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Experimental Investigation of Hydrodynamic Loads on Subsea Structures

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Abstract

Flexible riser systems are a commonly used and important component of floating production facilities. Mid Water Arches (MWA) are prominent features in such systems and understanding their response to prevailing environmental conditions is essential in effective design. This paper discusses experimental techniques developed to better understand the behaviour of these complex structures, achieved through model scale testing at the Australian Maritime College's (AMC) Circulating Water Channel (CWC) facility. The experimentation was carried out using two arrangements; the first being captured testing to investigate drag forces on the structure to calculate drag coefficients. The second involved the model in a tethered condition, where the offsets of the structure in varying flow conditions were measured and the tension in the tethers was determined.

The drag force on the MWA model varied with the orientation of the model. This was expected due to the complex geometry of the structure, although the largest axial forces were not observed for flow parallel to their respective directions. The variations in tether tensions coincided with the offsets observed, where correlation could be made between the incident force and model orientation. This work demonstrates the importance of model testing when studying MWAs and other complex structures.

Introduction

Flexible riser systems typically incorporate MWAs to achieve lazy-S and steep-S configurations [1]. The MWA structure is secured to the seabed by tethers and suspended in the water column to support the mid-section of the risers. The arrangement is commonly used to protect flexible riser integrity by accommodating vessel and wave motions whilst maintaining a constant touch-down point. It also prevents the development of excessive curvature in the risers and is an effective means to avoid clashing or entanglement of adjacent risers.

Analytical software is commonly used to model flexible riser systems so that the dynamic behaviour of MWAs can be understood for design purposes. For example, *OrcaFlex* uses Morison's equation to calculate the loads and motion responses of a structure, where various inputs must be specified including mass, dimensions and hydrodynamic coefficients [2]. While structural attributes of the MWA are easily defined, hydrodynamic coefficients are not readily available for complex structures and generally information is only given for simple shapes, such as cylinders, cubes and spheres [3]. Available software is capable of calculating these hydrodynamic coefficients and previous studies have determined values for different MWA designs [1, 4]. It was observed however that the complexity of the structure had to be simplified in both cases for the simulations to be completed. This gives motive for the necessity of model testing, as it offers an alternative means of determining the hydrodynamic loads and motions response for MWAs and other subsea structures, without the simplifications or assumptions. It is generally not practical to conduct testing at full scale and in many cases this is not possible. In this paper, the drag forces and motion response of a scale MWA model have been experimentally investigated. The MWA design has been provided courtesy of Technip and testing was carried out at the AMC's CWC facility. Figure 1 portrays a representation of the scale model MWA structure in the tethered condition, the coordinate system and flow directions referred to later in the paper are shown.

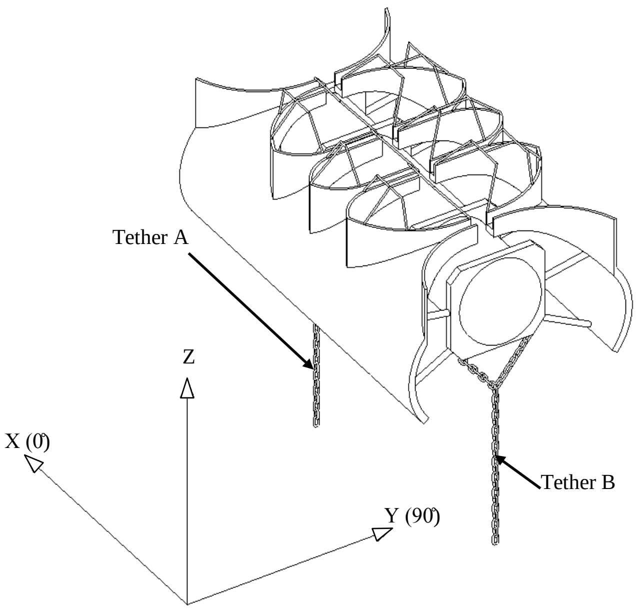

Figure 1 The MWA model configuration and coordinate system

The scope of work covered within this paper is aimed at achieving the following objectives:

- Developing model testing techniques.
- Determining the drag forces acting on the MWA structure.
- Investigating the tension loads developed in the MWA tether constraints.
- Studying the offset and motion response of the MWA for varying flow speeds and directions.

