On Wave Damping due to Oil Films

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Abstract-**Numerical analysis of wave damping due to oil films of finite thickness was performed. The influence of physical parameters of oil films (volume, surface and interfacial viscosity, surface and interfacial tension and elasticity) on the wave damping and the wave number values was analysed in the frame of the model of two fluid layers. The results were applied to describe the data of previous laboratory experiments on wave damping due to crude oil films. The physical parameters of oil films were estimated when tuning the film parameters to fit theory to experimental dependencies of the damping coefficient on film thickness. It is obtained that crude oil films can be characterized by a complex viscoelasticity coefficient with comparably low real elasticity and high surface viscosity. The estimated parameters can satisfactory describe results of field experiments with crude oil films.**

I. INTRODUCTION

The problem of remote sensing of oil pollutions is of strong importance last decades, because of increased contamination of the ocean environment due to intense oil mining and oil transportation and discharge of waste water. Remote sensing methods based on the surface roughness variantion in the contaminated areas are very perspertive to detect pollutions. Oil slicks appear as dark or light patches on radar and optical images because of wave damping due to oil. However, detection of "smooth" patches on the sea surface is insufficient to make a definite conclusion about oil contaminations, since the latter have to be distinguished from other phenomena, for example from biogenic slicks or wind shadows. To identify the origin of marine slicks some peculiarities of wave damping in different parts of the surface wave spectrum caused by different reasons should be revealed. The film action on wind waves depends strongly on physical parameters of films, which are still poorly investigated by now. Results of first systematic laboratory studies of wave damping due to crude oil/oil derivatives films in a wide range of film thickness were presented in [1,2], and some preliminary estimations of film parameters were given. In this paper the data from [1,2] are re-analysed using a wave model of two-layer fluid and physical parameters of oil films responsible for wave damping are estimated and discussed.

II. RESULTS OF LABORATORY MEASUREMENTS OF WAVE DAMPING DUE TO OIL FILMS

Laboratory measurements of wave damping due to oil films were carried out using a new method of parametrically generated waves developed at IAP [3]. In this method the damping coefficient and wavelength of parametrically excited gravity-capillary waves are measured, and surface tension and film viscoelasticity can be retrieved when comparing experiment and theory. The method was used to study characteristics of marine biogenic and artificial films [4,5,6], and also the effect of crude oil and oil derivatives films on surface waves [1,2]. The measured relative wave damping coefficient (normalized by wave damping for a clean water surface at the same wave frequency) and effective surface tension for three wave frequencies are presented in Figs.1 and 2. The effective surface tension is

$$\sigma = \frac{\omega^2 / th(kd) - gk}{k^3} \quad , \tag{1}$$

where ω – the wave frequency, k– the measured wavenumber, d – the fluid depth. Note, that the defined effective surface tension (1) for the case of a thick film (with the film thickness comparable or exceeding the oscillatory surface boundary layer) is not conventional surface tension coefficient, but depends on the surface tension, interfacial tension, film thickness, wavelength etc.

The relative wave damping (see, Fig.1) demonstrates slow growth for film thickness less than 0.1 mm and reveals a maximum at about thickness of 1 mm. At larger thicknesses the wave damping coefficient decreases tending to the damping due to bulk oil (this values are marked in the right part of figures). The effective surface tension in some cases also depends nonmonotonically on film thickness (see. Fig.2). One should note, that the thickness of oil films spread in a small container was not strictly uniform and increased near the walls of the container, this resulting in some errors in the film thickness in Figs. 1, 2.

