Experiments on the Ringing Response of an Elastic Cylinder in Breaking Wave Groups

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Summary

In order to gain understanding of the physical mechanism involved in the observed excitation of the structural response of large ocean structures by North Sea wind waves, experimental hydroelastic studies have been carried out in the OEL at UCSB. The experiment evolved through three separate tests beginning in October 1996, and concluding in August 1997. Since this work was begun very similar experiments with results overlapping those found here have been conducted in the UK by Chaplin et al. [1].

A thin-walled vertical cylinder pivoted at the tank bottom and held by an adjustable vertical tension wire was subjected to loadings by both non-breaking Stokes waves and by waves breaking in modulated wave groups, with a wave length of 2.3 m. Both downtank displacement and acceleration were measured in time. Two frequencies, the rigid body and first bending, were excited in the ringing style by the breaking waves, but not observably by the monochromatic waves. The free surface around the cylinder was visualized by a high-speed (250 Hz) video camera and a vertical jet is often seen to be produced at the front face during impact of the deformed-breaking waves. Tests were conducted over a large range of variables, and only a small sample is given here. The system parameters were deduced from free ringing experiments, and the loading was subsequently deduced from the measured responses. A strong correlation was found between the rigid body loading and the local wave slope at the cylinder. The onset of the high frequency response, however, was correlated with breaking jet impact on the cylinder. The rigid body response at frequencies in excess of the wave frequency decreased with increase in the former, and the response amplitudes depended on the phase between jet initiation and impact of the wave on the cylinder. In general, the highest loads were obtained when the plunging jet impacted the cylinder. Accelerations as large as 0.25g were measured.

The Experiments

Experimental techniques continuously evolved through a series of three different tests beginning in 1996. The present experiments were carried out during August 1997 in the large OEL wind-wave tank [150' L, 14' W, 8' D] using seeded side-bands [2,4], to generate groups of 2.3m waves, with initial steepness, ak_0 between 0.12 and 0.28. Periodic deformation and breaking at the wave group frequency occurred in the test section in the vicinity of a thin walled circular cylinder, elastically restrained with freedom of rotation about its bottom mounting, see fig.1. Rigid body motion and bending deformation of the elastic cylinder are measured using accelerometer and displacement probes. Wave wires are disposed on the front and back faces of the cylinder as well as in the far field. Two video cameras, 30 and 250 Hz, provide views of the deforming wave surface as it impacts the cylinder; this allows temporal correlation of the response and the wave shape. The rigid body natural frequency normalized by the wave frequency could be adjusted through the upper tension wire mounting, in the range 1.5 – 5.5; and high bending flexural frequency, 20, was also typically observed during deforming breaking wave impact.

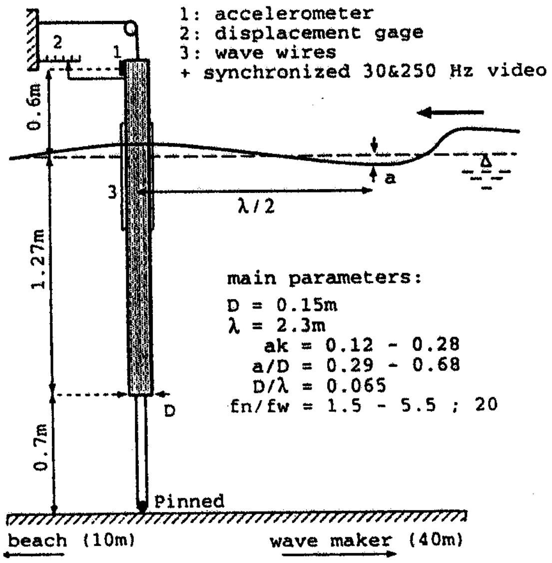

Figure 1: Experimental set-up.

