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VIV MODEL TEST DATA COMPARISON WITH SHEAR7 V4.5

G. Yang/ExxonMobil Upstream Research Company

W.R. Frank/ExxonMobil Development Company

R.B. Campbell/ExxonMobil Upstream Research Company

S.T. Slocum/ExxonMobil Upstream Research Company

ABSTRACT

The prediction of riser and tendon fatigue damage due to vortex-induced vibration (VIV) remains an active area of research in the offshore industry. In 2003, ExxonMobil performed VIV testing on a 10-m long, 20-mm diameter model in an effort to better understand the mechanics of VIV response of a long flexible pipe. Measured results from these tests, summarized in terms of response frequency, strain, and damage, were published in a series of papers in OTC 2004. Due to the dense array of instrumentation (17 cross flow and 35 inline stations along the riser span) and the use of strain gages in the experiments, the 2003 ExxonMobil data allows for a direct estimation of fatigue response and provides an excellent benchmark for validation of VIV predictions.

This paper extends our previous work by comparing the measured test results to simulations of the test conditions (for example, model properties, boundary conditions, and current profiles) using the widely used VIV prediction tool, Shear7. We compared measured and predicted response in terms of a "damage index" for bare, fully straked, and partially straked risers. The damage index, defined as response frequency times the third power of RMS strain ($f \times \varepsilon_{\text{rms}}^3$), is proportional to the fatigue life and thus can be used as a basis to assess the accuracy of predictions.

For the comparison work presented in this paper, ExxonMobil has utilized a latest version of Shear7 (version 4.5) which provides added functionality and increased user control over analysis assumptions through assignment of key input parameters. In order to investigate the influence of the analysis assumptions on the predictions, a matrix of 64 distinct input parameter sets was defined. The study indicated that the new "time-sharing" model in general can generate prediction results with reasonable bias and scatter for bare risers. However, prediction errors for straked risers are still high even when the most favorable parameters are selected for the analysis. These comparisons highlight the continuing need for improved formulations with smaller prediction bias and scatter and for high quality benchmarking data and benchmarking methods for objective assessment of VIV prediction accuracy.

INTRODUCTION

Vortex-induced vibration (VIV) is a riser response to time-varying hydrodynamic forces that arise when ocean currents cause vortices to form and shed into the riser's wake. Riser VIV prediction is difficult and complex due to a) the strongly non-linear nature of the viscous hydrodynamic forces associated with vortex shedding, and their interaction with structural response, b) varying current velocity along the span of a riser in ocean currents, and c) the potential for structural response at a number of frequencies, either singly or in combination.

Riser designers need reliable methods to predict VIV response in service conditions because bending vibrations excited by VIV in high-speed currents can cause significant long-term fatigue damage. The ultimate goal for VIV prediction is to develop fully coupled numerical hydrodynamic and structural models, but current techniques to numerically model the hydro-elastic response remain limited in their ability to address the practical riser design problem. Therefore, we rely on semi-empirical prediction formulations developed based on our best understanding of the riser VIV phenomenon and implemented into predictive software. These programs rely on empirical hydrodynamic force data coupled with an analytical structural model.

In order to use results from idealized laboratory tests to produce vibration response predictions for a broad range of riser design characteristics and for arbitrary current profiles, present semi-empirical formulations incorporate modeling assumptions and approximations in the VIV prediction software that need further validation for risers in deep-water, high-speed current environments. These assumptions and approximations may vary substantially from one formulation to the next.

As part of a larger effort to validate VIV modeling assumptions in available software, ExxonMobil undertook an extensive set of tests in 2003 to examine the VIV response of a 10-m long, 20-mm diameter flexible riser model and the test results were published in a series of papers in OTC 2004. These tests featured extensive instrumentation, high sampling rates, and careful time synchronization of the measurements allowing the global response to be reconstructed over the entire model length with good accuracy. Hence, the data from these experiments provide a valuable benchmark for both qualitative and quantitative validation of present and future riser VIV prediction formulations and prediction codes.

This paper focuses on comparing the measured 2003 ExxonMobil test results to simulations of the test conditions (for example, model properties, boundary conditions, and current profiles) using the VIV prediction tool Shear7 v.4.5. We selected a matrix of input parameters for this work to test assumptions made at key stages of the prediction procedure. The specific Shear7 parameters we varied are discussed briefly in the following sections.

The benchmarking methodology presented in this paper is not specific to Shear7 or the ExxonMobil VIV test, but it does require that the data is of high quality and the primary quantity measured in the test is strain. In addition, all comparisons shown in the paper have been made on a location-specific basis (i.e., predicted and measured quantities for a specific location on the riser model are compared directly). Others have sometimes used a comparison approach in which maximum measured and predicted fatigue damage over the riser span are compared without regard to location. We believe that conclusions drawn from this more lenient approach may be misleading to riser designers who need to assess fatigue damage at specific locations along the riser, and who may make local design changes to improve fatigue capacity at those specific locations.

PREDICTION APPROACH OF SHEAR7 V.4.5

One of the most widely used VIV prediction tools is Shear7 developed at MIT by Prof. Kim Vandiver and his students. This software identifies which riser vibration modes are likely to be excited in a steady current, and estimates the cross-flow VIV response amplitudes and resulting fatigue damage. In the formulation underlying Shear7, major steps in the prediction approach are the following:

1. Identify the riser resonant frequencies that may be excited by a given current profile.
2. At each possible response frequency, find a "candidate" solution of the vibration problem that satisfies global dynamic equilibrium:
   a) Determine which resonant riser modes may participate in the response.
   b) Determine the position and spanwise extent of hydrodynamic excitation and damping along the riser.
   c) Estimate the local hydrodynamic excitation and damping forces at each spanwise location along the riser from available empirical data.
   d) Use an iterative solution technique to determine the magnitude of vibration (i.e., the participation factors for the participating modes) that results in global dynamic equilibrium.
3. Assess the likelihood that each of the "candidate" solutions will contribute to the actual response, and eliminate "candidate" solutions that are unlikely to participate.
4. Determine independent time sharing zones and construct a final response prediction using one or more of the remaining "candidate" equilibrium solutions.

In Shear7, the "reduced velocity bandwidth" parameter influences Steps 1 and 2b of the prediction approach; a "power cutoff level" parameter influences Step 3; and a "primary zone amplitude limit" influences Step 4. These parameters are described in detail in the following section.

A substantial modification in Shear7 v.4.5 is the adoption of a "time-sharing" analysis model for use in Step 4. Previous versions of Shear7 (v.4.4 and lower) use a model that allows modes to occur simultaneously as part of the calculated response to a current. In this earlier model, the extent of the excitation region assumed for a "candidate" response solution is reduced due to the presence of simultaneously occurring response components at other frequencies.

