Lagrangian Motions Near the Surface of Capillary ~ Gravity Waves With Surface Active Films

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Abstract

We present an experimental investigation into the motion of water particles near a film covered surface in the presence of wave motion. The water waves were generated mechanically, but were chosen to have frequencies similar to wind generated waves found in the ocean. The fluid particles were found to move in elliptical paths which were determined and used to verify a number of theoretical concepts. The results have implications for the detection of surface films in remote sensing studies.

Introduction

The calming effect which a film of oil has on a water surface has been known for many centuries, as detailed in Scott's (1979) historical bibliography. Numerous laboratory and field studies, *e.g.* Huhnerfuss & Alpers (1986) and Onstott & Rufenach (1992), have shown that even films the thickness of a single molecule can have a significant effect on the initiation and propagation of surface waves. The general result of these films, whether formed by natural biological processes or mans' contamination, is to suppress wave formation, the practical significance of which is to alter the surface roughness of the body of water in question.

Active sea-surface remote sensing techniques such as Synthetic Aperture Radar (SAR) rely on the amount of microwave backscatter from waves at Bragg wavelengths. Thus an understanding of any physical process which effects such waves is essential to the correct interpretation of these images.

In order to understand the effect that the surface contaminant has on the wave generation process, an experimental programme was undertaken to examine in detail, the motion of the water particles near the surface using the techniques of Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV) (Pullen, 1998). In both PTV and PIV a number of tracer particles are added to the fluid. Images of the particles are then taken at short time intervals. When the seeding density of these particles is such that the average distance between particles is much greater than their displacement between images, we can obtain information about the flow at the positions of the particles; this technique is PTV (Cowen and Monismith 1997). If the seeding particle density is greater such that individual particles can be located but not tracked between images, then PIV can be used to obtaining non-intrusive quantitative velocity information using a statistical analysis (Adrian, 1991; Westerwell, 1997).

The investigation was carried out along 2 lines:

I. The investigation of the damping of wind generated waves by a thin soap film using cross-correlation digital PIV based on a novel, twin CCD camera system.

II. Quantitatively measure the effect of several films on the elliptical trajectories of surface particles beneath waves generated by a hinged paddle.

Part I has already been presented by Pullen *et al* (2001). However, the highly non-regular nature of the wind-generated waves in the wave flume used for those experiments, made it difficult to obtain repeatable results, when examining the water particle trajectories. In addition, when a film was added, the wave motion was damped completely. Therefore it was decided to use waves which were generated mechanically at frequencies similar to the dominant frequency component of the wind-generated waves, *i.e.* ≈ 3.5 Hz. The wave flume used in Part I is not capable of producing waves of such frequency, therefore a new, smaller, wave flume was constructed, providing waves which were highly repeatable. This new flume is shown in Figure 1 and was constructed using glass panels set into an aluminium frame.

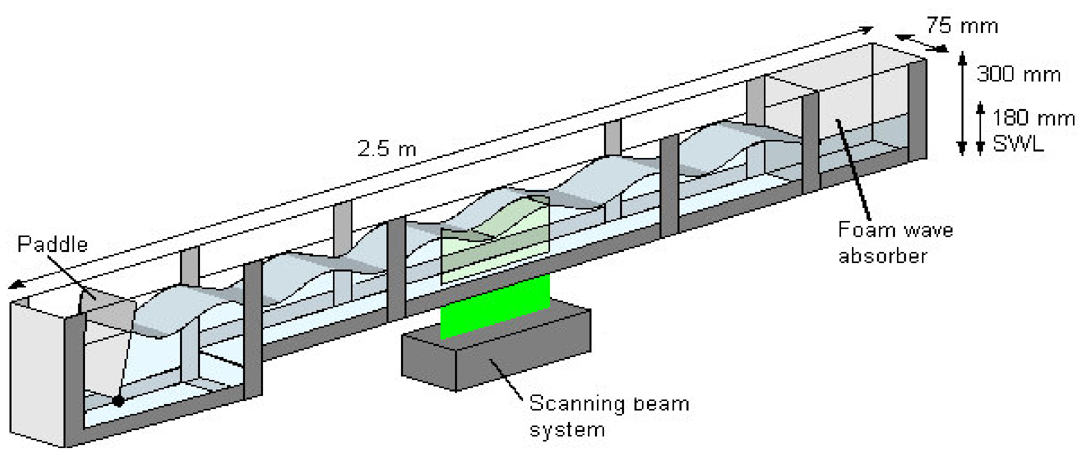


Figure 1. Schematic of the mini-flume facility.

