Measurements of Cloaking Produced by an Array of Circular Cylinders

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1 Introduction

In the field of water waves, there has been recent interest in a process known as cloaking. According to this concept, the waves scattered by a fixed body are manipulated in the region immediately surrounding the object to eliminate scattering at large distances from the body. Cloaking of a bottom-mounted vertical monopile was first proposed by Porter (2011), who manipulated the bathymetry in the surrounding region to minimise the scattered energy to values approaching zero. Newman (2013) investigated cloaking of a surface-piercing cylinder of finite draft by introducing an array of bodies or an axisymmetric structure around the central object. In this case, a multivariate optimiser was successfully coupled with the boundary-integral equation software WAMIT to identify geometric arrangements resulting in minimal far-field wave scattering at a specified wavelength. The existence of arrays of bodies capable of cloaking has more recently been confirmed numerically by Kashiwagi et al. (2015) using the theory of Kagemoto and Yue (1986) in conjunction with a higher-order, boundary-element method. Kashiwagi et al have furthermore presented experimental results supporting the numerical findings for array-type cloaking. From a practical perspective, the elimination of the mean drift force on a surface-piercing structure associated with the cloaking process may find application in the reduction of second-order mooring loads in large offshore structures.

This paper describes a further experimental investigation into the cloaking of a circular cylinder of finite draft using a circumferential array of eight surrounding cylinders. The aims of the work were:

- to identify a cloaking geometry suitable for investigation in the facilities available at DTU,
- to design and build an apparatus to investigate wave scattering by this and other geometries,
- to confirm cloaking at one wavelength by measuring the mean drift force and far-field scattering.

2 Experimental Setup

The experiment described here has proved challenging for several reasons. Firstly, the surge mean drift force is small in comparison to the surge excitation force (1.5% here), and therefore difficult to extract accurately from the total force signal. An additional problem in this regard is that the surge force sensor may register so-called cross-talk signals associated with the considerable heave excitation force and pitch moment acting on the apparatus. A second challenge is presented by the small differences between the mean drift forces and the scattered wave amplitudes at the uncloaked and cloaked conditions. For example, the maximum far-field scattered wave amplitude generated by the uncloaked cylinder is only 3.6 mm, compared to an incident wave amplitude of 18.8 mm. A third difficulty is the requirement that the generated incident waves should be spatially uniform and repeatable, with higher harmonics reduced to a minimum. Whilst the wave-generator used here was not ideal in this respect, attempts have been made to correct for the non-uniformities encountered.

The cloaking configuration investigated in this paper consisted of an inner cylinder surrounded by eight smaller outer cylinders. A variety of inner-cylinder diameters and drafts were considered, with the aim of maximising the ratio of the surge drift force to the surge excitation force at the cloaking frequency whilst limiting the size of the complete apparatus. Having selected a potential inner-cylinder radius and draft, computations using WAMIT coupled to a multivariate optimiser were performed by J. N. Newman to identify the radius, draft and mounting radius of the outer cylinders to minimise scattering. The finite depth of the tank was specified during this process. Having identified the optimised geometry, the forces on the inner and outer cylinder assemblies and the wave elevation at points around the structure, were independently confirmed by the authors using WAMIT. The final,

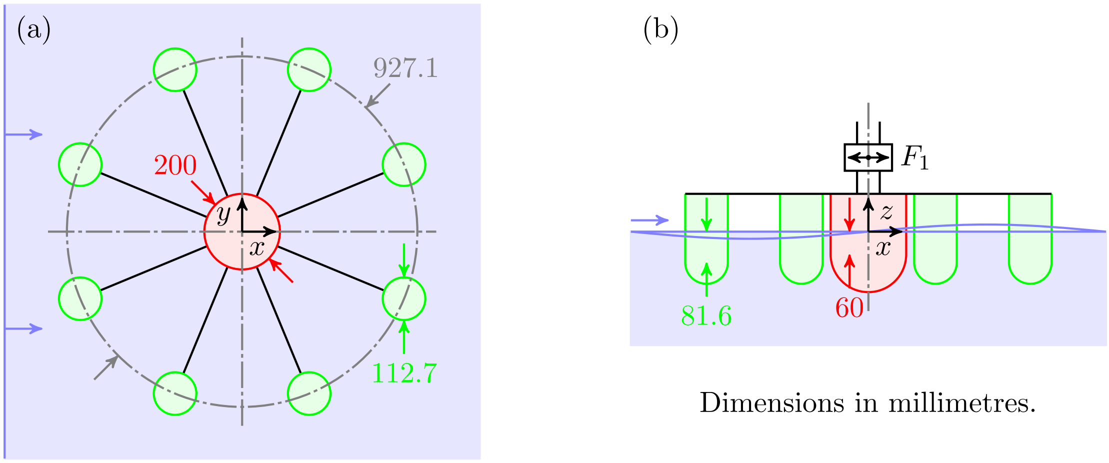

Figure 1: The configuration of the cloaking apparatus: (a) plan view, (b) side view.

selected configuration is illustrated in Figure 1. A hemispherical base was included on all cylinders to minimise viscous effects.

