The Damping Model for Sea Waves Covered by Oil Films of Finite Thickness

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Abstract— In combination with the wave action balance equation, the damping model for sea waves covered by oil film of finite thickness is presented. This damping model is not only related to physical parameters of oil film, but also related to marine environment parameters. Here, we conduct parametric analyzes to understand the sensitivity of the damping model to these parameters. Numerical simulations show that kinematic viscosity, surface/interfacial elasticity, thickness, and the fractional filling factor cause more significant effects on the damping ratio than the other physical parameters of oil film. On the other hand, the influences induced by wind speed and wind direction are also remarkable. In present work, fifteen ENVISAT ASAR images, which were acquired during Gulf of Mexico oil spill accident, are used to confirm the validity of the damping model.

1. INTRODUCTION

The hydrodynamic theory of wave damping by oil films of negligible thickness (e.g., monomolecular films) has been well established by Marangoni theory [1–4]. As a matter of fact, the thickness of mineral oil spill is generally much larger than that of monomolecular film, which results in different viscoelastic properties and, therefore, in different damping of the ocean surface waves. Thus, water wave damping by oil films of finite thickness is also of practical importance. However, the influence of the thickness of oil film on sea waves has not been widely investigated so far.

In present work, combining the wave action balance equation with the *Jenkins'* wave viscous damping function [5], a damping model for sea waves covered by oil films of finite thickness is proposed. Parametric analyses of the damping model indicate that kinematic viscosity, surface/interfacial elasticity, thickness, and the fractional filling factor cause significant effects on the damping ratio. Meanwhile, the influences induced by wind speed and wind direction are also remarkable.

2. THE DAMPING MODEL OF SEA SURFACE WAVES

The thickness of a mineral oil spill is generally much larger than that of monomolecular film, particularly, in the initial stages of an oil spill accident. Then, radar signal reduction by finite-thickness oil film has practical significance. In a system which consists of finite-thickness oil film covering on a Newtonian fluid of infinite depth, a viscous damping ratio model for gravity-capillary waves is theoretically derived by *Jenkins* [5]

$$y(k) = \frac{\mathrm{Re}(\delta)}{2\upsilon} \tag{1}$$

with

$$\begin{aligned}\delta \;=\; & \left\{2\upsilon + \frac{1}{2}\upsilon_T + j\Gamma^{-1/2}[\gamma(1-\rho_+) - \gamma_-]D + \frac{1}{2\upsilon^{1/2}j^{1/2}}\rho_+ D\Gamma^{1/4}\upsilon_T \right.\\ & \left. + \frac{1}{2\upsilon^{1/2}}j^{1/2}(\rho_+ D)^2\Gamma^{3/4}(R^2-1)\right\} \Big/ \left\{1 + \frac{1}{\upsilon^{1/2}\Gamma^{1/4}}j^{1/2}\upsilon_T + \frac{1}{j^{1/2}\upsilon^{1/2}}\rho_+ D\Gamma^{1/4}\right\}\end{aligned} \tag{2}$$

and the other parameters are related to the film thickness, the kinematic viscosities of the underlying water and the floating oil film, the surface tension, and so on (for more details, please see Ref. [4]).

However, it should be pointed out that the damping ratio evaluated by Eq. (1) is only available for very gentle wind regimes because not only the viscous dissipation but also wind speed, nonlinear wave-wave interaction, and wave breaking dissipation would induce significant influences on the damping behavior, too. In order to quantify these considerations, the evolution of surface wave spectrum can be described by the action balance equation [2, 3]

$$0 = \frac{dN^i}{dt} = S^i_{in} + S^i_{nl} - S^i_{vd} - S^i_{br} \tag{3}$$

where $i \in \{o; w\}$, and the superscripts (o) and (w) denote an oil-covered and an oil-free sea surface, respectively. The spectral action density $N^i = (\omega/k)\psi^i$, ω and ψ^i represent angle frequency and the full sea roughness spectrum. For oil-free sea surface, ψ^w is written as [6]

