Particle Image Velocimetry Study of the Effect of Surface Active Films on Capillary ~ Gravity Waves

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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, for example, 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.

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 (PIV) and Particle Tracking Velocimetry (PTV) (Pullen, 1998). The investigation was carried out in two parts:

1. 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.
2. Quantitatively measure the effect of several films on the elliptical trajectories of surface particles beneath waves generated by a hinged paddle.

This article concentrates on part 1 of the investigation, the 2nd part is described in a companion article (Pullen et al, 2001).

Construction of a wind/wave facility

Part 1 above necessitated the construction of a wind tunnel over an existing wave flume in order to measure the damping effect that surface films have on surface waves (Pullen, 1998). The flume is described fully by Skyner (1988), but briefly its dimensions are 9.75m in length $\times$ 0.4m in width, with a still water depth of 0.75 m. It is shown in figure 1, with the wind tunnel *in situ*. The wave maker, at the left end of figure 1, is a hinged-paddle, controlled by a PC. The system is equipped with feedback controls in order that it can act as an active wave absorber to remove incoming reflections. In addition, at the right hand end of the flume is a passive wave absorber.

Figure 1. Wave flume with wind tunnel in position at Edinburgh University.

The wind tunnel is of the open-ended, suckdown type, with the laboratory air providing the return circuit. The contraction ratio through the intake is 2:1, with the working section being 0.4 m wide × 0.75m high. The fan was run at maximum speed for almost all experiments, producing a maximum wind speed of approximately 5.5 ms^{-1}.

Wind/wave behaviour without any film

Before investigating the effects of the film, the "clean" wave behaviour was measured. Wave gauge and PIV measurements were taken at the locations shown in figure 2, for various wind speeds. This was done using conductive wave gauges which consisted of two metal rods with diameter 3 mm and separation 2 cm. More information on the PIV apparatus is given by Pullen (1998) and Dewhirst (1998).

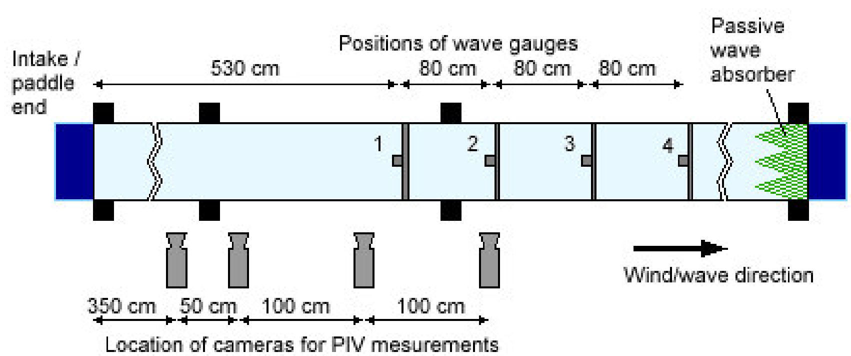

Figure 2. Plan view of wind/wave flume with locations of PIV and wave gauge apparatus.

Figures 3a & b are from PIV measurements at the positions in figure 2, with a wind speed of 5.36 ms^{-1}. As can be seen at the lowest fetch, the wind-induced wave motion is small and penetrates only a few millimetres into the bulk. At the maximum fetch, the wave motion is sufficient to induce vortices in the bulk of the water and the vertical motion is significantly greater than the background turbulence in the tank.

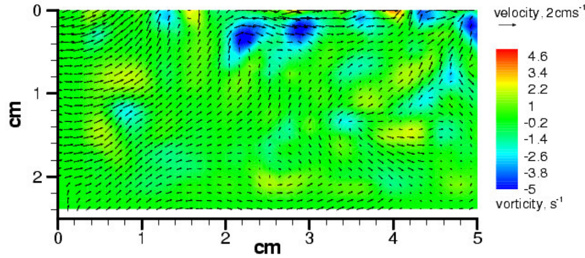

Figure 3a. Velocity vector and vorticity map at 3.5 m fetch. No film, wind speed = 5.36 ms^{-1}.

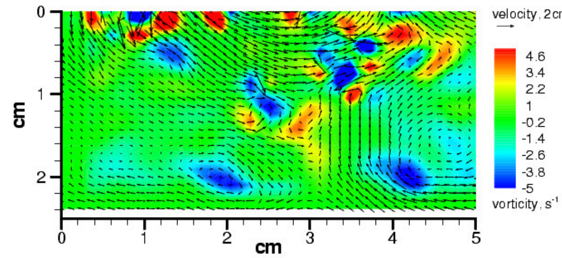

Figure 3b. Velocity vector and vorticity map at 6 m fetch. No film, wind speed = 5.36 ms^{-1}.

