Measurements of velocities and accelerations in steep irregular water waves

by

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ABSTRACT

An extended PIV system is employed to measure the velocities and accelerations in steep irregular waves in a laboratory wave tank. In parts of the experiments a complementary theoretical description provides a comparison with the measurements. The theoretical model is very precise, with an error term being less than 0.5% relative to the primary wave for the conditions of the experiments. The purpose with the comparison is to test the accuracy of the wave experiments under realistic and controllable conditions in the laboratory.

The experimental acceleration field is calculated from the difference between two consecutive velocity fields. The latter are measured using directionally resolved Digital Particle Image Velocimetry (DPIV). The system uses two separate cameras viewing the same region of flow to acquire PIV images with no limitation on the time between individual velocity measurements. Both cameras record the same field of view with a small angle between their respective viewing axes. Precise alignment between the two fields is achieved using cross-correlation analysis similar to that used to extract the velocity field from image pairs acquired from individual cameras. The error introduced by the small angle between the cameras is measured and found to be small and may therefore neglected.

Good agreement is found in the case of periodic waves where the theory is applicable. The relative accuracy in the present experiments may be quantified in terms of the standard deviation due to an ensemble of measurements. We find a relative standard deviation of 0.6% for the velocity measurements and 2% for the accelerations.

In the final part of the investigation we consider the dynamics of the leading transient part of the wave train. The velocities and accelerations of the leading wave of the wave train, of appreciable height, are measured. The experiments are performed for waves up to breaking. Of particular interest are the measurements of the velocity and acceleration profiles above the mean sea level. The measured quantities are significantly larger than those predicted by existing engineering methods for irregular waves, like linear, second order and third order theories. The measured waves exhibit quite pronounced non-symmetries in the velocity and acceleration fields. Quite good accuracy is obtained in the measurements (a few percentages for the velocity field and less than ten percents for the acceleration field).

INTRODUCTION

Offshore structures like Tension-leg platforms constructed by vertical cylinders may in high sea-states experience that responses very suddenly are generated at the resonance period of the platform. Many previous studies have been focused towards this phenomenon commonly referred to as ringing. Considerable attention has been paid to model testing (see e.g. Grue et al, 1993; Chaplin et al, 1997; Huseby and Grue, 2000) and theoretical and numerical studies (see e.g. Faltinsen et al. 1995; Malenica and Molin, 1995; Newman, 1996; Ferrant, 1998), but the generation mechanism of ringing of offshore structures is not yet well understood. The focus in this paper is to look at the transient leading part of a wave train which may lead to secondary loading cycles, like the one shown in figure 1, when the wave train interacts with a vertical cylinder. The upper plot in this figure shows the surface elevation with no cylinder present in the tank, while the lower figure shows the force measured on a cylinder subject to the same input wave. In this paper focus is paid to the kinematics of the steep waves that may cause violent forces on marine structures. We aim to demonstrate that our PIV system is capable of measuring accelerations and velocities in these waves, and this can be used to investigate if features in the incoming wave field may cause the secondary loading cycle.