In contrast, the new time-sharing model adopted in Shear7 v.4.5 allows modes to respond within their entire excitation region, but the time allowed to respond is reduced in accordance with the calculated time sharing probabilities. In recognizing that modes in high mode number cases have power-in regions far away from each other that may not interact, the new version of Shear7 allows up to three (one primary and up to two secondary) independent time sharing zones along the riser span that can respond simultaneously. These zones are treated independently and modes are assigned to zones based on dominant mode amplitude and "primary zone amplitude limit". Within each of the time sharing zones, the program assumes that each independent solution occurs for a percentage of the time that the riser is exposed to the analyzed current profile. The final solution for the analyzed current is a weighted sum of these individual fatigue damage estimates.

Shear7 v4.5 provides several user selected methods in combining the individual modal fatigue damage contributions. For example, power fraction weighting is based on the power ratios; uniform weighting option applies a uniform weighting factor to all of the fatigue damage components. In addition, users can choose to develop their own method for combining the fatigue damages by using the unweighted damage profiles provided in the Shear7 output. In this benchmark study, we utilized the power fraction weighting in calculating the damage indices.

SHEAR7 V4.5 - USER SELECTED PARAMETERS

In the work reported in this paper, we focused on varying the Shear7 parameters that control key assumptions in Shear7 formulation. This section provides a brief discussion of the user selected parameters which are investigated in this benchmarking study and identifies the assumption controlled by each parameter.

Reduced velocity bandwidth

Shear7 utilizes reduced velocity bandwidth as an input parameter to identify potential excited modes and to determine the spanwise extent of VIV excitation along the length of riser. The reduced velocity bandwidth dV_R is a number between zero and two defined as:

$$dV_R = \frac{\Delta V_R}{V_R} \quad \text{and} \quad V_R = 1/S_t \tag{1}$$

where ΔV_R is the lock-in reduced velocity range; V_R is the ideal lock-in reduced velocity; and S_t is the Strouhal number. Therefore, the lower and upper bounds of the reduced velocity range are

$$V_R^L = V_R(1 - dV_R/2) \quad \text{and} \quad V_R^U = V_R(1 + dV_R/2) \tag{2}$$

Assuming that the riser vibrates at its s^{th} mode with a natural frequency of f_s and local current speed on the riser is U, the reduced velocity of riser at location x can be calculated by

$$V(x) = \frac{U(x)}{f_s D(x)} \tag{3}$$

where $D(x)$ is the hydrodynamic diameter of the riser. If the calculated reduced velocity falls within the reduced velocity range, the portion of riser at location x becomes part of the power-in regions for the s^{th} mode. The power-in regions for the s^{th} mode can then be defined by repeating this process along the whole riser span.

Modes with a non-zero excitation region are considered potential contributors to the response and the parameters discussed below determine which components are included and how they are combined in the final prediction.

Power ratio cutoff

The power ratio cutoff is a number between zero and one which controls how many discrete modal power-in regions exist and controls the number of modes considered in the solution. In Shear7, the program first identifies the input power levels of each potentially excited mode. Then, the input power levels are divided by the maximum input power found for all modes evaluated. If the ratio for a particular mode is less than the power ratio cutoff, the mode is neglected; otherwise, the mode is identified as a participating mode and it is included in the subsequent calculation. When the power ratio cutoff is very small or close to zero, almost all potentially excited modes are included in the response calculation. When set to 1.0, only the mode with the maximum input power from the fluid or the dominant mode is included in the final response prediction.

Primary zone amplitude limit

To determine the existence and the number of secondary time sharing zones that are allowed to respond simultaneously with the primary zone, the developers added a new user selected input parameter in v.4.5, the primary zone amplitude limit. When the dominant mode wave travels from the center of its own power-in region, Shear7 calculates the dominant wave amplitude at the center of power-in regions associated with other participating modes, *i.e.* s^{th} mode. If the dominant wave amplitude at s^{th} mode is below the primary zone amplitude limit, Shear7 assumes that the s^{th} mode belongs to one of the secondary zones. Theoretically, up to two secondary zones can exist, one above and one below the primary zone. When the primary zone amplitude limit is set to 0, only one, the primary, time sharing zone exists on the riser, which includes all participating modes. Setting the amplitude limit to one, the primary time sharing zone in general only includes the dominant mode and the rest of participating modes are included in the secondary zones.

USER SELECTED PARAMETER SETS FOR BENCHMARKING

The user selected parameter sets used to conduct the benchmark study are summarized in Table 1, which includes a total of 64 cases with varying reduced velocity bandwidth, power ratio cutoff and primary zone amplitude limit. Note that Case 18 (reduced velocity bandwidth=0.4, power ratio cutoff=0.05, and primary zone amplitude limit=0.3) is the parameter set recommended by Shear7 User's Manual [1] for both bare and straked risers.

In order to generate the simulation results using Shear7, some additional user selected parameters (listed in Table 2) need to be chosen. These parameters were applied and held fixed for all cases investigated in this benchmark study. The Strouhal number of 0.14 was chosen to match vibration frequencies observed in the 2003 experimental data for uniform flow. For bare risers, Shear7 default hydrodynamic damping models are used for the still water, low and high reduced velocity regions, respectively; for straked risers, the hydrodynamic damping models twice that of bare risers are utilized in the calculation. In all cases, VIV excitation is modeled using a lift coefficient that depends only on the ratio of vibration amplitude to cylinder diameter. This option is activated by selecting lift coefficient "Table 1" in the Shear7 input file for bare risers and lift coefficient "Table 3" with a reduction factor of 0.2 for straked risers.

Table 1: Matrix of User Input Parameters

Case No	Reduced velocity bandwidth	Power ratio cutoff	Primary zone amplitude limit
1	0.2	0.05	0
2	0.2	0.05	0.3
3	0.2	0.05	0.6
4	0.2	0.05	1
5	0.2	0.4	0
6	0.2	0.4	0.3
7	0.2	0.4	0.6
8	0.2	0.4	1
9	0.2	0.7	0
10	0.2	0.7	0.3
11	0.2	0.7	0.6
12	0.2	0.7	1
13	0.2	1	0
14	0.2	1	0.3
15	0.2	1	0.6
16	0.2	1	1
17	0.4	0.05	0
18	0.4	0.05	0.3
19	0.4	0.05	0.6
20	0.4	0.05	1
21	0.4	0.4	0
22	0.4	0.4	0.3
23	0.4	0.4	0.6
24	0.4	0.4	1
25	0.4	0.7	0
26	0.4	0.7	0.3
27	0.4	0.7	0.6
28	0.4	0.7	1
29	0.4	1	0
30	0.4	1	0.3
31	0.4	1	0.6
32	0.4	1	1
33	0.7	0.05	0
34	0.7	0.05	0.3
35	0.7	0.05	0.6
36	0.7	0.05	1
37	0.7	0.4	0
38	0.7	0.4	0.3
39	0.7	0.4	0.6
40	0.7	0.4	1
41	0.7	0.7	0
42	0.7	0.7	0.3
43	0.7	0.7	0.6
44	0.7	0.7	1
45	0.7	1	0
46	0.7	1	0.3
47	0.7	1	0.6
48	0.7	1	1
49	1	0.05	0
50	1	0.05	0.3
51	1	0.05	0.6
52	1	0.05	1
53	1	0.4	0
54	1	0.4	0.3
55	1	0.4	0.6
56	1	0.4	1
57	1	0.7	0
58	1	0.7	0.3
59	1	0.7	0.6
60	1	0.7	1
61	1	1	0
62	1	1	0.3
63	1	1	0.6
64	1	1	1