Model Experimentation

Experiments were carried out in order to determine drag force in the horizontal plane and to measure static offsets and tether tension loads. Experimental data was measured using a body fixed coordinate system to replicate the typical full scale MWA arrangement. The flow parallel to the X-axis has been defined as 0 degrees and flow parallel to the Y-axis is 90 degrees. A series of tests were carried out in the AMC's CWC facility. The tank has a testing area 11 metres long, 5 metres wide and 2.5 metres deep. The tank is capable of generating flow speeds up to 1.5 m/s. A mobile observation carriage sits above the tank serving as a platform to secure models and house the interface for the data acquisition system.

The 1:15 scale MWA model has a length of 1160 mm, width of 720 mm and height of 490 mm. The MWA model's internal frame, arch and gutters were fabricated from aluminium tube and sheet metal. The gutter guides were made using moulded epoxy and the buoyancy tank was constructed using PVC pipe and fibreglass.

The Reynolds numbers, *Re*, encountered in MWA applications are relatively high. Consequently, it is not possible to use Reynolds scaling since the required flow speeds exceed the operating capabilities of the testing facility. This occurrence is commonly encountered when testing large subsea structures and it is resolved by implementing Froude scaling [3, 5]. The difference between model and full scale *Re* presents numerous shortcomings, since viscous forces are not accurately scaled using Froude number, *Fn*.

It was anticipated that the drag on the MWA would be pressure dominated due to its geometry. The flow separation caused by the sharp edges and appendages of the structure were expected to be considerably larger than the separation within the boundary layer. Therefore, the bias caused by Froude scaling should not significantly impact results.

Model Setup

The captured experimentation was conducted to determine the translational drag on the MWA model. This was achieved using the configuration shown in Figure 2, allowing the model to be orientated at various angles to the flow. Drag was measured by a load cell mounted between the top of the MWA and a vertical rod attached to a metal support frame. The support frame utilised two linear bearings to ensure the rod apparatus remained vertical while changing the model orientation. A gauge plate attached to the upper end of the vertical rod was used to accurately set the angle and secure the model.

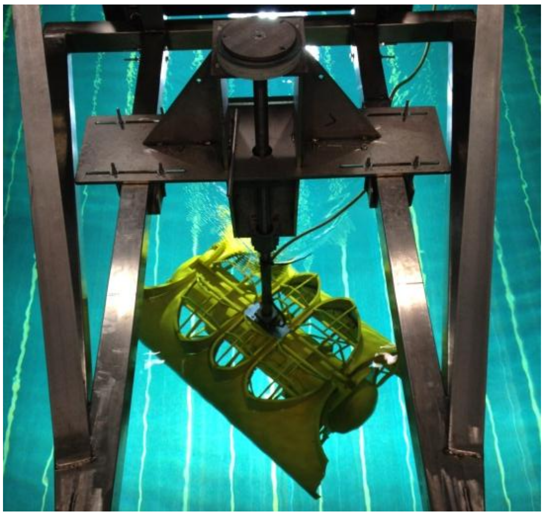

Figure 2 Captured testing of the model MWA setup (orientated at 45°)

The tethered MWA testing was designed to measure the static offsets and tether tension loads. The tests were carried out using the arrangement shown in Figure 3 for a range of flow directions and speeds. The static offsets were calculated from images taken of the model during testing and a load cell was placed at the upper end of each tether to measure tension load.

The MWA model was ballasted to achieve the full scale mass properties. Bifilar suspension tests were used to position the ballast through a trial of several arrangements, where the optimal mass placement was identified to achieve the required radii of gyration and centre of gravity. The lead ballast weights were then secured within the model buoyancy tank, then the end caps were reattached and the buoyancy tank sealed.

Two short chain lengths were attached to each end of the MWA to form the bridles and a longer length was used for each of the tethers. The bottom of the tethers was connected to the base foundation and the top to the bridles using shackles.

