A HYBRID ANALYSIS METHOD FOR INVESTIGATING
OIL CLEANUP OPERATIONS AT SEA

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ABSTRACT
The severe ecological and economical aftermath of the 2010 'Deepwater Horizon' catastrophe in the Gulf of Mexico clearly shows the insufficiency of current oil recovery systems which cannot operate in wave heights above 1.5 m. To prevent emulsification and weathering processes, it is necessary to skim the oil film off the sea surface shortly after the accident. The autonomous SOS (Sea State-independent Oil Skimming System) developed within the framework of the research project SOS3 features high transit velocities, the capability of operating in rough seas and a massive intake of oil polluted water - and is therefore a unique technology. Numerical analyses of realistic oil skimming operations require three-dimensional transient three-phase flow simulations in order to take into account wave-induced ship motions. Due to the computational effort, a simplified approach is chosen for systematic investigations. Model tests at a scale of 1:25 are conducted in two different irregular sea states. In order to represent oil cleanup operations as realistically as possible, towing tests at constant velocities are replaced by a series of experiments with a free-running model. A self powered tug pushes the oil skimming barge and experiences interactions with waves, influencing the velocity and therefore the skimming performance of the SOS. Data from optical motion measurements of the barge is then used as input for two-dimensional CFD simulations. The numerical analyses are focusing on the oil-water-separation process of the realistically moving coupled system in different irregular sea states.

INTRODUCTION
Marine oil pollution can be attributed to various sources — exploration, transportation, consumption of mineral oil as well as natural seeps on the sea bed. The application of classical oil recovery techniques is restricted to large scale spills, caused by tanker accidents or failures in offshore platform operations. From a statistical point of view, such accidents are notably decreasing over the last decades [1], which can be ascribed to stricter regulations and improved technologies. Nevertheless, recent disasters like the explosion of the Deepwater Horizon (see Fig. 1, right) which caused a spill of 206 million gallons into the Gulf of Mexico in 2010, or the grounding of the container vessel MV Rena (see Fig. 1, left) on the Astrolabe reef off the north coast of New Zealand, spilling ≈350 t from October 2011 to Jan-

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January 2012 show that neither technical nor human failure can be excluded. Especially the disaster in the Gulf of Mexico proves the insufficiency of the current oil combat fleet — in the United States and the rest of the world.

From 206 million gallons of spilled oil, 37.4 million gallons of oil polluted water were recovered by a total of 5,059 vessels [2]. This catastrophic summary could have been avoided by a modern, efficient fleet of specialized oil recovery vessels, that offer the essential features of

- high transit speed,
- operating range from calm water to rough seas,
- high intake of oil polluted water,
- high oil skimming efficiency $\eta$, defined as

$$\eta = \frac{\text{flux of skimmed oil}}{\text{total discharge of oil}}$$

which make it possible to start the recovery operation before the oil film continuously spreads over wide areas of the water surface and changes its chemical characteristics (emulsification).

A Sea State-independent Oil Skimming System (SOS) that satisfies these requirements has been developed at the Technical University of Berlin [3]. On the basis of various numerical and experimental analyses, this system has been gradually optimized and discussed in detail [4, 5]. The Sea State-independent Oil Skimming System has already been patented in Germany [6] and the United States [7]. The skimming concept is based on purely hydrodynamic principles and is extremely robust since it works without any moving parts. Fig. 3 shows a longitudinal cut through the current system design: A specially shaped bow segment glides on the water surface, damping the waves. The oil layer flows underneath the SOS bow towards a transverse blade, which separates oil from water. At the trailing edge of the bow segment, a vortex develops and accelerates the oil particles in addition to their positive buoyancy to the free water surface of the moon pool. Wave-induced sloshing effects convey the oil over slopes into oil sumps from where it is pumped off. As shown in Fig. 3, the moon pool is equipped with so-called CUSP designs. This special geometry similar to the geometry proposed to reduce resistance at the stern of vehicles [8]. In case of the SOS, the CUSP serves the purpose of stabilizing the vortex behind the bow segment as well.
as retaining the skimmed oil inside the moon pool. Furthermore, the moon pool is hermetically closed and equipped with a pressure regulation device as well as a flap system with separate inlet and outlet flaps — both features are already applied for patents [9,10]. The flaps are hinged and can either open outward or inward or they can be constructed to slide sideward. The concept also comprises a fixed bottom plate as integral part of the hull structure. When the pressure inside the enclosed moon pool is increased by the regulation system, the water level will be reduced by $\Delta z$ and — depending on the design — the draught of the vessel will also be reduced. Contrariwise the water level is going to rise when the pressure inside the moon pool is decreased. With this robust and economical approach, a controlled flow rate into the oil sumps, independent from operational conditions, is provided. The key advantages of this system are:

- Integration into different vessels or hulls requires minimum effort and costs
- The complete encapsulation of the moon pool together with the hazardous oil layer reduces the risk of explosions or fires
- Additional space due to the continuous deck
- Video surveillance and remote controlling of the pressure level from the bridge
- Control of discharge rate by individual adjustment of the ratio $\lambda$ (characteristic length of outlet to inlet opening)
- Fixed bottom plate shelters moon pool from hydrodynamic pressure of the sea
- Improved hull strength
- Fast evacuation of the moon pool in survival mode

![Figure 4. Overview of the hybrid analysis procedure](image-url)
In the following sections, the *FUTURA SOS* concept illustrated in Fig. 2 is investigated using a hybrid method. The system comprises of a barge with a specially shaped bow region (based on the hull design of the *FUTURA* series developed by the German company *Futura-Maritime GmbH*) and a tug as power and steering device that is coupled to the barge in a ’stern bay’ via two ram assemblies. This setup allows the tug only to pitch freely, while all other degrees of freedom match the barge motions. The hybrid method described in the following sections is applied to investigate the performance of the system in real oil recovery operations.

**HYBRID ANALYSIS PROCEDURE**

The investigation of oil recovery systems by model tests or numerical simulations is an intricate procedure. Model tests series require a facility where oil can be applied to a basin equipped with a wave maker. Afterwards the oil has be disposed according to environmental standards and the facility has to be cleaned. This issue can be avoided for numerical calculations — with the drawback of computational expenses. An appropriate numerical model requires a three-dimensional computational domain with dynamic meshing algorithms in order to take into account fluid-structure interaction in waves. Additionally, a transient three-phase flow (air/water/oil) has to be simulated. The hybrid analysis approach presented in this section seeks to avoid the disadvantages of both — model tests and numerical simulations. The procedure is schematically sketched in Fig. 4. On the basis of data from seakeeping tests, two-dimensional CFD calculations are conducted, where the waves are pre-processed by a fast and reliable potential theory solver and the body motions are predefined according to the experimental results.

**FIGURE 5.** MODEL OF THE TUG-POWERED FUTURA-SOS AT A SCALE OF 1:25 IN THE SEAKEEPING BASIN OF TU BERLIN

**FIGURE 6.** INPUT DATA FOR THE CFD-SIMULATIONS (FULL SCALE): POSITION OF THE WAVE GAUGE AND PRE-PROCESSED SURFACE ELEVATION (BLUE) AS WELL AS VESSEL POSITION AND HEAVE AND PITCH MOTIONS FROM THE MODEL TESTS (BLUE)

**Model Tests**

The experimental investigations are carried out in the seakeeping basin of Technical University of Berlin at a scale of 1:25. As illustrated in Fig. 5, the model of the *FUTURA SOS* barge is freely pushed by a tug model coupled via two ram assemblies in the ’stern bay’. The barge is equipped with three wireless, individually pulsed infrared sensors. The body motions in six degrees of freedom are precisely tracked by five cameras mounted on a carriage above the basin with a tracking range of 8 m by 10 m.
### TABLE 1. MATRIX OF THE MODEL TEST SERIES (FULL SCALE)

<table>
<thead>
<tr>
<th>Run #</th>
<th>$v$ [kn]</th>
<th>$\beta$ [$^\circ$]</th>
<th>$H_s$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.0</td>
<td>180</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>4.0</td>
<td>180</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>6.0</td>
<td>180</td>
<td>1.5</td>
</tr>
<tr>
<td>4</td>
<td>6.0</td>
<td>180</td>
<td>3.5</td>
</tr>
</tbody>
</table>

In order to analyse the operational conditions of oil recovery systems as realistically as possible, i.e. taking into account wave-structure effects which influence the forward speed as well as the oil skimming performance of the system, the model is not towed at constant speed, but is free-running and pushed by a self-powered tug. As listed in Tab. 1, the test series comprise of two different operating velocities (average values, due the effects described above, constant velocities cannot be achieved in these tests) and two different sea states where the vessel experiences head seas ($\beta = 180^\circ$) in all cases. Since the tracking range is limited, the camera carriage is moved together with the ship model. The results presented in the following are related to the conditions of run 3, as referred to in Tab. 1.

