HYDRODYNAMIC OPTIMIZATION OF AN OCEAN-GOING OIL RECOVERY SYSTEM IN HARSH SEAS

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ABSTRACT

Environmental consequences due to oil spills are disastrous - like the Prestige catastrophe in 2002. Therefore oil combating systems must be developed, which are capable of operating in rough seas.

This paper presents the design and optimization of a Sea-way independent Oil Skimming system - SOS. The principle of the system is to separate the wave damping from the skimming process without using moving parts. The system consists of a solid pontoon with a bow segment (inverse ramp) and an integrated collection tank (moon pool). The skimmer glides over the oil polluted water surface, smoothing the waves. Subsequently, the oil flows beneath the bow segment to an inlet slit, where a separation blade guides the oil film into the moon pool. Inside the moon pool, a vortex develops behind the bow segment, separating the oil from the main flow and transporting it to the free surface of the moon pool, where it is pumped off.

Computational Fluid Dynamics (CFD) calculations and model tests at different scales (1:9, 1:15 and 1:22) with and without oil layer have been conducted. Based on results at different speeds and random seas, the geometry of the separation blade and the moon pool are optimized. Oil tests yield an efficiency of the skimming process up to 90 % in random seas and up to 95 % in calm water.

The assessment of the system includes tests with the skimmer integrated into the carrier vessel MPOSS (Multi Purpose Oil Skimming-System).

INTRODUCTION

International and national efforts have been made to establish a high standard of tanker and seaway safety. Despite of all efforts, absolute safety is not achievable, because technical or human failure can not be excluded.

Over the last years, the oil accidents of the Prestige off the coast of Spain in 2002 or the Erika off the coast of France in 1999 illustrate the unacceptable consequences of such disasters. Fig. 1 shows that accidents are still occurring, but the total volume of spilled oil diminished notably during the last years (ITOPF (2004)). Nevertheless, those accidents are illustrating the catastrophic consequences to the environment and stress the necessity to improve oil combating systems in addition to an enhanced tanker safety program.

Fig. 1: Quantities of oil spilled in the last 35 years

The operation of conventional oil combating systems is limited to wave heights up to 1.5 m. In severe weather, they have to wait until conditions are improving (Clauss et al. (2002)). In the meantime, the oil film on the water surface is
spreading widely and changes its chemical characteristics (emulsification). Fig. 2 shows the eight main weathering processes of oil in water (ITOPF (2004)).

Fig. 2: Fate of oil spilled at sea showing the main weathering processes

To prevent these processes, it is necessary to skim the oil film off the sea surface as soon as possible after the accident. This can only be achieved by an oil combating system, which operates in calm water as well as in high waves.

A new Seaway independent Oil Skimming system (SOS) that satisfies those requirements is developed at the Technical University Berlin. It will be integrated into the carrier vessel MPOSS (Fig. 3). MPOSS has a length of 33.5 m, a width of 12 m and a variable draft of 0.8 m to 1.5 m.

The entire system (SOS and MPOSS) has been analysed and optimized by numerical simulations (Computational Fluid Dynamics – CFD) and experimental investigations at different forward speeds and with various types of oil at model scales 1:15 and 1:9, respectively.

NUMERICAL OPTIMIZATION OF THE OIL SKIMMER

The nonlinear numerical methods used for steady and unsteady viscous computation are based on the coupling of Reynolds Averaged Navier Stokes Equations (RANSE) and the Volume of Fluid (VOF) method (Ubbink (1997) and Fluent Inc. (2003)). CFD simulations provide a powerful tool for predicting the potential and limitations of oil skimming systems including mixing processes in front of the skimmer bow and inside the moon pool. Another advantage of numerical analyzes is the opportunity to investigate the consequences of variations of the skimmer geometry. Also, the global as well as the local flow in dependency of oil characteristics and forward speeds can be analyzed.

Two-phase flow simulation in still water without oil

The goal of the two-phase flow (air/water) simulation is to achieve a stable and optimum intake flow \( Q \) into the moon pool (see Fig. 6). During the numerical simulation (at a scale of 1:15), the geometry of the moon pool is optimized by varying the ratio of the outlet opening \( l_o \)

\[
A = \frac{l_o}{D},
\]
while keeping the inlet blade slit constant at \( D = 0.02 \) m (full scale \( D = 0.3 \) m, Fig. 5).

