A hybrid FEM-Kriging approach for fatigue assessment of steel pipe risers from field-measured motions

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Abstract. Real-time monitoring of FPU motions provides resources for a more realistic assessment of riser fatigue. Standard practice relies on FEM analysis to obtain the desired loads along the riser, however, it is a CPU-intensive approach which might be unable to provide results on a real-time basis depending on available resources. Often in a riser analysis, interest lies on a few critical points, and surrogate models offer a cost-effective alternative to this scenario. Previous work has shown Kriging to be a good choice for time series prediction, yielding adherent results for forces and moments in certain hotspots, by using only vessel motions as inputs. Fatigue analysis results are presented for a case study, where a SCR connected to a semi-submersible production unit had stresses and damage calculated from Kriging predictions.

Keywords: *Steel pipe riser, SCR, Fatigue analysis, Surrogate model, Kriging*.

1 Introduction

Fatigue analysis is a demanding step of a steel pipe riser project, which consists of evaluating a high number of environmental load combinations on the riser, such as waves and currents. These sources might act directly through hydrodynamic loads or have an indirect effect such as the motions of the FPU (Floating Production Unit) where the riser is connected. The most significant source of fatigue damage often comes from the alternating stresses caused by these motions. These effects are mostly evaluated through time-domain FEM simulations, yielding the riser internal stresses time series which are input to the cycle counting and histogram building process of the fatigue analysis post-processing.

Monitoring of FPU motions provides a source of information for more accurate fatigue damage evaluation on the riser, through the results of FEM simulations. However, real-time processing of FEM analysis might prove difficult, depending on the scale of the riser model. The present work aims to provide a less CPU intensive alternative through surrogate models.

Surrogate models aim to find a problem's solution through a heuristic approach. In engineering problems, this means that the model does not contain the mathematical formulations that describe the involved phenomena, such as the equilibrium equations in structural analysis. In general, its application can be divided into two steps: training and prediction. During training, the model is presented to a set of input and output data and calculates its internal parameters in a way that best establishes the relationship between them. From there on, the model can be used to predict the desired response from a new set of data points.

Kriging is a statistics-based method originating in geophysics field by Krige [1] and later developed by Matheron [2]. A more detailed historical analysis, including the evolution of the method, variations and possible approaches is presented by Chilès and Desassis [3]. It has been shown by Damasceno et al. [4] that applying Kriging as a surrogate model has the potential to provide adherent time series predictions for riser analysis. The method demands a short FEM simulation (~600 s) for training, to expand the desired outputs to a longer duration (~3,600 s). This reduces total CPU cost for long time series calculation and makes it well-suited for fatigue analysis, where a high number of long time series is needed.

2 Steel pipe fatigue analysis

It is important to have in mind that the analyzed riser is part of an offshore system composed of floating unit, mooring lines, other risers etc. When submitted to environmental loads such as waves, winds and currents, the system's response can be analyzed through either frequency or time domain methods. This paper will focus on the latter and, therefore, more attention will be given to it. The most established time domain method for this problem focuses on solving the static and/or dynamic equilibrium equations through the Finite Element Method (Bathe [5]). Its solution results on the structure displacements, through which it is possible to obtain other output time series, such as internal forces, moments and stresses.

With a single riser in mind, there are different types of analyses when it comes to the coupling with the rest of the system. For the analysis proposed in this paper, the floating unit's movements are acquired from GPS and accelerometers. These movements will serve as the boundary conditions for the riser top node, reducing the model and system of equations to be solved to the riser itself. Mourelle et al. [6] provides further explanation on the uncoupled methodology that resulted in the software ANFLEX, which was utilized in all FEM simulations described in this paper.

This step, also referred to as global analysis, yields the displacement time series of the finite element mesh nodes, from which the internal loads and stresses can be calculated. Steel pipe fatigue calculation is based on the axial tension component σ_{xx}, which can be calculated through eq. (1), a composition of axial force F_x and both bending moments, M_y and M_z. Coefficients C_1 and C_2 vary with the evaluated cross-section point's angle in the yz plane. ANFLEX post-processing calculates stresses for 16 points in total, 8 for both internal and external wall, each separated by 45 degrees.

$$\sigma_{xx} = \frac{F_x}{A} + r\left(C_1 \frac{M_y}{I} + C_2 \frac{M_z}{I}\right) \tag{1}$$

Once the σ_{xx} time series are calculated, cycle counting is performed through the Rainflow algorithm (Matsuishi and Endo [7]). It yields the number of cycles per stress range, which can be organized in histograms, so that damage can be properly calculated through S-N curves and the Miner's Rule.

