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BENCHMARKING OF SHEAR7V4.5: COMPARISONS TO FULL-SCALE DRILLING RISER VIV DATA AND LEGACY ANALYSES

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ABSTRACT

SHEAR7 [4], industry's most widely-used vortex-induced vibration (VIV) fatigue damage software analysis tool, has been recently revised to include a fundamental change in methodology based on observations from Deepstar's high-aspect-ratio, slender pipe towing tests in the Gulf Stream near Miami, Fla. The key revision pertains to the way in which VIV excitation zones (or "power-in" zones) are calculated along the length of the riser. Namely, it is no longer assumed that multiple structural modes are excited simultaneously by a given current profile along the length of the riser in a manner known as multi-mode response. Rather, based on the towing tests, it is assumed that potentially excited modes participate in the response one-at-a-time in a time-sharing fashion. The fraction of the total event time accorded to each responding mode is proportional to the input power of its exciting force, or, may be set to be uniformly distributed among all responding modes. This fundamental change can have a significant effect on the fatigue damage calculated for a given riser and current profile and direct comparisons to previous analyses are not straightforward as the input parameters of the software have been altered along with the analysis methodology itself.

In a recent paper [1], BP utilized measured data that it had collected from risers in the field during several of its worldwide drilling campaigns to calibrate SHEAR7v4.4 to yield an average safety factor of ten on fatigue damage when VIV occurs. Given the extent of the changes to the analysis method, it was important to revisit that study and ascertain whether the latest software version similarly captured the trends of the full-scale data and could be calibrated to maintain an appropriate factor of safety. Furthermore, where measured data were not available it was important for consistency to identify and rationalize differences between analyses with the current and penultimate versions of the software.

This paper describes BP's benchmarking of SHEAR7v4.5. Comparisons are made between predicted and measured VIV fatigue damage for several full-scale drilling risers to demonstrate the efficacy of a calibration for the latest version. In addition, comparisons are made between VIV fatigue damage predictions using SHEAR7 versions 4.4 and 4.5 for drilling risers as well as for a typical deepwater SCR in typical design Gulf-of-Mexico loop currents. The version-to-version differences are illustrated and explained. Finally, results of sensitivity studies conducted with respect to the new parameters in SHEAR7v4.5 are presented. A key finding is that while the predictions, on average, are similar from version to version; the scatter in predictions - which leads to requirements for large safety factors - is largely unimproved.

INTRODUCTION

The objectives of the work documented in this paper are to validate SHEAR7v4.5 for use in drilling riser and typical deepwater SCR VIV analyses and to determine the associated analysis parameter sets to use. Results from SHEAR7v4.5 are compared with corresponding results from SHEAR7v4.4. In the case of the drilling riser analyses, results are also compared with fatigue damage calculations from measured VIV response data. Some previous benchmarking studies [2][3] include benchmarking with experimental results. This paper emphasizes benchmarking the new version with the previous version and with measured data.

Full-scale SCR data are not available to substantiate the time sharing that appears in the Deepstar tests. Hence, in order to understand the effect of each parameter on the VIV fatigue response, sensitivity analysis is conducted for SCR analysis by varying different parameters in v4.5 analysis, one at a time, including power cutoff (PC), dominant power amplitude cutoff (DC), reduced velocity bandwidth (Vr), maximum lift coefficient factor (CLmax), and power ratio exponent (PR).

ANALYSIS METHODOLOGY AND ASSESSMENT METRICS

INTRODUCTION TO SHEAR7V4.5

SHEAR7 Version 4.5 introduces the concept of time-sharing between the modes, making spatial overlap elimination between the modes unnecessary. The concept of time sharing is based on observations from the Gulf Stream, Deepstar-funded, slender pipe experiments. The time sharing solution effectively assumes single-mode response in each mode but with an associated fraction of the total “event” duration or probability. Hence, the use of separate single and multi-mode reduced velocity bandwidth values has been replaced with a single input value. Different modes can also share the same power-in region since response is assumed to occur sequentially rather than concurrently. Both of these changes increase the length of the power-in region for any given mode and, thus, the resulting VIV amplitude when more than one mode is excited, although each modal contribution is scaled by its associated duration.

