AN ASSESSMENT OF EOF CURRENT SCATTER DIAGRAMS WITH RESPECT TO RISER VIV FATIGUE DAMAGE

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ABSTRACT
The accuracy of current modelling is critical when considering deepwater riser fatigue damage caused by vortex-induced vibrations (VIV). In the present study the use of empirical orthogonal functions (EOF) to extract the governing characteristics from huge amounts of current measurements has been assessed. The amplitudes of the time varying principal components (PC) have been organized into bins in scatter diagrams. The accuracy of this scatter diagram approach with different numbers of EOF modes involved has been evaluated in terms of riser VIV fatigue damage.

INTRODUCTION
For deepwater risers current is the governing environmental load, hence the accuracy of the applied current distributions become increasingly important with water depth. Traditionally enveloping current profiles are used, i.e. based on current measurements at selected depths the corresponding velocity distributions are established independently at each depth, and current profiles with the desired return period can be found. Spanwise coupling is thus disregarded and the established current profiles are unlikely to represent 'real' profiles. They might also be non-conservative. The latter has been shown in a paper by Adams and Thorogood (1998) where it is indicated that use of what they call concurrent profiles give fatigue lives an order of magnitude lower compared to conventional enveloping methods.

Current measurements at a field location generate huge amounts of data impractical to apply in any riser analyses. Hence a method to extract the most important characteristics of a current dataset into a manageable level of current profiles is very important for reliable riser analyses. When considering vortex-induced vibrations (VIV) of risers, the current velocity is of course important, but the spanwise coupling is equally important in terms of power-in regions. Power-in region is an expression common for semi-empirical VIV software codes such as SHEAR7 by Vandiver et al. (2002), reflecting the length of the region where the dominating response modes will have a positive lift coefficient. Uniform current profiles typically give the longest power-in regions. Traditional envelope methods may give current profiles that are more sheared than in reality by neglecting spanwise coupling, resulting in shorter “power-in” regions and thereby less VIV fatigue damage.

Lately, the use of empirical orthogonal functions (EOF) as a tool to simplify current data and derive design current profiles has been presented by several authors, see e.g. Forristall and Cooper (1997) and Jeans and Feld (2001). However, the EOF method is not new and has been applied by meteorologists and oceanographers for several decades to analyse complex time series. While the above authors focused upon extreme current profiles, the present study assesses the accuracy of the EOF method in terms of riser VIV fatigue damage, i.e. the EOF generated current profiles are used as input to the VIV code SHEAR7 (Vandiver et al. 2002), to predict fatigue damage caused by VIV.

NOMENCLATURE

cfd
EOF
PC
SVD
VIV

Computational Fluid Dynamics
Empirical Orthogonal Functions
Principal components
Singular Value Decomposition
Vortex-Induced Vibrations
THE EOF METHOD

The aim of EOF analysis is to provide a compact description of the spatial and temporal variability of data series in terms of orthogonal functions. These orthogonal functions play the same role as sine waves do in ordinary Fourier analysis. The data can be expressed as a sum of EOFs just as every time series can be expressed as a sum of sine waves.

It can be shown that the most efficient method of compressing data is the EOF method. Here efficiency is used in the sense of lowest total mean square error. The EOFs are ordered so the first mode expresses most of the variance in the data, and usually most of the variance in a data set can be explained by only a few orthogonal functions. Hence, even large data sets may typically be well approximated by 1-3 EOFs.

The EOF analysis is based on two main assumptions. Firstly, the time evolution of the dominant modes is assumed to be uncorrelated. Secondly, the dominant modes are assumed to be orthogonal in space. Even if the first modes should correspond to different physical mechanisms, the time variation of these processes should further be uncorrelated for the EOF analysis to give the "correct" result. As a result, a single physical process may often be spread over more than one EOF. In other cases more than one physical process may be contributing to the variance contained in a single EOF. Physical interpretation of the modes should therefore always be made with great care.

Two methods exist for computing the EOFs of time series. The first constructs a covariance matrix and then solves the eigenvalue problem to establish eigenvalues and eigenvectors. The second approach uses singular value decomposition (SVD) of the data matrix to obtain eigenvalues, eigenvectors and time varying amplitudes (principal components). With the latter method large covariance matrices are avoided, and it is generally a faster and more stable method. A brief description of the SVD method is given below.

