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Recent Development of the Empirical Basis for Prediction of Vortex Induced Vibrations

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Abstract. This paper describes the research activity related to VIV that has taken place at NTNU and MARINTEK in Trondheim during the last years. The overall aim of the work has been increased understanding of the VIV phenomenon and to improve the empirical basis for prediction of VIV. The work has included experiments with flexible beams in sheared and uniform flow and forced motions of short, rigid cylinders. Key results in terms of hydrodynamic coefficients and analysis procedures have been implemented in the computer program VIVANA, which has resulted in new analysis options and improved hydrodynamic coefficients. Some examples of results are presented, but the main focus of the paper is to give an overview of the work and point out how the new results can be used in order to improve VIV analyses.

Keywords: *analysis; empirical models; experiments; marine technology; pipelines; risers; vortex induced vibrations.*

1 Introduction

Empirical methods for prediction of vortex induced vibrations (VIV) have been available to the industry for more than thirty years. The earliest methods were based on a limited set of experiments and used single mode response models. Today we have access to large amounts of data and advanced structural models for dynamic analyses. However, we still have to accept that there are significant uncertainties in our predictions when we compare them to observations. These uncertainties are partly related to the prediction of response frequencies and amplitudes, but also to our present limited understanding of the stochastic nature of VIV.

Most of today's empirical methods are based on the assumption that VIV appears as a steady state response at a limited set of competing discrete frequencies. Concepts such as "simultaneously acting frequencies" and "time sharing between frequencies" have been proposed, but we are still not able to describe the mechanisms behind the frequency competition. Other important

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uncertainties are how in-line and cross-flow vibrations interact, and the significance of higher order frequency components. Although we have well documented observations of these phenomena, we are still unable to give reliable predictions.

The purpose of this paper is to present recent research on VIV at NTNU and MARINTEK and to discuss how new information has been used to improve the empirical response model in VIVANA. The shortcomings of today's model will be pointed out and alternative ways to improve the model will be presented.

2 Scope and Limitation of Original VIVANA Version

Key features and examples of analyses for the original VIVANA program were published by Larsen, *et al*. [1]. A brief presentation of the method can be summarized as follows

1. The response was assumed to be stationary and found as a sum of responses at discrete frequencies.
2. A finite element model based on a three-dimensional beam element with tension was used to define the structural properties. The model could account for varying diameter and material properties along the structure.
3. The static condition was found from a nonlinear analysis accounting for large displacements, nonlinear material and general boundary conditions including possible contact to the seafloor or other structural elements.
4. The frequency response method was used to calculate the dynamic response. The structure and seafloor contact, if present, were linearized at the static configuration.
5. Added mass was assumed to be independent of the response amplitude, but given as a function of the non-dimensional frequency at each position along the structure. An iterative eigenvalue analysis is carried out in order to find response frequencies that are eigenfrequencies with an added mass distribution consistent with the local flow and the eigenfrequency itself.
6. A simple response parameter was used to rank the competing response frequencies.
7. Each response frequency was assigned an excitation zone on the structure. If several frequencies compete for the same part of the structure, this part would be assigned to the highest ranked frequency. Thus, the excitation zones would not overlap. The local excitation force was defined as a function of the local response amplitude and found from a curve unique for a given non-dimensional frequency. Since the excitation forces depend on the response amplitude, an iteration had to be carried out in order to obtain consistency between the local response and excitation force amplitudes at each node along the structure.

8. Damping was introduced by simple coefficients outside the excitation zone and by negative excitation coefficients for large response amplitudes within the excitation zone.

Figure 1 presents the geometry, key parameters, excitation zones and response amplitudes for a drilling riser in 600 meters water depth. The hydrodynamic coefficients in this version of VIVANA were based on results for Gopalkrishnan [2], but modified for this use based on in-house experiments with slender beam models.

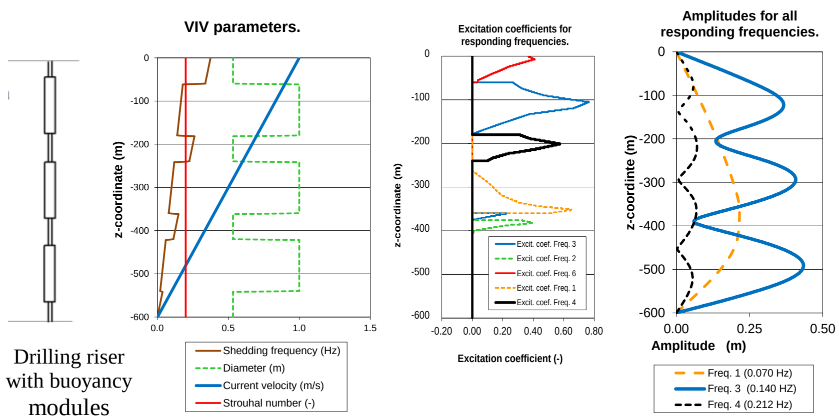


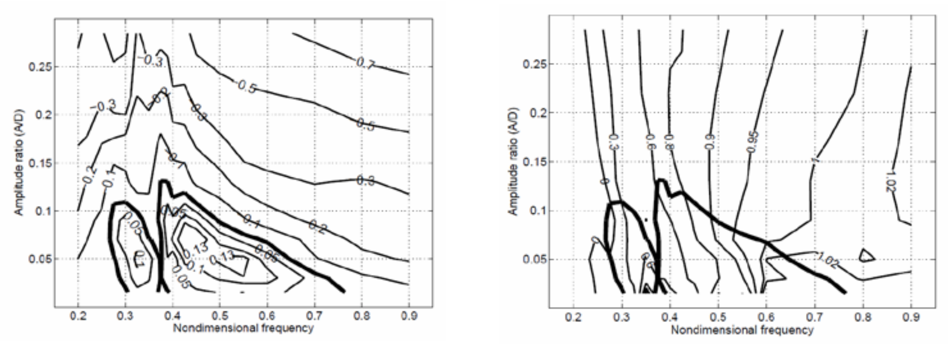
Figure 1 Key information from VIV analysis by VIVANA [1].