$$\psi^w = f(k,\varphi)\begin{cases} M_L(k) & k < k_{Lc} \\ M_M(k) & k_{Lc} \le k < k_{Hc} \\ M_H(k) & k \ge k_{Hc} \end{cases} \tag{4}$$

where the isotropic part and the angle spread function of the spectrum are

$$M_L(k) = \frac{\alpha_g v_g F_g}{2k^4 v_{ph}} \kappa^{\exp\left[-\frac{(\sqrt{k/k_p}-1)^2}{2\delta'^2}\right]} \exp\left(-\frac{5k_p^2}{4k^2}\right) \tag{5}$$

$$M_H(k) = \frac{A(k)}{k^4}\left(\frac{u_f}{c}\right)^{a(k)} \tag{6}$$

$$M_M(k) = \frac{(k_{Hc}-k)}{(k_{Hc}-k_{Lc})} M_L(k) + \frac{(k-k_{Lc})}{(k_{Hc}-k_{Lc})} M_H(k) \tag{7}$$

$$f(k,\Phi) = \frac{1}{2\pi}[1 + \Delta_E \cos(2\phi)] \tag{8}$$

and the other parameters can be found in Ref. [6].

In the right-hand side of (3), S^i_{in}, S^i_{nl}, S^i_{vd}, and S^i_{br}, represent source functions describing the wind input, nonlinear wave-wave interactions, viscous dissipation, and wave breaking dissipation, respectively. In the present work, only the cases for low to medium wind speeds are in question, and the impact of S^i_{br} can be neglected. Here, the wind input term S^i_{in} can be expressed as [2]

$$S^i_{in} = \beta^i N^i \tag{9}$$

β^i is the wind wave growth rate as

$$\beta^i = 0.04\cos\phi\left(\frac{u^i_*}{c_p}\right)^2 \omega \tag{10}$$

where c_p is the phase velocity of the considered wave. The angular frequency ω is defined by the dispersion relationship

$$\omega = \sqrt{gk + \frac{\tau k^3}{\rho_w}} \tag{11}$$

here, g is the acceleration of gravity, τ and ρ_w denote the surface tension and the sea water density, respectively. The frictional velocities u^i_* for oil-free and oil-covered areas are

$$u^\circ_* = \xi\, u^w_* \tag{12}$$

$$u^w_* = \sqrt{C_{10}} U_{10} \tag{13}$$

where, ξ is a coefficient due to the reduction of the friction velocity caused by surface film, and Gade et al. [7] suggested an average ξ value equal to 0.8. In our work, the experimental expression proposed by Wu [8] for the drag coefficient C_{10} is utilized and

$$C_{10} = (0.8 + 0.06U_{10}) \times 10^{-3} \tag{14}$$

where, U_{10} is the wind speed at a height of 10 m.

In (3), the viscous dissipation S^i_{vd} and the nonlinear wave-wave interaction terms S^i_{nl} can be written as [2]

$$S^i_{vd} = 2c_g \Delta^i N^i \tag{15}$$

and

$$S_{nl}^{i} = \alpha^{i} N^{i} \tag{16}$$

with $\Delta^w = \frac{4k^2\eta\omega}{\rho_w g + 3\tau k^2}$, $\alpha^w \approx -1.15\beta^i$, $\alpha^\circ = \alpha^w + \delta\alpha$, $\delta\alpha = 2c_g \Delta^\circ_{\max}(\frac{k}{k_M})^{3/2}(\frac{u_*^w}{u_{*c}})^2$. Here, c_g and Δ^i represent the wave group velocity and the viscous damping coefficient respectively. η and $\Delta^\circ_{\max}$ denotes the dynamic viscosity and the maximal value of Δ°. k_M is the Marangoni resonance wave number. u_{*c} is the critical wind stress at which the nonlinear energy transfer has reached the level