Singular Value Decomposition

Using matrix notation any \( M \times N \) matrix \( A \) can be factored into

\[
A = U \lambda V^T
\]  

(1)

where the columns of \( U \) \((M \times N)\) are the eigenvectors \( A^T \), and the columns of \( V \) \((N \times N)\) are the eigenvectors \( A^T \). The singular values on the diagonal of \( \lambda \) are the square roots of the nonzero eigenvalues of both \( A^T A \) and \( A A^T \). If the mean of \( A \) has been removed, then \( A^T \) and \( A^T \) represent respectively the temporal and spatial covariance matrices. \( U \) and \( V \) are orthonormal so that

\[
U^T U = I
\]  

(2)

\[
V^T V = I
\]  

(3)

Suppose we have a \( M \times N \) matrix \( A \) with \( M \) as time dimension and \( N \) as depth dimension. Then the \( N \) columns of \( V \) are the eigenvectors of the \( N \times N \) matrix \( A^T A \). Thus these eigenvectors are the EOFs of \( A \). The columns of \( U \) are the principal components. The values of \( U \) and \( V \) are linked by the singular values along the diagonal of \( \lambda \). These are sometimes called the magnitude of the modes, and they are square roots of the eigenvalues of \( A^T A \). Similarly to the covariance matrix approach, the original data can often to a good approximation be reconstructed by summing over the first few modes. This is because the magnitude (singular value) of the modes rapidly decreases towards zero.

\[
\hat{A}_{ij} = \sum_{k=1}^{K} U_{ik} \lambda_k V_{jk}
\]  

(4)

where \( i=1\ldots M \) and \( j=1\ldots N \). The error of this reproduction can be quantified by:

\[
e = 1 - \frac{\sum_{i} \sum_{j} (\hat{A}_{ij} - A_{ij})^2}{\sum_{i} \sum_{j} A_{ij}^2}
\]  

(5)

This is the error in variance between the observed and EOF reproduced data. When applied to current data we can use this formula to find the explained variance of every mode for all the depths. An example of this is shown in Figure 5.

EOF APPLIED ON CURRENT MEASUREMENTS

In the present study 3 different datasets of measured current profiles are considered at water depths ranging from 750m to 1060m. In general the ADCP current measurements are carried out with durations of approximately one year. Some general information about the datasets is listed in Table 1 below.

<table>
<thead>
<tr>
<th>Table 1: Information about current datasets applied</th>
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<tbody>
<tr>
<td>Set</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
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</table>
A plot of the current speeds in dataset 1 versus depth and time is shown in Figure 1. The maximum current speed during the year of data collection is found to be close to 80 cm/s. Even though data for current directions are also available, they are neglected in this study for two reasons. Firstly, most semi-empirical VIV codes, such as SHEAR7 and VIVANA (Larsen et al. 2001), can only handle unidirectional current profiles. Secondly, the main emphasis in this study is to compare how well a limited number of EOF current profiles reproduce the current loading from all the measured current profiles with respect to fatigue damage caused by VIV.

While dataset 2 is similar to dataset 1 in terms of current speed magnitudes and variation with depth, dataset 3 is dominated by low current speeds over the entire water column with the exception of a few incidents of a surface current that reaches 60 cm/s, see Figure 2 below.

Applying the SVD technique to dataset 1 gives the EOF modes shown in Figure 3. The corresponding time histories of the principal components are plotted in Figure 4. As seen in Figure 5, EOF mode 1 reproduces most of the variance in the measured data. For water depths down to 400m, EOF mode 1 covers more than 90% of the variance. Note that 100% means perfect reproduction of the measured data. However, for water depths beyond 400m EOF mode 1 reproduces only around 70% of the variance, while EOF mode 3 becomes increasingly important bringing the percentage of total variance back to approximately 90%. As shown in Figure 5, the contribution from EOF mode 2 at water depths beyond 400m is minor compared to EOF mode 3.
It is also worthwhile to note that both the mode shape of EOF mode 1 and the corresponding principal component are always positive, while the other mode shapes and principal components are varying between positive and negative values. Hence, the EOF modes beyond mode 1 correct the shape of the current profile given by EOF mode 1, by adding and subtracting speeds at the different water depths considered.

