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Citation: Zheng, Haining, Rachel Price, Yahya Modarres-Sadeghi, George S. Triantafyllou, and Michael S. Triantafyllou. "Vortex-Induced Vibration Analysis (VIVA) Based on Hydrodynamic Databases." Proceedings of the ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering, 19-24 June, 2011, Rotterdam, the Netherlands, ASME, 2011. © 2011 by ASME

As Published: http://dx.doi.org/10.1115/OMAE2011-50192

Publisher: ASME International

Persistent URL: http://hdl.handle.net/1721.1/120046

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

Proceedings of the ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering
OMAE2011
June 19-24, 2011, Rotterdam, The Netherlands

OMAE2011-50192

VORTEX-INDUCED VIBRATION ANALYSIS (VIVA) BASED ON HYDRODYNAMIC DATABASES

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ABSTRACT

We outline the procedures used by program VIVA, developed over the last sixteen years to estimate the cross-flow vibration of marine risers in arbitrary currents. The program theory is based on a combination of first principles, extensive hydrodynamic databases, as well as modifications introduced through comparison against experimental and field data. The program was built from the start to handle standing as well as traveling waves, or arbitrary combinations of traveling and standing waves, through the use of complex modes. Considerable effort was expended to develop a hydrodynamic methodology that is suitable for short and long risers and cables, and which provides results in agreement with recent observed mechanisms.

In particular, we outline changes to take into account:

- the influence of in-line as well as cross-flow oscillations;
- the influence of the Reynolds number;
- the effect of high force harmonics;
- modeling of lock-in in a sheared flow;
- modeling of straked sections.

The methodology is illustrated through several examples where predictions are compared with field and experimental data.

INTRODUCTION

The prediction of vortex-induced vibrations of risers using hydrodynamic databases derived from laboratory tests on rigid cylinders is still partly science and partly art. Whereas the structural response can be modeled as accurately as required, the hydrodynamic loads are predicted using laboratory data, which require the development of force models before they get applied. Field data are used systematically to add information in a meaningful way, while data from numerical simulations provide further insight into the mechanisms of VIV as they apply to long structures. Hence, there is a continuous dialogue between predictions using the experiment-based codes on one hand and field and experimental data on the other, as well as computational data.

Risers placed in cross-flow currents exhibit vortex-induced vibrations (VIV), which are self-limiting in amplitude to about one riser diameter, but of relatively high frequency, which result in an increased drag coefficient and can cause fatigue damage. Marine risers can be very expensive in design, construction, installation and maintenance. It is important, therefore, especially for ultra-deep water applications, to estimate the riser fatigue damage accurately before installation. The fundamentals of vortex induced vibrations of rigid cylinders as well as flexible structures placed in flow are discussed by Bearman (1984), Williamson and Govardhan (2004), and Vandiver (1993)

The most widely used methods for predicting the riser VIV are semi-empirical prediction programs like VIVA (Triantafyllou et al, 1999), SHEAR7 (Vandiver, 2003), and VIVANA (Larsen et al, 2005). Such programs typically consist of two parts: (1) a fluid-structure interaction model and (2) laboratory-derived or empirical databases. The fluid-structure intreaction 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 an elastically mounted rigid cylinder. It is a common practice (see Triantafyllou et al., 1999; Vandiver, 2003) to use a strip theory approach to subdivide the riser into small segments, which act similar to a series of interconnected, elastically mounted rigid cylinders, and estimate the vortex-induced forces on each of these segments: the excitation force in phase with velocity and the excitation force in phase with acceleration. As shown by Triantafyllou (1998), estimating these forces requires lift coefficient databases of added mass coefficient and lift coefficient in phase with velocity. From a structural dynamics viewpoint, a riser is adequately modeled as a tensioned beam with the appropriate boundary conditions, acted upon by the external hydrodynamic force.