** Case 18 is the parameter set recommended by Shear7 User's Manual*

Table 2: Other User Selected Parameters

	Bare Risers	Straked Risers
Strouhal number	0.14	
Global stress concentration factor	1.0	
Structural damping coefficient	0.003	
Hydrodynamic damping coefficient	default	2×default
Lift coefficient curve	Shear7 v.4.5 CL Table 1	Shear7 v.4.5 CL Table 3
Lift coefficient reduction factor	1	0.2
Added mass coefficient	1.0	2.0

EXXONMOBIL VIV TEST DATA

ExxonMobil conducted the tests used in this benchmarking study during the summer of 2003 with the goals of gaining better insight into the VIV phenomenon and providing a robust set of data for benchmarking existing and future VIV software. These tests featured extensive instrumentation, high sampling rates, and careful time synchronization of the measurements allowing the global response to be reconstructed over the entire model length with good accuracy.

Tests were performed for bare and fully straked risers as well as partially straked risers with 25%, 50% and 75% coverage. For each configuration, the risers were towed under 20 different speeds ranging from 0.2 to 2.38 m/s under both uniform and linearly sheared current profiles.

Properties of the bare risers are given in Table 3. The specific mass reported in Table 3, which is the ratio of the riser mass/unit length to that of the water displaced, is in the typical range of full-scale risers. For the straked risers, the triple-start helical strakes used in the tests were made from silicone material and glued to the riser model. The strakes had a triangular shape cross section with a height and a width of 5 mm, respectively. The pitch-to-diameter ratio was 16 and the strakes were neutrally buoyant. For additional information on the model test program see References [2&3].

Table 3: Bare Riser Model Properties

Length	9.63 m (31.6 ft)
Diameter	20 mm (0.78 in)
Material	Brass
Wall thickness	0.45 mm (0.018 in)
Specific mass	2.2
End conditions	Pinned in bending, constrained in torsion
Weight, in air	66.0 N (14.8 lbf), flooded
Buoyant weight	36.3 N (8.2 lbf), flooded
Pretension at top	~ 700 N (157 lbf)

VALIDATION METHODOLOGY

Our methodology for benchmarking VIV analysis tools is not specific to Shear7 or the ExxonMobil VIV test data and can be applied to any VIV prediction program or data set which uses strain gage instrumentation. The approach consists of the following three steps:

- Simulation of VIV model test conditions using the VIV analysis program (model the model).
- Qualitative comparisons between the model test measurements and the analysis program predictions.
- Quantitative comparisons between the model test measurements and the analysis program predictions.

All comparisons in this paper will be made in terms of the “damage index” which defined as the RMS strain to the third power multiplied by the riser response frequency ($f \times \varepsilon_{\mathrm{rms}}^3$). The damage index has been chosen because it is proportional to fatigue damage, our primary interest in benchmarking, and the index can be calculated directly from the measured test data.

Once we have simulated the test conditions in Shear7, we begin the qualitative comparison by examining individual test runs. Figure 1 shows bare riser test results under a uniform and a shear current profile at maximum speeds of 1.35 and 1.38 m/s, respectively. The Shear7 inputs for these results were a reduced velocity bandwidth of 1.0, a power ratio cutoff of 0.05, and a primary zone amplitude limit of 0. The plots show that the predictions are conservative and in general agree well with the trend observed along the length of the riser. In contrast to these results, Fig. 2 is a comparison of the same case using a power ratio cutoff of 1, which forces a single dominant mode solution. We find that the predictions are conservative near antinodes of vibration but unconservative near nodes and the predictions do not match well with the general distribution of damage along the riser span.

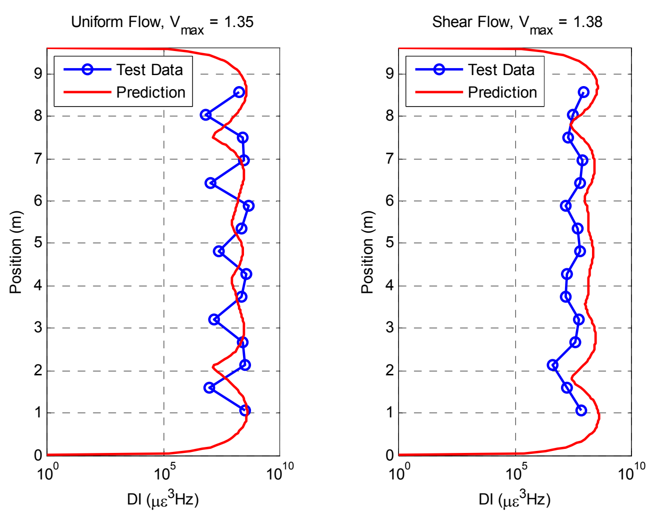


Figure 1: Comparison of predicted to measured fatigue damage along the bare riser in uniform and linearly sheared currents (reduce velocity bandwidth = 1, power ratio cutoff = 0.05, and primary zone amplitude limit = 0).

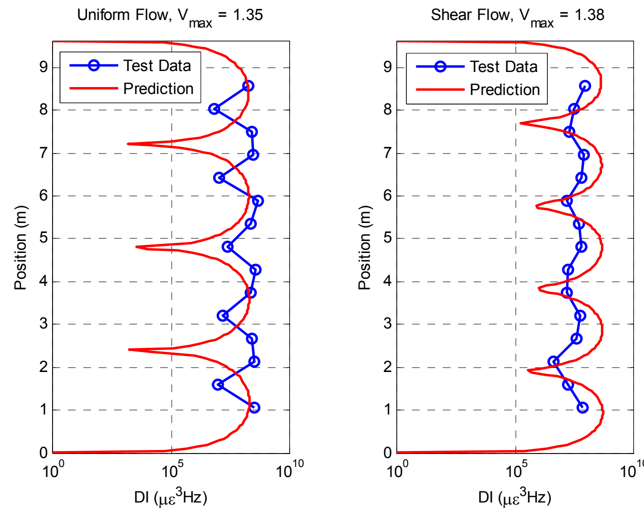


Figure 2: Comparison of predicted to measured fatigue damage along the bare riser in uniform and linearly sheared currents (reduced velocity bandwidth = 1, power ratio cutoff = 1, and primary zone amplitude limit = 0).

Plots such as Figs. 1 and 2 give us a degree of insight into the reasons for under- or over-prediction for individual test runs. To evaluate the general accuracy and any trends that appear in the predictions for a single Shear7 parameter set over all flow speeds tested, we plotted measured versus predicted damage indices in the plot format shown in Fig. 3. Note that the log-scale format used in the figure is to accommodate large range in damage and scatter. In the figure, each plotted point corresponds to a comparison at a measurement location when the riser is exposed under the current with a specific speed either in uniform or linearly sheared format. Points with identical colors represent comparisons made under the same current speed but at different measurement locations along the riser span. In the bare riser case shown in Fig. 3, the figure contains a group of 300 comparisons at 15 measurement locations under 20 different current speeds, and gives a general indication of prediction scatter and bias for a given set of Shear7 input parameters.