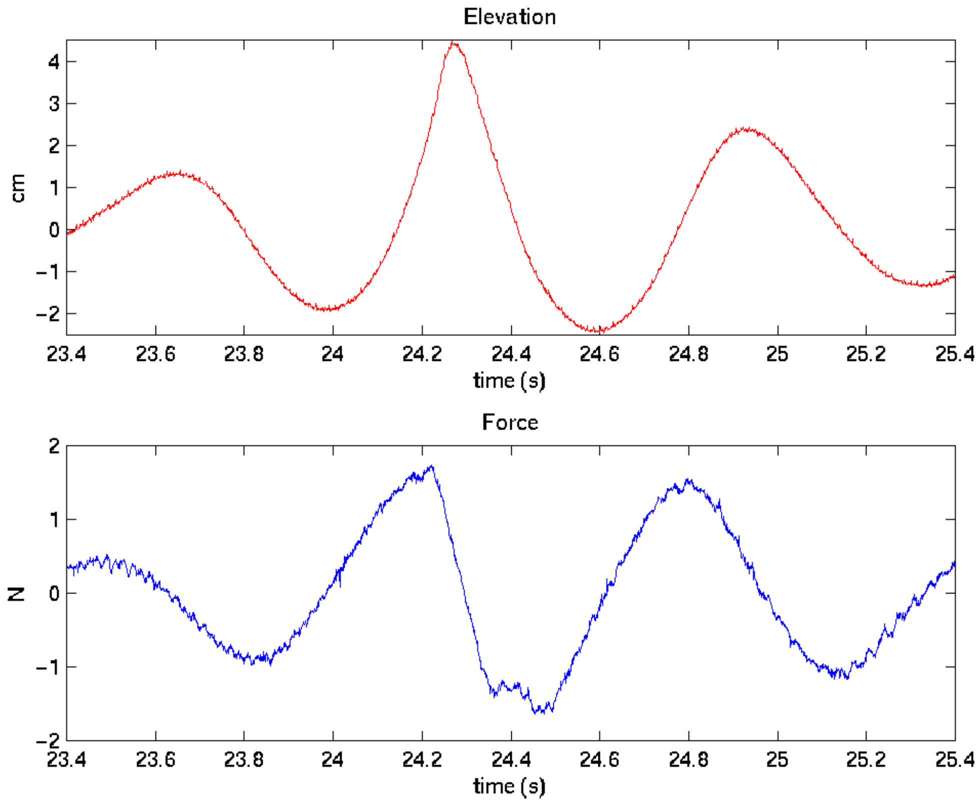

Figure 1. Upper figure shows surface elevation without cylinder present in the wave field. Lower figure shows force measurement on cylinder in the wave field

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1. EXPERIMENTS

The experiments are carried out in a channel in the Hydrodynamics Laboratory at the University of Oslo. The channel is 24.6m long, 0.5m wide and filled with water to a depth of 0.6m. In one end of the tank there is a computer controlled hydraulic piston wave maker. At the other end of the tank there is an absorbing beach, which damps the waves. Measurements of the velocity field, acceleration field and the surface elevation are performed at a distance of 12.5m from the wave maker. The measurements are terminated before any (small) reflected wave has returned to the measurement position. The wave tank and the motion of the wave maker are very precise. Complementary documentation of the accuracy of the wave tank and wave generation mechanism may be found in Huseby and Grue (2000).

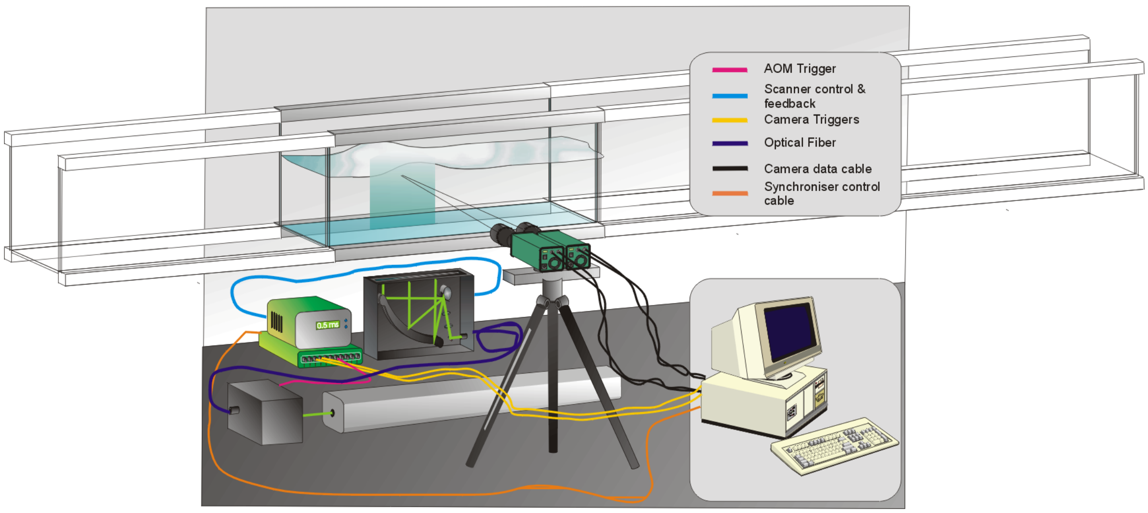

Figure 2. System overview.

