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An experimental study on surface wave attenuation by floating viscoelastic segments

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ABSTRACT

According to the 2018 report from the US National Oceanic and Atmospheric Administration, about 95 percent of the multiyear old ice in the Arctic sea has been lost due to global warming. The accompanying increasing vessel traffic in the Arctic Ocean motivated the present study on wave-ice interactions for safe navigation. So far, most of the theories on wave-ice interactions in the marginal ice zone where the vessel traffic takes place considers the individual scattering effect of discrete elastic elements. The generalized viscoelastic model for the wave-ice interactions represents the ice cover with effective values of material properties (elasticity and viscosity) instead. Its validity requires experimental evidence. Our previous experimental studies examined the effect of rheological property of a continuous viscoelastic floating cover on wave attenuation. The present study is an extension of the work with the integration of discontinuities in the floating cover. Viscoelastic floating covers of different properties are made of oil-doped polydimethylsiloxane, and their rheological properties are tested in an oscillatory rheometer. The surface elevations along the length of wave flume are recorded using ultrasound sensors at various locations including the cover region. These data are used to analyze the wave decay and corresponding attenuation coefficient along the cover. Notable changes in wave attenuation due to floating segments of different lengths and properties are observed.

KEY WORDS: Viscoelastic; Sea ice; Attenuation

INTRODUCTION

Sea ice decline due to global warming and associated Arctic Amplification has opened several sea routes across the Arctic Ocean, with the present-day sea ice largely marked by the growing extent of pancake ice cover (Jim Thomson, Earth and Space Science News, 2017).

The vessel traffic is more during summers and an early "ice free" Arctic Ocean is expected by 2020-2050 (Wang and Overland, 2009). In addition, vessel traffic through the Northern Sea Route had been reported even in extreme conditions (Northern Sea Route Administration, 2019). Safe navigation through the new Arctic shipping routes has motivated continuous research works on wave interactions with sea ice covers.

The transitional zone between the open water and central pack ice, referred to as Marginal Ice Zone (MIZ), plays a vital role in damping the waves from penetrating long distances into the ice-covered sea. The field experiments reported in Squire et al. (1995) previously suggested that the wave energy decays exponentially with distance along the MIZ. Recent wave experiments showed piecewise exponential decay with a unique pattern, and the value of attenuation coefficients obtained varied by a factor of 10 (Stopa et al., 2018). The decay pattern coincided with the young sea ice conditions viewed using SAR (synthetic aperture radar) imagery. These evidences show that the ice properties significantly affect the wave decay, however the dependency has not been fully verified due to limited information.

The viscoelastic model for sea ice cover (Wang and Shen, 2010) considers its two distinct properties namely elasticity and viscosity. The elastic part is primarily accountable for the wavelength change compared to open water (Squire, 1993). The viscous part, on the other hand, is responsible for wave dissipation. The wave-ice experiments conducted by Zhao and Shen (2015) inversely determined the effective values of elasticity and viscosity for various types of ice covers created in a refrigerated wave tank based on the viscoelastic model. Such inverse analysis is however insufficient to validate the model.

To further examine the viscoelastic model for sea ice, Sree et al. (2018) conducted experiments on the wave interaction of a continuous viscoelastic cover with known properties. They found that the material property of the cover plays a significant role in the wave attenuation, and that the theoretical model underpredicts the attenuation coefficient. Since ice covers in nature often consist of discrete floes, hence it is also of interest to study the wave propagation over a discontinuous cover with arrays of floes. To this end, Sakai and Hanai (2002) conducted wave experiments with floating elastic segments of different lengths. Significant change in wavelength was observed in their study, but the aspect of attenuation was not considered. The theoretical predictions for surface elevation profile by Kohout et al. (2007) observed the wave attenuation along an array of elastic segments, however the attenuation coefficient was not quantified. Furthermore, the material used was nearly pure elastic with low viscous effect. The combined effect of discontinuities with viscoelastic effects over an array of discrete floes has not been studied experimentally so far. The present study is the first of such attempt.

