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Inline-Crossflow Coupled Vortex Induced Vibrations of Long Flexible Cylinders

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ABSTRACT

The inline motion of long flexible cylinders caused by Vortex Induced Vibrations (VIV) has been long neglected due to its small amplitude compared to the cross-flow response amplitude. However, the inline motion has a major impact on fatigue life due to its higher frequency (second harmonic) and more importantly, because it triggers a third harmonic stress component in the crossflow direction along with a broad-band frequency stress component. We introduce an inline response prediction module to VIVA, a VIV response prediction program widely used in the offshore industry, to be able to consequently predict the higher harmonic and chaotic VIV response characteristics of flexible cylinders. Extensive forced inline and combined inline-crossflow experiments were employed to provide hydrodynamic coefficient databases for input to VIVA, in addition to existing crossflow hydrodynamic coefficients. The Norwegian Deepwater Programme (NDP) experimental data were used to validate this prediction methodology.

1. INTRODUCTION

The study of vortex-induced vibrations (VIV) and the resulting material fatigue is particularly important in design for ultra-deep water oil exploration and development. Long cylindrical structures such as risers and mooring lines can be outfitted with VIV-cancellation systems or subjected to aggressive replacement schedules; however the cost of these measures can be high. Effective VIV and fatigue prediction programs offer the prospect of design and replacement schedule optimization. Software package Vortex-Induced Vibration

Analysis (VIVA) [1] has been widely used in numerous academic and industrial applications in order to predict VIV of flexible cylinders. Vortex-Induced Vibration has been an intensively studied field in the past 30 years [2,3], however the significant influence of the inline motion on fluid forcing and stress harmonics has long been ignored due to low observed inline amplitudes, until recently [4,5,6]. In this paper, we extend the response prediction obtained through VIVA from purely a crossflow response to a combined inline and crossflow response. We achieve this expansion of response prediction capabilities by conducting a series of fine-grid two-dimensional forced VIV experiments on a rigid cylinder.

2. METHODOLOGY

The prediction program, VIVA, consists of two parts: (1) a fluid-structure interaction model and (2) laboratory-derived or empirical databases. The fluid-structure interaction model consists of a fluid force model and the equations of structural dynamics. The hydrodynamic databases primarily contain hydrodynamic information in the form of the lift force coefficients (lift coefficient in phase with velocity and added mass coefficient) and drag coefficients. These force coefficients are often obtained from extensive laboratory experiments using a rigid cylinder.

The free vibration of a rigid cylinder that is elastically mounted demonstrates a response that can be divided into three regions [7], Figure 1, : (i) At reduced velocities less than 4, inline motion is dominant; (ii) if the reduced velocity is larger than 8, the crossflow motion is dominant, and (iii) when the reduced velocity is between 4 and 8, there is a strong coupling

effect between the inline and crossflow vibrations. Thus we will use different hydrodynamic databases to predict VIV motion depending on the dominant reduced velocity, namely pure inline database, pure crossflow database, and inline-crossflow coupled database, corresponding to the regions discussed above.

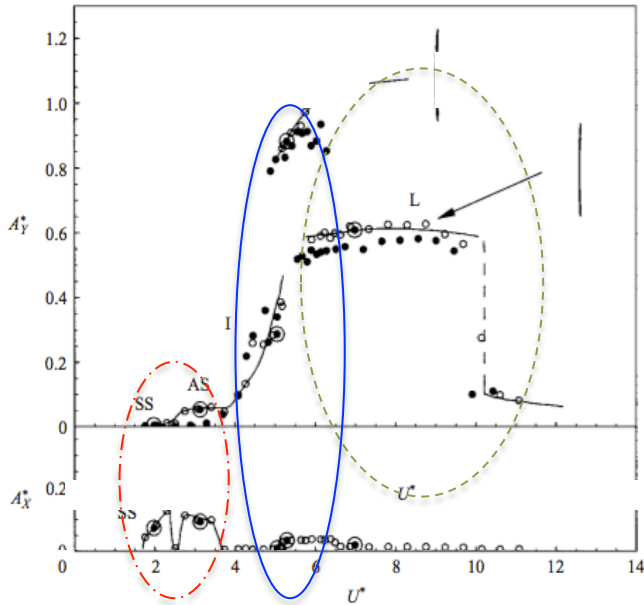


Figure 1: VIV Response Regions, Crossflow motion dominant region is marked with -- on the right, Inline-Crossflow motion region is marked by - in the middle and Inline motion dominant region is marked by - - on the left. (Figure altered from Jauvtis and Williamson [7])