Monochromatic Response vs. Wave Groups

In tank tests with irregular waves, it has previously been reported, [3], that a correlation exists between ringing responses and impact by deformed breaking waves in wave groups. On the other hand, several studies have attempted to find the source of ringing response solely within the high frequency structure of Stokes waves. It was the chief purpose of these tests to compare monochromatic and wave group response in

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order to clarify the physical cause of ringing, and the set-up described above is well able to do this. The loading is well in the inertial range (wave amplitude / cylinder diameter < 0.70 here), and the response in Stokes waves was found be highly periodic and linear in the peak values up to the highest steepnesses tested, ak_0=0.28. Despite this linearity, the effect of harmonics on the temporal response is evident, see Figure 2a. For all rigid body frequencies tested, there was no clear evidence of "ringing" type behavior during the Stokes wave loading, i.e. suddenly large response decaying in time, until the next excitation. On the other hand, ringing responses were highly noticeable during loading in breaking wave groups, the excitation clearly originating during impact by the deformed or breaking wave, see fig. 3, but not in the other, smaller waves in the group. The period of ringing response is thus the period of the wave group, in this case six times the wave period. The temporal response for a discrete ringing event is shown in fig.2b, where the height of the breaking wave just before 105s was chosen identical to the height of the Stokes wave with which it is compared, fig. 2a. The peak displacement is about twice those in the Stokes waves and the peak accelerations over 5 times as great. These factors would be even larger had the comparison been made with a wave group of the same time-averaged energy density as for the Stokes wave. Notice, too, the excitation of high frequency bending mode accelerations by the breaking wave.

Ringing Responses

As might be anticipated, the observed level of the response increases as the normalized pitching resonant frequency reduces toward unity, fig.3. It is also observed that the level of response depends on the phase between the deforming-breaking wave and the front face of the cylinder. We utilize the following brief classification of wave regimes, see fig.5 and 6, based on a more precise description [4]:

- Steepening - Cresting (CR, ECR). The wave is deforming assymmetrically, its crest rising, front face steepening, and crest sharpening, as shown in fig.5. The nomenclature (CR) means that this process is culminating in the immediate vicinity of the front face of the cylinder; (ECR) means that the process has not yet culminated there, but will before the crest reach the rear face of the cylinder.
- Plunging Jet (JT). A jet has formed at the crest of the deformed wave and is moving forward and downward, see fig.6, while impacting the front face of the cylinder.
- Splashing - Ploughing (SP)._ The plunging jet has splashed into the front face of the wave, throwing water upwards as it ploughs forward and strikes the cylinder.

As shown in fig.3, waves impacting during the plunging jet phase (JT) usually produce the highest response, for all natural frequencies; during the evolution of the breaking wave, the free surface becomes vertical in this regime.

Wave Loads

Data from an example of a jetting breaker impacting the cylinder are presented in fig. 4a-c, showing, respectively, the displacement, acceleration, and wave induced moment. The latter, fig. 4c, has been deduced from the response data using a linear response equation of the mass-spring type; the added mass, damping, and restraint stiffness were determined from free oscillation tests in water, at the structural resonant frequency. The wave elevation measured at the front (#1) and the back (#2) of the cylinder are also shown in fig. 4d; their difference, which is proportional to the local wave slope at the cylinder is denoted by #3 in the same figure.

It is remarkable to note that the variation of the hydrodynamic moment on the cylinder, fig. 4c, is highly correlated with the local wave slope there, as measured by the cylinder mounted wave wires. This is simply seen by comparing the time at which both the peak hydrodynamic moment and its zero are reached, with the same times for the wave height difference. Perhaps this new experimental correlation can be used in the development of a useful engineering theory for the prediction of ringing loads in this frequency range. Incidentally, the same correlation between transverse loading and wave slope is predicted by Morison's formula when applied to cylinder wave loadings in waves of small steepness.

The excitation of the high frequency bending mode is indicated by the vertical arrows in fig. 4b-c, and this seems closely to coincide with a very rapid change in the slope of the longitudinal displacement of the system, i.e. to a "discontinuity" in the velocity. The equations of motion show that this requires the application of an impulse in momentum applied to the cylinder. The timing of this event indicates that the source of this impulse was the impact of the jet itself on the cylinder surface.

References

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3- Davies, K.B., Leverette S.J., Spillane M.W., Ringing Response of TLP and GBS platforms, BOSS'94, Boston- Ma, 1994.

