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PARTIAL STRAKE COVERAGE VORTEX-INDUCED VIBRATION BENCHMARKING USING SHEAR7V4.5

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ABSTRACT

A VIV benchmarking study was undertaken using SHEAR7v4.5 against NDP high mode VIV response laboratory data. The purpose of which was to derive an improved set of modeling parameters for partial strake coverage cases whilst not comprising previous accuracy of shear flow bare riser response predictions. Fifty percent (50%) partial strake coverage experimental data was utilized from both uniform and shear flow conditions while bare data was also included in the activity for reference purposes. The results showed that such an activity can derive an improved set of modeling parameters that significantly improve the ability to match experimental results and also highlight where future improvement efforts can be targeted.

INTRODUCTION

The Vortex-Induced Vibration (VIV) dynamic response of long flexible ocean structures to steady current loads has been an active area of research and of interest to Ocean Engineers for the last thirty years. Whilst the understanding of the VIV response problem has made steady progress over time, experimental measurements have kept revealing new and highly complex behavior that require a detailed understanding before implementing in a prediction process.

In an effort to ensure that prediction tools are adequately predicting and bounding the problem and to also better understand the physics of longer aspect ratio flexible structures, there have been a number of recent industry championed VIV experimental test campaigns.

The recent interest in benchmarking of VIV predictions has been additionally heightened as a result of discussions at OMAE 2007 and subsequent effort towards compiling a data repository [1].

This paper serves to use a benchmarking methodology, primarily proposed in [3], to improve the predictive ability of a commercially available VIV software, through standard user adjustable parameters, and in doing so have the following objectives:

- Aim to reveal any characteristics not previously observed in the measurement data.
- Determine if a VIV benchmarking procedure involving user adjustable parameter variations can significantly improve the predicative ability of VIV empirically based software.
- If the previous step is possible, determine as general a set of modeling parameters as possible that can be applied as universally as possible.

SHEAR7v4.5

SHEAR7v4.5 is the 2007 release of the VIV prediction program developed by Vandiver at MIT [2]. V4.5 reflects some of the research findings from the DeepStar/MIT VIV testing program involving towing slender pipes. The most significant modification introduced involves a change in the way the power-in regions are apportioned in time and space [2].

The apportion of power-in regions is made once the program determines candidate structural resonant modes of vibration. In v4.5 there are several possible mode sharing

calculation options that in turn affect the power-in region definition and the final prediction of response. In the study presented herein the options include: single mode dominant response; time sharing multi-mode response that assigns equal probability of occurrence to modes and time sharing multi-mode response that assigns a probability of occurrence in proportion to the predicted modal power ratio.

There are numerous other modeling parameters that a user can modify when running SHEAR7 that make it an ideal test bed for systematically varying parameters in a benchmark study. Some of these parameters have been utilized in this study.

EXPERIMENTAL DATA SET

A detailed laboratory data set of a long flexible riser with aspect ratio L/D approx 1400 was used in the benchmarking exercise. The model was tested by the Norwegian Deepwater Programme (NDP), the detailed test description is available for public download [1]. The experimental data forms an ideal dataset for benchmarking as it is taken in a laboratory which is a higher quality control environment than the field, yet utilized a relatively long aspect riser model which lead to natural modes of response similar to realistic applications. The riser model was 38m in length with an outside diameter of 0.027m. By changing the way the model was towed, a uniform or linear shear flow profile could be generated. Flow speeds varied up to a maximum of 2.2m/s in 0.1m/s steps, such that Reynolds number varied up to a maximum of 60,000. Whilst a number of different configurations of strakes were tested, in this paper the following data is utilized for the benchmarking and is pictorially shown in Figure 1:

1. Uniform Flow, bare riser [Top left in Figure]
2. Uniform Flow with 50% strakes [Top right]
3. Linear Shear Flow, bare riser [Bottom left]
4. Linear Shear Flow with 50% strakes (in the high velocity region) [Bottom right]