The available extensive databases used in the original VIVA were obtained in the MIT Towing Tank by Gopalkrishnan (1993). The lift coefficients and added mass coefficients are functions of reduced velocity and amplitude of response. Figure 1 shows surface plots of these databases. The databases were obtained: (i) at a Reynolds number around 10,000; (ii) for cylinders undergoing harmonic motion at a single frequency and restricted to the cross-flow direction only. To overcome these limitations, Mukundan et al. (2009) developed a systematic method to extract information from field and experimental data from risers and update the existing databases. A formal procedure to optimize this process was discussed by Mukundan et al. (2009) and a heuristic method, whereby a small number of parameters were allowed to vary, was used by Chasparis et al, 2009.

In this paper, we extend this idea by using experimental data obtained from a series of lab and field experiments for both bare and straked cylinders in our optimization methodology to come up with a universal database.

METHODOLOGY OF DATABASE OPTIMIZATION

In semi-empirical VIV predictive tools, strip theory is used, requiring that the fluid force is slowly varying along the length and hence can be locally approximated by a 2-D flow; and that a force correlation model is available. It is also required that databases provide the sectional lift coefficient and added mass coefficient in terms of the local reduced velocity and the non-dimensional amplitude.

The original lift coefficient in phase with velocity, C_{lv}, and the added mass coefficient, C_m, are functions of the reduced (non-dimensional) velocity $V_r = U/(fD)$, where U is the current velocity, f the frequency of vibration, and D the cylinder diameter; and the non-dimensional amplitude $A^* = A/D$, where A is the amplitude of oscillation. Surface plots of C_{lv} and C_m are shown in Figure 1.

A new parametrized database is shown in figures 2 and 3. To avoid computationally expensive 3D interpolations and to help numerical convergence, we consider cross-sections of the above 3D surfaces for various reduced velocities, V_r, as shown in Figure 2. For convenience, these 2D plots can be estimated by straight lines as shown in Figure 3. In Figure 3, the first subplot shows the C_{lv} at zero non-dimensional amplitude as a function of non-dimensional frequency. The second subplot shows the C_m at zero non-dimensional amplitude as a function of non-dimensional frequency. The 3rd and 4th subplots show the first and second average slopes of C_{lv} as indicated in Figure 2. The 5th subplot shows the point where C_{lv} reaches its maximum and also the transaction points of the above two slopes.

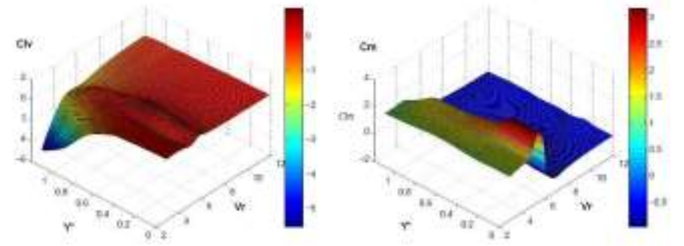

Figure 1. Surface plots of lift coefficient C_{lv} (left) and added mass coefficient C_m (right) as functions of reduced velocity (x-axis) and non-dimensional amplitude (y-axis) (Gopalkrishnan, 1993).

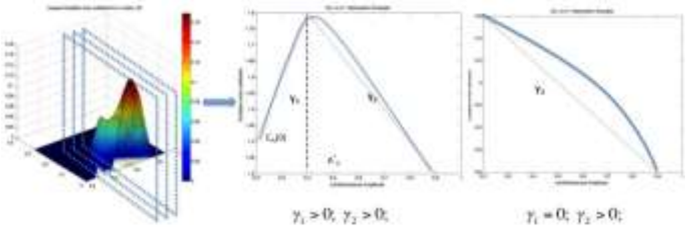

Figure 2. Two dimensional representation of the lift coefficient C_{lv} and added mass coefficient C_m surfaces.

