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An Improved, Free Surface, Topographic Technique

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Abstract : Current techniques of water wave visualization such as shadowgraphy and stereo photography are widely used but are deficient in many aspects. Refraction based visualization observes the bending of light as it traverses across a liquid-air interface. This work describes the continued development of techniques to measure the surface height of a liquid free surface. The method, Reference Image Topography, utilizes refraction of light at the free surface as a function of the local angle of that surface. Particle Image Velocimetry (PIV) software is used to evaluate apparent dislocations of the target image viewed through the free surface, which are approximately proportional to the surface angle. High-resolution images are presented of the dynamic surface topography for a point source and the shallow water flow around a vertical cylinder.

Keywords : Visualization, Free Surface, Topography, PIV.

1. Introduction

Water wave visualization is important to the shipping and off shore mining industries. 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 visualization 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 visualization on a water table has primarily been limited to optical techniques including stereo photography, 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.

Refraction 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 increase, 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 1D spatial resolution (or 2D in time) and their application is consequently limited.

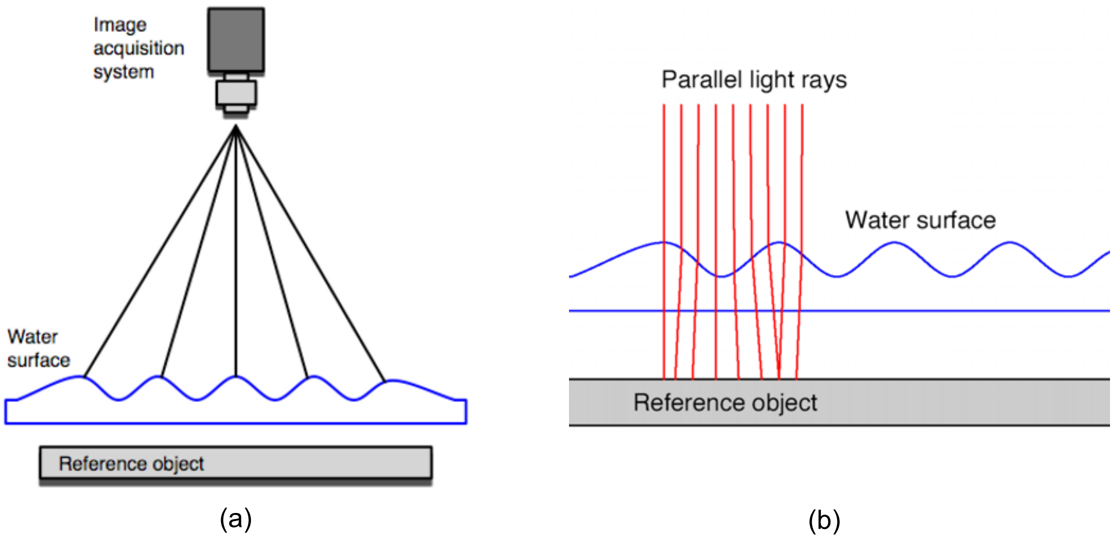


Fig. 1. (a) Schematic of system showing reference object, liquid surface, image acquisition system and general case of ray tracing. (b) Ray tracing diagram showing light rays from illuminated reference object being refracted at liquid surface. In this case imaging system is sufficiently far from liquid surface that rays traveling from liquid surface are nearly parallel.

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 visualization 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 reliability and quantity of data such a system can supply is strongly coupled to the skill of the operator. 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. In the simplest case of ray tracing, the light from the wavy surface being collected by the imaging system is parallel. To satisfy this condition, collimating optics are employed between the free surface and the camera, or the ratio of the camera to surface distance and surface to reference distance is sufficiently high and 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 Fig. 1). Ordinary light globes, placed inside a long aspect ratio box, lined with reflective coating, back illuminate the semi-translucent reference object. This reference image setup is very inexpensive, requires little skill to operate and yields PIV performance of high quality with excellent reproducibility.