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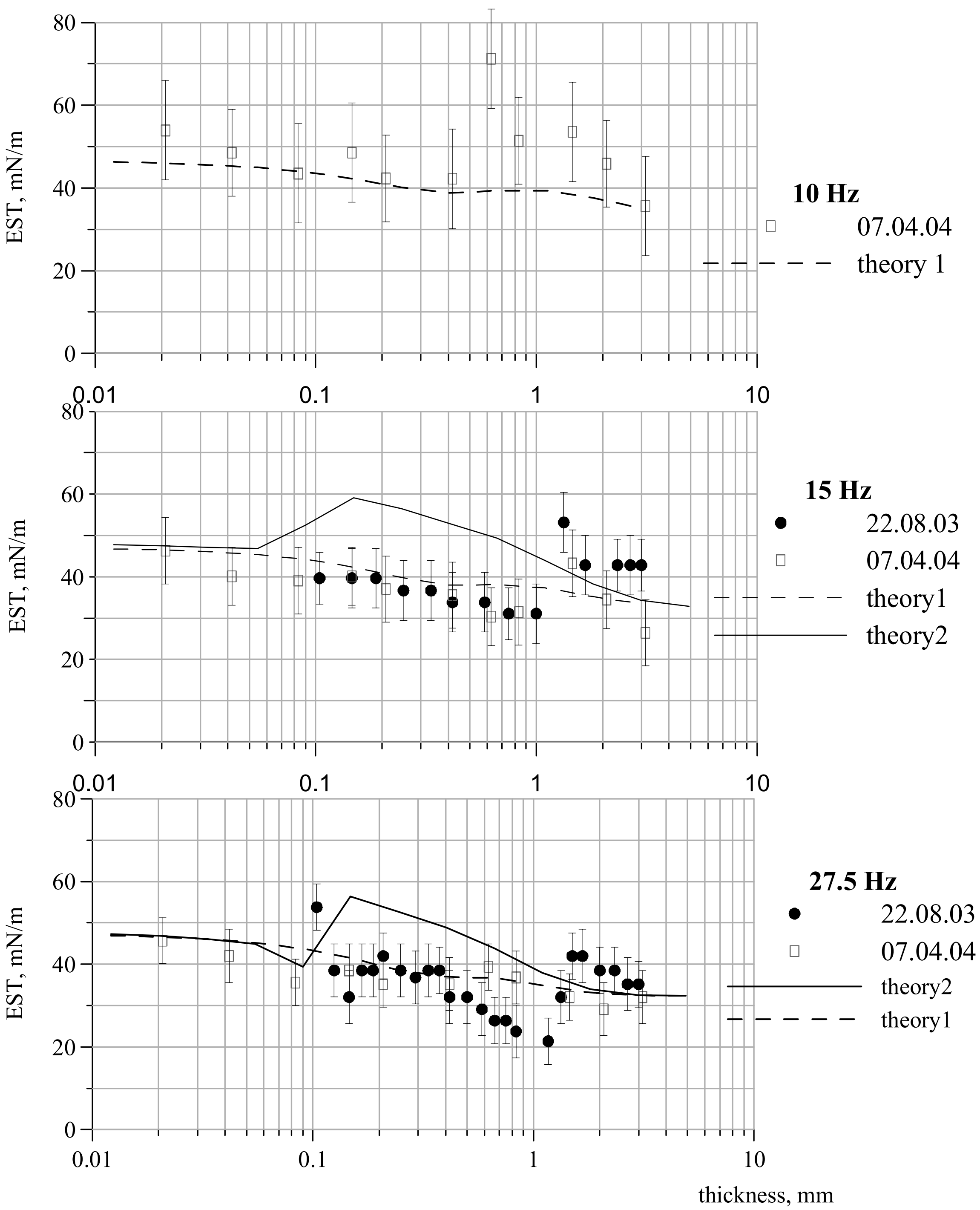

Fig.1 Effective surface tension vs. oil film thickness.

III. ANALYSIS OF WAVE DAMPING AND RETRIEVED OIL FILM PARAMETERS

The damping of short surface gravity-capillary waves is investigated in the frame of two-layer fluid model. The system consists of an upper layer of Newtonian viscous fluid (oil) of finite thickness floating on a Newtonian fluid (water) of infinite depth. Following [7] we assumed that the system is described by linear Navier-Stocks equations with corresponding boundary conditions on the surface of the oil layer and at the interface oil/water. According to [7] the wave damping depends on the