While applying 3 EOF modes reproduces around 90% of the total variance over the entire water column for dataset 1 and 2 (Figure 6) the situation is somewhat more complex for dataset 3 (Figure 7) where EOF mode 1 explains more than 90% of the total variance only for the upper most water depth, and below 50% of the variance for the bottom layer. At the two deepest layers, 5 EOF modes are required in order to bring the percentage of the total variance close to 90%. Hence, the benefit of the EOF method in terms of reducing the complexity of current measurements is less for dataset 3 than for datasets 1 and 2.

VIV SENSITIVITY TO CURRENT INPUT

A common question related to the use of the EOF method in terms of representing current data, is how much of the total variance in the measurements needs to be reproduced. It may not be 90% as focused upon in the previous section. The missing percentage in variance means that some of the largest peaks in the current measurements are being reproduced with too low amplitudes. In this study the aim is to assess what the consequences of underestimating the peaks in current velocity will be to the prediction of riser VIV fatigue damage. Hence, the accumulated VIV fatigue damage has been calculated for all the measured current profiles and compared with the results from the EOF profiles.

Riser model

The riser model applied in the present study is based on a SHEAR7 (Vandiver et al. 2002) example model. It is a drilling riser with buoyancy modules attached from sea bottom to top-end. In addition the upper 30% of the riser is covered with VIV suppression devices. The original model was for a water depth of 668m, however in this study the water depth is adjusted to the actual water depths where the currents are measured. The main characteristics of the riser model are listed in Table 2, and the most important VIV analyses settings used by SHEAR7 are given in Table 3.
Table 2: Main particulars of the riser models considered

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
</tr>
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<tr>
<td>Buoyancy outer diameter</td>
<td>[m] 1.1303</td>
</tr>
<tr>
<td>Pipe outside diameter</td>
<td>[m] 0.5334</td>
</tr>
<tr>
<td>Pipe inside diameter</td>
<td>[m] 0.5017</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>[N/m²] 2.107 x 10¹¹</td>
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<tr>
<td>Moment of inertia</td>
<td>[m⁴] 0.8637 x 10⁻³</td>
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<tr>
<td>Mass of pipe</td>
<td>[kg/m] 908</td>
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<tr>
<td>Submerged weight of pipe</td>
<td>[N/m] 1087</td>
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<tr>
<td>Bottom tension</td>
<td>[N] 1.743 x 10⁶</td>
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<tr>
<td>Structural damping</td>
<td>[%] 0.3</td>
</tr>
<tr>
<td>Suppression device</td>
<td>[%] 30 (upper part)</td>
</tr>
<tr>
<td>Water depths</td>
<td>[m] 750, 995, 1060</td>
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<tr>
<td>Number of riser elements</td>
<td>- 226</td>
</tr>
<tr>
<td>Boundary conditions</td>
<td>- Pinned-pinned</td>
</tr>
</tbody>
</table>

Table 3: VIV settings used in the SHEAR7 analyses

<table>
<thead>
<tr>
<th>Parameters</th>
<th></th>
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</thead>
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<td>Added mass coefficient</td>
<td>1.0</td>
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<tr>
<td>Strouhal number</td>
<td>Curve 200 (rough cylinder)</td>
</tr>
<tr>
<td>Single-mode reduced velocity bandwidth</td>
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<tr>
<td>Multi-mode reduced velocity bandwidth</td>
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</tr>
<tr>
<td>Cut-off level for participating modes</td>
<td>0.7</td>
</tr>
<tr>
<td>Reduction factor of C₁ for suppression device zones</td>
<td>0.1</td>
</tr>
<tr>
<td>SN - curve</td>
<td>E-curve</td>
</tr>
</tbody>
</table>

**EOF scatter diagrams**

In the papers by Forristall and Cooper (1997) and Jeans and Feld (2001) the main focus was on deriving extreme current profiles. However Forristall and Cooper (1997) also proposed a method for applying the EOF method in fatigue analyses. Similar to scatter diagrams for significant wave height, Hs, and spectral peak period, Tp, the amplitudes of the principal components can be combined into bins generating scatter diagrams as shown in Figure 8 below. For each bin there exists a current profile determined by the product of the bin’s PC amplitude and the EOF eigenvectors. The damage contribution from that bin is then weighted by its occurrence rate.