Tests to examine the effect of different wind speeds on the velocities in the capillary waves were also conducted. The PIV measurements were depth averaged over 20 images taken in each case and the velocity profiles plotted in figures 4a & b. The exposure time was 0.0078125 s and the seeding particles were silver coated spheres with a mean diameter of 5 μm and density 1.6 $gcm^{-1.}$

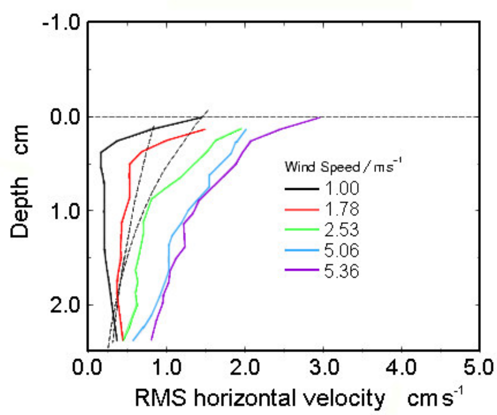

Figure 4a. RMS horizontal velocity profiles for various wind speeds at 4m fetch (no film).

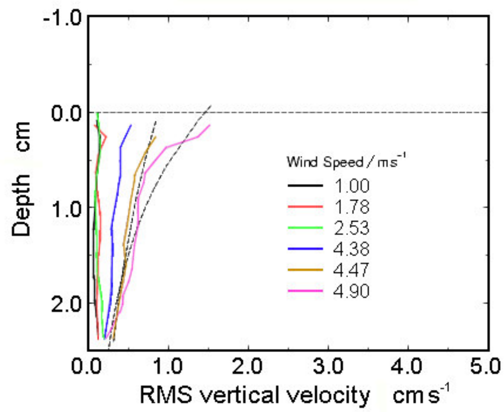

Figure 4b. RMS vertical velocity profiles for various wind speeds at 4m fetch (no film).

At very low wind speeds, there was negligible vertical motion and only surface horizontal drift was evident. As the wind speed was increased up to approximately 3ms^{-1}, the vertical motion remained negligible; the depth of the horizontal shear layer increased. Above 4ms^{-1} however, waves were observed with associated increases in the vertical velocity component. This is consistent with the notion of a critical wind velocity (Kahma & Donelan, 1988).

The time series wave gauge records were Fourier transformed to obtain the dominant frequencies in the wind waves (figure 5a). The peak frequency present in the waves was found to decrease with fetch, an expected result due to small, high frequency waves coalescing with distance downstream to produce larger waves, but of longer wavelength. Phillips (1958) suggested that the spectral components were independent of fetch at the higher frequencies. The experimental results were fitted to his experimental law in Figure 5b, where they are in good agreement over the range 14 Hz to 20 Hz.

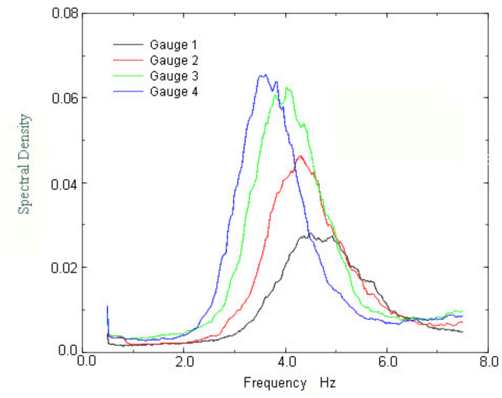

Figure 5a. Frequency spectrum - no film, wind speed = 5.36 ms^{-1}.

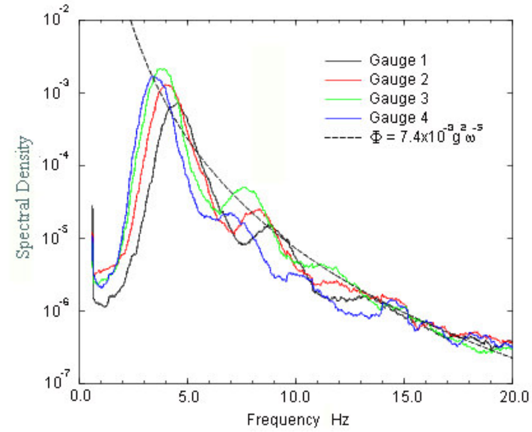

Figure 5b. Comparison of Phillips theory and experimental results, wind speed = 5.36 ms^{-1} (no film).

