Hydrodynamic Performance of Multi-Component Structures in Oscillatory Flow, from Blow-out Preventer to Dual Cylinder Interference

by

Dixia Fan

Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Author ......................................................
Department of Mechanical Engineering
August 5th, 2016

Certified by ....................................................
Michael S. Triantafyllou
William I. Koch Professor of Marine Technology
Thesis Supervisor

Accepted by ....................................................
Rohan Abeyaratne
Quentin Berg Professor of Mechanics
Chairman, Committee for Graduate Students
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Abstract

As one of the key components for the wellhead integrity, the Blow-out Preventer (BOP) is designed and constructed to prevent abnormal pressure change in the well and keep the blow-out from happening, and therefore is essential for the whole well-being of the offshore drilling system, and this calls for a careful investigation on the understanding of the BOP dynamics and its effect on the whole system. However, due to the complexity of the structure itself, the hydrodynamics of the BOP are difficult to model and therefore is the main focus on this thesis.

First a general overview will be given on the challenges of offshore systems during the drilling phase when the BOP is installed directly above the wellhead. The current industrial standard suggested by DNV on the modelling of the BOP will be given. In order to re-evaluate the problem, the non-dimensional analysis will be carried out and the key hydrodynamic effect parameters of the KC number, $\beta$ number and the angle of attack $\alpha$ will be identified.

First sets of the experiments on scale-down BOP model conducted in the MIT Towing Tank show that the experimental measured hydrodynamic coefficients are drastically different from the industrial recommended modeling coefficients that the added mass coefficient $C_m$ and the drag coefficient $C_d$ both have a much larger value than the industrial model provided, and they vary significantly as the function of the key parameters.

An equivalent box model was built and tested to capture the external shape of the BOP and used to address unusual hydrodynamic behavior. The box experiments successfully captured some major trends of the BOP model. It revealed that, first, the externally rectangle shape of the BOP will have a major impact on the variation of the added mass coefficient; second, the BOP model works in the range of overall laminar flow regime and thus, results in an inversely proportional relationship between the drag coefficient and KC number. However, the box model does not exhibit the large values of drag and added mass coefficient found in the BOP, which must be attributed
to the multi-component structure of the BOP and the hydrodynamic interaction of the components. This was later confirmed through numerical and experimental visualization.

Experiments on a model consisting of multiple cylinders exposed to the oscillatory flow are carried out in the MIT towing tank with varying parameters on KC number, $\beta$ number, Gap ratio and angle of attack $\alpha$. Experimental results show that for side-by-side, at certain gap ratio, the drag coefficient of each cylinder will experience an increase, compared to the hydrodynamic of the single cylinder. This confirmed the BOP multi-structure hydrodynamic interaction effect. Also numerical work has been carried out through a 2D BDIM code, named Lilypad. The result confirms the experimental work, revealing that the increase in the drag coefficient is due to the formation of a jet between the Karman streets of the two adjacent cylinders.

Thesis Supervisor: Michael S. Triantafyllou
Title: William I. Koch Professor of Marine Technology
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Chapter 1

Introduction

With the increasing demand for oil supply, the petroleum industry has now embarked on an era of the offshore oil drilling systems, with offshore platforms built for increasingly deeper sea regions further away from land support. For such systems, the key factor is the safety, since, once a part of the system fails, it may cause accidents with large economic and environmental consequences and even life loss. In complicated offshore systems with millions of components, the subsystem of Blow-out Preventer (BOP) plays a key role in keeping the wellhead integrity and preventing any kind of disaster from happening, whose function is to close the valve or even cut the pipe when abnormal well behavior happens, such as extreme erratic pressures and uncontrolled flow and its result, the "blow out"[21].

Hence, it is crucial to identify the dynamic response of the Blow-out preventer, and this requires an assessment of hydrodynamic performance of the BOP in a variety of the flow settings. Since the BOP is an extremely complicated multi-component structure, experiments on a detailed model help us identify its hydrodynamics, especially for oscillatory flow. However in order to facilitate further understanding of fluid mechanism of the hydrodynamic interaction of the complicated structures (they are commonly seen everywhere in the ocean engineering and marine engineering field), research will also be extended into the problem of simplier configuration of the double cylinders in oscillatory flow.

In this chapter, the general overview of the thesis layout is given.
1.1 Thesis Objectives

1. A description is given of the components in the offshore drilling system and their connection to the BOP stack, together with the problems rising because of the presence of the BOP in the system.

2. Current industrial practice for the BOP modeling is reviewed and an assessment of current research is given with the help of non-dimensional analysis.

3. Experimental methods and procedures which are used in the current study to determine the hydrodynamic response of the BOP stack is discussed. Relevant model and experimental setup are also to be displayed.

4. Detailed MIT experiment results are shown conducted on the BOP stack model built by 3D print technology.

5. Experiments on an "equivalent" rectangle box model are used to compare against the BOP model results. Basic flow visualization methods are used to shed light on the unexpected behavior of the hydrodynamic coefficients.

6. A multi-body model is tested in order to understand the BOP multi-component interaction in oscillatory flow and a review of past research on the bluff bodies in oscillatory flow is given.

7. The results of the single cylinder experiment in oscillatory flow are presented to compare with previous research and with dual cylinders results.

8. Dual cylinders of the same diameter with a side-by-side and tandem configurations are experimentally and numerically investigated. Hydrodynamic coefficient obtained from the dual cylinder experiment are used to compare with the corresponding single cylinder experiment, while flow visualization from numerical work provides us fluid pattern information to understand the hydrodynamic interaction.
1.2 Thesis Structure

Chapter 1 gives an introduction to the topic of blow-out preventer in offshore platforms and describes the layout of this thesis.

Chapter 2 presents the major components in the offshore drilling process and their connection with the BOP. The main research focus and main research methods on the BOP stack are presented.

Chapter 3 presents the experimental results on the detail-captured 3d printed BOP stack model, reporting on the hydrodynamic performance of added mass coefficient and drag coefficient.

Chapter 4 presents experiments on the box model to reveal the external shape effect on the hydrodynamic performance. Dye visualization result is also displayed on the box model.

Chapter 5 introduces a multi-body model to address the BOP’s multi-component hydrodynamic interaction and later a review of the past research on cylinders in oscillatory is given.

Chapter 6 presents the experimental results on the single cylinder in oscillatory flow and dual cylinder configuration in side-by-side and tandem setup are experimentally and numerically investigated.

Chapter 7 presents the contributions of the current work and the suggestions for future work.
Chapter 2

BOP in Offshore Drilling Systems

2.1 Introduction

In this chapter, first the overall offshore drilling systems are discussed with a focus on the connections between the BOP and each components. Then the challenges with the presence of the BOP will then be presented, and the current industrial practice on the modelling of the BOP will be given. Later, we raised the questions on the accuracy of the industrial model and then give a more clear statement on the problem.

We carried out a non-dimensional analysis on the hydrodynamics of the BOP system. and the analysis helped us to identify the governing parameters that may influence the hydrodynamics of the BOP. In the current research, we focused on three main parameters: KC number, $\beta$ number and angle of attack $\alpha$.

The last part of this chapter will give an introduction of the major experimental methods and setups applied in the current research including the force measurement, the coefficient extraction and the flow visualization methods.

2.2 An Overview of the Offshore Drilling System

An offshore system is a large complicated system involving millions of component and requires hundreds of millions dollars investment. A typical offshore system involves supporting platform, riser, wellhead [7] [8], mooring system, etc. [3], shown as the
following figure. In this section, the major components and their load applied from environment in the following figure are discussed.

2.2.1 Major Components of Offshore Drilling Systems

In this section, apart from BOP, three other major components in the offshore drilling system are described. They are supporting floating platform, Riser system and Wellhead system.

Supporting Platform

In the ocean production process, a large structure area is needed above the water surface for machine operation, temporary oil storage, workforce accommodation, etc,
and hence the platform.

Depending on the circumstances, the type of platform may vary but can be generally divided into two parts: fixed platform and floating platform. In a large number of offshore system, because of the water depth, it is almost impossible to build a fixed platform for economic and safety consideration. And therefore nowadays, when ocean exploration moves into the deep water, many more floating platforms were built and put into practice. The following figure shows the feasibility for different type of the platform with the changing water depth.

![Evolution of the ocean platform](image)

Figure 2-2: Evolution of the ocean platform (Shell International, 1998).

