# Local structural dynamics identification in offshore wind turbines based on experimental data

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## I. INTRODUCTION

STANDARD approaches to determine stress in structural components typically use geometrically detailed FEM models including the effect of external loads. Loads are provided by aero-hydro-servo-elastic models, which are geometrically simplified to account for global modes and most relevant non-linarites. However, a common approach for component FEM models assumes a linear and quasi-static w.r.t. global system dynamics. Therefore, actual non-neglectible effects such as local dynamics or local non-linearities are not considered during the structural design process. The present study aims to establish a methodology to study whether those effects are present or not in real prototypes.

Each new Wind Turbine design is validated by means of a real prototype. In there, main parameters affecting its performance are monitored; strain gages are installed in main sections to characterize reaction loads; and numerically detected critical positions are also instrumented in order to characterize their stress.

## II. APPROACH

The present study proposes a novel approach in order to investigate the structural response of the components using experimental time-series data from relevant physical magnitudes. The methodology is based upon parametric model-based methods such as autoregressive moving average models with exogenous inputs (ARMAX) applied to multiple inputs and single output (MISO) system. The post-process of the identified model allows identifying local modal parameters (natural frequencies, damping and mode shapes) in order to reproduce structural frequency response function (FRF) and, in consequence, impulsive responses (IR). The implementation of the method can be described in the following steps:

### A. System definition

As it is mentioned, the case of a MISO system is considered. Inputs are structural reaction loads at the boundaries of the component measured by means of calibrated strain gauges (Figure1). The output would be a single stress

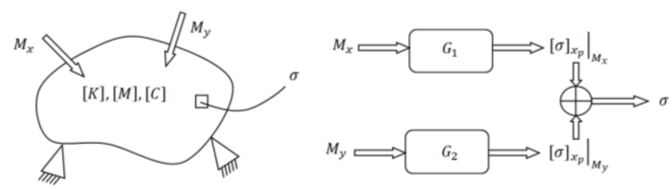


Figure1: In a general structural component loads are applied at different boundaries that produce a stress response in a critical point. Transfer function G1 and G2 characterize the local dynamics of structural component. Behavior. ARMAX representation is used to infer these transfer functions.

measurement at a critical location of the structure. The particular implementation discussed in this paper deals with reduced jacket structure in which inputs are bending moments from tower and the output is the stress obtained by strain gauge at critical point of the jacket base (Figure2).

### B. Model identification

The formulation of the model is considered polynomial in ARMAX form [1]. Regarding Figure2 definition of the MISO system is:

$$\sigma(Z) = M_x(Z)\frac{B_1(Z,\boldsymbol{\theta})}{A(Z,\boldsymbol{\theta})} + M_y(Z)\frac{B_2(Z,\boldsymbol{\theta})}{A(Z,\boldsymbol{\theta})} + E(Z)\frac{C(Z,\boldsymbol{\theta})}{A(Z,\boldsymbol{\theta})}$$

$$\begin{aligned} A(Z,\boldsymbol{\theta}) &= 1 + a_1 z^{-1} + \cdots + a_{na} z^{-na} \\ B_1(Z,\boldsymbol{\theta}) &= b_0^1 + b_1^1 z^{-1} + \cdots + b_{nb1}^1 z^{-nb1} \\ B_2(Z,\boldsymbol{\theta}) &= b_0^2 + b_1^2 z^{-1} + \cdots + b_{nb2}^2 z^{-nb2} \\ C(Z,\boldsymbol{\theta}) &= 1 + c_1 z^{-1} + \cdots + c_{nc} z^{-nc} \end{aligned} \quad (1)$$

where inputs $X = [F_{x_1} F_{x_2}]$ and the output corresponds to $y = \sigma$. Error, $E(Z)$, is also modeled. Polynomials are expressed in z-domain, so $z^{-1}$ is a unit delay operator, being $z^{-1}F_{x_1}(Z)$ the z-transform of the sequence $\{F_{x_1,k-1}\}$. A parameters vector, $\boldsymbol{\theta}$, is defined as coefficients of polynomia in (1), namely:

$$\boldsymbol{\theta} = \{-a_1, \dots, -a_{na}, b_0^1, b_1^1, \dots, b_{nb1}^1, b_0^2, b_1^2, \dots, b_{nb2}^2, c_1, \dots, c_{nc}\}^T \quad (2)$$

