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A Laboratory Study of Wave-Ice Interactions in the Marginal Ice Zone using Polydimethylsiloxane (PDMS) as a Viscoelastic Model

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Global warming has significantly changed the environment of Earth's coldest regions. While in the Antarctic, sea ice is expanding its areal coverage, in the Arctic a dramatic decrease is observed. Consequently, the Arctic region is now more accessible for shipping and offshore constructions than before, hence the emerging needs to understand the sea-ice and wave interactions. Previous studies have modeled the floating ice field as a viscoelastic material. However, experimental validation of the theoretical model is still lacking. In this study, we propose using polydimethylsiloxane (PDMS) as the scalable viscoelastic material for laboratory modelling and testing. Viscoelastic characterization of the PDMS material using a rotational rheometer was first established. Then, preliminary experiments with a PDMS cover on water were performed with a small rocking tank that emulated a combination of standing and traveling wave conditions. Rocking tank experiments using both water-only and oil-on-water were done for comparison. A discussion on the corresponding wave responses is given in this paper. The future experimental plan for the scaled study in a small wave flume is also presented.

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1. Introduction

The extent of the Arctic sea ice has reduced dramatically in recent years, significantly surpassed all existing model predictions (Overland and Wang, 2013). Instead of an ocean mostly covered by a continuous ice cover, the Arctic now has a large expanse of open water adjacent to a dynamically changing ice cover called the Marginal Ice Zone (MIZ). Forecasts of further increase in global temperature of 1-2^{o}C may continue or even accelerate the Arctic ice reduction in the near future (Wang and Overland, 2009). In a positive light, the opening up of the Arctic increases the possibility of shipping and offshore engineering in the area. The challenge, however, is the insufficient understanding of the air-ice-ocean system. In particular, more open water in the Arctic has increased the wave intensity. Thus, understanding the wave-ice-ocean process in MIZ has become a critical element to be further understood for planning and assessment purposes.

One approach to model the sea ice and wave interaction in the MIZ is to consider each floating ice floe as a wave scatterer (Squire 2007). Since the real ice field is very complex, often consists of a multitude of floes mixed with frazil and brash ice, there is also another approach which considers the whole sea ice field as a continuum (e.g. Squire 1984, Wadhams 1986, Wang & Shen 2010). In this approach, the ice cover is modeled as a viscoelastic material. The idea of including both viscous and elastic properties in an ice cover is supported by field and laboratory observations. These models, although plausible based on physical grounds, have not been tested.

In this study, we propose the use of polydimethylsiloxane (PDMS) as the scalable viscoelastic material for laboratory modeling and testing. PDMS elastomer has been used intensively in the fabrication of microfluidics devices for lab on chip applications. A popular commercial product for the fabrication is Sylgard 184 from Dow Corning. Nase *et al.* (2008) used this particular PDMS as the material of varying viscoelastic property from viscous liquid to soft elastic solid, to investigate the pattern formation during the deformation of confined viscoelastic layer. PDMS offers the opportunity to test the viscoelastic theories for wave-ice interaction due to its floatability with less than water density after mixing with lighter oils, its precisely controlled material properties, and the achievable broad range of their elasticity and viscosity.

In this article, we show some preliminary results on the viscoelastic properties of PDMS-based samples for applications in ice-wave interaction. An experiment to test the viscoelastic cover using a rocking mixer was also done as a first approach on the problem. Some initial results regarding viscoelastic cover on a rocking water tank and its comparison with viscous oil cover and water-only cases are given. Future experiment plan for a small wave flume is also presented.

2. Polydimethylsiloxane-based viscoelastic model

In our experiments, rheological properties were investigated using a rotational rheometer (MCR 302, Anton Paar, Germany). For purely viscous material, concentric cylinder measuring geometry (CC27) with measuring bob radius 13.33 mm and measuring cup radius 14.46 mm was used. For viscoelastic samples, plane plate geometry (PP20) of 20 mm diameter and 0.5 mm plate gap width was used.