To make quantitative comparisons in this study, two metrics are used: the “logarithmic difference” (logΔ) and the “percentage of over-predictions”. The logΔ value is calculated at each point of comparison in Fig. 3 by

$$\log \Delta_i = \log(PD_i) - \log(MD_i) \qquad (4)$$

which is simply the prediction error as viewed on a log-log plot as schematically illustrated in Fig. 4. In Eq. (4), *PD* is the predicted damage index calculated from analysis program and *MD* is the damage index calculated from measurement data. A positive logΔ_i means an over-prediction and a negative one stands for an under-prediction.

To better understand, Eq. (4) can also be written as

$$\log(PD_i) = \log(MD_i) + \log \Delta_i \qquad (5)$$

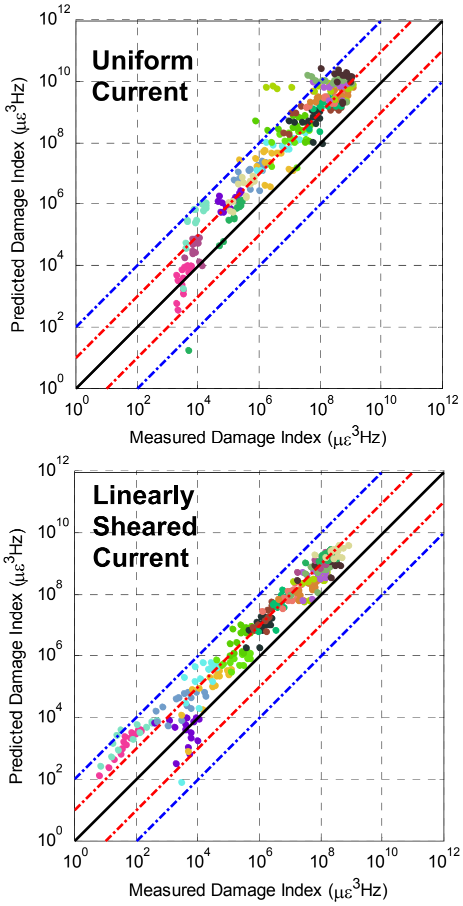
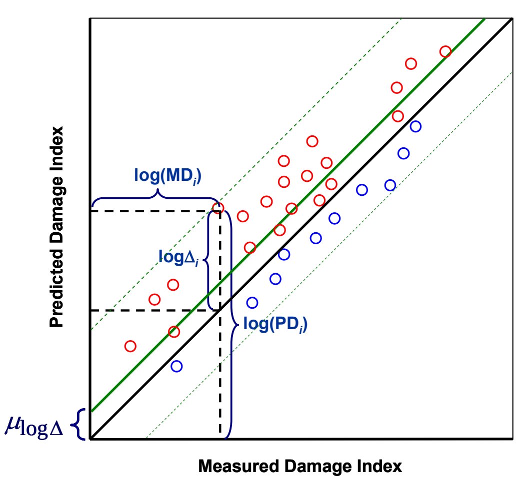


Figure 3: Comparison of predicted to measured fatigue damage for bare riser (reduced velocity bandwidth = 1, power ratio cutoff = 0.05 and primary zone amplitude limit = 0).



$$\log\Delta_i = \log(PD_i) - \log(MD_i)$$

Figure 4: Schematic illustrating measure of prediction error.

which is a straight-line equation with a slope of one and a *y*-intercept of $\log\Delta_i$. From Eq. (5) and Fig. 4, one can readily see that if there is a perfect match between the measurement and prediction ($\log\Delta_i$=0), the corresponding comparison point will lie on the diagonal equality line. Because the equality line has a slope of one, $\log\Delta_i$ actually is the vertical offset or bias between the comparison point and the equality line, as graphically shown in Fig. 4. Thus, the mean of $\log\Delta_i$ ($\mu_{\log\Delta}$) provides a quantitative measure of the average offset between prediction and measurement for a specific Shear7 parameter set over all flow speed tested; and the standard deviation of $\log\Delta_i$ ($\sigma_{\log\Delta}$) gives us a quantitative indicator of the prediction scatter away from the mean offset.

The percentage of over-predictions indicates the percentage of comparisons for which the predicted damage index is higher than measured, without regard for the magnitude of the error. This percentage can also be used to assess the general level of conservatism associated with predictions based on a given set of Shear7 input parameters.

By comparing Shear7 predictions using different user-selected parameter sets in uniform or linearly sheared current profiles, statistics of logΔ and percentage of over-prediction can be utilized to measure the impact of input parameter changes on prediction results. These two metrics served as our basis for assessing the input parameter sets that we tested in Shear7 v.4.5.

RESULTS OF COMPARISON WITH BARE RISER TEST DATA

To compare bare riser test results, we began by reviewing the plots of the measured versus predicted damage index as shown in Fig. 3. For the specific user-selected parameter set depicted in Figure 3, one can see that the prediction scatter is larger in general for uniform current than it is for the linearly sheared current; and the predictions are generally conservative, sometimes by large amounts.

Figure 5 summarizes the mean and standard deviation for prediction error logΔ in both uniform and shear current profiles. Since the reduce velocity bandwidth of 0.2 is too small for Shear7 to capture measured VIV response at low current speeds, results of Cases 1–16 (listed in Table 1) are not included in the figure. As can been seen from Fig. 5, standard deviation in shear current profiles are smaller than that in uniform flow with a same parameter set. This indicates that prediction errors in shear flow have less scatter, which is consistent with what we have observed in Fig. 3.

Results shown in Fig. 5 can be divided into three groups. Each group consists of 16 cases: Cases 17–32, 33–48 and 49–64 with reduced velocity bandwidths of 0.4, 0.7 and 1.0, respectively. By comparing the statistics of logΔ of these three groups from Fig. 5, one can see that a larger reduced velocity bandwidth makes prediction errors more sensitive to the change of power cutoff level. For example, the mean of logΔ varies between (0.50, 0.62) in uniform flow and (0.22,