PIV analysis performs best when it tracks particles in a flow that are of the order 5 pixels. The glass plate was coarsely sand blasted to give the best image quality with image grains of this order. The glass plate can be replaced to suit the required field of view and camera resolution and maintain this image grain size. In this way, the performance of the PIV can be maximized.

The pattern on the speckled reference image is more uniformly distributed and more evenly illuminated than a typical laser illuminated PIV image or laser specklegram. The authors have found standard PIV software can obtain sufficient information from laser speckle images to achieve good signal to noise ratio with interrogation window sizes of 32 pixels square. This means independent measurements are spaced 32 pixels apart. With ground glass images the data density is so much higher that a higher signal to noise ratio can be achieved with interrogation windows of 8 pixels square and an acceptable quality at 4 pixels square. This leads to a linear increase in data density of at least a factor of 4 and a total increase in the quantity of measurements of a factor of between 16 and 64.

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. Black and white cameras of moderate framing rate are relatively inexpensive. While the framing rate of a given imaging system is partly limited by the intensity of the illumination system, very bright lights can be purchased quite inexpensively. 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. This means that simpler, standard cameras can be utilized as opposed to double framing cameras, which are typically used for cross correlation PIV image acquisition. These simpler cameras are at least 3-4 times cheaper than their more complex counterparts.

The reference image (image acquired under still conditions) is compared to each image taken under wavy conditions in turn. The images will appear to have local distortions whereby relative local displacements can be measured using a standard PIV analysis of each image pair.
As mentioned above, these relative displacements between images are directly proportional to the 2D angle vectors dh/dx and dh/dy, where h is the liquid free surface elevation. The constant of proportionality can be readily achieved either by direct calibration of the system or by mathematical analysis.

A straightforward integration of these vectors then yields the scalar quantity h 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. The use of this additional information is of significant benefit and means that even relatively noisy gradient data can yield highly accurate elevation data.

3. Validation of Methodology

To validate the technique, the surface of a portion of wavy glass was measured. This offered substantial benefits, in terms of validation, over measuring wavy water surfaces because the glass can easily be measured for surface properties allowing not only quantitative comparison of the nature of the wavy features of the glass but also their height. Figure 2 shows both a photograph (a) and a shadowgraph (b) of the glass plate used.