Notice that $n_a, n_{b1}, n_{b2}, n_c$ correspond to the order of polynomials $A(Z,\boldsymbol{\theta}), B_1(Z,\boldsymbol{\theta}), B_2(Z,\boldsymbol{\theta}), C(Z,\boldsymbol{\theta})$ respectively. Models are identified using regressive standard methods described in [2]. Polynomia $G_i(Z,\boldsymbol{\theta}) = \frac{B_i(Z,\boldsymbol{\theta})}{A(Z,\boldsymbol{\theta})}$, for $i$ from 1 to n inputs, are reformulated using a partial fraction decomposition (PFD), as:

$$G_i(Z,\boldsymbol{\theta}) = \sum_{k=1}^{n_a^i} \frac{r_k^i}{1 - p_k^i z^{-1}} \tag{3}$$

where $p_k^i$are the poles of $G_i(Z,\boldsymbol{\theta})$ and $r_k^i$ the residuals that contains information of zeros. Natural frequencies and damping ratio per mode are calculated depending on $p_k^i$. Number of modes $nm$ identified depends upon restrictions of polynomia order. Inversely, some constrains can be defined in the model order parameters based on the number of modes to be identified:

- $n_a = 2nm$ since the structures have an underdamped system features with complex conjugate poles.
- $n_{b1} = n_{b2} = n_a - 1$ based upon structural system definition [2].
- $n_c \leq n_a$.

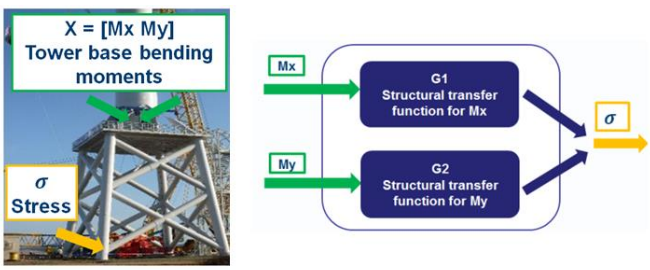


Figure2: MISO system workflow. A jacket critical point is studied taking into account bending moments at tower base. Structural transfer functions $G_1$and $G_2$ are the dynamic characterization of jacket structural component.

In principle, the number of modes to identify will depend how complex the model is. Nevertheless, we can overfit using several different configurations in order to analyze stability of the result. Stability diagram is built depending on a range of possible models whose polynomia order is defined by range of $nm = [nm_{min}\ nm_{max}]$ where $nm_{min}$ and $nm_{max}$ are the minimum and maximum number of modes respectively.

### C. *Filtering stability diagram*

Once stability diagram is performed spurious modes must be filtered. The data reduction is based on 5 steps:

- C.1 – A 1st filtering eliminates non-complex conjugate poles, damping and frequency must be less than a threshold (20% for damping,[5] and 10 Hz).
- C.2 – A Supervised clustering performs a model based clustering [3] based on information of modes and damping [4].
- C.3 – A 2nd filtering removes disperse clusters with high covariance of natural frequencies, [5].
- C.4 – A 3rd filtering removes modes with the same model order to get a more accurate diagram.

At the end of the procedure, each cluster represents a potential actual mode and for each cluster a set of modal parameter is obtained.

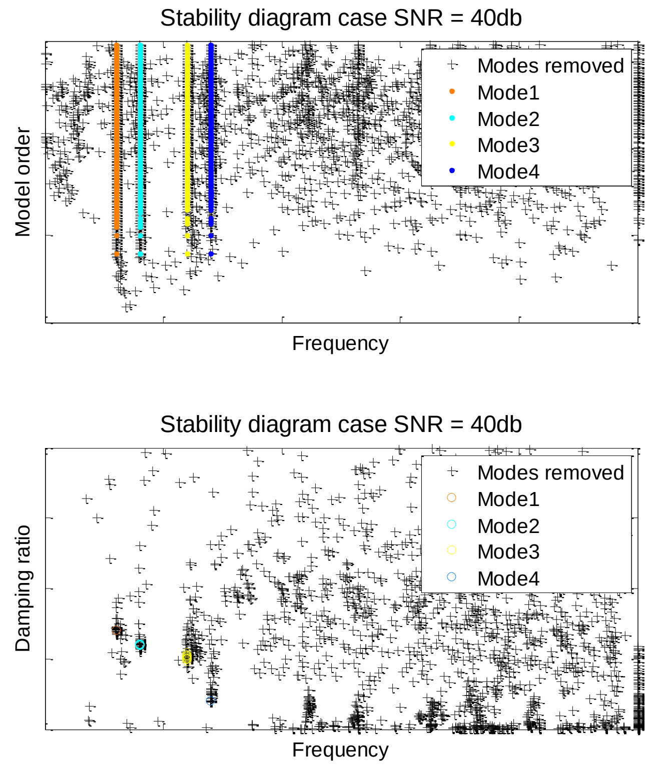


Figure3. Stability diagram in the case of synthetic data. Removed points by filtering step (black crows). Modes drawn in colored circles.

### D. *Best model representation*

In this step information of filtered stability is postprocessed in order to get the best representation of model coefficients. A set of probability distributions is fitted and the best one is selected based on Bayesian index criteria (BIC). The most probable value for each modal parameter is chosen regarding the best probability distribution.