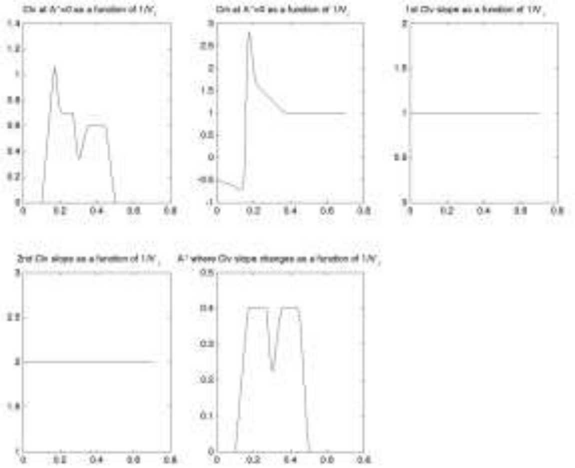

Figure 3. Two-dimensional linear plots of lift coefficient C_{lv} and added mass coefficient C_m curves for bare cylinder.

When we optimized the database, we parameterized the 2D curves of lift and added mass coefficients, allowing (a) the curve of the lift coefficient in phase with velocity as function of reduced velocity to expand in width and to be adjustable in height so as to accommodate Reynolds number effects and the effect of the in-line motions; (b) the slope of C_{lv} as function of A* to be adjustable to accommodate Reynolds number effects; and (c) the transition of the added mass coefficient C_m from high to low values as function of the reduced velocity to be adjustable (Chasparis et al., 2009).

Similar procedures were followed for the hydrodynamic coefficients for straked cylinders. These have different shape, since the lift coefficient is mostly of the damping type, and the added mass coefficient is practically constant, as shown in Figure 4. In order to provide for differences between field data and laboratory data, we allowed the slope of the lift coefficient as function of A* to vary, and the added mass coefficient to be adjustable.

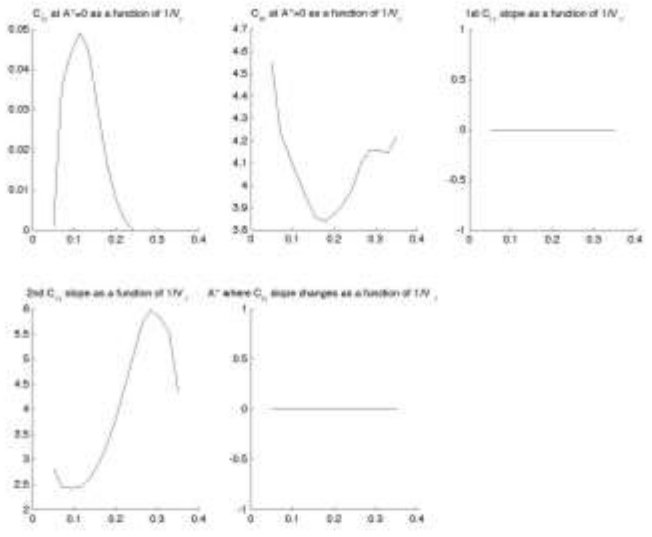

Figure 4. Two-dimensional linear plots of lift coefficient C_{lv} and added mass coefficient C_m curves for straked cylinder.

In order to extract a set of universal hydrodynamic coefficients, we compared VIVA (multi-mode) predictions with an entire set of experimental data as described in the following section.

EXPERIMENTAL DATASET AND PROCESSING

In our optimization, we have compared against the following experimental databases, some of which are available online at the MIT VIV Data Repository.

Chaplin's (Chaplin et al., 2005) experiment was carried out with a model vertical tension riser, 28 mm in diameter, 13.12 m long and with a mass ratio (mass/displaced mass) of 3.0, in a stepped current in May 2003.

DEN (BP, 2008) field experiment (part of BP bare full-scale riser datasets) was conducted with full-scale riser (1.3081 m in diameter and 1738.9 m in length) in the Gulf of Mexico in April-July, 2007.