Riser

The marine riser in the oil industry refers to pipe systems of various functions, which include the structural support, drilling tubes, electronic conduits, and the oil transport cylinders, etc. And their shared character is to connect the upper floating platform down to the seabed wellhead during all kinds of offshore operations, and they are essential lifelines between the sea surface and the sea floor [4] [10]. Nowadays offshore oil production tends to move to a much deeper area, during the drilling process, there are normally two main types of the drilling risers, which will cause a different location of the BOP.
1. low pressure drilling risers
   
   a. Open to the atmospheric pressure
   
   b. Low cost
   
   c. Subsea BOP

2. High pressure drilling risers

   a. Closed to the atmospheric pressure
   
   b. High cost
   
   c. Deck BOP

Currently, considering the cost and safety issues, etc., most of the offshore drilling operations choose low pressure drilling risers, which results in the BOP located close to the seabed, right above the wellhead. For deep water operations, there are various types of design of riser system. In general, in order to reduce the high mode effect, the risers will consist of several joints, separating the riser into pieces with 9-25 meter. Outside the riser lines, buoyancy elements are installed to reduce the weight of the riser in water. Also a variety of the Vortex Induced Vibration (VIV) suppression devices will also be installed outside the riser.

Blow-out Preventer Stack

Blow-out Preventer (BOP) stack [11] is a large stack of hydraulic valves collections, which is used, in the offshore system, when drilling the intermediate and reservoir sections. The main purpose of the BOP is to monitor, control and seal oil and gas wells during drilling process, coping with erratic pressures and uncontrolled flow from well reservoir.

BOP is essential to the safety of the drilling system. In the offshore engineering, starting from 1980s, the common height of BOP was around 12-14 meters, and the weight 125-160 tons. Yet nowadays, with the growing emphasis on the safety issue due to environmental perspective, etc., the redundant valves have been placed on the
same BOP, which contribute to the huge increase in BOPs size and weight. Now, the typical height of the BOP is around 16-18 meters and weight 270-365 tons. Due to the increase in weight, the static load it placed on the wellhead and marine riser hugely increases. For example the buckling problem of the casing system becomes a problem that cannot be neglected. At the same time, the size increase contributes to the importance of the dynamic problems of BOP. A heavier BOP stack will cause a possible decrease in the system natural frequency and therefore cause it to have a stronger response to the dynamic effects from the wave and VIV loads.

The BOP stack is actually composed of two parts. The upper part is the Lower Marine Riser Package (LMRP), and the lower part is blow-out preventer (or ram-preventer) [4]. The following figure shows the connection of the lower and upper part of BOP stack.

- The Lower Marine Riser Package (LMRP) is a collection of a flex joint, LMRP connecter and most importantly an annular preventer (sometimes it can be redundantly installed two annular preventer). The annular preventer is the device used to seal the space between drill pipe and wellbore, inwardly squeezed with hydraulic driven donut-like rubber rings.

![Figure 2-3: Sketch of the Lower Marine Riser Package [4]](image)
The lower part of BOP stack is commonly referred to the BOP directly and it comprises wellhead connector and several ram-preventers. Normally, there are redundant different ram preventers installed in a series around this space. Tow common rams are pipe rams and blind shear rams. Pipe rams are designed to close around the drill pipe, restricting the flow between the drill pipe and wellbore. And the blind shear rams are intended to seal the wellbore via cutting the drill string directly off the well.

Figure 2-4: Sketch of the Ram-Preventers [4]
2.2.2 Environmental Loads on Offshore Drilling Systems

An offshore system is subjected to various environmental loads, all of which will affect the BOP motion through riser and wellhead connections. The following figure shows the various loads on the offshore system.

The loads and forces acting directly on the BOP are considerably small (holding BOP still), since the current speed is relatively negligible close to the sea bottom. When drilling the well, the whole system is connected to the BOP stack with flex joint onto the riser. Thus the total environmental forces acting on the floating platform and the drilling riser are transmitted through the riser to the BOP stack. Driven by the forces from the riser, BOP will experience hydrodynamic force responding to its particular motion in the water. These driven forces depend on the system properties and also the environmental conditions during the operation. And the study shows that when operation depth arrives over 250 meters, the vortex induced vibration force on the drilling riser becomes the dominating load onto the BOP. [20]

Vortex Induced Vibration

When flow passes bluff bodies, owing to the flow separation, consistent shedding vortex will appear in the wake behind the bodies, forming the conical Von Karman vortex street [22]. Such periodic vortex formation will provide the structure with an oscillatory force in the cross-flow direction, and, when the body is free to moving, thus there exists the phenomenon of vortex induced vibration (VIV) [15]. VIV is one

Figure 2-5: Von Karman vortex street behind a bluff body
of the dominating factor for the fatigue damage for the riser system for the offshore engineering. Nevertheless, in the current study VIV of the riser is also the driving force for the BOP to move periodically in the still water, as BOP is directly connected to the riser on top and therefore driven by the riser motion excited by VIV.

2.3 Industrial Practice on BOP Modeling

In mid 2010, a joint industry project on the wellhead has been launched by a number of renowned world-leading oil companies (Statoil, DNV, Marathon, Lundin, Eni, Total, ExxonMobil, BP, BG Group, Talisman, Det Norske and Shell), hoping to come up with a unified analysis methodology for assessing the fatigue damage of the wellhead system. And BOP hydrodynamic modelling are one of the important tasks as the BOP is installed right above the wellhead [20] [9] [7].

2.3.1 Difficulties of BOP Modelling: Equivalent Diameter

The BOP stack is a very complicated structure to describe as it does not have a simple geometry, such as the riser configuration, and therefore is hard to find the reference diameter for later non-dimensional coefficient. So, to begin with, it is very important to come up with a unified way to define the reference diameter for both industrial and scientific use.

Therefore, the equivalent diameter is selected for the BOP stack, which is defined as the diameter of a uniform circular cylinder with the same height as the BOP model and the same overall displaced volume. As shown below, this calculate, therefore,
yields for the model built in the current research to be 2.05”.

Figure 2-7: Sketch of Equivalent Diameter of the BOP

2.3.2 Body in the Unsteady Flow: Morison Equation

As BOP stack is close to the seabed right above the wellhead, the environmental velocity is really small and almost close to zero. The motion of the BOP, as mentioned in the last section, is mainly driven by the periodic riser motion, and namely BOP is moving periodically in the still water.

For a body in oscillatory flow, Mr. Morison came up with the famous Morison Equation [5] in 1950, with the following form written for a moving cylinder:

$$F = -C_d \frac{1}{2} \rho U |U| DL - C_m \pi \frac{D^2}{4} L \frac{dU}{dL}$$

(2.1)

In which, the periodic hydrodynamic force acting on the object is divided into two parts, one of which is in phase with the object’s relative acceleration component to the fluid, and the other of which is in phase with the relative velocity component.

2.3.3 Re-evaluation on the BOP Modeling: Non-dimensional Analysis

Currently, industry solution for the BOP is to use Morrison Equation to model the BOP as an object moving periodically in the still water, and the key question is the determination of the two empirical coefficient $C_m$ and $C_d$. And Suggest by JIP [20], added mass coefficient $C_m$ is chosen to be as a potential flow solution for a circular cylinder, as $C_m = 1$, and the drag coefficient $C_d$ is set to be constant 1 too.
Here in our research, we will examine such choice and relook at the hydrodynamics of the BOP, starting from the use of non-dimensional analysis to determine the research scope. First, we will re-state the problem in a more clear format, as following.

BOP stack is a structure of equivalent diameter $D$ and height $H$ moving sinusoidally with translational amplitude $A$, at frequency $f$, within fluid of density $\rho$, dynamic viscosity $\mu$, at angle of attack $\alpha$.

In this way, the hydrodynamic load $F$ on the BOP are a function of all the parameters mentioned above.

$$F = -F(D, H, A, f, \alpha, \rho, \mu) \quad (2.2)$$

With the non-dimensional analysis, we will reduce the number of the parameters and get as following,

$$G(C_d, C_m, KC, \alpha, \beta) = 0 \quad (2.3)$$

Namely, $C_d$ and $C_m$ is a function of $KC = 2\pi \frac{A}{D}$, $\beta = \frac{\rho f D^2}{\mu}$ and $\alpha$.

### 2.4 Experimental Setup and Analysis Method

This chapter gives an overview of general experimental facilities and corresponding experimental setup, together with measured signals as well as their definitions and sign conventions in the experiments. Besides an overview is given for the interested coefficients that are derived from the measured signals.