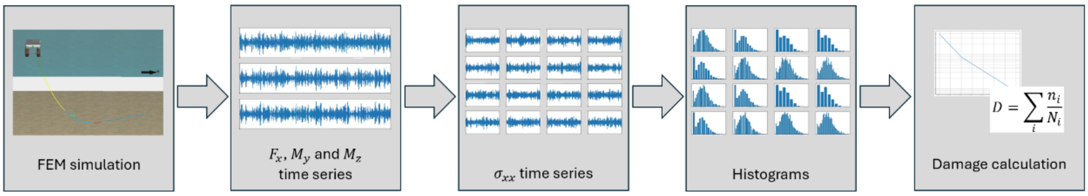

Figure 1. Fatigue damage calculation flowchart

S-N curves are the most common way of assessing fatigue life of a steel pipe submitted to cyclical loads. They provide the number of cycles N for a given stress range S. The following analysis will utilize log-bilinear S-N curves such as eq. (2), where the slope of the curve changes from a certain point S_c.

$$\log N = \begin{cases} \log a_1 - m_1 \log S\,, & S \leq S_c \\ \log a_2 - m_2 \log S\,, & S > S_c \end{cases} \tag{2}$$

Then, it is possible to calculate the damage D_i for a given stress range through the ratio between the number of cycles n_i, a result of the Rainflow count, and the denominator N_i, obtained from the S-N curve. However, the histograms built from the global analysis time series rarely contain a single stress range. Eq. (3) defines that total damage is the sum of each stress range's contribution, known as Miner's Rule.

$$D = \sum_i D_i = \sum_i \frac{n_i}{N_i} \tag{3}$$

3 Kriging application

The fatigue analysis of a steel pipe needs three time series to be determined for each load case: axial force (F_x) and the bending moments (M_y and M_z). The application of surrogate models consists of predicting these time series for the points of interest by using the top node movement signals as inputs, which are known beforehand for the whole long-term duration.

Therefore, the objective is to obtain the long-term F_x, M_y and M_z time series from the input signals ($X_1, X_2, \ldots, X_{N_{in}}$) with total duration t_{total}, by performing a short FEM simulation with duration $t_{train} < t_{total}$. It will provide the outputs ($Y_1, Y_2, \ldots, Y_{N_{out}}$) until $t = t_{train}$ (Fig. 2), destined to training the N_{out} surrogate models. Once training is complete, they provide the output predictions ($\hat{Y}_1, \hat{Y}_2, \ldots, \hat{Y}_{N_{out}}$) from t_{train} to t_{total} (Fig. 3).

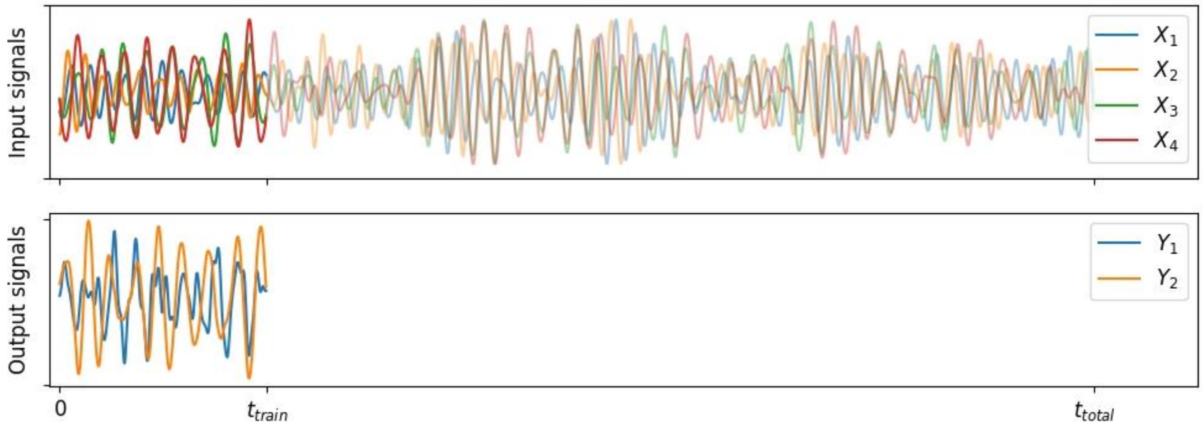

Figure 2. Example of short FEM simulation results, highlighting the points destined for training