Miami field experiments were part of Deepstar-MIT Gulf Stream 2006 tests (Vandiver et al., 2006) and were conducted on a 500-foot long and 1.43 inches diameter pipe in Oct 2006.

NDP10 lab experiments (Lehn, 2003) were conducted on a straked riser model (10m long) for various linearly sheared and uniform flow velocity cases in June 2003. These datasets correspond to experiments conducted with various strake coverage (25%, 50%, 75% and 100%).

NDP38 lab experiments (Braaten and Lie, 2004) were conducted by the Norwegian Deepwater Programme in December 2003. They were carried out on a 38-meter long riser model for various linearly sheared and uniform flow velocity cases for both the bare and either partially or fully straked straked riser configurations.

The derivation of the new database, shown in Figures 5 and 6 was done heuristically, as this allowed us to ensure that physical mechanisms are adequately represented, especially the effects of Reynolds number and in-line motion. In-line motion changes drastically the shape of the database for all Reynolds numbers (Dahl et al 2010); to properly model the effect of in-line motion we relied on the extensive database by Dahl (2008), derived at the MIT Towing Tank.

OPTIMIZATION RESULTS

Following the optimization methodology, we use the program VIVA to predict the VIV response of the above-mentioned experimental cases. Then we compare the response predicted by VIVA with experimental results and adjust the hydrodynamic coefficients until the error between prediction and experiment is minimized. The bare cylinder database was obtained using the bare cylinder results, and the straked database was obtained using the partially straked riser results in conjunction with the previously optimized bare database. The results of hydrodynamic force coefficients for bare and straked riser are shown in Figures 5 and 6, respectively. The surface plots of the optimized C_m and C_{lv} are shown in Figure 7.

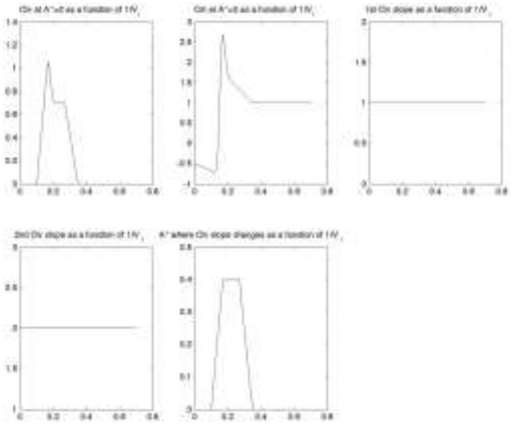

Figure 5. Optimal 2D linear plots of lift coefficient C_{lv} and added mass coefficient C_m curves for bare cylinder.

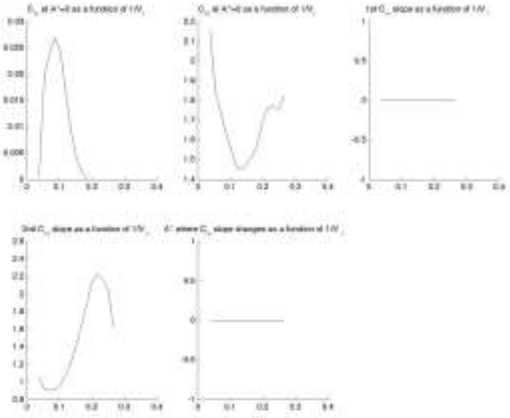

Figure 6. Optimal 2D linear plots of lift coefficient C_{lv} and added mass coefficient C_m curves for straked cylinder.

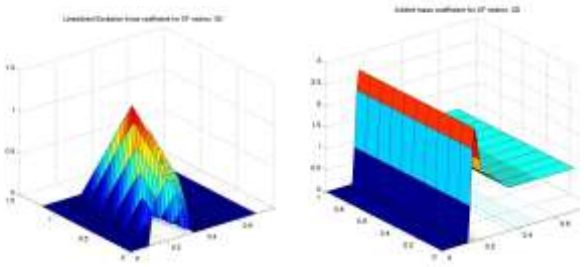

Figure 7. Optimal 3D linear plots of lift coefficient C_{lv} (left) and added mass coefficient C_m (right) curves for bare cylinder.