EXPERIMENTS

The experiments are carried out using viscoelastic floating covers made of oil-doped polydimethylsiloxane (PDMS). The properties of the cover can be varied by altering the extent of crosslinking, which depends directly on the mass percentage of curing agent (m_{CA}). For the present study, viscoelastic sheets of two different properties are used: m_{CA} = 4% and 10%. The rheological properties of the floating cover are determined using small amplitude oscillatory shear tests in a rheometer. The detailed preparation and rheological testing procedures are described in Sree et al. (2017, 2018). The measured properties, shear modulus (G) and viscosity (ν), are closely approximated by the linear Voight model. Since the properties are frequency dependent, the rotational frequency of the rheometer used in the material testing (ω) is equated to the frequency of the wave tests (σ).The cover with m_{CA} = 10% is stiffer compared to m_{CA} = 4%, with smaller values for shear modulus and viscosity as shown in Table 1.

Table 1. Rheological properties of viscoelastic cover

ω (rad/s)	m_{CA} = 4%		m_{CA} = 10%	
	G (k Pa)	ν (m²/s)	G (k Pa)	ν (m²/s)
12.56	23.18	0.23	145.11	0.42
11.42	23.06	0.24	144.91	0.44
10.47	22.95	0.26	144.75	0.47
9.67	22.85	0.27	144.58	0.50
8.98	22.73	0.28	144.39	0.52
8.38	22.64	0.29	144.23	0.55
7.85	22.55	0.30	144.09	0.57
7.39	22.48	0.32	143.96	0.59
6.98	22.41	0.33	143.85	0.62
6.61	22.35	0.34	143.75	0.64
6.28	22.30	0.35	143.66	0.67

Figure 1 shows the schematic diagram of the transparent wave flume at the Environmental Process Modelling Centre (EPMC), NEWRI, Singapore where the experiments are carried out. The length of flume is 8.0 m and the width is 0.3 m. A piston type wave generator is provided at one end to generate waves of desired wave period and amplitude. At the other end, a mesh type beach is installed to reduce the wave reflection. For the present experiments, the water depth is maintained at 0.3m, and only linear waves are considered. The wave periods, $T = 2\pi/\sigma$, are varied from 0.5 s to 1.0 s with 0.05 s interval, while the open water wave steepness ~ 0.07 is maintained for all the experiments.

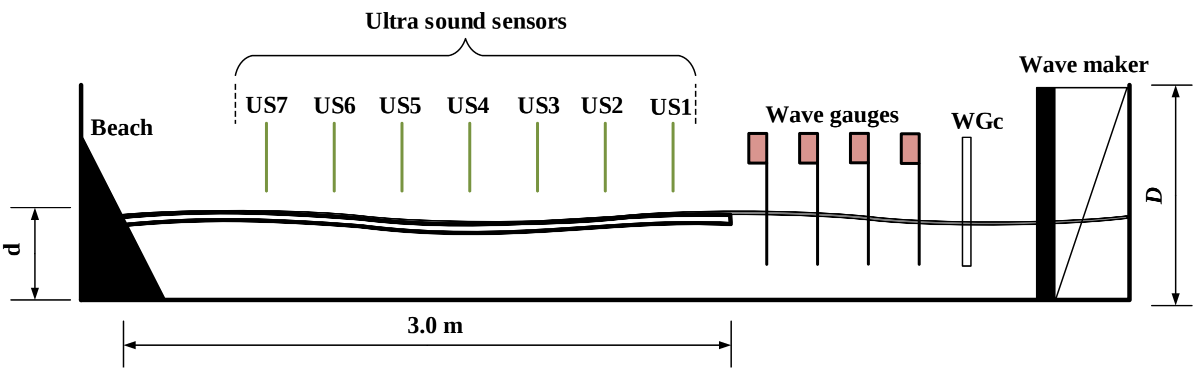

Figure 1. Schematic diagram of wave flume

Seven ultrasound sensors (US 325, ULS 40D, General Acoustics) are used to record the vertical displacement of the viscoelastic cover during the wave action (see Figure 1). The positioning of the ultrasound sensors is described in Sree et al. (2018). Each experiment is performed three times to confirm the repeatability of the results, and only the first three fully developed waves are considered to avoid errors caused by the beach reflection. Two different segment lengths of the viscoelastic cover are considered: (a) continuous cover with l_s = 3.0 m and (b) 12 segments with l_s = 0.25 m (total 3.0 m). The thickness of the covers is 0.01 m.

