VIOLENT WAVE INTERACTIONS WITH A VERTICAL CYLINDER - APPLICATIONS TO OFFSHORE WIND TURBINE FOUNDATIONS AND "RINGING" RE-VISITED

Jun Zang (1), Paul H Taylor(2), Gerald CJ Morgan(1), Jana Orszaghova(2), James Grice(2), Manases Tello(3) & Robert Stringer(1)

(1) Dept. of Arch. and Civil Engineering, Univ. of Bath, UK, E-mail: j.zang@bath.ac.uk
(2) Dept. of Engineering Science, Univ. of Oxford, UK, E-mail: paul.taylor@eng.ox.ac.uk
(3) Instituto Superior Técnico, PORTUGAL, E-mail: manases.tello@mar.ist.utl.pt

In these experiments we report on the interaction of steep waves, both non-breaking and breaking, hitting a bottom-founded vertical circular cylinder. Both the scattered wave surface elevations around the column and the total horizontal forces were measured. In contrast to most previous experiments we concentrate on hitting the column with localised wave groups not on regular or random waves. By repeating the tests with both focussed wave groups and the same wave groups inverted, so each tall crest in one is replaced by a deep trough in the inverted form, we are able to identify unambiguously the complete Stokes expansion type representation of the applied force: linear, second order two-frequency sum and difference, 3rd order triple-frequency sum etc. The cumulative effect of this relatively small but significant high frequency excitation is to produce dynamic response or 'ringing' of the column if the lowest resonant frequency is in the right range. Remarkably, much of this harmonic structure survives even with violently breaking waves.

1. INTRODUCTION

Offshore wind turbines farms are constructed in areas of high winds where large waves will also occur. Thus, wave induced loads are an important design constraint. In this work we concentrate on nonlinear components of the hydrodynamic loading on a surface piercing column as a model of the base of an offshore wind turbine. The loads which we identify are potential in form – drag forces appear to be negligible, consistent with a Keulegan-Carpenter parameter KC~O(10) for the largest waves reported here.

Most wave-structure interaction experiments are performed either with regular waves or in realisations of random sea-states. The first lacks any representation of the broadband spectrum of real ocean waves, the second suffers problems of wave reflections in finite sized tanks and also the rarity of extreme wave events of interest for design in a random sea-state. In contrast, we have performed a large set of focussed wave group tests, where both the frequency spectrum and phase of the components are carefully controlled. In these tests, the key feature is the use of focussed wave groups. The aim of this is twofold: first to ensure that each short test contains an interaction of interest, and second to allow the unambiguous extraction of the harmonic structure of the fluid loading on a vertical column.

2. EXPERIMENTS

The shallow water basin at DHI was used for these tests. A vertical cylinder of diameter $0.25m$ was suspended from a stiff triangular frame via a load-cell. For the tests reported here the water depth across the basin was constant at $0.505m$ and the cylinder extended downwards to the basin floor, leaving a thin gap of $1mm$ beneath. The cylinder was located at $7.8m$ from the paddles in the centre of the tank. An array of wave gauges was used to monitor the wave-field around the cylinder, pressure gauges were installed at 4 vertical locations on the front stagnation line of the cylinder and the wave kinematics were measured with an ADV.

A range of wave conditions was tested, from small close to linear waves up to spilling and plunging breakers. In each case a compact wave group focussed at the front stagnation point of the cylinder was used to avoid reflections from the basin walls. Figure 1 shows an incident breaking wave (left) and the consequences of such a wave hitting the column (right).
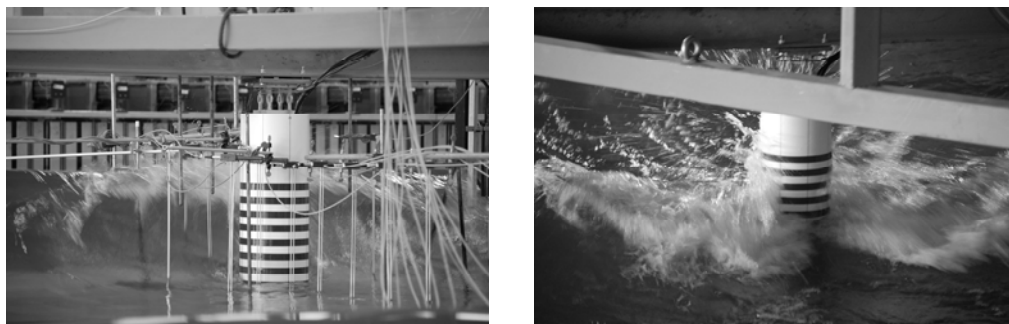

Figure 1.
Left: Breaking wave about to hit the vertical cylinder, showing the wave gauge array
and the cylinder supported from above.
Right: Vertical sheet of water wrapped around the front of the cylinder as a wave impact occurs.

In other experiments, the cylinder was embedded in a caisson on the bed of the basin, and also located midway up a 1:20 plane beach on a small horizontal ledge at a depth of 0.5m. Further data analysis is underway to compare the effects of these changes in wind turbine foundation geometry and also the nature of the incident waves for the sloping bed case on the force time history.