3. INLINE VIV MOTION MODELING AND PREDICTION

3.1 Pure Inline VIV Motion Experiments

In order to produce a database for the inline hydrodynamic forces, we conducted a series of forced VIV tests in a small towing tank. The tank is 2.4 m long, 0.9 m wide, and 0.64 m deep, filled with clear, deionized water while a small towing carriage rides along the top of the tank. Figure 2 shows a photo of the tank with the carriage. The carriage traverse holds two linear motors that are used to force cylinder motions both in the transverse and inline directions.

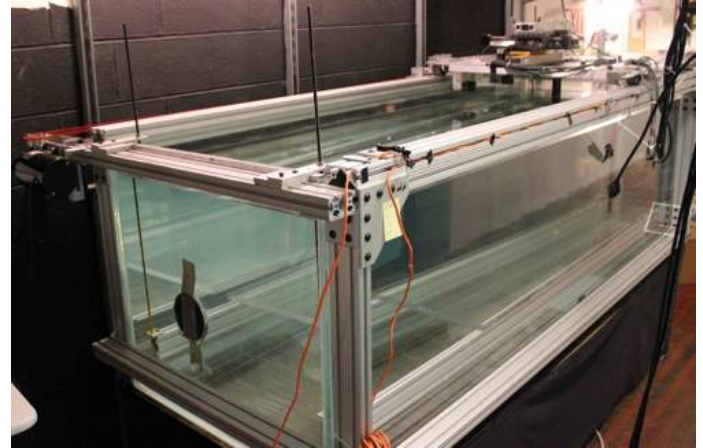


Figure 2: Small Towing Tank.

A six-axis sensor, located on a cantilevered arm connecting the linear motors and the test cylinder, is used to measure forces on the cylinder. A six-axis calibration was performed to correct voltage measurements based on the large moments exerted on the cantilevered test cylinder. The test cylinder, with a diameter of 0.038 m and a wetted span length of 0.64 m is mounted vertically and extends the entire depth of the towing tank. The tests were conducted following the matrix shown in Figure 3 with finer grids at low frequency and amplitude. The Reynolds number (Re) of the test is 7600.

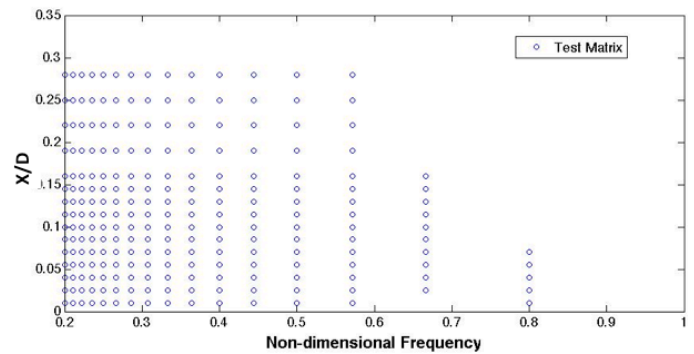


Figure 3: Test Matrix.

Figure 4 shows a sample of experimental signals. The blue signal is the velocity of the carriage, which represents the relative motion of the current to the cylinder and two clear jumps observed at the beginning and end of the signal indicate the duration of the experiment. The pink vertical lines indicate the section of signal that is stable and consequently used for hydrodynamic coefficients extraction. The signal in black is the measured linear motor position based on the motor encoder reading. The green signal is force in the inline direction measured from force sensor mounted on the cylinder.