3 Hydrodynamic Coefficients

Hydrodynamic coefficients used in the first version of VIVANA were mainly based on measured forces on a rigid cylinder during forced cross-flow (CF) motion in uniform flow. The most obvious shortcoming of these data was the absence of in-line (IL) motions. It was well known that VIV for a flexible beam would have both CF and IL response, but no data for combined oscillation cases were known at that time. The Ormen Lange project west of Norway caused an increased interest in VIV for free spanning pipelines and led to a substantial test campaign. One important finding from these tests was that fatigue from pure IL oscillations would in many cases exceed the damage from CF response. However, added mass, excitation or damping coefficients for pure IL oscillations were not available.

3.1 Pure IL Forced Oscillations

Figure 2 shows contour plots for the excitation and added mass coefficients valid for pure IL oscillations. These curves were key results of Aronsen's PhD research [3,4], and enabled an extension of VIVANA to handle pure IL response. The coefficients were used in the same way as the corresponding data for pure CF response; iterations were needed both to find the response frequencies from frequency depending added mass and to find the response amplitudes from amplitude depending loads.

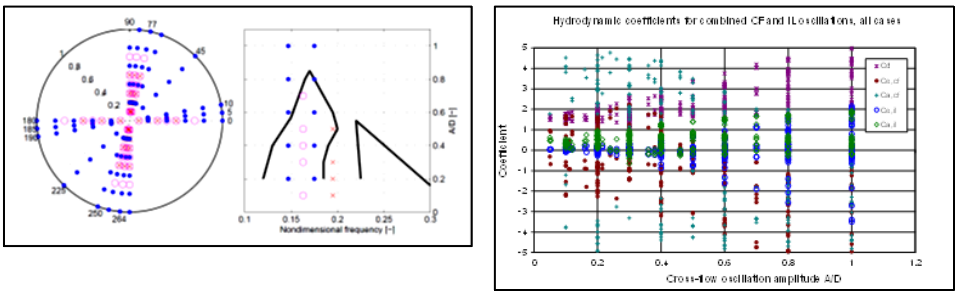


a b

Figure 2 Contour plots of excitation (a) and added mass coefficients (b), pure IL oscillations, from Aronsen [3].

3.2 Combined IL and CF Harmonic Oscillations

It is well known that the amplitudes of pure IL oscillations will be small (< 0.2D), but may increase considerably when combined CF and IL oscillations take place. Hence, the coefficients found for pure IL cannot give valid results for combined response. It is also obvious that pure IL will take place only if the reduced velocity related to the first CF eigenfrequency is low; a value of 3.5 may be taken as an approximate limit.

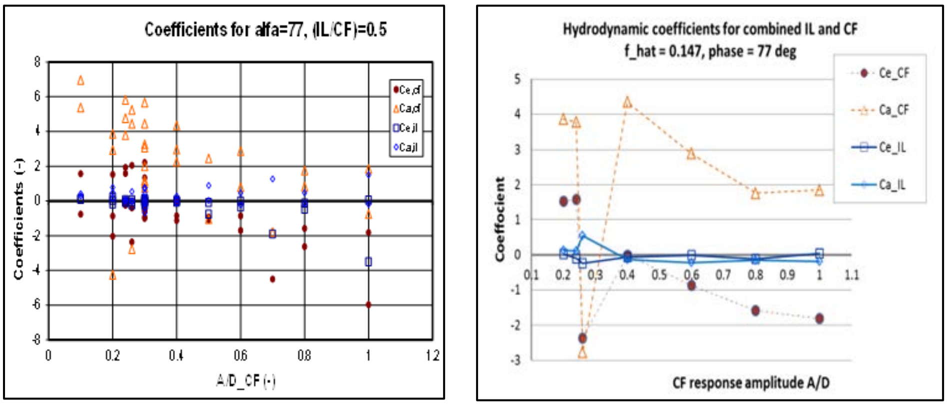


(a) (b)

Figure 3 Test matrix (a) and results (b) from Aronsen's experiments with combined IL and CF motions, from Aronsen [3].

Aronsen [3,4] made some tests with combined CF and IL forced oscillations. He measured forces for combined harmonic oscillations with IL amplitudes of 0.5 the CF amplitudes, but varied amplitudes and phase angle between the two components. The test matrix defined by phase angle, cross-flow amplitude and non-dimensional frequency is illustrated in Figure 3(a), while Figure 3(b) presents results in terms of drag coefficient and CF and IL excitation and added mass coefficients.

It is not possible to see clear trends between the coefficients and CF amplitude on Figure 3(b) for any of the coefficients. It is, however, obvious that frequency, IL amplitude and phase between IL and CF are important, which is no surprise.



(a) (b)

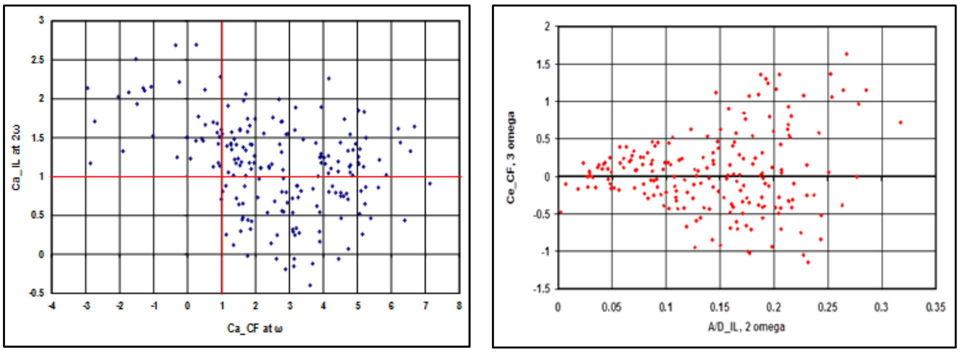
Figure 4 Results for identical phase angle (a) and identical phase and frequency (b), data from Aronsen [4].