4- Tulin M.P.& Waseda T., Laboratory Observations of Wave Group Evolution Including Breaking Effects, 1997, submitted to JFM.

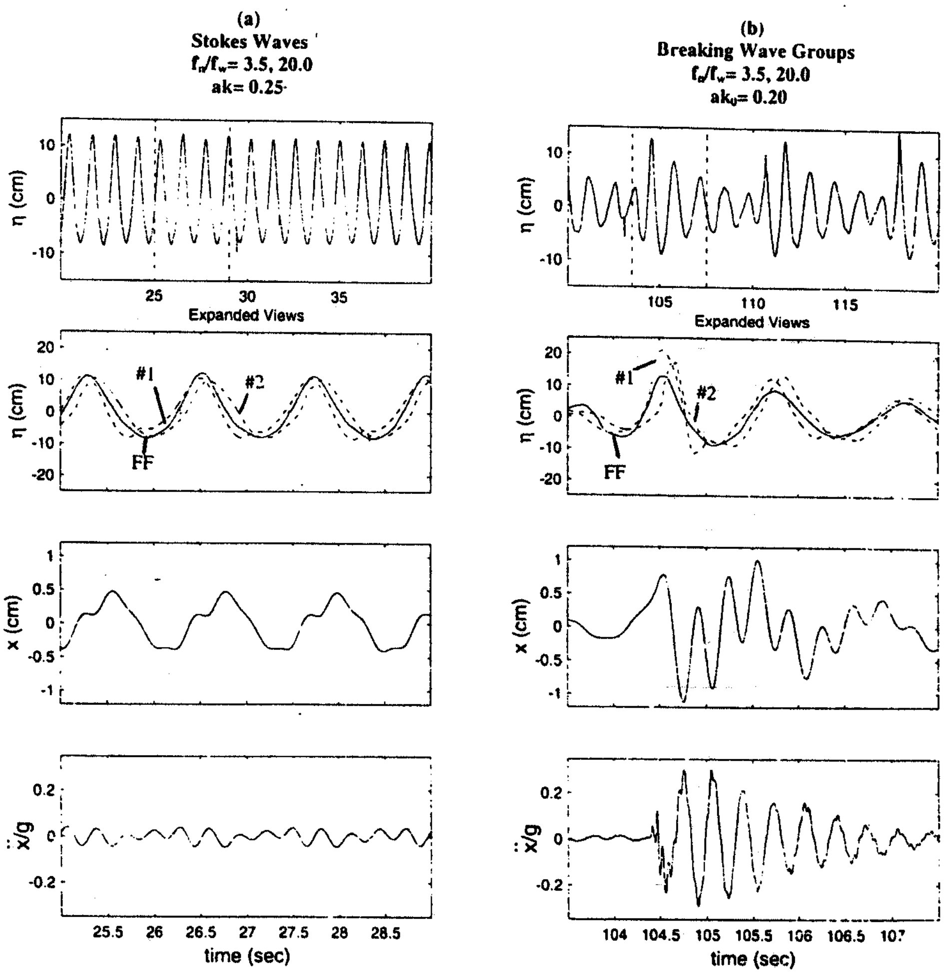

Figure 2: Displacement (x) and Acceleration (ẍ) Responses Due to Stokes Waves (a) and Breaking Wave Groups (b). η, free surface elevation; #1 cylinder front; #2 cylinder rear; FF far field.