Damping of wind waves by hand soap

Like the "clean" surface experiments, these were performed at a wind speed of 5.36ms^{-1}, the wind waves being allowed to become fully developed before measurements being taken.

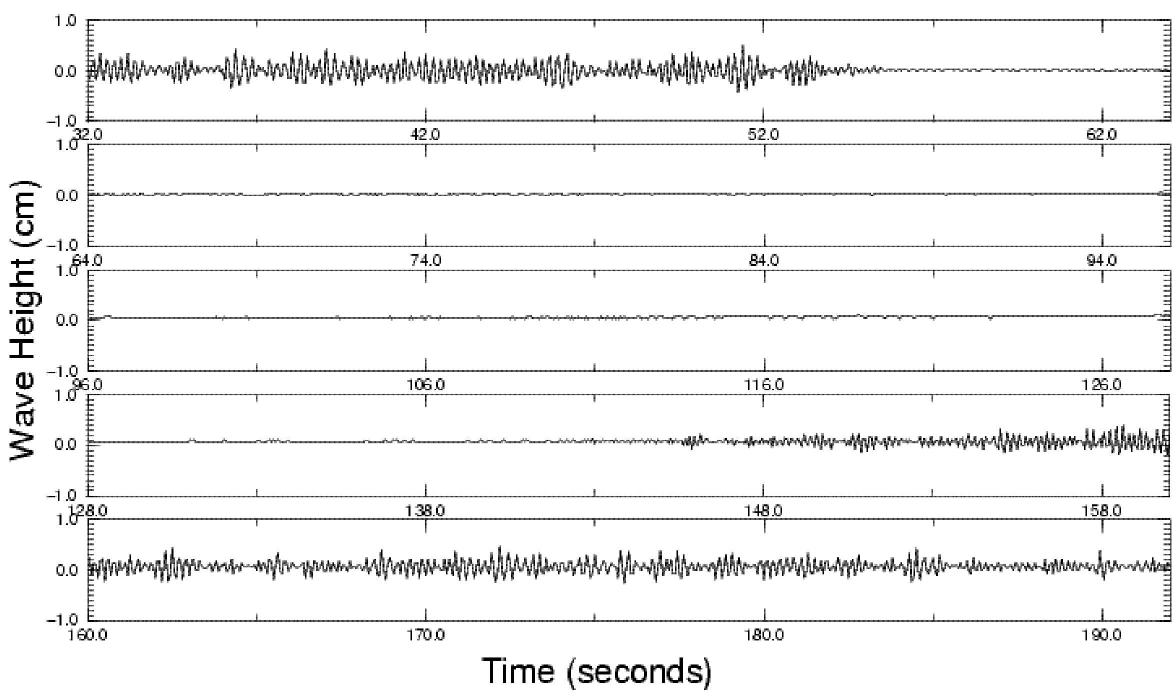

Figure 6. Record of wave height recorded by gauge 4

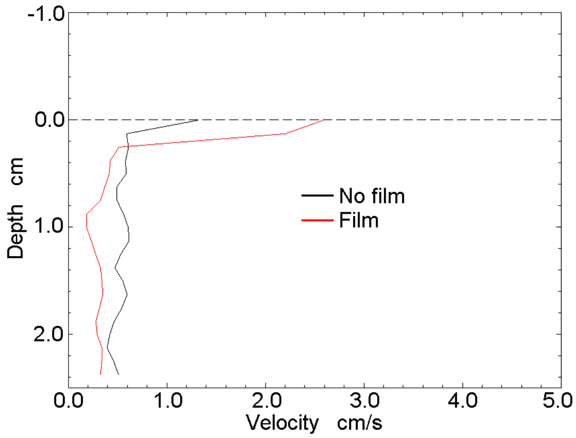

Figure 7a. RMS horizontal velocity at PIV position 1, fetch = 3.5 m.

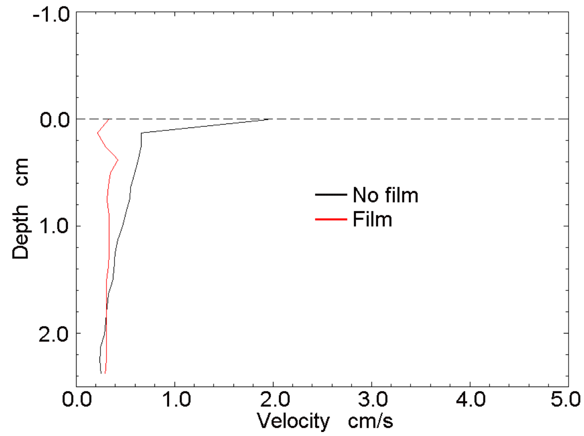

Figure 7a. RMS vertical velocity at PIV position 1, fetch = 3.5 m.