#### 2.4.1 Experimental Details

Experimental Facility

MIT small glass tank is strengthened with T-slot aluminum frame, with the size of 8ft by 3ft by 3ft. It is equipped with a velocity-controlled towing carriage riding along the top structures of the tank, which generates a smooth towing motion that simulates the
current scenario. Besides, two additional position-controlled linear motors are placed directly on the carriage platform to provide accurate in-line and cross-flow motion. Therefore, the testing tank allows for the measurement of hydrodynamic forces during prescribed oscillations with and without a free-stream current. In addition, the tank is also equipped for use with capturing and recording Particle Imaging Velocimetry (PIV) data, complete with an integrated laser, high speed camera, and software system. [11]

Figure 2-8: The 8ft by 3ft by 3ft glass tank, which has a smooth carriage and motors capable of imparting motions in the in-line and cross-flow directions

Experimental Setup

For both BOP stack model and box model test, although the research focus is on its hydrodynamic performance in oscillatory flow, experiments of imposed translational oscillation while towing (for stream velocity) has also been done for the complicity of the experiment. In this way, total 4 different types of experiments have been carried out.

- Test type 1: Imposed translational oscillation while towing.
- Test type 2: Imposed translational oscillation in still water.
- Test type 3: Imposed rotational oscillation in still water.
Figure 2-9: imposed translational oscillation while towing (left); imposed translational oscillation (middle); imposed angular oscillation (right);

In this thesis, only the Imposed translational oscillation in still water are discussed in detail

2.4.2 Experimental Analysis Method

Coefficient Extraction

As mentioned the above sections, the force acting on a body undergoing harmonic forced vibration in still water (zero free stream flow), in-line with the imposed motion, can be represented in the famous Morison form as follows:

\[ F = -C_d \frac{1}{2} \rho U |U| DL - C_m \frac{\pi}{4} D^2 L \frac{dU}{dL} \]  

(2.4)

We find the motion \( y = A \cos(\omega t) \) of the structure, and then we will have the coefficient as the following format:

\[ C_d = \frac{1}{T} \int_0^T F(t)U(t)dt \frac{\rho U |U|}{2\pi \rho DL(A \omega)^3} \]  

(2.5)

\[ C_m = \frac{1}{T} \int_0^T F(t)a(t)dt \frac{\pi}{8 \rho D^2 L(A \omega^2)^2} \]  

(2.6)

Flow Visualization

For fluid structure interaction problem, flow visualization methods are often called for fundamentally understand the fluid pattern in order to understand the fluid force
being applied onto the structure. One of the qualitative method is dye visualization. The following figure is used dye into the fluid, forming clear vortex pattern behind the bluff body.

Figure 2-10: Dye injection behind a circular cylinder
Chapter 3

BOP Model in Oscillatory Flow

3.1 Introduction

In the last chapter, we have addressed the challenges in the offshore drilling systems risen by the BOP. And we reviewed the current industrial model people use to address the hydrodynamics of the BOP in oscillatory flow. At last, using non-dimensional analysis, we identified the three main parameters may govern the hydrodynamics of the BOP, which are KC number, $\beta$ number and angle of attack $\alpha$.

In this chapter, the experimental results of the BOP model in oscillatory flow will be presented with an emphasis on their difference between the industrial recommended coefficients. And the hydrodynamic coefficients relationship with the key parameters will also be analyzed.

The results show that the current industrial hydrodynamic model predicted coefficients are far from accurate in terms of both value and trend, and this will affect the description of the BOP dynamics.

3.2 BOP Model Design and Construction

The BOP is an extremely complicated structure, and therefore it is almost impossible to replicate the details using traditional method. Yet with the 3d printed technology, we constructed a 1:38 models that captures even the small details, such as, the top
First of all, the 3d model was established using Solidworks, and then major components of BOP were printed separately and later were combined together.

3.3 BOP Model Cross Flow Vibration Experiment in Uniform Flow

Sometimes near the sea bottom, there exists small velocity current, and this may cause the BOP being self-excited due to the vortex shedding. In this section, experiments (the setup is shown in the following figure.) have been performed to simulate the
Figure 3-2: Experimental model of BOP;

BOP cross-flow vibration in a uniform current. The results of $C_{lv}$ in the current experiments show that it is of small chance for the BOP to be self-excited.

3.3.1 Experimental Matrix

- Towing speed $U = 0.2m/s$
- Angle of attack $\alpha$: 0, $\frac{\pi}{4}$, $\frac{\pi}{2}$
- Oscillation Amplitude (A/D): 0.05, 0.1, 0.15
Figure 3-3: Experimental model of BOP in uniform flow;

- Oscillation Frequency: 0.907 Hz (targeted scaled down frequency)

3.3.2 Experimental Results

It was found that $C_d$ depends on the angle of attack. The $C_d$ trend is consistent with the variation in projected area as the angle of attack of the model was varied, while selected trials at different flow velocities demonstrated that $C_d$ was independent of velocity.

As in the steady tow, the drag coefficient $C_d$ is found to depend on the angle of attack, and the range stayed consistent, between approximately 2.7 and 4.0. shown in the above figure.

The added mass coefficient $C_m$ is also found to vary with the change of the angle of attack $\alpha$. 
For all angles of attack $\alpha$, and $A/D$ values, the lift coefficient in phase with velocity $C_{lv}$ is found to be negative. This result indicates that the BOP will only vibrate as a result of external forcing, and will not undergo self-excited vibrations.

### 3.4 BOP Model Experiment in Oscillatory Flow

In the last section, we demonstrate that BOP under certain flow condition will not be self-excited. In this section, experiment are performed to simulate the scenario of the BOP oscillating in the still water.
The BOP model is set in the MIT small tank and is controlled to oscillate along the carriage direction to achieve maximum oscillation cycles. The experimental setup is shown in the following figure.

3.4.1 Experimental Matrix

- Towing speed $U = 0 m/s$
- Angle of attack $\alpha$: 0, $\frac{\pi}{8}$, $\frac{\pi}{4}$, $\frac{3\pi}{8}$, $\frac{\pi}{2}$
- Oscillation Amplitude (A/D): 0.025, 0.05, 0.075, 0.1, 0.125, 0.15, 0.175, 0.2
Figure 3-8: Experimental model of BOP in oscillatory flow;

- $\beta$ number: 1220, 1810, 2440, 3650, 4880

3.4.2 Experimental Results

In the current experiment, a very large drag coefficient values were found for the zero current case, especially at low $KC$. For all five angles of attack, $C_d$ was found to be inversely proportionally decrease as the $KC$ was increased. This dependence on $KC$ is different from the uniform current case where $C_d$ was found to be nearly constant across the range of $KC$ values. Also it can be observed that, compared to the large $KC$, $C_d$ will have a larger value difference for different angles of attack setup at smaller $KC$ range.

In the current experiment, the added mass coefficients $C_m$ was found between approximately 2.2 and 4.2. $C_m$ was found to strongly depend on the angle of attack of the model. The largest $C_m$ values were found for the case of 0 angle of attack and the smallest values for the $\pi/2$ case. For all five angles it is also found that $C_m$ increased slightly with $KC$. 
We have performed experiment at five different $\beta$ number. The $\beta$ number governs the vibration frequency of the BOP in the experiment. The following two figures show the $\beta$ effect on the hydrodynamic coefficient of the BOP at angle of attack $\alpha = 0$.

For drag coefficient in phase with the velocity, the $\beta$ number has the similar effect
Figure 3-11: Added mass coefficient for BOP at various angles of attack in oscillatory flow ($\beta = 2440$);

Figure 3-12: Added mass coefficient for BOP at various angles of attack in oscillatory flow ($\beta = 4880$);

on different $KC$ number cases. In the current experiment, $C_d$ will reach a local minimum at $\beta = 1810$ and then increase slightly with the riser of the $\beta$.

For added mass coefficient, compared to the $C_d$, the $\beta$ number too has the similar effect on different $KC$ number cases that $C_m$ will reach a local minimum at $\beta = 1810$ and then increase slightly with the riser of the $\beta$.

3.5 Conclusions

In the current experiment on the BOP, we can draw the following conclusions that
Figure 3-13: Drag coefficient in phase with velocity for BOP at angle of attack $\alpha = 0$ in oscillatory flow with varying $\beta$;

Figure 3-14: Added mass coefficient for BOP at angle of attack $\alpha = 0$ in oscillatory flow with varying $\beta$;

- The BOP has a low chance to be self-excited in a low velocity free stream.
- The current industrial recommended coefficients are far from accurate in terms of value and trend
  - Compared to industrial coefficient, $C_m$ is 3 times larger and $C_d$ is an order of magnitude larger.
  - $C_m$ is strongly dependent on the angle of attack $\alpha$.
  - $C_d$ will decrease inverse proportionally with the increase of the $KC$, and the angle of attack $\alpha$ has a much stronger effect on $C_d$ at small $KC$ range.
Chapter 4

External Shape Effect: Box in Oscillatory Flow

4.1 Introduction

In the last Chapter, the result of the BOP model experiment in oscillatory flow shows that the current industrial model is far from accurate. The added mass coefficient $C_m$ is averagely three times large than the current potential flow prediction coefficient and also has a strong dependency on the angle of attack $\alpha$, and this may strongly affect the predicted natural frequency. The drag coefficient $C_d$ is even an order of higher than the current industrial model coefficient and also has an almost inversely proportional decay relationship with the increasing KC number.

