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An Improved, Free Surface, Topographic Technique

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Abstract: Current techniques of water wave visualisation such as shadowgraphy and stereophotography are widely used but are deficient in many aspects. Refraction based visualisation observes the bending of light as it traverses across a water wave -air interface. This work describes the continued development of techniques to measure the surface height of a liquid free surface. The method utilizes refraction of light at the free surface as a function of the local angle of that surface. Particle Image Velocimetry (PIV) is used to interrogate a target image viewed through the free surface.

Keywords: Visualization, Free Surface, Topography, PIV

1. Introduction

Water wave visualisation is important to a number of industries including shipping, open channel flow, and marinas. Water wave generation, interaction and evolution can have a number of implications on their design, such as the degree of vibration and erosion.

Water wave visualisation can be achieved in a number of ways. The simplest way to reconstruct a water surface is to observe a number of floats in a grid. At some point in time, a photograph is taken and the heights of each float can be manually recorded. Similar approaches that detect water height at some point include pressure, capacitance and resistance gauges (Jahne et al., 1994). These methods are intrusive to the flow/waves and are therefore of limited application.

Non-intrusive wave visualisation on a water table has primarily been limited to optical techniques including stereophotography, shadowgraphy, laser slope gauges and optical displacement sensors (Brocher and Makhsud, 1997). These methods have a number of shortcomings, including poor spatial resolution, low sensitivity and yield a lack of quantitative data.

Refractional techniques have been reported to have the highest sensitivity to small waves (Jahne et al, 1994).

Laser slope gauges measure the gradient of a water surface by observing the refractional dislocation of a collimated laser beam between a reference (flat water) and test (wavy) condition. As the wave angle and height increases, the laser beam is deflected or dislocated further. Appropriate inclusions of lenses into the system can remove the effect of water height on dislocation and yield accurate slope information (Hughes et al., 1977). Laser slope gauges are simple to create but only give ID spatial resolution (or 2D in time) and their application is consequently limited.

The emergence of Speckle Photography followed by digital speckle photography has facilitated the observation of optical inhomogeneities over entire test bodies (Fomim et al., 1999). Speckle photography uses image correlation software to quantify the shift that a laser specklegram undergoes when observed through a test section. The distortion of the image can be related to the system by pertinent physical equations.

There is little in the literature discussing the use of refraction based water wave visualisation in 3-D. Hence it is the purpose of this investigation to design, fabricate and test a system that reconstructs the topography of a water surface with reference to a distorted image. This work describes the continued development of techniques to measure the surface height of a liquid free surface. The method utilizes refraction of light at the free surface as a function of the local angle of that surface. This method utilizes Particle Image Velocimetry (PIV) interrogation of a target image viewed through the free surface.

Similar methods have been developed by at least two groups.

Zhang et al. (1994) have developed a system that utilizes different sources of coloured light illuminating the free surface from different angles. The result is that the reflected light is colour coded by surface angle. Tanaka et al. (2000) developed a system that measures the distortion of a collimated speckle pattern. This in turn was based on the laser speckle techniques from which PIV itself has developed. This is a technically superior system, but does require the use of a good quality laser and a high degree of skill to create a collimated speckle pattern. The system outlined in this paper is a variation of the system developed in Tanaka et al., leading to a simpler, more economical and more accessible system.

2. Methodology

The current system is based on the simple concept of viewing a reference image through the free surface. By imaging this reference while the free surface is still (and level) and then at later times when the surface is disturbed, we can compare the images using any PIV software. By performing ray tracing, it is then possible to establish the local free surface angle as a function of the measured local displacement of the reference image. If collimating optics are employed between the free surface and the camera, or if the ratio of the camera to surface distance and surface to reference distance is sufficiently high, the local surface angle is directly proportional to the reference distortion.

The reference object used is a ground glass plate illuminated by a nearly parallel white light source (see Figure 1). This light source is generated by ordinary light globes placed inside a long aspect ratio box lined with reflective coating. The glass plate can be replaced to suit the required field of view and camera resolution. In this way, the performance of the PIV can be maximized. This setup is very inexpensive, requires little skill to operate and yields PIV performance of high quality with absolute reproducibility.