However, while the wave scatter diagrams usually cover periods of 30 years or more, the current data is usually limited to periods of a year or even less. Hence the fatigue damage contribution from the most extreme current profiles will be missing in a scatter diagram such as Figure 8. One way to include the effects of the most extreme current profiles is to apply the EOF method to establish extreme current profiles and include them in the scatter diagram.

The scatter diagram shown in Figure 8 is established for dataset 1 when 2 EOF modes are considered. It consists of 49 bins where each bin has a probability of occurrence, here given in percent. By including more modes the scatter diagram becomes increasingly complex, e.g. by 3 EOF modes a 3 dimensional scatter diagram is generated where the number of bins increases from 49 to 209 with equal spacing of the PC amplitudes. By including 5 EOF modes 2175 bins would be required. Hence the possible benefit of the EOF method decreases rapidly with the number of EOF modes required. The present study focuses on the number of EOF modes required in order to replicate the measured current profiles for riser VIV fatigue damage analysis.

**Results from the VIV fatigue damage analysis**

In order to evaluate the EOF scatter diagram approach, the “true” VIV fatigue damage has been calculated by accumulating the damage contribution from each of the measured current profiles in a dataset. The accumulated VIV damage predicted by using current profiles from EOF scatter diagrams based upon 2, 3, 4 and 5 EOF modes are then compared as shown in Figure 9.
Figure 9: Accumulated VIV fatigue damage along the riser for different current representations of dataset 1. Measured refers to the measured current profiles, EOF_2 … EOF_5 to number of EOF modes applied to generate the EOF current profiles and Weibull refers to current profiles established by separate 3 parameter Weibull fits to the data at each measurement depth.

In Figure 9 the accumulated damage along the riser is shown, and the label Weibull refers to VIV fatigue damage predicted by applying current profiles from conventional enveloping techniques, i.e. at each depth of measurements a 3-parameter Weibull distribution is fitted to the measured current speeds. It is anticipated that the datasets represent 1 year of data, therefore 18 current profiles with probability levels of non-exceedance ranging from 0.3 to 1-year level have been applied.

As seen in Figure 9, current profiles based upon 2 EOF cause underestimation of the accumulated VIV fatigue damage - in the order of 20% for the maximum value. Hence 2 EOF modes do not reproduce the measured data accurately enough in this case when focusing on VIV. Adding an EOF mode changes the picture, and an almost perfect match between the curve labeled “measured” and the curve labeled “EOF_3” is seen. Increasing the number of EOF modes to 4 and 5 does not make any difference, i.e. one might conclude that the EOF method has “converged” at 3 modes for this case. The Weibull curve shows that the conventional enveloping method overestimates the fatigue damage by 25% at the maximum value. The shape of the Weibull damage curve is also somewhat different from the others, indicating that some other eigenmodes of the riser have been excited with this approach.

Figure 10: Accumulated VIV fatigue damage along the riser for different current representations of dataset 2. The different current representations are explained in the caption of Figure 9.

The results for dataset 2 are shown in Figure 10. The predictions based on current profiles generated by 2 EOF modes underestimate the maximum fatigue level even more than for dataset 1, in the order of 50%. Adding an EOF mode lifts the fatigue damage level significantly, however 3 EOF modes do not give as good a match as in the previous case. The maximum peak is underestimated by 14%, but otherwise the match is still very good. Adding 1 or 2 EOF modes in addition brings the maximum fatigue damage level slightly above the level of the “measured” curve – in the order of 5-10%. The “Weibull” curve reproduces the maximum fatigue damage level well, however, the “Weibull” curve shape is again different from the other curves.