In this chapter, in order to answer the trend of the hydrodynamic coefficients in the BOP model experiments, a box model is built and tested that helps to capture the general external shape of the BOP model. And the results of the box model successfully replicated some major trend of the BOP experiments. This indicates that the external shape plays an important role in the BOP’s hydrodynamic performance. Later a simple dye visualization setup is applied on the box model to reveal different flow regimes in the different KC range, this helping to explain the hydrodynamic coefficient behaviors, especially the inversely proportional decay trend for the drag coefficient $C_d$ with KC number.
However there is still a large value difference between the box model and the BOP model. And the numeric. This suggests an upgraded model needed to study the multi-structure hydrodynamic interaction.

4.2 Box Model Design and Construction

A 1:57 scale waterproof box shaped model, serving as equivalent simplified BOP, was built in HDPE (high density polyethylene). The model was mounted in the same glass tank at the MIT Testing Tank facility and shared the same experimental setup as for the 1:38 BOP model. A comparison between BOP model and box model can be seen in the following figure

![Figure 4-1: The BOP model (bottom) and box model (top)](image)

In order to control the total weight, the box shaped model was constructed by 6 HDPE sheets (0.5 in), which are cut into the target shape by water jet. Then, epoxy has been used to glue the sheets together and also serve as waterproof coating, hence resulting in slightly larger dimensions of 3.08" x 3.77" x 11.38", compared with the original dimensions of 3.0" - 3.67" - 11.33".
4.3 Box Model Experiment in oscillatory flow

In this section, the results of the box model experiment in oscillatory flow are presented.

4.3.1 Experimental Matrix

- Towing speed $U = 0 m/s$
- Angle of attack $\alpha$: $0, \frac{\pi}{6}, \frac{\pi}{4}, \frac{\pi}{3}, \frac{\pi}{2}$
- Oscillation Amplitude (A/D): 0.015, 0.025, 0.05, 0.075, 0.1, 0.125, 0.15, 0.175, 0.2
- $\beta$ number: 2440

4.3.2 Experimental Results

![Graph](image.png)

Figure 4-2: Coefficient of drag in phase with velocity $C_d$, at $\beta = 2440$, as a function of the amplitude to projected diameter ratio for 5 different angles of attack.

The above figure shows the added mass coefficient $C_m$ for the box model in oscillatory flow for five different angles of attack $\alpha$. We find that the added mass coefficient $C_m$ strongly depends on the angle of attack, capturing the major trend for the BOP model. Also, the values of $C_m$ for box model is relatively close to potential flow
predictions on a 2D square section, and the added mass coefficient is $C_m = 1.1885$. However, unlike the experiments on the BOP model, the box model does not show any noticeable dependence on $A/D$.

![Figure 4-3: Added mass coefficient $C_m$, at $\beta = 2440$, as function of the amplitude to projected diameter ratio for 5 different angles of attack.](image)

The above figure shows the drag coefficient in phase with the velocity $C_d$ for the box model in oscillatory flow for five different angles of attack $\alpha$. For $C_d$, we find that there are two different trends for the box model as function of $A/D$. When $A/D$ is small, $C_d$ has a large value that decreases inverse proportionally with increasing $A/D$, same as the BOP model experiment. But up to a threshold $A/D$ value, $C_d$ slightly increases with increasing $A/D$. Also no strong dependence on the angle of attack $\alpha$ has been noted.

4.4 Flow Patterns around the Box Model: Dye Visualization

The box model in oscillatory flow helps us to capture a large amount of the features shown in the BOP model too, such as following

- the added mass coefficient $C_m$ show a strong dependence on the effect of angle of attack $\alpha$.

- the drag coefficient in phase with velocity $C_d$ shows an inverse proportion relationship with $A/D$ (up to a threshold for box model).
Through these features, we can conclude that the external shape of the BOP which is a rectangle profile has a strong effect on the BOP hydrodynamics. And in order to understand the hydrodynamic coefficient behavior, the proper flow visualization has been applied to shed light on the flow patterns around the box model. Through that, two separate flow regime was recognized, thus explain the $C_d$’s different behavior dependence on $A/D$.

![regime.png](Body/Images-chap4/regime.png)

Figure 4-4: Two different flow regimes of the box shape with the change of the $KC$ number. The two circled cases are the experimental dye visualization results.

### 4.4.1 Low $KC$: Non-Separated Flow Regime

In the above figure of the dye visualization, the two different color at the free surface around the box model remain almost identical after one complete oscillation cycle. This suggest that the flow around the box model at this $KC$ number is in a non-separation flow regime, in another word, laminar flow regime [1]. Hence for a square cross section, the drag coefficient in phase with velocity $C_d$ can be expressed as

$$C_d = 3\pi^2 B (KC)^{-1} (\pi \beta^{-0.5} t)$$

we can see in the above equation that the $C_d$ has an inverse proportional relationship with $KC$ number. In the following figure it shows that in the small $KC$ range, the theory prediction match extremely well with the experiment result, while with the increase of the $KC$, the difference between the theory prediction and experimental result becomes larger and larger.

### 4.4.2 High $KC$: Separated Flow Regime

In the dye visualization experiment for the high $KC$ number for the box model. Large edge vortex has been observed in the experiment, which indicts a flow separated
regime and hence the failure of the theoretical model used to predict $C_d$ for the laminar regime. As for such flow around the square shape cross section, before the formation of the vortex street, the drag coefficient in phase with velocity $C_d$ is only dependent on the local flow around each sharp corner [5]. And the $C_d$ can be expressed as following,

$$C_d \sim KC^{-\gamma}$$

In which $\gamma = (2\delta - \pi)/(3\delta - 2\pi)$, and $\delta$ is the inner corner angle. And therefore $C_d$ is constant for a facing square.
4.5 Flow Patterns around the BOP Model

In the last section, we successfully use dye visualization to identify the two separate flow regime and recognize the inverse proportional relationship of the $C_d$ with $KC$ number. However compared to the simple box model, there are still large value difference from the BOP model for both $C_m$ and $C_d$. And this suggests that there are still unknown hydrodynamic factors affecting the BOP model. And the flow visualization on the BOP model is applied to reveal the mechanism behind it.

4.5.1 Numerical Simulation

The numerical work is a courtesy from the Alan Le Goallec. In the above figure, a simplified numerical model has been constructed, capturing the major feature of multi-structures openings.

The following figure shows that because of the multi-structure hydrodynamic interaction of the BOP, the flow patterns become extremely complicated. Flow structure,
Figure 4-7: Dye visualization on the Box model at high $KC$ number

Figure 4-8: Numerical model of the BOP (courtesy from Alan Le Goallec) [11]
such as flow jet motion from the opening can be identified. To look at the inner

![3D vortex pattern of the BOP in oscillatory flow](image)

Figure 4-9: 3D vortex pattern of the BOP in oscillatory flow (courtesy from Alan Le Goallec)

structure and opening of the BOP model, one slice on the 3d numerical result has been extracted. It shows that shedding vortices from the inner structure and outer structure highly interact with each other. This unique vortices generation pattern by the several internal members will cause jets which expel energy from the openings, resulting also in a complex external flow pattern.

In the snapshot of the long time evolution of the flow patterns around BOP, we find that shedding vortices forming vortex pair and help each other traveling far away from the structure while still being able to preserve its own original shape.

4.5.2 Flow Visualization

Dye visualization method has also been applied onto the BOP model, showing in the above figure. And this has confirmed the flow jet phenomenon from the opening in the numerical work.
Figure 4-10: 2D Z-vorticity snapshot plot for numerical BOP slides denoted in the model figure (courtesy from Alan Le Goallec)

Figure 4-11: 2D Z-vorticity (long time evolution) plot for numerical BOP slides denoted in the model figure (courtesy from Alan Le Goallec)
4.6 Conclusions

Through the box model experiments, we investigate the external shape effect on the BOP model and use dye visualization to shed light on the unique hydrodynamic behavior.

- The external shape effect of the BOP will cause added mass coefficient $C_m$ a dependence on angle of attack $\alpha$.

- BOP is in the non-separation flow regime, which causes the drag coefficient in phase with velocity $C_d$ display an inverse proportional relationship with $KC$ number.