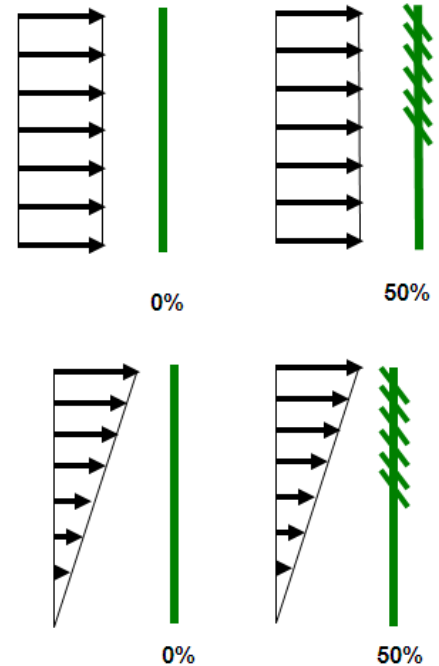


Figure 1: Different riser configurations examined in the present benchmark study

Although the focus of the paper is on partial straked riser modeling, the bare riser cases have been added to establish the performance of the prediction program on the more well established understanding of bare riser VIV prediction behavior. This is done so that any sets of general modeling parameters (non-strake specific) identified that lead to improved partial strake modeling performance will still have general applicability to the bare riser cases.

In order to establish an appropriate Strouhal number to use for the predictions, the fundamental (1x) response frequency, f_{1x} , was found for the bare riser uniform flow test and the Strouhal constant was calculated per:

$$St = f_{1x} D / U$$

where D is the riser diameter and U is the uniform flow speed. A reasonably consistent St number of 0.137 was found to occur and used in the rest of the cases.

The data was observed to have higher harmonics of cross-flow response present at the 3x and 5x multiples of the fundamental Strouhal frequency. However, the relative amount of higher harmonics present is less than that observed in longer aspect ratio riser field tests [4]. As SHEAR7, along with most other existing empirical based VIV prediction programs currently only predicts the 1x response, the benchmarking effort was focused on improving the ability of predictions to match the 1x response only as closely as possible. The topic of

predicting higher harmonics is the subject of current and future research for future publications.

The experimental data set consists of cross-flow strain gauges measuring vortex induced bending strain (at 22 locations along the axis of the riser) allowing fatigue damage rate to be better assessed than would be possible from accelerometer signals. The root mean squared (rms) value of the bending strain was taken from the steady test conditions. In order to establish a fatigue damage rate, explained in a later section of the paper, a single valued frequency was required. To ease the computation process, the single frequency value was derived for each test based on the maximum flow velocity and using a Strouhal value of $St = 0.137$.

BENCHMARKING PROCEDURE AND METRICS

The benchmarking procedure used in this paper involved the following steps:

- Determine sets of VIV modeling parameters to include as benchmark cases.
- For each specific set of parameters perform predictions of VIV response for every single riser configuration and flow velocity test.
- Compare the prediction versus measurement with the use of some benchmarking metrics to help understand which set of chosen VIV modeling parameters provides the best performance.

It is not the objective of this particular benchmarking exercise to determine a conservative set of modeling parameters (although the method could easily be modified to), but rather to determine a set of modeling parameters that leads to the closest match between predictions and measurements with the least amount of scatter. If a set of predictions that closely matched measurements were to be used in a design scenario it would be expected that conservatism would be introduced for the design, an example of which could be use of an appropriate factor of safety.

Figure 2 shows a steady state example of the predictions versus measurements of the rms cross-flow bending strain VIV response of the NDP 38m riser for a single test using some pre-defined VIV modeling parameters.

