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Numerical Simulation Technology of Oil Containment by Boom

Feng Xing
Department of Marine Engineering Dalian Maritime University
Dalian, China
windstar19850310@gmail.com

Wu Wanqing, Wu Wenfeng
Department of Marine Engineering Dalian Maritime University
Dalian, China

***Abstract*—The development of the numerical simulation technology of oil containment by boom is introduced here and the vital role of oil boom on clearing up the spilled oil is elaborated. Based on the numerical wave tank using the momentum source method, oil containment by boom in waves and currents is numerically analyzed here utilizing the commercial CFD software FLUENT. Finally, the relationship between wave parameters and loss rate is investigated.**

Keywords- analytic relaxation wave generating method, numerical wave and current tank, loss rate

I. INTRODUCTION

Marine oil spills can cause serious damage to the marine ecological environment. Once a slick has been established through oil spill accident, it is immediately transported under the influence of winds, waves and currents. An effective way of preventing the spread of oil is to collect the oil by using booms. A lot of numerical studies have been carried out on the problem of oil containment. Wicks（1969）carried out one of the earliest investigations and identified three different regions in an oil layer through experiment: the headwave region, the middle region and the near boom region. CHANG-FA AN et al. demonstrated oil boom failure mechanisms under the two-dimensional uniform flow using the computer animation based on the software FLUENT. D.Violeau et al. adapted SPH, a fully Lagrangian method, to the prediction of multiphase flow including floating booms. FANGXIN FANG et al. brought out a local two-phase nonlinear hydrodynamic numerical model to simulate oil containment by a fixed boom under open-sea conditions, and the effects of wave parameters, wind, oil type on the failure velocity and the relationship between the failure velocity and oil volume and boom draft were investigated. Although few studies have been carried out on oil containment considering wave conditions, there is no quantitative numerical investigation about the wave and loss rate of oil containment.

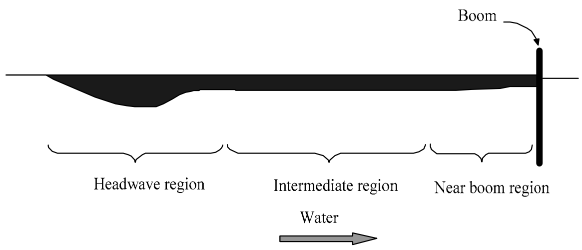

Figure 1. Oil slick contained by oil boom

Hence, the present investigation focuses on the establishment of the numerical experimental platform based on the Navier-Stokes equations for viscous, incompressible fluid and VOF method, utilizing the commercial CFD software FLUENT, and the waves are generated by the analytic relaxation approach. Then oil containment by rigid boom in waves and currents is simulated on that platform.

II. BASIC MODEL AND MATHEMATICAL EQUATIONS

For the flows of incompressible fluid with the free surface, the governing equations are the continuity equation and the Reynolds-averaged Navier-Stokes equations (Arikawa T., et al., 2003):

Continuity equation：

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}=0 \tag{1}$$

In the flow area and the wave-absorbing area, the momentum equations have the unified form:

$$\begin{aligned}&\frac{\partial(\rho u)}{\partial t}+u\frac{\partial(\rho u)}{\partial x}+v\frac{\partial(\rho u)}{\partial y}\\&=2\frac{\partial}{\partial x}\left[(\mu+\mu_t)\left(\frac{\partial u}{\partial x}\right)\right]\\&+\frac{\partial}{\partial y}\left[(\mu+\mu_t)\left(\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}\right)\right]-\frac{\partial p}{\partial x}+S_x\end{aligned} \tag{2}$$

$$
\frac{\partial(\rho v)}{\partial t}+u\frac{\partial(\rho v)}{\partial x}+v\frac{\partial(\rho v)}{\partial y}
=\frac{\partial}{\partial x}\left[(\mu+\mu_t)\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)\right]
+2\frac{\partial}{\partial y}\left[(\mu+\mu_t)\frac{\partial v}{\partial y}\right]-\frac{\partial p}{\partial y}+S_y-\rho g \tag{3}
$$

The standard $k-\varepsilon$ model is adopted to compute the Reynolds stress and the free surface is computed by the VOF method.