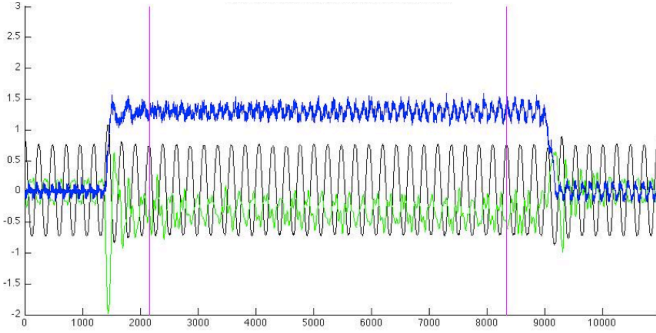


Figure 4: Samples of Experimental Signals.

The experimental data processing diagram is shown in Figure 5. The starting point of the signal is determined through the carriage velocity and linear motor motion and Butterworth filter is employed to filter the measurement drifting and high frequency noise. After the stable section of force measurement is identified, the data is trimmed and scaled to calculate the lift and drag coefficients.

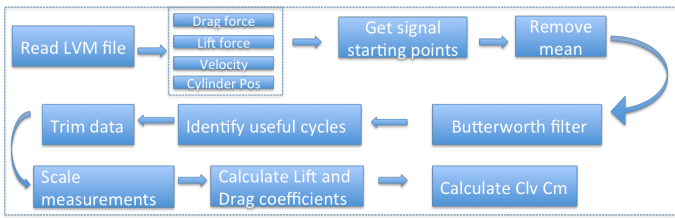


Figure 5: Experiment Data Processing Diagram

The resulting lift coefficients in phase with velocity and added mass coefficients versus the crossflow amplitude of oscillations and the reduced velocity are shown in Figures 6 and 7, respectively.

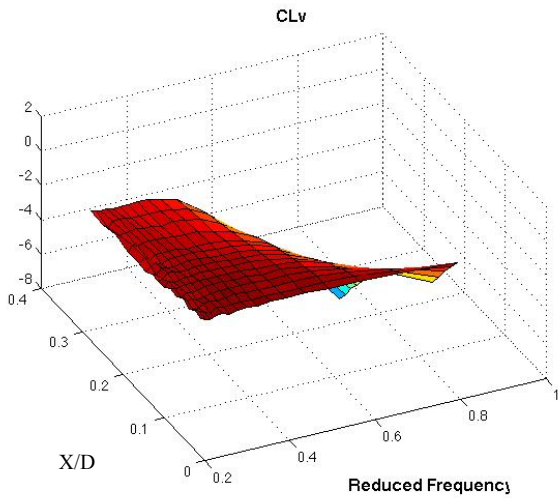


Figure 6: Lift Coefficients in Phase with Velocity (C_{lv}) for Purely Inline Oscillations.

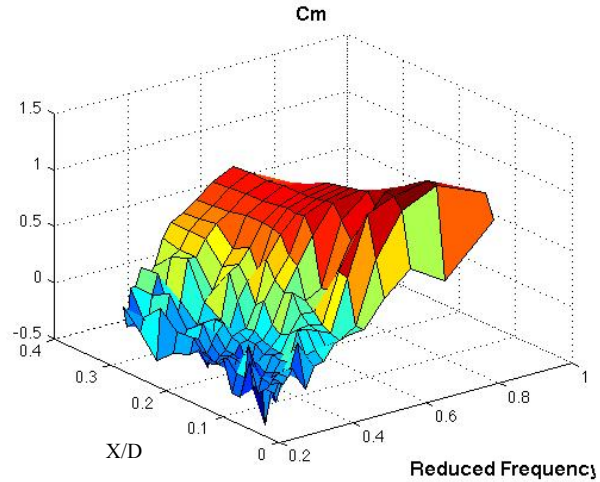


Figure 7: Added Mass Coefficients (C_m) for Purely Inline Oscillations.