It is somewhat surprising that dataset 2 requires more EOF modes to match the “measured” curve, than dataset 1. By looking at the variance plots, approximately 90% of the total variance is covered by 2 EOF modes for dataset 2, see Figure 6, while dataset 1 requires at least 3 modes to be close to cover 90% of the total variance, see Figure 5. Hence, one might expect that 2 EOF modes would do the job for dataset 2. One reason why it turns out to be different when it comes to fatigue damage might be the difference in water depth. Case 2 goes 300m deeper than case 1, hence higher modes might be excited, and higher modes are more sensitive to minor differences in current speed. When comparing the shape of the fatigue damage curves shown in Figure 9 and 10, it is obvious that higher modes are excited for dataset 2 than for dataset 1.
The results for dataset 3 are shown in Figure 11. This time, all the EOF curves, except “EOF_3”, underestimate the maximum fatigue damage level, while the Weibull approach gives more and less double the maximum fatigue damage level. It is not unexpected that the fatigue damage level is underestimated for this dataset since even 5 EOF modes did not manage to explain 90% of the total variance. The reason why the EOF method with 3 modes overestimates the maximum fatigue level is most likely linked to the low current speeds for this dataset, which gives fatigue damage levels 4 orders of magnitude lower than for dataset 1 and 2. Hence, small changes in current speeds and profile shape may have a significant impact on the overall fatigue damage level. The overestimation shown by the “EOF_3”-curve in Figure 11, is caused by 2 current profiles out of 120, see Figure 16.

To assess whether the somewhat unexpected results from dataset 3 are caused by low fatigue damage levels compared to dataset 1 and 2, the strakes covering the upper 30% of the riser were removed (by changing lift reduction factor in SHEAR7 from 0.1 to 1.0) and all the analyses were redone. As seen in Figure 12, the results are now more in line with what is expected when the fatigue damage level is increased by one order. By applying 2 EOF modes less than 20% of the “true” fatigue damage level is predicted, whilst 3 EOF modes reaches 70%. This time 4 and 5 EOF modes predict correct maximum fatigue damage level, however there are some minor discrepancies of the fatigue damage curve shapes along the riser. It might be concluded that the EOF current scatter diagram approach becomes more consistent, i.e. less sensitive to single bins, with increasing fatigue damage levels.

The fatigue damage plots presented so far are all based on EOF scatter diagrams with steps of 1 [-] in PC amplitude. The sensitivity to this step size has been investigated for dataset 1 with 3 EOF modes for various the step sizes from 2 to 0.5 in PC amplitude. This change in step sizes increases the number of bins in the EOF scatter diagram from 49 to 923. If 5 EOF modes had been considered, the increase in number of bins with decreasing step sizes would have been even more significant since a 5-dimensional scatter diagram would be involved. The results from the sensitivity study are shown in Figure 13 below. It is clearly shown that the two coarsest scatter diagram densities cause overestimations of the VIV fatigue damage level, while step sizes of 1.0 and 0.5 reproduce the “measured” curve well.

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**Figure 11:** Accumulated VIV fatigue damage along the riser for different current representations of dataset 3. The different current representations are explained in the caption of Figure 9.

**Figure 12:** Accumulated VIV fatigue damage along the riser for dataset 3, now without strakes.

**Figure 13:** Accumulated VIV fatigue damage along the riser for different scatter diagram densities (3 EOF modes, dataset 1).
Even though the original number of current profiles has been significantly reduced, e.g. from 14351 to 209 profiles for dataset 1, approximately 200 current profiles may still be too many profiles to consider. For wave scatter diagrams it is common to group the bins into larger blocks, which are approximately weighted and applied in the riser analysis. To assess how many current profiles out of 209 are actually contributing to the overall fatigue damage, the maximum fatigue damage for each bin has been predicted and plotted versus bin number, see Figure 14. To evaluate the accuracy of EOF current profiles on bin level, the accumulated fatigue damage from measured current profiles belonging to a bin has also been calculated for each bin and the maximum values are plotted in Figure 14. Figure 15 is included to illustrate the involved current profiles for one bin, here represented by bin 191 where 15 measured current profiles occur. By accumulating the weighted VIV fatigue damage predicted for all 15 current profiles and then finding the maximum value, the point for EOF group 191 for the “measured” curve in Figure 14 is found. The corresponding point on the “EOF_3” curve is simply the weighted maximum fatigue damage found when running SHEAR7 with the EOF current profile shown in Figure 15.

As seen in Figure 14, only a limited number of the current profiles contribute to the fatigue damage. For this dataset 12 profiles generate more than 50% of the total fatigue damage, and 45 profiles 93%. Typically the bins with highest occurrence rate and the bins with highest U1 amplitudes dominate the damage contribution. Hence, combining bins into larger blocks should be a possible strategy. However, SHEAR7 simulations take only a few seconds on a standard PC requiring only a few minutes in total simulation time for 209 different current profiles. Thus only CFD simulations would benefit of grouping the bins into larger blocks.