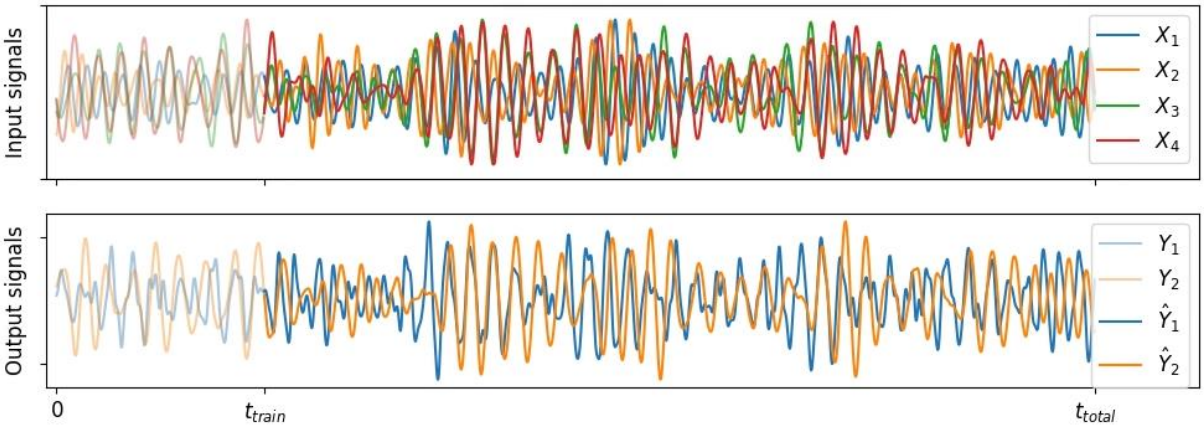

Figure 3. Surrogate model prediction from the remainder of the input signals

However, it was observed that training the model in such a way might leave out important parts of the input-output relationship that, evidently, the model will not be able to predict since they were not present in the training dataset. One alternative is to consider a different time interval for the FEM simulation, with the same duration t_{train}, that can incorporate more information into the training dataset. Determining this interval is certainly a challenge, yet a method used in extreme analysis was chosen as an alternative, called the window method. It consists of selecting a time window centered around a time step where $t = t_{max}$, which fits a chosen criterion such as maximum vertical acceleration. Once t_{max} is identified through the known long-term inputs, the window is determined by maintaining a total duration of t_{train} (Fig. 4).