1.1.1 PIV system

The PIV system employed in this investigation is designed by Optical Flow Systems, Scotland. It is based on the use of pairs of velocity measurements and hence measures the change in velocity over a known time interval, e.g.

$$\mathbf{a} = \frac{\mathbf{v}_2 - \mathbf{v}_1}{t_2 - t_1}.$$

Illumination is provided by a 10 W Argon-Ion laser. The laser beam is shut on and of by an Acousto-Optical Modulator (AOM) that controls the length of image exposures. A 2D light sheet is formed by a scanning beam box (Gray et al, 1991), which produces a very uniform light sheet with high intensity. The system uses two separate PCO Sensicam cameras that view the same region of flow. The cameras are high sensitivity CCD cameras with a resolution of 1280*1024 pixels, cooled CCD-sensors and with 12-bit digital output. Images are transferred to a PC through a high-speed digital fiber-optic cable. Synchronization is provided by an OFS TC412, which generates the camera and AOM control pulses based upon a synchronization pulse from the scanner at each scan of the flow field. Thus the scan period determines the time separation between images on each camera and also the time separation between the two velocity fields. The two cameras are aligned with the same field of view, viewing from slightly different perspectives. They are positioned side-by-side and rotated by an angle of 4.4 degrees in the horizontal plane. Precise alignment of the two fields is achieved using conventional cross correlation analysis and in general we are able to align them to within 2-3 pixels across the field of view resulting in an error on the order of 1.9%-2.6% relative to the displacement. A thorough analysis and further technical details about this measurement system can be found in Jensen et al. (1999).

1.1.2 Software

A dedicated PC is connected to both the cameras and the synchronizer, and a single software package (VidPIV3.0X-Rowan, Optical Flow Systems 1999) provides total control of both acquisition and analysis. Subsequent analysis is also performed using another PIV software (MatPIV1.4, Sveen 1999) finding excellent agreement (see for example figure 4). MatPIV is a free software-package for PIV evaluations written for use with MATLAB™ following the book by Raffel et al (1998). We employ interrogation window shifting as proposed by Westerweel et al. (1997). The images are interrogated in three steps where the two first are used to estimate the displacement (and hence the window shift) with integer accuracy. In the final step the displacement is estimated to sub-pixel accuracy using a three point gaussian peak fit. The images are interrogated using 64 by 64 pixels large interrogation windows. The final velocity fields are filtered using three different filters. The first is a Signal-to-Noise ratio filter where the Signal-to-Noise ratio is taken as the ratio of the highest peak in the correlation plane to the second highest peak. Filtering is followed with a global filter that excludes vectors based on the mean of the ensemble plus a factor times the standard deviation. Finally a local median filter is applied, followed by interpolation of outliers.

1.2. Measurements of velocity and acceleration

The wave maker generates waves using a sinusoidal motion with frequency ω, after a startup period of 1 second. The wave train has a transient leading part followed by periodic waves, and the PIV system is first applied to measurements of velocities and accelerations in the periodic part of the wave train. Existing wave theory provides a comparison for the measurements in the cases where it is valid.

1.2.1 Periodic waves

The surface elevation of the periodic waves may be described by the first harmonic wave amplitude a, the angular frequency ω, the wave number k and the wavelength λ. With a wavelength comparable to the water depth the incoming waves may be regarded as deep-water Stokes waves and the velocity potential, φ, may to a good approximation describe the fluid motion. Thus we have

$$\varphi = \frac{ag}{\omega} \exp(ky) \sin(kx - \omega t) + O(a^4),$$

where $\omega^2 = gk(1 + a^2k^2)$, g denotes the gravitational acceleration, the vertical y-axis pointing upwards with y=0 at the mean free surface. Figure 3 shows a velocity measurement taken from Jensen et al. (1999). The measurement is performed in the periodic part of the wave train with amplitude a=2.2cm and angular frequency $\omega = 8.95 s^{-1}$, giving ak = 0.16. The figure shows the magnitude of the velocity with the solid line being theory, and it exploits the fact that the magnitude of the acceleration is independent on the horizontal coordinate;

$$\alpha = \frac{\omega\,|v|}{agk} = \frac{\omega}{agk}\,[u^2 + v^2]^{1/2} = \exp(ky).$$

In that paper it was found that in the best cases the standard deviation was about 2% for the acceleration measurements and 0.6% for the velocities.