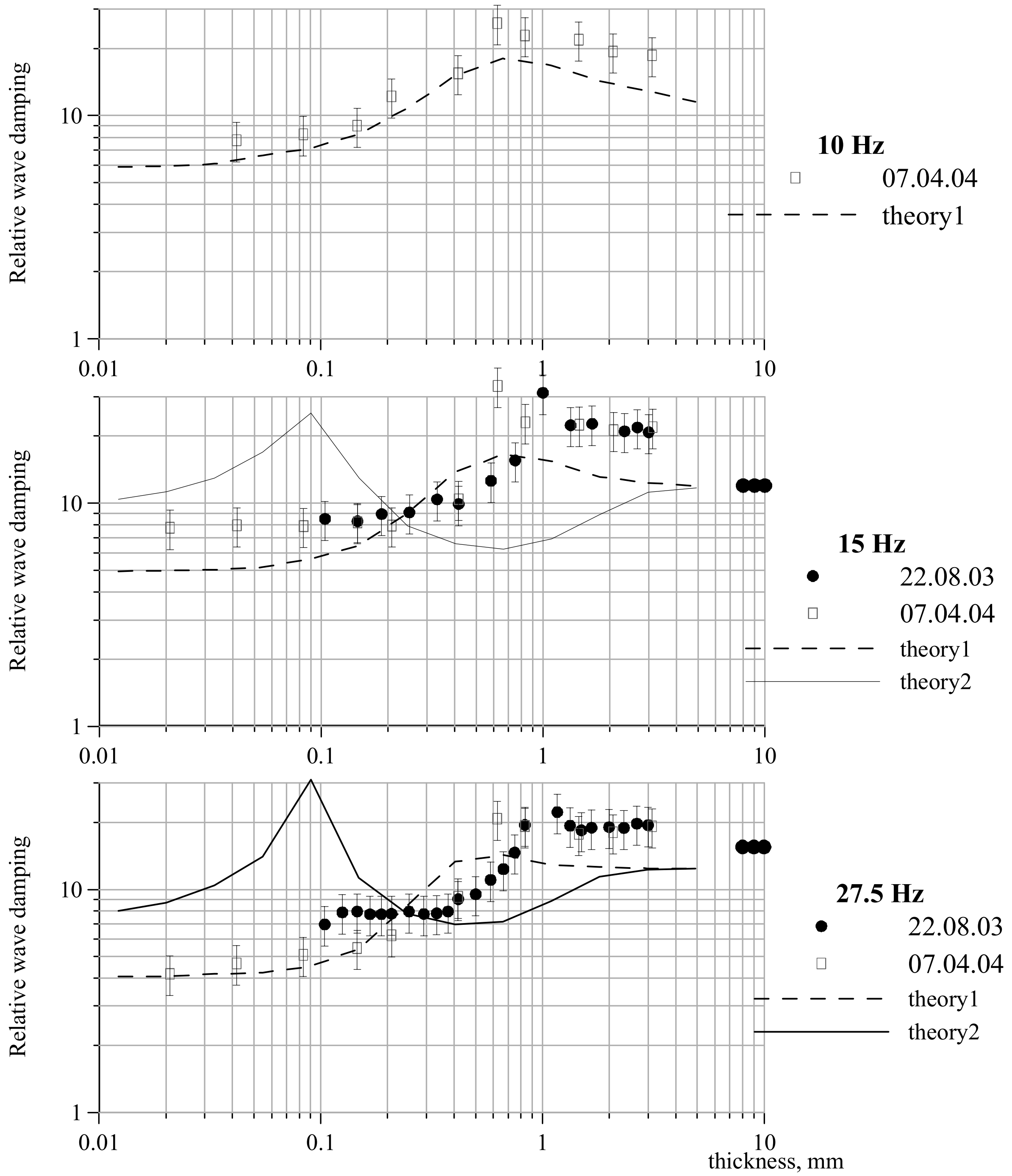

Fig.2. Relative wave damping vs. oil film thickness.

following physical parameters: *d* – the film thickness, ν_{water} - the water viscosity, ν_{oil} - the oil viscosity, σ_+ - the surface (air/oil) tension, σ_- - the interfacial (oil/water) tension, E_+ the surface elasticity (air/oil), E_- the interfacial elasticity (oil/water), μ_+ - the surface viscosity (air/oil) and μ_- the interfacial viscosity (oil/water). We assumed that all the mentioned parameters do not depend on the wave frequency and the film thickness. Note, that in our experiments oil films can be of larger thickness than the viscous boundary layer, therefore the results of model [7] cannot be applied to the considered results.

