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NONLINEAR WAVE LOADS WHICH MAY GENERATE 'RINGING' RESPONSES OF OFFSHORE STRUCTURES

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Tension-leg platforms and gravity-based platforms, constructed by vertical cylinders, may have a resonance period being $\sim 3 - 5sec$. These platforms may in high sea-states experience that responses of considerable amplitude very suddenly are generated at this resonance period, which is a concern with respect to extreme loading. The generation of these responses are characterized by a resonant build-up during a time-interval being of the order one wave period. These responses are called ringing responses. A typical wave period when this occurs may be $\sim 15sec$, which means a period being 3 - 5 times longer than the resonance periode of the marine structure. The generation mechanism of the higher harmonic loads leading to 'ringing' of offshore structures is not completely understood yet.

Motivated by this problem we consider laboratory measurements of wave loads acting on one restrained vertical cylinder. The aim is to study wave loads which may generate high frequency resonant responses of offshore structures composed by vertical cylinders. Thus, we select wave parameters and a cylinder dimension being relevant for the large scale conditions where high frequency responses are experienced.

The experiments are carried out in a wave tank being $14.2m$ long, $0.47m$ broad and is filled with water at a depth $0.42m$. The tank is at one end equipped with a wave maker. The vertical circular cylinder is $69.5cm$ high, the diameter is $11.9cm$, the draught is $41.1cm$. The forces are recorded by two force transducers, one at a location $27.5cm$ above, and one at a location $36cm$ below the mean water line. We record the horizontal force along the centerline of the wave tank.

The incoming waves is a transient wave group with a local wave period at the cylinder position being $1s$, see table 1 and figure 1. The local wave characteristics obey the dispersion relation for nonlinear gravity waves. The wave parameters are selected to be relevant to waves occuring due to an irregular sea.

A positive interference between the components of the wave group creates a high leading wave at the position of the cylinder. Working with a transient wave group is found to be of advantage in a wave tank with limited breadth. The main events in the present experiments then occur before reflections from the tank walls are disturbing the flow at the cylinder. The main results of the experiments are, however, believed to be valid when the incident waves is a regular wave train of constant amplitude in an open sea condition, or in a broad wave tank where the reflections from the tank walls are very limited.

In the present experiments the wave height is varied between a lowest value, such that the generated waves are in the regime of linear wave theory, up to a largest value leading to a plunging breaker. For small wave height the wave loads are found to be well predicted by the inertia term of Morison's equation.

By increasing the wave height the recorded forces become skewed. More important is that a *secondary oscillation* appears in the force-recordings, see table 2 and figure 2. The secondary oscillation occurs about one quarter wave period *after* the main peak in the loading. It starts when the wave crest is about one cylinder radius behind the rear of the cylinder and reaches a maximum when the wave crest is about one cylinder diameter behind the rear of the cylinder. It lasts for about 15% of the wave period, has a magnitude up to 11% of the peak-to-peak value of the total force and has a resultant acting approximately one cylinder radius below the mean water line. Simultaneous recordings of the free surface reveal that a considerable low-pressure is present behind the cylinder during the same time period as the secondary force oscillations occur, indicating that this secondary force oscillation is a *suction force*. Since the secondary force oscillation occurs about one quarter period after the main peak in the loading, a build-up of resonant responses may be experienced by marine structures having a resonance period at about one quarter of the peak period of the wave spectrum.

When the wave height is small, the local fluid accelerations determine the wave forces. A non-dimensional number characterizing the fluid accelerations is then the wave number multiplied by the cylinder diameter. If the wave height is large compared to the cylinder diameter, the value of the Keulegan-Carpenter number and the Reynolds number become important parameters in the problem. In the present experiments $\sim 2 < KC <\sim 4.8$, while $\sim 30000 < Re \sim 70000$. We have, however, not observed that flow separation occurs in our experiments, which could be a possible reason for the occurrence of the secondary force oscillation. Furthermore, Sarpkaya (1986, figure 3) obtains that the viscous drag force on a circular cylinder is very small for the values of KC and Re in the present experiment.