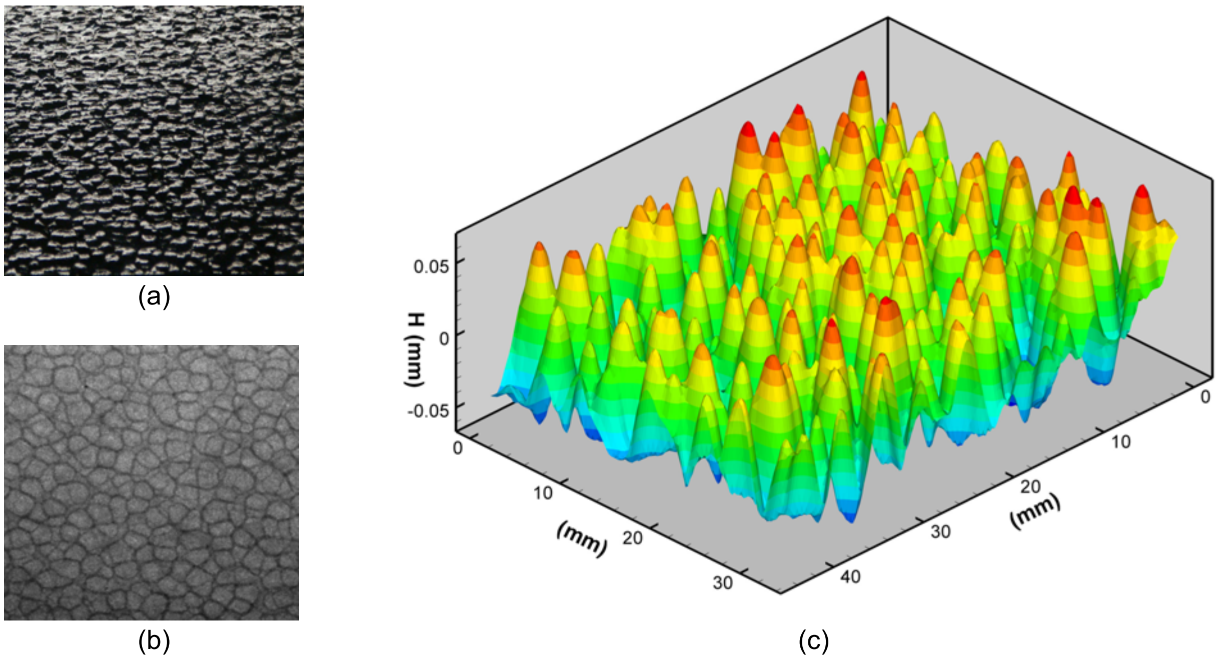


Fig. 2. Photo (a) and shadowgraph (b) of a wavy glass panel used to validate surface heights measured using the surface topographic technique. Surface plot (c) of height elevation data of same portion of wavy glass. Notice contour lines and surface elevation heights listed on H-axis (scaled by 100 to show detail).

Shown in Fig. 2(c) are the results of this calibration. The heights of wavy features in the surface of the glass were measured by passing an extremely fine pointed dial gauge along straight-line paths over the glass surface. Over the measurement area, the peak to trough displacement, was measured to be 0.005"+/-0.0002" or 0.127 mm with an uncertainty of 4%. From the free surface topographic measurements taken of the same area, a peak to trough displacement of 0.125 mm was measured. This falls well within the measurement uncertainty. The shape and spatial distribution of the surface waves on the glass were also found to match the measurements. This provides validation of the ray tracing methodology and in particular the quantitative nature of the measurement. Further validation of the technique was achieved by measurement of several predictable water wave conditions in a ripple tank and shallow water table.

4. Results and Discussion

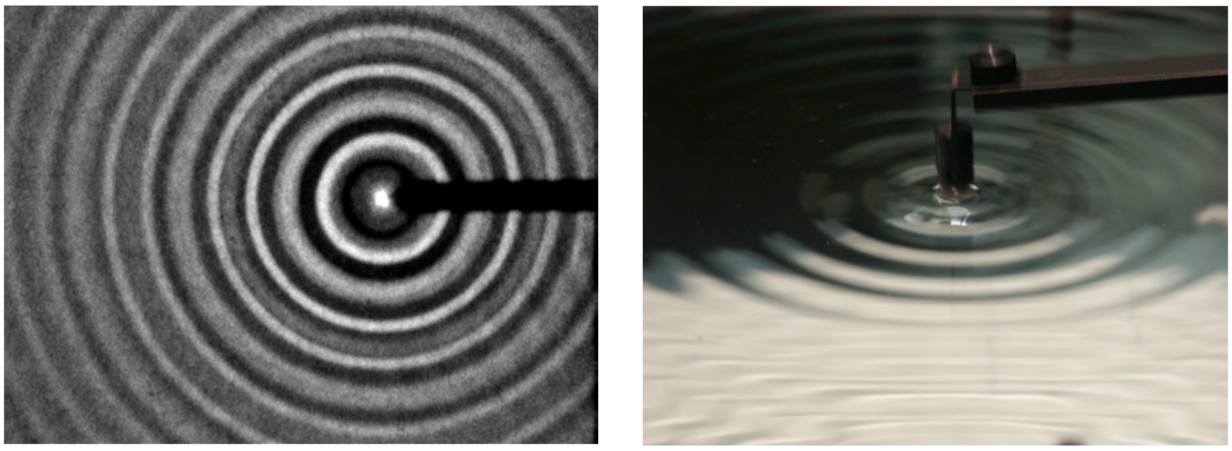
The system has been extensively validated and calibrated against many known surface wave conditions, such as the double slit, various reflecting conditions and, reported here, a periodic point source and the shallow flow around a vertical circular cylinder. The first experiment was conducted by measuring the surface waves created by applying a point source disturbance of varying frequency and amplitudes. Both the spatial and temporal wave characteristics were found to be well captured.