To investigate rheological property of the PDMS components, rotational tests were done using the rheometer. The two components of Sylgard 184 were initially stored separately and behaved as Newtonian liquids on their own, i.e. they had approximately constant viscosity for shear rate from 0.1 to 100/s. The viscosities for the curing agent and silicone oil base were approximately 0.0588 and 5.07 Pa.s, respectively. Viscoelastic PDMS was formed by mixing of the two components, then heat curing the polymer fluid at 80 °C for at least 5 hours. Varying the amount of the curing agent changed the degree of the crosslinking in the cured PDMS, hence altered the viscoelastic property of the material (Nase *et al.*, 2008). The curing agent mass percentage is defined as

$$\%CA = \frac{m_{CA}}{m_{CA}+m_{SO}} \quad \textbf{[1]}$$

where m_{CA} and m_{SO} are mass of the curing agent and mass of silicone oil of Sylgard 184 used in the mix.

Sylgard 184 cured final product has specific gravity slightly larger than 1, hence it is heavier than water. To achieve a lighter material, we mixed white oil (density of approx. 0.833 gr/cm^3) into the PDMS. For later quantification purpose, the mass percentage of the doping liquid in the mix is defined as

$$\%L = \frac{m_L}{m_{CA}+m_{SO}+m_L} \quad \textbf{[2]}$$

with m_L is the mass of the doping liquid.

The white oil viscosity is approximately constant at 0.0298 Pa.s throughout the diverse range of shear rates. We produced samples with different percentages of curing agent and white oil, and then characterized the linear viscoelastic properties using oscillatory shear tests on plane plate geometry with amplitude of 5×10^{-4} mm and frequency of 0.01 to 100 rad/s. The test results were the (elastic) storage modulus G' and (viscous) loss modulus G". G' is a measure of the deformation energy stored by the sample during the shear process. G" is a measure of the deformation energy used up by the sample during the shear process (Mezger, 2006). Sample results with different amount of the curing agent and doping oil are shown in Fig. 1.

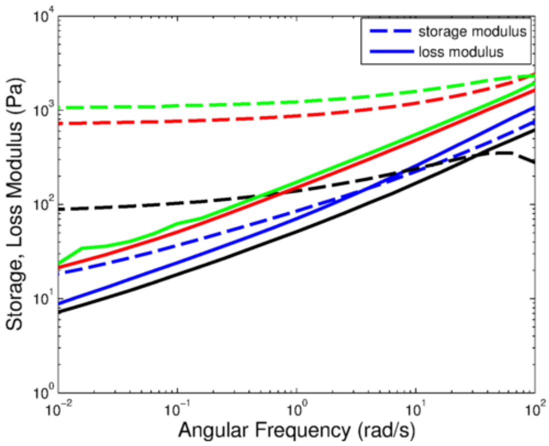

Figure 1. Samples of white oil mixed with PDMS. Linear viscoelastic properties are represented by G' (dashed lines) and G" (solid lines). Blue: 1.41% curing agent and 33.39% white oil; black: 1.61% curing agent and 33% white oil; red: 1.88% curing agent and 33.09% white oil; and green: 1.94% curing agent and 32.68% white oil.

Using white oil as the doping liquid, the increase of curing agent percentage hardened the sample as apparent in Fig. 1. The softest sample made using 1.41% curing agent and 33.39% white oil (blue lines) was at first dominated by its G' at low ω. However, the transition to G" dominated regime appeared as early as ω = 3 rad/s. Next, increasing the curing agent mass percentage to 1.61% with 33% white oil (black lines) apparently increased G' but reduced G", compared to those with lesser curing agent (blue lines). Transition to more liquid-like regime began to appear at the higher angular frequency of ω = 10 rad/s. The other harder samples, with 1.88% curing agent and 33.09% white oil (red lines) and 1.94% curing agent and 32.68% white oil (green lines), were more solid-like throughout the ω range tested.

3. Rocking tank experiments

To test the viscoelastic wave-ice interaction models, a wave flume is being built with a tentative completion date late this summer. Prior to that, we utilized an existing equipment of a rocking tank to examine the behavior of the interaction between the PDMS and water under gravity wave conditions. These rocking tank experiments have their own intrinsic values in addition to preparing for the wave flume studies. For example, they provide fundamental understanding of resonance in confined liquid containers (Ibrahim 2005) which has broad industrial applications.