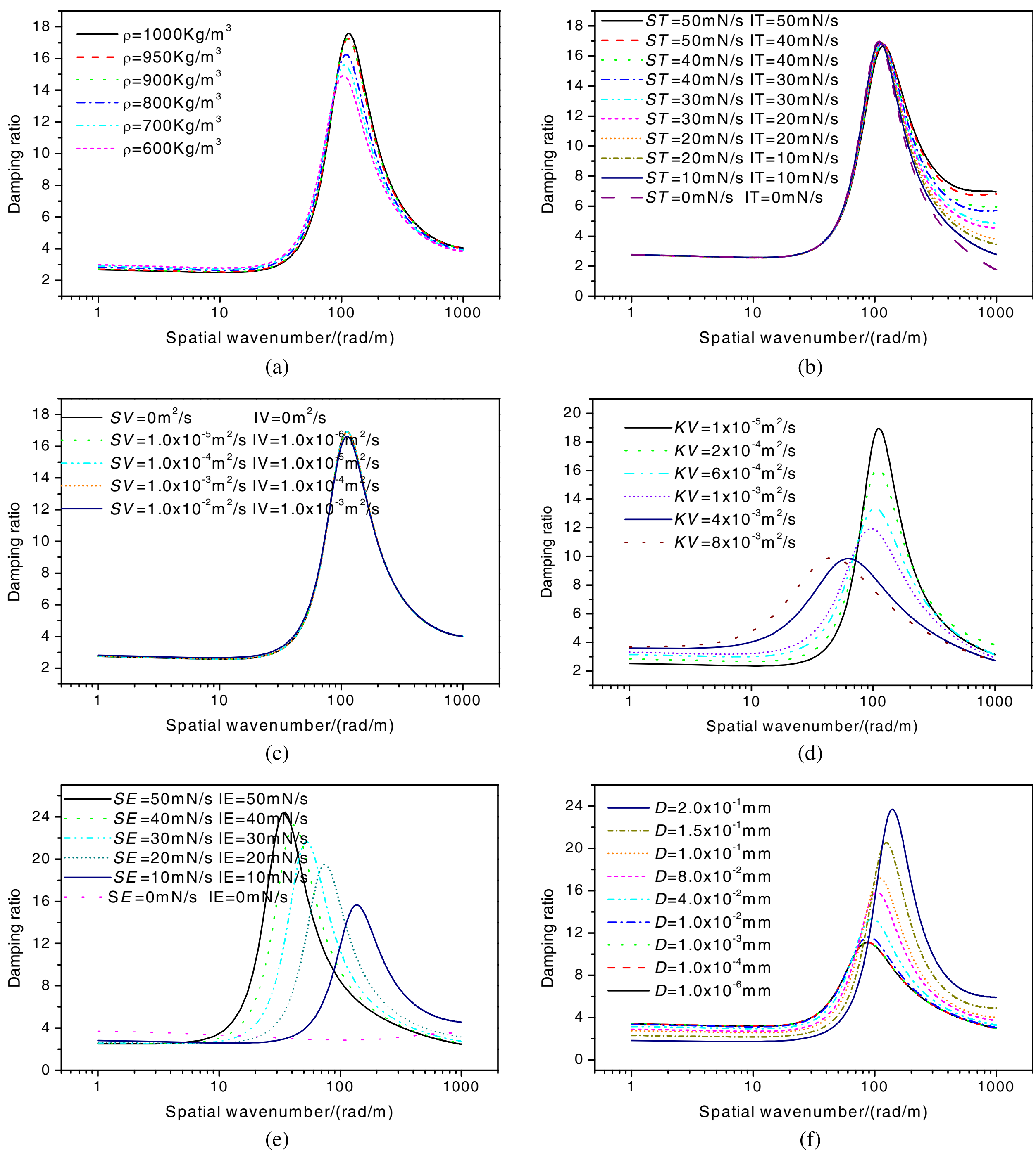

Figure 1: Damping ratio of sea wave spectrum for different physical parameters of oil film with wind speed $U_{10} = 5\,\text{m/s}$, fractional filling factor $F = 1$, and wave spread azimuth angle $\phi = 0^\circ$ (a) for different oil density ρ; (b) for different surface tension ST and interfacial tension IT; (c) for different surface viscosity SV and interfacial viscosity IV; (d) for different kinematic viscosity KV; (e) for different surface elasticity SE and interfacial elasticity IE; (f) for different film thickness D of the oil film.

where it just balances the oil damping. And u_{*c} is generally determined by experiment [2].

Substituting Eqs. (8), (14), and (16) into (6), we can obtain that

$$\frac{\psi^{\circ}(k,\phi)}{\psi^{w}(k,\phi)} = \frac{\beta^{w} - 2c_g\Delta^{w} + \alpha^{w}}{\beta^{\circ} - 2c_g\Delta^{\circ} + \alpha^{\circ}} \tag{17}$$

and the surface roughness spectrum for oil contaminated sea waves is

$$\psi^{o}(k,\phi) = \psi^{w}(k,\phi)/y'(k), \quad y'(k) = \frac{\beta^{\circ} - 2c_g\Delta^{\circ} + \alpha^{\circ}}{\beta^{w} - 2c_g\Delta^{w} + \alpha^{w}} \tag{18}$$

Generally, the oil film may be partially dispersed by wind and waves, so a fractional filling factor, F (i.e., the ratio of the area covered by film with respect to the total considered area) is introduced to modify the damping ratio. In this case, a modified damping ratio model $y'_m(k)$ can be written as [9]

$$y'_m(k) = \frac{1}{1 - F + F/y'(k)} \tag{19}$$

3. NUMERICAL RESULTS AND DISCUSSIONS

Figure 1 illustrates the damping ratios for different physical parameters of oil film. From Fig. 1, we can find that the damping ratio would be obviously affected by the kinematic viscosity, surface elasticity and thickness of oil film. As shown in Fig. 1(d), the damping ratio decreased with the increasing kinematic viscosity, and peaks of damping ratio move to lower spatial wavenumber.