3.2 Inline VIV Prediction using VIVA

The experimental database of force coefficients is first used to predict the response of an elastically mounted, rigid cylinder. The governing equation [8] of a rigid cylinder of mass, m , mounted on springs with spring constant, k , and dashpots with damping constant, b , under a uniform current of velocity U is

$$m_x \ddot{x} + b_x \dot{x} + k_x x = D_f \quad (1)$$

where

$$D_f(t) = \text{Re}\{[m_{a,IL} A_y (2w)^2 + i C_{lv,IL} (\frac{\rho_f U^2 DL}{2})] e^{i(2wt - \theta)}\} \quad (2)$$

The hydrodynamic force is decomposed into two terms: one in phase with velocity and one in phase with acceleration (added mass force). The lift coefficient in phase with velocity $C_{fv,IL}$ and added mass coefficient $C_{a,IL}$ are defined as

$$C_{fv,IL} = \frac{F_0 \sin(\phi)}{\rho_f U^2 DL / 2} \quad (3)$$

$$C_{m,IL} = \frac{-F_0 \cos(\phi)}{\rho_f \pi D^2 LA w^2 / 4} \quad (4)$$

Where F_0 is the magnitude of hydrodynamic force, ρ_f is the density of the fluid, D is diameter of the cylinder, L is the span length of cylinder and A_w is the wet area. The lift coefficient values correspond to the experimentally obtained coefficients and the resulting system response using the mass-spring-damper model is shown in Figure 8. The resulting inline response of the cylinder is very similar to the freely vibrating

inline response observed for a low mass-ratio cylinder allowed to move with combined crossflow and inline motions [9].

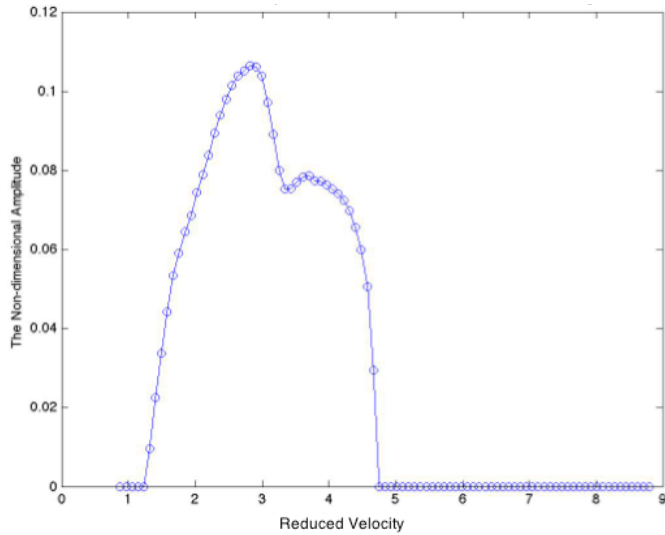


Figure 8: Nondimensional Amplitude of the Inline Oscillations vs. Reduced Velocity for a Flexibly Mounted Rigid Cylinder.

Upon demonstrating that a purely inline database gives an expected response for an elastically mounted, rigid cylinder, VIVA is adapted to predict the vortex-induced vibrations of a flexible marine riser in the inline direction for low reduced velocities. VIVA uses a linear theory to describe structural oscillations since VIV oscillations have small amplitude relative to the length of the riser. The calculation of the response is done using a strip theory approximation, where the long riser is divided into a number of small sections over which the fluid forces acting on the riser are assumed to be the same as for an elastically mounted rigid cylinder. Using strip theory, the response is combined along the length to form the overall riser response.

To simulate a long flexible cylinder, a linear, tensioned beam model is employed:

$$m \frac{\partial^2 x}{\partial t^2} + b \frac{\partial x}{\partial t} - \frac{\partial}{\partial z} \left(T \frac{\partial x}{\partial z} \right) + \frac{\partial^2}{\partial z^2} \left(EI \frac{\partial^2 x}{\partial z^2} \right) = f(x, z, t) \quad (5)$$

where, m is the mass per unit length of the structure; b is the structural damping; T is the tension; EI is the flexural rigidity, and f is the fluid load per unit length, which is a function of the motion of the structure.