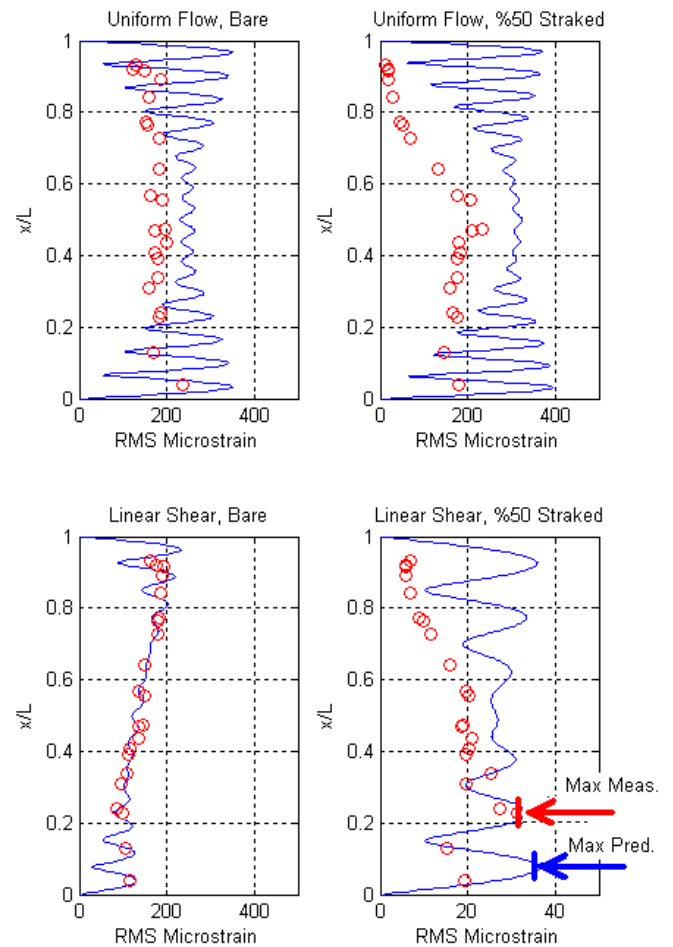


Figure 2: RMS strain comparisons along the riser. Predictions compared to measurements for selected single cases of [top left] uniform flow bare; [top right] uniform flow 50% strakes; [bottom left] linear shear bare; and [bottom right] linear shear 50% strakes.

The quantitative metrics that were used in the benchmarking process are summarized as:

1. The fatigue damage index, D_i , at each point on the riser where:

$$D_i = (CFrms\mu\epsilon)^3 freq.$$

$CFrms\mu\epsilon$ is the cross-flow rms bending micro-strain and is raised to the power of three to simulate an S-N fatigue curve with a slope of three, multiplied by frequency, or the rate of cycles. PD_i is the predicted fatigue damage index and MD_i is the measured fatigue damage index. The fatigue damage index is used rather than rms strain in the benchmarking process as it

represents a closer metric to what riser designers ultimately require.

2. The bias, B_i , defined as the ratio of PD_i / MD_i (predicted fatigue damage index over measured fatigue damage index) for every sensor location. The logarithm of the bias, $\log B_i$ is an easier parameter to interpret results from rather than the bias.
3. The mean of $\log B_i$, $\mu_{\log B_i}$, represents an inherent over or under-prediction, with a zero mean representing perfect prediction.
4. The standard deviation of $\log B_i$, $\sigma_{\log B_i}$, represents the scatter (assuming Gaussian or normally distributed) about the mean.
5. Max prediction versus max measured fatigue index (regardless of location on riser) for each individual experiment was also computed. The reason being that often riser designers are only concerned with the maximum values.

Figure 3 is an illustrative example showing a comparison of the ensemble of individual measurement points taken during 22 different flow speed (linear shear bare riser) experiments for a specific set of *poor performing* modeling parameters. A point on the 45 degree line going through the origin represents perfect agreement. Above the line is over-prediction, while below the line is under-prediction. The two parallel lines either side of the line going through the origin represent one and two orders of magnitude difference respectively in the prediction.

By choosing sets of modeling parameters, conducting all the predictions and making comparisons to measurements, pairs of $\mu_{\log B_i}$ and $\sigma_{\log B_i}$ can be computed that are associated with each set of modeling parameters to indicate their respective performance.

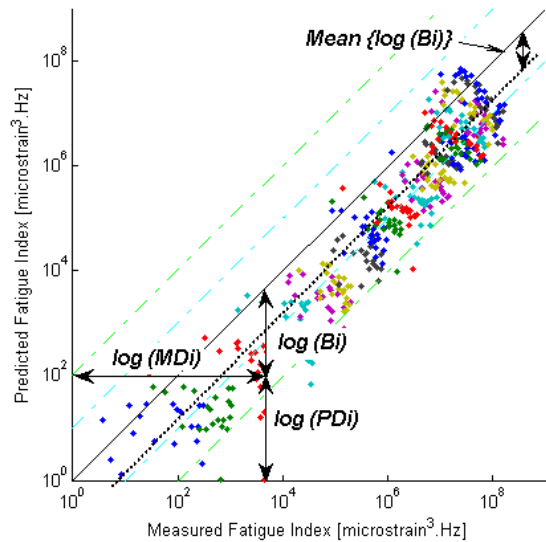


Figure 3: An example fatigue index comparison plot of predictions against measurements. $\log(MDi)$, $\log(PDi)$ and the resulting $\log(Bi)$ (the bias) are indicated for an individual measurement point. The ensemble average of $\log(Bi)$ is shown as $\text{Mean } \log(Bi)$ with the standard deviation of $\log(Bi)$ representing scatter (not shown). This example shows a poor performer parameter set that leads to an under-prediction bias