The PIV software has been designed to track particles in a flow that are of the order 5 pixels. The image source was required to give the appearance of a fine and random array of small particles. The glass plate was coarsely grit blasted on both sides. When the glass is placed above the light box, the speckles are observable by eye and are of the order 40-100 microns. The speckled image is much finer and more uniformly distributed than a typical PIV image.

The rate at which this system can acquire free surface elevation fields is limited only by the rate at which the camera system employed can capture single frames of data. Very bright lights can be purchased quite inexpensively and, as opposed to most PIV type systems, the images are compared to a single reference image captured during setup and not to an image captured over an interrogation time scale which is small.

Once standard PIV analysis has been performed, the resultant 2D vector fields readily yield the 2D angle vectors dh/dx and dh/dy, where h is the water free surface elevation. A straight forward integration of these vectors then yields the scalar quantity h – the free surface elevation at all points. Since this set of derivatives over-specifies the scalar quantity, sophisticated integration schemes can be used to significantly reduce the signal to noise ratio.

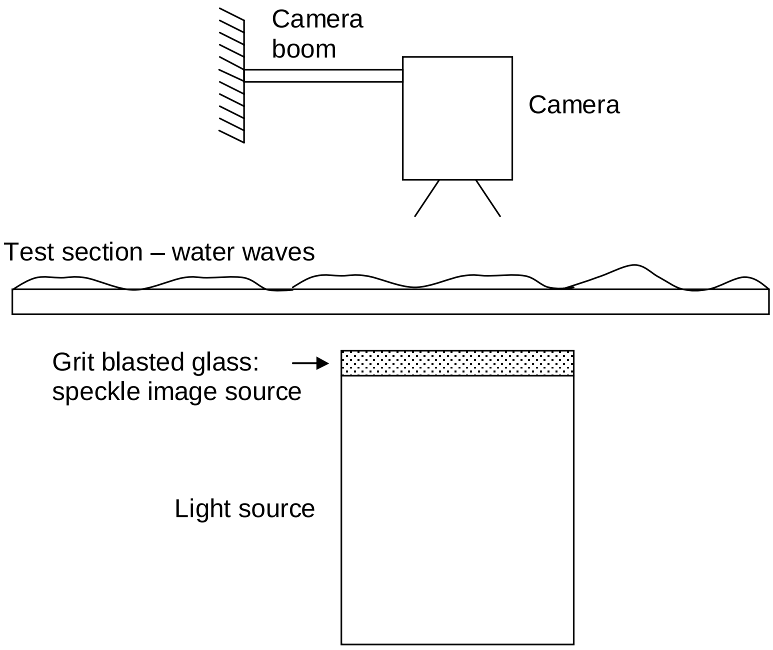

Fig. 1. Schematic of the visualisation system

2. Results and Discussion

The system has been extensively validated and calibrated against known surface wave conditions, such as the double slit and, reported here, a periodic point source. This experiment was conducted by measuring the surface waves created by applying a point source disturbance of varying frequencies. Both the spatial and temporal wave characteristics are found to be captured well.

Shadowgraphy is a traditional qualitative method for viewing wave patterns on water. A typical shadowgraphy image of radially emanating waves in a ripple tank is indicated in Figure 2. A periodic source produces a series a circular waves or expanding radii.

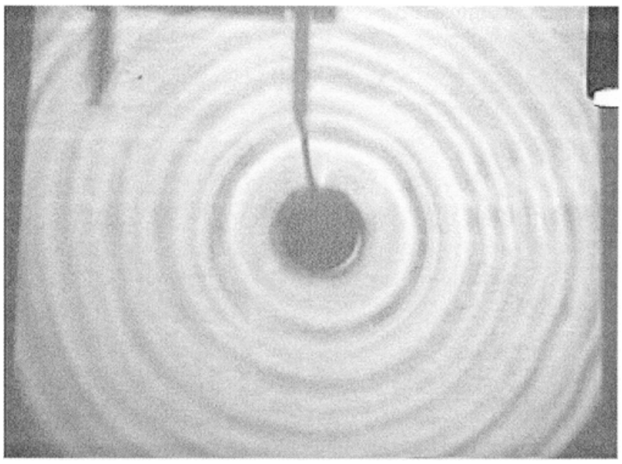

Fig. 2. Shadowgraphy visualisation of a point source emanating radially concentric waves (see Ripple Tank Demonstration at http://www.physics.umd.edu/lecdem/services/demos/demosg4/g4-02.htm).

