

## Chapter 12

# Machine Learning based Automated Operational Modal Analysis for monitoring of large infrastructure



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**Abstract** Modal analysis is a valuable technique for understanding a structure's natural vibration characteristics by analyzing modal parameters such as natural frequencies, damping ratios, and mode shapes. However, traditional modal analysis is time-consuming, subjective, and challenging with complex structures, making long-term monitoring impractical. To address these challenges, this work introduces an Automated Operational Modal Analysis (AOMA) methodology using DBSCAN, a density-based machine learning clustering technique, combined with modal verification steps inspired by expert judgment. This approach minimizes user interaction, reduces human error and decreases processing time, facilitating long-term structural monitoring. The AOMA methodology was applied to the Infante Dom Henrique bridge in Porto and an onshore wind turbine for long-term monitoring. A modal tracking procedure was implemented to correlate a reference set of modes for each structure throughout the measurement campaigns. The results demonstrated high accuracy and successful long-term monitoring, confirming the applicability of this AOMA methodology to different structures.

**Keywords** Operational modal analysis · Arch-bridge · Onshore wind turbine · Automated modal analysis · Machine learning

## Introduction

Operational Modal Analysis (OMA) is a method employed in structural dynamics to identify the modal parameters of a structure (natural frequencies, damping ratios, and mode shapes) while it is functioning. Unlike conventional modal analysis, which necessitates the use of external excitation methods such as shakers or impact hammers, OMA utilizes the natural vibrations produced by the structure during its normal operation. These vibrations can result from environmental influences, including wind, waves, traffic, machinery, or human activities. OMA is especially advantageous for large structures, such as bridges [1], buildings [2], or wind turbines [3], where applying artificial excitation may be impractical or pose safety risks.

The automation of modal analysis allows to process the large measurement campaigns of structural monitoring without user interaction and with repeatability. In recent years, several automated methods for conducting modal analysis have been developed. Most of these automated modal analysis (AMA) techniques utilize clustering algorithms due to their effectiveness as versatile unsupervised learning tools. Applications of these methods have been implemented using various clustering approaches, including fuzzy clustering [4, 5], hierarchical clustering [6, 7, 8], and density-based clustering [9, 10].

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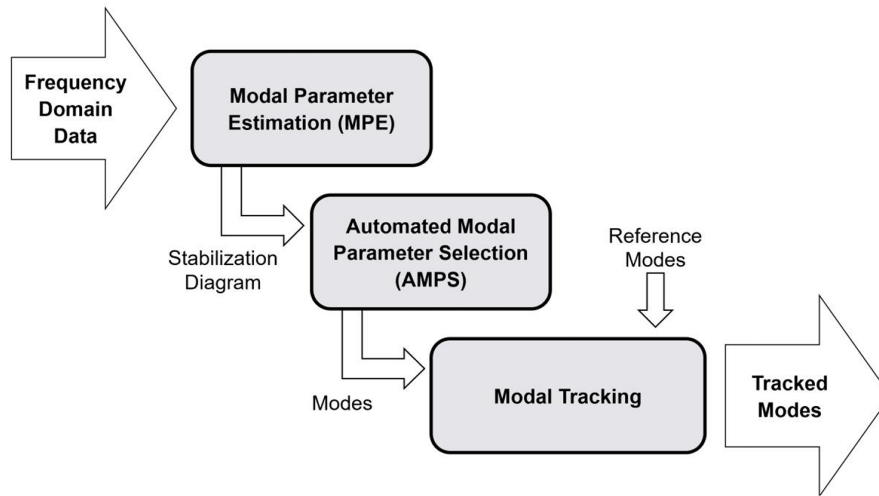
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This study introduces an automated modal analysis (AMA) methodology that employs the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm, along with mode verification steps based on the expert judgment of modal analysis. The methodology is applied to monitor two different structures: a) the Infante Dom Henrique bridge in Porto - a 280m arch-bridge monitored using two accelerometers and subjected to regular traffic, and b) a 2.0MW wind turbine with a 80m hub height operating in different environmental and operational regimes.