KNOWN ISSUES

Going into this study there were a number of known issues relating to best practice use for improving prediction accuracy. These prior learnings were:

1. The previous SHEAR7 CL (lift) curves (“Table 3” and “Table 5”) for modeling the straked region were too conservative.
2. It has been shown from model tests that strakes are extremely efficient with no significant excitation produced compared to bare regions.
3. Hydrodynamic damping models of flexible cylinders undergoing VIV response require some improvement. Existing hydrodynamic models are based on knowledge gained from rigid cylinder tests.
4. The use of “Code 200” in SHEAR7 produces a widely varying St number (as a function of Reynolds number) with step changes that do not appear to match full scale observations well and cause the edges of predicted power-in zones to shift in an unrealistic manner due to step changes in computed vortex shedding frequencies.
5. VIV response has been shown to consist of a time sharing between resonant modes on towed long cylinders. However, the modeling parameters relating

to time sharing have not previously been thoroughly benchmarked to experimental data.

6. SHEAR7 was originally developed for predicting the VIV response of bare risers in shear flow. It is continually shown to be very good in these cases. In undertaking a benchmark activity to derive improved sets of modeling parameters for partial strake coverage cases, the accurate predictions of bare riser response should not be compromised.

CL lift curve for straked region

Figure 4 shows a CL curve for modeling straked regions that was used in this benchmark study.

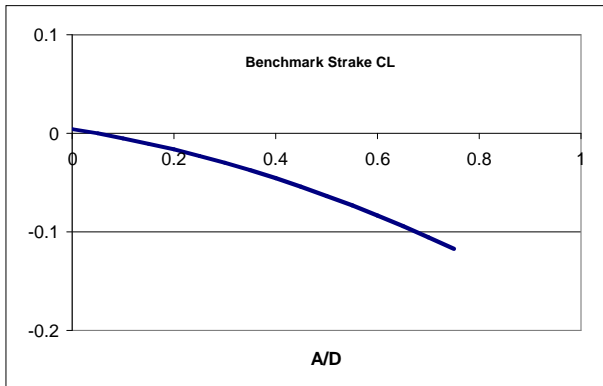


Figure 4: CL Curve used in straked region

The most important feature of the curve in Figure 4 is that it has very little positive CL. The curve works well when comparing predictions of partial strake coverage cases from Miami and the present NDP data sets as it ensures the bare region is predicted to drive the response. This is no clearer than in situations when the bare region is in a low velocity region and is observed in experiments to dominate response.

BENCHMARK CASES

A set of nine (9) benchmark trial parameter set cases were chosen for the study to realize the best possible modeling parameter set with the most general application. The cases involve three (3) different values of High Vr (reduced velocity) damping and three (3) different weighting factors for single or multi-mode response.

High Vr damping term for straked region

When comparing predictions of response driven from a bare region, the relative influence of hydrodynamic damping from strakes in a high reduced velocity region of the riser appears to have less significance than current prediction models suggest. For this reason, the High Vr damping term for the straked region was investigated as a key benchmark parameter.

Single or Multi-Mode Response

Three (3) different choices were selected for single or multi-mode response, these were:

1. Single mode response
2. Multi-mode time sharing with an assignment of mode probability of occurrence in proportion to predicted modal power.
3. Multi-mode time sharing with an equal probability of occurrence.

Table 1 shows the nine (9) trial benchmark parameter sets.

Table 1 – Trial Benchmark Parameter Sets Defined

No.	High Vr Dmp Coef.	Mode Calculation	Power Cutoff	Time Share Option
1	0.2	Single	1	-
2	0.2	MM Time shr, Pwr dstrb	0.5	1
3	0.2	MM Time shr, Unif dstrb	0.5	0
4	0.1	Single	1	-
5	0.1	MM Time shr, Pwr dstrb	0.5	1
6	0.1	MM Time shr, Unif dstrb	0.5	0
7	0.02	Single	1	-
8	0.02	MM Time shr, Pwr dstrb	0.5	1
9	0.02	MM Time shr, Unif dstrb	0.5	0

Remaining SHEAR7v4.5 user selected modeling parameters left unchanged for the benchmark study are shown in Table 2.