PREDICTION OF HIGH HARMONICS

High harmonic VIV stresses were identified relatively recently (Jauvtis & Williamson 2004, Vandiver et al., 2006, Dahl et al., 2007). They are closely associated with strong in-line motions and they can be very significant for fatigue. Programs that model cross-flow motions only, can take a worst-scenario approach and calculate high harmonics assuming resonance in-line as well as in the transverse direction, and counter-clockwise orbits, which cause high harmonic stresses (Dahl et al., 2007, 2010). This approach was used together with the extensive database by Dahl (2008) to generate a capability for predicting high harmonic forces and then calculate high harmonic stresses (Modarres-Sadeghi et al., 2010). Within this approach, first the transverse motion is calculated on the basis of the new hydrodynamic database; then the in-line motion is inferred on the basis of the hydrodynamic data by Dahl (2008), and hence the high harmonic forces can be found from the same database. The forces are applied to the riser and the resulting stresses are calculated.

CORRELATION LENGTH AND LOCK-IN REGION

The lock-in region for a vibrating rigid cylinder is parametrized on the basis of the reduced velocity and the amplitude of vibration. The lock-in region for a riser in a sheared current is a different concept referring to the length of the riser over which the wake locks in to the principal frequency of vibration of the riser. VIVA uses the data from rigid cylinders to determine the lock-in region, i.e. the extent of the lock-in region is determined by the bounds of lock-in as found in experiments on rigid cylinders. Until recently this was a working hypothesis; detailed CFD calculations have shown conclusively that this is an accurate way to determine the lockin region (Bourguet et al., 2010).

We are presently addressing the question of the lock-in region for multi-frequency response through detailed CFD studies.

RESULTS

We provide some sample results using the optimized databases and the new high harmonic subroutine.

Figure 8 shows a comparison between VIVA predicted rms amplitudes (solid line) and measured values (red dots) for 12 cases from the NDP data as function of riser length (x/L). The flow is uniform and indicated for each case in m/s; the first half of the riser is covered with triple-start strakes with pitch to diameter ratio 16.5 and strake height equal to 25% of the diameter.

Figure 9 provides the same data for six cases of the 50% straked riser in linearly sheared flow, from the NDP data. Again solid lines denote VIVA preditions and red dots experimental data; all are rms motions – the green line shows the incoming current velocity profile along the riser span, in meters per second. It should be noted that predictions are very good for modes higher than the first couple of modes; for the first two modes, VIVA overpredicts the response by about 20%

due to the assumed worst-case scenario of strong in-line motion. The responses for the mid-range of velocities shown in Figures 8 and 9 are very good, particularly in capturing the effect of the strakes.

Figure 10 provides the predicted first and third harmonics of stress for one particular case of linear shear flow on a bare riser (NDP data). VIVA predicts a range of modes that are likely to be excited as function of frequency in Hz. The first harmonic is shown in solid line and the third harmonic in dotted line; they are both parametrized with respect to the frequency of the first harmonic. The multi-frequency algorithm selects the most likely mode which is found at the peak response, in this case at about 5.8 Hz. As shown, the corresponding third harmonic stress component is about 45% of the first harmonic component. The experimental data show a third harmonic component close to 30% of the first harmonic. The agreement is fair given the several assumptions involved in the calculation.

Figure 11 provides the predicted rms amplitude of response along the riser length for four cases from Chaplin et al (2005). The current profile consists of two parts, a uniform flow part for about 40% of the riser length, followed by zero current velocity part, as shown in Figure 11 through a green dotted line.

