QUESTIONS & ANSWERS ABOUT VIVA

M.S. Triantafyllou
MIT Testing Tank Facility
Cambridge, Massachusetts 02139 USA

OUTLINE

This document is part of the program VIVA manual and provides answers to some basic questions on the structure and properties of the program VIVA, as it stands on it own and in relation to other existing predictive programs. Although we do not provide a side by side comparison with other programs, we include all pertinent information that such a comparison can be made by the user.

1 How does VIVA determine the lock-in region

VIVA finds internally whether lock-in occurs or not, based on an extensive hydrodynamic database. The user does not need to specify any parameters to influence this process. We outline below some of the details of the evaluation of lock-in, so as to be able to compare with other programs' predictions.

1.1 What is lock-in?

First, we must define what **lock-in** means. As the name suggests, lock-in refers to the phenomenon where the frequency of vortex shedding behind a rigid cylinder mounted on springs – or a flexible cylinder, does not follow the Strouhal law, i.e. it does not occur in accordance with the wake properties, but instead locks on to another frequency, which is presumed to be the natural frequency of the cylinder. Since the natural frequency, however, depends on the added mass, which is highly variable in VIV, we need to be more specific. Hence, we must define first two regions of interest to this problem, both obtained from experiments on cylinders forced to vibrate harmonically with amplitude A and frequency f within an oncoming stream U:

1. The **region of positive energy flow** from the fluid to the cylinder, or equivalently the region in the plot of amplitude of vibration to diameter ratio, A/d, versus non-dimensional frequency $f^* = f\, d/U$, where the lift coefficient in phase with velocity, c_{lv}, is positive (Figure 1). This area is determined experimentally and is delineated by the line where $c_{lv} = 0$.