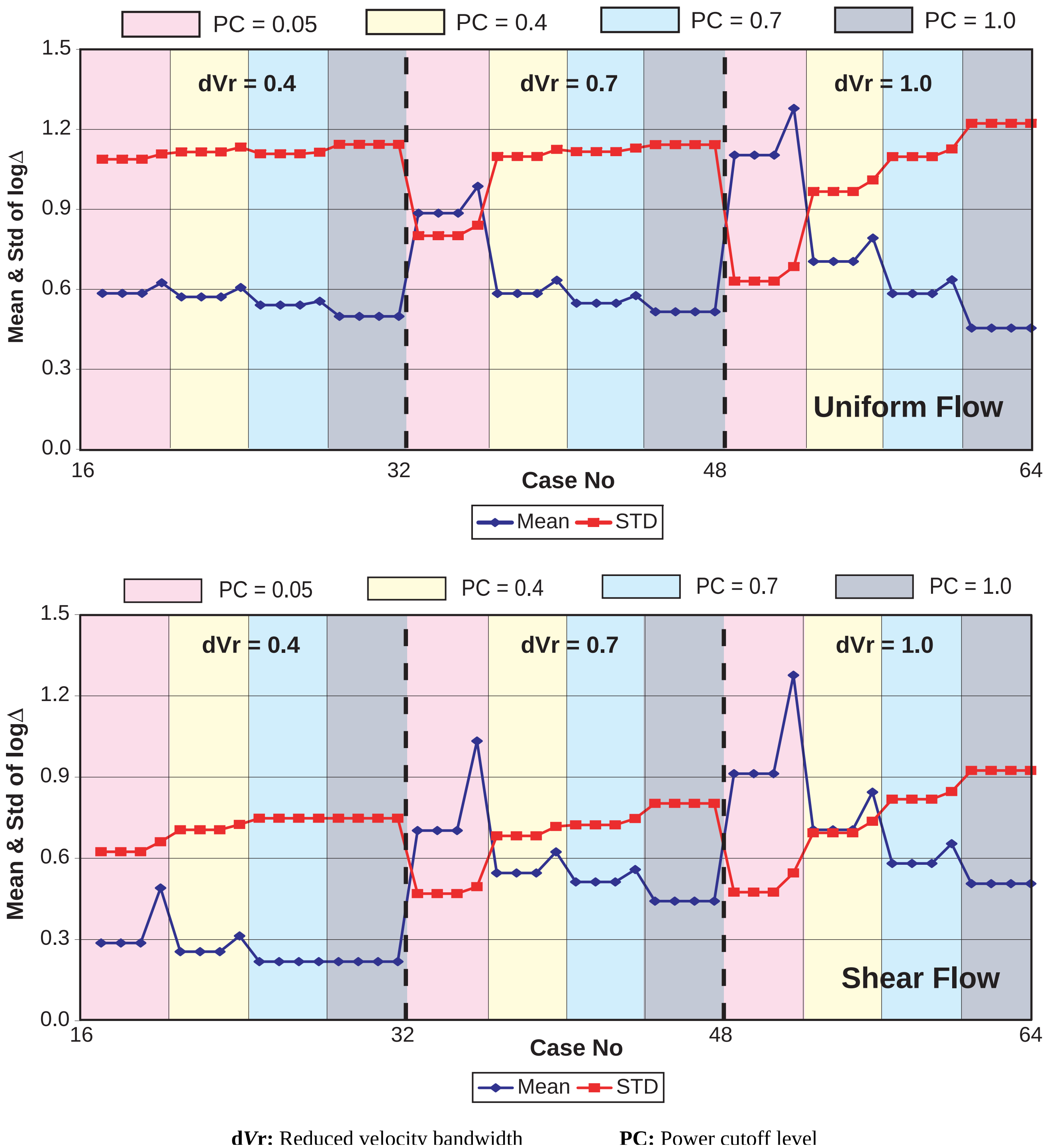
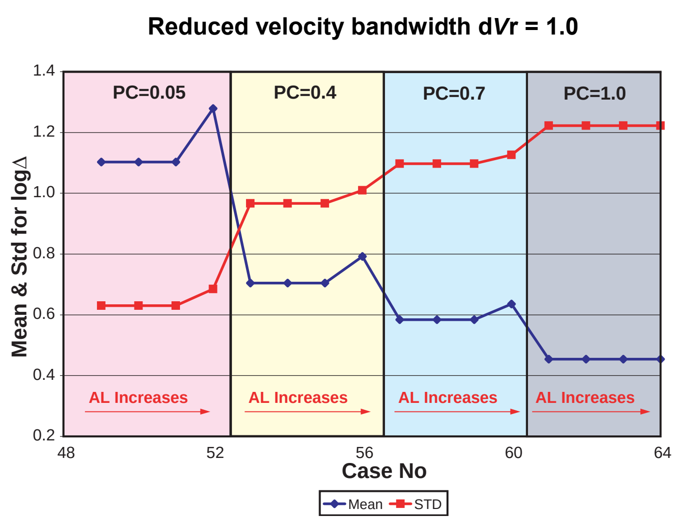


Figure 5: Mean and standard deviation of logΔ in uniform and linearly sheared currents.

0.49) in shear flow when the reduced velocity bandwidth is 0.4. When the reduced velocity bandwidth is 1.0, the mean of logΔ changes between (0.45, 1.28) in uniform flow and (0.51, 1.28) in shear flow. Similarly, the standard deviation of logΔ varies between (1.09, 1.14) in uniform flow and (0.62, 0.75) in shear flow when the reduced velocity bandwidth is 0.4. When the reduced velocity bandwidth is 1.0, the standard deviation of logΔ changes between (0.63, 1.22) in uniform flow and (0.47, 0.92) in shear flow.

To look into the impact of power cutoff levels on prediction results, those 16 cases within each individual group can be further divided into four subgroups (shaded with different colors as shown in Fig. 5) with power cutoff levels of 0.05, 0.4, 0.7 and 1.0, respectively. From each group, we can see that, in both uniform and shear flows, increasing the power cutoff level reduces the prediction offset and increases the scatter. To illustrate, results in Fig. 5 for a group of cases with reduced velocity bandwidth of 1.0 in uniform flow (Cases 49–64) are redrawn in Fig. 6 as an example. As shown in Fig. 6, the mean of logΔ reduces from approximately 1.2 to 0.45 and standard deviation increases from around 0.65 to 1.2 when the power cutoff level increases from 0.05 to 1.0. Similar tendency is also exhibited in all other groups both in uniform and shear current profiles.



PC: Power cutoff level **AL:** Primary mode amplitude limit

Figure 6: Mean and standard deviation of logΔ for Cases 49–64 with reduced velocity bandwidth of 1 in uniform currents.

Moreover, a couple of other trends can also be observed from Fig. 5 by comparing cases with same power cutoff level but with different reduced velocity bandwidths:

1. When power cutoff level is small, *e.g.* Cases 17–20 (d*V*r=0.4), 33–36 (d*V*r=0.7) and 49–51 (d*V*r=1.0) with power cutoff level of 0.05, increasing the reduced velocity bandwidth increases the prediction offset (mean of logΔ) and reduces the scatter (standard deviation of logΔ).
2. When power cutoff level is large, *e.g.* Cases 29–32 (d*V*r=0.4), 45–48 (d*V*r=0.7) and 61–64 (d*V*r=1.0) with power cutoff level of 1.0, increasing the reduced velocity bandwidth slightly increases the prediction scatter in uniform flow. For shear flow, both prediction offset and scatter increase as reduced velocity bandwidth increases.