The database for the IL oscillations is introduced to VIVA through 5 inputs that describe the shape of the surfaces defining the added mass and lift in phase with velocity as functions of the amplitude response and the reduced frequency (inverse of the reduced velocity). These input surfaces are shown in Figures 6 and 7. Since it is computationally expensive to manipulate the complete 3D surfaces, the surfaces are divided into cross-sections for various reduced frequencies, which act

as a standard input for VIVA. Figure 9 shows the five input functions, which describe the input surface for a particular cross-section. In general, for a constant amplitude of motion, the lift coefficient in phase with velocity can be described by a point-wise linear function with an initial slope at low reduced frequencies, a transition point at a particular reduced frequency, and a second slope at higher reduced frequencies. For example in Figure 9, we show: a) C_{lv} at zero non-dimensional amplitude as a function of non-dimensional frequency, b) C_m at zero non-dimensional amplitude as a function of non-dimensional frequency, c) the average slope of C_{lv} for low reduced frequency indicated in Figure 9a, d) the average slope of C_{lv} for high reduced frequency as indicated in Figure 9a, and e) the point where C_{lv} reaches its maximum and transitions between the two linear slopes.

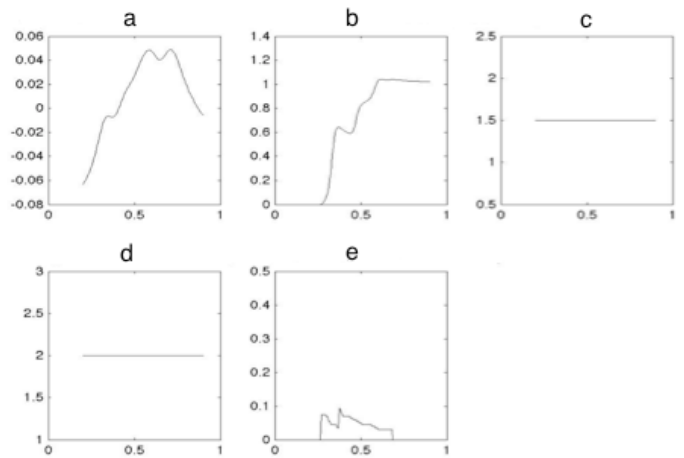


Figure 9: The Inline Basic Bare File Input to VIVA.

A prediction of the inline vibration of a flexible riser was made using the structural characteristics of a riser from the Norwegian Deepwater Programme (NDP) Riser High Mode VIV tests [10,11]. This allowed for a direct comparison between the prediction method and observed vibrations from experiments. The experimental tests were conducted on a 38-meter riser with the characteristics shown in Table 1, kept under tension and towed horizontally at varying speeds with either uniform or sheared flow profiles. In the uniform flow cases, the flow velocity was varied from 0.3 to 2.2 m/s, in 0.1 m/s increments. Measurements of the in-line strain were taken at 40 points along the riser, while measurements of the cross-flow strain were taken at 24 points.

Table 1: NDP 38m Test Riser Properties [10]

Riser Properties	
Length between pinned ends	38m
Outer Diameter	0.027m
Wall Thickness	0.003m
Young's Modulus	$2.25 \times 10^9 \text{ N/m}^2$
Bending Stiffness	598.8 Nm^2
Mass/Unit Length (air filled)	0.761 kg/m
Mass/Unit Length (water filled)	0.933 kg/m

Figure 10 shows the ratio between the theoretical predicted dominant frequency of inline motion and the observed frequency of inline motion from experiments for a number of experimental cases. The dotted line indicates the condition over which there is a perfect match between the predicted frequency and the observed experimental frequency. One can see that there is very good agreement between the predicted frequency and observed frequency from experiments.