SHEAR7 INPUT PARAMETER SETS

The parameter sets used for drilling riser analysis are delineated as follows in this paper: *Adjusted v4.4* are parameters calibrated (for use with v4.4 in Ref. [1]) against measured field data, and *v4.5 Calibration Set* are chosen in the course of this study to produce statistically analogous results to those produced by the *Adjusted v4.4* parameters.

The parameter sets used for SCR analysis are identified as follows: *v4.4 Adjusted Set* are parameters used in SCR analysis conducted in a previous BP study and are very similar to those appearing as defaults in the SHEAR7v4.4 users manual, *v4.5 Calibration Set* are chosen in the course of this study to be analogous to the *v4.4 Adjusted* parameters. Parameters for straked sections of riser reflect increased added mass parameter and reduced maximum lift coefficient.

SENSITIVITY ANALYSIS

The sensitivity analysis case matrix for the SCR analysis is shown in Table 1. The base case parameters are taken from the defaults for bare risers from the users manual [4] as follows:

- Reduced velocity bandwidth (Vr) = 0.4;
- Power cutoff (PC) = 0.7;
- Dominant mode amplitude cutoff (DC) = 0.3;
- Maximum lift coefficient (CLmax) = 0.7;
- Power ratio exponent (PR) = 1.0.

Sensitivity Matrix					
Riser	Vr	Power Cutoff	Dominant Mode Amplitude Cutoff	CLmax	Power Ratio Exponent
Bare	0.1 to 1 in steps of 0.1	0 to 1 in steps of 0.2	0 to 1 in steps of 0.2	0.7, 0.35	1.0, 0.0
Straked	0.1 to 1 in steps of 0.1	0 to 1 in steps of 0.2	0 to 1 in steps of 0.2	0.7, 0.35	1.0, 0.0

Table 1 Sensitivity Matrix for Deepwater SCR (In straked cases, CL is scaled in analyses by a reduction factor)

A brief discussion of the parameters investigated in the sensitivity study follows. More detail may be found in [4].

Reduced Velocity Bandwidth

The reduced velocity bandwidth parameter limits the length of the power-in region for each mode based on the local reduced velocity relative to that modal frequency.

Power Cutoff

The power cutoff is applied so that all modes with power above the cutoff are allowed to participate. Lowering the power cutoff allows more modes to participate. When the power cutoff is specified as 0.0 all modes are allowed to participate, when the power cutoff is 1.0 single mode response occurs.

Dominant Mode Amplitude Cutoff

This is a new v4.5 input parameter. The dominant mode is assumed to have a range of influence near its power-in region in which no other frequency may respond at the same time as the dominant mode. This is the primary response zone. Within this zone, only one modal excitation frequency at a time is allowed to be active. The limits of the primary response zone are determined by the primary zone amplitude limit, or the dominant mode amplitude cutoff.

Maximum Lift Coefficient

The maximum lift coefficient defines the peak of the Cl vs A/D curve used in the analysis.

Power Ratio Exponent

This is also a new v4.5 input parameter. The power ratio exponent is the exponent to which the power ratio is raised in order to compute the time sharing probabilities for all modes. The default value of 1.0 implies that the time sharing probabilities are proportional to the power ratios. If 0.0 is used, all the time sharing probabilities are uniformly distributed among participating modes.

STATISTICAL PARAMETERS

The following statistical parameters are used to quantify the SHEAR7 Version 4.5 benchmarking analysis:

Weighted Fatigue Damage Bias

If comparison is made between v4.5 and v4.4, then the weighted fatigue damage bias is expressed as:

$$\alpha = \frac{\sum (D_{\max, pred, v4.5} \times \Pr obability)}{\sum (D_{\max, pred, v4.4} \times \Pr obability)} \tag{1}$$

If comparison is made between v4.5 and measured data, then the weighted fatigue damage bias is expressed as:

$$\alpha = \frac{\sum (D_{\max, pred, v4.5} \times \Pr obability)}{\sum (D_{\max, measured} \times \Pr obability)} \tag{2}$$

where damage summation is the sum over all events of maximum predicted fatigue damage on the riser multiplied by the probability of the associated event.