In Figure 11 it was shown that the EOF method with 3 modes generated current profiles that caused an accumulated VIV fatigue damage that exceeded the damage level of the “measured” curve, while the EOF method 2, 4 and 5 modes generated current loadings that significantly underestimated the VIV fatigue damage. As mentioned earlier, a likely reason why the “EOF_3” curve in Figure 11 does not follow the trend of the other EOF curves is that at these low current speeds and damage levels the VIV predictions are very sensitive to small changes in current speeds and profile shape. This is clearly shown in Figure 16, where especially one EOF current profile causes VIV fatigue damage that exceeds the absolute maximum level on the “measured” curve by more than 400%.
CONCLUSIONS

In the present study it has been shown that the EOF current scatter diagram approach can be a powerful tool to extract the governing characteristics from huge amounts of current field measurements. A limited set of current profiles with a certain probability can be obtained by organizing the combined amplitudes of the principal components into bins that generate a scatter diagram of the current data.

The accuracy of the EOF scatter diagram approach depends on the size of the bins in terms of step sizes in PC amplitudes and number of EOF modes applied. It has been shown that a step size of 1 [-] in PC amplitude is the best choice for the current datasets considered in this study. It is also found that the dominating bins in the EOF scatter diagram with respect to fatigue damage are the ones with highest occurrence rate and the ones with largest amplitude of principal component 1.

A possible indicator of the “goodness” of the EOF method and the required number of EOF modes might be the percentage of total variance of the current data that the EOF method reproduces. However the present study does not show a clear trend supporting that idea. For dataset 1 the current profiles generated by applying 3 EOF modes caused VIV fatigue damage along the riser that matched the “true” VIV fatigue damage curve along the riser almost perfectly. Here true is used in the sense of fatigue damage that is accumulated by applying all the measured current profiles. For dataset 1 the total variance reproduced by 3 EOF modes varied from 85% at the bottom to close to 100% at the top of the water column.

The results for dataset 2 are different. Here 3 EOF modes cover more than 90% of the total variance over the entire water column. However when applying 3 EOF modes the maximum VIV fatigue damage is under predicted by approximately 15%. By increasing the number of EOF modes to 4 and 5 the maximum fatigue level is slightly over predicted, approximately by 5%. Hence even if a higher percentage of total variance is reproduced by 3 EOF modes for dataset 2 than for dataset 1, 4 EOF modes are required to predict a VIV fatigue damage level that is not non-conservative for dataset 2. Then it is somewhat surprising that EOF mode 4 hardly contributes to the total variance level as shown in Figure 6.

For dataset 3 even when 5 EOF modes are applied the maximum fatigue damage level is underestimated. And 5 EOF modes cover close to 90% of the total variance over the entire water column. However dataset 3 is a low current speed case generating little fatigue damage. Hence small changes in current profile and current speeds might separate between VIV and no VIV. That is the reason why 3 EOF modes cause a clear over prediction of the maximum fatigue damage level for dataset 3.

The effect of low fatigue damage level on the EOF current scatter diagram approach is investigated by running case 3 without strakes covering the top 30% of the riser. That increased the fatigue damage level by an order of magnitude, and then 4 and 5 EOF modes predicted correct maximum fatigue damage level. Hence, it might appear that the accuracy of the EOF current scatter diagram approach improves with increasing fatigue damage levels. However, this statement needs further verification by considering more current datasets.

Hence for the datasets considered in the present study 4 EOF modes are required to generate current scatter diagrams that when applied in a VIV analysis cause conservative fatigue damage levels. This statement is also valid for dataset 3 when a bare riser is considered. If this statement is generally valid requires further studies of more datasets and different riser configurations. It has also been shown for the present current data that using a standard envelope technique, such as Weibull distributed current profiles, does not cause non-conservative results as opposed to Adams and Thorogood’s (1998) findings. However this may not be the case for other field locations and riser configurations.

A general conclusion is that further assessments of the EOF method are required in terms of more current datasets and different riser configurations to explore the possible benefits of the method and obtain general recommendations for conservative usage.

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REFERENCES