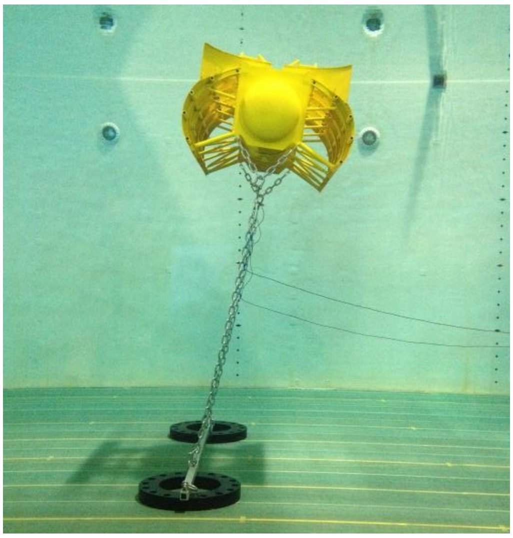

Figure 3 MWA model during tethered testing (orientated at 90°)

Data Acquisition

A waterproof 6 component load cell with 250lb capacity was used to measure the forces and moments during the captured testing. Prior to testing it was calibrated to determine the force and moment components in the X, Y and Z axes. A multi-channel data acquisition (DAQ) system was used to collect the data, where it was recorded and analysed using *LabVIEW* software.

For the tethered experimentation, linear S-beam load cells were used to measure the tension load at the topmost end of each tether. A remotely operated camera was mounted to the observation carriage above the CWC to capture images of the MWA model. These images were post-processed to determine the offset and rotation of the structure. A protractor fixed to a scope with crosshairs was positioned at the observation window of the CWC to measure the angle of the tethers for the varying flow conditions.

Experimental Procedure

The test conditions for the captured and tethered experimentation are given in Table 1. The flow speed was kept constant for captured testing while 20 second data intervals were collected for each model orientation. Zero readings were taken prior to and after completion of testing and multiple sets of data were recorded for each condition to maintain accuracy.

Parameter	Value	Units
Flow speed	0.23 - 0.53	m/s
Orientation	0° - 90°	deg.

Table 1 Testing conditions for captured and tethered experimentation

For tethered testing, flow direction was varied by stopping flow and adjusting the gravity base. The complete range of flow speeds were tested prior to altering flow direction. Zero readings were recorded and images taken of the MWA at the beginning and end of testing to provide the necessary reference data. To account for the slight oscillations, multiple images were taken to obtain average values for offset and rotation. Both tether angles were measured with the scope and protractor.

Data Analysis

The translational forces in the X and Y directions were the primary drag components obtained during captured testing. The tension loads measured from the tethered testing have been presented with respect to the flow speed. The static offsets of the MWA model were determined by importing the image taken prior to testing (flow speed = 0 m/s) into a drafting and modelling program, *Rhinoceros 4.0*. The image was then scaled and the centre of the MWA was marked on the image. The image taken at each flow speed was imported in the same place as the initial image and the MWA model offset in each axis were determined. Because the model was tethered to the bottom of the CWC, the experienced motion was not purely in the horizontal plane. As a result, the fixed camera position did not incorporate the varied elevation of the MWA model and basic trigonometry was used to make necessary adjustments to the offset values.

Results and Discussion

Captured Model Tests

The drag forces in the X and Y direction for varying flow directions and speeds are shown in Figure 4 and Figure 5 respectively. The results show that the drag force in the X-direction is largest for flow at 45 degrees. This occurrence may be considered uncharacteristic due to the seemingly decreasing face area; however it is justified by the complex geometry of the MWA structure. This is explained by the fact that for flow at 0 degrees only one gutter is directly subject to the incident flow, where those downstream are shielded. However when the model orientation changes a varying extent of every gutter is directly subject to flow and each of these surfaces will experience a drag component along the X-axis. The drag force is largest in the Y-direction for flow at 67.5 degrees and this may be justified by similar reasoning to the drag trend in the X-direction.