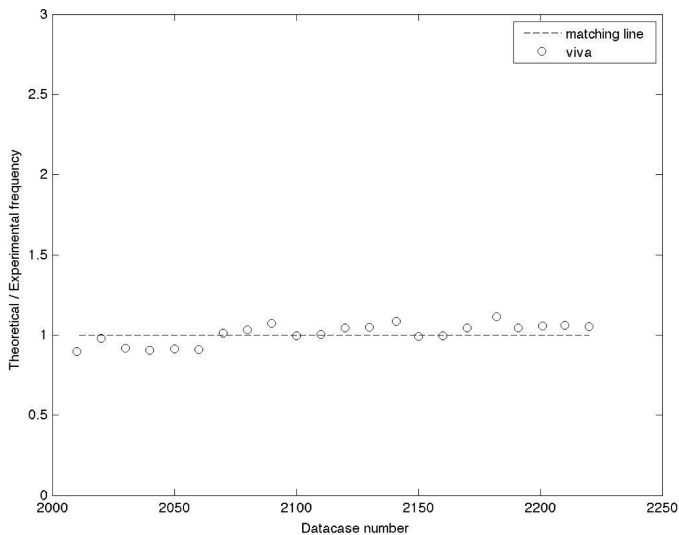


Figure 10: Inline VIVA Predicted Frequencies Versus Experimental Values.

The amplitude of the predicted and observed VIV response in the inline direction are shown in Figure 11. The red circles indicate the experimental data obtained from the NDP experiments at discrete locations and blue solid lines show the prediction from VIVA. In general, VIVA tends to underpredict the amplitude in the in-line direction. The inline amplitude is relatively small from the experimental cases, so the assumption used in the prediction method that there is no crossflow motion may have an impact on the resulting prediction of inline motion, since there is likely still coupling effects between the inline and crossflow response in this region.

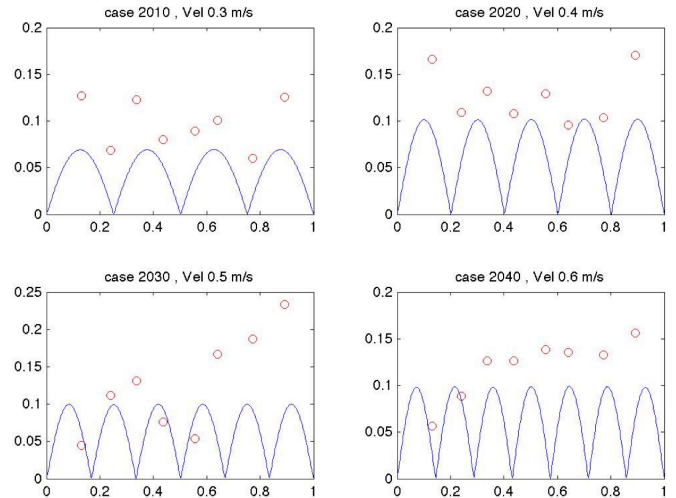


Figure 11: Inline VIVA Predicted Amplitude Versus Experimental Values.

4 INLINE-CROSSFLOW VIV MOTION EXPERIMENTS AND MODELING

4.1 2D Forced VIV Motion Experimental Database

An experimental database is necessary to extend the capabilities of VIV prediction in VIVA to allow prediction of coupled 2D inline-crossflow response. A series of 2D forced vibration experiments were conducted at the MIT towing tank to produce this database [9] with a total of 2304 experimental runs, which cover 6 transverse amplitudes, from 0.25 to 1.5 in increments of 0.25; 6 in-line amplitudes, from 0 to 0.75 in increments of 0.15; 8 phases, from -180 to 180 degrees in increments of 45 degrees; 8 reduced velocities, from 4.5 to 8 in increments of 0.5. One challenge with extending the prediction method to include combined inline and crossflow motions is that the number of variable parameters increases, which results in a large number of experiments necessary to define the hydrodynamic coefficients governing the problem. The experiments described in [9] were an initial attempt to characterize the force coefficients over a relatively small range of reduced velocities, and this series of experiments still resulted in a very sparse representation of the hydrodynamic forces governing a combined crossflow and inline response. While this set of experiments provides useful information on the forces exerted on a rigid cylinder undergoing combined crossflow and inline motion, in order to be able to use it as a hydrodynamic database in VIVA, it is necessary to increase the resolution of the experimental grid. The same experimental set up used for the pure inline forced VIV experiments is employed with the additional usage of a second linear motor in the crossflow direction.