There is, however, another non-dimensional number which is of importance to the wave loading. The experiments indicate that the particle velocity under the wave crest is an important parameter in the problem. Furthermore, the force-recordings indicate that the secondary force oscillation is due to a free surface effect, i.e. the effect due to gravity. A non-dimensional particle velocity is then given by the Froude number, i.e. $Fr = U/(gd)^{1/2}$, where U denotes the particle velocity under the wave crest, g the acceleration due to gravity and d the cylinder diameter. The particle velocity under the wave crest may be estimated by $U \simeq \zeta_{max}\omega$, where ζ_{max} denotes the local crest height and ω the local wave frequency. The flow at the cylinder is, during the small time-interval when the wave crest is passing the cylinder, effectively a slowly varying horizontal current. The particle excursions are small, however. This current has a forced wave with wave length being $\lambda_U \simeq 2\pi U^2/g$. In fact, the secondary force oscillation is present with a pronounced effect when the Froude number equals 0.4, which means that λ_U equals the cylinder diameter, d, see figure 3. A resonance between the free surface and the body may then take place, creating a skewness in the problem, giving rise to a suction force.

Reference: Sarpkaya, T. 1986. Force on a circular cylinder in viscous oscillatory flow at low Keulegan-Carpenter numbers. J. Fluid Mech. 165, pp. 61-71.

case	λ	ζ_{max}	H	$K\zeta_{max}$
A	144cm	13mm	22mm	.06
B	151cm	35mm	53mm	.15
C	155cm	50mm	74mm	.20
D	157cm	60mm	87mm	.24
E	158cm	70mm	100mm	.28
F	162cm	80mm	117mm	.31
G	164cm	90mm	129mm	.34
H	165cm	90mm	141mm	.34

Table 1: Wave characteristics, cases A – H. The wave characteristics of the incident wave group at the location of the cylinder axis are: ζ_{max}: the measured local crest height, H: the measured local wave height, λ: the measured local wave length, $K\zeta_{max}$: the local wave slope ($K = 2\pi/\lambda$).

case	δ_u	δ_l	Δ_u	Δ_l	$(\delta_u + \delta_l)/(\Delta_u + \Delta_l)$
B	0	0	4.7N	9.9N	0
C	0	0	6.3N	12.4N	0
D	0.2N	0.3N	7.2N	13.5N	2%
E	1.0N	1.0N	8.2N	15.3N	9%
F	1.3N	1.4N	9.5N	16.1N	11%
G	1.6N	1.6N	11.1N	16.8N	11%
H	1.3N	1.3N	11.4N	17.7N	9%

Table 2: Peak-to-peak values of the horizontal forces on the cylinder. δ_u: the height of the secondary oscillation at the upper force transducer, δ_l: the height of the secondary oscillation at the lower force transducer, Δ_u: the peak-to-peak value of the force at the upper transducer, Δ_l: the peak-to-peak value of the force at the lower transducer.

case	λ	ζ_{max}	H
C	349m	11.0m	16.7m
D	353m	13.5m	19.6m
E	355m	15.8m	22.5m
F	365m	18.0m	26.3m
G	369m	20.0m	29.0m

Table 3: Wave characteristics in large scale, cases C – G. Local wave period: $15s$. Cylinder diameter: $26.8m$.

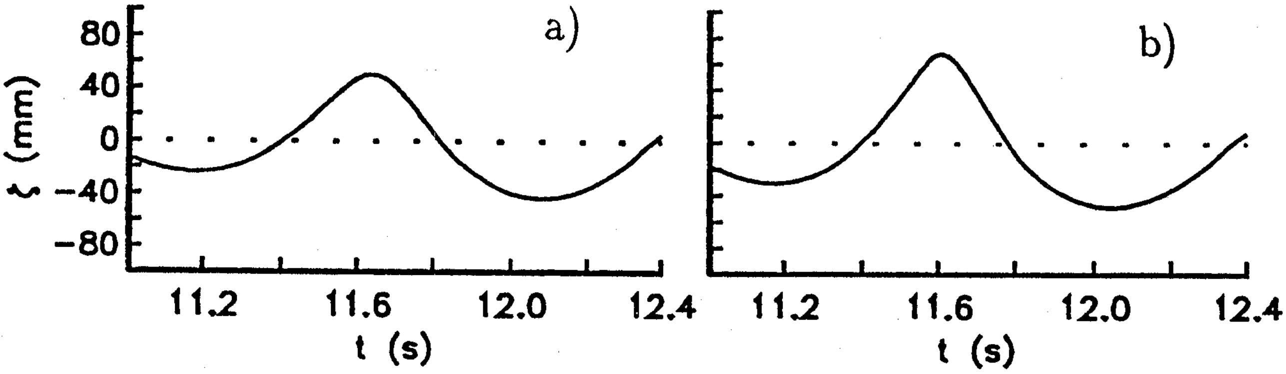

Figure 1. Time histories of the recorded surface elevation ζ_0 at the location of the cylinder axis. a) case C for $11s < t < 12.4s$, b) case E for $11s < t < 12.4s$.