Figure 4(a) shows coefficients for a set of tests with identical phase angle between IL and CF. Hence, the shape and motion direction of the trajectories are identical for all tests, while amplitude and frequency have been varied. A significant scatter is still seen, in particular for the IL and CF excitation coefficients. This scatter is seen to be reduced by limiting the selection in Figure 4(a) to cases with identical non-dimensional frequency, see Figure 4(b). However, one case for the excitation coefficients is an exception from the trend. A careful inspection of the test conditions showed that the phase angle in this particular test had an error of 2-3 degrees, which was the only reason we could find for this drop-out. The phase discrepancy in itself can probably not be the only explanation, but if another vortex shedding pattern had been triggered, the large discrepancy from the trend can be understood. The main conclusion from this observation is therefore that small changes in the test conditions may lead to large changes of the hydrodynamic forces, which underlines the complexity of VIV. Another example of such behaviour is the classical hysteresis behaviour of an elastically supported cylinder subjected to increasing or decreasing flow velocity.

3.3 Forced Oscillations with Observed Trajectories

The limited success with use of harmonic forced motion tests was the reason for developing alternative test techniques. It is not feasible to measure hydrodynamic forces in an experiment with a flexible beam. However, measured accelerations and/or bending strains can be post-processed to give trajectories for motions at selected positions along the beam. These motions can then be applied as forced motions of a rigid cylinder with larger diameter, and forces may now easily be measured. Reynolds number and the non-dimensional amplitude and frequency for the flexible beam and rigid cylinder tests must be identical. This test technique was applied by Soni [5] in his PhD research.

It has been difficult to find simple trends for the coefficients that have been found from these tests, and it has therefore not yet been possible to define a universal set of excitation or added mass coefficients. Figure 5 illustrates, however, two interesting findings. CF and IL added mass for a large set of experiments are presented in Figure 5(a). The red lines define the still water values of 1.0. Few cases of CF added mass lower than 1.0 are seen, while there are almost equal numbers of cases with increased and decreased IL added mass relative to the still water values. But most interesting – there are no observations of simultaneous reduction of CF and IL added mass.



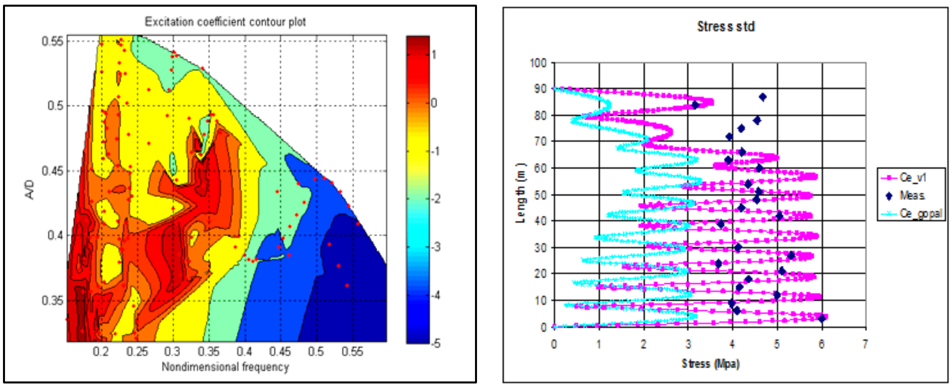
(a) (b)

Figure 5 CF and IL added mass coefficients (a) and third order CF excitation coefficient versus IL amplitude (b).

Higher order frequency components are shown to be important for VIV. Aronsen [3] observed that a CF force component at three times the CF motion frequency was not seen unless an IL motion component at two times the CF frequency was present. This was confirmed from the tests with observed trajectories by Soni [5], which is illustrated on Figure 5(b).

3.4 Coefficients from Inverse Analysis

The normal use of finite element models is to calculate displacements and stresses from a known set of external loads and forced displacements. The goal of inverse analysis is to identify the forces that must have been present in order to obtain a known displacement condition. It is hence a promising strategy to apply inverse analysis to VIV experiments with flexible beams. Both measured bending strains and accelerations may be used to calculate displacements for use in an inverse analysis, and as results we will have the hydrodynamic loads. By decomposing the loads into frequency components and further into components in phase with the local response acceleration and velocity, the wanted hydrodynamic coefficients can be identified.



(a) (b)

Figure 6 Contour plots of CF excitation coefficients found from inverse analysis (a) and comparison of stress standard deviation from analyses with traditional coefficients (aqua) and coefficients from inverse analysis (violet) to measured stresses (black) (b).

The first attempt to apply inverse analysis to VIV was made by Barnardo [6], and published by Mainçon, *et al.* [7]. Wu [8] continued this work and was able to produce improved sets of hydrodynamic coefficients for use in empirical models. Example of coefficients from Wu, *et al.* [9] and comparison of calculated response are shown on Figure 6. Figure 6(a) shows contours of CF excitation coefficients from inverse analysis on a frequency and amplitude map. Bending stresses found by use of the original VIVANA data and excitation coefficients from inverse analyses are compared to measured stresses in Figure 6(b).

4 Combined Frequency and Time Domain Analysis

Vortex induced vibrations will normally have small amplitudes relative to the global geometry of the structure. This means that the structural behaviour is normally linear or almost linear, while the hydrodynamic forces are linked to the response through complex nonlinear relationships. Iterations are therefore necessary to find a solution with consistency between the loads and response. However, even if the global behaviour of the structure is linear, significant local nonlinearities may be present. In some cases, the local nonlinearities will be important for the design of a structure.

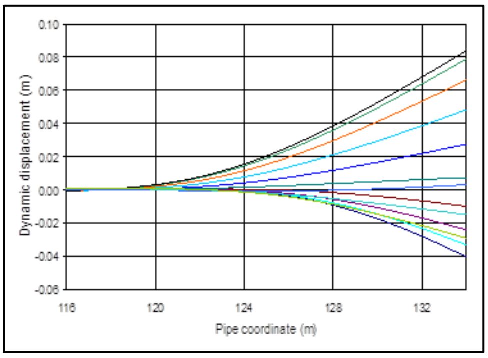
An example is the seafloor contact at shoulders of free spanning pipelines and at the touch-down point of catenary risers. A similar example is risers or umbilicals passing through guide tubes or bell mouths. It is also important to note that such local nonlinearities often will have a negligible influence on the global behaviour of the structure. One way of investigating the influence of the local nonlinearities on stresses caused by VIV is to combine linear frequency and nonlinear time domain analyses:

1. Perform an ordinary VIV analysis with a linear model. The result from this analysis is a response that does not account for local nonlinearities. Added mass and excitation forces along the structure will be available.
2. Use the added mass and excitation forces from step 1 in a nonlinear time domain analysis where local nonlinearities are included. The result from this analysis is expected to have the same overall response as for the original linear analysis, but will have a more correct response in regions with local non-linearities.

