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The attenuation of monochromatic surface waves due to the presence of an inextensible cover

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HIGHLIGHTS

- Direct observations of wave attenuation under an inextensible surface cover.
- Observations consistent with viscous attenuation for frequencies 1 to 2 Hz.
- Attenuation is due to no-slip boundary condition and independent of cover type.

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ABSTRACT

The attenuation of surface gravity waves is an important process associated with air–sea and wave–current interactions. Here we investigate experimentally the attenuation of monochromatic surface gravity waves due to the presence of various surface covers. The surface covers are fixed in space such that they do not advect with the wave motion and are selected such that the bending modulus is negligible for the wave frequencies used in the experiment in order to minimize any flexural effects. Wave attenuation rates are found to be independent of wave steepness and the type of cover used over the tested parameter range. Results are consistent with the theoretical attenuation rate for an inextensible surface cover.

1. Introduction

Knowledge of the effect of modifying the water surface on attenuating surface waves goes back to antiquity [1]. This changing of the surface rheology can arise from the presence of oil [2], ice [3], or from certain atmospheric and meteorological conditions [4]. Wave attenuation is frequency dependent [5,6], which generally increases with increasing frequency, although this can depend on the nature of the surface cover [2,7]. Wave attenuation is an important component of many physical processes such as those associated with air–sea interactions [8], wave–current interactions [9], surface drift [10], and stabilizing wave modulation [11] to name a few.

In the absence of a surface film, wave attenuation is primarily due to the straining motion of the irrotational component of the wave motion (see [5,6]) and theoretical values have been verified in laboratory experiments in cases where the surface was meticulously cleaned, see [12,13]. In the presence of a surface film, a viscous boundary layer develops which acts to increase the attenuation of surface waves (see [5,6]). If this surface film is elastic then the wave attenuation becomes much more complicated as some of the wave energy can also go into longitudinal waves, also known as Marangoni or dilational waves [2,14].

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The inextensible model of [5] has been applied to wave attenuation in ice and requires viscosity values several orders of magnitude greater than the molecular value to match observed attenuation rates [3,15–17]. In ice there are many processes which also attenuate energy such as scattering from ice floes [18] and ice creep [19], which might contribute. These observations are limited to oceanic conditions and often the argument is made that the boundary layer is turbulent, predominantly due to the ridges and keels present under the ice, and hence the larger eddy viscosity is justified on these grounds (see [3]).

While laboratory experiments of wave attenuation involving clean water (see [12] and references therein) and water in the presence of surfactants (see [2]) have been performed, there has been little attention paid to investigating inextensible surface covers. More recently, it has been shown by [13] that observations of the attenuation of ocean swell by [20,21] are consistent with the theoretical attenuation rate of an inextensible surface cover. However, the physics as to why swell attenuation is best modelled by an inextensible surface cover is not clear.

The main objective of this study is to investigate the attenuation of monochromatic surface waves due to the presence of an inextensible surface cover. The paper is outlined as follows: a brief review of the theoretical background for wave attenuation is described in Section 2. A description of the experimental setup is presented in Section 3. Section 4 presents the results of the experiment followed by a summary and discussion in Section 5.

2. Theoretical background

2.1. Linear wave attenuation

Wave amplitudes have been observed to attenuate exponentially, i.e.

$$\frac{\partial a}{\partial x} = -\alpha a \tag{1}$$

where a is the wave amplitude, x is the distance along the wave flume, and α is the total wave attenuation. Linear wave attenuation arises from viscous dissipation within the fluid [5,6] as well as boundary effects from the bottom and sidewalls of a wave flume [22], viscous effects from the air above the interface [23] and the presence of surfactants on the water surface [10,12,13].

In the absence of a boundary layer, whether it be at the surface or due to the finite dimensions of a wave flume, the temporal wave attenuation rate, as given by [5], is

$$\frac{\partial a}{\partial t} = -2\nu k^2 a, \tag{2}$$

where t is time, ν is the kinematic viscosity, and k is the wave number. It is often difficult to clean the surface sufficiently such that there are no particles or natural surfactants present, and thus the clean water attenuation rates are difficult to obtain in wave flumes, see [13].

In the presence of a surface film, the wave attenuation is greater than (2) as the film acts to enhance vorticity in the boundary layer created by the film. In the inextensible limit the boundary condition is assumed to be no-slip and the wave attenuation, as given by [5], is

$$\frac{\partial a}{\partial t} = -\frac{1}{2}\nu\gamma k a, \tag{3}$$

where $\gamma = \sqrt{\omega/2\nu}$ is the inverse boundary layer thickness [5].

The temporal attenuation rate in (2) and (3) can be related to the spatial attenuation rate by using the relation of Gaster [24], i.e.

$$\frac{\beta}{\alpha} = c_g \tag{4}$$

where β is the temporal attenuation rate, as shown in (2) and (3), α is the spatial attenuation rate, and $c_g = \partial\omega/\partial k$ is the group velocity. Using (4) with (2) and (3) gives the spatial attenuation rates for clean water,

$$\alpha_{cl} = 2\nu k^2/c_g, \tag{5}$$

and

$$\alpha_{in} = \frac{1}{2}\nu\gamma k/c_g \tag{6}$$

for the inextensible surface cover.

In general, the ratio (k/γ), which is the ratio of the boundary layer thickness to the wavelength, is small with $k/\gamma = 2 \times 10^{-3}$ for a 1 Hz deep water wave and $k/\gamma = 2 \times 10^{-2}$ for a 5 Hz deep water wave. It can easily be shown that $\alpha_{cl}/k = \mathcal{O}(k/\gamma)^2$ while $\alpha_{in}/k = \mathcal{O}(k/\gamma)$, and since $k/\gamma \ll 1$, is consistent with $\alpha_{cl} \ll \alpha_{in}$.