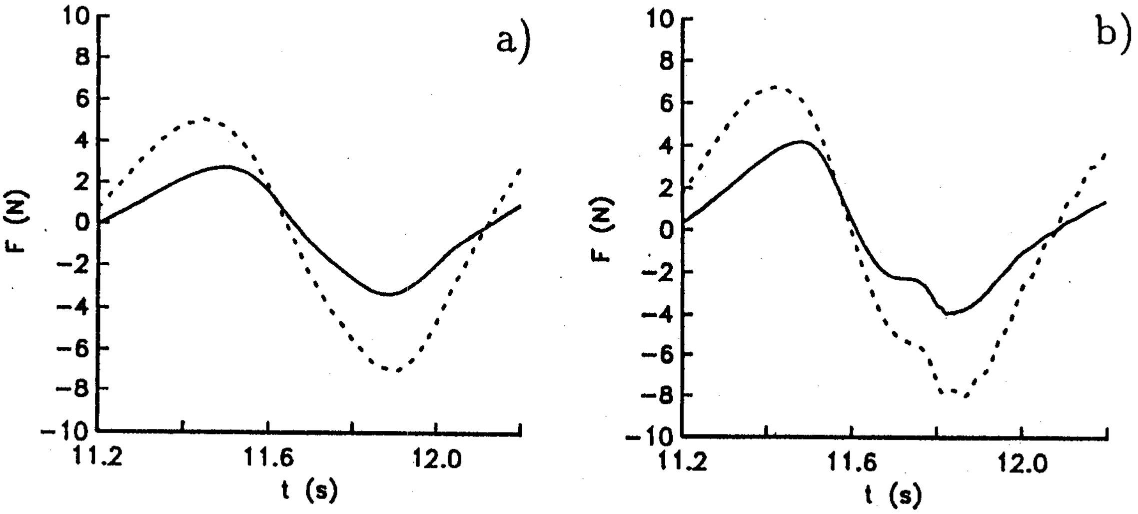

Figure 2. Forces along the centerline of the wave tank. Recorded forces in *Newton* (N). Solid line: The upper force transducer. Dashed line: The lower force transducer. a) case C for $11s < t < 12.4s$, b) case E for $11s < t < 12.4s$.

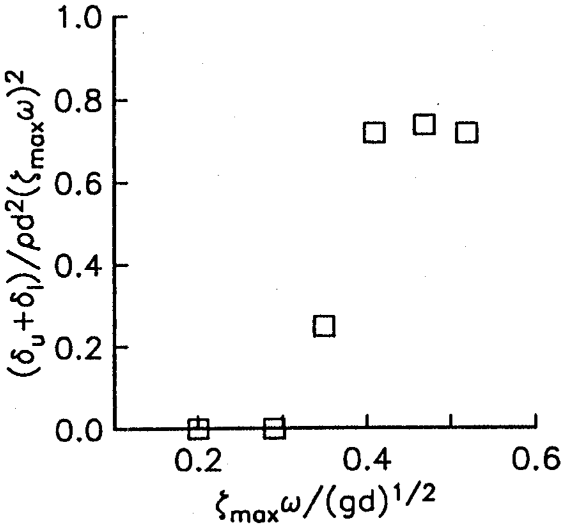

Figure 3. Non-dimensional peak-to-peak values of the secondary oscillation in the force, $\delta_u + \delta_l$, vs. local Froude number.

DISCUSSION

Tuck E.O.: Are you saying that this phenomenon is not special to a wave, but would also occur if one replaced the wave by a current of magnitude equal to the local particle velocity?

Grue J.: Yes, provided that we still consider it as a free surface effects i.e. the effect due to a local current and gravity.

Lu Y.: How did you obtain the criterion of ringing responses? Did you get it statistically? How about the validity of the criterion? Is it also valid when there were no walls in the flow?

Grue J.: The criterion of ringing responses is obtained by numerous experimental data. It can be used even in the case where no walls are present.