The laboratory experiments were conducted in the open rectangular glass tank as shown in Fig. 2. The system was periodically forced along the longitudinal axis with an angular frequency ω. The motion was recorded using a high resolution video camera.

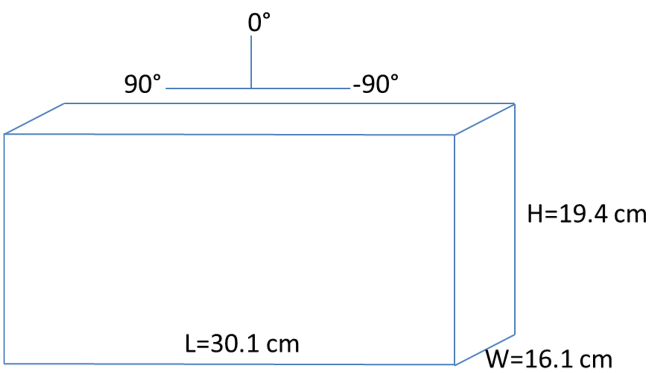

Figure 2. (Left) The geometry sketch of the experimental tank with its dimensions (Length x Width x Height) and definition of angles. (Right) A picture of the setup consists of viscoelastic cover on water inside a tank on the rocking mixer.

For experiments with the rocking tank, we made a viscoelastic sample slightly smaller than the tank dimension. The sample was made using 1.94% curing agent and 32.68% white oil, corresponding to the green line in Fig. 1. The thickness of the viscoelastic sample (0.5 cm) was set to be 1/8 of the total depth.

The tripod of the camera was levelled with level tube and the line of sight of the camera was made perpendicular to the length of the tank. The PDMS sample had the tendency to stick to the wall of tank at low forcing frequency, the adhesion was prevented by providing an oil film on the part of tank wall touching the viscoelastic sample. The conversion of video to frames was performed using Matlab. Plot Digitizer was used to digitize the values of the interface and the surface of waves. The inclination of the tank walls in each frame was obtained using the software *ImageJ.*

The rocking motion of the tank was recorded after 5 minutes from the time of forcing to achieve the steady state motion, at the rate of 25fps (frames per second) for 15 oscillations of the tank. For comparison, three experiments were performed: water-only, oil-on-water, and PDMS-on-water. The oil had a density of 0.91 gr/cm^3 and viscosity of 0.065 Pa.s. The instantaneous surface profiles during steady state with a forcing frequency of ω = 3.27 rad/s are shown in Fig. 3 at the moment when the tank bottom was horizontal. Compared to water-only and PDMS-on-water cases, oil-on-water case had generally smoother surface profiles. However, the oil-water interface had some interfacial waves with magnitudes comparable to the surface waves on water-only case. The PDMS-on-water case had the largest surface wave amplitude and the water-PDMS interface move in phase with the surface.