As such, the weighted fatigue damage bias is driven by / weighted by the most damaging events.

Non-weighted Fatigue Damage Bias

Non-weighted fatigue damage bias is expressed as:

$$\beta = 10^{Mean\ X_d} \tag{3}$$

where $Mean\ X_d = \frac{\sum_{i=1}^{N} X_d}{N} = \frac{\sum_{i=1}^{N} \log_{10}\left(\frac{D_{\max, pred, v4.5}}{D_{\max, pred, v4.4}}\right)}{N}$ (4)

(if comparison is made between v4.5 and v4.4)

or $Mean\ X_d = \frac{\sum_{i=1}^{N} X_d}{N} = \frac{\sum_{i=1}^{N} \log_{10}\left(\frac{D_{\max, pred, v4.5}}{D_{\max, measured}}\right)}{N}$ (5)

(if comparison is made between v4.5 and measured data)

and where N is the number of VIV events in a dataset, each event represents a 10 minute duration.

In case of the non-weighted fatigue damage bias, each event contributes an equal weighting towards the bias irrespective of fatigue damage magnitude.

Scatter

Scatter or variability in fatigue damage from its mean value is determined by taking the standard deviation of Xd:

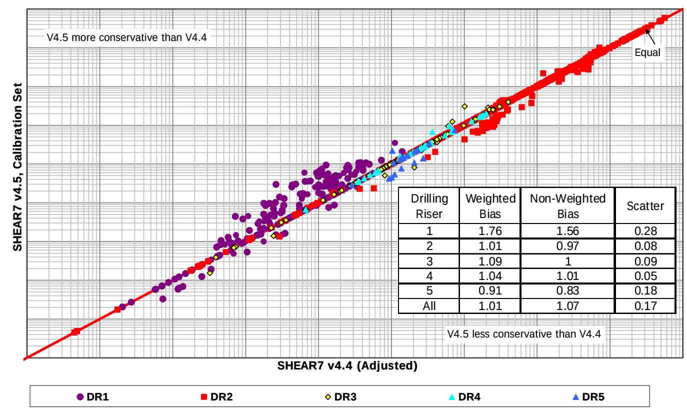
$$S_{X_d} = \sqrt{\frac{\sum \left(X_d - \overline{X}_d\right)^2}{N-1}} \tag{6}$$

DRILLING RISER ANALYSIS BENCHMARKING

SHEAR7 Version 4.5 benchmarking is conducted with five typical deepwater drilling risers: DR1 to DR5. Fatigue damage calculations from SHEAR7 Version 4.4 and Version 4.5 are compared with each other and with calculations from measured data to determine appropriate input parameters.

COMPARISON OF VERSION 4.4 AND VERSION 4.5 RESULTS

The fatigue damage comparison between SHEAR7 Version 4.5 and Version 4.4 is shown in Figure 1. Data points above the equality line show that SHEAR7 Version 4.5 gives higher fatigue damage results than SHEAR7 Version 4.4, and any data points below the equal line show that SHEAR7 Version 4.5 gives lower fatigue damage results than SHEAR7 Version 4.4. The statistical parameters are calculated and are also shown in Figure 1.



Drilling Riser	Weighted Bias	Non-Weighted Bias	Scatter
1	1.76	1.56	0.28
2	1.01	0.97	0.08
3	1.09	1	0.09
4	1.04	1.01	0.05
5	0.91	0.83	0.18
All	1.01	1.07	0.17

Figure 1 Fatigue Damage Comparison for Drilling Risers, Version 4.4 and Version 4.5

The comparison of SHEAR7 Version 4.5 and Version 4.4 results shows that analyses with v4.5 Calibration Set yield, on average, results similar to those for v4.4. This is due to the fact that most of the predicted response for the drilling risers considered is predominantly single-mode.

The prediction difference between these two versions can be explained by the time-sharing concept in SHEAR7 Version 4.5 which assumes a longer power-in region for any given mode than SHEAR7 Version 4.4 during multiple-mode response. It can be demonstrated that there is no difference between versions when single-mode response is predicted.