It should be noted that when processing the experimental data, one finds that the reponse is not statistically stationary and often consists of modal transitions. When modal transition is random, the power spectral density appears wide-band, characteristic of a chaotic process (Modarres-Sadeghi et al., 2011).

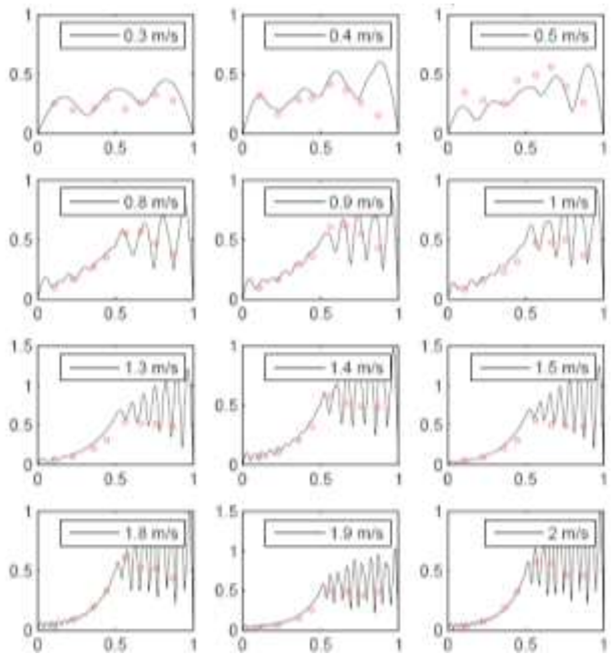

Figure 8. Sample cases of the NDP dataset for 50% straked riser in uniform flow. RMS VIV amplitude (A/D) versus length (x/L); VIVA prediction (continuous line), experimental data (circles).

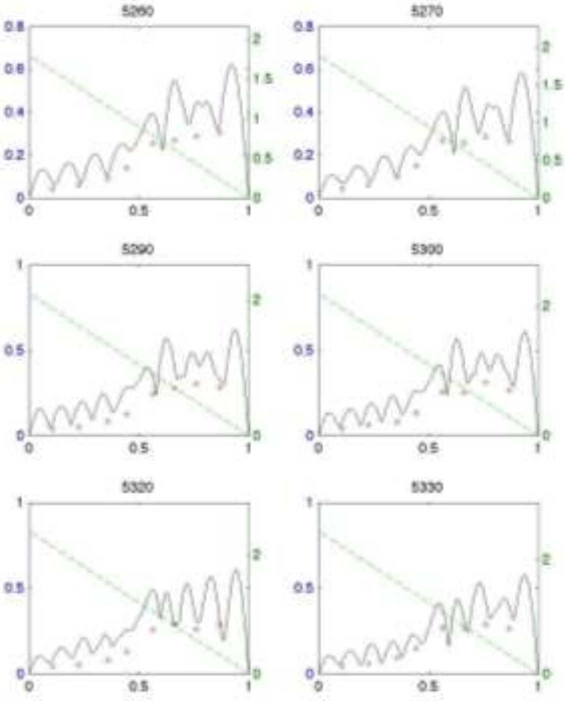

Figure 9. VIV amplitude comparison between VIVA prediction and experimental data for the NDP dataset for sheared flow, 50% straked riser (NDP data).