To identify the primary mode amplitude limit's impact on prediction results, we look into cases in each subgroup. As shown in Fig. 6, every subgroup has 4 statistical data points, from left to right corresponding to 4 cases with primary mode amplitude limit of 0, 0.4, 0.7 and 1.0, respectively. From Fig. 6 and Shear7 output files, we found that:

1. When the primary mode amplitude limit is 0, 0.4 or 0.7, only one time sharing zone exists on the riser. Thus, change of primary mode amplitude limit has no impact on prediction offset and scatter.
2. When the primary mode amplitude limit is one, there are three independent time sharing zones along the riser span when the power cutoff level does not equal to one, resulting in the increase of prediction offset and scatter.
3. When the power cutoff level is one, only the dominant mode is utilized in the calculation. Thus, the primary model amplitude limit has no impact on prediction results.

The same trends can also be found in other groups in Fig. 5. In general, if increasing the primary mode amplitude limit results in the increase of the number of independent time sharing zones, this will increase prediction offset and scatter; otherwise there is no impact.

Figure 7 provides the percentage of all comparisons in which the predicted damage index is greater than the measured. We can see from the figure that, for cases in Fig. 5 in which the mean is larger than the standard deviation of logΔ (Cases 33–36 and 49–52), the percentages are all above 90% for both uniform and shear flows.

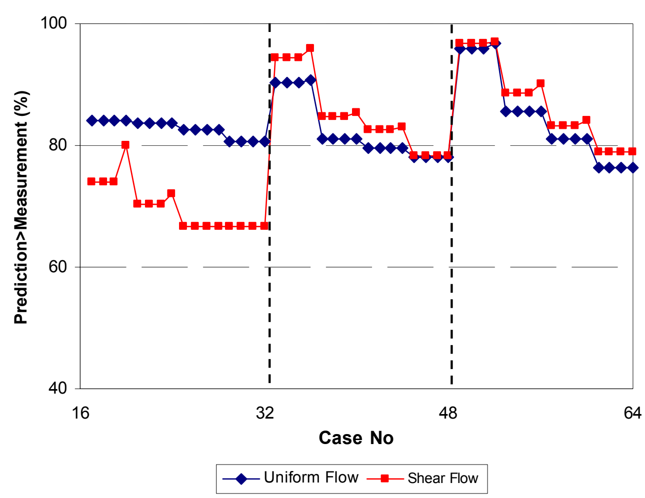


Figure 7: Percentage of predicted damage index above that of measured in uniform and shear currents.

RESULTS OF COMPARISON WITH STRAKED RISER TEST DATA

Figure 8 shows fully straked riser test results under a uniform and a shear current profile at maximum speeds of 1.34 and 1.38 m/s, respectively. Figure 9 provides the plots of measured versus predict damage indices for all flow speeds.

The Shear7 inputs for these results were a reduced velocity bandwidth of 1.0, a power ratio cutoff of 0.05, and a primary zone amplitude limit of 0, same as what was used in Figs. 1 and 3. Comparing the measured response for bare risers in Fig. 1 and fully straked risers in Fig. 8, it is clear that strakes can reduce the vibration 5-6 orders of magnitude smaller, indicating that the 16D pitch, 0.25D height strake is effective for VIV reduction. Plots in Figs. 8 and 9 also show that, under this specific parameter set, the predictions are very conservative and are about five orders of magnitude larger than the measurement along the entire riser span for all flow speeds tested.

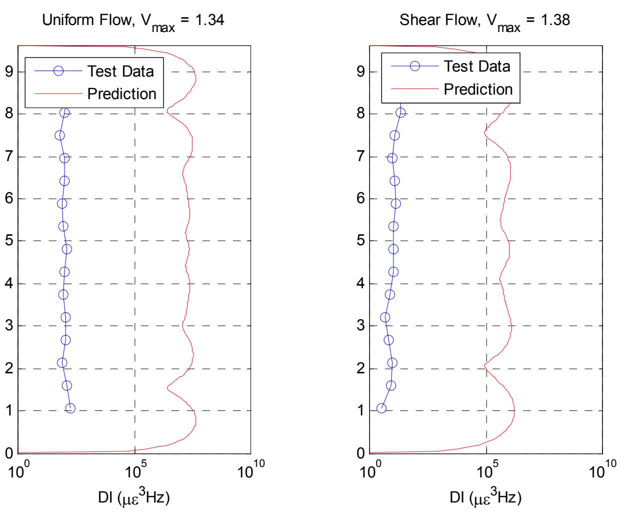


Figure 8: Comparison of predicted to measured fatigue damage along the fully straked riser in uniform and linearly sheared currents (reduce velocity bandwidth = 1, power ratio cutoff = 0.05, and primary zone amplitude limit = 0).

For all parameter sets listed in Table 1, the means of logΔ for fully straked risers are consistently close to 5 in uniform flow, which indicates that the predictions are five orders of magnitude larger than the measurements. In linearly sheared flow, the means of logΔ increases from about 3 to about 5 as reduced velocity bandwidth increases. Thus a smaller reduced velocity bandwidth predicts the measurement better with less bias, but still the prediction is 1000 times larger.

To reduce the large over-prediction for fully straked risers, one possible approach is to reduce positive portion of the lift coefficients in small non-dimensional response amplitude (A/D) region. This will reduce the power going into the riser system and subsequently decrease the predicted vibration amplitude. In one of our studies, we tuned the lift coefficients down so the prediction matches pretty well with ExxonMobil 2003 test results. However, when the same lift coefficients were applied to other datasets available to the company, the prediction error was significantly different.

This approach fails because the physics governing VIV are fundamentally different for a riser with the power in region fully straked. Results reported by Frank *et al.* [3] indicated that the response of fully straked risers was more like a broadband Gaussian random vibration. Therefore, using the understanding based on this observation, ExxonMobil developed a random excitation model for fully straked risers and presented on OMAE2007 [4]. Due to the topic of this paper, we are not going to discuss this model in detail. However, the presentation slides are available to interested readers upon request. Figure 10 shows a comparison of predicted to measured fatigue damage. As can be seen, the new strake model significantly improves the agreement between measurement and prediction both in terms of bias and scatter.

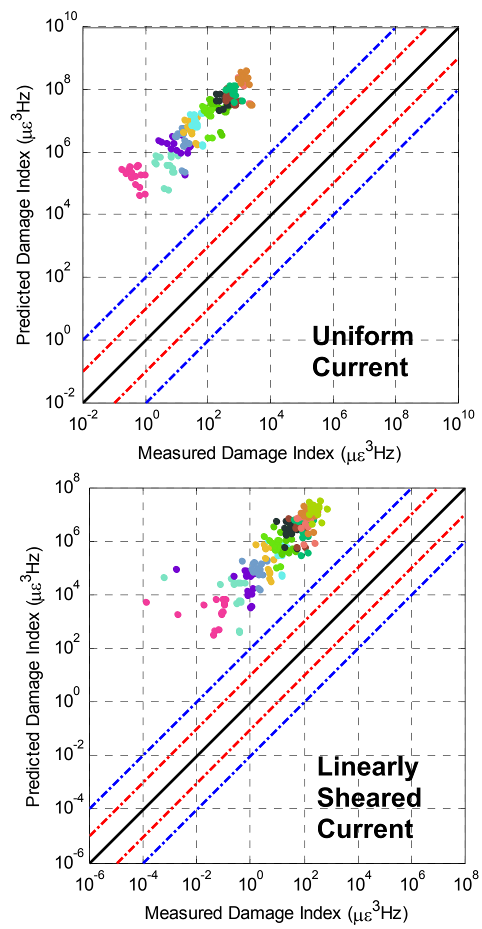


Figure 9: Comparison of predicted to measured fatigue damage for fully straked riser (reduced velocity bandwidth = 1, power ratio cutoff = 0.05 and primary zone amplitude limit = 0).