COMPARISON WITH MEASURED DATA

Fatigue damage calculations between analyses using SHEAR7 Version 4.4 and measured data are compared and shown in Figure 2. An analogous comparison using SHEAR7 Version 4.5 (Calibration Set) is shown in Figure 3.

Overall, both SHEAR7 Version 4.4 and Version 4.5 show a factor of 10 times overestimation in fatigue damage calculation compared to measured data. Again, this is likely due to the fact that there is predominantly single mode response for the drilling risers considered.

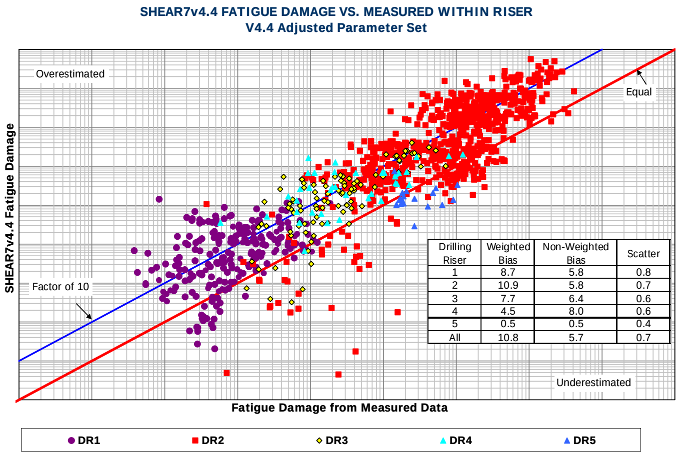


Figure 2 Fatigue Damage Comparison for Drilling Risers, SHEAR7 Version 4.4 Vs. Measured Data

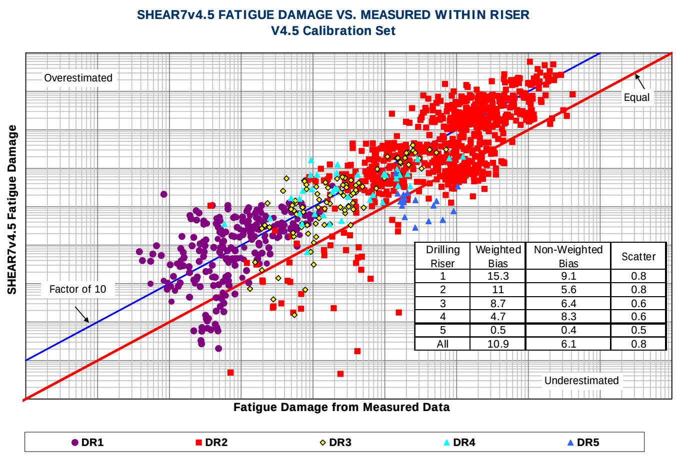


Figure 3 Fatigue Damage Comparison for Drilling Risers, SHEAR7 Version 4.5 Vs. Measured Data

SCR VIV BENCHMARKING

SHEAR7 Version 4.5 is benchmarked for a typical deepwater SCR with both bare and straked (top 25% straked) configurations. Typical Gulf of Mexico design currents and probabilities are assumed. Calculated fatigue damage results using SHEAR7 Version 4.5 and Version 4.4 are compared with each other. To investigate sensitivity of the results to different parameters and to determine the optimized parameter set, sensitivity analysis is conducted.

Unlike the drilling riser cases, measured VIV fatigue data are not yet available for field SCRs. And, it is uncertain whether the tow tests to date are representative of the full scale. Thus, the goal of benchmarking for SCRs is to identify an analysis parameter set that would attain average prediction conservatism equal to Version 4.4, with equal or lesser scatter than the predictions of Version 4.4.

COMPARISON OF VERSION 4.4 AND VERSION 4.5 RESULTS

Fatigue damage comparisons for individual current conditions for the bare and straked SCRs using SHEAR7 Version 4.5 and Version 4.4 are shown in Figure 4 and Figure 5, respectively. The aggregate VIV fatigue life along the SCR (both bare and straked) in a representative deepwater Gulf of Mexico environment, using SHEAR7 Version 4.4 and Version 4.5 is shown in Figure 6.