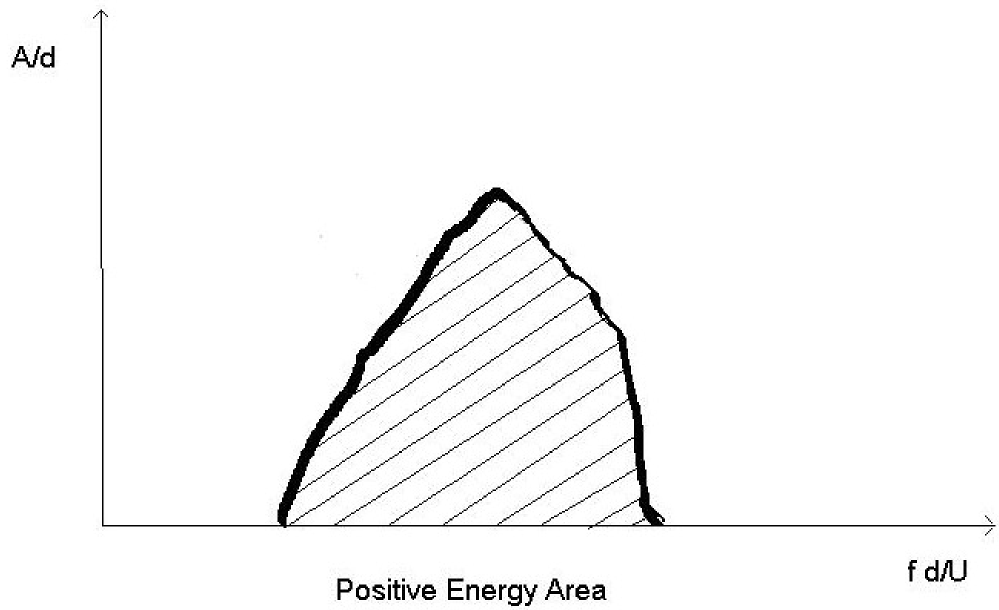


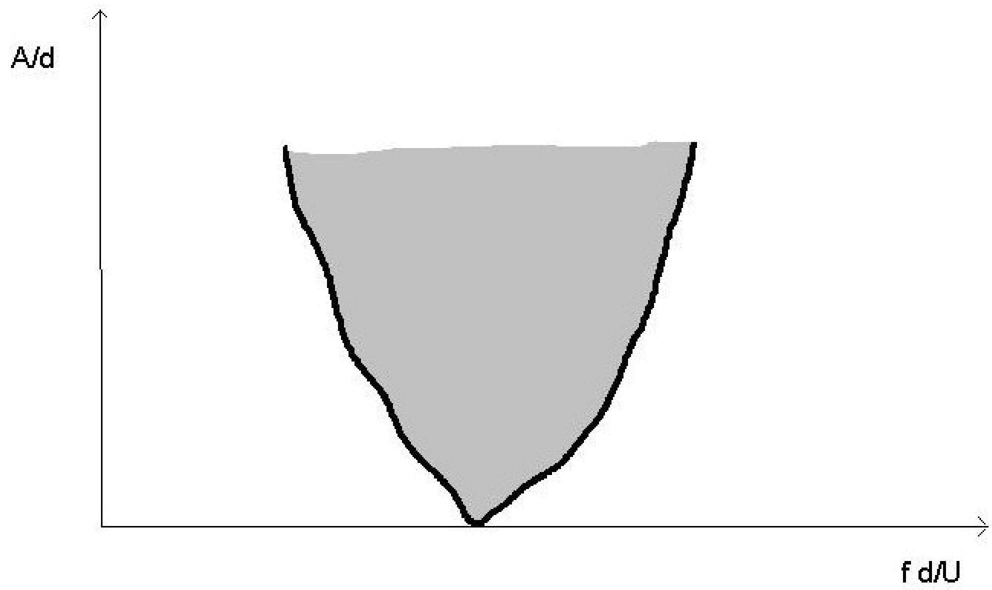
Figure 1

2. The region in the plot of amplitude of vibration to diameter ratio, A/d, versus non-dimensional frequency $f^* = f\,d/U$, where the frequency of vortex formation f_v is equal to the frequency of cylinder vibration f, i.e. $f_v = f$ (Figure 2), and no other frequency is detected in the lift force. This area is determined experimentally and is called the **frequency capture region**, i.e. the region within which the frequency of vortex shedding is "captured" by the frequency of cylinder oscillation. Outside this region two frequencies are measured in the lift force, the frequency of cylinder oscillation and the frequency dictated by the Strouhal relation.

The overlap of these regions determines the region where lock-in may occur, i.e. the region within which self-excited oscillations may occur (c_{lv} positive) and the frequency of vortex shedding is the same as the frequency of cylinder vibration. We call this the **region of lock-in** – see Figure 3.

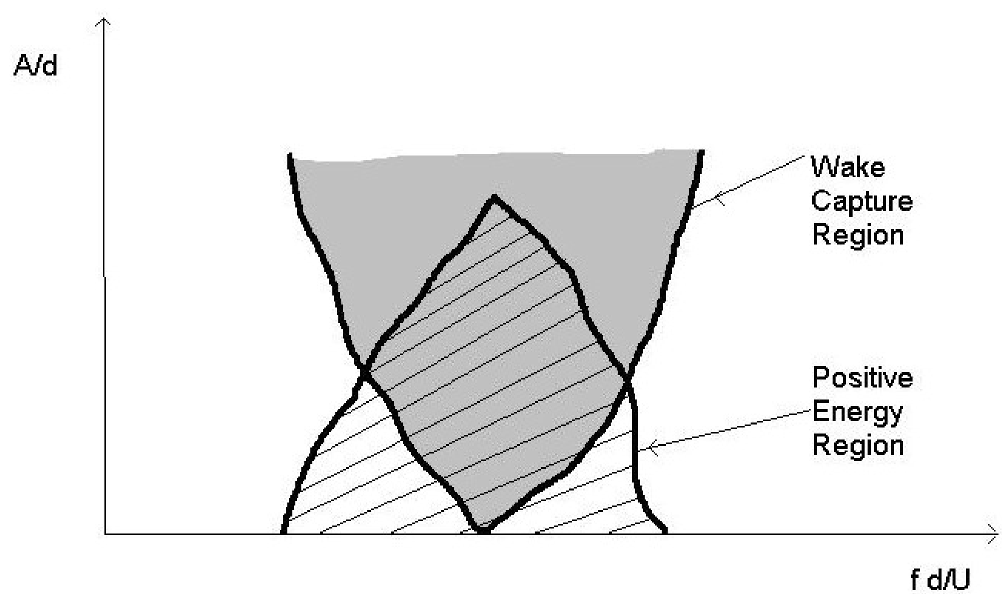
But for VIV to occur, another condition must be satisfied, that of force equilibrium. The governing equation for a rigid cylinder with mass m, diameter d, span s, structural damping b and spring constant k, is:

$$m\frac{d^2 y}{dt^2} + b\frac{dy}{dt} + ky = Y(t) \tag{1}$$



Wake Capture Region

Figure 2



Wake Lock-in Region

Figure 3

where $y(t)$ is the transverse motion of the cylinder, and $Y(t)$ is the transverse (lift) force, caused by the vortex shedding process.

The lift force is decomposed into a component in phase with velocity, $Y_v(t)$, and a component in phase with acceleration (added mass term):

$$Y(t) = Y_v(t) - m_a \frac{d^2 y}{dt^2} \quad (2)$$

where m_a denotes the added mass coefficient. For harmonic response at frequency $f = \omega/(2\pi)$ and amplitude A:

$$y(t) = A\sin(2\pi f t) \quad (3)$$

we substitute equation (3) and decompose equation (1) into two equations:

$$(-(m + m_a)\omega^2 + k)A = 0 \quad (4)$$

$$\omega b A = \frac{1}{2}\rho c_{lv} d s U^2 \quad (5)$$

where c_{lv} the lift coefficient in phase with velocity, and the added mass is expressed in terms of the added mass coefficient, c_m, as:

$$m_a = \frac{\pi}{4} c_m \rho d^2 s \quad (6)$$

Equations (4) and (5) are not as easily solvable because both the added mass coefficient and the lift coefficient in phase with velocity are functions of the amplitude A and frequency f, i.e. $c_m(A/d,f^*)$ and $c_{lv}(A/d,f^*)$, with $f^* = f\, d/U$. An iterative solution of the equations provides the response parameters A and f. **IF THE VIV RESPONSE LIES WITHIN THE REGION OF LOCK-IN, THEN WE HAVE CONDITIONS OF LOCK-IN**.

1.2 How does VIVA calculate lock-in?

We discuss here how VIVA solves the equations for mono-frequency response. VIVA solves equations such as (4) and (5), but formulated for a beam with variable properties, to find the amplitude and frequency of response of the riser. The frequency is the same for the entire riser, but the amplitude varies along the length, since a "mode" is excited.

After such a solution is obtained, VIVA determines on the basis of plots such as shown in Figures 1 and 2, whether lock-in occurs or not at each point of the riser. The fact that this decision is made after the calculation does not affect the accuracy of prediction, since the hydrodynamic data used by VIVA have already incorporated the consequences of lock-in or non-lock-in. Where the condition of lock-in does have an impact within VIVA is in choosing which of the excited modes is most likely to occur, i.e. if a mode is in lock-in conditions, is deemed more likely to occur than a mode that is not in lock-in.

In other programs which do not use detailed hydrodynamic data, the condition of lock-in influences the selection of data to be used. Since this is not the case for VIVA no such input a priori is required.

2 How are excitation- vs. damping-regions defined?

Some programs, other than VIVA, define areas of the riser for which the fluid inputs energy in the riser, and other areas over which energy is dissipated. Then the response is found in terms of the balance of energy-in versus energy-out of the system. In a sheared current, for example, an area of high current velocity can be an area over which the riser is subject to excitation (energy-in), while in areas of low velocity the energy, propagated by the structure of the system, is dissipated. The reverse may also happen, however, albeit more rarely; i.e. an area of relatively low velocity can input energy-in, which is dissipated in an area of high velocity -- so it is important to have a rational way to determine all the possible modes of response.