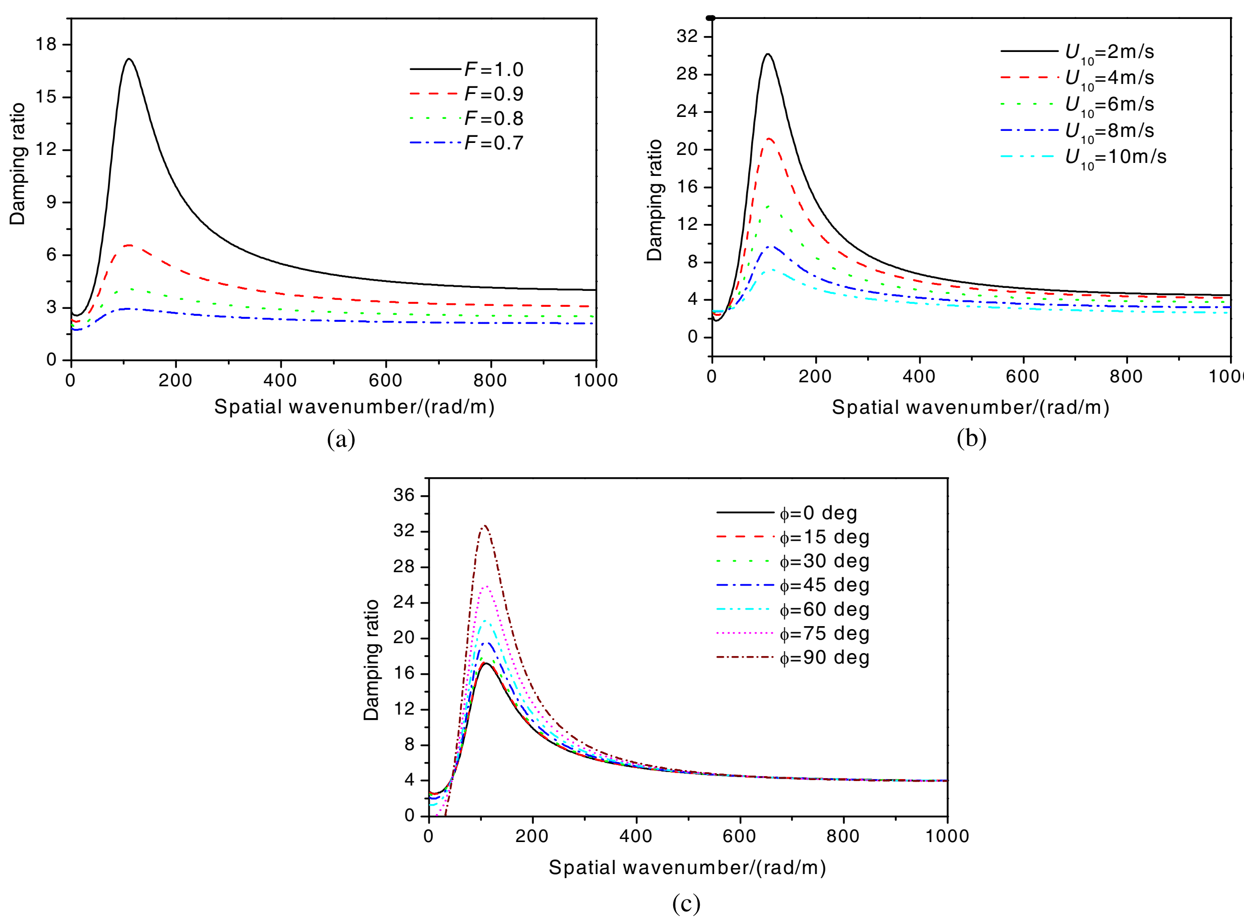

Figure 2: Theoretical damping ratio of sea wave spectrum evaluated by (19) for different environment parameters (a) for different fractional filling factors F with $U_{10} = 5\,\text{m/s}$, $D = 0.1\,\text{mm}$ and $\phi = 0°$; (b) for different wind speeds U_{10} with $D = 0.1\,\text{mm}$, $F = 1$ and $\phi = 0°$; (c) for different wave spread azimuth angles ϕ with $U_{10} = 5\,\text{m/s}$, $D = 0.1\,\text{mm}$ and $F = 1$.

Fig. 1(e) shows that the damping ratio increases with the increase of the surface/interfacial elasticity, and peaks of the damping move to lower spatial wavenumber too. In Fig. 1(f), the damping ratio induced by oil film with thickness less than ~ 0.01 mm are only slightly different from that of a monomolecular film (a film of almost zero thickness); while the effect of the film thickness becomes noticeable if it is increased to ~ 0.01 mm, the damping ratio increases on the whole as the increasing thickness of the oil film, and peaks of damping ratio move to the higher spatial wavenumber.

From Fig. 2(a), we can find that the damping ratio is very sensitive to fractional filling factor F. It is found that the damping ratio for $F = 1$ is about twice larger than the value of the damping ratio for $F = 0.9$. The influences of wind speed and wind direction are illustrated in Figs. 2(b) and (c), respectively. And the figures show that the damping ratio decreases with increasing wind speed, and increases with the wave spread azimuth angle. One reason for this phenomenon is that the higher the wind speed, the higher the wind input energy, hence, the weaker the Marangoni damping effect. The other reason is that the wave-wave interaction becomes stronger when wave spread azimuth angle ϕ is small. And from (10), it is easy to find that the stronger the wave -wave interaction, the weaker the Marangoni damping effect.

