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Current blockage and extreme forces on a jacket model in focussed wave groups with current

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ABSTRACT

This paper documents large laboratory-scale measurements of hydrodynamic force time histories on a realistic 1:80 scale space-frame jacket structure exposed to combined waves and in-line current. The aim is to investigate the fluid flow (and the associated hydrodynamic force) reduction relative to ambient fluid flow due to the presence of the jacket structure as an obstacle array, interpreted as wave–current blockage. Transient focussed wave groups, and embedded wave groups in a smaller regular wave background are generated in a towing tank, and the jacket is towed under different speeds opposite to the wave direction to simulate wave loading with different in-line uniform currents. The measurements are compared with numerical predictions using Computational Fluid Dynamics (CFD), with the actual jacket represented in a three-dimensional numerical wave tank as a porous tower modelled as a uniformly distributed Morison stress field. Good agreement is achieved, both in terms of incident surface elevation as well as total force time histories, all using a single set of Morison drag (C_d) and inertia (C_m) coefficients. Substantial force reduction is observed under transient large crest relative to prediction from the present industry design guideline with the same Morison coefficients. We demonstrate the generality of our findings: without influence of Keulegan–Carpenter (KC) number effect, a single invariant set of C_d and C_m is all that is required to numerically explain and reproduce the measured total force time histories on a realistic jacket model for a large range of wave heights and non-zero current speeds.

1. Introduction

The hydrodynamic forces on a single cylinder and arrays of cylinders have been studied extensively in the past. Many studies have considered periodic waves only without current (or periodic oscillation without steady flow), whilst some examined the effect of waves and steady current simultaneously, see e.g. Sarpkaya and Isaacson (1981), Sarpkaya et al. (1984), Heideman and Sarpkaya (1985), Rodenbusch and Källström (1986), Allender and Petrauskas (1987), Reed et al. (1990), and Chaplin et al. (1992). Large scatter in the Morison drag and inertia coefficients (C_d and C_m) is observed, and no general conclusions have been drawn, because of the complexity of the problem due to the presence of a current interacting with waves and the structure. In this paper, we propose that a solution to the problem can be obtained by looking at realistic flow

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around a geometrically complicated space-frame jacket model; at least in terms of the overall loads on the entire structure. This model is a realistic representation of a typical oil and gas production platform for intermediate water depth and harsh ocean environment. It is made of multiple cylinders arranged in different orientations, and it is subjected to transient wave groups and regular waves, all with steady uniform current present.

It should be noted that the estimation of loads on space-frame structures as a topic has not been an active area of research over the last few decades. Allender and Petrauskas (1987) measured the peak forces on a complete 3 m high model of a Gulf of Mexico platform in regular waves and current in a very large wave tank. They observed what we interpret as significant wave–current blockage for a wide range of regular wave heights and steady tow speeds. In terms of the standard design methodology (see API 2000), they reported the necessity to use a lower value for the Morison drag coefficient C_d of $0.7 - 0.8$ to fit the measured peak forces for waves with in-line current. In contrast, a C_d of $1.3 - 1.6$ was required for regular waves with no current. These important but apparently little known observations prompted us to re-visit the whole problem of the hydrodynamics of flow through space-frame structures. Whilst framed in terms of fixed jackets, this flow–structure interaction problem is obviously relevant to deepwater compliant towers, jack-up rigs and, most recently of practical importance, the lightweight space-frames being used to support large offshore wind turbines.

This paper extends our research of current blockage on statically-responding (fixed bottom-founded) offshore structures. The presence of such structures can be treated as obstacle arrays, which provide resistance to the incident wave and current flow on the structures. Hence, reduction in the flow and the associated hydrodynamic force is observed. This phenomenon has been reported as current blockage. The first provision to the standard offshore industry design codes, such as API (American Petroleum Institute, 2000), was due to the work by Taylor (1991), which improves the Morison equation (Morison et al., 1950). This accounts only for flow reduction due to steady current flow. Recent studies by Taylor et al. (2013) analytically demonstrated the additional flow reduction from regular waves on top of steady current, and this has been validated extensively in both experiments as well as numerical simulations using Computational Fluid Dynamics (CFD), see Santo et al. (2014a, b, 2015, 2017).

Moving on from an idealised regular wave which is simply periodic in form, we consider in this paper the effect of transient and non-periodic waves which are more representative of large waves on the open sea. To model the transient effect, we consider focussed wave groups, and to account for the presence of large waves in an on-average smaller sea-state, we embed these focussed wave groups within a smaller regular wave background. We then examine the total force time histories on a realistic jacket model obtained from laboratory-scale measurements conducted in a large towing tank. We also assess and compare the force time histories from CFD results, with the actual jacket represented in a three-dimensional numerical wave tank as a porous tower modelled as a uniformly distributed Morison stress field. We also compare the predictions using the present API recommended practice and our novel porous tower modelling approach which accounts for wave–current blockage effects, all with the measurements taken as the reference. For force prediction, the industry approach in the past required calibrating the Morison C_d and C_m using the open sea fluid kinematics without otherwise taking into account the presence of the structure. The present industry approach (such as API) has started to account for the presence of the structure due to steady flow (current blockage effects), but not the complete wave–current blockage effects. We will show that this present approach is incapable of producing the experimentally measured force time histories, and in general will result in a scatter in C_d. On the other hand, using our proposed approach, the complete measured force time histories for almost all cases with current can be reproduced using a single and consistent set of C_d and C_m.

2. Experimental and numerical setup

These experiments were conducted in the towing tank of the Kelvin Hydrodynamics Laboratory, University of Strathclyde, Glasgow. This is 76 m long, 4.6 m wide and 2.5 m deep. The tank is equipped with four paddles of Edinburgh Design Limited (EDL) 'flap-type' wavemakers with force-feedback at one end, and a sloping beach acting as a passive absorber at the other end. In the experiments, linear wave generation was used. A self-propelled carriage runs along the longitudinal direction of the tank. Fig. 1 shows a plan view as well as two photographs of the towing tank facility.

A 1:80 jacket model was hung below the carriage, which was moved at constant speed along the tank to simulate uniform current, and the model was exposed to a range of focussed wave groups. Fig. 2 shows a photograph of the jacket model with three of the authors (left), and a 3D CAD model of the jacket with relevant geometric information (right). Being made of stainless steel, the jacket model resembles a typical second generation North Sea 4-legged jacket structure. It stands at 1.74 m tall and weighs around 50 kg in the air. The cross-section of the jacket at the top is 0.39 m $\times$ 0.34 m, and at the bottom is 0.60 m $\times$ 0.34 m. The jacket is tapered when viewed end-on and rectangular broadside. Four large cylindrical hollow members (or pipes) with a diameter of 38.2 mm (1.5") form the jacket legs. Additional smaller pipes with a diameter of 16 mm form the diagonal bracings and the vertical conductor pipes, with 24 conductors in total. These run the full height of the jacket. Square hollow members with cross section of 20 mm $\times$ 20 mm are used as conductor support frames at each horizontal level. These are supported on horizontal bracings at each end-on face of the jacket instead of extending from the jacket legs within the jacket (as commonly found in actual offshore jackets) to ease the model fabrication process. In these experiments, only the end-on configuration was tested, as this will provide more blockage and a more severe test of the modelling.

The jacket was suspended from the carriage such that the still water level is at 0.12 m below the centre of the top X-brace, or a distance of 1.33 m up from the jacket base. This is necessary to ensure the largest crest do not hit the top support frame.