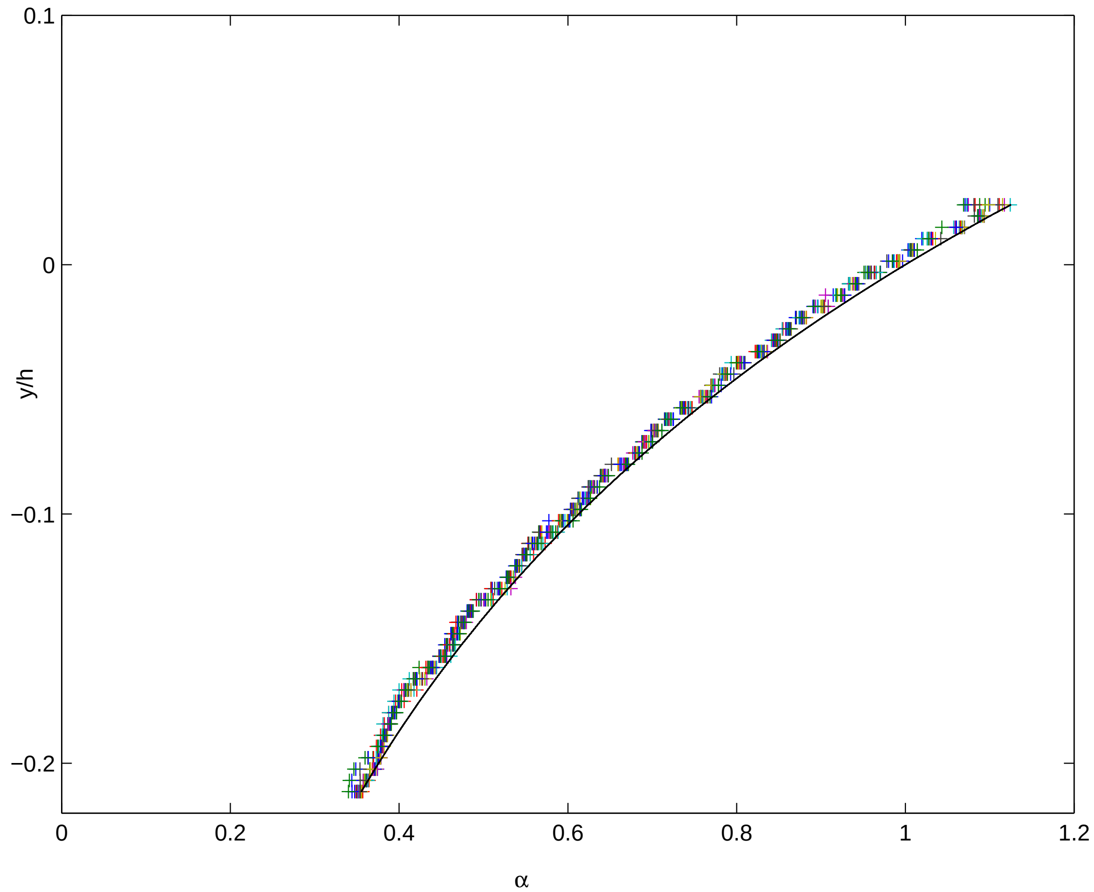

Figure 3. Measurements are taken from Jensen et al (1999). Figure shows the magnitude of the velocity (crosses) plotted against Stokes theory (solid line). α is defined in the text.

1.2.2. Transient waves

Now we turn our attention to the leading transient part of the wave train and more specifically to the tallest peak of this part (leading wave).