Having selected the geometry, an apparatus was constructed to support the cylinder assemblies from above. This structure was designed to be as stiff as possible, whilst allowing a degree of adaptation for future investigations of other cloaking geometries. The support structure incorporated a load cell to measure the surge force on the inner cylinder alone, the outer cylinders alone, or the entire structure. As the measurement uncertainties are typically specified as a percentage of the full-scale reading, the range of the load cell was carefully selected to only slightly exceed the maximum predicted surge excitation force. Furthermore, a sensor with a particularly low cross-talk was specified to minimise the effects of the wave-generated heave forces and pitch moments. To further minimise measurement uncertainties, the inner and outer cylinder assemblies were ballasted to achieve neutral buoyancy.

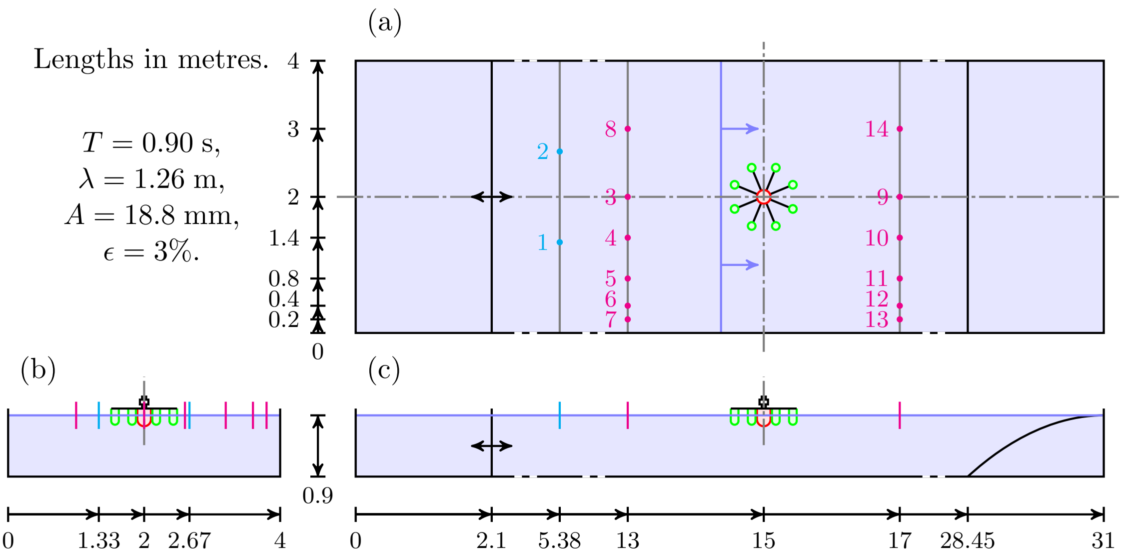

Figure 2: The experimental configuration (a) plan view; (b) end view; (c) side view.

The entire cylinder assembly was installed in a wave tank 31 m long by 4 mwide by 0.9 m deep, located at DTU. This arrangement is illustrated in Figure 2. Waves with a period of 0.90 s and a steepness of 3%, were generated by a piston-type wavemaker. Resistive wave gauges were installed at a variety of locations to measure the free-surface elevation. Among these were two lines of gauges deployed two metres up- and downwave of the cloaking apparatus (numbered 3-7 and 9-13 respectively). These wave gauges were installed at transverse intervals designed to coincide with points of small and large scattering amplitude for the uncloaked case. Ten test runs were conducted for each of three cylinder configurations: no cylinders, the inner cylinder installed alone, and the inner and outer cylinders both installed. Data corresponding to ten complete wave periods were extracted from each time series. A sinusoidal least squares fit was made to the data, and the amplitude of the mean and the fundamental was extracted from the force and the surface-elevation data for comparison with the numerical results.

3 Results

The numerical and experimental results for the excitation and mean drift forces are presented in Figure 3. Whilst the original intention was to measure the force on the entire structure with the cloaking cylinders installed, unexpected compliance of the load cell led to a small pitching motion of the structure in waves. Having observed this, the cloaking structure, consisting of the eight outer cylinders, was locked in position, and the surge force on the inner cylinder alone recorded. At the cloaking wavelength, the mean drift force on the inner cylinder alone should also be zero. Furthermore, the numerical results suggest that the excitation force on the outer cylinder assembly should be zero as well, suggesting that there should be no difference between the excitation force measured on the total structure and that measured on the inner cylinder alone.