Measurements of surface particle trajectories

Lucassen-Reynders & Lucassen (1969) predicted that the particle trajectories at the water surface would be altered from circular to elliptical orbits in the presence of a film. Additionally at the limit of an inextensible film being on the surface, only vertical motion could be present. To test these predictions, PTV experiments were carried out using the mini-flume shown in Figure 1, using a high resolution digital camera capable of "long" exposures (≈ 0.5 s) compared to conventional PIV imaging. The system enabled multiple images of each particle to be captured on single frame (great care was needed in seeding the water in the flume, since it was necessary to distinguish individual particles).

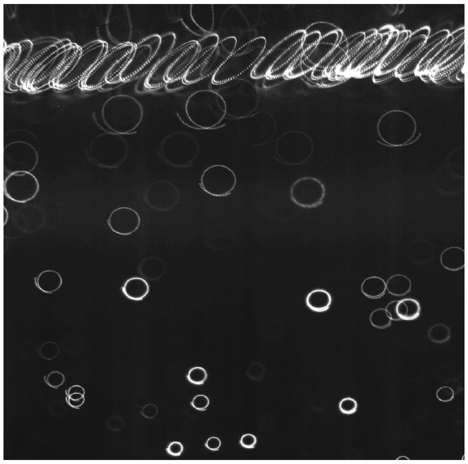


Figure 2. Surface and sub-surface particle trajectories with a film of hand soap.

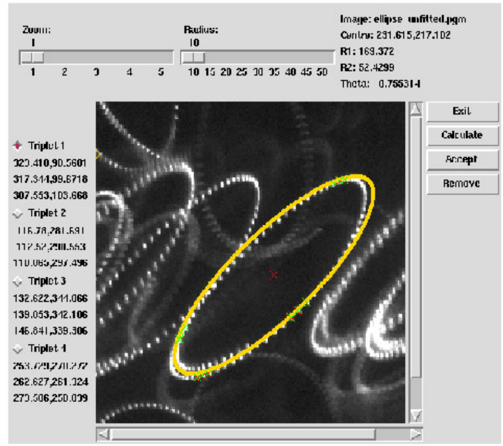
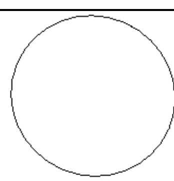


Figure 3. Screen dump of ellipse-fitting software.

The experiments were conducted with 4 different surface films formed by adding 3 different amounts of *Dymapearl Amber* hand soap or 1 drop of mineral oil (see Appendix). Figure 2 shows a sample image of the particle motion in the tank with a film of soap present. The surface particles can be seen clearly to move in elliptical paths, whereas those below the surface continue to move with circular motions.

For each of the films added, 30 images were acquired and analysed using custom-written software based on a Randomised Hough Transform, described more fully by Pullen (1998). An example image generated by the software is shown in Figure 3. The software fits ellipses to the particle tracks, enabling measurements of the major:minor axis ratio and angle of the ellipses from the vertical. The results are presented in table 1, along with the ideal case of a clean surface and schematic representations of the mean ellipse shape in each case.

Table 1. Ellipse parameters for various surface conditions. The standard deviation is given in brackets

Surface	Clean	1 drop soap	2 drops soap	3 drops soap	1 drop oil
Major/minor axis ratio	1	1.837 (0.131)	3.136 (0.336)	3.317 (0.285)	3.471 (0.454)
Angle of ellipse from vertical / radians	-	0.41 (0.08)	0.459 (0.026)	0.497 (0.059)	0.028 (0.04)
Schematic diagram of trajectory					

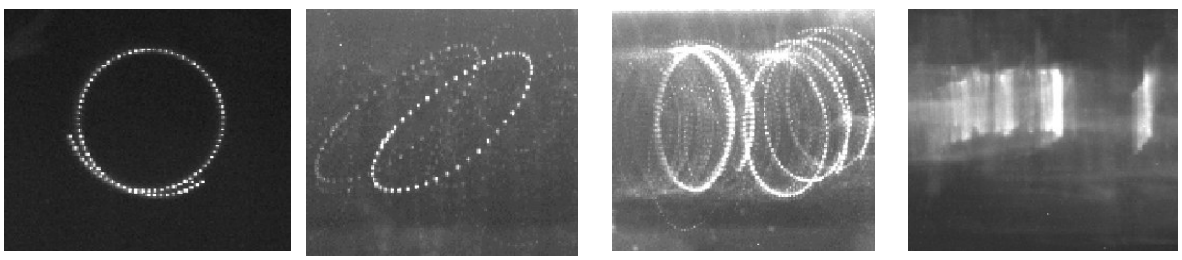
From the results, the following points can be noted:

1. The angle of the ellipse from the vertical is dependant on film type and concentration.

2. It seems that the major:minor axis ratio increases with the film concentration, although it is not possible to draw a firm conclusion due to the standard deviation in the measurements. This indicates a phase shift between the horizontal and vertical components, consistent with the theories presented earlier.
3. Although the axis ratio for the mineral oil film is similar to that for the film formed from 3 drops of soap, the ellipse angles are considerably different. It is believed that this is due to the physical chemistry of the film.

The relatively high standard deviations in the results arise from the particle trajectories not being perfect ellipses. A slight surface shear is present, which produces a variation in horizontal velocity with depth. This leads to the water particles not returning exactly to their starting position, but drifting slightly in the direction of wave propagation.

Figure 4 shows actual images of the surface particle trajectories for each case. In addition, *clingfilm* was also placed on the surface to represent an inextensible film and a sample image is shown in Figure 4d, although it was difficult to observe the motion due to reflected light from the film. In all cases, the particles were observed to be moving in a clockwise sense.



a) Clean water b) soap c) light oil d) cling film

Figure 4. Particle trajectories for clean water, soap-, oil- and *cling*-films.

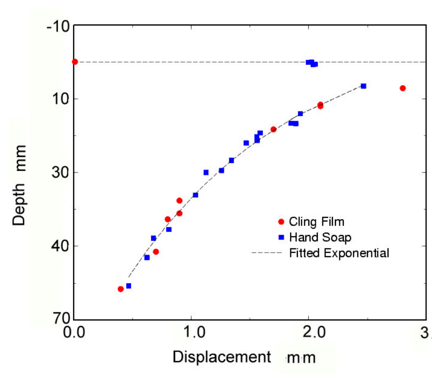
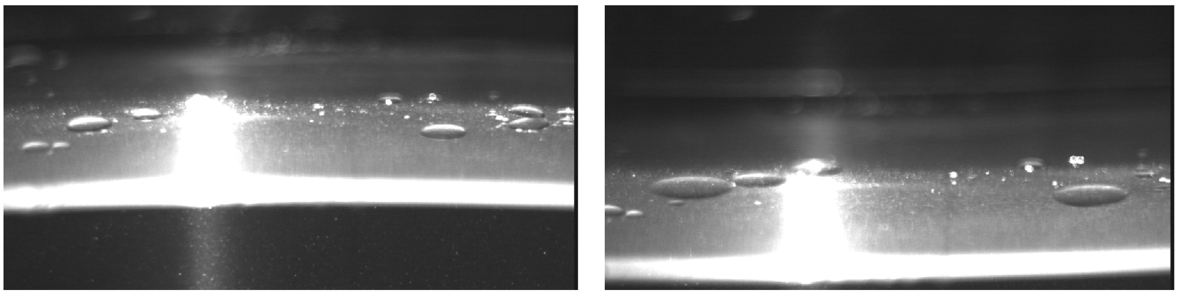


Figure 5. Maximum horizontal displacement of particles on and below films.

The ellipse fitting routine was used to calculate the maximum horizontal displacement of particles on and below both a soap film and *clingfilm*. These were used to verify the theoretical model of Dorrestein (1951) and are plotted in Figure 5, which shows that the horizontal displacement does decrease exponentially with depth.

Effect of wave motion on surface tension

Hardman (1941) and Huhnerfuss & Garrett (1977) hypothesised that the water surface is compressed and dilated by wave motion. In order to test this the camera was moved so that both the top of the water and tank side could be observed. Small drops of oil were then placed on the water surface and whilst waves were being produced, images were taken of the oil drops. Two such images are shown in Figure 6, where it can be seen that as the wave trough passes, the drop is expanded in the direction of the wave and compressed at the wave crest. From these images, it was possible to measure their size through the wave cycles and the amplitude of the waves.



a) Wave crest passing　　　　b) Wave trough passing

Figure 6. Images of oil drop on water surface

The results for one particular oil drop over a series of such images are shown in Figure 7, along with the amplitude of the waves (which has been offset so it can appear on the same graph). A sinusoid based on the frequency of the waves has been added also through both sets of points. There are 2 interesting features of this graph:

- The graph verifies the statement of Davies & Vose (1965): "in general, the surface tends to contract at a wave crest and expand at a trough".
- There appears to be a small phase shift between the 2 curves in Figure 7; the maximum oil drop diameter leading the wave trough slightly.