Fig. 5: The schematic skimmer geometry at model scale 1:15

The critical parameter is the discharge rate \( q \) at the moon pool entrance

\[
q = \frac{Q}{Q_o} = \frac{Q}{v_0 D},
\]

defined by the ratio of the intake flow \( Q \) to the total flux \( Q_o = v_0 D \), related to unit width.

Fig. 6 presents the discharge rate \( q \) for four different ratios \( A \) as a function of time at a model forward speed of \( v_0 = 0.7 \) m/s (corresponding to \( v = 5.2 \) knots at full scale). Obviously, low values of \( A \ll 4 \) are causing strong fluctuations and even nega-
tive flow velocities \( (\Lambda = 0.5 \text{ at } t = 6 \text{ s}, \Lambda = 14.8 \text{ s and } \Lambda = 17.5 \text{ s}) \), which indicates a backflow out of the moon pool. At \( \Lambda = 4 \) a stable discharge of \( Q \approx 0.8 \cdot Q_0 \) is observed (Clauss et al. (2006)).

Fig. 6: Discharge rate at the moon pool entrance (scale 1:15)

The following CFD analyzes and towing tests are conducted on the basis of the optimized value \( \Lambda = 4 \).

Sloshing effects induced by the motions of the system develop inside the moon pool. These effects destabilize the vortex behind the bow segment and lead to high fluctuations of the discharge rate \( q \) at the moon pool inlet. By the installation of a so called CUSP (Fig. 7, bottom) inside the moon pool, the vortex is stabilized. As a consequence, minimum fluctuations of the discharge rate \( q \) are obtained. The CUSP-shape at the rear of vehicles (e.g. buses, trucks; Hucho (2005)) has been developed to reduce resistance. In case of the SOS, the CUSP serves to stabilize the vortex behind the bow (Clauss et al. (2006)).

Despite modern high performance computers, the simulation of a vessel in arbitrary seas with hydrodynamically induced motions requires extensive computation time and capacity. Therefore the simulations are conducted in still water with “numerically” generated sloshing inside the moon pool.

“Numerical” sloshing is achieved by initializing the simulation with a velocity \( v_0 \neq 0 \text{ m/s at } t = 0 \text{ s} \), whereby the water inside the moon pool is accelerated contrary to the cruising direction (Fig. 8, left \( t = 0.15 \text{ s} \)). Subsequent reflections at the walls lead to typical sloshing effects (Fig. 8, right \( t = 0.6 \text{ s} \)).

Fig. 8: “Numerical” generated sloshing inside the moon pool at a cruising speed of 0.3 m/s (scale 1:15)

The results of the numerical investigations in Fig. 9 suggest, that the discharge rate \( q \) is subjected to high fluctuations without CUSP (Fig. 7, above). With the integration of a CUSP and a slope, the fluctuations of the discharge rate \( q \) at the moon pool entrance are minimized (Fig. 9).

Therefore all following investigations are conducted with CUSP and slope as well as with the optimized value of the outlet/intake ratio \( \Lambda = 4 \).

Fig. 9: Influence of the CUSP on the discharge rate (scale 1:15)

Based on the conducted analyzes, it is not possible to judge the efficiency (ratio of skimmed oil to total amount of oil) of the optimized skimmer in dependency of the type of oil and the cruising speed. Hence, in the following section a three-phase flow analysis (air/oil/water) of the optimized skimmer geometry with different oil characteristics and varying cruising speeds is presented.

Three-phase flow computation with oil

For evaluating the separation process of oil and water in the bow area as well as inside the moon pool, oil is introduced as a third phase into the calculations. In the following, the simulation of the three-phase flow (air/oil/water) around the oil skimmer (model scale 1:15) is presented.

In order to resolve the transition of density and viscosity between the three phases, the grid close to the phase interface must be particularly fine. Fig. 10 presents the grid structure with local refinements (near the water surface) for RANSE/VOF based CFD simulations.
Fig. 10: Adapted skimmer geometry with refined grid

Fig. 11 illustrates the setup of the numerical tank with the oil skimmer. Cruising speed and oil film characteristics are defined by modifying the inlet boundary condition in dependency of time.

Fig. 11: Schematic representation of the numerical tank with boundary conditions, UDF is User Defined Function

The atmospheric pressure $p_0$ is defined at the upper boundary above the fluid surface (pressure outlet). The static pressure

$$p_{sta} = p_0 + \rho g (h_{max} - z)$$

(3)

can be described by an UDF, where $\rho$ is the fluid density, $g$ the acceleration of gravity and $h_{max}$ the maximum water depth with $z = 0$ on the tank bottom. The bottom edge of the tank is defined as a wall with slip.