From the free vibration experiments [10, 11], the inline and crossflow motions are significant in the reduced velocity region of 4 to 8, as shown in Figure 1; therefore, experiments are

conducted in this range of reduced velocities. Also, from Dahl et al free vibration experiments [12], reproduced in Figure 12, the ratio of the inline to crossflow amplitude in this region is less than 1/3. In order to limit the number of experiments necessary to expand the resolution of the experimental database experiments are conducted only for ratios smaller than 1/3, as show in Table 2.

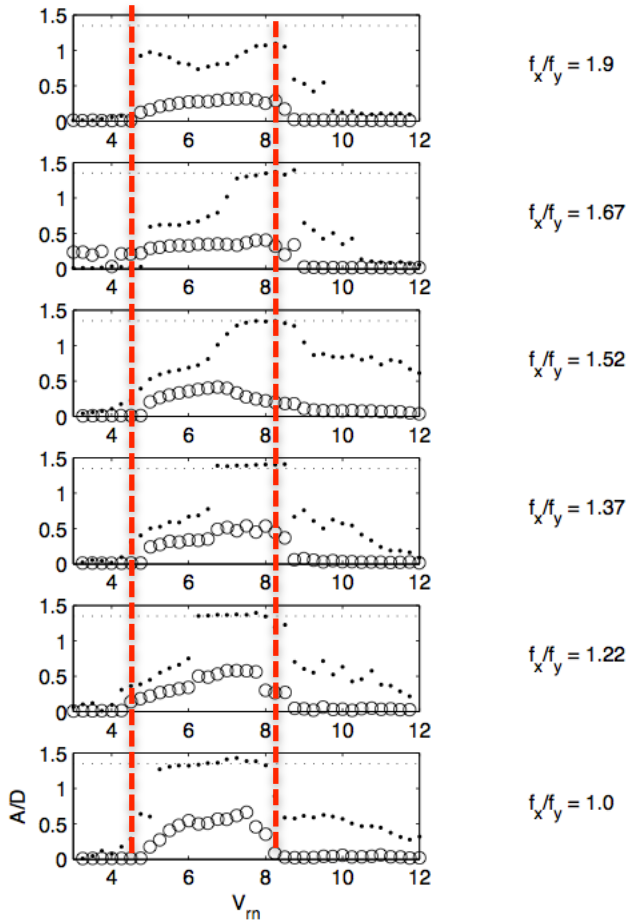


Figure 12: 2D Motion Regions in Free Vibration Experiments. (Figure altered from Jauvtis and Williamson [7])

Table 2: 2D Experiment Amplitude Matrix. The first column is the crossflow non-dimensional amplitude and the first row is the inline non-dimensional amplitude.

$\gamma \setminus x$	0.05	0.1	0.15	0.2	0.25	0.3
0.15	1	x	x	x	x	x
0.25	1	1	x	x	x	x
0.5	1	1	1	1	x	x
0.75	1	1	1	1	x	x
1	1	1	1	1	1	1

It was observed by Jauvtis and Williamson [7] and Dahl et al [13] that for the free vibration of cylinders with two degrees of freedom, the phase between the in-line and transverse motion can vary greatly, from -180 to 180 degrees, especially if the nominal natural frequency ratio between inline and crossflow motions is variable (as may exist on a long riser), Since the entire range of phases is shown to exist for freely vibrating rigid cylinders, 18 phases are chosen from -180 to 180 degrees in increments of 15 degrees from -45 to 45 degree and increments of 22.5 degrees otherwise in order to expand the phase resolution of the database, which previously only included data for 8 phases.