The numerical experimental platform consists of three sections: wave generation section zone Ⅰ, working section zone Ⅱ and wave absorbing section zoneⅢ, as shown in Figure1. The length of the tank is 200m, and the steady water depth 6.2m. The computational zones are discrete by the structured grids using GAMBIT, and the mesh length is 0.2m, and the mesh height is 0.05m.

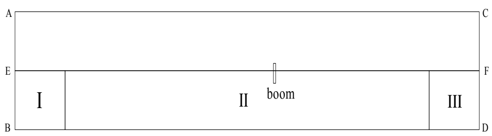

Figure 2. Sketch of numerical wave tank: Ⅰ-wave generation zone, Ⅱ-working section, Ⅲ-wave absorbing zone

III. NUMERICAL WAVE AND CURRENT TANK

A. *Numerical Wave Generation and Absorption Technology*

An analytic relaxation approach is developed to implement the wave generation and absorbing in the numerical wave flume. The relaxation algorithm for velocity and pressure within the wave generation zone can be written as:

$$
\begin{aligned}
u_{im} &= Cu_{ij}+(1-C)u_{il}\\
p_m &= Cp_j+(1-C)p_l
\end{aligned} \tag{4}
$$

According to Eq. (2), Eq. (3), Eq. (4), the source function in wave generation zone can be derived as:

$$
\begin{aligned}
S_i =\; & \frac{\rho}{\Delta t}(C-1)\left(u_{ij}^n-u_{il}^n\right)
+\rho(1-C)\left(\begin{array}{l}\frac{1}{\rho}\frac{\partial p_j}{\partial x_i}+\frac{\partial u_{il}}{\partial t}+\\ u_{1l}\frac{\partial u_{il}}{\partial x_1}+u_{2l}\frac{\partial u_{il}}{\partial x_2}+g_i\end{array}\right)\\
& -\rho\left\{\begin{array}{l}
\left(C^2-1\right)\left(u_{1j}\frac{\partial u_{ij}}{\partial x_1}+u_{2j}\frac{\partial u_{ij}}{\partial x_2}\right)\\
+(1-C)^2\left(u_{1l}\frac{\partial u_{il}}{\partial x_1}+u_{2l}\frac{\partial u_{il}}{\partial x_2}\right)\\
+C(1-C)\left[\begin{array}{l}\left(u_{1j}\frac{\partial u_{il}}{\partial x_1}+u_{2j}\frac{\partial u_{il}}{\partial x_2}\right)\\ +\left(u_{1l}\frac{\partial u_{ij}}{\partial x_1}+u_{2l}\frac{\partial u_{ij}}{\partial x_2}\right)\end{array}\right]
\end{array}\right\}
\end{aligned} \tag{5}
$$

in which, the subscript i denotes the coordinates in two-dimensional case, and the subscript j stands for the computed value, the subscript L denotes the incoming wave value, $C=C(x)$ the relaxation function depending on the spatial location. Details of the relaxation function can be found in Lin and Zhou.

According to the above method, the relaxation algorithm for velocity and pressure within the wave absorbing zone can be written as:

$$
u_{im}=Cu_{ij},\, p_m=Cp_j \tag{6}
$$

here, the relaxation function $C=C(x)$ should be satisfied: $C_{x\min}=1$, $C_{x\max}=0$, the source function in wave generation zone can be derived as:

$$
\begin{aligned}
S_i &= (1-C)\left(\frac{\partial p_j}{\partial x_i}-\rho\frac{u_{ij}^n}{\Delta t}\right)\\
&+\rho(1-C^2)\left(u_j\frac{\partial u_{ij}}{\partial x}+v_j\frac{\partial u_{ij}}{\partial y}\right)
\end{aligned} \tag{7}
$$