DATA ANALYSIS AND DISCUSSIONS

The time series of the vertical displacement of viscoelastic cover recorded using the ultrasound sensors are collected using LABVIEW software. The crests and troughs of the first three fully developed waves in the time series data are determined using *findpeaks* function in MATLAB. The wave height is determined as the elevation difference between the crest and trough. Being linear waves, the wave amplitude is calculated as half of the wave height.

A generally smooth reduction in wave amplitude along the cover length is obtained for the continuous cover as shown in Figure 2, but the presence of discontinuities creates sudden jumps in amplitude near the discontinuities. This could be due to the pitching motion of segments as well as the presence of any damped travelling wave. For the same value of l_s, the heightened vertical displacement near free edges directly depends on m_{CA}. The stiff cover with m_{CA} = 10% has larger vertical displacements near the free edges as compared to the flexible cover with m_{CA} = 4%.

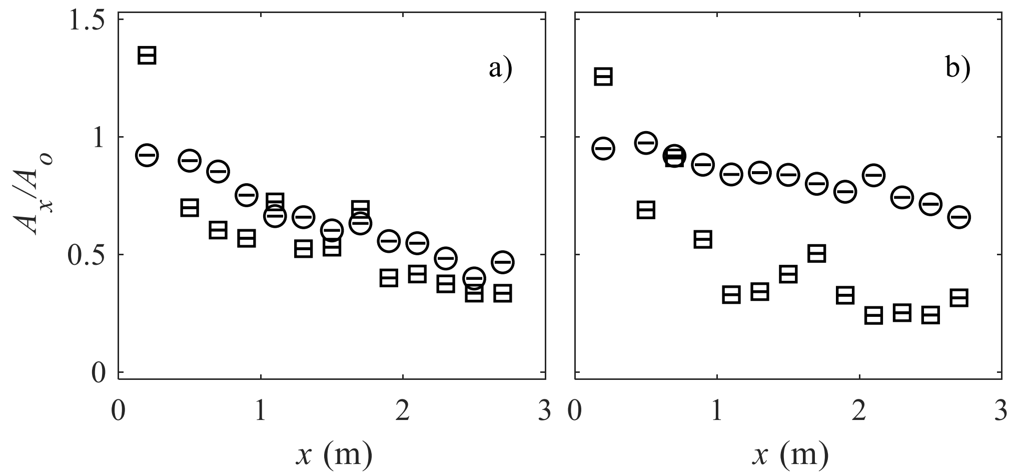

Figure 2: Wave amplitude along the length of cover, l_s (m): Circle = 3.0 m, and Square = 0.25 m. T = 0.5 s, m_{CA}: a) 4%, and b) 10%.

A comparison of the experimentally obtained wave amplitude along the length of cover with discrete elastic floating segments by Kohout et al. (2007) is shown in Figure 3. Larger values for vertical displacement are predicted near to the discontinuities as compared to experimental results. The discrete elastic model predicted a zig-zag behavior even for 3.0 m long continuous floating cover. Unlike the falling trend observed from the experimental results with viscoelastic cover, no notable decay was observed for the theoretically predicted wave amplitudes.

The attenuation coefficient is thus calculated for the viscoelastic case by fitting the amplitudes along the length of cover by an exponential curve using single-term exponential fit model in MATLAB as shown below.

$$A_x = A_0 e^{-\alpha x} \quad (1)$$

where A_x is the wave amplitude at x from leading edge, A_0 is the wave amplitude the leading edge and α is the attenuation coefficient. Only the data collected from locations away from the free edges are considered for the segmented cases (Figure 4), though the ideal case is to only consider the values corresponding to the node points of the oscillatory motion. This could result in a wider range for the confidence interval of the fitted curve.