In the present experiments, images were recorded for a point source generating waves. Shadowgraphy is a traditional qualitative method for viewing wave patterns on water. A shadowgraph and matching photograph of the radially emanating waves in the ripple tank is indicated in Fig. 3. A periodic source produces a series of circular waves at expanding radii.

Figure 4 illustrates the results of the free surface topographic technique applied to the wavy conditions for a forcing frequency of 2 Hz in the form of (a) a PIV vector plot, (b) a rendered surface elevation plot and (c) a projection of the reconstructed heights coloured by height values.

In Fig. 4, the patterns we would expect and that can be seen from the photograph of the experimental setup in Fig. 3 are clearly visible. When the sequence of images was scrolled through, clear evidence of wave movement could be resolved. In Fig. 4(a), the surface displacement gradient vectors point towards the troughs and away from the crests. The rendered surface elevation plot shows the water surface in striking detail. As an aid to visualization the data (measured on the right hand side) have been mirrored about the plane of symmetry passing through the point source. The clarity and spatial resolution of the data is such that the interference pattern formed by the primary waves and the secondary waves caused by their reflection at the nearby wall of the apparatus (seen in Fig. 4(b)) are clearly visible.

The authors stress that the data in Fig. 4 are quantitative representing over 250,000 discrete measurements of the height of the liquid surface. The same data can be readily displayed as a contour plot to allow easier extraction of quantitative information on the surface elevation.



(a) (b)

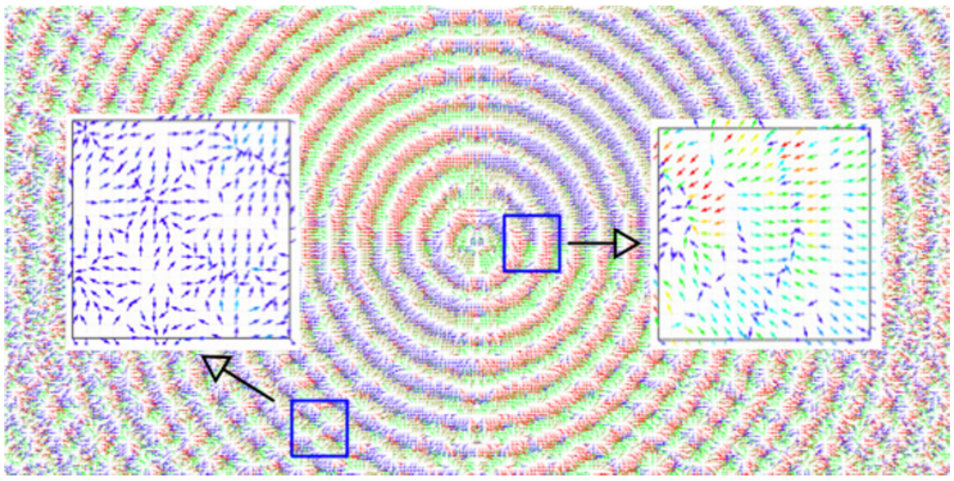
Fig. 3. Shadowgraph (a) and photograph (b) of ripple tank used to conduct experiments shown in Fig. 4. This qualitative visualization shows the familiar concentric rings formed when a liquid surface is disturbed. As the apparatus used was quite small, reflected waves can be seen at the top and more clearly at the bottom of this photograph.

