The attenuation of short surface wind waves by monolayer oil films*

OCEANOLOGIA, No. 32
pp. 41–47, 1992.
PL ISSN 0078-3234

Gravity surface waves
Monomolecular oil films
Scattering of ultrasonic signals
Water pollution

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Manuscript received October 3, 1991, in final form May 18, 1992.

Abstract

The damping effect of short surface waves of active monolayer oil films with different physical properties was investigated under natural conditions in the Gulf of Gdańsk. The spectra of the scattered acoustic signals amplitude from clean and covered sea surfaces was analysed in the frequency range of 1–40 Hz. Short capillary and gravity surface waves were damped by monolayer oil films with viscoelastic properties at a relatively constant wind velocity (1.7–2.3 $m \cdot s^{-1}$). Within such a monolayer 'static and dynamic properties' can exist which give rise to additional viscous damping (Maragoni effect). For a better comparison, the computed damping ratio $k(f)$ in the same frequency range is presented.

1. Introduction

The spectral analysis of acoustic signal amplitudes scattered specularly from a clean sea surface and one covered with artificial oil films (Gasoline 94, Gasoline 86, Selectol plus engine oil) was performed. The effects of the damping of the specular energy density by an artificial monolayer sea slick of an oleyl alcohol and methyl alcohol (slick/nonslick area) in the frequency range of 2–20 Hz on short gravity and capillary waves were demonstrated (Hühnerfuss and Garret, 1981; Hühnerfuss *et al.*, 1981; Leonard, 1970).

The relative spectrum $k(f)$ expressed by the spectral wave intensity was obtained for an olein-vegetable oil slick and nonslick area, the frequency

* The investigations were carried out as part of the research programme CPBP 02.03, co-ordinated by the Institute of Oceanology of the Polish Academy of Sciences.

range (2–20 Hz) clearly corresponding to the wave damping by a film in the presence of a light breeze (1.0–1.5 $\mathrm{m \cdot s^{-1}}$ (Ermakov and Plinovsky, 1984; Ermakov *et al.*, 1986)). The spectral ratio of wind-generated waves of a clean sea surface and a polluted surface can be presented by the low-frequency-range damping ratio of the amplitude fluctuation spectra of high frequency scattered signals. The analysis of the signals scattered from an open sea with oceanographically relevant elastic properties characterized by the $k(f)$ pattern damping ratio was obtained from the static and dynamic properties (Cini and Lombardini, 1978; Cini *et al.*, 1985).

In theoretical treatments damping is expressed in terms of the elasticity modulus, in order to characterize the nature of insoluble surface films. The damping coefficient ranges from β_o (for a non-viscoelastic surface) for a free surface to $\beta_{\max}$ (at infinite elasticity) at a relatively low value of the surface dilational elastic modulus (Linde *et al.*, 1984a,b). The damping ratio of short surface waves in the presence of insoluble oil films (Cini and Lombardini, 1978; Cini *et al.*, 1985) is given by

$$k(f) = \beta_{CO}/\beta_o = \frac{1 - 2\tau - 2\tau^2 - X_o - Y_o(X_o + \tau)}{1 - 2\tau + 2\tau^2 - 2X_o + 2X_o^2}, \tag{1}$$

where β_{CO} and β_o are the respective damping coefficients for film-covered and clean surfaces,

$$X_o = \frac{E_o K^2}{\rho(2\eta\omega^3)^{1/2}}, \qquad Y_o = \frac{E_o K}{4\rho\eta\omega} \qquad \text{and}$$

$$\tau = (2t_r/\omega)^{1/2},$$

where

η	– the viscosity of water.
ρ	– density of water,
$K = 2\pi/\lambda$	– wave number,
$\omega = 2\pi f$	– angular frequency,
$E_o = -A(\delta A/\delta \Pi)$	– the dilational elasticity modulus accounting for adsorption or desorption variation during compression and dilation.

2. Experimental conditions

The influence of oil layers of different properties on the amplitude fluctuation spectra of scattered ultrasonic signals on a wind-driven water surface was examined under natural conditions in Gdynia's Naval Port (Pogorzelski, 1990). The air and the sea water temperatures during the measurements were 285 and 287 K respectively. An acoustic system was used in these investigations (Pogorzelski *et al.*, 1984; Khalifa, 1990).

The registered acoustic signals were played back on a level tape recorder and analysed using a Brüel & Kjaer 1621 analogue tunable band bass filter with a width of 1/3 octave (23%) and a V 543 digital multimeter over a frequency range of 1–50 Hz. The crude oil substances were used as oil-film-slick-forming monolayers on the sea surface. The oils applied in these investigations were dissolved in hexane to make a volatile solution and spread carefully onto the sea surface. It should be noted that the intensity of the high-frequency scattered signals I_s is inversely proportional to the square of the slope of the surface, $I_s \sim 1/(h/\lambda)^2$ and linearly related to the scattered signal amplitudes $I_s \sim A2$. The damping ratio $k(f)$ of the oil films spread on the open sea surface can be measured on the basis of the following expression for the specular density proportional to the surface wave height $S(\omega) \sim h^2$ described by Philip (Khalifa, 1990; Leonard, 1970; Pogorzelski, 1991a,b, in press a, b)

$$k(f) = \frac{S_o(\omega)^2}{S_{co}(\omega)^2} = \frac{h_o(\omega)}{h_{co}(\omega)} = \frac{I_{co}(\omega)}{I_o(\omega)} = \frac{A_{co}^2}{A_o^2}. \tag{2}$$

The physical properties and the viscoelastic properties were obtained for the selected oil substances from additional measurements using the Langmuir trough system (James and Prichard, 1974; Pogorzelski, 1991a).