An excitation versus a damping region can be defined in terms of the sign of the lift coefficient in phase with velocity c_{lv}: If c_{lv} is positive then it is a region of excitation, otherwise it is a damping region.

In the case of VIVA the user does not need to specify areas of excitation and damping, or supply criteria for them: **The hydrodynamic database provides this information in terms of the lift coefficient in phase with velocity, so it is an integral part of the calculations of VIVA**. The accuracy of the database determines the accuracy of the proper prediction of areas of excitation

3 How is the change in added mass taken into account?

The added mass coefficient, c_m, varies significantly as function of frequency of oscillation f and amplitude of response A. For example, the added mass coefficient can be as high as 3.0 and as low as -0.5, deviating substantially from the nominal value of 1.

This variability is caused by the shedding of vortices, which act as areas of low pressure – hence they can alter the added mass substantially, depending on the timing of vortex shedding.

For risers with low mass to nominal added mass ratio, $m^* = m/m_a$, the effect of the added mass variability is very significant, since the total mass $m+m_a$ can vary a lot, causing the natural frequency to vary accordingly.

VIVA uses hydrodynamic data for the added mass and the lift coefficient in phase with velocity, c_{lv}. It finds the natural frequencies and modal response iteratively fully accounting for the variability of added mass and c_{lv}. **The user need not specify any additional information on the added mass variability, other than making sure that the standard hydrodynamic database is available**.

4 How does the lift coefficient vary with Reynolds number?

The lift coefficient c_l and its two components, i.e. the added mass coefficient c_m and lift coefficient in phase with velocity c_{lv}, vary with Reynolds number Re: These variations are small within the subcritical regime (below Re = 250,000 for a smooth cylinder), but significant and rapidly varying in the transition from subcritical to critical flow; and again substantial, albeit more smooth in the transition from the critical to supercritical flow, which starts at about Re = 500,000 and ends at about Re = 2,500,000.

For rough cylinders, cylinders with attachments, such as kill and choke lines etc, or cylinders in turbulent flow, these changes occur differently and are not as dramatic as for smooth cylinders.

There are significant databases for subcritical flow, while very sparse data exist for critical and supercritical flows. While we are presently engaged in a major effort to obtain data for high Reynolds number, which will allow input precise hydrodynamic information, VIVA presently uses the following working hypotheses:

- Due to the presence of turbulence in the ocean, some roughness on the surface of risers, and attachments, a single transition occurs from the subcritical regime to the supercritical regime, i.e. the critical range is omitted. The transition is set for Re = 250,000.

- The data for supercritical flow can be obtained from the data for subcritical flows with the following two transformations:

  1. change the frequency in accordance to the rule $f_1 = f\,(0.22/0.17)$, where f_1 is the frequency in the supercritical regime and f is the frequency in the subcritical regime. The values of 0.22 and 0.17 are respectively the frequencies of peak excitation for the supercritical and subcritical regimes.

  2. change the amplitude of the lift coefficient in accordance with the rule $c_{l1} = c_l\,(0.7/1.16)$, where c_{l1} is the lift coefficient in the supercritical regime and c_l is the lift coefficient in the subcritical regime. The values of 0.7 and 1.16 represent respectively the width of the wake for the supercritical and subcritical regimes. The rule applies to the components of the lift coefficient, but for the added mass it is applied to the incremental part of the added mass, i.e. to the quantity c_m-1, since the value of 1 is the potential part of the added mass and does not scale with the wake width.

5 Are there limitations on how the riser properties vary along the length?

VIVA can handle a riser with variable properties, i.e. consisting of several segments with entirely different properties, or segments with variable properties along the segment. There is no limitation for the program to work.

However, for the finite difference program to provide accurate solutions, the variations must be slowly varying, i.e. the characteristic length of property variation must be at least five times the discretization length. To remedy this limitation at the intersection of two segments with different properties, it uses a finite volume methodology at the intersection; for this reason, the step change at the intersection of two segments causes no numerical problems.