Table 2 – Modeling parameters unchanged in the benchmark study

Parameter	Value
Strouhal Numer	0.137
Structural damping	0.004
Hydrodynamic damping parameters	Default (except High Vr)
Ca bare	1
Ca straked	2
Cl reduction factor	1.0
Bare region CL table number	2
Bandwidth	0.5
PZAL	Default (0.3) {riser too small in this study to have affect}

BENCHMARK RESULTS

Figure 5 shows a graphical display of the results for linear shear flow 50% strake tests. The results of all the test setups (uniform bare, uniform 50%, linear shear bare and linear shear 50%) are shown in Table 3.

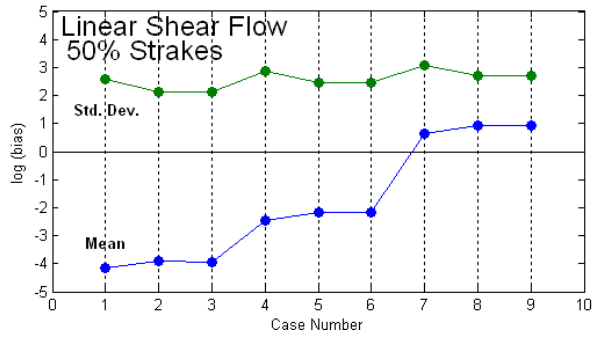


Figure 5: Benchmark Case results for linear shear, 50% strakes showing mean and standard deviation of $\log B_i$.

Table 3 – Benchmark results of all test setups (uniform bare, uniform 50%, linear shear bare and linear shear 50%)

Case	Uniform Bare		Uniform 50%		Linear Shear Bare		Linear Shear 50%	
	μ	σ	μ	σ	μ	σ	μ	σ
1	-0.5	2.6	1.8	3.1	-1.3	1.5	-4.1	2.6
2	0.0	1.8	1.8	3.0	-1.1	1.1	-3.9	2.1
3	0.0	1.8	1.8	3.0	-1.1	1.1	-3.9	2.1
4	-0.5	2.6	1.8	3.1	-1.3	1.5	-2.5	2.9
5	0.0	1.8	1.8	3.0	-1.1	1.1	-2.2	2.5
6	0.0	1.8	1.8	3.0	-1.1	1.1	-2.2	2.5
7	-0.5	2.6	1.8	3.1	-1.3	1.5	0.6	3.1
8	0.0	1.8	1.8	3.0	-1.1	1.1	0.9	2.7
9	0.0	2.0	1.8	3.3	-1.1	1.6	0.9	2.7

As a general trend the set of parameters relating to Case 8 offer the best universal performance.

Linear Shear Flow 50% strakes

As shown in Figure 5 the mean of the bias improves for the highest case number set, being closest to zero for the cases where High Vr damp coeff = 0.02. Of these cases (7,8,9) the standard deviation of the bias (recall $\sigma_{\log B_i}$ is the scatter in error between predictions and measurements) is highest for the single mode case and lower for the other cases (8,9).

Figure 2 comparisons of the spatial response suggest that there is considerable scatter arising from an over-prediction of standing wave response, whereas prediction based more on a traveling wave model would tend to spatially smooth the response which in turn is likely to reduce the scatter.

Figure 6 and Figure 7 present the comparison of predictions against measurements, run with the most successful parameter set (Case 8), for all sensors and maximums only respectively of all 22 flow velocity cases.

Uniform Flow 50% Strakes

It can be observed that the standard deviation is high for all cases, showing a large scatter is present in the predictions. The reason for the large scatter is obvious in Figure 2 which shows the predictions not decaying in the straked region (high x/L) as the measurements do for these uniform flow conditions.

Figure 8 and Figure 9 present the comparison of predictions, run with the parameter set Case 8, against measurements, for all sensors and maximums only of all 22 flow velocity cases. As previously stated, it is obvious from Figure 8 that the response in the straked region is too conservative under uniform flow conditions and requires improvement.

Linear shear bare

The performance of the program remains accurate for the shear flow bare riser tests with the least standard deviation (scatter) of all configurations. The best parameter set, is marginally Case 8 which is a time sharing with a *power rule* probability distribution.

Figure 10 and Figure 11 present the comparison of predictions against measurements, run with the power rule parameter set (Case 8), for all sensors and maximums only of all 22 flow velocity cases.