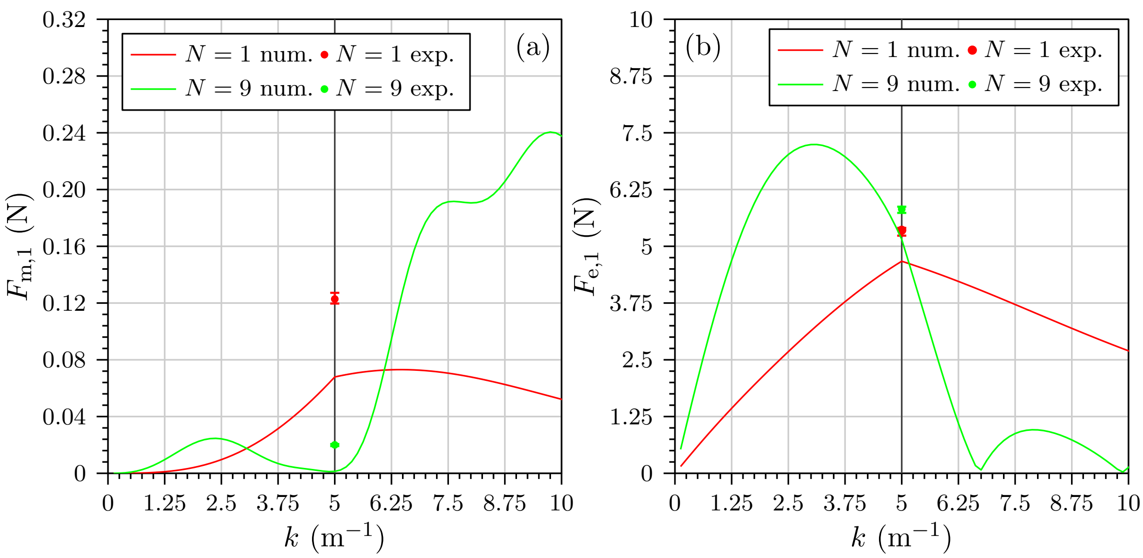

Figure 3: Surge forces with N cylinders installed: (a) mean drift forces, (b) excitation forces.

The numerical results for the force on the total structure are presented for a range of wave numbers, where $k = 5$ corresponds to the cloaking value. In accordance with plans for future experiments at other wavelengths, for wavenumbers less than the critical value, the amplitude has been limited to that at the critical value, whereas a constant steepness is maintained for larger wavenumbers. The experimental results for the excitation force show reasonable agreement with the numerical results, but all forces are larger than predicted by theory. This is especially evident for the mean drift forces. Here, the error bars represent solely the variability in results between tests. Whilst these values are small, a full error analysis will be presented at the Workshop. It is suspected that the primary source of error in these results is cross-talk contributions to the surge signal from the heave force and pitch moment also being applied to the structure. Compensation for these effects should be achievable and is being investigated.

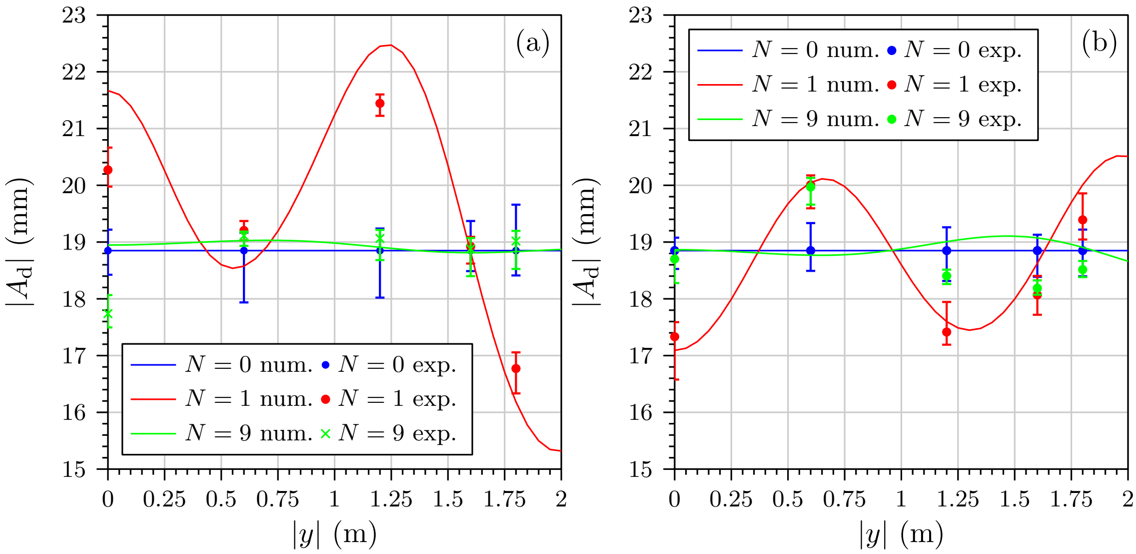

Figure 4: Diffraction wave amplitude with N cylinders installed: (a) 2 m upwave (gauges 3-7), (b) 2 m downwave (gauges 9-13).

The numerical and experimental results for the wave amplitude upwave and downwave of the assembly are presented in Figure 4. Due to irregularities in the wave generation, the spatial variation of the wave amplitude was significant without any structure in place. The results have therefore been corrected for the variations in the amplitude of the incident wave by dividing the uncloaked and cloaked structure wave amplitudes by the true incident amplitude and multiplying by the target amplitude. The experimental results are then seen to be in general agreement with the numerical predictions. The error bars presented here again correspond to the test-to-test variation alone. The uncertainty associated with the elevation itself is likely to be less than 1 mm, but the specific value is also presently being identified for the particular design of wave gauge used here.

Acknowledgements

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