- There are still huge value difference between the BOP and the box’s hydrodynamic coefficient.
• The numerical and experimental flow visualizations help to capture the unique jet motion from the opening of the BOP. Such complex flow patterns cannot be addressed by the simple box model.
Chapter 5

New Model of Multi-Body Interaction in Oscillatory Flow

5.1 Introduction

In the last chapter, in order to answer the unique hydrodynamic performance of the BOP, experiment has been performed on the simple box model to address the external shape effect. The result shows that the external shape does have a strong effect on the BOP model. However, revealed from dye visualization and numerical work, the large value differences are largely owing to the BOP’s porosity that cause a unique jet motion pushing out fluid from its openings.

In this chapter, an upgraded model involving two circular cylinder in oscillatory flow is built and tested to address hydrodynamic interaction caused by the multi-structures. A review of the past research work of cylinders in oscillatory flow is given. And then the design of the experiment and the 2D numerical work scheme will be presented.

5.2 Review on Cylinders in Oscillatory Flow

In order to study the complexity of the hydrodynamic interaction of the multiple structure in oscillatory flow, for the simplicity, a dual cylinders model is proposed in
order to reveal the hydrodynamic interference caused by the dual cylinders in oscillatory flow [13]. However, to begin with, the start point are look at the single cylinder hydrodynamic response in oscillatory flow under different vibrational amplitude and frequency, namely $KC$ and $\beta$ number.

In the fluid mechanics research, the study of basic shape, such as the circular cross-sectional cylinder, is of a great importance, as it reveals the fundamental fluid mechanics principal as well as the fact that circular shape structure can be seen everywhere in the nature and industrial application [24].

So in this section, a general review on the past research work on the problems of the hydrodynamics of the cylinders in oscillatory flow are given, and are expanded into three sub-sections.

5.2.1 Single Cylinder in Oscillatory Flow

Compared to the classical problem of circular cylinder response in a uniform stream, the problem of cylinder in oscillatory flow or cylinder oscillating in the still water is far less studied. And yet, it is still a great interest to the scientists and offshore engineers, etc., since we see such scenarios of cylinder in oscillatory flow as Pump tower in the LNG tanker experiencing sloshing load, or even more generally, the wave induced flows around subsea structures like pipelines[24], etc. In this section, oscillatory force and flow patterns of the single cylinder in oscillatory flow are separately reviewed.

Oscillatory Force on the Cylinder

When a circular cylindrical structure sits in oscillatory flow or the structure oscillates in the still water, the force align with the motion direction is normally expressed in the Morrison Form [2] [19], as shown in the Chapter 2. Also the flow and force characters of the cylinder are highly dependent on the two parameters of $KC$ number and $\beta$ number, as being deeply discussed in the last 3 chapters. Because of the non-existence of the uniform stream, the Reynolds number is defined with the maximum
oscillation velocity, as following,

\[
Re = \frac{U_m D}{\nu} = KC \ast \beta
\]

Experimental-wise, Bearman first comprehensively reported the experimental data on the cylinder of different cross sections \([1]\), including circular one, in oscillatory flow at relatively small \(KC\) number. He found the critical \(KC\) number determine the on-set of the flow separation and therefore different trends for the \(Cd\). Later Sarpkaya \([13]\) \([14]\) carried out an extensively experiment in the U-shape water tunnel, and in his paper he presented the in-line force data for one rough and three smooth cylinder at a wide range of \(KC\) and \(\beta\) number with an emphasis on the \(KC\) effect on the \(C_d\) and \(C_m\) variation and their connection to the flow separation, vortical instability and boundary-layer transition.

Williamson originally \([24]\) reported the both the lift force and in-line force for a single cylinder in oscillatory flow and use the flow visualization method, being able to synchronize the vortex shedding with the force behavior.

flow patterns Around the Cylinder

A majority work of the cylinder in oscillatory flow is focusing on the flow patterns around the cylinder both experimentally and numerically.

Apart from a correlation between the force and vortex formation, Williamson \([24]\) also discuss the flow patterns for the single cylinder at \(\beta = 730\) and \(KC < 40\). He found that the number of the vortex shedding will increase with the rise of the \(KC\) number. He separates the flow regime into the vortex pair attachment regime \((0 < KC < 7)\), single pair regime \((7 < KC < 15)\), two pairs regime \((15 < KC < 24)\), three pairs regime \((24 < KC < 32)\) and four pairs regime \((35 < KC < 40)\). At the same time, Tatsuno Bearman \([18]\) did a more thorough experimental investigation on both \(\beta\) and \(KC\) on the flow patterns around circular cylinder. The experiments were performed at \(KC\) ranging from 1.6 to 15 and \(\beta\) between 5 and 160. In their research, 8 flow regimes were identified, denoting with \(A_*, A, B, C, D, E, F\) and \(G\).
On the other hand, the flow patterns around the circular cylinders will transit from 2D to 3D with the change of the $KC$ and $\beta$ number. A large number of work has dedicated to the 2D to 3D flow transition [6] [17] [16].

At the same time, many numerical studies have also been performed to simulate oscillatory flow affect on the circular cylinder, which provides a richer physical insight into the problem. Justensen [12] did a 2D simulation on the single cylinder in oscillatory flow with $\beta = 196, 483, 1035$ and $0 < KC < 26$. Bearman Graham [1] performed the simulation on the same problem with a different $\beta = 76$. Good flow patterns were successfully repeated compared to the experiment.

5.2.2 Dual Cylinders in oscillatory flow

Compared to researches on the single cylinder in oscillatory flow and the work on the two cylinders in the uniform flow, the studies are much rare.

One of the most comprehensive and original experimental work on the two cylinders in oscillatory flow is by Williamson [23] [24], he found in his work, for two cylinders oscillating in the still water while having a moderate gap (distance is comparable to oscillation amplitude.), vortex shedding from the two cylinders will either be in phase or anti-phase with each other, depending on the configuration gap ratio, $KC$ number. Such flow patterns has therefore strongly alter the lift and in-line force of the system.

The numerical work on the two cylinders is recently conducted by Zhao Cheng [25]. They have conducted a wide-range of numerical simulation cases on the problem with gap ratio $G = \frac{L}{D}$ ranging from 0.5, 1, 1.5, 2, 3, 4 and 5, $KC$ ranging from 1-12 with an increments of 0.25 and the varying $Re = 50, 75, 125, 200, 275$ for $0.5 < G < 2$ for both side-by-side and tandem cases. The results showed that they successfully reenacted flow features for some of the experimental cases, compared the Williamson experiments. Besides, like Bearman’s classification on the flow region, they proposed, summarize and classify the different types of the flow regime into $A^* - A^*$, $A - A$, $D - D$, $A - D$, $GVS$, $GVS - D$, $GVS - E$ and irregular for side-by-side case and $A^*$, $A^* - A^*$, $A$, $A - A$, $D$, $D - D$ and irregular for the tandem case.
5.3 Experimental Design and Setup

The above section reviews the past work on the cylinders in oscillatory flow, from forces and flow patterns discovered in the single cylinder case to much rare experimental and numerical work on the dual cylinders in different configurations.

In this section, we will present the experimental setup that has been applied in the current research and also we will discuss the experimental cases that we have performed.

5.3.1 Experimental Design

The experiments are performed in the MIT Towing Tank Small Tank facility, same as the BOP experiment mentioned in the above chapters. In order to address the dual cylinders experiment with a changeable gap ratio setup, a new frame has been designed, built and installed on the small tank facility.

In the following figure 5-1, it shows the design of the current frame installed on the small tank carriage with the holder on the two cylinders with the side-by-side setup (The current setup is also allowed Tandem setup with a small alternation.).

The figure 5-2 shows the total frame setup on the small tank in the real life. In the figure 5-3, it gives a closer look on the frame connection with the holder and cylinder models. The holders (showed in figure 5-4) are bolted onto 6-axis force meters which are connected to the sliding plate on the 8020 frames. Apart from the frame setup, in order to reduce the free surface effect and also the end effect of the setups, another two smooth plastic plates has been applied in the design and experiments, as shown in the figure 5-5, close to the cylinder model top and bottom ends. The following figure 5-6 shows the cylinder model of different diameters used in the experiments. Each cylinder has a holding shaft with a diameter of 0.5”. At the same time, each cylinder has been through the treatment of the galvanization to ensure a long-lasting smooth surface.
Figure 5-1: Overall design for dual cylinders experiment in oscillatory flow in the tank

Figure 5-2: Lab setup for dual cylinders experiment in oscillatory flow setup design in the tank
5.3.2 Experimental Matrix

Here in the following figure 5-7 shows the $KC$ and $\beta$ experimental cases have been performed.
Figure 5-5: Sketch of the setup for the end plates in the dual cylinders experiment

Figure 5-6: Cylinder models used in the experiment. The diameters are, from top to bottom, 2.0in, 1.0in, 1.0in, 0.75in, 0.5in.
5.4 Single Cylinder in oscillatory flow

Before the research on the dual cylinders in oscillatory, it is necessary to present the work on the single cylinder experiment, helping to validate the credibility of result with a comparison to the former research and at the same time, to shed some light on the new phenomenon. In this section, the single cylinder experiment and 2D simulation result are presented.