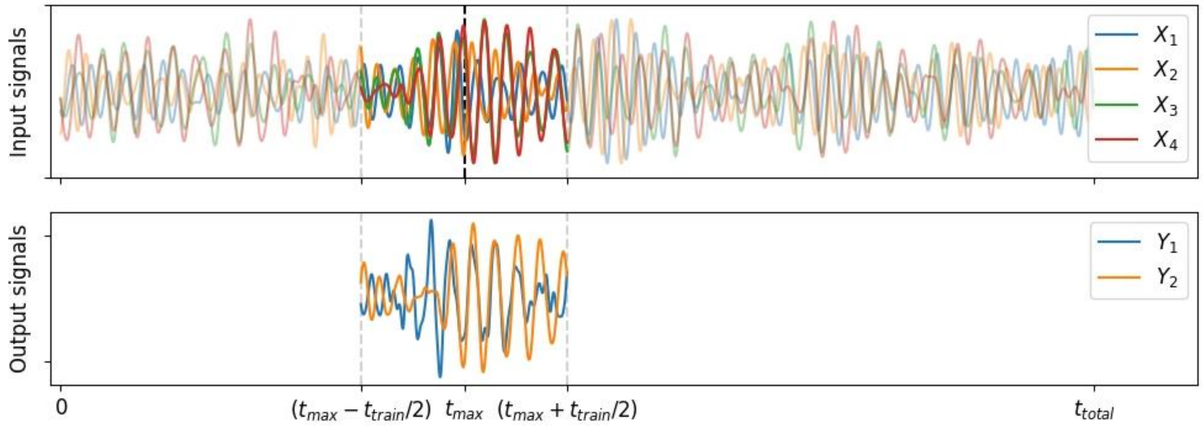

Figure 4. Short FEM simulation results from the selected time window

4 Case study

The object of study is a Steel Catenary Riser installed in a semi-submersible platform (Fig. 5). FPU motions were obtained from GPS and accelerometer measurements from the year of 2018. However, there were periods of unavailability which led to a total of 5715 hours of data out of 8760.

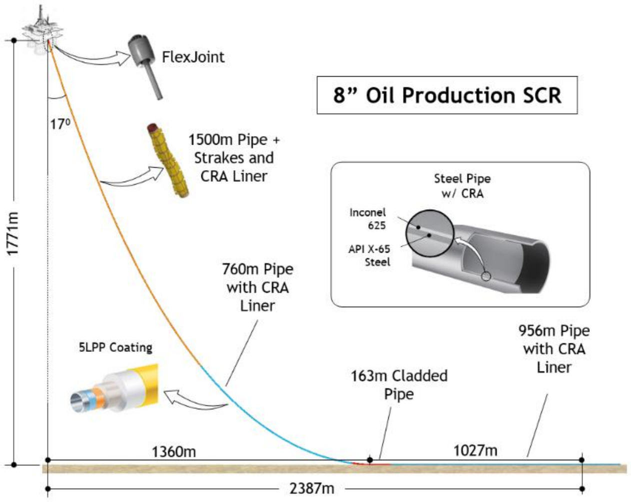

Figure 5. Overview of SCR composition

Figure 6 shows motion data availability and how it is unevenly distributed throughout the year. In a proper fatigue assessment scenario such as a Digital Twin application, this raises concern whether fatigue life is being properly calculated due to seasonal characteristics of the environmental loads and requiring a method to deal with unavailability, suggested here as a future topic of research. However, it's not a concern for the demonstration purposes this paper of comparing FEM and Kriging performance.