In the present experiments, images were recorded for a point source generating waves. Figure 3 illustrates the results for a forcing frequency of 6 Hz in the form of (a) raw test image (b) dislocation vector plot, (c) computer enhanced test image, and (d) contour image. The surface region viewed was just to the right of the point source.
Waves in the raw test image (Figure 3a) are difficult to detect. There is some evidence suggesting that concentric waves exist on the left most edge of the image. The PIV vector plot (Figure 3b) shows clear evidence of dislocation emanating in concentric rings from the left of screen. When the sequence of images was scrolled through, clear evidence of wave movement to the right could be resolved. The vectors point towards the troughs and away from the crests. The computer enhanced test image (Figure 3c) highlights the presence of concentric radial rings. There is little indication of whether the rings are peaks or troughs, but the geometry of the rings is consistent with the vector plot. The contour plot (Figure 3d) highlights the troughs and crests and can provide quantitative information on the surface elevation.

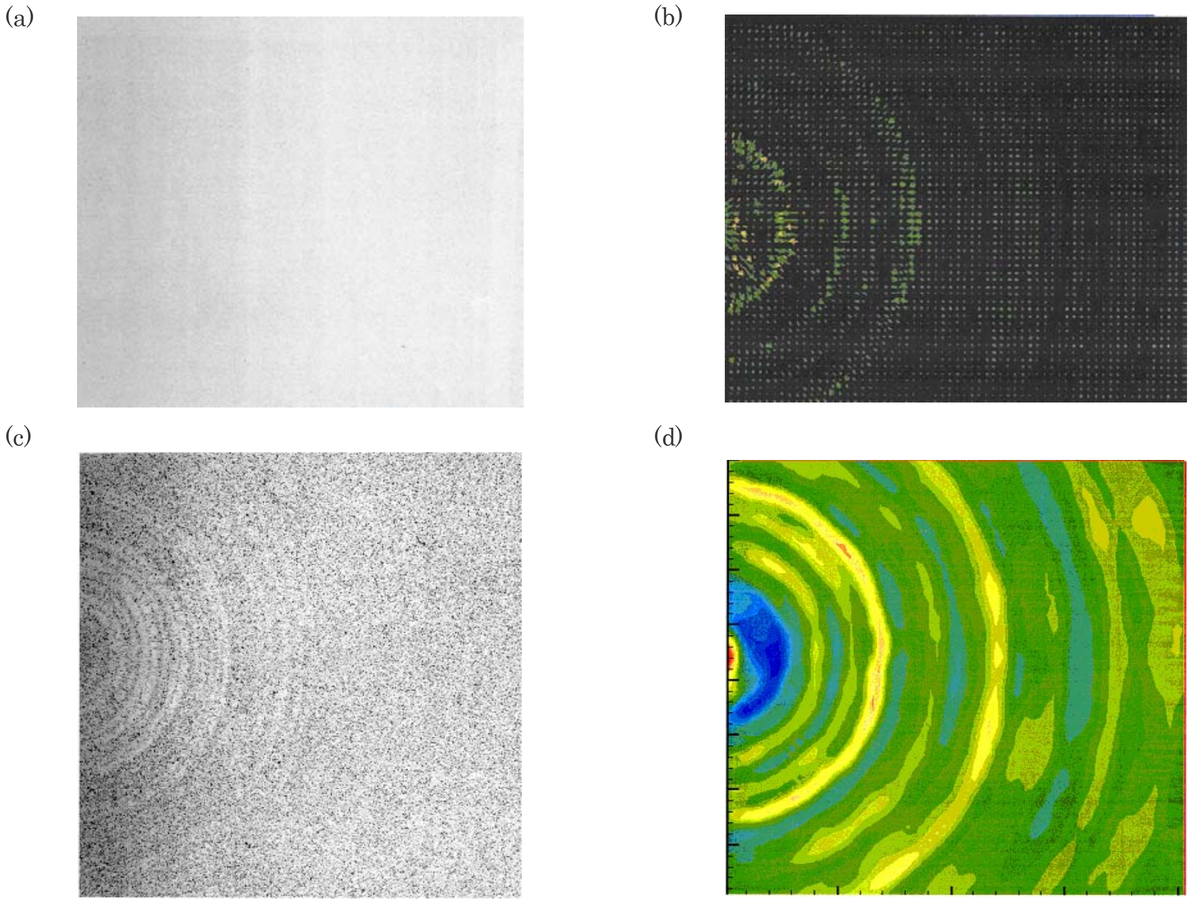

Fig. 3. Wave images for a 6Hz Point Source. (a) Raw test data. (b) PIV image correlation dislocation vector plot. (c) Computer enhanced (hot waxed) test image. (d) Contour plot.