Further interesting scope for the use of this technique has been highlighted by recent study by Fu and Rockwell (2005). This work has been focused on the flow around simple bodies submerged in shallow water. In this case, the flow studied was flow around a circular cylinder (diameter D) at a Reynolds number of 500 and at a depth of 0.8 D. Shown in Fig. 5 is the wake immediately behind the cylinder in this flow. Consistent with the results of Fu and Rockwell (2005), the wake pattern observed here is very nearly symmetric. This demonstrates that substantially different mechanisms control this flow than those at work in the more fully immersed or deep water case. While a study of this flow is beyond the scope of this work, it highlights the utility of this technique and is well worth further investigation in the near future.

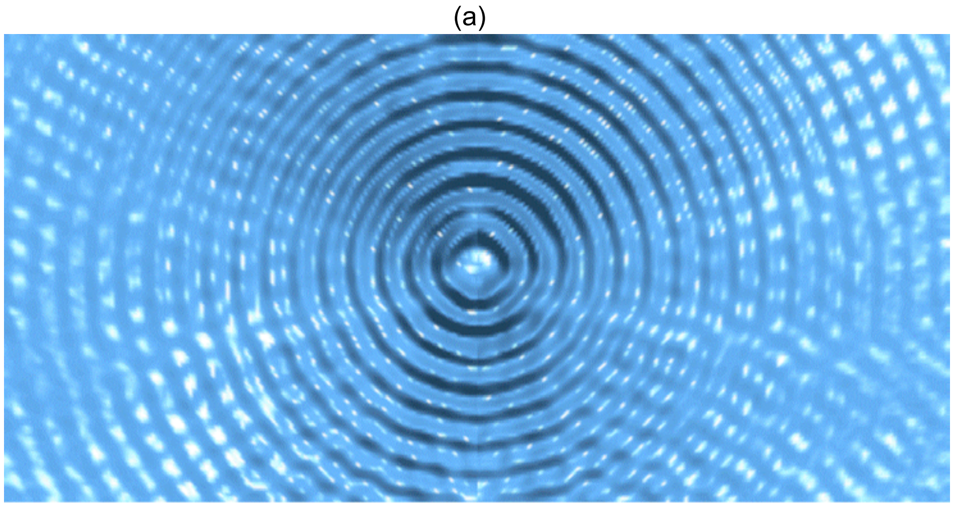
Finally, it should be pointed out that there are fundamental differences between Speckle Photography and the current method, Reference Image Topography. In Speckle Photography, the camera must be defocused from a speckle image in order to record the shift associated with refractive index change. In laser 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.

5. Conclusions

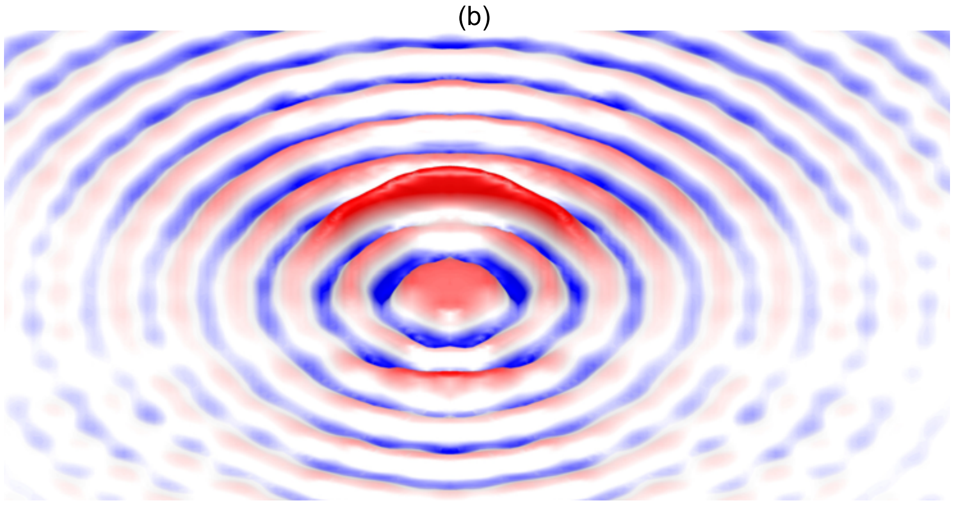
The method of Reference Image Topography to investigate liquid surface distortions has been economized and improved. A number of existing technologies and theories to reconstruct a water surface have been integrated into the diagnostic system.