To validate the efficiency of the numerical wave tank, two cases were achieved in the following:

A regular wave and a second order Stokes wave were generated in this numerical wave tank. The comparisons between numerical results and the theoretical results are presented in Figure (3) and Figure (4):

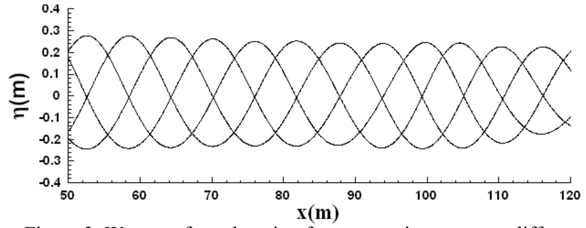

Figure 3. Wave surface elevation for progressive waves at different instants(regular wave amplitude a=0.3m, wave period T=4s)

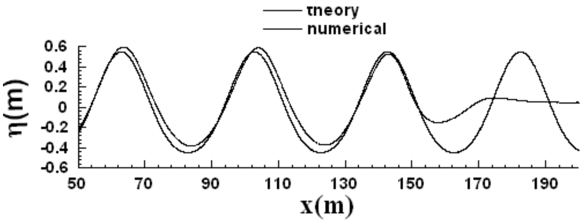

Figure 4. Comparison between numerical results and analytical solutions of wave propagating at t=50s(second order Stokes wave amplitude a=0.5m, wave period T=5.8s)

As shown in Figure3 and Figure4, a good agreement is found and the numerical results demonstrate that the reflected wave is dissipated well within the wave absorption zone.It is confirmed that the relaxation algorithm works well for the establishment of the numerical wave tank.

B. The Current Inlet Boundary

The inlet boundary is regarded as current velocity inlet boundary and the velocity is prescribed. Additionally, k , ε at inlet boundary can be evaluated according to the following equations(Lin Zhao, Zegao Yin, et al, 2009):

$$U_{in} = U_0,\ k = 0.004U_{in}^2,\ \varepsilon = k^{1.5}/0.42d$$

At this point, the analytic relaxation method mentioned above is developed to generate waves and currents by simplifying the coupled wave-current numerical model set up in reference[9] . The current generation is achieved through the AB boundary. The relaxation algorithm for velocity within the wave and current generation zone Ⅰ can be renewed as (Wang, et al., 2005):

$$\begin{aligned} u_m &= Cu_j + (1-C)(u_l + U_C) \\ v_m &= Cv_j + (1-C)v_l \end{aligned} \tag{8}$$

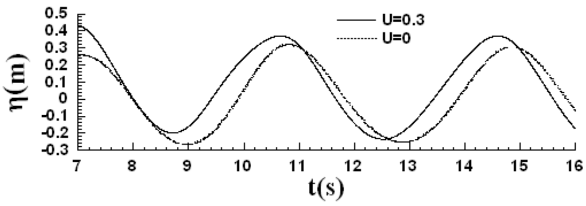

Figure 5. Numrical results of time series of wave elevations with and without current at x=40m

Figure5 shows the numerical result of time series of wave elevations at t=16s when the horizontal uniform current velocity $U_C = 0$, $U_C = 0.3m/s$, the wave period is 4 s and the wave amplitude $a = 0.3m$. The coupling process of wave and current is complex, and the wave-flow interaction shows very strong nonlinear behavior, and the variation of wave parameters in the process when a wave encounters a current and their coupling interaction in the wave-current coexisting field is not yet very clear. The different current velocity may lead to the wave scattering and drifting as shown in Figure5.