Uniform flow bare

It must be noted that Cases 1 – 3 are effectively repeated twice as the only changes in Cases 4 – 6 and Cases 7 – 9 are strake specific parameters.

Figure 12 and Figure 13 present the comparison of predictions against measurements, run with parameter set (Case 8), for all sensors and maximums only of all 22 flow velocity cases. It can be seen that the performance of the predictions has less scatter in linear shear bare cases compared to uniform flow bare cases. Figure 2 comparisons of the spatial response suggest that again there is considerable scatter arising from an over-prediction of standing wave response, whereas prediction based more on a traveling wave model would tend to spatially smooth the response which in turn is likely to reduce the scatter.

Summary

The benchmark study found that the overall best performance for the different riser configurations resulted from the parameter set identified as Case 8. Case 8 had the smallest High Vr damping term in the straked region and the time sharing option with probability of occurrence in proportion to predicted modal power.

Table 4 summarizes the recommended parameters for use in a full scale analysis that would be **non-conservative. For design purposes, conservatism should be included on top of these best fit results. An example of including conservatism would be through the use of a factor of safety.**

Table 4: Best performance parameter sets found from benchmark study

Parameter	Value
Ca bare	1
Ca straked	2
Cl reduction factor	1.0
Bandwidth	0.5
Hydrodynamic damping parameters for Bare regions	0.2, 0.18, 0.2
Hydrodynamic damping parameters for straked regions	0.2, 0.18, 0.02
Single mode or Multi-mode option: <i>Time sharing – Pr. Of Occurrence in proportion to power distribution</i>	Power cutoff = 0.5 Time Share Option = 1
Non-Conservative Bare region CL table	2
PZAL (Primary Zone Amplitude Limit)	Default value (0.3) {The riser was too small in L/D to draw conclusions about PZAL in this study}

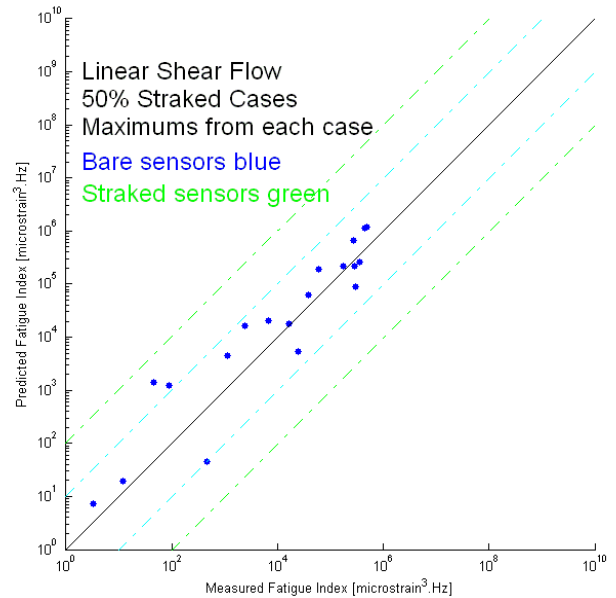


Figure 7: Best performer scatter plot of linear shear 50% strakes maximums from each test