6 What is multi-frequency response?

In a shear current, different parts of the riser are subject to different excitations: the local Strouhal frequency varies as function of the current velocity which can vary significantly along the riser length.

As a result, there may be several frequencies for which balance of energy is found, resulting in a program output with potentially many modes which may be excited.

The subject of how many modes – or which ones may be excited, is still open to research and there are no satisfactory answers yet – we are working on this. The program offers first a single frequency response, calculating all possible frequencies individually.

Then, VIVA offers a multi-frequency response calculation, where all modes found in the single frequency response are assumed to be simultaneously present. The new calculation uses modified lift coefficients for the calculation: It assumes that all modes have the same frequency and added mass originally calculated in the single-frequency response, but the lift coefficient in phase with velocity, c_{lv}, is modified in accordance with the following rules:

1. The sum of all energies put in the various modes (found as the product of the lift force in phase with velocity times the velocity must be equal to the energy for single-frequency response.

2. The individual lift coefficients are multiplied by experimental factors which depend on the distance of the frequency from the Strouhal frequency. These factors have been determined from experiments with two-frequency and three-frequency forced vibrations.

An iterative process is needed to implement the two rules above. As a result the multi-frequency response gives different amplitudes for the participating modes than the single-frequency response does.

Single-frequency response is the worse-case scenario as far as fatigue is concerned (conservative calculation).

7 Are there any restrictions on how the current varies?

The current can vary arbitrarily along the length of the riser. The program will work with arbitrary current, but one must note that the current variability must be "slow", i.e. its characteristic length of variation must be equal to several times the discretization length. Very fast variations of the current, compared to the discretization length, may result in numerically inaccurate solutions, although the program produces an answer.

8 Are there limitations in using a three-dimensional current?

The current can be three-dimensional and can vary arbitrarily along the length of the riser. The input of the program requires, at each point of the riser, the two components of the current projected on the plane perpendicular to the static configuration of the riser.

The program has been derived originally on the basis of a co-planar current, and the extension to a three-dimensional current has been obtained on the basis of the following working assumptions (see write-up on the three-dimensional current version of VIVA):

- At each point we define a local current direction and use the hydrodynamic data for VIV for the local transverse direction; in the in-line direction we use a Morison type drag formulation.
- The response at each point is decomposed into two components, a transverse and an in-line response.

Hence, still, the most checked and confident calculation is the one for a two-dimensional current. The extension to a three dimensional current is available and is being checked. Also, note the section on the restrictions on how fast the current can vary.

9 Risers with large static curvature: In-plane vs. out of plane response

When a riser has a large static curvature in one plane, such as a steel catenary riser, then the in-plane modes and natural frequencies (in-plane refers to motions within the plane that contains the static configuration with the large curvature) are quite different than the frequencies of a straight riser. This is true for the first few modes, while for the higher modes the difference becomes increasingly smaller -- for any mode larger than the fifth mode the difference is quite small, but for the first two or three modes this difference can be significant. For the out-of-plane modes, the difference with those of a straight riser is negligible.

The governing equations for a straight riser can not be easily changed to account for the effects of curvature. For this reason, we opted to offer the option to the user to input the natural frequencies and modes of the riser, rather than having VIVA calculate them.

Hence, it is possible to import the modes and make calculations for the in-plane modes of a steel catenary riser. There is a penalty, though: VIVA usually iterates to get the final mode shape, fully accounting for added mass influence. This iteration has to be cut off at the first step when using external modes, since the equations for the straight riser are not compatible with those of the curved riser. As a result the accuracy may be somewhat reduced.

10 What is mode switching?

Mode switching is the phenomenon of having the riser oscillate at a certain frequency and modal shape, and then switch spontaneously to a different modal shape while the frequency changes relatively little. Then, after some time, the riser may switch back to the original modal shape and frequency, and so on.

The explanation for this phenomenon lies in the influence of the added mass coefficient. As explained in the section on added mass variability, the added mass coefficient can vary from a value of 3.0 all the way to a value of -0.5. Hence it is possible to alter the original natural frequencies, calculated using c_m=1, by a significant amount, especially if the mass is comparable to the nominal added mass.