**Validation of the three-phase flow simulations**

At first the oil skimming efficiency without waves is analyzed, applying oil ($\rho = 922$ kg/m$^3$ and $\mu = 0.0608$ Pa·s) on the still water surface. The results of this investigation are compared to results obtained from tests performed in a towing tank covered by a layer of colored edible oil (Fig. 12 and Fig. 13). Oil film thickness is about 0.25 mm (model scale 1:15), i.e. the tests refer to a full scale oil layer of 3.75 mm.

Towing tests and CFD simulations with oil layer have been conducted at three different cruising speeds. The efficiency $\eta$ of the SOS is defined as:

$$\eta = \frac{\text{quantity of skimmed oil}}{\text{total amount of oil}}$$

(4)

The comparison of CFD simulations and experimental test results shows good agreement, with a mean deviation of 3% (Fig. 12).

In both, numerical and experimental towing tests, an oil skimming efficiency up to 89% at a forward speed of 3 knots (full scale) is achieved. Efficiency is decreasing at higher speeds since oil particles are escaping from the moon pool before ascending to the water surface.

**Fig. 12: Comparison of the CFD computations with the experiments**

In order to visualize the flow process inside the moon pool, a camera is attached to the MPOSS model. Fig. 13 compares photographs of the towing tests with images of the flow visualization of the CFD calculations for cruising speeds of 3 and 4.5 knots (full scale). The upper pictures ($v = 3$ knots) show a vortex directly above the separation blade, for both, numerical and experimental investigations. In this case most oil particles are ascending to the moon pool surface and skimming efficiency is close to 90%. At a cruising speed of 4.5 knots (Fig. 13, bottom), the position of the vortex is significantly shifting towards the outlet of the moon pool, and a smaller fraction of oil particles is ascending to the moon pool surface. More than 46% of the entrained oil is escaping through the rear outlet of the moon pool.

**Fig. 13: Position of the camera (above), comparison of CFD results and towing tests at $v = 3$ knots and $v = 4.5$ knots**

To improve the oil skimming efficiency at higher speed, different moon pool outlets are analyzed. Fig. 14 illustrates the simple MPOSS moon pool outlet (left) as well as an improved outlet design, which optimizes the flow inside the moon pool (right). The numerical simulations have been conducted with
mineral oil ($\rho = 960$ kg/m$^3$ and $\mu = 0.048$ Pa s) instead of edible oil at three different speeds.

**Original MPOSS outlet**  
**Improved outlet design**

Separation blade  
Separation blade

Fig. 14: Schematic representation of the moon pool with original MPOSS (left) and improved outlet design (right)

Comparing the results of the three-phase flow simulation for the different designs proves the high efficiency of the new outlet design (Fig. 15).

![Fig. 15](image)

**Fig. 15:** Comparison of the numerical results for the original MPOSS and the improved outlet at different speeds (full scale)

Associated flow visualization in Fig. 16 (left) reveals that high velocities induce suction effects along the contour of the original MPOSS moon pool outlet. This effect causes oil particles leaving the moon pool - even if they are already ascending to the free surface (Fig. 16, left). In contrast, the improved design results lower particle velocities close to the outlet of the moon pool and more oil particles ascend to the surface (Fig. 16, right).

![Fig. 16](image)

**Fig. 16:** Oil particle tracks inside the moon pool with MPOSS (left) and improved outlet (right)

### EXPERIMENTAL ANALYSIS AND IMPROVEMENT OF THE OIL SKIMMER

In CFD simulations and towing tests, the successful operation of the SOS has been proven in still water. In the next step, the numerically optimized skimmer is being integrated into the carrier vessel MPOSS (model scale 1:15 and 1:9, Fig. 17) for seakeeping tests. In the first set of model tests scaling effects are investigated. Subsequently, the optimized system is being towed in a wave tank covered with a layer of mineral oil, applying different towing speeds and random sea states.

![Model scale 1:9](image)

**Fig. 17:** MPOSS model at a scale of 1:15 (left) and 1:9 (right)

The efficiency $\eta$ of the system is defined as

$$\eta = \frac{\text{quantity of skimmed oil}}{\text{total intake of oil between hulls}},$$

where the quantity of skimmed oil in the moon pool and the oil sump is related to total intake of oil between the hulls, i.e. the amount of oil passing between the catamaran hulls during one towing test over a length of 46 m (see Fig. 18).