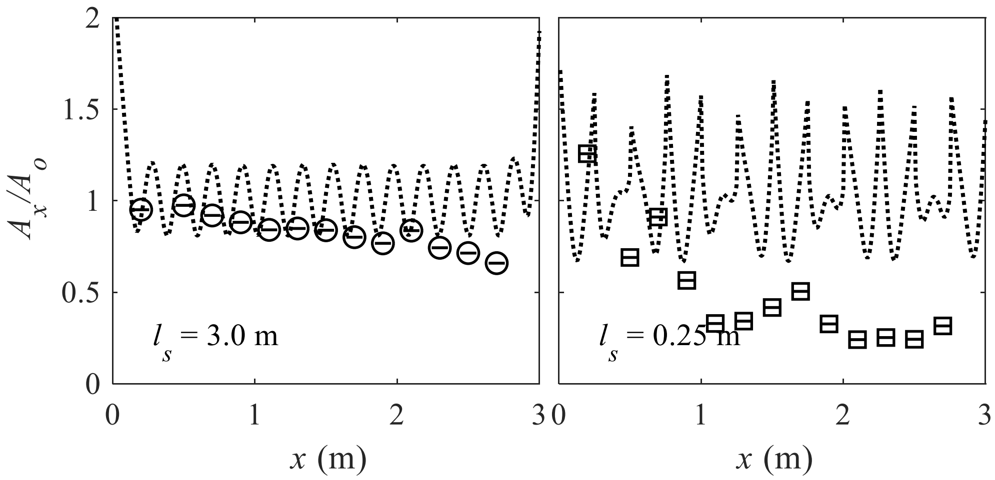

Figure 3: Comparison of normalized wave amplitude for viscoelastic cover with thin elastic floating segments for T = 0.5 s, m_{CA} = 10%. Dotted line represents theoretical predictions by Kohout et al., 2007.

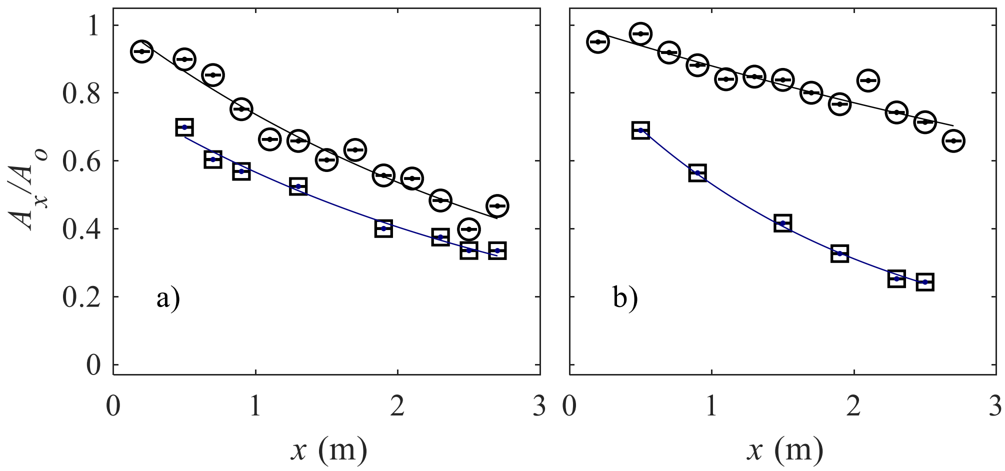

Figure 4: Exponentially fitted curves for the wave amplitude along the length of cover, l_s (m): Circle = 3.0 m, and Square = 0.25 m. T = 0.5 s, m_{CA}: a) 4%, and b) 10%.

The variation of attenuation coefficient with wave period and segment length is provided in Figure 5. The experiments show good repeatability, the notable error bars represent the 95% confidence bounds of the attenuation coefficient obtained from the fitting model. The range of the error bars reflect the oscillation of the surface profiles shown in Figure 3. The attenuation coefficient shows a low pass filtering trend except for the continuous cover with m_{CA} = 10%. The roll-over effect, which is clearly visible for the continuous stiff cover vanishes with the addition of discontinuities. For the flexible cover with m_{CA} = 4%, no significant change in attenuation is observed between the continuous and segmented covers for T = 0.5 s, while noticeable increase can be observed for other wave periods. The contribution of discontinuities on the attenuation coefficient is very significant for the stiff cover with m_{CA} = 10%. For T = 0.5 s, the value increases by ~9 times. The difference however decreases with the wave period.