Let us estimate first physical parameters affected the wave damping on the surface of bulk oil, using a model of the wave damping [7,8]. Since the crude oil is a mix of different materials we have to assume that the wave damping coefficient on bulk oil is determined not only by oil viscosity, but also by the surface elasticity and the surface viscosity. The surface tension can be retrieved from the dispersion relation accounting the wave damping. The value of surface tension retrieved from our data is 29 ± 3 mN/m. Note that the error of the obtained value does not exceed the error of the measurements. The wave damping on the bulk oil normalized on the wave damping on the bulk water surface at a given wave number can be written as [8]

$$\gamma = \frac{\nu_{oil}}{\nu_{water}} \cdot \frac{1-\varepsilon \cdot x + \varepsilon^2 \cdot xy}{1-2\varepsilon \cdot x + 2\varepsilon^2 \cdot x^2}, \quad x = \frac{k^2}{\rho_0 \sqrt{2\omega \nu_{oil}}\,\omega}, \quad y = \frac{k}{4\nu_{oil}\rho_0 \omega}, \quad (2)$$

where $\varepsilon = E_+ - i\omega\nu_+$ - the parameter of viscoelasticity. If $\varepsilon = 0$ γ does not depend on wave frequency and is equal to the relative oil viscosity ($\frac{\nu_{oil}}{\nu_{water}}$). Fig.3 presents the value of γ for three frequencies at which the experiment was carried out. One can see that the regime when $\varepsilon = 0$ can be realized. Our analysis shows that the surface elasticity should be smaller that 1 mN/m and the surface viscosity should not exceed 0.01 $mN \cdot s / m$ to satisfy the measured values of damping.

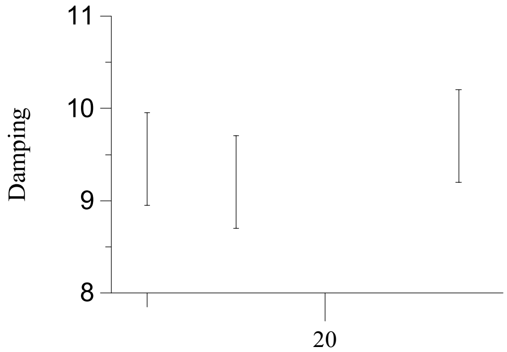

Fig.3. Relative wave damping on the bulk oil vs. wave frequency.

As it is follows from [7] the effective surface tension on the surface covered with a very thin films is a sum of the surface and the interfacial tensions. This allows us to obtain the interfacial tension.

So there are only two undetermined parameters: interfacial elasticity and interfacial viscosity. Figs. 4 and 5 demonstrate the impact of the interfacial elasticity and the interfacial viscosity on the wave damping. It is seen that the wave damping monotonically increases with film thickness if the interfacial elasticity or the interfacial viscosity are small and has a maximum for large values of the interfacial parameters. The maximum is located at the film thickness value smaller than we obtained in the experiment: this can be a result of the error mentioned above. The dependencies of the effective surface tension vs. film thickness are different for large interfacial elasticity and large interfacial viscosity. One can see that two different dependencies of effective surface tension that we obtained in our experiments can be realized when the interfacial parameters are quite different.

The solid lines in Figs. 1 and 2 correspond to the effective surface tension and the relative wave damping calculated using the parameters from Table 1.

TABLE 1.