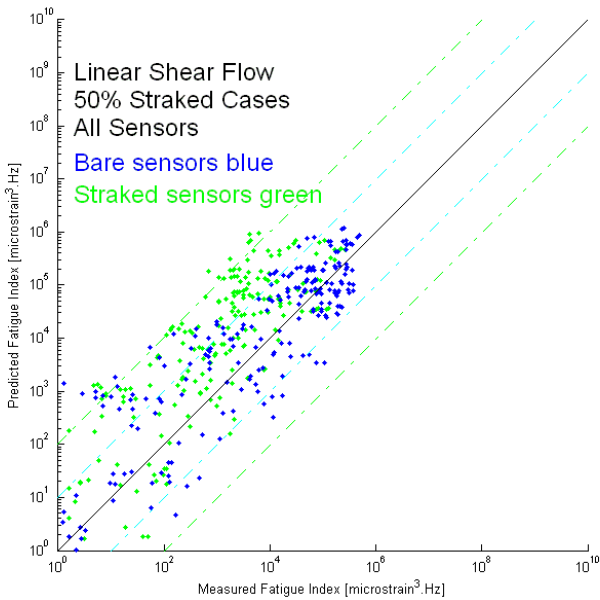


Figure 6: Best performer scatter plot of linear shear 50% strakes all sensors

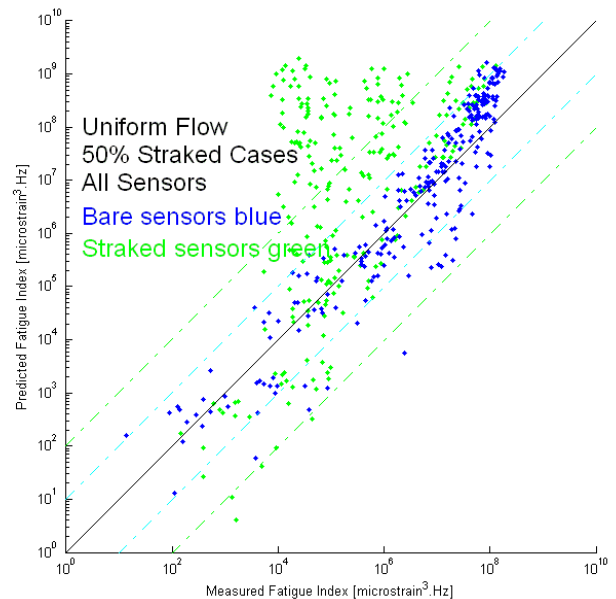


Figure 8: Best performer scatter plot of uniform flow 50% strakes all sensors

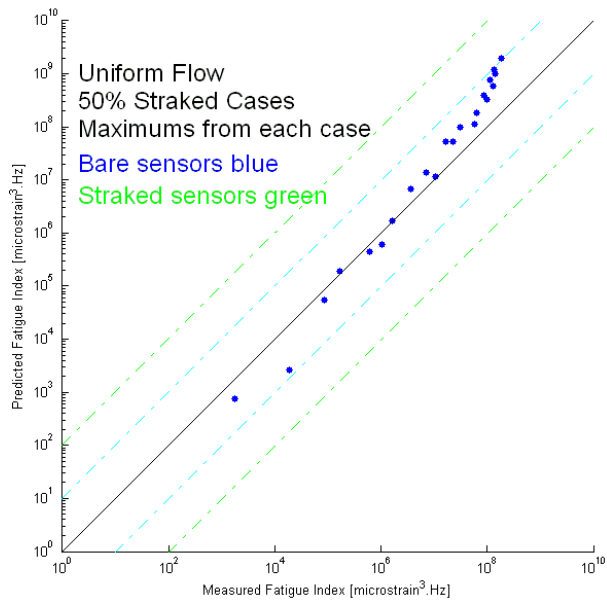


Figure 9: Best performer scatter plot of uniform flow 50% strakes maximums only from each test

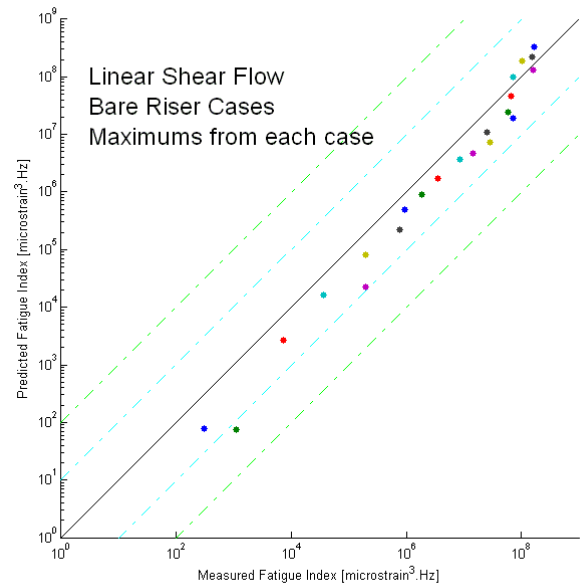


Figure 11: Best performer scatter plot of linear shear bare maximums only from each test