## Automated Modal Analysis

Automated Modal Analysis (AMA) consists of three main stages: 1) Modal Parameter Estimation (MPE), where the stabilization diagram is calculated; 2) Automated Modal Parameter Selection (AMPS), which focuses on automatically identifying and selecting poles from the stabilization diagram that best represent the physical resonance modes of the structure; and 3) Modal Tracking, which enables the continuous observation of a set of reference modes over time and throughout extended measurement periods for a specific structure. The third stage, Modal Tracking, is particularly used for long-term structural monitoring.



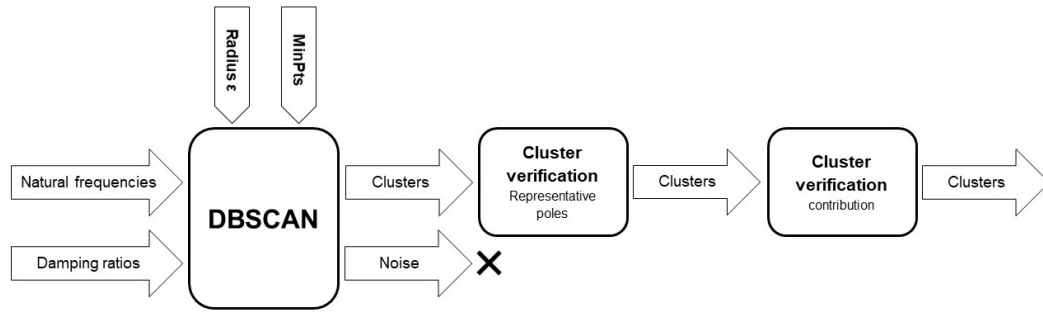
**Fig. 1** Automated Modal Analysis (AMA) process for long-term monitoring.

### Automated Modal Parameter Selection (AMPS)

The Automated Modal Parameter Selection (AMPS) process, illustrated in Figure 2, involves three main steps. Initially, clusters are formed based on the poles shown in the stabilization diagram, with the estimated modal parameters serving as input. For this task, a density-based clustering algorithm known as DBSCAN is used, which also filters out poles identified as noise during the initial phase. Following this, the resonance modes identified through clustering are subjected to two verification stages. The first ensures that none of the modes are split into multiple clusters, especially in complex structures where certain conditions might apply. The second verification step seeks to detect and remove any spurious or numerical modes by examining the cluster characteristics and their influence on the final modal model synthesis.

Using natural frequencies ( $f$ ) and damping ratios ( $\xi$ ) as inputs, the initial clusters of poles in a stabilization diagram are created using the DBSCAN algorithm. A key step in this process is calculating the distance between poles, which is based on the absolute differences in normalized frequency and damping to account for their differing magnitudes and units. To ensure the AMPS methodology is adaptable to various structural characteristics, such as different modal densities and model sizes, DBSCAN hyperparameters are carefully selected. The minimum number of points (MinPts) is set at one-sixteenth of the model size, with a lower limit of 3, while the epsilon distance ( $\epsilon$ ) is defined as 0.06, corresponding to tolerances of 1% for frequency and 5% for damping to classify stable poles. In this way, the distance between two points,  $p_1$  and  $p_2$ , can be described by equation 1.

$$d = d_f + d_\xi = \frac{|f_{p_1} - f_{p_2}|}{f_{p_1}} + \frac{|\xi_{p_1} - \xi_{p_2}|}{\xi_{p_1}} \quad (1)$$



**Fig. 2** Methodology for Automated Operational Modal Analysis (AOMA).

DBSCAN assigns each pole either to a specific cluster or labels it as noise if it does not meet the density criterion. After the initial clusters are formed, two verification steps are conducted. The first ensures that no single mode has been divided into multiple clusters, while the second eliminates any spurious modes, which could be numerical artifacts from the stabilization diagram rather than actual physical modes. In the first step, a similarity check is performed between the representative poles of each cluster (the pole closest to the median frequency and damping of the cluster is chosen as the representative). This check ensures that representative poles fall within a 2% frequency range and a 20% Modal Assurance Criterion (MAC) range between modal participation factors ( $L$ ) (see equation 2). If these conditions are met, the corresponding clusters are merged. The second step evaluates how each representative pole contributes to the final modal model synthesis. If a representative pole has a marginal contribution to the modal model fit or results in a highly complex mode shape (suggesting spurious poles), the corresponding cluster is flagged as spurious and excluded from the final mode set.