For example, consider the case where the riser has two consequent natural frequencies of f_1 = 1 Hz and f_2 = 2 Hz, a diameter d = 0.25 m and is subjected to a current speed of U = 2 m/s, while the mass ratio is m^* = 1. Then, the added mass for f_1 is c_{m1} = 0.1 and for f_2 it is c_{m2} = 2. This results in final frequencies of f'_1 = 1.3 Hz and f'_2 = 1.33 Hz, i.e. frequencies which are very close together.

Hence it is easy to switch form one mode to the other since the frequencies are so close together and small spatial variations can cause a transition from one shape to the other.

11 Limitations in using a current plus waves, plus slow drift oscillations

When a riser is subject to the action of waves and slow drift oscillations, in addition to a current, VIVA can still produce a credible answer, provided the following criterion is valid:

The frequency of the waves is much slower (by a factor of five or more) than the frequency of VIV. If the ratio is less than five, accuracy becomes increasingly smaller as the ratio decreases.

Since the waves are varying with time, it is necessary to have a nonlinear time domain program, such as RISERSIM, working together with VIVA: RISERSIM simulates the response of the riser to the waves, slow drift oscillations and current, while at each time step VIVA can be called with the instantaneous riser configuration and input velocity (current plus instantaneous wave profile plus slow drift motion) to evaluate the VIV response.

12 Effect of mass ratio

The mass ratio, m^*, for a cylinder with mass m, diameter d and span s, is defined as the ratio of the mass over the nominal added mass, i.e.

$$m^* = \frac{m}{(\pi/4)\rho d^2 s} \tag{7}$$

When the mass ratio is small, close to one, then the variability of the added mass (see corresponding section) has a significant effect on the total mass $m+m_a$, hence the natural frequency can vary substantially. As a result, the region of nominal reduced velocity $U_{rn} = U \big/ \hat{f}_n d$, where $\hat{f}_n$ is the nominal natural frequency, calculated for added mass coefficient of 1, over which the riser may respond, stretches and becomes very wide.

On the contrary, for large mass ratios m^*, the range of reduced velocities, over which VIV develops, becomes narrow.

13 Effect of structural damping

The structural damping constant b, or equivalently the structural damping ratio ζ, is a significant parameter in VIV response, because it determines the amplitude of response. The total damping is the sum of the structural and hydrodynamic damping, so the ratio between the two is an important parameter. The ratio of structural to hydrodynamic damping is measured by the following quantity ξ:

$$\xi = \frac{bA\omega}{\frac{1}{2}\rho d s U^2} = 4\pi^3 \zeta (1+m^*)(f^*)^2 \tag{8}$$

where A the amplitude and f the frequency of response, with $f^* = f\, d/U$, m^* is the mass ratio, d the diameter and s the span of the cylinder, and U the stream speed.

VIVA uses presently the same value for the structural damping ratio ζ for all modes. Its value, however, for very high frequency modes is not based on experimental data. This may be an area where testing is needed, since damping can have a very significant effect on the amplitude of high frequency modes, which are crucial for fatigue calculation.

14 Effect of shear in the current

A sheared current has the effect of providing a range of frequencies of excitation: At various points of the riser the velocity is different, hence the Strouhal frequency of excitation varies as well.

Since there are many frequencies of excitation, the possibility for multi-frequency response becomes increasingly probable, especially as the water depth increases, or the structural stiffness (tension plus bending) decreases - see the corresponding section.

There is a reverse effect of shear, however: Areas of high velocity pump in much more energy than areas of low velocity and may dominate the energy balance process. Also, the correlation length is affected by the presence of shear, ultimately - for very sharp shear - causing a total elimination of VIV. While the mechanics of the effects of shear, i.e. how many modes can be excited as shear increases, are included in VIVA, there are still some questions that remain outstanding. For example, the process by which some modes may be excluded due to shear is still under investigation.

Hence, for very sharp shear one may anticipate reduced response with fewer modes participating, while for mild shear the response is likely to be multi-frequency response with somewhat reduced amplitudes of motion due to shear.