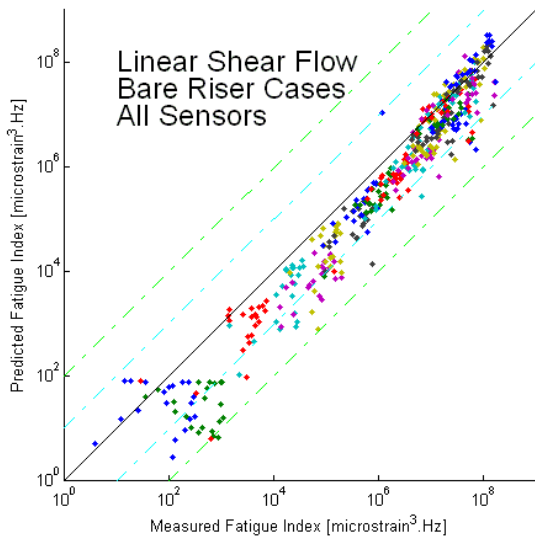


Figure 10: Best performer scatter plot of linear shear bare all sensors

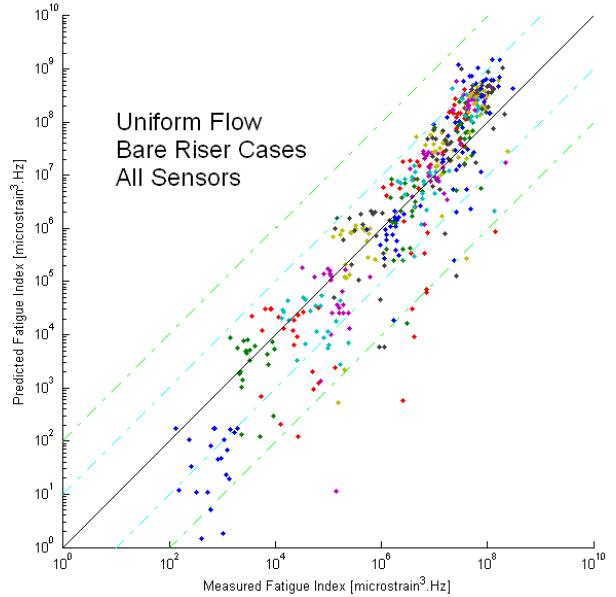


Figure 12: Best performer scatter plot of uniform flow bare all sensors

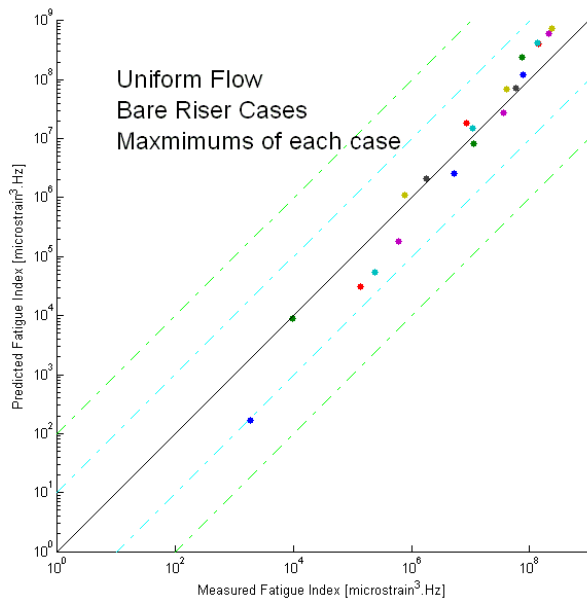


Figure 13: Best performer scatter plot of uniform flow bare maximums only from each test

CONCLUSIONS

The benchmark study shown in this paper revealed there is much value to be gained in undertaking a VIV benchmark exercise. The value is in both revealing characteristics of the measured data that were not initially obvious and in improving the performance of prediction software.

The exercise identified the following about the measurements and the ability to predict them:

- Reduction of the High Vr Straked Zone damping term lead to an improved performance of prediction in the linear sheared partial straked cases. It could be that this term has less importance for strakes in flexible riser sheared flow scenarios than in rigid cylinder model tests in which its understanding was derived.
- Linear shear flow bare riser predictions were shown to be very accurate with the least amount of scatter of all the configurations.
- The experimental data suggests that the measured rms response is much 'smoother' spatially than the predictions provide, which is likely to be due to an over-prediction of standing wave response. Prediction based more on a traveling wave model would tend to spatially smooth the response which in turn is likely to reduce the scatter.
- Under uniform flow conditions with partial strakes, the straked region predicted response is far too conservative and requires further work to

reduce the predicted response. However the maximum responses are in good agreement.

- One set of single parameter values was found to provide a reasonable level of performance in a number of different riser configurations and flow speeds considered.
- Incorporation of the effect of higher harmonics is a logical next step in developing prediction code and benchmarking.

ACKNOWLEDGMENTS

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