5.4.1 Force coefficient for single cylinder in oscillatory flow

The inline force, as described in the above chapters, can be decomposed into two parts, the drag coefficient in phase with the velocity $C_d$ and the added mass coefficient $C_m$ (namely drag coefficient in phase with acceleration).

In the above figure 5-8, we can see how $KC$ number will affect $C_d$. At the small $KC$ number, $C_d$ decreases drastically with the increase of the $KC$ number, which is explained the above chapters as it stays in region of the non-separation flow, and therefore a inverse proportional relationship can be formed. When the $KC$ keeps increasing beyond the number around 2.5, $C_d$ starts to steadily rise until reaching
Figure 5-8: Single cylinder in oscillatory flow: $KC$ effect on $C_d$.

$KC$ around 10, and they start to converge on a constant value in the current $KC$ range. Such trend shows in all the $\beta$ cases.

Figure 5-9: Single cylinder in oscillatory flow: $KC$ effect on $C_m$. 
The corresponding trend for $C_m$ vs $KC$, can be shown in the figure 5-9. And we do find similarity for $C_m$ and $C_d$ in terms of trend change $KC$ point. For $C_m$, below $KC = 2.5$, $C_m$ in general increases with the $KC$ number. But from $KC = 2.5$ to $KC = 10$, we saw a strong decrease, as matter of fact, from 1.6 to 0.4 for $C_m$ value. After that point We saw $C_m$ starting to recover and converge close to the potential flow value, which is 1.0.

At the same time, we can also express our force in the root mean square format for both inline and lift force. The Inline RMS force coefficient is shown in the following figure 5-10.

![Image of graph showing $C_{fRMS}$ vs $KC$]

**Figure 5-10:** Single cylinder in oscillatory flow: $KC$ effect on $C_{fRMS}$.

The above figure 5-11 shows the lift force coefficient RMS value. The interesting part we found is that at around $KC$ around 10, same as the transition point for $C_d$ and $C_m$, a peak in the lift force coefficient can be observed. This may due to the vortex wake mode transition, as mention by Williamson. In figure 5-13 and 5-14 we saw the power spectral for the lift force coefficient showing the force harmonic term transiting from first harmonic to second harmonic at different $KC$ number.
Figure 5-11: Single cylinder in oscillatory flow: $KC$ effect on $C_{l_{RMS}}$.

Figure 5-12: A close look on the peak in $C_{l_{RMS}}$. 

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5.4.2 2D flow patterns around single cylinder in oscillatory flow

In order to elucidate the force trend reported on the last section, it is necessary to address the fluid pattern around the single cylinder to help better understanding this fluid structure interaction phenomenon. So in this section, using home-developed code Lilypad, we simulated three case with different $KC$ number, 6, 8 and 12 and also adjust the $\beta$ number in order to keep the same $Re$ number, which is $Re = KC \times \beta = 120$.
$Kc = 6$

The following 5 figures, from figure 5-15 to figure 5-19 reveals the flow patterns around the single cylinder in one period for $KC = 6$ and $\beta = 20$. It is clear that at this relatively small KC number case, the vortical wake pattern around the single cylinder displays in a format of one pair of vortices continuously attached to the cylinder surroundings in the first half period before the new developed vortices in the base of the cylinder. These two vortices later will depart from the cylinder surface from the other sides of the cylinder corresponding to its birth side. However the vortices will not travel far away, instead, it will merge with the former shedding vortices in the close vicinity of the cylinder and therefore form the blob of vortical wake around single cylinder oscillating in the still water at $KC = 6$ and $\beta = 20$.

Figure 5-15: Wake pattern for single cylinder at $t = 0T$ for $KC = 6$ and $\beta = 20$.

Figure 5-16: Wake pattern for single cylinder at $t = 0.25T$ for $KC = 6$ and $\beta = 20$. 

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Figure 5-17: Wake pattern for single cylinder at $t = 0.5T$ for $KC = 6$ and $\beta = 20$.

Figure 5-18: Wake pattern for single cylinder at $t = 0.75T$ for $KC = 6$ and $\beta = 20$.

Figure 5-19: Wake pattern for single cylinder at $t = 1T$ for $KC = 6$ and $\beta = 20$.

$Kc = 8$

The following 5 figures, from figure 5-20 to figure 5-24 reveals the flow patterns around the single cylinder in one period for $KC = 8$ and $\beta = 15$. 

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Figure 5-20: Wake pattern for single cylinder at $t = 0T$ for $KC = 8$ and $\beta = 15$.

Figure 5-21: Wake pattern for single cylinder at $t = 0.25T$ for $KC = 8$ and $\beta = 15$.

$KC = 12$

The above 5 figures, from figure 5-25 to figure 5-29 reveals the flow patterns around the single cylinder in one period for $KC = 12$ and $\beta = 10$. It clearly shows in the half cycle, 4 vortices are shedding away, with two pair generated in each side of the cylinders.
Figure 5-22: Wake pattern for single cylinder at $t = 0.5T$ for $K_C = 8$ and $\beta = 15$.

Figure 5-23: Wake pattern for single cylinder at $t = 0.75T$ for $K_C = 8$ and $\beta = 15$.

5.5 Conclusions

In this chapter, inspired by the unique flow patterns around the BOP, caused by the hydrodynamic interaction of the multiple components, a simplified dual cylinders model in oscillatory flow has been proposed and constructed, helping to address the problem that can not be accessed via simple box model.

Later a review of the research on the circular cylindrical structures in oscillatory
flow is provided in this chapter, discussing the former research topics covering, force
and flow patterns associated with the single cylinder, two cylinders, and cylinder
bundles in oscillatory flow.

After a discussion about the current experimental design and experimental case
matrix, the experimental result of the single cylinder has been presented, followed by
three typical case of the 2D flow patterns around single cylinder in oscillatory flow
with different $KC$ number.
Figure 5-26: Wake pattern for single cylinder at $t = 0.25T$ for $KC = 12$ and $\beta = 10$.

Figure 5-27: Wake pattern for single cylinder at $t = 0.5T$ for $KC = 12$ and $\beta = 10$. 
Figure 5-28: Wake pattern for single cylinder at $t = 0.75T$ for $KC = 12$ and $\beta = 10$.

Figure 5-29: Wake pattern for single cylinder at $t = 1T$ for $KC = 12$ and $\beta = 10$. 
Chapter 6

Dual Cylinders in Oscillatory Flow

6.1 Introduction

In the last chapter, we propose a new model of dual cylinders in oscillatory flow as the simple building block to study the multi-bodies interaction in oscillatory flow.

In this chapter we will first present experimental result on the single cylinder in oscillatory flow with a changing KC number and $\beta$ number and compare with the existing research work. Then we are focusing on the experiment and numerical work on one of the configurations for the dual cylinders, the Side-by-Side case with a diameter ratio $D_r = 1.0$. And the experimental are also performed with a changing KC number, $\beta$ number and Gap Ratio $G_r$.

The result shows that, compared to the single cylinder, the dual cylinder will experience an increase of the drag coefficient $C_d$ at certain Gap ratio. And the corresponding numerical work displays an interesting phenomenon that at certain gap ratio, there exists a jet flow inside the gap and also the shedding vortices between the gap will form a vortex pair that induce each other to move far away from the body, which expels the energy away from the structure and therefore explains the increase of the drag coefficient.
6.2 Dual Cylinders in Oscillatory Flow: Experiment

In this section, we are going to present the force coefficient results for dual cylinder setup from both Side-by-side and Tandem. And we will focus on two β number and mainly discuss the KC number effect on the hydrodynamic force coefficient.

6.2.1 Drag coefficient $C_d$

![Figure 6-1: $C_d$ for Side-by-Side Setup of different gap ratio at $\beta = 540$.](image)

Figure 6-1 and figure 6-2 show $C_d$ changing trend at different Gap Ratio at $\beta = 540$ and $\beta = 1460$ distinctly. The first thing we recognized is that the dark purple line represent result of the farthest distance of $C/D = 5$, and hence obtaining a really close both trend and value, compared to the single cylinder result (dashed line). This suggests that the Hydrodynamic interference at this distance become relatively small at the current KC and β number range.