To model partially straked risers, two structural zones were utilized, one for bare portion and the other one for the straked portion of the riser. Corresponding structural and hydrodynamic properties (listed in Table 2) were applied to each individual zone, which include added mass coefficient, lift coefficient curve and its reduction factor, hydrodynamic damping coefficients, mass, etc.

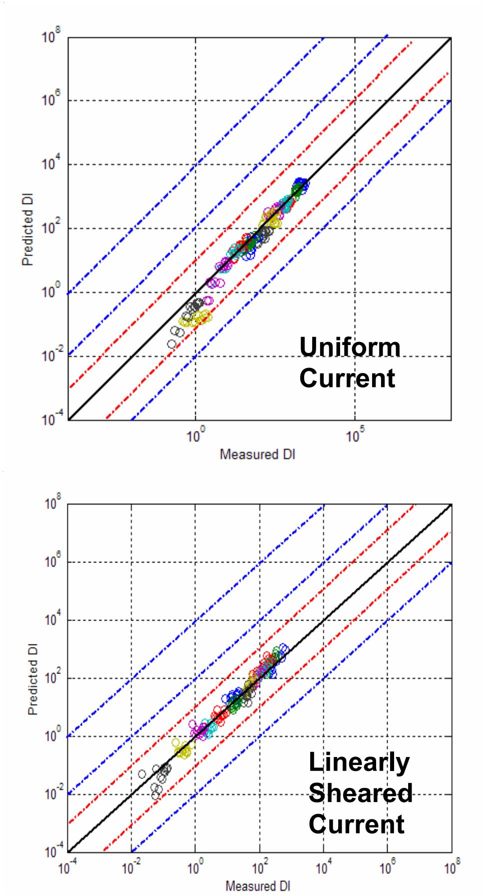
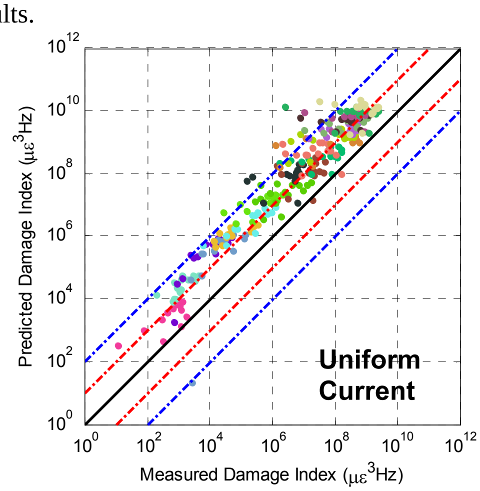


Figure 10: Comparison of predicted to measured fatigue damage for fully straked riser using the random excitation model.

Figures 11–13 provide plots of measured versus predicted damage indices for risers with 25%, 50% and 75% strake coverages. As shown in the figures, the test results for 25% straked risers are close to the bare riser results with almost the same order of magnitude prediction bias. For risers with 75% strake coverage, the prediction bias has a large order of magnitude similar to what we have seen in fully straked riser test results.



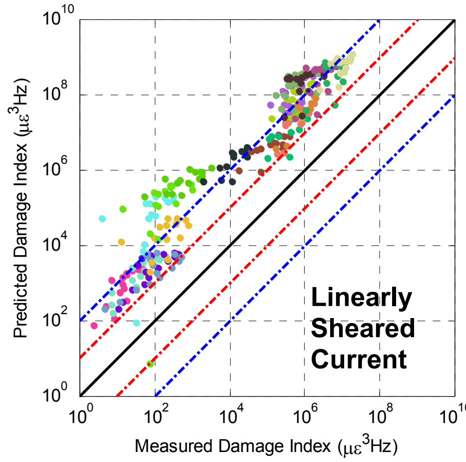


Figure 11: Comparison of predicted to measured fatigue damage for 25% straked riser (reduced velocity bandwidth = 1, power ratio cutoff = 0.05 and primary zone amplitude limit = 0).

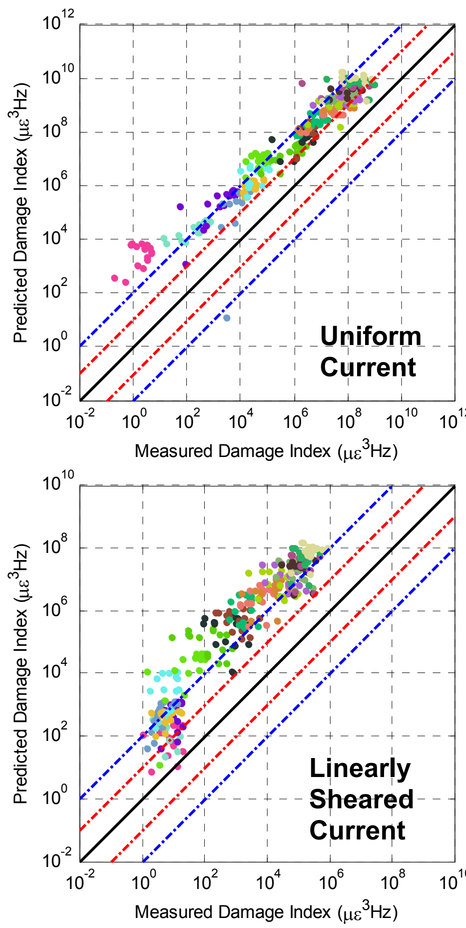


Figure 12: Comparison of predicted to measured fatigue damage for 50% straked riser (reduced velocity bandwidth = 1, power ratio cutoff = 0.05 and primary zone amplitude limit = 0).

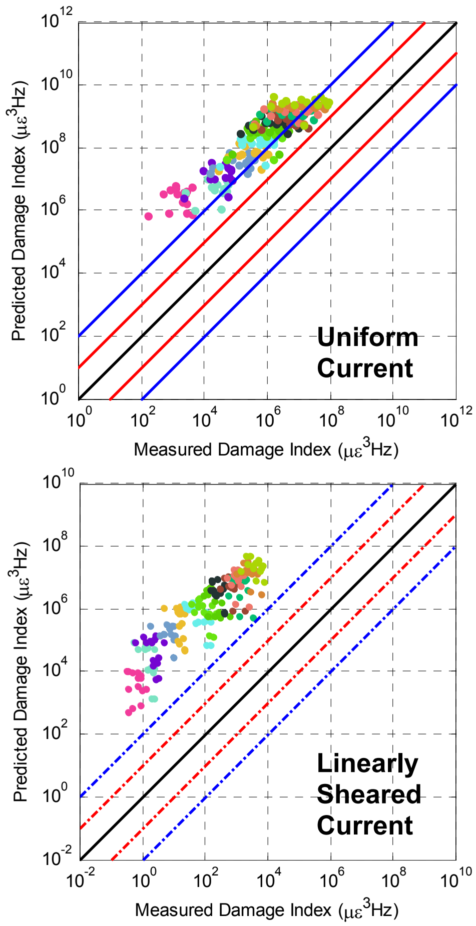


Figure 13: Comparison of predicted to measured fatigue damage for 75% straked riser (reduced velocity bandwidth = 1, power ratio cutoff = 0.05 and primary zone amplitude limit = 0).