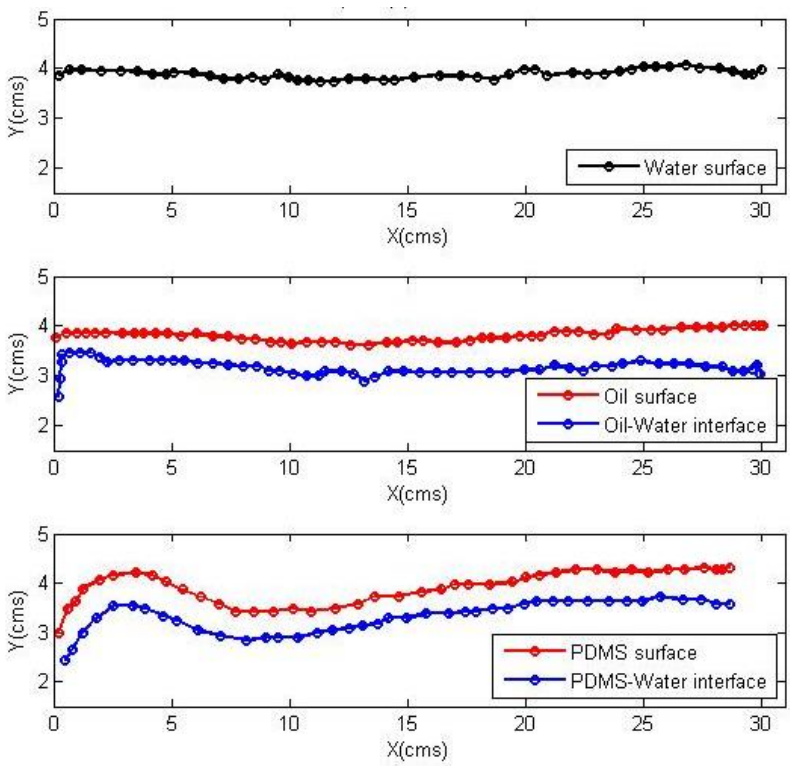

Figure 3. Snapshots of the tank at the instance when the tank bottom was horizontal (ω = 3.27 rad/s): (Top) Water-only experiment; (Middle) Oil-on-water experiment; (Bottom) PDMS-on-water experiment.

Next, we investigate the attenuation characteristics of the wave on PDMS cover when the forcing is stopped. The track the surface and interface motion more precisely, a point is marked in the PDMS sample which is at a distance of 6.3cm from the left side of the sample. The forcing was given with different frequencies and then turned off. The positions of the surface and PDMS-water interface at the marked point are shown in Fig. 4 as functions of time, where the forcing was stopped at t = 8 s for ω = 1.29 rad/s and at t = 3 s for ω = 3.27 rad/s. By observing Fig. 4, it is apparent that both the amplitude and the attenuation of the wave is larger for the high frequency case compared to the lower frequency case.

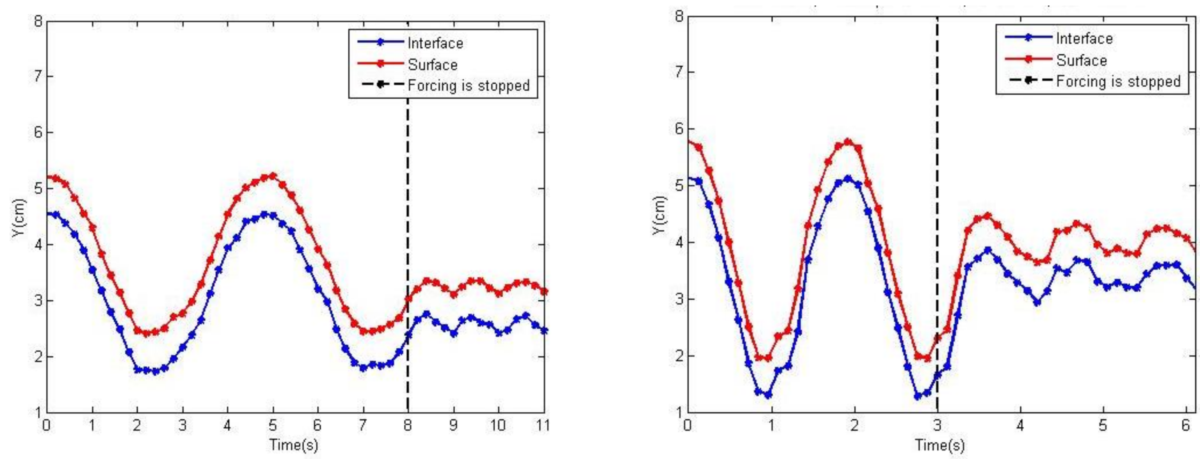

Figure 4. Attenuation experiments of water with viscoelastic cover. Lower frequency of ω = 1.29 rad/s (left) and higher frequency of ω = 3.27 rad/s (right) were investigated. Periodic forcing to the tank was stopped at t = 8 s for ω = 1.29 rad/s and at t = 3 s for ω = 3.27 rad/s.

4. Discussions

The steady-state experiments use rocking water tank as a base for comparison with cases of oil-on-water and PDMS-on-water. Water and oil represent pure viscous fluids with low and high viscosities, respectively. PDMS not only has higher viscosity than oil and water, but has also elasticity which is absent in oil and water. In the steady state experiments, viscosity seems to affect the smoothness of the surface profile. It appears to slightly smooth out the surface profile as can be seen by comparing surface profile of water (Fig. 3, top) and oil (Fig. 3, middle). The oil/water interface (Fig. 3, middle), however, has similar surface profile of the water-only case.