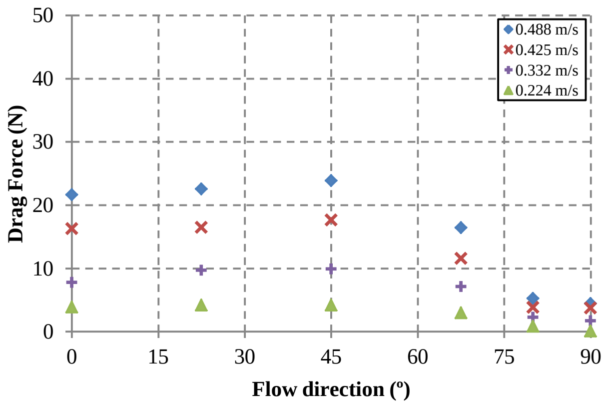

Figure 4 Drag force in the X-direction vs. flow direction for varying flow speeds

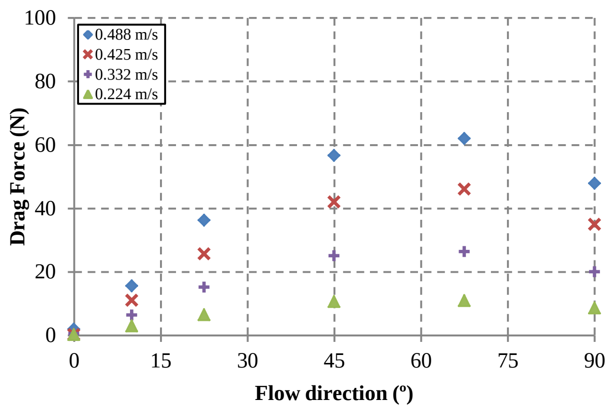

Figure 5 Drag force in the Y-direction vs. flow direction for varying flow speeds

Tethered Model Tests

The variation in tether tension for flow at 0 degrees is presented in Figure 6 for a range of flow speeds. For this flow condition the tension variation indicates that the MWA model experiences a moment about the Y-axis, since the tension in tether A decreases and the tension in tether B increases. This is likely caused by the asymmetry of the structure about the X-Y plane, which will cause an unevenly distributed drag force to generate a moment.

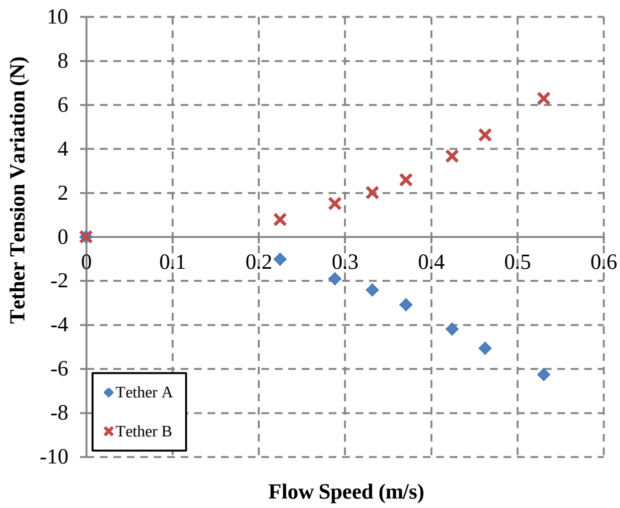

Figure 6 Variation in tether tension vs. flow speed for flow in the X-axis direction

For flow at 90 degrees the variation in tether tension is shown in Figure 7. As the flow speed increases, the tension decreases and therefore it is evident that the MWA generates a downward force for flow in this direction. The force acting on the MWA model should ideally be symmetrical about the Y-axis for this condition, however the difference between tether tensions suggests it is slightly unsymmetrical. The difference between tether A and tether B increases with flow speed and since there is no variation at 0 m/s it can be associated with an unsymmetrical flow profile, lack of symmetry in the model, an incorrect model orientation, or any combination of the three possibilities.