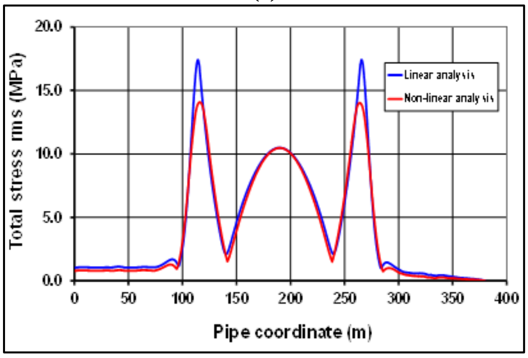
Note that this approach can be used only if the nonlinear effects are local since the forces from vortex shedding are strongly dependent on the response. If the nonlinear analysis gives a global response that is significantly different from the initial linear analysis, the new results are not valid. Two examples are discussed below; a free span with shoulder contact and an SCR with seafloor contact.

4.1 Free Spanning Pipelines

One obvious example of local nonlinear effects that are important for fatigue is the interaction between a free spanning pipeline and the seafloor on the shoulders of the span, see Larsen, *et al*. [10].



(a)



(b)

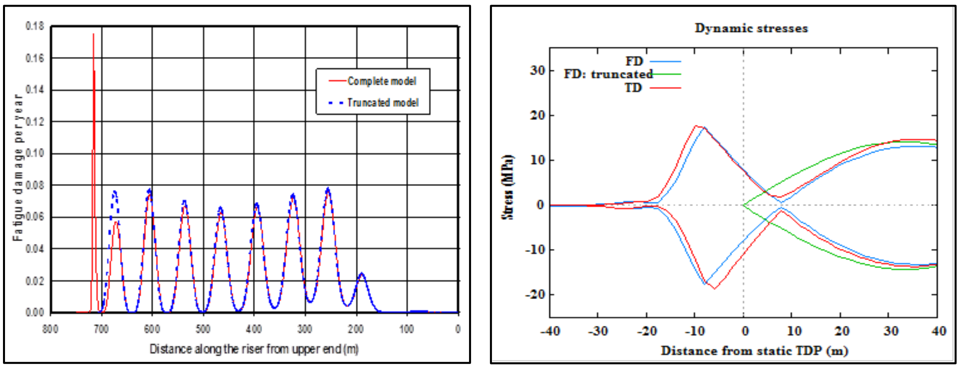
Figure 7 Snapshots of the dynamic displacements of a free spanning pipeline, results from linear (a) versus nonlinear (b) analyses

Figure 7 illustrates the difference between linear and nonlinear analyses. Snapshots of the pipeline close to the shoulder are shown. A linear model with harmonic loads will always give a symmetric response, while the nonlinear solution shown on Figure 7(a), shows an asymmetric behaviour. The nonlinear method will remove contact springs as soon as the pipe is lifted off the seafloor, and introduce new contact springs if the pipe comes in contact with the seafloor. The nonlinear analysis will therefore normally reduce bending stresses at the shoulders relative to the linear solution, partly by reducing curvatures and partly by spreading the location of the largest bending stresses along a section of the pipe.

The reduction of the bending stresses at the shoulders is illustrated in Figure 7(b). The standard deviation of stresses from linear frequency domain and nonlinear time domain analyses are very similar in the middle of the free span. Near the shoulders, however, the stresses are reduced by approximately 15%. For an SN curve with slope of 3.0 this will reduce the fatigue damage by almost 40%, The reduction in stress and fatigue damages will vary with the stiffness and damping properties of the seafloor, the local geometry of the seafloor, the length of the free span, and bending stiffness and tension of the pipeline. In the cases studied, the stress range at the shoulder was always reduced in the nonlinear analyses.

4.2 Steel Catenary Risers

VIV for a steel catenary riser (SCR) was studied by Larsen & Passano [11]. Accumulated fatigue damage will normally have its maximum value at or very close to the touch-down point. One may apply two different boundary conditions in a linear analysis; truncation of the model by a moment free support at the touch-down point, or use a longer model with the seafloor represented by an elastic contact surface. Figure 8(a) illustrates the difference between bending stresses from linear analysis with these two boundary conditions for a current perpendicular to the catenary plane. The longer model gives a high peak at touch-down. The height of this peak depends on the stiffness of the seafloor relative to the riser and it is far form simple to tune a linear model so that the peak becomes the same as the peak obtained from a nonlinear analysis. This peak is for obvious reasons not found in the results from the truncated model (blue curve), so these results will in most cases be non-conservative.



(a) (b)

Figure 8 Bending stresses in a steel catenary riser caused by VIV, boundary conditions and analysis options varied.

Minimum and maximum bending stresses from various analysis options are presented in Figures 8(b) for current perpendicular to the catenary plane. This current direction leads to vertical displacements of the riser on the seafloor. The vertical stiffness will be the most important parameter for the stresses in this region. In the case presented here, there is a slight increase in the minimum and maximum stresses in the nonlinear analysis. However, the location of the maximum and minimum stresses in the nonlinear analysis is shifted apart, so that the stress ranges – and thus fatigue damage – are not increased by the same amount, or may even decrease.

In-plane current was also studied by Larsen and Passano [11]. In this case there will be horizontal motions in the touch-down zone, which means that friction between the pipe and the bottom must be accounted for. The most important lesson to learn from this study is that fatigue at touch-down for steel catenary risers is difficult to predict, and that the predicted stresses and fatigue will be strongly dependent on both analysis method and boundary conditions and soil stiffness.