The image acquisition is triggered by a signal sent from the computer that controls the wave maker. The period of the scanner is set to δt_1 = 4ms and the time between velocity measurements is set to δt_2 = 12ms. In this case we also use ω=8.95s^{-1} but with the first harmonic amplitude of the periodic part of the wave train slightly larger using that ak = 0.18. Calculations with both VidPIV and MatPIV are performed. Figure 4 shows velocity at the second camera non-dimensionalised by the local ω=10.3s^{-1} times the local maximum surface elevation η_{max} = 4.47cm. The local ω is found from the trough-to-trough frequency of the local peak. We observe a very good agreement between the two different software codes. Furthermore we observe that the maximum velocity in this wave is about 15% larger than an estimate of $\omega\eta_{max}$ (with η_{max} = 4.47cm and ω = 10.3s^{-1}). Figure 5 shows the full acceleration field superimposed on one of the measurement images and figure 6 shows the horizontal and vertical components of the acceleration under the crest of the wave. The acceleration profile of the horizontal component is quite clearly contaminated by noise as this component is close to zero under the crest of the wave. The measurement of the vertical acceleration component is better and indicates that the acceleration is about 30% larger than an estimate of $\omega^2\eta_{max}$.

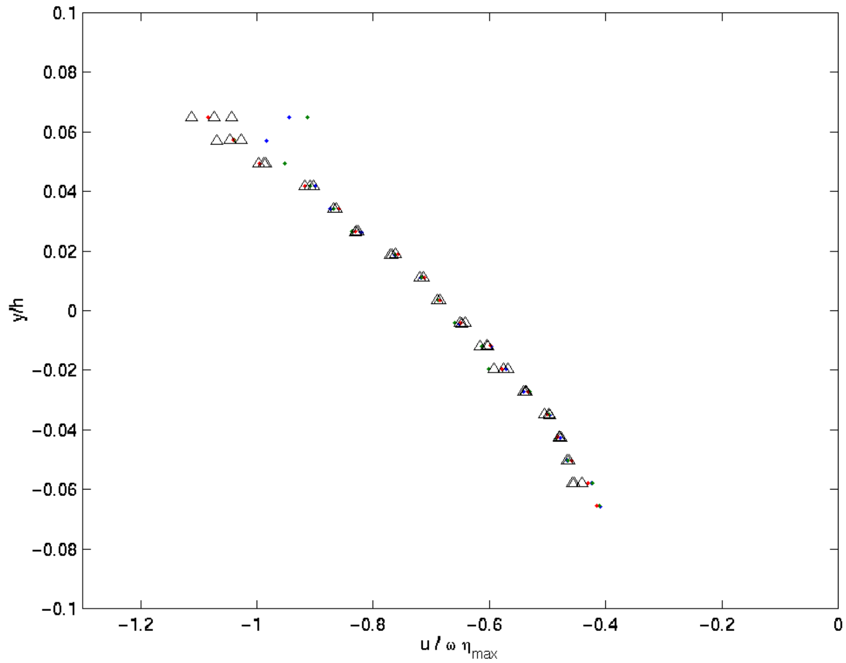

Figure 4. Horizontal velocity at the crest of the wave as measured by camera 2. Dots are measurements by MatPIV and triangles are measurements by VidPIV.

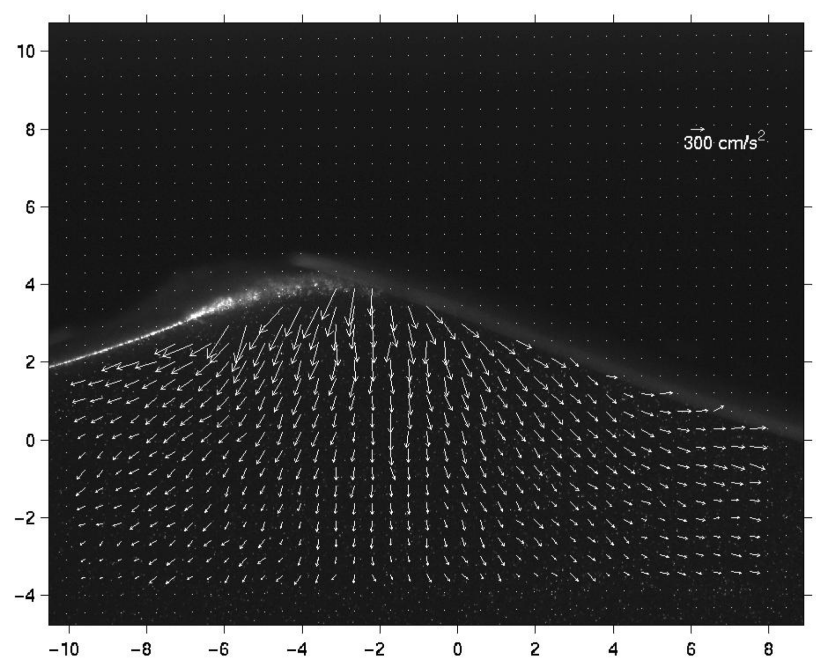

Figure 5. Acceleration field. X and Y axis is shown in cm.