Striking differences can be seen in the PDMS-on-water case compared to the other cases. Introducing elasticity into the system appeared to significantly increase the wave amplitude of the PDMS surface and its PDMS-water interface. The elastic behavior of the PDMS can better transfer the rocking tank input energy to the wave motion. Even though the loss modulus of the PDMS is higher than the viscosity of water and oil, due to the dominance of G' over G" in the sample we used, elasticity effect still governs.

Note that ω used for the oscillatory tests in the rheometer and in the rocking tank experiments were physically different parameters. Viscoelastic properties are directly related to shear rates. The average shear rate in the rheometer geometry is $s\omega/2h$, where s is the amplitude of the rheometer oscillation, h is the gap size of the geometry; and that in the rocking tank is $A\omega^3/2g$, where A is the amplitude of the wave. With different waves, the effective G' and G" in the rocking tank should be determined from equating the corresponding shear rates of the two different configurations.

For the attenuation experiments shown in Fig. 4, after the rocking forcing was stopped, the PDMS surface seemed to oscillate in the same natural frequency for both cases. The case on the right gave rise to larger wave amplitude A thus a larger shear rate. From Fig. 1, G" increased faster with frequency than G'. Therefore the higher amplitude case damps faster.

5. **Future work**

Oil-doped PDMS is a stable viscoelastic model for the experiments of water wave interactions with a viscoelastic cover. The presence of the viscoelastic cover affects how surface wave propagates by damping and storing of the wave energy for later release. Elasticity promotes wave energy transfer while viscosity promotes wave energy damping.

To test the wave-ice interaction theories, the wave tank currently being built is shown in Fig. 5. We will use this facility to measure the wave speed and the attenuation as functions of the G' and G" for waves in the range of 0.25Hz to 2Hz. The acquired data will be used to verify the existing viscoelastic wave-ice interaction theories to substantiate these theories before their application to the field condition.

In addition, the rocking tank experiments will also continue in parallel to study the resonance behavior and standing/propagating wave responses with the viscoelastic cover. Such studies have their own immediate applications besides enhancing our general understanding of wave-ice interactions.

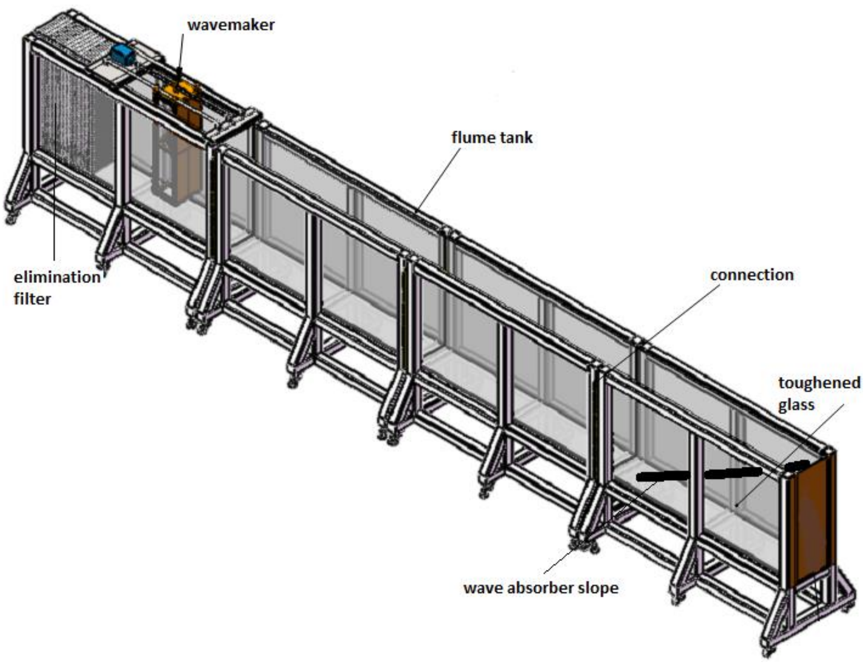

Figure 5. Schematic design of the wave flume. Its dimension is 8.0 m x 0.3 m x 1m (Length x Width x Height).

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