### E. *Build FRF and IR*

Transfer functions with modal parameters of potential modes $G_i(Z,\boldsymbol{\theta})$ are built and FRF and IR are calculated.

## III. Main Body Of Abstract

The present study is based on two steps: the validation using synthetic data and the application in a real case. Inputs are loads (bending moments) at tower base and output is the response of synthetic model or the real strain from a gauge.

### A. *Validation with synthetic data*

In this phase, the method is tested using a synthetic output obtained by means of a pre-defined model. This exercise pretends to define the capabilities of the method, tune it and investigate the set of parameters, more suitable for a proper identification [6]. There are 2 inputs, $X = [Mx\ My]$ and 2 known transfer functions. In addition a white noise is added to the output at different signal to noise ratio (SNR), representing the measurement error. Stability diagram has been filtered as shown in Figure3.

As shown in Figure4 the method is more accurate than classical frequency domain methods.

### *B. Applying to real case*

The method is applied to a 6MW prototype real example, an offshore intended product placed onshore to avoid the effects of marine currents in the study. The study is focused its reduced jacket substructure. The aim is to characterize it dynamically at a critical point for different wind conditions in order to evaluate jacket local dynamics. Figure1 shows where strain gauges are placed. The results are compared with frequency domain methods (Figure5).

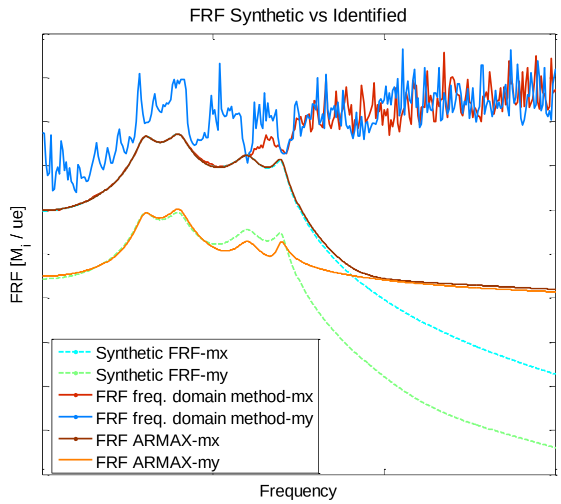


Figure4. FRFs synthetic obtained from known transfer functions. FRFs are obtained by classical method in frequency domain and time domain ARMAX model-based. (ue = micro strain, Mi = bending moment)

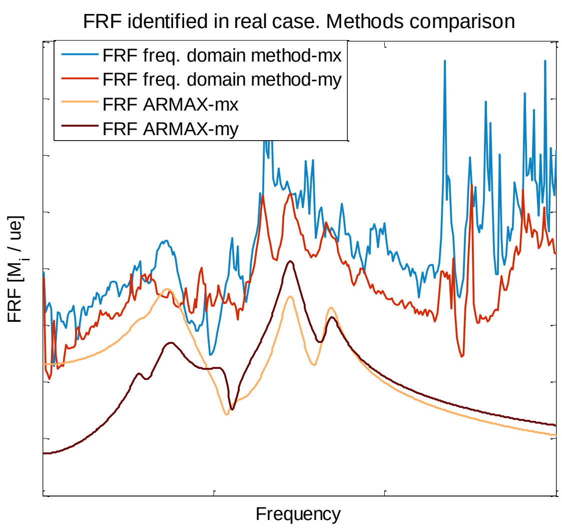


Figure5. FRFs in real case obtained by frequency domain method and time domain ARMAX model based. Results are smoother providing better modal

## IV. CONCLUSION

The present work proposes a new methodology in order to investigate the loads-to-stress relations in structural components, in order to identify those cases where local dynamics play a relevant role in the stress time series. Dynamic characterization of wind turbines structural components is a crucial step of the design validation, specifically in terms of quantifying the contribution of local dynamics to fatigue damage.

The proposed method are suited for MISO systems and uses ARMAX models. Such models a feed with boundary reaction loads as inputs and local stress measurements as outputs. From them, local modal frequencies, damping, and residuals are identified, leading to the identification of FRF and IR.

The method shows more accurate than classical methods in frequency domain. Nevertheless, the filtering of the stability diagram is needed. Thus, the method relies on an expert intervention to select the real modes, which means a previous knowledge of structure dynamics.

## V. LEARNING OBJECTIVES

Experimental data from prototypes is highly important to validate models and get plausible information for designers.

The audience will be able to understand how to extract useful knowledge from experimental data of prototypes by means of advanced time-domain parametric models. Details of the various advantages and drawbacks of the technique will be shown in terms of complexity, accuracy, reliability and practical implementation. Furthermore, its application to a real case will show how these techniques could help on the correlation processes bringing practical information to the design validation.

Finally, the proposed method can be understood as a transversal method, extendable as an input-output black box to other types of problems. Depending on the necessities of the system to study, the user will apply distinct time series.

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