(a)



(b)



(c)

Fig. 4. Mirrored surface plot of (a) vector dislocation data (vectors are drawn with fixed length and are coloured by magnitude) (b) rendered surface elevation data (c) projection of surface elevation measurements coloured by height.

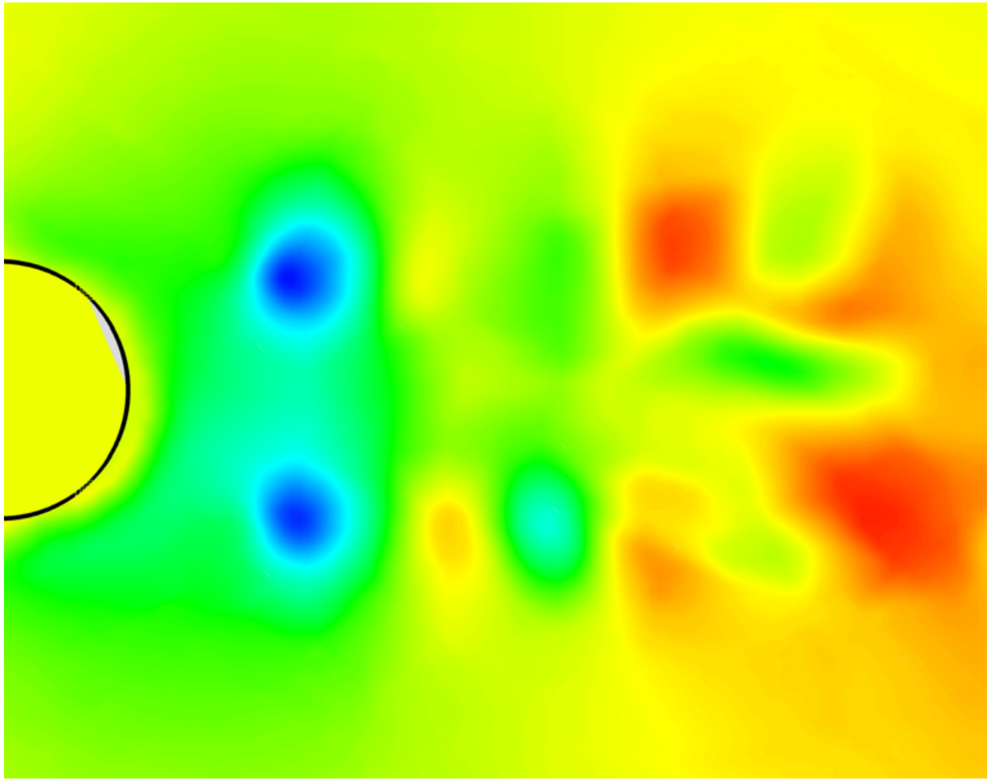


Fig. 5. Surface height measurements of the wake behind a circular cylinder at a Reynolds number of 500 and at a depth of 0.8 D. Yellow indicates neutral height, green/blue and red indicate below and above neutral respectively.

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 visualization of the water surface. This software utilizes the over specification of the integral equations to substantially improve signal to noise ratio.

The system has yielded some visualizations of wave structures that were produced by a point source. These visualizations capture detailed quantitative fields of surface distortions. While not shown here time resolved measurements of similar phenomena have been achieved. The system has also accurately resolved the detail of the surface of a piece of wavy glass, measuring the heights of those waves to within accuracy of the measurements of those heights.

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 approximately three orders of magnitude for the light source and at least a factor of three for the camera. Furthermore, by using sandblasted glass as the reference image, not only is superior image quality possible, but also 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.

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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