The light oils were treated as monolayers with positive spreading coefficients (Pogorzelski, in press b). The Selectol-plus oil has a negative spreading coefficient and it appears on the sea water surface as floating lenses or spots with an equilibrium thickness of 0.39 cm.

The static and dynamic properties characterized by the elasticity modulus E_o, the surface pressure Π and the relaxation time τ, were introduced in equation (1) over a frequency range of 1–40 Hz for two oil substances 2 (Gasoline 94, Gasoline 86) for a better comparison (Pogorzelski, 1991a, in press b).

3. Results and discussion

The damping ratio results were obtained in the presence of oil substances under natural conditions at a constant wind velocity above the sea surface. The damping ratios within a frequency range of 1–40 Hz were analysed. The frequency relationships of the damping ratio are illustrated in Figure 1 (see also Pogorzelski, 1991a,b, in press b).

It is clear from the figures that the wave damping ratios appear to have low values (0.5–1.5) in the frequency region of f $\gg$ 20 Hz. The theoretical damping ratio (contrast) values of $k(f)$ were computed for Gasoline 94 and Gasoline 86 by means of equation (1) and repeated in Figures 1 and 2.

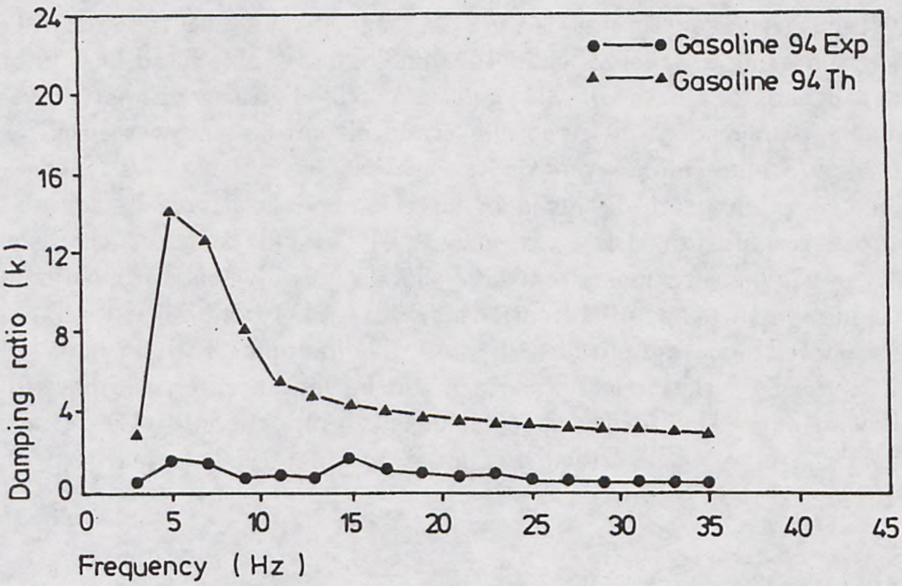

Fig. 1. The damping ratios of sea surface relationships versus frequency (1–40 Hz) in the presence of a Gasoline 94 film. The theoretical damping ratios are computed from equation (1) in which the static and dynamic parameters were taken from experimental measurements (reproduced by permission of Dynamics of Atmosphere Oceans)