Figure 2 shows two horizontal force time-histories for wave groups on constant depth hitting the cylinder. The spectrum of the wave group is JONSWAP (γ=3.3) in shape with a peak frequency of 0.61Hz. The upper part of the figure shows the free-surface time history in the absence of the cylinder and the horizontal force on the cylinder, both resulting from a relative small non-breaking unidirectional wave group (steepness AK=0.197, KD=0.995). The middle section of the figure shows the incident free-surface motion and the force in the same now mean-wave direction caused by a bi-directional wave system consisting of two unidirectional wave groups crossing at ±20°. Each of these component groups is the same as that producing the force record in the upper part of the figure. The two groups cross at the cylinder, producing a combined breaking wave of twice the height of the individual groups in isolation. Whilst wave height is locally doubled, the peak horizontal force is 3× and there is clear evidence of 'ringing' force components on the column both before and after the instant when this peak force occurs.

Both the incident wave free-surface elevation and the horizontal force time-histories contain significant higher harmonic structure well above the linear frequency range, as can be seen at the bottom of Figures 2. The resonant frequency of the 'wet' cylinder on its load-cell support was 3.8Hz, so force harmonics up to the 5th are not significantly affected by the system dynamics. The data sample rates used were 1000Hz in the tests. From both of the bottom sub-plots of Figure 2, the possibility of the excitation of the 'ringing' response of cylinder at its natural frequency is clear. This high frequency excitation of a surface piercing column beyond the 2nd harmonic of the incident waves, albeit here in a shallow water wind turbine context, is comparable to the excitation of deep water concrete structures of concern to the oil industry in the 1990s, see Faltinsen et al. (1995), Newman (1996), Chaplin et al. (1997). However, we observe not only the large 3rd order component discussed in the FNV-model but also 4th and 5th harmonic excitation as well.

The various harmonics can be extracted by combining the time-histories for the force for a crest-focussed group (C, say) with that for exactly the same wave packet but inverted (T), obtained by multiplying the paddle command signal by -1. These are combined into (C-T)/2 which contains linear, 3rd order, 5th order etc., and (C+T)/2 containing 2nd order difference, 2nd order sum, 4th order... The individual components can then be extracted by digital filtering. This technique assumes the existence of a Stokes-like series in frequency harmonics, and wave steepness. It has been successfully applied to surface elevation data in a study of wave scattering off the bow of a grossly simplified FPSO geometry by Zang et al. (2006); and previously to shoaling waves on a plane beach by Hunt et al. (2002), Borthwick et al. (2006).
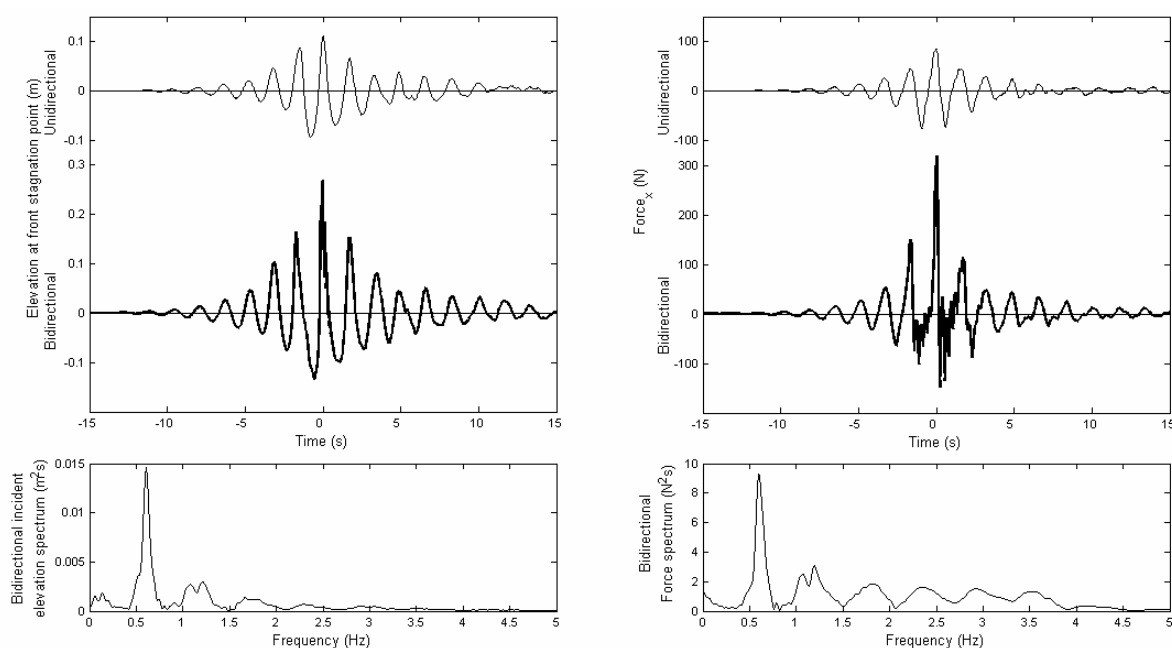

Figure 2

Wave impact with the vertical cylinder: incident wave time histories (left) and horizontal forces on the cylinder (right), for unidirectional group (top) and bi-directional pair ±20° (middle). Bottom figures: incident wave spectrum (left), force spectrum (right), both for bi-directional pair only.