$$d_{MAC(L)} = 1 - \frac{|L_{p_1} L_{p_2}|^2}{(L_{p_1} L_{p_1})(L_{p_2} L_{p_2})} \quad (2)$$

### Modal tracking

Modal tracking is the process of identifying similarities between resonance modes by assessing their modal parameters. This technique is particularly important for long-term structural monitoring, as it helps establish a connection between the resonance modes calculated for specific measurements and a set of reference modes evaluated over time. By tracking the evolution of modal parameters, engineers can detect any structural changes, thereby gaining insights into the health and behavior of the structure under observation.

Modal tracking is a crucial step in the overall Automated Modal Analysis (AMA) process, following Modal Parameter Estimation (MPE) and Automated Modal Parameter Selection (AMPS). Once the stabilization diagram is created, the AMPS step automatically evaluates the poles to derive a final set of resonance modes. For structures monitored over multiple measurements, modal tracking is employed to follow a set of reference modes over time by calculating the distances between respective modal parameters. A correlation between modes is established if both the natural frequency (equation 3) and Modal Assurance Criterion (MAC) for mode shapes ( $\phi$ ) (equation 4) distances exceed certain thresholds, which may vary based on the specific application and the number of Degrees-of-Freedom (DOF) measured.

$$d_f = \frac{|f_{p_1} - f_{p_2}|}{f_{p_1}} \quad (3)$$

$$d_{MAC(\phi)} = 1 - \frac{|\phi_{p_1} \phi_{p_2}|^2}{(\phi_{p_1} \phi_{p_1})(\phi_{p_2} \phi_{p_2})} \quad (4)$$

### Infante Dom Henrique bridge

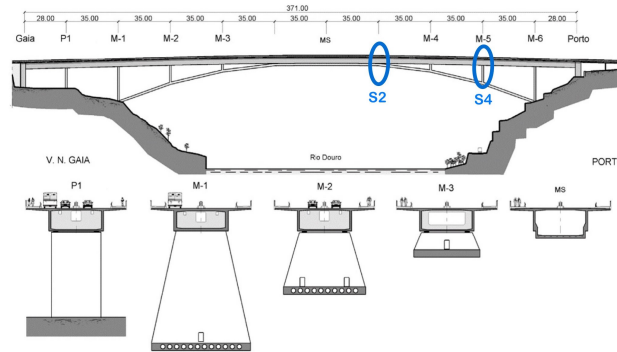
In this section, the Infante Dom Henrique bridge, located in Porto, Portugal, will be analysed with the AOMA procedure, as explained in the "Automated Modal Analysis" section. These developments are further detailed in [11].

The Infante Dom Henrique Bridge, a concrete arch bridge, consists of two interacting components: a highly rigid pre-stressed reinforced concrete box girder, 4.50 meters deep, supported by a very shallow and slender reinforced concrete arch,

1.50 meters thick, as shown in figure 3. The arch and the deck converge in the 70 meters central segments, forming a 6m-deep box beam. While the arch maintains a constant thickness, its width gradually increases from 10 meters at the central span to 20 meters at the springs. The arch spans 280m between the abutments and rises 25 meters at its crown, giving it a shallowness ratio greater than 11:1. The structure behaves as a beam bridge, defined by the abutments and intermediate elastic supports 35 meters apart, due to the high stiffness of the deck compared to the slenderness of the arch [12].

### Dataset characterization

The monitoring system installed on the bridge consists of two acceleration nodes developed at FEUP, located in sections S2 and S4, as shown in figure 3. These sensors are cost-effective and have the advantage of being battery-powered, which eliminates the need for installing cables throughout the structure.