The relevant data measured during each test run include the $x$-position of the vessel relative to the wave board and the vessel’s heave and pitch motions. The respective surface elevation is re-generated in a pre-processing run 83 m ahead of the cruising vessel (full scale). At this position, the inlet of the computational domain for the subsequent calculations is located. Fig. 6 presents the time series for run 3, where the vessel-related results are denoted by red lines and the fluid-related results by blue lines, respectively. Note that due to the constant distance between the wave gauge and the vessel’s center of gravity in the $x$-direction, $CG_x$ the motions are not directly related to the surface elevation.

### Numerical Investigations

For efficient numerical studies of the *FUTURA SOS*, two tools are combined: Nonlinear wave propagation over long distances is pre-calculated by the numerical wave tank WAVE-TUB (WAVE simulation code developed at Technical University Berlin), based on potential theory. This code is coupled to the commercial CFD package ANSYS FLUENT where fluid structure interactions in viscous multi-phase flows are simulated by solving the Navier-Stokes Equations (NSE), extended by a Volume Of Fluid (VOF) approach. In WAVE-TUB, the fluid domain is discretized by a Finite Element approach (FE). The two-dimensional nonlinear free surface flow problem is solved in time domain using potential theory (POT): the fluid is considered inviscid, incompressible, and the flow is irrotational. The atmospheric pressure above the free surface is constant and the surface tension is neglected. Hence, the flow field can be described by a velocity potential which satisfies Laplace’s equation. At each time step, a new boundary-fitted mesh is created and the velocity potential is calculated in the entire fluid domain using the Finite Element method. From this solution the velocities at the free surface are determined by second-order differences. For long time simulations, a ‘numerical beach’ is implemented at the end of the wave tank by adding artificial damping terms to the kinematic and dynamic free surface boundary condition in order to suppress reflections. To develop the solution in time domain, the fourth-order Runge-Kutta formula is applied. The procedure is repeated until the desired time step is reached, or the wave train becomes unstable and finally stops due to the occurrence of wave breaking. With this tool, wave propagation can be simulated at different water depths and various types of wave generators (wave board motions from the model tests are used as input data for wave generation in the numerical code as well), taking into account non-linear evolution of wave trains and wave-wave interactions [11]. Coupling WAVE-TUB and FLUENT, as illustrated in Fig. 7, results in an efficient and accurate simulation process, taking into account the advantages of both numerical approaches. WAVE-TUB is used as a fast and reliable tool to compute the wave propagation through the numerical wave tank on basis of a potential theory approach. For simulating the efficiency of oil skimming systems at high seas, FLUENTs ability to simulate...
multi-phase flows as well as wave-structure interactions such as wave-induced body motions is essential. For the present application with a free-running model, the coupling of these two codes is realized at a moving position within the wave tank [12, 13]. A special User Defined Function (UDF) and an adjusted finite volume grid is necessary to continue the simulation with FLUENT. Velocity profiles and surface elevations calculated by WAVETUB are input to FLUENT via a transient velocity inlet condition for each time step. In order to set up a fast and efficient, but sufficiently accurate simulation, the coupling of WAVETUB and FLUENT is implemented at a constant distance as close as possible to the floating body — here 83 m ahead of the vessel’s CG (full scale). With the method described above, a continuous wave propagation is provided. In FLUENT, the viscous, incompressible flow is described by the conservation equations of mass and momentum, resulting in a system of four nonlinear partial differential equations — the Navier-Stokes-Equations — which describe the pressure and velocity field of the entire fluid. The problem of pressure-velocity coupling in the conservation equations is solved iteratively by introducing a pressure correction equation. Here, the segregated Pressure-Implicit with Splitting of Operators (PISO) scheme is chosen. Since an accurate resolution of the free water surface — including wave breaking phenomena — is critical for simulating wave-induced body motions, the multi-phase flow is computed by the explicit VOF method with Compressive Interface Capturing Scheme for Arbitrary Meshes (CICSAM). For appropriate accuracy, the spatial discretization of the pressure is done by the Body Force Weighted method while the momentum is discretized by a second order upwind scheme and the transient discretization by a first order implicit scheme, respectively. The Re-Normalisation Group (RNG) k-ε turbulence model with standard wall functions and second order upwind discretisation for the turbulent kinetic energy and the turbulent dissipation rate is applied. In order to customize the CFD solver for oil recovery analyses, the grid structure, boundary conditions and physical properties of the relevant media have to be specified as follows: Special demands are made on the grid to provide accurate wave propagation, body motions and forward speed and to suppress wave reflection. Therefore, the unstructured grid — which consists of a total of 298,000 tetrahedral cells (and the hexahedral boundary layer) — is divided into three cell regions, that serve the purpose of grid coarsening with increasing distance to the hull. Zone 1 includes a fine hexahedral boundary layer adjacent to the submerged hull boundary (see Fig. 8).