![Model scale 1:15](image)

**Fig. 18:** MPOSS model with integrated SOS during the oil tests (scale 1:15)

The results of the scaling effects are presented in Fig. 19. The efficiency is presented for two towing speeds and five random sea states. Note that each of the areas refers to a specified sea state starting with still water tests (left column) and ending at a sea state with $H_s = 2.5$ m (right hand side). Obviously the large model (scale 1:9) always performs better than the small model (scale 1:15), as the oil particles have more time to ascend towards the water surface due to the greater length of the moon pool.

![Fig. 19](image)

**Fig. 19:** Comparison of the skimming efficiencies for the small (1:15) and the large model (1:9) at different cruising speeds and varying sea states

Since the comparison of the results indicates that the efficiency improves with increasing model scale, it can be assumed...
that the full scale system will yield even better efficiencies than the 1:9 model.

Based on these promising results, further experiments have been conducted with two different hydraulic oils, which have properties corresponding to diesel oil and heavy oil. At first, a set of tests is accomplished applying light oil (Renolin DTA 10, \( \rho = 852 \, \text{kg/m}^3 \) and \( \mu = 0.0188 \, \text{Pa s} \)), followed by a series of tests with a mix of light and heavy oil (Valona MS 8015 D, \( \rho = 923 \, \text{kg/m}^3 \) and \( \mu = 0.0415 \, \text{Pa s} \)).

During these model tests, the system has been investigated in five different sea states at three different cruising speeds. In addition to the original MPOSS moon pool outlet (Fig. 20, left) two further modified designs are analyzed.

Fig. 20: Schematic illustration of the three different moon pool outlet designs (top), photographs of the segments at a scale of 1:9 (bottom)

Beside an improved outlet design (Fig. 20, center) featuring a vertical wall at the rear outlet, a third design (Fig. 20, right) including a second CUSP with a variable slope is analyzed, stabilizing the vortices on both ends of the moon pool as well as damping the sloshing motions.

In still water, the third version achieves very high efficiencies (Fig. 21), with better performance at all sea states and forward speeds. The gain of efficiency \( \eta \) of the optimized outlet variant compared to the improved design is insignificant for low sea states (\( H_s < 1 \, \text{m} \), all values refer to full scale). At a significant wave height of \( H_s = 2 \, \text{m} \) and a cruising speed of 2.25 knots the gain, however, is 12 percent as compared to the original MPOSS moon pool outlet and increases from 47 % to 59 %.

Fig. 21: Comparison of the efficiencies of three different outlet designs for light oil (\( \rho = 852 \, \text{kg/m}^3 \) and \( \mu = 0.0188 \, \text{Pa s} \))

To assess the influence of the different moon pool outlet designs, the flow conditions inside the moon pool are visually inspected. Two cameras are installed perpendicular to the inlet and outlet of the moon pool. Fig. 22 presents particle tracks of a test cruise at \( v = 3 \, \text{knots} \): For the original MPOSS outlet, most oil particles (88 %) ascend to the surface due to the vortex behind the bow segment (Fig. 22, right), the rest (12 %) escapes through the outlet and reenters the main stream. This efficiency is decreasing with higher sea states. In this case, however, the advantage of the CUSP-design becomes evident as shown in Fig. 22 for \( H_s = 2 \, \text{m} \) and \( T_0 = 6 \, \text{s} \). Here, the visualization of the flow at the MPOSS moon pool outlet is compared to the optimized outlet design conditions: Despite the sloshing motions caused by the waves, a stable vortex forms above the inlet of the moon pool (Fig. 22 right). At the outlet we observe an increased efflux for the original design (Fig. 22, center left) compared to the optimized version, as the rear CUSP induces a second stable vortex, reducing the amount of oil particles leaking into the main flow (Fig. 22, bottom left). This improves the efficiency of the optimized moon pool outlet design by 19 % and an efficiency of 49 % is achieved at a sea state of \( H_s = 2 \, \text{m} \), \( T_0 = 6 \, \text{s} \) (crusing speed \( v = 3 \, \text{knots} \) (Fig. 21)).

The sloshing motions inside the moon pool transfer the skimmed oil over the adjustable slope into the oil sump where it is pumped off. This process is illustrated in Fig. 23.