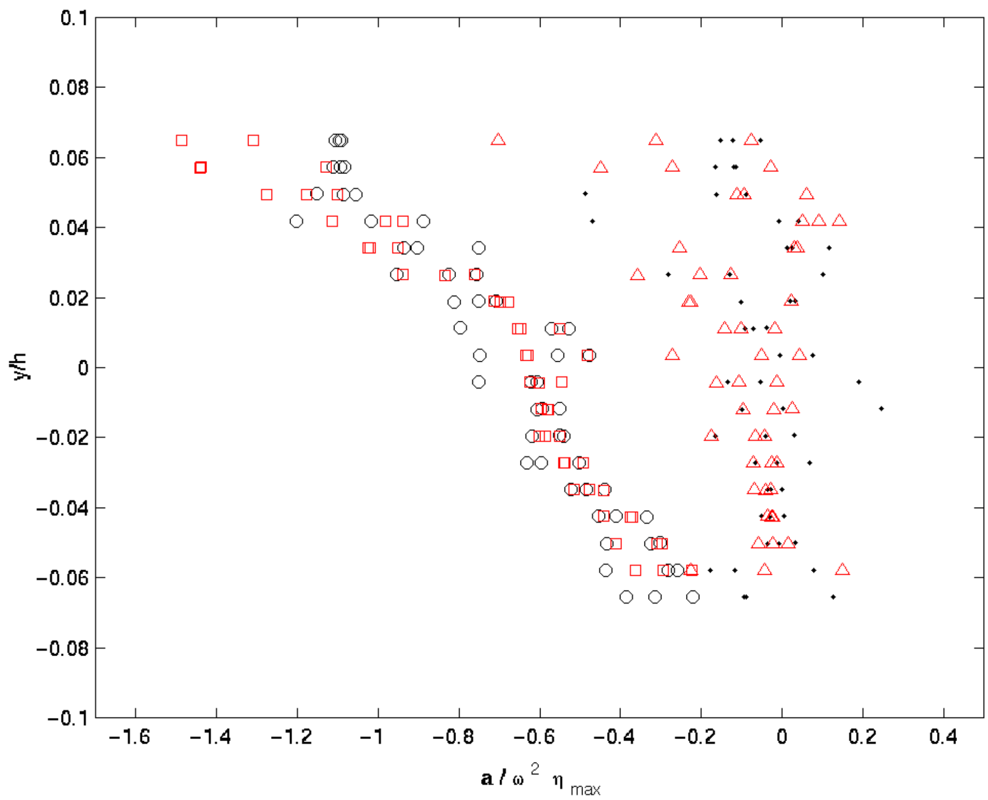

Figure 6. Red triangles and black dots denote horizontal acceleration measured by MatPIV and VidPIV respectively. Red squares and black circles denote vertical acceleration measured by MatPIV and VidPIV respectively.

2.Discussion and conclusion

An extended PIV system is employed to measure velocities and accelerations in regular and irregular surface water waves. We have performed measurements of velocity and acceleration in both the periodic part and the transient part of a wave train generated in a laboratory wave tank. Results from the periodic part of the wave train have previously been published in Jensen et al (1999).

In the periodic part of the wave train the waves are rather steep, with ak = 0.18. Furthermore we obtain quite good accuracy in the measurements, with errors being, in the best cases, on the order of a few percentages for the velocity field and less than ten percents for the acceleration field.

In the second part of this paper we consider the dynamics of the transient leading part of the wave train. The velocities and accelerations of the leading wave are measured.

The state of the art of non-linear wave modeling show that simplified theoretical and engineering models, like linear theory, wheeler stretching and second order theory have severe shortcomings. We have here outlined a measurement system that is well suited for obtaining the full velocity and acceleration fields in steep irregular water waves. The system may be used for further references and development of nonlinear wave modeling.

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