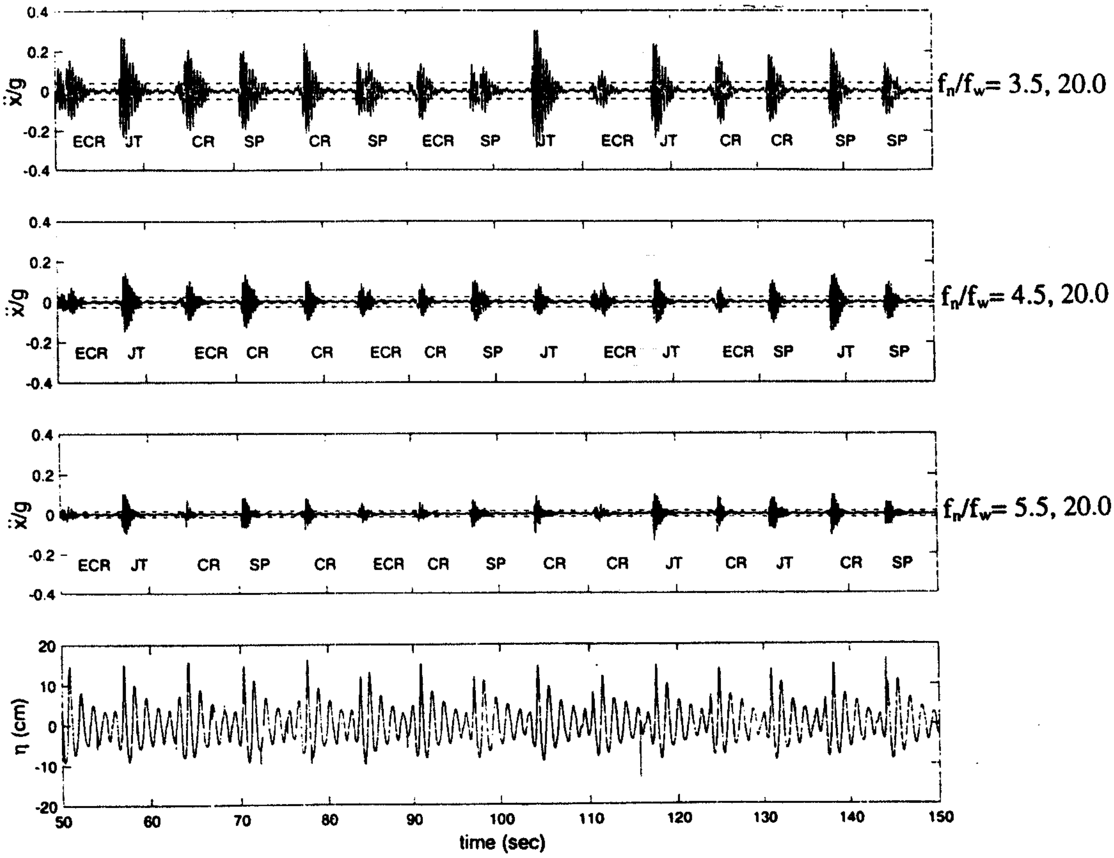

Figure 3: Acceleration Records Showing Ringing Responses Due to Breaking Wave Groups.