Overall, SHEAR7 Version 4.5 is more conservative than SHEAR7 Version 4.4. Results for single mode response match well between SHEAR7 Version 4.4 and Version 4.5. The outliers in both Figure 4 and Figure 5 are associated with multiple-mode response, and Version 4.5 is more conservative by a factor of 6 (weighted bias) compared to Version 4.4 if the response is multiple-mode / time sharing. The time sharing concept for multiple mode response in SHEAR7 Version 4.5 results in more power-in compared to Version 4.4, thus causing higher fatigue damage.

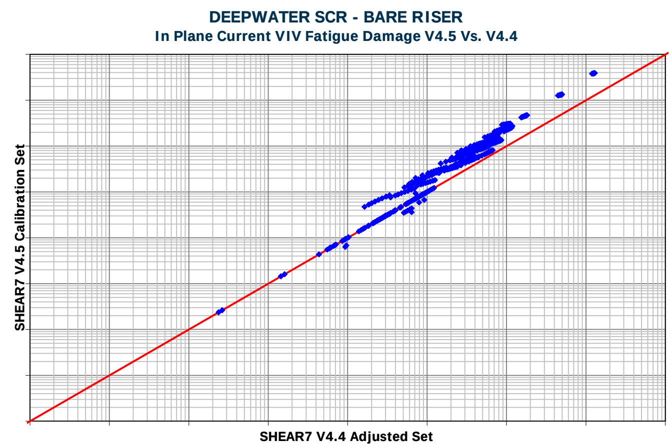


Figure 4 Fatigue Damage Comparison for SCR (Bare Riser), Version 4.4 and Version 4.5

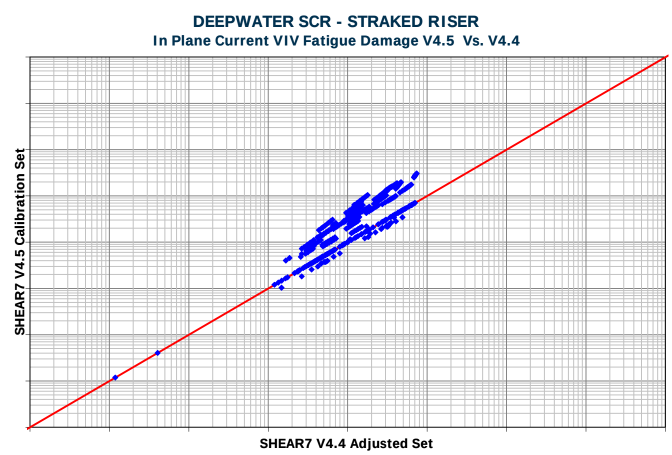


Figure 5 Fatigue Damage Comparison for SCR (Straked Riser), Version 4.4 and Version 4.5

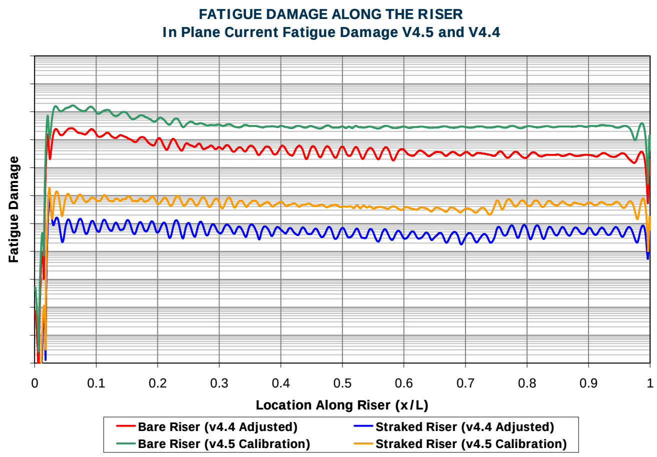


Figure 6 Overall Fatigue Lives Along the SCR (Bare and Straked), SHEAR7 Version 4.5 Vs. Version 4.4

SENSITIVITY ANALYSIS

To understand the sensitivity and to find the optimum parameter set for SCR analysis, sensitivity analysis was carried out by varying different parameters in Version 4.5 analysis, one at a time. Recall that these parameters are: reduced velocity bandwidth (Vr), power cutoff (PC), dominant mode amplitude cutoff (DC), maximum lift coefficient (CLmax), and power ratio exponent (PR).