In summary, a total of 2754 experimental runs are scheduled covering 6 in-line amplitudes, from 0.05 to 0.3 in increments of 0.05; 5 transverse amplitudes, from 0.15 to 1. (0.15, 0.25, 0.5, 0.75, 1); 18 phases, from -180 to 180 degrees in increments of 15 degrees from -45 to 45 degree and 22.5 degrees otherwise, and 9 reduced velocities, from 4 to 8 in increments of 0.5. These data points are chosen in order to expand the existing database of values from [9], including some overlapping points in order to verify previous results.

The resulting lift coefficients in phase with velocity and added mass coefficients at reduced velocity 4.5 are shown as iso-surfaces of lift coefficient as a function of inline amplitude, crossflow amplitude, and phase between inline and crossflow motion in Figure 14. The same results are show as contours in Figure 15 for fixed values of the phase between inline and crossflow motion.

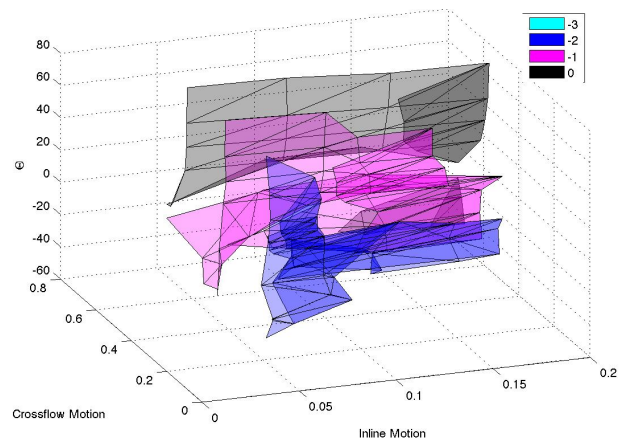


Figure 14: Lift Coefficients Extracted from the Experiments at a Reduced Velocity of 4.5 as Iso-surfaces.

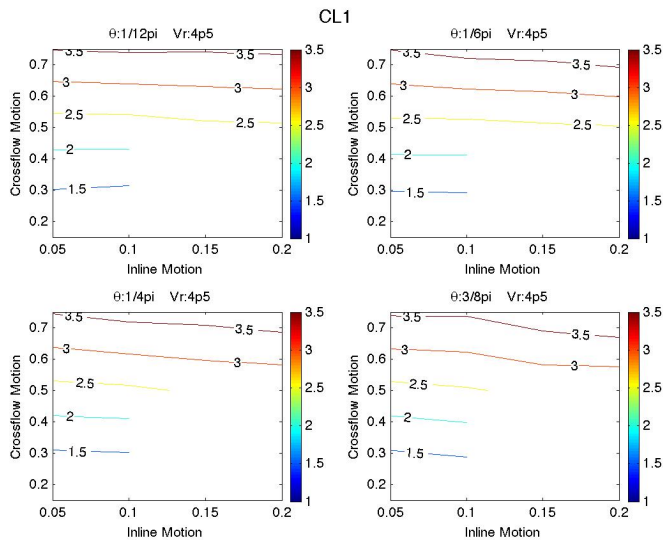


Figure 15 Lift Coefficients Extracted from the Experiments at a Reduced Velocity of 4.5 as Contours at Different Phases.

5. CONCLUSIONS

In this paper, we address the coupled inline and crossflow VIV prediction through systematic modeling and extensive experiments. The ultimate goal is to include the inline prediction module to VIVA and extend its capabilities to predict the coupled crossflow-inline VIV of flexible cylinders. We conducted a series of experiments on a rigid cylinder forced to oscillate in the inline direction only and measured the lift coefficient in phase with velocity and the added mass coefficient for various inline amplitudes and frequencies, and used these measurements to make a hydrodynamic database for the inline VIV. We used this database in order to predict the inline oscillation of a flexibly mounted rigid cylinder, and then extended this method to the case of a flexible cylinder and obtained reasonable agreement with the experimental results of the NDP tests. In order to extend this prediction method to the case of coupled crossflow-inline oscillations, we made a hydrodynamic database using the measurements conducted on a rigid cylinder forced to oscillate in two dimensions. The resulting database can be used in coupled VIV prediction of flexible cylinders.

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