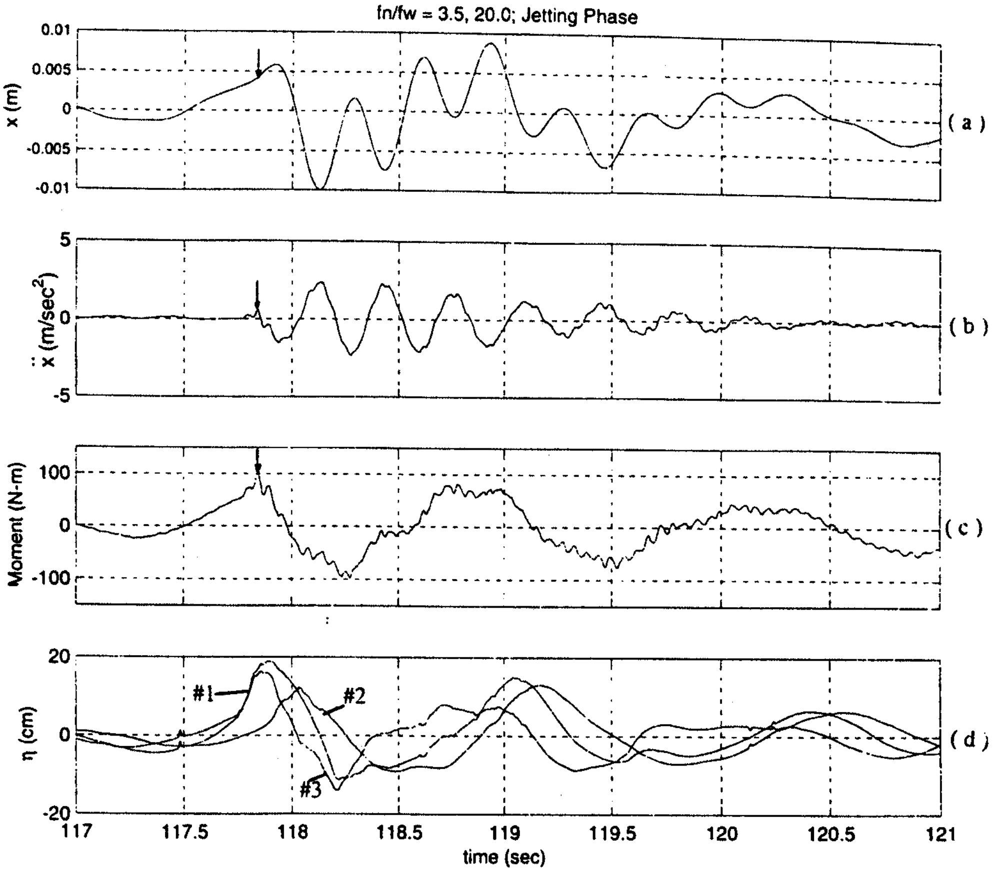

Figure 4: Moment (c) Based on Measured Displacement, x, (a) and Acceleration, $\ddot{x}$, (b) . Free Surface Elevation, η, (d) as Measured on the Cylinder Front Face (#1), Cylinder Back Face (#2) and their Difference (#3).

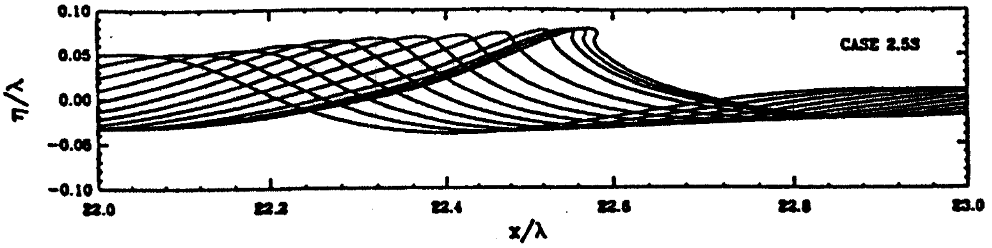

Figure 5: The Deformation of a Breaking Wave, Beginning at far Left. Front Face Steepens. Crest is a Maximum Near Jet Origination. Trough Continually Rises. LONGTANK Simulation (from [2]).

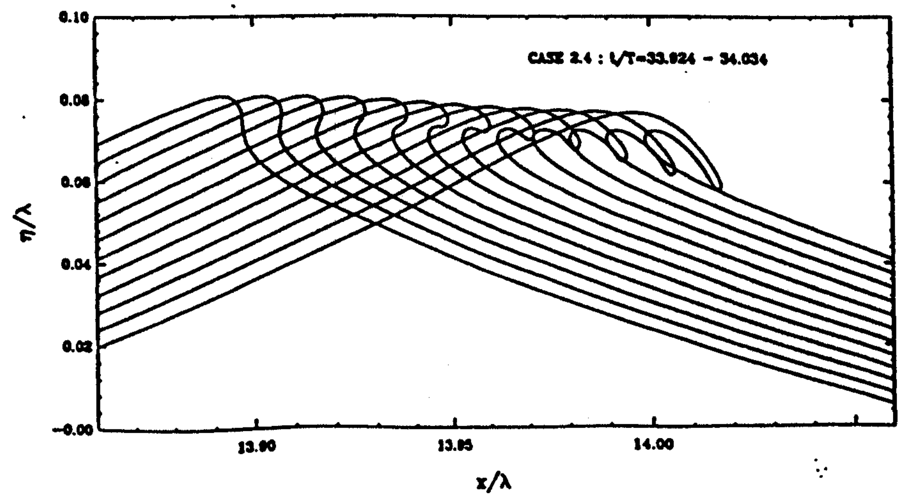

Figure 6: The Evolution of the Jet in Time. In Final Stages, Particles are in Ballistic Trajectory. LONGTANK Simulation (from [2]).