5 Combined CF and IL Response

The original version of VIVANA was developed for prediction of pure CF response only. Some years later, an option for prediction of pure IL VIV was added based on Aronsen's experiments [3]. Recently, a procedure for predicting simultaneous CF and IL response was developed and added to VIVANA. The procedure for this type of analysis is as follows:

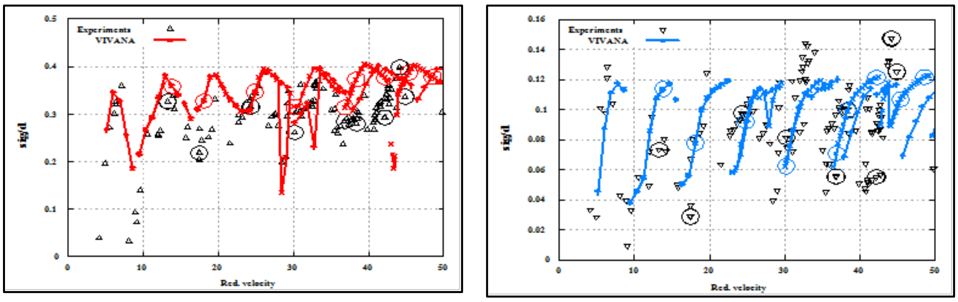
1. *Find potential CF response frequencies.* These are found through iterative eigenvalue analyses until there is consistency between each CF eigenfrequency and the CF added mass used to calculate this frequency. The resulting set of CF eigenfrequencies is then assumed to include all potential CF response frequencies.
2. *Find potential IL response frequencies.* These are found by performing iterative eigenvalue analyses where the IL added mass is adjusted in order to obtain an IL eigenfrequency that is twice the CF response frequency. At present, the neighbouring IL mode with the higher mode number will normally be selected. This will tend to be conservative as a higher mode will tend to give higher curvature, bending stress and fatigue damage.
3. *Calculate response for each pair of CF and IL response frequencies.* At present, there is no interaction between the CF and IL response other than the frequency relationship. The allocation of excitation zones to competing frequencies will depend on whether concurrent response frequencies (space sharing) or consecutive response frequencies (time sharing) are chosen by the user.
4. Combine response from all response frequencies to obtain total response, stress and fatigue damage. The user may specify either concurrent or consecutive response frequencies.

5.1 Comparison with the Bearman and Chaplin Experiments

In the Bearman and Chaplin experiments [12] a 13.1 m long tensioned riser model was partly subjected to a constant current and partly shielded from the current. Both CF and IL response was measured.

Figure 9 shows a comparison of calculated and measured CF and IL response from a large number of tests, Passano, *et al.*[13]. The compared response is the standard deviation of the response along the whole length of the riser model. The experimental results are shown in black, the calculated response in colour; CF in read, IL in blue. The circles mark nine selected experiments where the experimental conditions are available in detail and used in the blind prediction study, Chaplin, *et al.* [12]. The other analyses have been added to investigate trends between the nine cases and may not correspond exactly to any of actual experiments.

The calculated CF and IL response are in the same region as that found in the experiments, but with somewhat less variations. Coloured lines connect the analysis results that correspond to the same pair of response modes. Both experiments and analyses show similar trends. With increasing reduced velocity the response drops as each new pair of response modes take over and then increases while this pair is active. This trend is seen both for the experiments and calculations.



(a) (b)

Figure 9 CF and IL response from analyses compared to experiments (triangles), (a) Standard deviation of CF response along the riser, (b) Standard deviation of IL response along the riser.

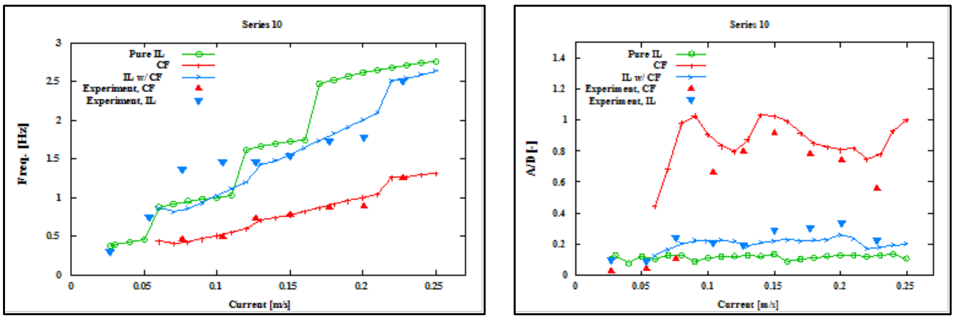
5.2 Comparison with the Ormen Lange Free Span Experiments

Calculated CF and IL response were compared by Passano, *et al.* [14] to the Ormen Lange free span experiments for three different free span configurations. In Figure 10 response frequencies (Figure 10(a)) and maximum response amplitudes (Figure 10(b)) are compared for test series 10 with an 11.4 m span.

The procedure described above for calculation of combined CF and IL response can only be used when the current speed is high enough to cause CF response. Below this level, a pure IL response procedure must be used together with IL excitation coefficients valid for pure IL response. In the case of only IL response, the IL response frequency can obviously not be based on the CF response frequency. The procedure for pure IL response is to iterate until each IL eigenfrequency is consistent with the IL added mass used in its calculation. Results from theses analyses are shown in green in the figures and are denoted "Pure IL", while the use of coefficients for combined CF and IL response ar shown in blue and denoted “IL w/ CF”.

The pure IL analyses give good results for the two first experiments where there is zero – or very small - CF response. Above this level, the IL response calculated from the excitation coefficients for combined IL and CF response gives quite good results. The calculated IL response is somewhat low, especially at higher current speeds. Since this study, the IL excitation coefficients in VIVANA have been modified to give increased IL response.

The CF response frequencies from the analyses are quite good. The CF response amplitudes are somewhat over predicted, especially for low current speeds. The two other experiments studied in this paper had significantly shorter spans of 4.7 and 3.4 m. For low current speeds these short spans had mode 1 response at both CF and IL response frequencies. The analyses tended to predict mode 1 CF response and mode 2 IL responses, due to the decision to prefer higher IL modes.