The computational domain is set up as an open channel flow domain, where the position of the oil skimmer geometry remains constant with respect to the grid fixed observer. As schematically shown for three time steps in Fig. 9, the entire grid moves through the fluid with predefined skimmer motions composed of cruising speed, surge, heave and pitch as evaluated from the model tests. The major advantage of this approach is that the initial grid structure is preserved through the entire simulation process, and no mesh morphing is required. In order to avoid reflections from wall boundaries, the bottom of the domain has

![FIGURE 8. ILLUSTRATION OF THE COMPUTATIONAL DOMAIN STRUCTURE WITH BOUNDARY CONDITIONS AS WELL AS CELL REGIONS INCLUDING THE HEXAHEDRAL BOUNDARY AT THE SHIP HULL.](image-url)
to be specified as a velocity inlet with zero inlet velocity. A specially implemented UDF accounts for the dynamic correction of the free fluid surface at the front and rear vertical domain boundary.

Furthermore, the boundaries of the computational domain have to be adapted to the hybrid procedure (see also Fig. 8). The vertical inlet is segmented into three parts — transient velocity inlets for all three phases oil, water and air. Velocity profiles calculated for a transient location 83 m ahead of the vessel’s center of gravity in WAVETUB are introduced at the velocity inlet for the water phase in the CFD solver domain to continue wave propagation. The vertical outlet region of the open channel is also divided. Here, pressure outlet conditions are applied for water and air separately in order to assure the correct backflow behavior with a specially adapted UDF, taking account of the hydrodynamic pressure magnitude. At the upper boundary of the open channel wave tank, a pressure outlet condition is set. Special demands are posed by the FUTURA SOS system: As described above, the encapsulated moon pool is equipped with a pressure regulation system. This feature is implemented by a pressure outlet boundary, where the difference to the atmospheric pressure in the domain is adjusted to control the liquid level inside the moon pool with respect to the vessel motions. To prevent overflow of the oil sumps, which have capacity limitations, additional pressure outlet boundaries are defined at the lower rear wall of each sump. Besides air (\( \rho = 1.225 \text{ kg/m}^3, \mu = 1.7894\text{E-05 Pa s} \)) and water (\( \rho = 998.2 \text{ kg/m}^3, \mu = 1.003\text{E-03 Pa s} \)), oil is defined with a density of \( \rho = 919.5 \text{ kg/m}^3 \) and a dynamic viscosity of \( \mu = 0.138 \text{ Pa s} \). The surfaces tension between oil and water is set to \( \gamma = 18.6\text{E-03 N/m} \), between oil and air to \( \gamma = 34.6\text{E-03 N/m} \) and between water and air to \( \gamma = 75\text{E-03 N/m} \). Impressions from a simulation run with conditions referred to as run 3 in Tab. 1 (\( H = 1.5 \text{ m}, v = 6 \text{ kn} \)) are shown in Fig. 10. The distribution of the three phases air (grey), water (blue) and oil (red) is shown at three representative time steps to get an impression of the capabilities of the hybrid approach. At \( t = 10 \text{ s} \) simulation time (top), the FUTURA SOS moves through the incoming waves, a patch of oil is right before the bow. Two seconds later (center picture, \( t = 12 \text{ s} \) simulation time), the oil layer a guided along the bow contour of the skimmer and is about to enter the moon pool through the inlet opening. After simulating 14 s of the oil recovery procedure, a large amount of oil has already entered the moon pool and has partly surfaced. The vortex above the inlet opening is clearly identifiable by the path of the ascending oil particles. At this instant, it can also be observed that a part of the initial oil layer flows past the inlet opening underneath the separation blade towards the stern of the vessel and cannot be recovered. It is expected that the FUTURA SOS — that achieves efficiencies of \( \approx 95\% \) in calm water — shows a reduced but still convincing efficiency in a sea state with \( H_\text{max} = 2.8 \text{ m} \). The efficiency of the system is calculated by comparing the amount of oil the vessel has run over to the amount that is recovered in the sumps and the moon pool. From recent test series, 60-70\% efficiency can be expected under the simulation conditions. The efficiency cannot be deduced from Fig. 10 alone, instead a sufficiently long, representative calculation run would have to be evaluated. The present work focuses on the methodology of oil recovery simulations rather than on efficiency investigations.