Curve	Relative oil viscosity	Surface tension	Surface elasticity	Surface viscosity	Interfacial tension	Interfacial elasticity	Interfacial viscosity
Theory1	9	30 mN/m	0	0	20 mN/m	0	0.5 mN·s/m
Theory2	9	30 mN/m	0	0	20 mN/m	8 mN/m	0

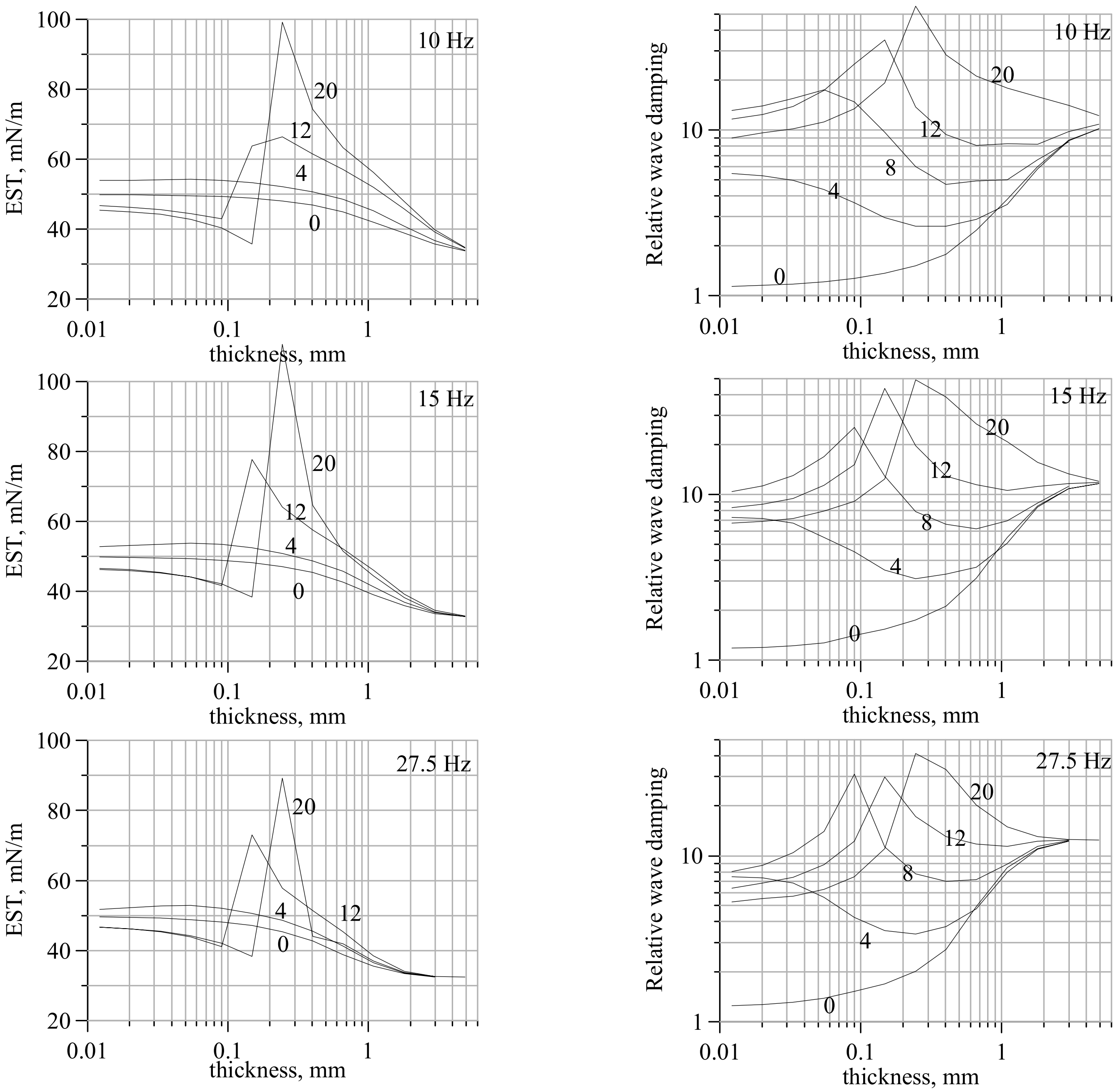

Fig. 4. Calculated effective surface tension and relative wave damping vs. oil film thickness. $\nu_{-} = 0.$
Numbers near curves denote the interface elasticity in mN/m.