Zang's results, based on model tests at Imperial College, showed large 2nd order scattering from a cylindrical front of a long box with head-on waves but *no* significant higher harmonics beyond 2nd. In direct contrast, the surface elevation spectra and particularly the forces measured on the circular cylinder in this work show that *all* harmonics up to at least 6th are important. So, there is a sense in which the rear half of the cylinder is required for there to be large components beyond the 2nd harmonic.

In order to identify the order and time-scale of the various harmonic components, we also show wave envelopes for each harmonic on Figure 3. These are all derived from the envelope of the linear force (3rd plot down). The square of the linear envelope is scaled to fit the size of the maximum of the measured 2nd harmonic, the cube of the linear to the third etc. This localisation in time of the higher harmonics works well until the terms beyond 5th (on the figure the 5th power of the linear envelope is plotted again) containing the 'ringing' mechanical response of the column. In this context, the second pulse of waves in the second harmonic component, in both cases centred at +6s, is an error wave train generated by the paddle which takes longer to reach the model than the main group. These error waves are observed at the location of the cylinder at this time even when the cylinder was removed. They arise because only linear transfer functions are used to drive the paddles, but the waves which are created are inherently nonlinear so instantaneous cancellation occurs between the correct 2nd order bound waves for the main group and these error components which then propagate down the tank as free components.
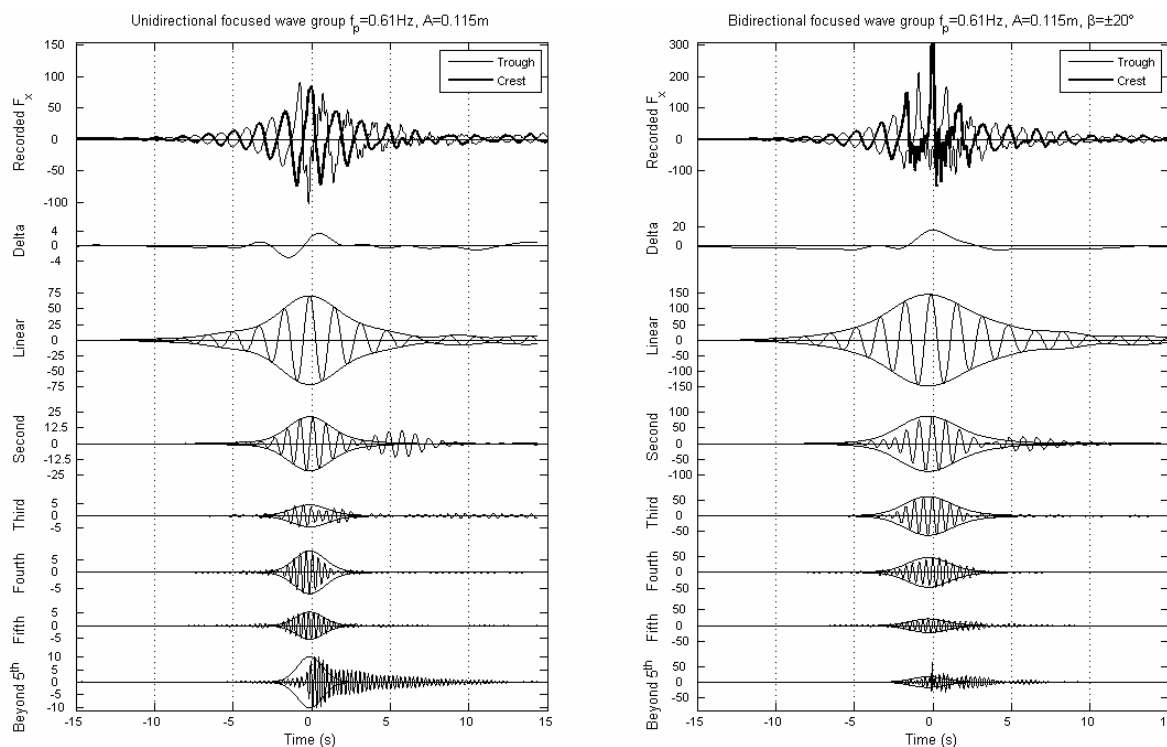
Figure 3
Measured force histories for crest- and trough focussed wave groups (top), then harmonic decomposition in order: 2nd order difference, linear, 2nd, 3rd , 4th and 5th harmonics, rest beyond 5th (bottom). Left: single uni-directional group. Right: bi-directional combined group ±20°.

3. CONCLUSION

A single vertical cylinder was exposed to a large series of carefully controlled incident wave groups. Manipulation of the phase of these groups allows extraction of the harmonic structure of the loading. Even for violently breaking waves, much of the harmonic structure of the resulting horizontal loading is still apparent and consistent with that measured for smaller non-breaking waves.

ACKNOWLEDGEMENT

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