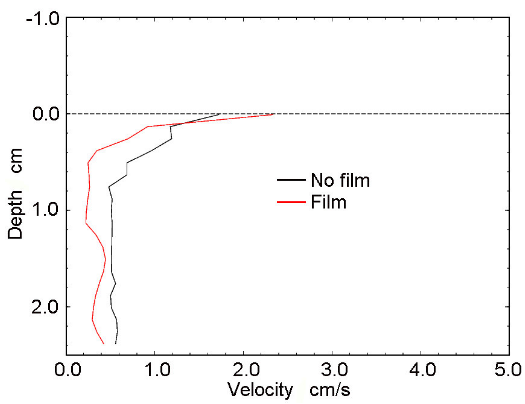

Figure 8a. RMS horizontal velocity at PIV position 2, fetch = 4 m.

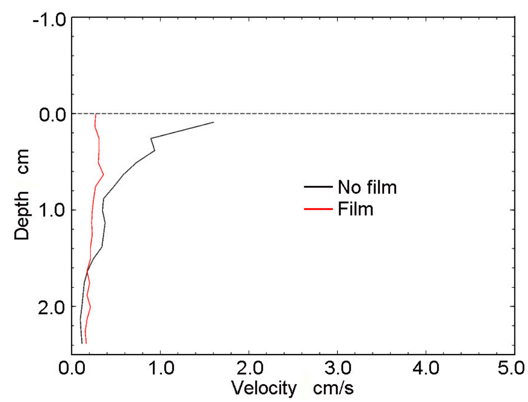

Figure 8b. RMS vertical velocity at PIV position 2, fetch = 4 m.

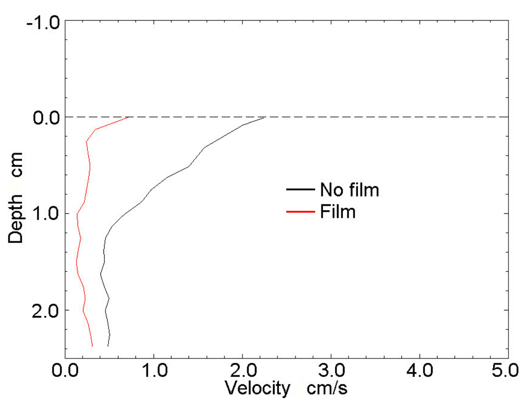

Figure 9a. RMS horizontal velocity at PIV position 4, fetch = 6 m.

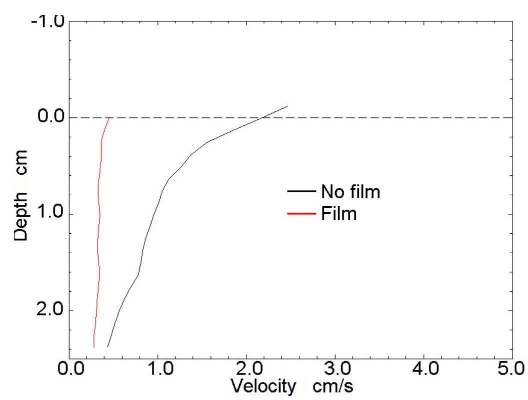

Figure 9b. RMS vertical velocity at PIV position 4, fetch = 6 m.

The film was formed from a single drop of *Dymapearl* hand soap (see Appendix) added from a syringe, 1 m downstream of the intake, 32 s after the waves were fully established. The film spread along the whole length of the flume, the waves being damped completely, although there was considerable surface drag which, after time, forced the film towards the far end of the flume and allowed the wind waves to be re-established. The hand soap is considered to be *self cleaning* since with time it will mix with the bulk fluid leaving the surface, in effect, clean. It is not thought that mixing a fraction of a millilitre of soap into over 3000 litres of water will greatly effect the bulk characteristics. Measurements verified that the wind waves return to the same state after the soap has mixed sufficiently. This is illustrated by figure 6, which shows the film passing wave gauge 4, similar records being obtained for the other 3 wave gauges.