Fig. 22: Position of mini cameras (top), freeze images of a video sequence illustrating flow conditions in the moon pool for the original MPOSS (center) and the optimized outlet design (bottom, \( H_s = 2 \, \text{m} \), \( T_0 = 6 \, \text{s} \), \( v = 3 \, \text{knots} \))

The sloshing motions inside the moon pool transfer the skimmed oil over the adjustable slope into the oil sump where it is pumped off. This process is illustrated in Fig. 23.
A comparison of the results with Renolin DTA 10 (\(\rho = 852 \text{ kg/m}^3\) and \(\mu = 0.0188 \text{ Pa s}\)) illustrates that the optimized outlet design including a CUSP and slope performs best of all three designs (Fig. 21). Furthermore 2.25 knots proves to be the cruising speed for optimum efficiency at all sea states.

To investigate the efficiency of the system with oil of higher density and viscosity an additional test series is conducted at a scale of 1:9. In this case only the optimized outlet design (CUSP and slope) is tested at a speed of 2.25 knots, while an oil mix of 20% Renolin DTA 10 and 80% Valona MS 8015 D (\(\rho = 923 \text{ kg/m}^3\) and \(\mu = 0.0415 \text{ Pa s}\)) is used.

The comparison of the results for light oil and oil mix in Fig. 24 proves that the SOS also yields an excellent efficiency of 90% in still water and of 40% at a sea state with \(H_s = 2.5\) m.

Due to the shape of the skimmer bow, slamming effects occur in certain sea states. The influence of slamming on the efficiency of the system (robust concept without moving parts) is negligible. To control the dynamic loads the structure has to be strengthened accordingly.

The reduction of efficiency for all moon pool outlet designs with increasing sea states is mainly attributed to the size of the carrier vessel. Due to its length of 33 m, MPOSS shows significant motions in low sea states, which leads to a reduced efficiency \(\eta\). As an improvement the length of the parent vessel is increased to 80 m.

For this test series, the earlier model of the MPOSS (length 3.7 m, width 1.3 m, draft 0.16 m) is used, and the oil tests are carried out at a scale of 1:22.

To analyze the influence of the vessel proportions on the efficiency at identical sea states, Fig. 25 displays the results for MPOSS (length 33 m) and for an 80 m parent vessel. The results are presented for the optimized moon pool geometry and three different cruising speeds. As expected, the larger vessel performs better than MPOSS, particularly at high sea states. At \(H_s = 2.5\) m the 80 m vessel achieves an efficiency of 61% and at \(H_s = 3.0\) m this value only reduces to reasonable 47%.

It is noteworthy that the larger vessel owns its optimum cruising speed at 3.75 knots while the optimum speed for the MPOSS is 2.25 knots. This tendency corresponds to the observations during the model testing, where at speeds of \(v < 3\) knots the oil impounds in front of the bow but does not pass the separation blade. This phenomenon becomes particularly apparent in still water and a low cruising speed of 2.25 knots (Fig. 25).

The reason is that the bigger vessel features a draft of 3.5 m while the MPOSS is characterized by a draft of only 1.5 m.

Finally at the last test series, the 80 m carrier vessel is analyzed in the heavier oil mix at a speed of \(v = 3.75\) knots. The efficiencies achieved in oil of higher density and viscosity are excellent, with only small deviations with respect to the results for light oil (Fig. 26).

**CONCLUSIONS AND PERSPECTIVES**

The goal of this project is the optimization of the complete oil skimming system (carrier vessel MPOSS and skimmer). The first step is the numerical optimization, using CFD calculations to optimize the moon pool geometry. In a second step, the skimming unit is integrated into a model of the carrier vessel MPOSS (scale 1:15 and 1:9).
With the system (\textit{MPOSS} + \textit{SOS}), ample towing tests with edible and mineral oil in random head seas at different speeds are being conducted. The results of these optimizations show that the system is working as expected, with an efficiency of the skimming process up to 90\% in random seas and up to 95\% in calm water.

In the next phase, the \textit{SOS} will be integrated into the bow section of the tanker vessel “\textit{Futura}” (see Fig. 27) (\textit{New-Logistics GmbH (2005)}). Regarding the oil skimming efficiency, the proposed system has to be numerically and experimentally analyzed. For the validation of the numerical results a new model of the \textit{Futura} and the skimming unit will be built at a scale of 1:36 (model dimensions: length 2.7 m, width 0.38 m).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig27}
\caption{\textit{SOS} integrated into tanker vessel “\textit{Futura}” (schematic representation)}
\end{figure}

Since the bow of the \textit{Futura} Tanker has a shape similar to the \textit{SOS} bow geometry (Fig. 28), a cost-effective implementation of the \textit{SOS} would be possible. With only slight modifications, the tanker could be upgraded to a multi purpose oil skimming vessel.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig28}
\caption{Bow of the \textit{Futura}}
\end{figure}

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