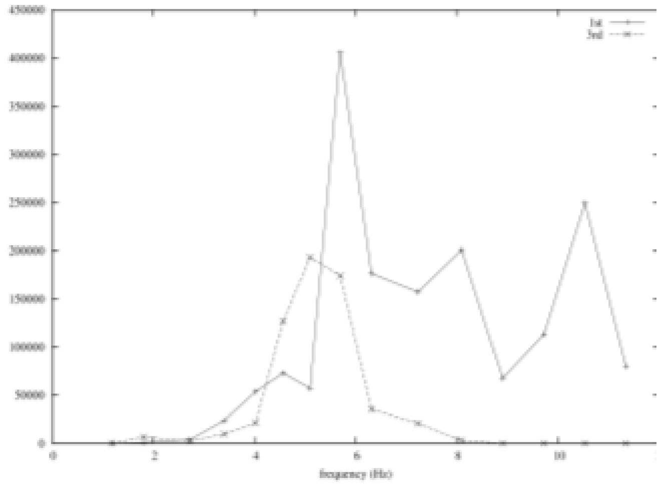

Figure 10. VIVA prediction of first harmonic stress (in Pa) as function of frequency (solid curve) and the corresponding third harmonic stress component (dotted line) for a bare riser in linearly sheared flow (NDP data).

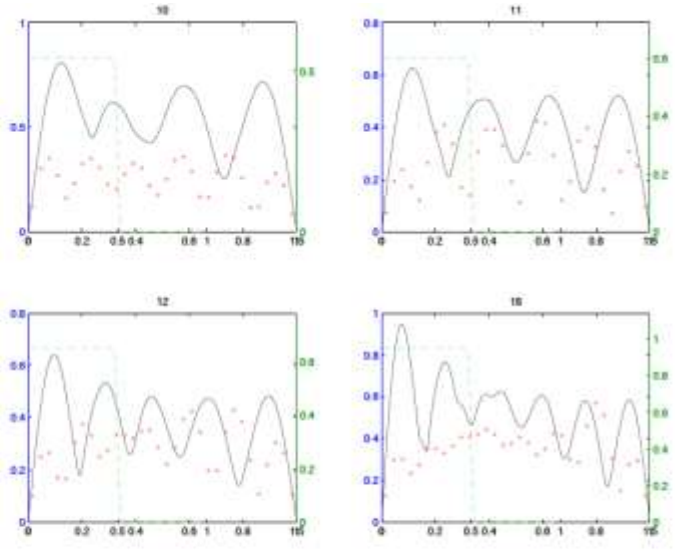

Figure 11. RMS amplitude (A/D) versus the riser length (x/L) for four cases from Chaplin et al (2005). VIVA predictions (continuous line) versus experimental data (red dots). Current profile in green dotted line.

CONCLUSIONS

We present the basic assumptions and working hypotheses employed in the program VIVA, a code developed to calculate amplitude and frequency of response, stress, and fatigue damage along the length of a multi-segment riser in sheared flow.

The first basic hypothesis is that strip theory can be employed, using data from laboratory databases, combined with a correlation length model, based on wake capture region data from the laboratory. The original database was developed by Gopalkrishan (1993) for cylinders at Reynolds number 10,000. Subsequent data at higher Reynolds number (Dahl et al., 2010), and the discovery of the singular effect of the in-line motion required adjusting the database. This was done in two complementary ways: A new detailed database by Dahl (2008) was developed for cylinders in in-line as well as cross-flow; also, data-mining procedures allowed the identification of trends and quantitative data from field and experimental data. These resulted in the development of new databases for bare and straked cylinders as presented in Figures 5 and 6.

Detailed CFD studies allowed the confirmation of the accurate prediction of the lock-in region by using wake capture data. New lock-in properties have been found through these CFD studies (Bourguet et al., 2011) for multi-frequency response, which are currently being implemented in the code.

Finally, new subroutines were developed that allow the prediction of high stress harmonics. The database in use is that of Dahl (2008).

As shown in Figures 8 through 11 VIVA predictions versus experimental data are consistent. It is important to note that both the experimental data and VIVA predictions demonstrate traveling waves combined with standing waves as evidenced by the lack of nodes in the response.

ACKNOWLEDGMENTS

The authors acknowledge with gratitude the permission granted by the Norwegian Deepwater Programme (NDP) Riser and Mooring Project to use the Riser High Mode VIV tests. Financial support was provided by the BP-MIT Major Projects Program. The authors are also grateful to Professor John Chaplin for making his experimental data available to them.

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