IV. NUMERICAL ANALYSIS OF THE LOSS RATE OF OIL CONTIANMENT BY BOOM UNDER WAVE CONDITION

The total time required for cleaning up and the recuperation following oil spill is rather long for most accidents. Hence, even small loss rates from booms may compromise the cleanup procedure, as it continues for a long time. Accordingly, many investigations have considered the initial failure velocity rather than the loss rate and have tried to determine the so-called no-leak conditions (Fannelop, 1983). The loss rate was affected by several parameters, and it was pointed out by Delvigne (1989) that after lowering the interfacial tension of oil to 20% of the initial value, the entrained droplets were considerably smaller but was not more numerous, and there was no change in the initial failure velocity or the loss rate. And recently, Azin Amini brought out a formula for predicting the loss rate in the absence of wave:

$$\begin{aligned} q_E &= 122.79DV^{2/3}\exp(22.65I_U) \\ &\quad + \frac{2.43I_U}{D^3V^{7/3}} - 0.74 \end{aligned} \tag{8}$$

where q_E is the loss rate, I_U the increment of the flow velocity compared to the initial failure velocity, V the initial oil volume, D the barrier draft. And she also pointed out that the formula for predicting the loss rate was almost the same for experiments with weak waves(s<0.01).

The relationship between wave parameters on the loss rate has never been evaluated, hence, the present investigation focused on this point, and the loss rate of the oil containment under weak waves and aggressive wave conditions is investigated base on the above numerical experimental platform. The oil slick shape before boom under wave can be found in Figure (6).

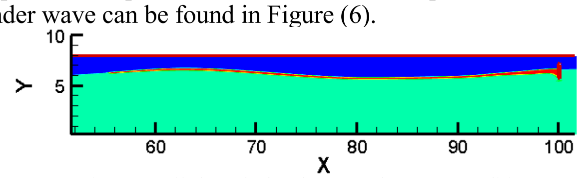

Figure 6. Oil shape before boom under wave condition

The variation of the oil slick thickness with time is predicted based on this numerical experimental platform. The spilled oil on the sea rides the wave very well and propagates towards the wave propagating direction. We can find the variation of oil thickness under effect of the wave as Figure 7 shows. The thickness of the oil slick and the free-surface elevation are approximately in phase. The oil slick moves towards the boom and the oil thickness increases induced by the current. When the wave is at its crest (trough), the oil achieves its maximum (minimum) thickness, and the oil thickness decreases with time.

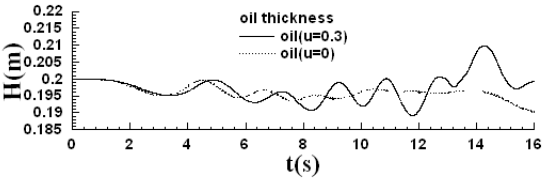

Figure 7. Variation of oil thickness under effect of the wave with and withou current

Figure 8 illustrates the loss rate for rigid boom with $0.5\,m$ boom draft under wave and current conditions. As for no wave conditions the loss rate increases also exponentially by increasing the flow velocity but much faster as waves become stronger. In the case of an aggressive wave such as the second order Stokes wave with H/d=0.16, the loss rate increases very rapidly after the initiation of failure. For experiment with weak waves, the loss rate is almost the some with the formula.

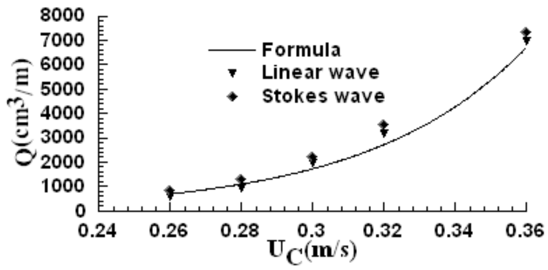

Figure 8. Prediction of loss rate using formula (8) for rigid boom under effect of weak wave and aggressive wave steepness

V. CONCLUSION

A two dimensional numerical experimental platform of oil containment by rigid boom under wave and current conditions has been successfully established, utilizing the software FLUENT and its function of the secondary development. Once the entrainment failure starts, the loss rate increases exponentially with flow velocity. The loss rate is higher and increases more rapidly with higher flow velocity in case of aggressive wave. The effect of wave steepness on the loss rate is significant in the presence of waves.

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