When oil drops are present at the surface of the water a *lens* can form (Adamson, 1990). The lens will have its own inertial properties and its own characteristic frequency. A frequency difference between the wave paddle and the characteristic frequency of the lens may explain the observed phase shift.

Conclusions

A particle tracking routine based on a Randomised Hough Transform, has been implemented to fit ellipses to the trajectories of water surface particles. Digital PTV measurements of surfactant-covered waves generated mechanically in a flume provided quantitative evidence that damping is not only confined to capillary waves. Measurements of particle trajectories verified a number of published theoretical concepts on the motion of water particles at the surface. These are believed to be the first attempt at measuring and quantifying these trajectories. These results have potentially important consequences for remote sensing of the world's oceans, where a full understanding of the motion of a film covered water surface is important.

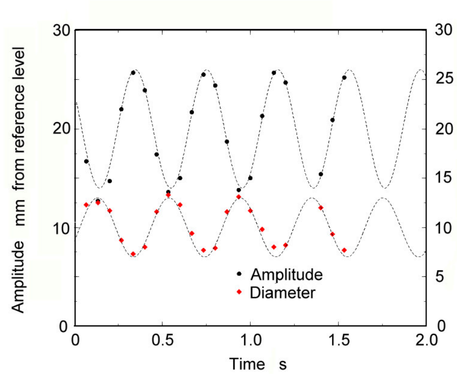


Figure 7. Change in oil drop diameter compared to wave cycle

Appendix

Dymapearl Amber hand soap is a 27% active solution of sodium lauryl (3mole) ether sulphate based on a synthetic alcohol. The average drop size was found to be 22 ± 2 μl, see Pullen (1998). The mineral oil was **3-in-1** oil (Pullen, 1998).

Acknowledgements

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References

Adamson AW, 1990.

Physical Chemistry of Surfaces, 5th edition, Wiley Interscience, New York.

Adrian RJ, 1991.

Particle-imaging techniques for experimental fluid mechanics. Annual Review of Fluid Mechanics, **23**, pp 261-304.

Comen EA & Monismith SG, 1997.

A hybrid digital particle tracking velocimetry technique. Experiments in Fluids, **22**, pp199-211.

Davies JT & Vose RW, 1965.

On the damping of capillary waves by surface films. Proceedings of the Royal Society of London, Series A, **286**, pp 218-234.

Dorrestein R, 1951.

General linearised theory of the effect of surface films on water ripples. Proceedings of the Academy of Science, Amsterdam, **54**, pp 260-272.

Hardman Y, 1941.
Surface tension of Wisconsin Lake waters. Transactions of Wisconsin Academy of Sciences, Arts and Letters, **33**, pp 395-404.

Huhnerfuss H & Alpers W, 1986.
The molecular structure of the system water/monomolecular surface film and its effect on water waves. In "Role of surfactant films on the interfacial properties of the sea surface", ONRL workshop proceedings, ed. Frank L & Williams J, US Office of Naval Research, London, UK, pp 121-157.

Huhnerfuss H & Garrett WD, 1977.
On the variability of surface tension with mean wind speed. Journal of Physical Oceanography, **7**, pp 567-571.

Lucassen-Reynders EH & Lucassen J, 1969.
Properties of capillary waves. Advances in Colloid Interface Science, **2**, pp 347-395.

Onstott R & Rufenach C, 1992.
Shipboard active and passive microwave measurement of ocean surface slicks off the Southern Californian Coast. Journal of Geophysical Research, **97(C4)**, pp 5315-5323.

Pullen J, 1998.
Particle image velocimetry applied to waves with surface active films. PhD thesis, The University of Edinburgh, Scotland.

Pullen J, Arnott AD, Buick JM & Greated CA, 2001.
Particle image velocimetry study of the effect of surface active films on capillary ~ gravity waves. To be published in proceedings of EuroMech meeting 387 "Surface slicks and remote sensing of air-sea interactions", 6-8 April 1998, Warwick, UK.

Scott JC, 1979.
Oil on troubled waters. Pub. Multi Science Publishing.

Westerweel J, 1997.
Fundamentals of digital particle image velocimetry, Measurement Science and Technology, **8**, pp 1379-1392.