The sensitivity analysis results are expressed in terms of statistical parameters including fatigue damage weighted bias and scatter. Recall that we are comparing version to version in this section; we are not comparing against measured data. A bias of 1.0 and scatter of 0.0 occurs when Version 4.5 results match Version 4.4 results exactly. Since bare and straked SCRs exhibit similar trends, only sensitivity analysis results for the bare SCR are given in this paper.

There are twenty-eight cases for the sensitivity analysis based on the case matrix shown in Table 1, and composite plots of weighted bias and scatter for single-mode excitation and multi-mode excitation are shown in Figure 7 and Figure 8. Single-mode excitation in Figure 7 indicates single mode response in *both* v4.4 and v4.5, and multi-mode excitation in Figure 8 indicates multi mode response in *both* v4.4 and v4.5. In both Figure 7 and Figure 8, cases 1 to 10 correspond to sensitivity analysis conducted on reduced velocity bandwidth (Vr = 0.1 to 1.0), cases 11 to 17 correspond to sensitivity analysis on power cutoff (PC = 0.0 to 1.0), cases 18 to 24 correspond to sensitivity analysis on dominant mode amplitude cutoff (DC = 0.0 to 1.0), cases 25 and 26 correspond to sensitivity analysis on maximum lift coefficient (CLmax = 0.7, 0.35), and cases 27 and 28 correspond to sensitivity analysis on power ratio exponent (PR = 1.0, 0.0). All the base cases are circled in Figure 7 and Figure 8.

For single-mode response, the base case results of Version 4.5 match Version 4.4 well, showing bias of 1.0 and scatter of 0.0 in Figure 7.

In both single- and multi-mode cases, predicted fatigue damage is found to be relatively insensitive to dominant mode amplitude cutoff or power ratio exponent.

Not unexpectedly, the weighted bias increases with increasing Vr values in Version 4.5, and for multi-mode response, as shown in Figure 8, Version 4.5 with Vr = 0.1 yields relatively lower prediction scatter than other cases.

Power cutoff of 0.7 (which is the base case) yields relatively to the best comparison to Version 4.4 for multi-mode response. When power cutoff is one, all responses are forced to be single mode, and there are no cases left for multi-mode response in v4.5. This situation explains the anomalous case 17 in Figure 8.

A reduced CLmax (case 26) gives closer results to Version 4.4 for multi-mode response.

V4.5 is generally more conservative than v4.4 when response is multi-mode/time sharing.

If we accept time sharing, then the recommended parameters are suitable. However, v4.4 is already considered a conservative tool and there is, to date, limited-to-no full scale riser data to support the time sharing concept. Hence, the additional conservatism of v4.5 is yet to be justified. This sensitivity study demonstrates that as a possible solution, the additional conservatism of v4.5 in multi-mode predictions can be reduced by adjusting reduced velocity or lift coefficient.

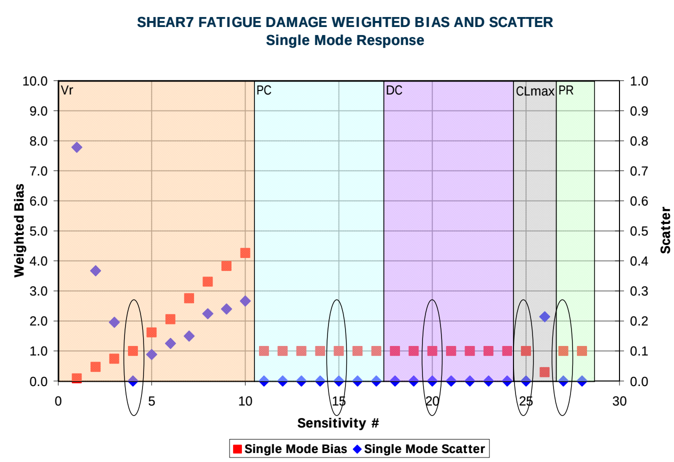


Figure 7 Sensitivity Analysis Results for Bare SCR: Weighted Bias and Scatter, SHEAR7v4.5 Vs. v4.4 (Single Mode Response)

