluding 217 s for case 19.

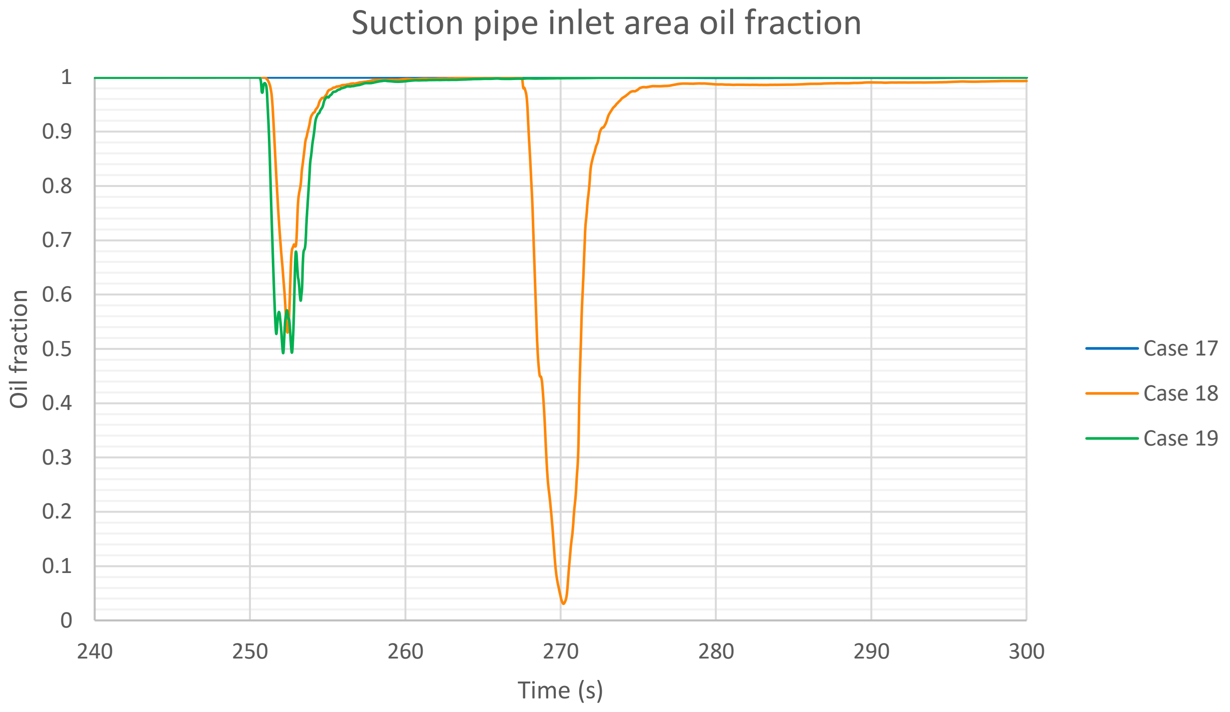

Figure 4-20: Clipped interval oil fraction suction pipe inlet area Viking Sky motion cases 17-19

5 Summary

This report contains computational fluid dynamic simulations of lubricating oil in Viking Sky Oil Sump N. 05 STBD.

The primary goal of the simulations is to evaluate the likelihood of the lube oil suction pipe being exposed to air if the Viking Sky would be subject to vessel motion as specified in the dynamic requirement of SOLAS, Chapter II-1, Part C Regulation 26.6. (22,5' roll and 7,5' pitch motion amplitude simultaneously). The dynamic SOLAS criteria has been interpreted as sinusoidal motions with maximum pitch and roll amplitude occurring with the same period. The periods are chosen from the characteristic periods of the ship.

The computational fluid dynamic simulations of lubricating oil in Viking Sky Oil Sump N. 05 STBD have established that the worst-case scenario will likely occur at the ship's natural roll period of 17.5 seconds, with a 45° phase shift between pitch and roll. This resulted in the suction pipe being exposed to air for 4 seconds with the highest oil filling level recommended by the Engine Maker.

In addition, simulation cases using the recorded motion experienced by Viking Sky during the time of the accident were run. For the estimated actual oil level, this showed that the suction pipe would be exposed to air at about the same time as the ship experienced engine shutdown signals. This supports the validity of the Viking Sky motion case simulation results. The fundamental physics behind the Viking Sky and SOLAS motion studies are the same, therefore validation of the Viking Sky cases simultaneously gives confidence in the results of the SOLAS cases. Simulations using the highest oil filling level recommended by the Engine Maker and the recorded ship motion indicate that the suction pipe inlet area would remain completely covered in oil with approximately 20 cm margin at the least.

6 Uncertainties and remarks

The simulation model and procedure consist of the following simplifications:

1. Oil density and viscosity are constant and homogeneous
    - A sensitivity study comparing the results when using oil properties of 70 °C and 75 °C show negligible difference. This simplification is therefore considered to have an insignificant effect on the results.
2. Motion centre is located at a fixed position
    - The change in motion centre cannot be estimated with current information. However, results show that the oil dynamics are resilient against change in motion centres, derived from extremal loading conditions, and therefore a dynamic motion centre is not expected to have a significant impact on the results.
3. Distribution of oil through the return pipes are equal
    - Effect is assumed to have miniscule impact on results as the hydrodynamic residence time is far higher than the motion periods.
4. Heave, sway, yaw, and surge motions are not included in the Viking Sky motion cases
    - These motions cannot be estimated with current information. However, the simulation result support actual events without heave, sway, yaw, and surge motions, indicating that roll and pitch motions were the most dominant contributor to engine shutdown signals.
5. Oil circulation is not included in SOLAS and Viking Sky motion cases
    - An investigation into the effect of oil circulation has demonstrated that circulation results in a reduced level of oil around the suction pipe, i.e., the suction pipe inlet area would be exposed to air earlier if the effect of the circulation had been considered. The effect is probably in the range of 0 to 5 cm.

Two of the simplifications above (points 2 and 4), which impacts only the Viking Sky motion cases, can be further evaluated by performing e.g., numerical seakeeping calculations in a tool such as SO's VERES of Viking Sky. The ship can be exposed to a variety of sea-states and the ship's response to these sea-states are simulated. The full 6-DOF motions can then be prescribed in the CFD simulations. Seakeeping calculations will give further insight in how the ship will move for a given sea-state and the probability for motions at or above the SOLAS criteria to occur. The results could also be used to investigate the effect from dynamic changes in roll/pitch centres as well as importance of neglecting heave, sway, yaw, and surge on the local motion of tank position.