(a) (b)

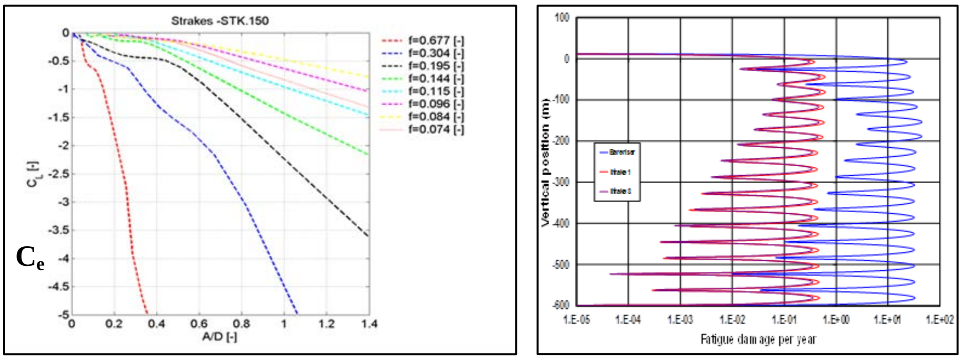
Figure 10 CF and IL response from analyses compared to experiments (triangles), (a) Response frequency; (b) Maximum response amplitude A/D.

6 Special Applications

6.1 Helical Strakes

Helical strakes are known to reduce and even eliminate the oscillation amplitude of VIV response. This reduction will increase fatigue life, and also reduce the drag magnification caused by CF vibrations. However, sections with strakes will have a larger initial drag coefficient than the bare sections. Hence, the length of a section with strakes along a riser should be long enough to reduce oscillations, but not too long in order to limit drag forces from current and waves. The optimum length and position of strakes for a given riser will therefore vary with the specific wave and current conditions, and the need for reliable VIV analysis of risers with strakes is obvious.

Hydrodynamic coefficients for cross sections with strakes can be found using the same experimental techniques as used for smooth cylinders. The excitation coefficients shown in Figure 11(a) were found by Huse & Sæther [15], who used a pendulum arrangement in a towing tank. The excitation coefficient is seen to be negative for all non-dimensional frequencies and response amplitudes. Results in this format can be used in the VIVANA program, which makes it possible to analyse risers and pipelines with strakes.



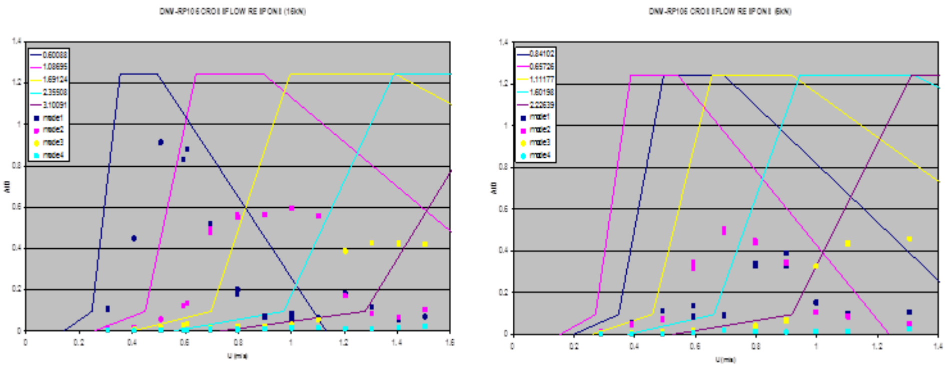
(a) (b)

Figure 11 Excitation coefficients for helical strakes (a) and fatigue damage (b).

The influence of strakes on a drilling riser exposed to a set of current profiles was studied by Larsen, *et al*. [16] with respect to fatigue from VIV, static deflection and wave induced stresses. Examples of results are shown in Figure 11(b). A significant reduction of fatigue damage from VIV is achieved, but at the expense of increased static deflections and also increased fatigue from waves. However, the net benefit from strakes is obvious, and strakes are therefore extensively used on deep water production risers. The key decision for designers of risers is therefore not whether or not to use strakes, but to find the optimum extent and position of the strakes.

6.2 Umbilicals

A free span VIV test of a 20m full-scale prototype-section of the Ormen Lange umbilical was carried out in the Ocean Basin at MARINTEK. Key results were published by Lie, *et al.* [17]. The umbilical consists of hydraulic stainless steel tubes and electrical and fibre optic control cables. The objective of the experiment was to estimate fatigue damage from VIV in the steel tubes in a free spanning umbilical exposed to ocean current. The umbilical had an outer diameter of 120 mm and a free span length of 20m, and was towed horizontal from a carriage above the Ocean Basin at a towing speed range of 0.3-2.5 m/s, corresponding to Reynolds numbers 30,000-260,000. The velocities up to 0.9m/s represent expected full-scale velocities. The higher velocities were included for studying multi-mode response and VIV in the critical Reynolds number regime.



(a) (b)

Figure 12 Modal cross-flow A/D responses vs. tow speed for a high (a) and low (b) pretension case (15kN).

The key result from the tests was that measured fatigue damage was orders of magnitude less than obtained from standard design procedure for free spanning pipelines. This was due to lower cross-flow and in-line modal responses. Figure 12 (a) and (b) show the modal amplitude to diameter ratio vs. towing speed for the lowest and highest pretension levels. For high pretension the VIV response shows behaviour similar to short free spans pipe lines and to rigid elastic mounted cylinders (2D free oscillation tests), confer Figure 12(a). For lower pretension the VIV response in the umbilical was significant reduced (Figure 12(b)), leading to longer fatigue life than predicted by use of standard prediction method for short free span pipes. One possible explanation for these low VIV displacements is that the responding natural frequencies in CF and IL direction are affected by static sag and are no longer a near integer multiples of each other.

Although the tests were in the critical Reynolds number regime, turbulence stimulation did not alter the VIV response relative to tests without turbulence.

Towing speed in the range 0.9-2.5 m/s was included for the purpose of studying multi-mode response at critical Reynolds numbers. When increasing the speed to this range, the following observations on the bare umbilical tests were made:

1. The displacement amplitude decreased for increasing speed.
2. The dominating mode increases for increasing speed.
3. The CF response seemed to be dominated by one mode for all velocities.
4. The peak frequency of the dominating mode increased almost linearly with the tow speed in both tow speed ranges of 0.2-0.9 and 0.9-2.5 m/s.
5. Based on inspection of the material damping for the three first modes it seems likely that the material damping will increase even more for the fourth mode

Thus, the response in the high speed range changes its character, where the most notable observation seems to be the reduced displacement. It has not been possible to isolate the exact reason to the reduced displacement, but it is probably caused by an increase in the material damping and the shift to the critical Reynolds Number regime. However, it is important to note that no change in the trends for amplitudes is seen when moving into the critical Reynolds number range.