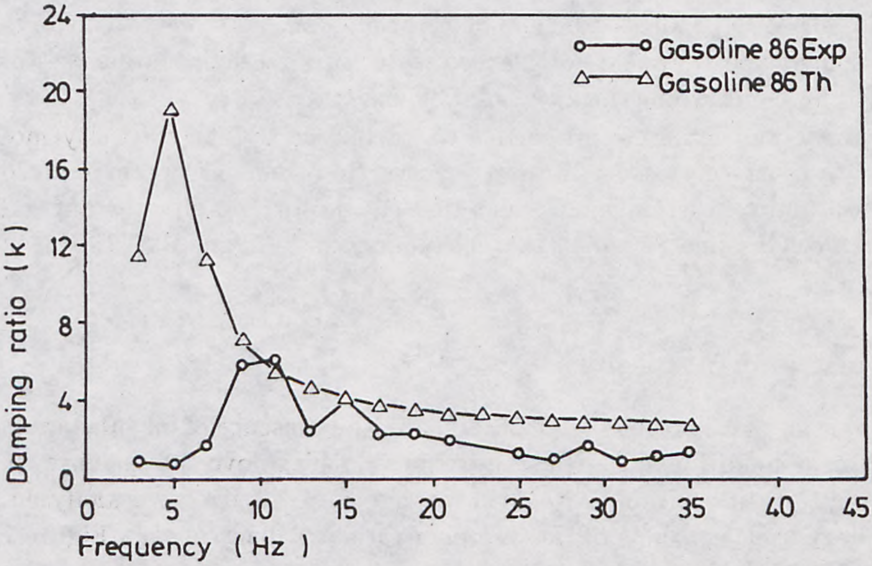

Fig. 2. The damping ratios of sea surface relationships versus frequency (1–40 Hz) in the presence of a Gasoline 86 film. The theoretical damping ratios are computed from equation (1) in which the static and dynamic parameters were taken from experimental data (reproduced by permission of Proceedings of the Conference Acoustical Imaging, Bohum, 1991)

We believe the not -very- good agreement between the theoretical and experimental curves to have resulted from other environmental factors (temperature, currents, non-uniform slick deposition, *etc.*), *i.e.* this disagreement may have arisen from the fact that the static and dynamic parameters introduced in the theoretical relationship in equation (1) were taken from laboratory measurements made under different conditions. In the open sea investigation the monolayer films were not completely uniform on the sea surface. In addition, elastic films spread on the sea surfaces with different physical properties may break; any holes that occur and the surface oil films will move slowly as a result of Stocks wave drift and currents. The other factor responsible is the roughness of he sea water surface modified by an oil film at lower wind velocities. From the damping ratios $k(f) = S_{\rm clean}/S_{\rm dirty}$ obtained in the presence of the insoluble oil substances *in situ*, which are depicted in Figure 3, it can be seen that a peak in the frequency region of 5–10 Hz is observed in all cases (Pogorzelski, 1991b, in press a, b).

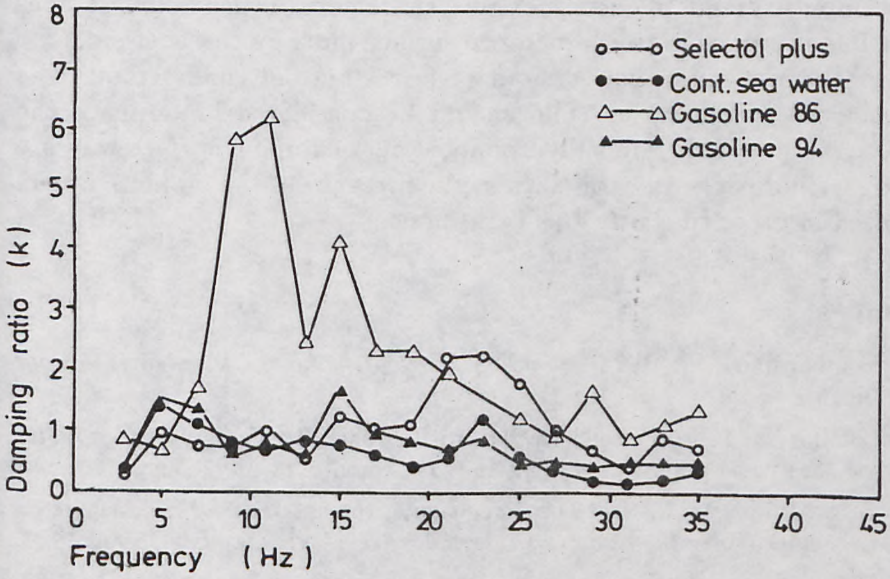

Fig. 3. Acoustically obtained damping ratios for the oil films studied versus frequency (1–40 Hz) under natural conditions and at wind speeds of $u = 2$–$2.3\ {\rm m \cdot s^{-1}}$ (reproduced by permission of Dynamics of Atmosphere Oceans)

The damping intensity (peak height) and peak frequency may be introduced as the maximum of the damping ratio k_m and the frequency resonance f_m (Tab. 1 (Pogorzelski, 1991a)). From the theoretical $k(f)$ relationship one can see that the respective maximum damping ratio values for Gasoline 94 and Gasoline 86 are 20 and 13, occurring at a maximum frequency of 5 Hz.

Table 1. The maximum contrast and maximum frequency values for the selected oil films (reproduced by permission of the American Institute of Physics

Oil substance	Maximum contrast value $y(f)_{max}$	Maximum frequency value f_{max}
Gasoline 94 oil	1.7	5
Gasoline 86 oil	6.8	11
Selectol plus oil	2.5	5
Contam. sea surface	1.5	5

In conclusion it can be said that the measurements of the $k(f)$ pattern may enable the nature of the surface film to be characterized. It is of course too early to deduce the physical and chemical nature of sea surface films from the intensity and frequency of this characteristic peak, but it does seem feasible in principle to characterize surface films by this method.

The mechanism of the wave damping effect is not fully understood. The direct influence of the surface film should be considered in terms of the chemical structure of the film's hydrophobic part damping surface waves.

However, more experimental data in the presence of the oil films *in situ* are required in order to clarify this hypothesis.

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