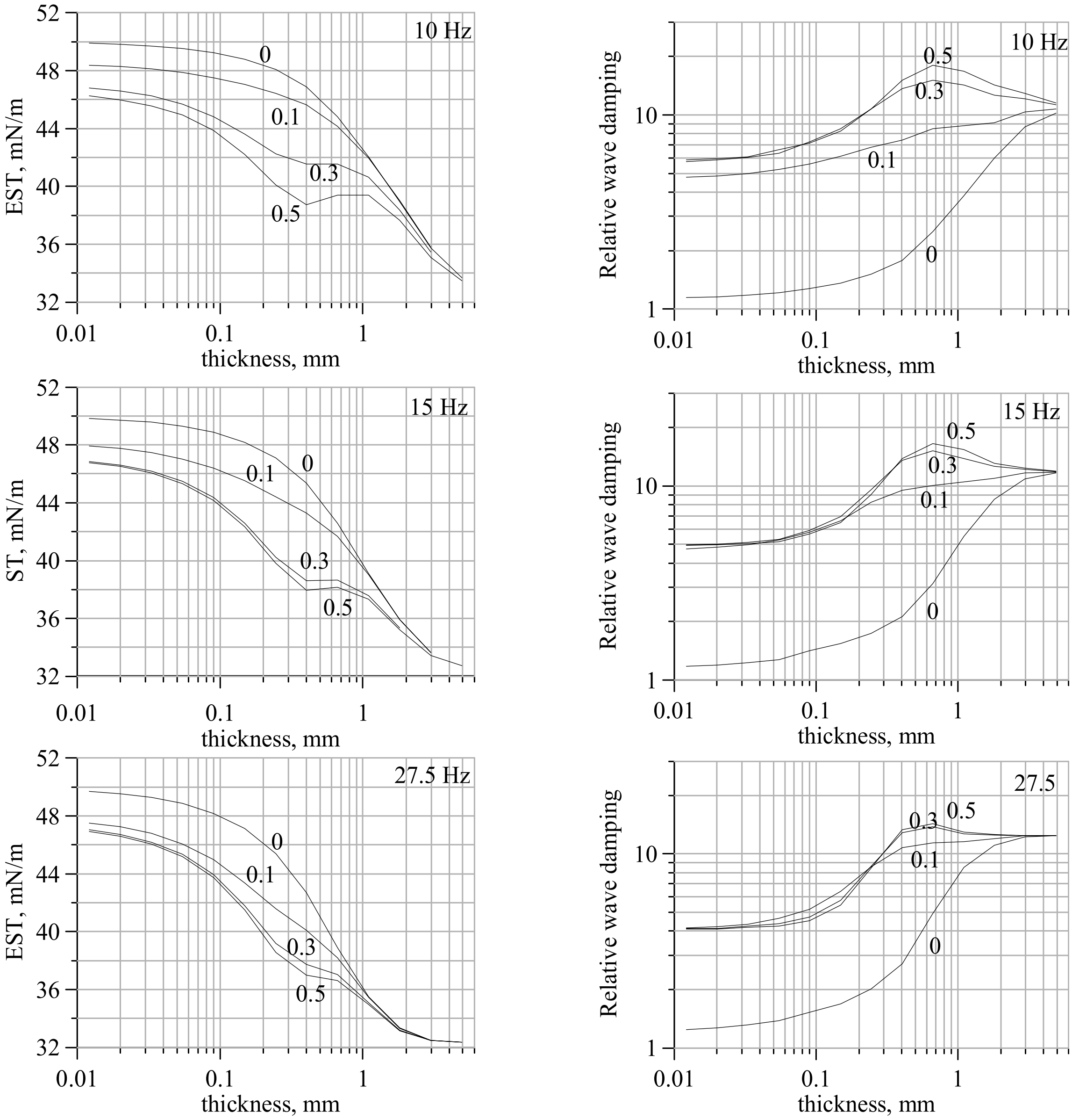

Fig. 5. Calculated effective surface tension and relative wave damping vs. oil film thickness. $E_{-} = 0$.
Numbers near curves denote the interface elasticity in mN/m.

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