Figures 14–15 summarizes the mean and standard deviation of logΔ for all riser configurations including bare, fully straked and partially straked risers. In the figures, 0% strake coverage represents bare risers. As the strake coverage increases, the overall riser responses start to be dominated by the straked portion of the riser. Since prediction errors for straked risers using Shear7 are much larger than those for bare risers, the prediction errors increase as the strake coverage increases. This pattern can be seen in Figs. 14–15 except for some cases for 50% strake coverage with reduced velocity bandwidths of 0.4 and 0.7 in shear flow. The reason for this needs further investigations. In addition, the plots also show that, with a specific strake coverage, the trends for logΔ follow exactly the same patters as bare risers that we have discussed in the previous section.

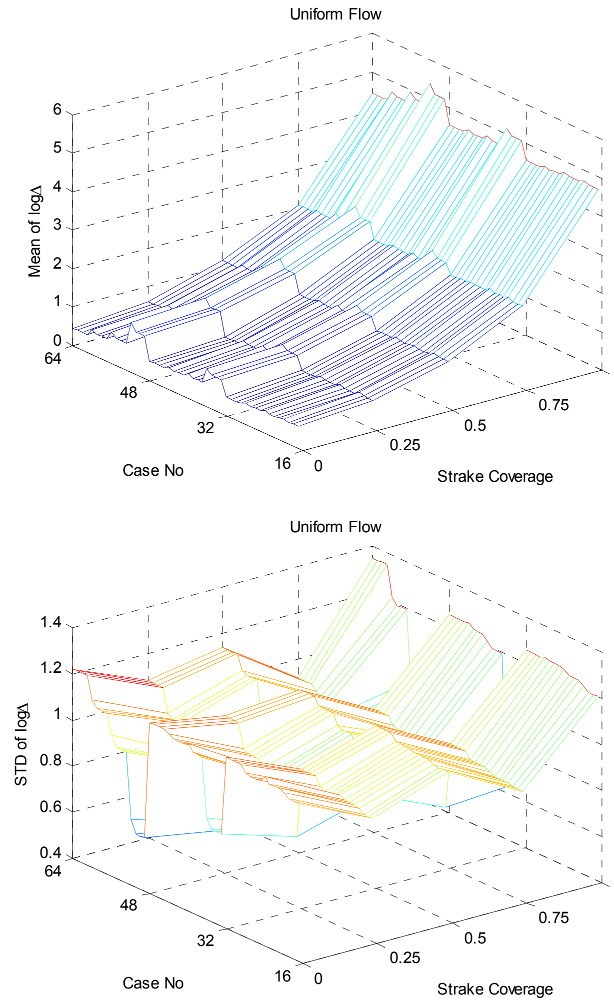
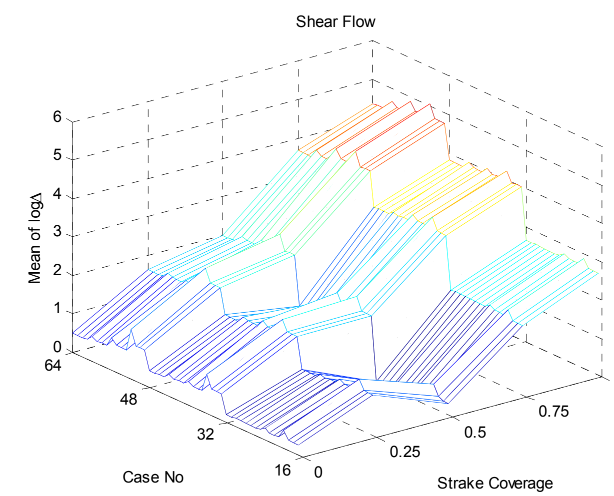


Figure 14: Mean and standard deviation of logΔ in uniform currents with different strake coverages.



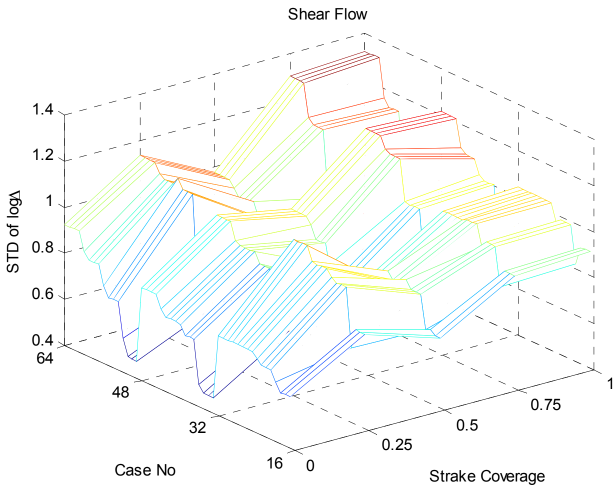


Figure 15: Mean and standard deviation of logΔ in linearly sheared currents with different strake coverages.

CONCLUSIONS

In this benchmarking effort, we focused on comparing the measured responses from ExxonMobil's 2003 VIV model tests to simulations of the test conditions using the newest version of the widely used VIV prediction tool, Shear7. Three user-specified parameters were selected and comparisons were performed to investigate their influence on prediction results. The study indicated that the new "time-sharing" model in general generates prediction results with reasonable bias and scatter for bare risers. However, the prediction errors for straked risers are still high even when the most favorable parameters are selected for the analysis. This is due to the significant difference between the narrowband forcing mechanism used in Shear7 formulation and the broadband excitation observed in the experiment.

Results and observations presented in this paper are specific to Shear7 and the ExxonMobil test data and are not necessarily general conclusions for all cases. However, the benchmarking methodology presented is applicable to any VIV prediction program and any tests which measure strain in the riser. Using this approach with other existing and future experimental data sets will help provide a robust validation of modeling assumptions and parameter selections, and will provide riser analysts and designers with an improved understanding of VIV prediction accuracy and uncertainty.

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3. Frank, W.R., et. al, "Flow-Induced Vibration of a Long, Flexible, Straked Cylinder in Uniform and Linearly Sheared Currents," OTC 16340, Offshore Technology Conference, Houston, TX, 2004.

4. Campbell, R.B., Frank, W.R. and Slocum, S.T, "Prediction of Flow-Induced Vibration for Risers with Effective Strakes," Oral Presentation, OMAE, San Diego, 2007.