One thing particularly interesting about the $C_d$ for the Side-by-Side case experiments is the increase of the $C_d$. This can be especially clearly seen in the figure 6-2 of $\beta = 1460$ case. The red solid line represents the close case of $C/D = 1.5$. For example, at $KC = 5$, the $C/D = 1.5$ case obtains a $C_d$ of 3 while the single cylinder
Figure 6-2: $C_d$ for Side-by-Side Setup of different gap ratio at $\beta = 1460$.

The case is below 1. This $C_d$ increase can also be found in the $\beta = 540$ case, however, there are cases, such as $C/D = 3.0$, at some $KC$ number shows a lower $C_d$ than single cylinder case. This drag coefficient increase will later be again addressed in the numerical simulation and then explained.

Figure 6-3: $C_d$ for Tandem Setup of different gap ratio at $\beta = 540$.

The $C_d$ in the tandem case behaves a lot differently from the side-by-side case.
But first thing we also notice again is that at larger gap ratio of $C/D = 5$, the $C_d$ at $\beta = 540$ is close to the single cylinder case, which means the shedding vortex from another cylinder has a maximum effective distance for given $KC$ and $\beta$ number.

Apart from that, we found in this time, $C_d$ in the tandem case is normally lower than the single cylinder case at $\beta = 540$. However in the $\beta = 1460$ case, the $C/D = 5.0$ some time shows a higher $C_d$ value than single cylinder case.

6.2.2 Added mass coefficient $C_m$

The figure 6-5 and figure 6-6 show the $C_m$ of the dual cylinder in the side-by-side configuration, with a comparison to the single cylinder. Again we found that when the gap ratio becomes large as $C/D = 5.0$, the single cylinder and dual cylinder behaves quite similarly regarding to the $C_m$ value and trend with the $KC$ number.

Another thing we noticed with the $C_m$ is that for the single cylinder, it will experience a strong decrease around $KC = 10$, which appears in both $\beta = 1460$ and $\beta = 540$ cases. And also when gap ratio is large it also shows the similar trend with a strong decrease. However in the $C/D = 1.5$ case (the smallest gap ratio), we do not observe any kind of strong decrease trend for both two $\beta$ number, and at the same
time, at the small gap ratio, dual cylinders obtain a much higher $C_m$. 

![Figure 6-5: $C_m$ for Side-by-Side Setup of different gap ratio at $\beta = 540$.](image1)

Compared to the last two figures, figure 6-7 and figure 6-8 reveals the relationship of the $C_m$ and $KC$ with different gap ratio. Here again we found the added mass is generally large than the single cylinder, for the dual cylinder setup, which is not
predicted by the potential flow model. Also we found that when the gap ratio increase, in the tandem setup, it is not necessary that the $C_m$ for the dual cylinders converges to the single cylinder, as we can see in the $\beta = 1460$ case.

Figure 6-7: $C_m$ for Tandem Setup of different gap ratio at $\beta = 540$.

Figure 6-8: $C_m$ for Tandem Setup of different gap ratio at $\beta = 1460$. 
6.2.3 Lift force coefficient $C_l$

The root mean square value of the lift coefficient is shown in the figure 6-9 to figure 6-12 for both the tandem and side-by-side case.

We saw in the side-by-side configurations, dual cylinders with different gap ratio will all experience an peak value with the change of the $KC$ number. And in the current result, we saw this peak $KC$ number varies with the gap ratio that in the current $\beta$ range, the smaller the gap ratio, the earlier this peak will show up for the $KC$ number.

![Figure 6-9: $C_l$ for Tandem Setup of different gap ratio at $\beta = 540$.](image)

While in the tandem configuration, we did no see much lift force coefficient variation, which may be explained by the fact the cylinder will directly affect by the shedding vortices from the neighbour cylinder. This later can be revealed int the 2D numerical simulation result.

6.3 Dual Cylinders in Oscillatory Flow: 2D Simulation

In the last section, we have discussed about the force coefficient in the dual cylinder experiment in both tandem and side-by-side configuration. Compared to the single
Figure 6-10: $C_l$ for Tandem Setup of different gap ratio at $\beta = 1460$.

Figure 6-11: $C_l$ for Tandem Setup of different gap ratio at $\beta = 540$.

cylinder case, dual cylinders setup display unique force pattern, such as the drag coefficient increase. In this section, we have applied 2D numerical simulation using BDIM algorithm based code LilyPad. We are trying to address and explain several phenomena in this fluid structure interaction problem from the wake pattern analysis. one case of tandem and one case of side-by-side has been picked out, with more are
Figure 6-12: $C_l$ for Tandem Setup of different gap ratio at $\beta = 1460$.

given in the Appendix B and Appendix C.

6.3.1 Cylinders in Side by Side Arrangement

Figure 6-13: Dual cylinders in side-by-side configuration of $KC = 6$, $\beta = 20$, $C/D = 1.5$ at $t = 0T$;

The series of the vorticity plot of the side-by-side setup of a gap ratio $C/D = 1.5$, we discover that because of the interaction of the dual cylinder, there are a strong
jet induced by the pair of the vortices between the gap, and later these vortex pair will self induced velocity to move away from the structure, which helps the energy dissipation, and hence the high $C_d$. 

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6.3.2 Cylinders in Tandem Arrangement

The series of the vorticity plot of the tandem setup of a gap ratio C/D = 1.5 shows that the cylinders are highly affected by the neighbouring cylinder’s vortex shedding.

Figure 6-16: Dual cylinders in side-by-side configuration of KC = 6, β = 20, C/D = 1.5 at t = 0.75T;

Figure 6-17: Dual cylinders in tandem configuration of KC = 6, β = 20, C/D = 1.5 at t = 0T;
Figure 6-18: Dual cylinders in tandem configuration of $KC = 6$, $\beta = 20$, $C/D = 1.5$ at $t = 0.25T$;

Figure 6-19: Dual cylinders in tandem configuration of $KC = 6$, $\beta = 20$, $C/D = 1.5$ at $t = 0.5T$;
Figure 6-20: Dual cylinders in tandem configuration of $KC = 6$, $\beta = 20$, $C/D = 1.5$ at $t = 0.75T$;
Chapter 7

Main Contributions and Future Work

7.1 Contributions

7.1.1 Experimental work on the BOP in Oscillatory Flow

Through non-dimensional analysis, we re-evaluated the problem of hydrodynamic coefficient prediction of the BOP in oscillatory flow and identified the key parameters governing its hydrodynamic performance, \( KC \), \( \beta \) and angle of attack \( \alpha \).

Through experiments using a 3d printed model, we find that the current industry model coefficients are not accurate enough to capture the hydrodynamic performance of the BOP.

- The added mass coefficient \( C_m \) is on average 3 times larger than the potential flow model and is strongly dependent on the angle of attack \( \alpha \). Using the potential flow, the model will cause an overestimation of the natural frequency for the system.

- The drag coefficient in phase with velocity \( C_d \) is an order of magnitude larger than the industrial recommended value and is also inversely proportional with the increasing \( KC \) number.
7.1.2 Experimental work on the Box in Oscillatory Flow

The box model is constructed in order to understand the unique hydrodynamic coefficients measured in the BOP experiments.

The experimental results of the box model capture some of the major trends of the hydrodynamic coefficients in the BOP experiments. They confirm that the external shape has a strong effect on the BOP’s hydrodynamic performance. The dye visualization on the Box and the BOP model shed light on the flow patterns around the structures, and shows a laminar flow regime at low $KC$ number and therefore explains the inverse proportional relationship between $C_d$ and $KC$ number.

- The experimental results for the hydrodynamic coefficient of the box confirm that the external shape of the BOP matters and therefore needs to be taken into consideration during the modeling work.

- The dye visualization on the box model shows that the box is in the laminar flow regime at low $KC$ number, and in a separated flow region at high $KC$ number.

- The numerical simulation and dye visualization on the BOP model reveal a complicated and unique flow patterns around BOP structure, including flow jet from the BOP openings, which can not be addressed by a simple box model.

7.1.3 Experiments on Dual Cylinders in Oscillatory Flow

The dual Cylinders model has been tested and experiments of side-by-side tandem arrangement with varying gap ratio have been performed. The results are used to investigate the hydrodynamic interaction caused by multiple structures in oscillatory flow.

- In the experiment, $C_d$ in the side-by-side arrangement was found to experience an amplification compared to the single cylinder setup. And, with the decrease of the gap ratio, such amplification effect are more and more prominent.
The added mass coefficient $C_m$ in both side-by-side and tandem configuration is largely different than for the single cylinder case. In single cylinder experiments, $C_m$ experiences a strong decrease around $KC = 10$, while such phenomenon are not found in the dual cylinder experiment.