Data obtained using the Reference Image Topography method can be also represented as a surface plot (see Figure 4). In this case the frequency of the periodic point disturbance was 4Hz. The radially spreading concentric waves are clearly seen. The degree of noise that appears to be in the results is mostly due to reflections from the walls of the apparatus and not from the measurement system.

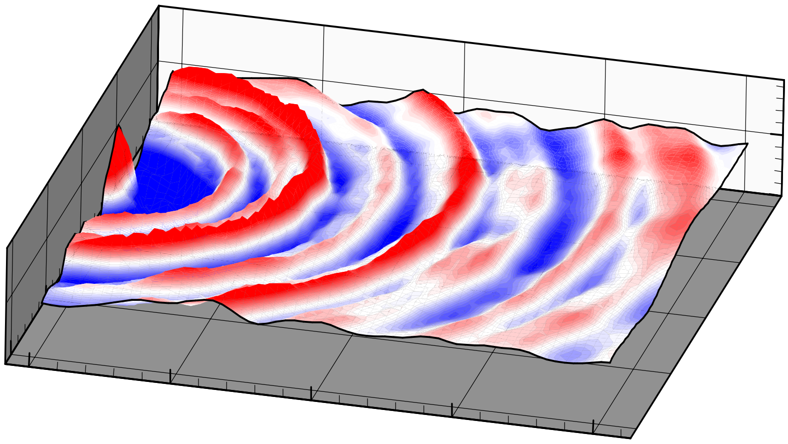

Fig 4. Surface plot of measurements of instantaneous water surface heights of waves generated by a point source (just left of image) with a frequency of 4Hz in a shallow tank (crests are denoted by red, troughs by blue).

The current system is inexpensive, requiring only standard light globes for an illumination source in the place of a laser, and can use any kind of camera for imaging. This is a relative cost saving of between 2 and 3 orders of magnitude for the light source. Furthermore, by using sandblasted glass as the reference image, not only is superior image quality possible, but repeatability is guaranteed, with quality of results being substantially de-coupled from the skill and experience of the practitioner. By the use of a least squares or similar integration scheme, the signal to noise ratio of the system is further improved.

Finally, it should be pointed out that there are fundamental differences between Speckle Photography and the current method, Reference Image Topography. In Speckle Photography, the camera must be defocused from a speckle image in order to record the shift associated with refractive index change. In laser Speckle Photography, a single beam is observed. That is, the same beam is tracked from the reference to the test situation. The test and reference images can be sharply focused and still result in image dislocation. However, the optical system of Reference Image Topography requires no defocus from the speckle source, since there are no "preferred rays". This method is unlikely to suffer from the meticulous defocusing problems associated with Speckle Photography.

3. Conclusions

The method of Reference Image Topography to investigate liquid surface distortions has been economized and improved. A number of existing technologies and theories to reconstruct a water surface have been integrated into the diagnostic system.

This optical system has been designed to capture the distortions/dislocations that emerge when water waves travel along a test section. The rig designed uses a speckled glass light box and a camera mounted below and above the test section respectively to capture the reference (still water) and test (wavy water) images.

The correlation of images has been successfully achieved using PIV software to quantify the dislocation between the reference and test speckled images. A sound physical relation approximation has been devised to relate the dislocation of an image into surface angles. A surface reconstruction program facilitates the visualisation of the water surface.

The system has yielded some visualisations of wave structures that were produced by a point source. These visualisations capture detailed quantitative fields of surface distortions. A point source visualisation when resolved in time correlates within uncertainties to the source driving frequency.

In conclusion, Reference Image Topography is potentially a very effective means for studying water waves simply and economically. Further testing on the system will be undertaken. Nevertheless, there exists a potential for the wider application of the technology in topographical characterisation involving transparent test media.

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