CONCLUSIONS

A novel laboratory experimental study on surface wave attenuation by discontinuous viscoelastic covers is performed. For flexible viscoelastic floating cover, the effect of the material property is significant for wave damping. The effect of discontinuities on wave attenuation is significant for stiff covers. The total attenuation shows the monotonous relation of low pass filtering effect, except for the case with roll-over effect.

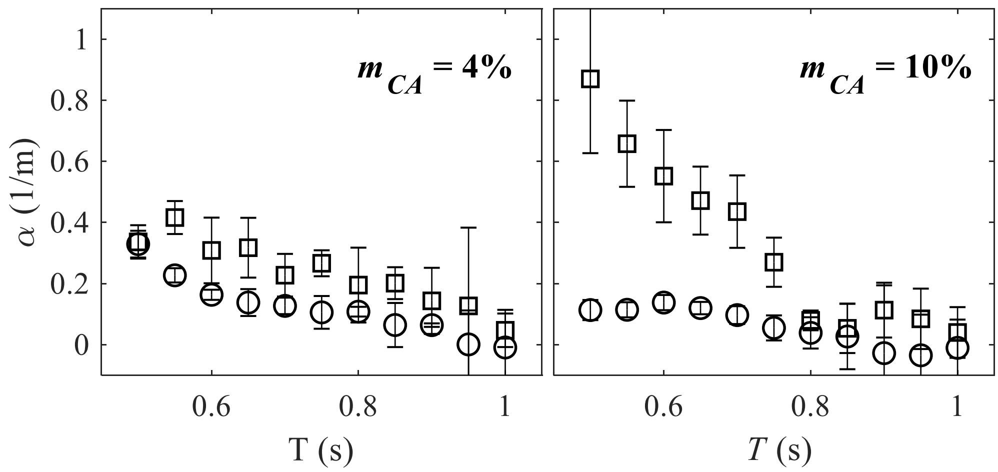

Figure 5: Variation of attenuation coefficient with wave period for different viscoelastic floating segments, l_s (m): Circle = 3.0 m, and Square = 0.25 m.

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REFERENCES

Kohout, A. L., Meylan, M. H., Sakai, S., Hanai, K., Leman, P., & Brossard, D., 2007. Linear water wave propagation through multiple floating elastic plates of variable properties. *Journal of fluids and structures*, 23(4), 649-663.

Sakai, S., & Hanai, K., 2002. Empirical formula of dispersion relation of waves in sea ice. In Ice in the environment: *Proceedings of the 16th IAHR International Symposium on Ice*, 327-335.

Squire, V. A., 1993. A comparison of the mass-loading and elastic plate models of an ice field. *Cold regions science and technology*, 21(3), 219-229.

Squire, V. A., Dugan, J. P., Wadhams, P., Rottier, P. J., & Liu, A. K., 1995. Of ocean waves and sea ice. *Annual Review of Fluid Mechanics*, 27(1), 115-168.

Sree, D. K., Law, A. W. K., & Shen, H. H., 2017. An experimental study on the interactions between surface waves and floating viscoelastic covers. *Wave Motion*, 70, 195-208.

Sree, D. K., Law, A. W. K., & Shen, H. H., 2018. An experimental study on gravity waves through a floating viscoelastic cover. *Cold Regions Science and Technology*, 155, 289-299.

Stopa, J. E., Ardhuin, F., Thomson, J., Smith, M. M., Kohout, A., Doble, M., & Wadhams, P., 2018. Wave attenuation through an arctic marginal ice zone on 12 October 2015. 1. Measurement of wave spectra and ice features from Sentinel 1A. *Journal of Geophysical Research: Oceans*, 123, 3619-3634.

Wang, M., & Overland, J. E., 2009. A sea ice free summer Arctic within 30 years? *Geophysical Research Letters*, 36(7), L07502, 1-5.

Wang, R., & Shen, H.H., 2010. Gravity waves propagating into an ice-covered ocean: A viscoelastic model. *Journal of Geophysical Research: Oceans*, 115(C6), C06024(1-12).

Zhao, X., & Shen, H. H., 2015. Wave propagation in frazil/pancake, pancake, and fragmented ice covers. *Cold Regions Science and Technology*, 113, 71-80.