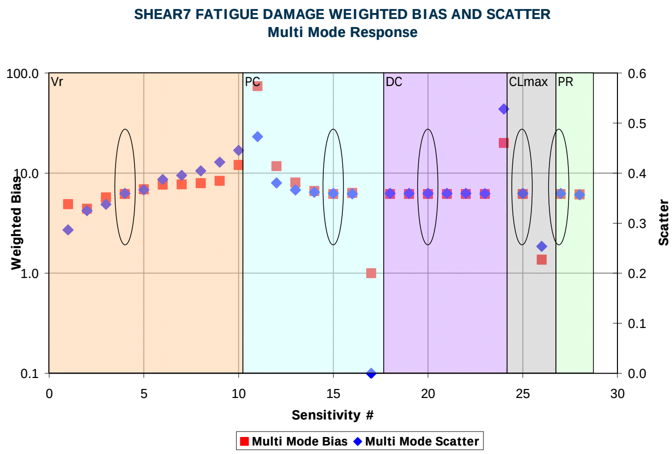


Figure 8 Sensitivity Analysis Results for Bare SCR: Weighted Bias and Scatter, SHEAR7v4.5 Vs. v4.4 (Multi Mode Response)

CONCLUDING REMARKS AND RECOMMENDATIONS

The benchmarking analysis conducted with measured drilling riser data shows that results produced by SHEAR7 Versions 4.4 and 4.5 are similar. This is because the predicted response for the drilling risers and current conditions considered is predominately single-mode. By judicious parameter selection, SHEAR7 Version 4.4 and Version 4.5 show an average factor of 10 times overestimation when compared to field measurements.

For the SCR considered, the comparison between SHEAR7 Version 4.4 and Version 4.5 results shows that:

- Single-mode results match;
- Multiple-mode fatigue damage in Version 4.5 is approximately 6 times greater (weighted bias) than in Version 4.4.

The difference in fatigue damage is due to the time sharing concept for which different modes are assumed to occur sequentially rather than concurrently. As a result the multi-mode reduced velocity bandwidth has been removed and different modes can share the same power-in region. Both of these changes increase the power-in region for any given mode and, thus, the resulting VIV amplitude when more than one mode is excited, although each modal contribution is scaled by its associated duration.

Sensitivity analysis is conducted to understand the effect of each parameter on the VIV fatigue response and to investigate the new parameters introduced in SHEAR7 Version 4.5. Fatigue damage in SHEAR7 Version 4.5 is found to be:

- Sensitive to reduced bandwidth velocity (Vr), power cutoff (PC) and maximum lift coefficient (CLmax);
- Relatively insensitive to dominant amplitude cutoff (DC), or power ratio exponent (PR).

If the time-sharing concept is assumed and the default parameters given in the SHEAR7 Version 4.5 user guide are adopted the resulting fatigue damage predictions may be five to seven times greater than those determined using Version 4.4.

At present, the authors are not aware of SCR (or drilling riser) VIV data from the field that demonstrate significant time sharing, nor are we aware of in-house or public-domain full-scale data that indicate a need for further conservatism in VIV analysis. In this case, when the time sharing concept is not assumed and Version 4.5 is to be used the following two-step approach produces fatigue damage results closer to previous version for the SCR considered:

- Conduct initial analysis in v4.5 with calibrated parameters and determine if response is single mode or multiple mode;
- For cases identified as having single-mode response, do nothing further (this should yield the same results as Version 4.4);
- For cases identified as multiple mode response, adjust Vr or CLmax to reduce difference between v4.4 and v4.5 results.

A key finding is that the prediction scatter - which leads designers to large factors of safety - is not reduced from version to version.

Generally, it is recommended: (i) to obtain more measured, full-scale VIV fatigue and current data (particularly, from SCRs) for better calibration, benchmarking, and development of VIV fatigue analysis methods; and (ii) to consider improved/new analysis models that will reduce prediction scatter by better reflecting the physics of the phenomenon as it continues to be revealed in the measurements.

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