The PIV measurements indicated that at the shortest fetch, the horizontal velocity component in the presence of the film (figure 7) was found to be higher than the no film case. This may be due to the film allowing a strong shear layer to be established due to wind drag. The vertical motion was damped to the residual background value due to small-scale turbulence in the tank.

As the fetch increased, in figures 8 & 9, the horizontal velocity profile with no film present approached the expected exponential profile. In the presence of the film, the horizontal velocity was damped at the higher values of fetch. The surface drift in figure 9a was found to be smaller than expected. This may be due to some effect of the end wall of the tank, a build up of film at the end of the tank or passive wave absorber. Again the film damped out the now significant vertical motion.

By Fourier transforming sections of the wave gauge traces (see figure 4) for all 4 gauges, it was possible to see how the frequency spectrum of the waves changed as the film spread downstream (figure 10a) and eventually dispersed due to wind drag (figure 10b). In the former figure, there is virtually no change in the value of the spectral components at the most upstream gauges as the film approached. However further downwind, the effect of the film is noticeable before it reaches the gauge. The film has damped the small, high-frequency waves upstream, preventing the formation of the larger, lower frequency waves produced by their coalescing and the dominant frequency at the downstream gauges becomes higher until the film reaches each gauge in turn.

As the film is dispersed past the gauges (figure 10b), it can be seen that the peak spectral component for each gauge can be found as soon as the back edge of the film passes the gauge. The highest peak was found at gauge 1 (*i.e.* at the shortest fetch) and the lowest at gauge 4, as would be expected. The peak spectral value reduces with time for all 4 gauges, until a quasi-steady state is reached once more, as the high frequency waves coalesce to form the longer, higher waves. We also note that the spectral peak frequency is seen to increase just before and just after the film arrives and departs.

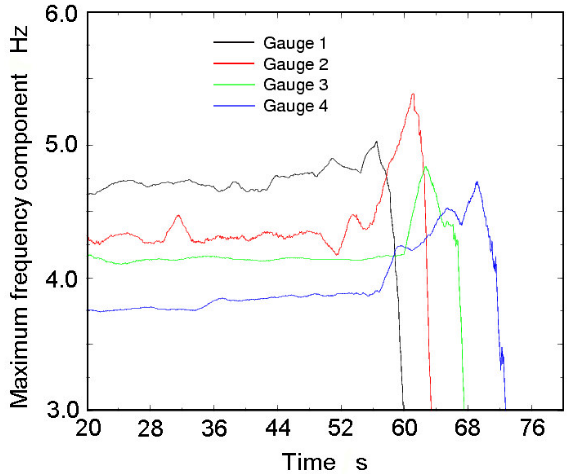

Figure 10a. Peak spectral component measured by gauges as the front of the spreading film reaches each gauge in turn. Film added at 32 s.

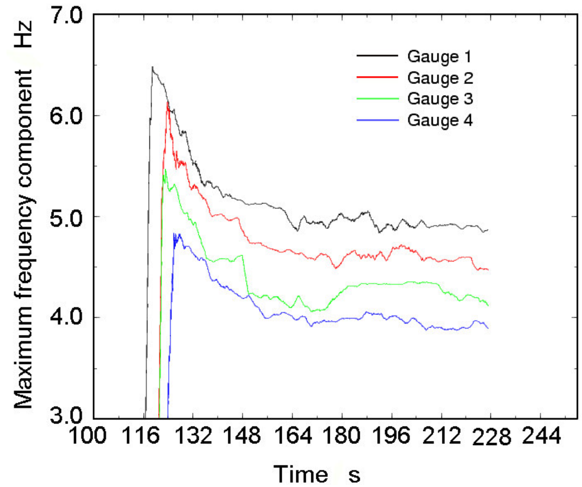

Figure 10b. Peak spectral component measured by gauges as the rear edge if the film is swept downstream.

Conclusions

- A custom-made facility for the study of surface active films on the mechanics of waves has been constructed.

- Digital Particle Image Velocimetry measurements have been carried out to establish the surface and sub-surface velocity profiles within wind waves in the absence of a film. These indicated the depth to which the wind - induced motion penetrated the bulk of the water.

- The Digital PIV system was used to acquire velocity measurements beneath a water surface contaminated with a soap film. Velocity information at various values of fetch are presented along with the alteration of the surface profile caused by the damping action of the film.

Appendix

Dymapearl Amber hand soap is a 27% active solution of sodium lauryl (3mole) ether sulphate based on a synthetic alcohol. Average drop size was found to be 22 ± 2 μl.

Acknowledgements

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