**CONCLUSIONS**

The FUTURA SOS — developed within the framework of the research project ’SOS3’ — is an innovative and patented oil recovery system designed for operations from calm water conditions to harsh seas. Regarding efficiency and intake rates of oil polluted water, this system clearly outperforms currently operating systems. Since it is a challenging task to investigate the performance of oil recovery systems either by model tests or numerically, a hybrid analysis procedure that avoids expensive model tests with oil on the one hand and saves computational effort on the other hand is proposed. This approach takes advantage of both, experimental studies and simulations. At first, model tests with a free-running model at a scale of 1:25, which is pushed by a self-powered tug, are conducted in the seakeeping basin of TU Berlin, where the vessel’s position relative to the wave board as well as motions in six degrees of freedom are measured. For the numerical analysis, two established codes are coupled. Nonlinear wave propagation up to a transient position 83 m ahead of the system’s CG (full scale) is calculated by the potential theory solver WAVETUB. At the coupling point, the velocity profile is transferred from WAVETUB to the CFD solver FLUENT, where wave propagation continues to the position of the FUTURA SOS. The measured motions from the model tests are imposed on the vessel that is simulated in a three-phase flow (oil/water/air) where the oil-water-separation process can be analysed in detail.
FIGURE 10. SCREEN CAPTURES FROM THE NUMERICAL CALCULATION OF THE FUTURA SOS UNDER CONDITIONS OF RUN 3 ($v = 6$ kn, $H_s = 1.5$ m) AT MODEL SCALE (1:25) SIMULATION TIMES OF 10 S (TOP), 12 S (CENTER) AND 14 S (BOTTOM), SHOWING THE OIL BEING GUIDED UNDER THE HULL AND ENTERING THE MOON POOL OF THE VESSEL.
A representative calculation under the conditions of run 3 (see Tab. 1) shows that the numerical method — which is based on an dynamically moving open channel flow domain — is capable to simulate the entire oil-water separation process. The selected phase distribution images reveal that all hydrodynamic principles on which the SOS technology is based are reproduced realistically. These results underline that the proposed hybrid concept, consisting of model tests for the seakeeping data and fast and efficient 2-D CFD simulations for the oil-water separation simulation, is an efficient and reliable method to investigate the performance of oil recovery systems at sea.

PERSPECTIVES

Continuative investigations with the FUTURA SOS are planned including performance tests for different types of oil as well as the determination of the operational range regarding a minimum oil skimming efficiency. In order to validate the numerical part of the hybrid approach, model tests with granulate as substitute for oil will be conducted. Furthermore, GeoSim (Geometrically Similar) test series at model scales of 1:16 and 1:36 are carried out in order to fully understand scaling effects that are possibly involved in the oil-water separation process and to eliminate their influence on the extrapolation of results for the full scale vessel (see OMAE2012-83624). Currently, a demonstrator for the SOS technology is on very promising trials in Hamburg on the river Elbe.

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