7 Concurrent or Consecutive Response Frequencies

Ten years ago, the common assumption was that VIV of a long structure exposed to sheared current would appear at a limited set of discrete response frequencies, all acting concurrently, confer theory manuals for SHERA7 [18] and VIVANA [19]. The first attempt to describe a time varying response process was made by Swithenbank [20] and Vandiver [21]. They introduced the term “time sharing”, which may also be characterized as consecutive response frequencies. One way to illustrate the consequences of the two different assumptions is to show how the excitation zones for each frequency will be defined. If response frequencies are assumed to act concurrently, the excitation zones on the structure cannot overlap since the vortex shedding process must go with one frequency only. If we assume that VIV appears as a set of consecutive response frequencies (time sharing), the zones may overlap since the response frequency – and hence also the vortex shedding frequency – is assumed to vary with time.

When assuming concurrent response frequencies we must have a way to rank all possible frequencies. Similarly, we need a way to determine the relative duration of active frequencies for consecutive frequencies. So far the same excitation parameter has been used to serve both purposes in the today's version of VIVANA [22]. This parameter is based on energy considerations, but is in fact a pragmatic choice and little has been done so far to verify its relevance.

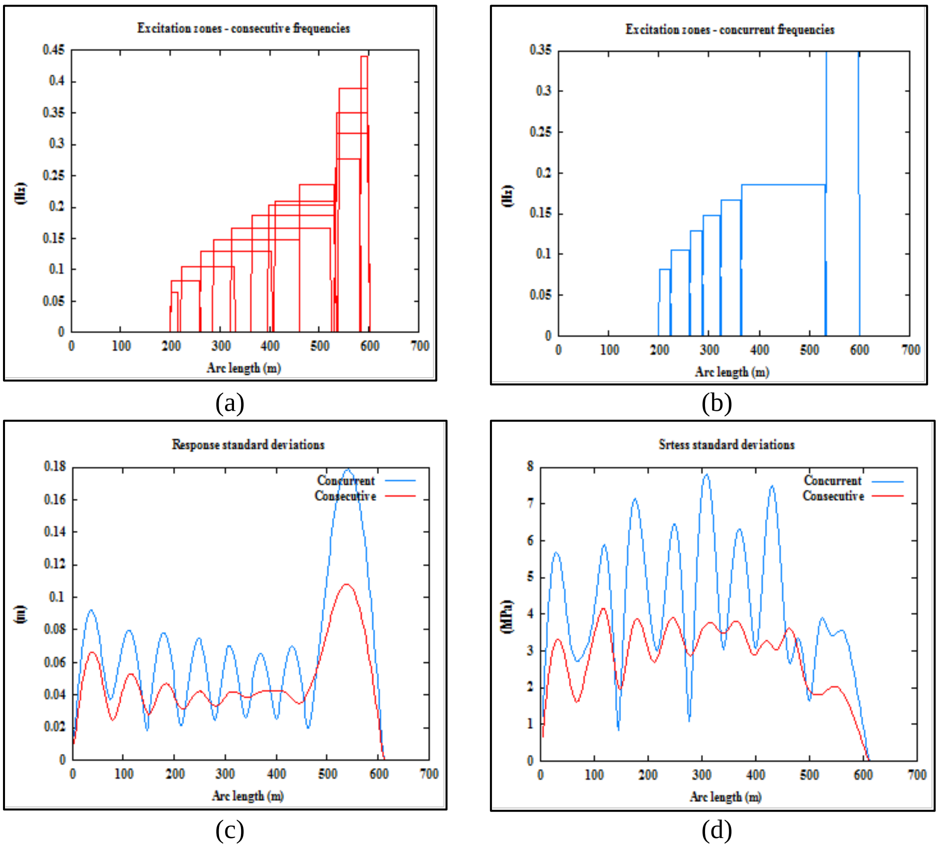
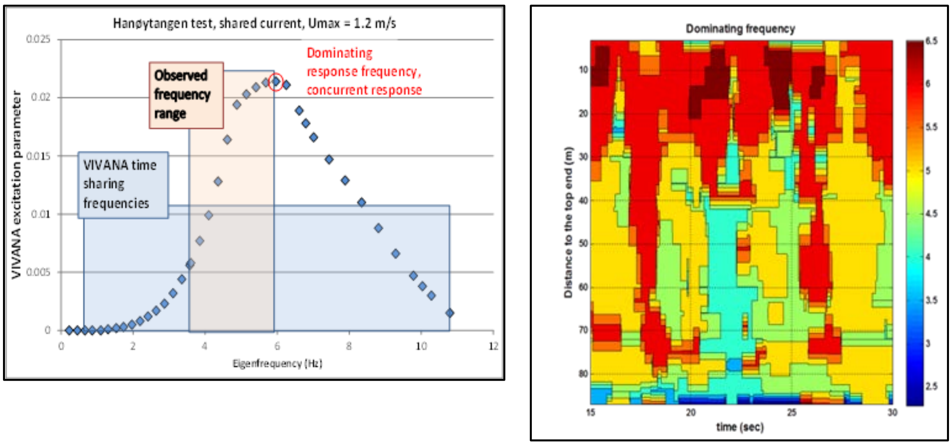


Figure 13 Excitation zones and response standard deviations from analyses using consecutive frequencies ((a) and (c)) and concurrent frequencies ((b) and (d)).

Figure 13 illustrates an important difference between the analyses based on concurrent and consecutive frequencies. Figure 13(a) and (b) show the excitation zones for each frequency. The horizontal axes give the position of the zones along a typical drilling riser, while the vertical axes indicate the response frequency for each zone. The riser is exposed to a linearly sheared current profile with zero velocity at the bottom. The excitation zones for the consecutive frequencies (a) are seen to overlap, while zones for concurrent frequencies do not. The dominating frequency has the same excitation zone for both cases (highlighted by fill colours) and the response at this frequency will be the same in both cases. In the case of concurrent frequencies, this frequency will be active all the time, together with all active frequencies. In the case of consecutive frequencies, this frequency will be active only part of the time, but will then be the only active frequency.