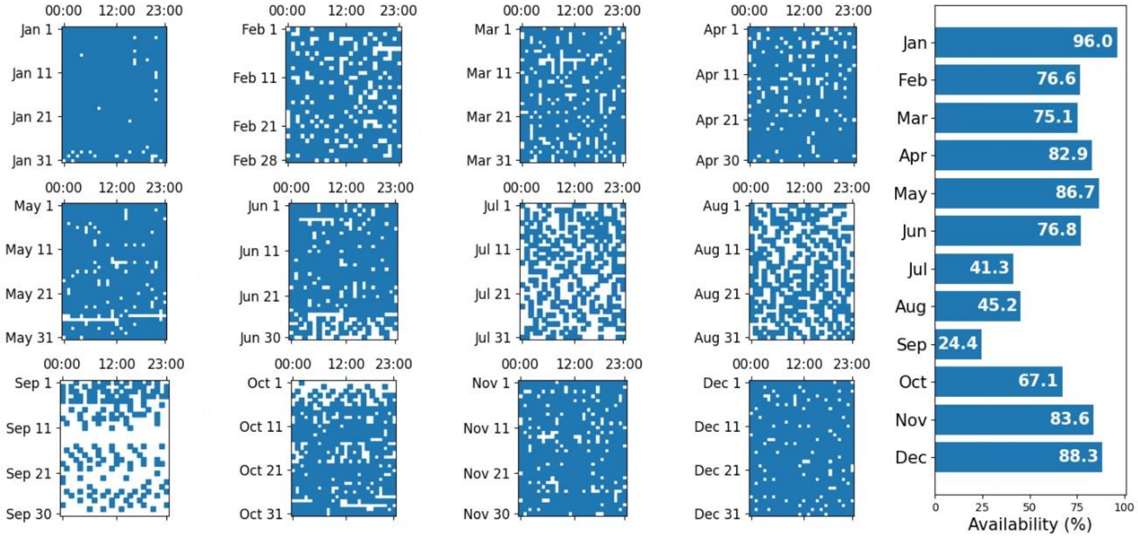

Figure 6. FPU motion availability throughout 2018

The FPU motions are used to calculate displacement and rotations at the riser top node, which feed the FEM dynamic analyses and calculate the damage for one year duration. The horizontal plane X and Y positions were acquired from the GPS system and were utilized as constant values for each hour, which defines a load case in the FEM analysis. This means each simulation is carried out for the duration of the motion signals of 1 h duration and the static offset applied in the static portion of the analysis, which corresponds to the initial FPU position from the GPS measurements. Figure 7 shows its distribution for all load cases. In the dynamic portion of the analysis, motions are applied for the remaining degrees of freedom: vertical displacement Z and rotations R_x, R_y and R_z.

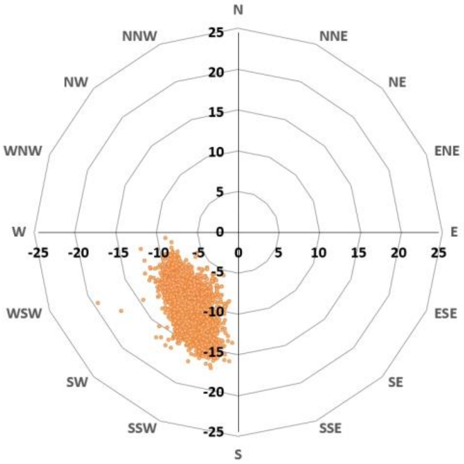

Figure 7. Initial FPU offset by load case (in meters)

For fatigue calculation, it is conservatively assumed that any mesh node may coincide with a weld. Therefore, log-bilinear curves D (with cathodic protection) and E (in air) from DNV [8] are applied to the external and internal pipe walls, respectively. Their parameters are presented in Tab. 1.

Table 1. Utilized S-N curves

S-N curve	log a_1	m_1	log a_2	m_2
D w/ CP	11.764	3.00	15.606	5.00
E in Air	12.010	3.00	15.530	5.00

Damage calculated from FEM simulations is assumed to be yearly recurring and is therefore extrapolated to calculate expected service life (without safety factors). Figure 8 shows results obtained through these steps for 756 nodes along the riser, where two notable points can be identified: one at the top section (TOP) and another at the touchdown zone (TDZ). These two points will be further analyzed through the proposed FEM-Kriging method.