15 Effects of stiffness

The stiffness of the riser consists of the combined tension stiffness and bending stiffness. When the stiffness decreases, then for a given speed of current, a higher-order mode can be excited. Also, as the stiffness decreases, the "density" of natural modes increases, because the fundamental natural frequency decreases, so its multiples populate densely the frequency axis.

A shear current offers a much wider range of frequencies of excitation, hence as stiffness decreases, a larger number of modes may be excited (note, though, some opposite effects in the section on shear current).

16 Effect of the number of points selected for numerical calculation

The choice of the number of points for numerically calculating the natural frequencies and modes is determined on the basis of the anticipated number of modes to be excited.

A rough rule is to have at least seven calculation points for each wavelength. To estimate the number, use your judgment or the following simple procedure:

Let l be the length of the riser (top to bottom), k the average stiffness, T the average tension, m the average mass, a the average added mass, d the average diameter and V the average velocity of the current. Also let ω be defined by:

$$\omega = 2\pi St \frac{V}{d} \tag{9}$$

Where St is the Strouhal number, i.e. $St = 0.17$ for subcritical Reynolds number (less than 250,000) and $St = 0.21$ for supercritical Reynolds number.

Then the required number of points is given by:

$$N = 12 \frac{l}{\lambda} \tag{10}$$

The quantity λ is defined by:

$$\lambda = \frac{\pi}{g} \tag{11}$$

where g is given by:

$$g = \sqrt{\frac{-T + \sqrt{T^2 + 4(m+a)k\omega^2}}{2k}} \tag{12}$$

17 How do I choose single frequency versus multi-frequency response

This is a question on which we are still working. In fact there are two parts to the question: Which of the single-frequency modes do I choose to base the calculation of fatigue; and when does a multi-frequency response become more likely than single-frequency response.

Full scale data show that up to four modes are likely to coexist, so a multi-frequency response is clearly possible. We have no full scale or model scale data showing many modes to participate, such as fifty co-existing modes, but this may simply due to the fact that we have not yet considered such cases.

Until we have corroborated data on how many modes are possible to be excited in a shear current, as function of shear and the natural frequency distribution of the riser, both calculations should be used: The single -frequency response is the worse-case approach, while multi-frequency response may represent a more likely scenario in certain cases.

18 Specifying natural frequencies and modes externally

VIVA has been modified to allow the user to import natural frequencies and modes. This is particularly necessary for studying risers with large static curvature, such as the steel catenary riser (see corresponding section) on large curvature risers.

When this option is selected, the program does a one-iteration calculation only, since the governing equations (for a straight riser) are incompatible with those of a curved riser (imported modes), so the accuracy will be different if imported modes are used.

19 What if I see many modes predicted?

When many modes are predicted – for example one hundred modes, the highest modes are likely to dominate the fatigue calculation, although their amplitude may be quite small. Also, the multi-frequency response calculation is very likely to produce substantially different fatigue predictions.

This type of predicted response is observed in high current - large depth riser applications. It is a matter of current research to determine how realistic this prediction is, so there are no guidelines presently.

Also, the modeling of the structural damping of very high order modes is another unresolved issue that may have significant consequences for this type of calculation: If the structural damping is larger for high frequency vibrations, then the high order modes may simply not be excited.

20 How are strakes modeled in VIVA?

There are two ways to model strakes.

The first is using a hydrodynamic database contained in file "file_s", which is valid for triple strakes with pitch to diameter 17 and height to diameter ratio 0.22. When different geometric parameters are desired, however, these data do not apply.

The second way to model strakes is using "standard data" from the literature. This data was obtained for triple strakes with pitch to diameter form 8 to 12 and height to diameter ratio from 0.05 to 0.18. The data show relative insensitivity to pitch to diameter ratio, so this parameter was not included in modeling strakes. The height to diameter ratio is the only parameter that the user can change. This set of data is not as detailed as the previous one, and hence the accuracy is smaller; on the other hand it provides an added flexibility.

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