Figure 3 shows the damping ratio versus wind speed. The solid squares correspond to the damping ratios evaluated by fifteen SAR images which are acquired in Gulf of Mexico during the 2010 BP oil spill accident, and the lines correspond to the theoretical damping ratios calculated by Eq. (19) with oil film thickness 0.01 mm. In Fig. 3, we can see that the evaluated data by SAR with lower wind speed agree the theoretical result with higher oil fractional filling factors better, meanwhile the evaluated data by SAR with higher wind speed agree the theoretical result with lower oil fractional filling factors better. And it seems reasonable that the fractional filling factor decreased with the increasing wind speed.

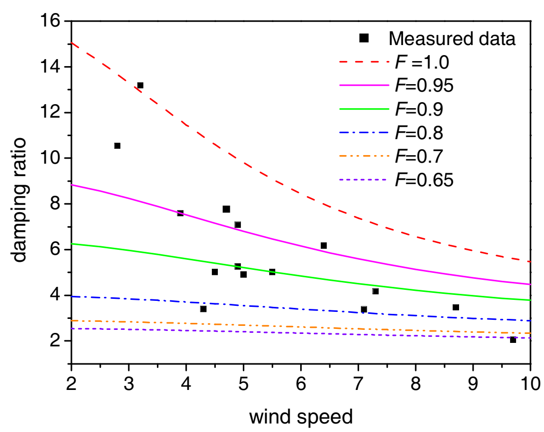

Figure 3: The damping ratio versus wind speed.

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REFERENCES

1. Huhnerfuss, H., W. Alpers, W. D. Garrett, P. A. Lange, and S. Stolte, "Attenuation of capillary and gravity waves at sea by monomolecular organic surface films," *J. Geophys. Res.*, Vol. 88, No. C14, 9809–9816, 1983.
2. Alpers, W. and H. Huhnerfuss, "The damping of ocean waves by surface films: A new look at an old problem," *J. Geophys. Res.*, Vol. 94, No. C5, 6251–6265, 1989.
3. Franceschetti, G., A. Iodice, D. Riccio, G. Ruello, and R. Siviero, "SAR raw signal simulation of oil slicks in ocean environments," *IEEE Trans. Geosci. Remote Sensing*, Vol. 40, No. 9, 1935–1949, 2002.

4. Pinel, N., N. Déchamps, and C. Bourlier, "Modeling of the bistatic electromagnetic scattering from sea surfaces covered in oil for microwave applications," *IEEE Trans. Geosci. Remote Sensing*, Vol. 46, No. 2, 385–392, 2008.
5. Jenkins, A. D. and S. J. Jacobs, "Wave damping by a thin layer of viscous fluid," *Phys. Fluids*, Vol. 9, No. 5, 1256–1264, 1997.
6. Wang, Y. H., Y. M. Zhang, H. H. Chen, and L. X. Guo, "Effects of atmospheric stability and wind fetch on Microwave sea echoes," *IEEE Trans. Geosci. Remote Sensing*, Vol. 52, No. 2, 929–935, 2014.
7. Gade, M., W. Alpers, H. Huhnerfuss, V. R. Wismann, and P. A. Lange, "On the reduction of the radar backscatter by oceanic surface films: Scatterometer measurements and their theoretical interpretation," *Remote Sens. Environ.*, Vol. 66, No. 1, 52–70, 1998.
8. Wu, J., "Wind-stress coefficients over sea surface near neutral conditions-a revisit," *J. Phys. Oceanogr.,* Vol. 10, No. 5, 727–740, 1980.
9. Lombardini, P., B. Fiscella, P. Trivero, C. Cappa, and W. Garrett, "Modulation of the spectra of short gravity waves by sea surface films: Slick detection and characterization with a microwave probe," *J. Atmos. Ocean. Technol.* , Vol. 6, No. 6, 882–890, 1989.