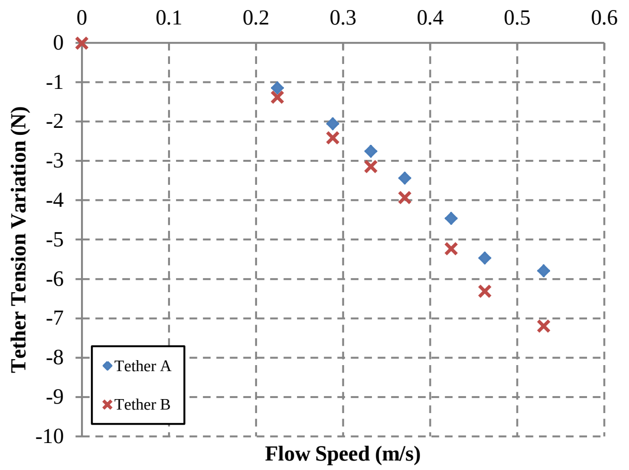

Figure 7 Variation in tether tension vs. flow speed for flow in the Y-axis direction

The MWA offsets for flow at 0 degrees and 90 degrees are shown in Figure 8 and Figure 9 respectively, where the flow is parallel to the axis in each instance. The general trend observed from the results is an increase in offset with flow speed. It is also apparent that the offset in the Y-direction is over twice that for flow in the X-direction. This is due to the projected area of the MWA model in the Y-direction being approximately twice that for flow in the X-direction and therefore the drag force is larger.

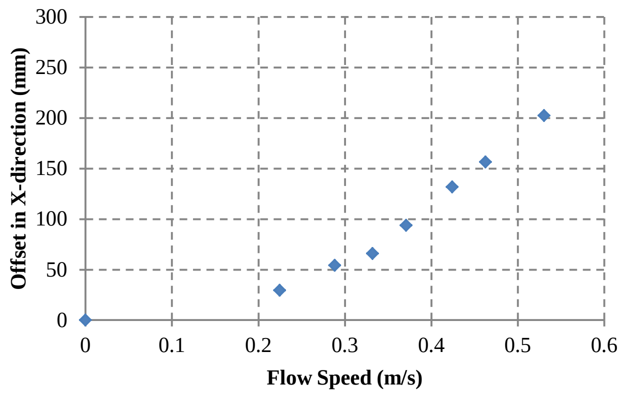

Figure 8 Offset in the X-direction vs. flow speed for flow at 0 degrees

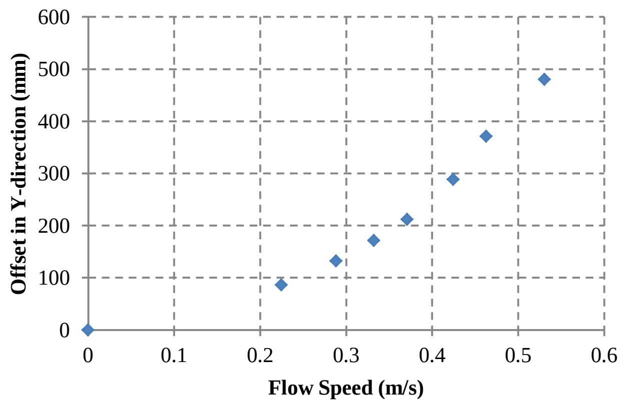

Figure 9 Offset in the Y-direction vs. flow speed for flow at 90 degrees

Conclusions

This paper presented drag forces on the MWA for a range of flow directions and speeds. The static offsets and tether tension loads obtained from tethered testing were only presented for flow directions of 0 degrees and 90 degrees. The results from captured testing indicated that the force component in the X direction was largest for flow at 45 degrees, whereas in the Y direction it was largest for flow at 67.5 degrees. The tension loads observed during tethered testing indicated that flow around the MWA generated varying phenomena depending on direction. The opposing tension curves for flow at 0 degrees suggest that a drag moment was generated about the model centroid. The negative tension slope for flow in the Y direction supported the presence of a downward force. Static offsets coincided with typical drag expressions, indicated by the parabolic inclination and the difference between offset in the X and Y directions being proportional to the difference in respective projected areas. The experimental methods developed were found to provide a viable method of determining drag forces and coefficients. They also provided a detailed understanding of the response to varying flow conditions for the particular MWA design.

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