8 Stochastic Nature of VIV

Both the consecutive and concurrent response frequencies approaches describe VIV as a response process consisting of harmonic components with constant amplitudes. However, it is well known that real VIV often appears as a non-stationary stochastic process. Amplitudes and frequencies may change in time, even if the flow is stationary, and the amplitudes may have time slots with almost constant values, but then change to a stochastic process.



(a) (b)

Figure 14 Observed range of active frequencies (a) and frequency variation along the structure through time (b); from Larsen, *et al*. [23].

An energy based response parameter is used in VIVANA to define and rank potential response frequencies among eigenfrequencies for the structure. Experience indicates that number of active frequencies is far lower than the total number of possible frequencies one may find by considering available eigenfrequencies to the bandwidth of vortex shedding frequency. Figure 14(a) shows that the energy parameter will find all active frequencies, but a general criterion is needed in order to find the contributing frequencies among all candidates

Analysis of measured data tells that both the concurrent and consecutive response frequency concepts are valid, but none of them tells the whole truth. One way to illustrate the response of a long flexible beam is to carry out the following sequence of analyses:

Step 1 Make wavelet analyses for all measurement points along the beam for a specific current case. This type of analysis will map the peak frequency at a specific point on the structure as function of time

Step 2 Give colour codes to the peak frequencies, blue for low, red for highest frequency

Step 3 Plot the colours in a position versus time plot. We will now see how the dominating frequency shifts in time and space, see Figure 14(b).

The end result of these analyses is an illustration of the non-stationary frequency process. We can easily see cases of concurrently active frequencies, and also time sharing. But the two processes are more or less uncoupled, but can be studied more in detail by this type of analysis.

9 Time Domain Analysis

There are obvious advantages to carry out calculations of VIV in time domain. Non-linear effects like tension variation and varying contact between the structure and the sea bottom can be accounted for. Time varying velocity for situations with current and waves will also require a time domain method. Thorsen, *et al.* [24] discuss various methods for time domain analyses of VIV, and present a novel method that is able to analyse simultaneous cross-flow and in-line vibrations. In this model, the hydrodynamic force is represented as a sum of excitation, damping and added mass, where synchronization between the exciting force and structure motion is taken into account.

The force model is applied in combination with the finite element method to simulate VIV of a tensioned riser in stepped current, and the results are compared to experimental observations by Chaplin, *et al.* [12]. Figure 15 shows results from simulations together with data from the experiment. Curvature, which is equivalent to bending stress, is compared for IL (upper plot) and CF (lower plot) response. The agreement is not perfect, but illustrates the potential for this method. The computing time is of the same order of magnitude as for frequency domain analyses, and the method may therefore show to be useful for engineering purposes.

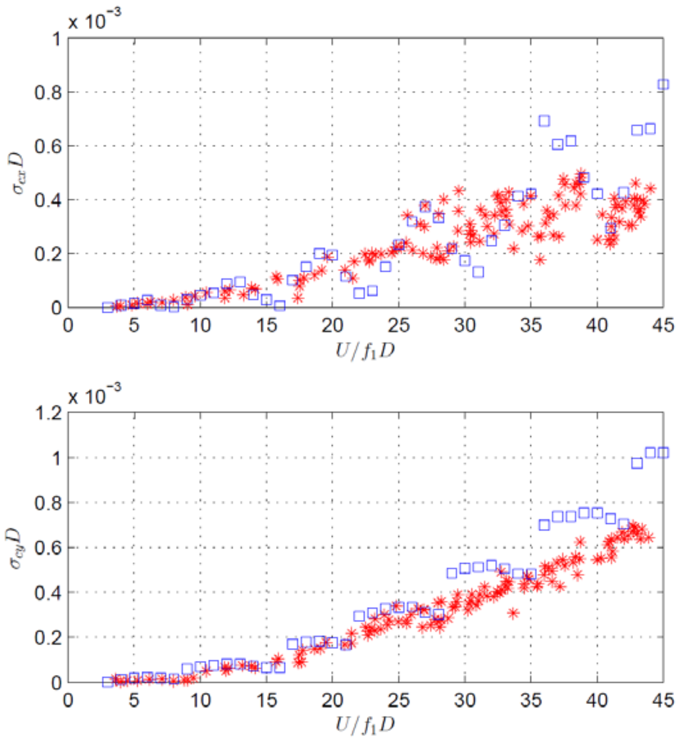


Figure 15 Standard deviations of in-line (top) and cross-flow (bottom) curvature. Blue squares are simulated while red stars are experimental results (from [12]).

10 Future Work

Empirical codes for prediction of VIV have existed for 20 years, but there are still important uncertainties with regard to the use of these codes in design. A typical requirement from design guidelines is that fatigue damage during the expected lifetime of a structure should not exceed the capacity with a certain safety margin. Studies on the safety factor have been published by Leira, *et al.* [25] and Fontaine, *et al.* [26], but none of these methods have been accepted as standards by authorities or industry.

When using an S-N curve combined with a traditional Miner-Palmgren approach for long term fatigue damage accumulation, the acceptance criterion might be that the damage should not exceed a given fraction of the fatigue capacity. But even this criterion leaves important questions unanswered. The following list contains some – but not necessarily all- questions of importance:

1. How to combine fatigue damage from VIV and damage found from a traditional analysis with wave forces?
2. How should varying current directions be accounted for – both change of direction with time and varying direction in the water column? Principles for a general 3D model has been described by Lie, *et al.* [27], but never implemented in computer programs.
3. How should we estimate fatigue caused by higher order response frequencies – by making sure that our results always are sufficiently conservative, by a safety factor or by additional dynamic analyses?
4. How should results from one single analysis be applied when summing up fatigue damage – should we accept the large variations along the structure that we often can see in our solutions, or should we apply an "envelope curve" approach that accounts for the uncertainty linked to impact from traveling waves in contrast to standing waves.
5. How should we calculate fatigue from cases with several active frequencies – apply consecutive frequency approach or the more conservative concurrent frequency approach?

11 Concluding Remarks

The long term goal for research on VIV at NTNU and MARINTEK is to improve the empirical model for predicting VIV. Some progress has been made since the first version of VIVANA, but there are still unwanted shortcomings and model uncertainties. The work will continue even if we all know that increased computer performance before or later will give engineers efficient and reliable methods based on CFD for their VIV analyses.

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