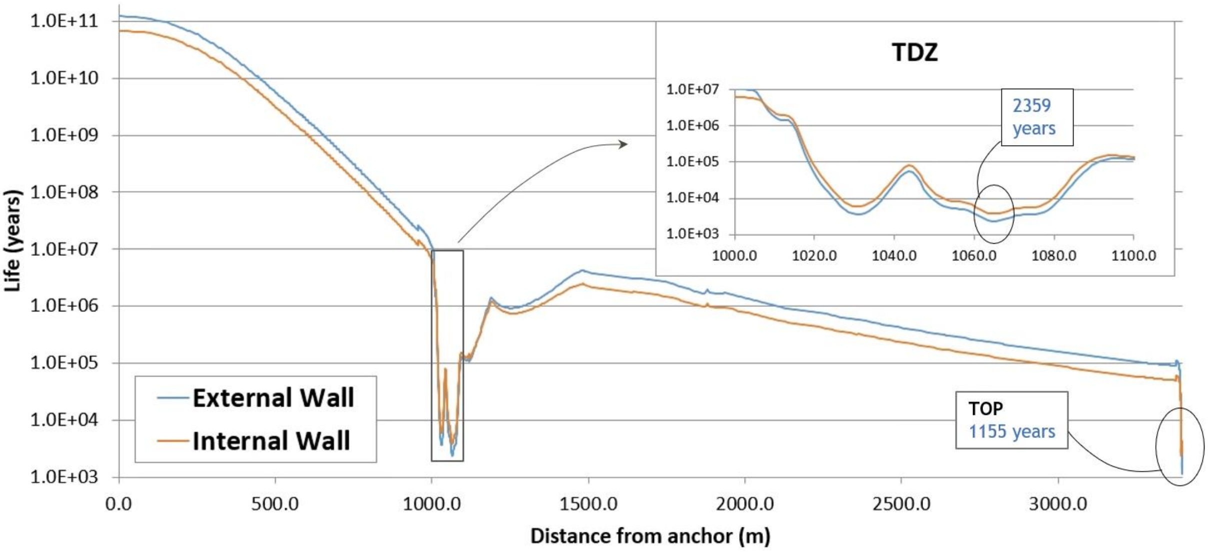

Figure 8. Full FEM analysis fatigue results

The hybrid method follows a similar procedure, but the stress histograms are calculated from Kriging-generated time series instead. For each load case, the previously explained time window FEM simulation of 600 s duration is performed. Training and predictions were performed by having the first and second order derivatives of the movement signals as inputs as well, which account for its respective velocity and acceleration. Each node and load case has a dedicated surrogate model for F_x, M_y and M_z. This leads to a total of 34290 Kriging models (2 nodes x 3 outputs x 5715 load cases) to perform the fatigue analysis for both TOP and TDZ, yielding the results shown in Tab. 2.

Table 2. Fatigue life results (in years)

Node	FEM	Kriging
TOP	1155	1176 (+1.8%)
TDZ	2359	2272 (-3.7%)

Since the use of surrogate models over FEM has the purpose of reducing computational cost needed for fatigue assessment, it is important to measure this reduction to justify Kriging as an alternative. Results obtained through Kriging showed low percentual error on both TOP (+1.8%) and TDZ (-3.7%) and were obtained with a substantial reduction of total CPU time (Tab. 3). Note that the Kriging portion of CPU time is given by node, since each additional node requires separate training and prediction for their respective F_x, M_y e M_z outputs. This makes it so that the Kriging/FEM relationship has a breakeven point: when the number of points of interest is too high, the cost associated with Kriging might surpass the full FEM simulation, which provides results for every node of the FE mesh at no additional cost (other than memory/storage availability).

Table 3. Average CPU elapsed times per load case

Method	FEM (s)	Kriging (s/node)	# of nodes	Total
Full FEM	3852.1	-	-	3852.1
FEM-Kriging	631.6	3.2	2	638.0 (-83.4%)

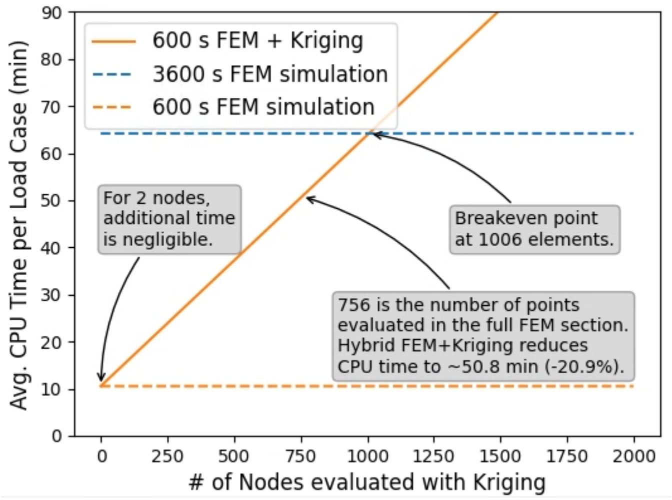

Figure 9. Analysis of average CPU times per load case

5 Conclusions

Through this paper, a hybrid methodology that utilizes FEM and Kriging surrogate models was explored to calculate fatigue damage on critical SCR points. The full FEM simulations fed by the measured data provide the most accurate stress time series to calculate fatigue analysis, at the cost of longer simulations and CPU times. Kriging, however, provides a faster alternative that benefits from scenarios with fewer points of interest along the riser, such as the TOP and TDZ points that were analyzed. It should be noted that the two analyzed points were known because full FEM simulations were carried out beforehand. In a scenario where the critical TDZ point is unknown, for example, it might be necessary to evaluate more than one through the hybrid FEM-Kriging method. Assuming the average time spent remains the same, Fig. 9 shows how time per load case grows as the number of points evaluated through Kriging increases. The proposed method proves to be a low computational cost alternative, yet sufficiently accurate for estimating riser fatigue life through vessel motions.

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