7.1.4 Numerical Simulations on Dual Cylinders in Oscillatory Flow

In addition to the experiments on the dual cylinders in oscillatory flow, in order to identify the flow patterns around the dual cylinders at different gap ratios, 2D numerical simulations using Lily-Pad has also been performed. Although at different $\beta$ number, the simulations replicate some phenomena found in the experiments. The vortex a flow jet formation through vortex pairing is the basic flow mechanism responsible for the unusually high hydrodynamic coefficient in the BOP.

- The simulated side-by-side dual cylinder with a gap ratio $C/D = 1.5$ successfully captured the phenomenon of strong jet formation in the cap, together with the generation of a vortex pair with self induced velocity that causes it to move away from the structure. This helps to understand and explain the phenomenon found in the experiment of $C_d$ amplification due to the strong energy dissipation from the structure to fluid.

- The flow patterns of the tandem case simulation shows the neighbouring cylinder will shed vortices that directly and strong interact with the other cylinder, as the cylinder, due to the tandem setup, will swim inside the wake of the neighbouring cylinder.

7.2 Future Work

The current research work starts at the investigation on the industrial structure of BOP in the offshore engineering field. The research on the BOP and box models in oscillatory flow reveals that the external shape has a strong influence and will affect the trend of the hydrodynamic coefficient of the system and hence the dynamics.
However, because of the hydrodynamic interaction from the multiple structural component of the BOP, several unique hydrodynamic phenomena can not be addressed by a simple solid box model.

A more comprehensive model is needed in order to generate the insight into the problem of hydrodynamic interaction caused by multiple objects, and hence the dual cylinders model in oscillatory flow. The experimental and 2D numerical result on the dual cylinder with different gap ratio and same diameter ratio of the side-by-side configuration reveals several interesting results, such as the self-sustained vortex pair expelling away from the the gap opening between the cylinders.

The current research opens a new and, most importantly, fundamental topic of multiple cylinders in oscillatory flow. The dual cylinders model will already involve the research on the effect of gap ratio, diameter ratio, configuration (angle of attack respect to the motion direction), 2D motion, etc. And the result is of great importance, it helps to get a insight on the fluid structure interaction problem of multiple objects interaction in oscillatory flow. And the results can be also applied in the real engineering field, such as the BOP in the offshore engineering, newly emerged wave-energy farm configuration, pump tower in the LNG tanker when experiencing sloshing load, etc.
Appendix A

BOP Model Experimental Results in oscillatory Flow

A.1 Drag Coefficient in Phase with Velocity at various angles of attack $\alpha$

Figure A-1: Drag coefficient in phase with velocity for BOP at various angles of attack in oscillatory flow ($\beta = 1220$);
Figure A-2: Drag coefficient in phase with velocity for BOP at various angles of attack in oscillatory flow ($\beta = 1810$);

Figure A-3: Drag coefficient in phase with velocity for BOP at various angles of attack in oscillatory flow ($\beta = 2440$);

A.2 Added Mass Coefficient at various angles of attack $\alpha$
Figure A-4: Drag coefficient in phase with velocity for BOP at various angles of attack in oscillatory flow ($\beta = 3650$);

Figure A-5: Drag coefficient in phase with velocity for BOP at various angles of attack in oscillatory flow ($\beta = 4880$);
Figure A-6: Added mass coefficient for BOP at various angles of attack in oscillatory flow ($\beta = 1220$);

Figure A-7: Added mass coefficient for BOP at various angles of attack in oscillatory flow ($\beta = 1810$);
Figure A-8: Added mass coefficient for BOP at various angles of attack in oscillatory flow ($\beta = 2440$);

Figure A-9: Added mass coefficient for BOP at various angles of attack in oscillatory flow ($\beta = 3650$);
Figure A-10: Added mass coefficient for BOP at various angles of attack in oscillatory flow ($\beta = 4880$);
Appendix B

Flow Pattern of Dual Cylinders in Side-by-Side Configuration in 2D Simulation

Figure B-1: Dual cylinders in side-by-side configuration of $KC = 6$, $\beta = 20$, $C/D = 2$ at $t = 0T$;
Figure B-2: Dual cylinders in side-by-side configuration of $KC = 6$, $\beta = 20$, $C/D = 2$ at $t = 0.25T$;

Figure B-3: Dual cylinders in side-by-side configuration of $KC = 6$, $\beta = 20$, $C/D = 2$ at $t = 0.5T$;
Figure B-4: Dual cylinders in side-by-side configuration of $KC = 6$, $\beta = 20$, $C/D = 2$ at $t = 0.75T$;

Figure B-5: Dual cylinders in side-by-side configuration of $KC = 6$, $\beta = 20$, $C/D = 4$ at $t = 0T$;
Figure B-6: Dual cylinders in side-by-side configuration of $KC = 6$, $\beta = 20$, $C/D = 4$ at $t = 0.25T$;

Figure B-7: Dual cylinders in side-by-side configuration of $KC = 6$, $\beta = 20$, $C/D = 4$ at $t = 0.5T$;
Figure B-8: Dual cylinders in side-by-side configuration of $KC = 6$, $\beta = 20$, C/D = 4 at $t = 0.75T$;

Figure B-9: Dual cylinders in side-by-side configuration of $KC = 12$, $\beta = 10$, C/D = 1.5 at $t = 0T$;
Figure B-10: Dual cylinders in side-by-side configuration of $KC = 12$, $\beta = 10$, $C/D = 1.5$ at $t = 0.25T$;

Figure B-11: Dual cylinders in side-by-side configuration of $KC = 12$, $\beta = 10$, $C/D = 1.5$ at $t = 0T$;
Figure B-12: Dual cylinders in side-by-side configuration of $KC = 12$, $\beta = 10$, $C/D = 1.5$ at $t = 1T$;

Figure B-13: Dual cylinders in side-by-side configuration of $KC = 12$, $\beta = 10$, $C/D = 2$ at $t = 0T$;
Figure B-14: Dual cylinders in side-by-side configuration of $KC = 12$, $\beta = 10$, C/D = 2 at $t = 0.25T$;

Figure B-15: Dual cylinders in side-by-side configuration of $KC = 12$, $\beta = 10$, C/D = 2 at $t = 0.5T$;
Figure B-16: Dual cylinders in side-by-side configuration of $KC = 12$, $\beta = 10$, $C/D = 2$ at $t = 0.75T$;
Appendix C

Flow Pattern of Dual Cylinders in Tandem Configuration in 2D Simulation

Figure C-1: Dual cylinders in tandem configuration of $KC = 6$, $\beta = 20$, C/D = 2 at $t = 0T$;
Figure C-2: Dual cylinders in tandem configuration of $KC = 6$, $\beta = 20$, $C/D = 2$ at $t = 0.25T$;

Figure C-3: Dual cylinders in tandem configuration of $KC = 6$, $\beta = 20$, $C/D = 2$ at $t = 0.5T$;
Figure C-4: Dual cylinders in tandem configuration of $KC = 6$, $\beta = 20$, $C/D = 2$ at $t = 0.75T$;

Figure C-5: Dual cylinders in tandem configuration of $KC = 6$, $\beta = 20$, $C/D = 4$ at $t = 0T$;
Figure C-6: Dual cylinders in tandem configuration of $KC = 6$, $\beta = 20$, $C/D = 4$ at $t = 0.25T$;

Figure C-7: Dual cylinders in tandem configuration of $KC = 6$, $\beta = 20$, $C/D = 4$ at $t = 0.5T$;
Figure C-8: Dual cylinders in tandem configuration of $KC = 6, \beta = 20, C/D = 4$ at $t = 0.75T$;

Figure C-9: Dual cylinders in tandem configuration of $KC = 12, \beta = 10, C/D = 1.5$ at $t = 0T$;
Figure C-10: Dual cylinders in tandem configuration of $KC = 12$, $\beta = 10$, C/D = 1.5 at $t = 0.25T$;

Figure C-11: Dual cylinders in tandem configuration of $KC = 12$, $\beta = 10$, C/D = 1.5 at $t = 0.5T$;
Figure C-12: Dual cylinders in tandem configuration of $KC = 12$, $\beta = 10$, $C/D = 1.5$ at $t = 0.75T$;

Figure C-13: Dual cylinders in tandem configuration of $KC = 12$, $\beta = 10$, $C/D = 2$ at $t = 0T$;
Figure C-14: Dual cylinders in tandem configuration of $KC = 12$, $\beta = 10$, $C/D = 2$ at $t = 0.25T$;

Figure C-15: Dual cylinders in tandem configuration of $KC = 12$, $\beta = 10$, $C/D = 2$ at $t = 0.5T$;
Figure C-16: Dual cylinders in tandem configuration of $KC = 12$, $\beta = 10$, C/D = 2 at $t = 0.75T$;
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