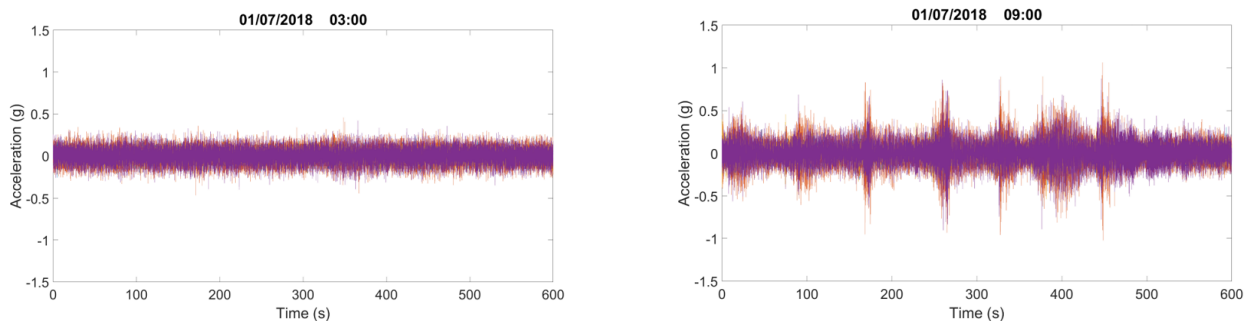


**Fig. 3** Elevation and cross-sections of the bridge, including position of the monitoring system.

The modules in operation are built around an Arduino-based microprocessor, which processes the data acquired by an ADXL355 MEMS accelerometer from Analog Devices. The sampling frequency for this application was set at 60 Hz. Data was collected in 10-minute intervals and stored locally on a microSD card [13].

### Different operational conditions

The Infante Dom Henrique Bridge serves as one of the primary entrances to Porto's city center. As a result, it experiences a high volume of vehicle traffic, particularly during the morning and afternoon rush hours. This leads to two distinct periods, as shown in figure 4: one at night, characterized by lower excitation, and the other during morning and afternoon rush hours, marked by increased traffic on the bridge.



**Fig. 4** Acceleration time series during the night (left) and the morning (right).

### Automated Modal Analysis results

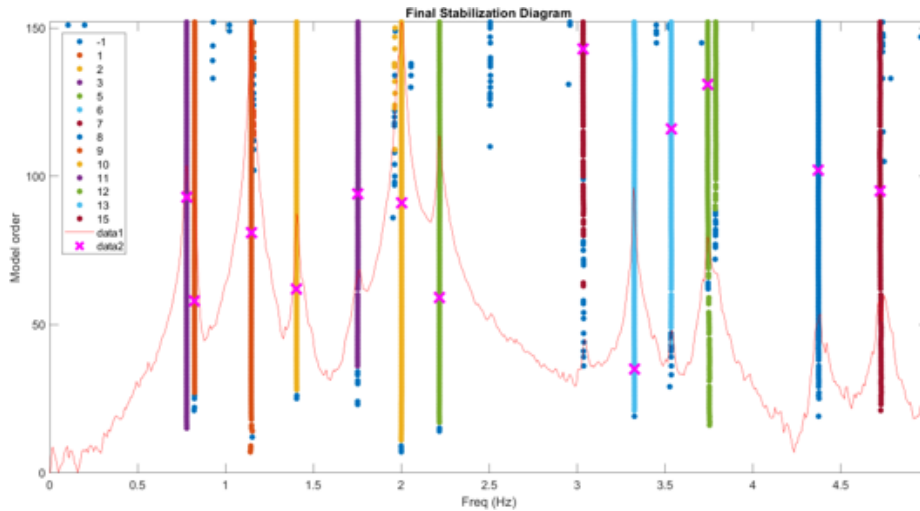
The frequency-domain Modal Parameter Estimation (MPE) technique, Polymax [14], is used throughout this work to compute the stabilization diagrams. In this section, the stabilization diagrams processed using the Automated Modal Parameter Selection (AMPS) methodology, as explained in the previous section, will be analyzed for the bridge dataset. Following this,

the Automated Modal Tracking methodology, also presented before, will be applied to the complete dataset for the month of July 2018.

### Stabilization diagram

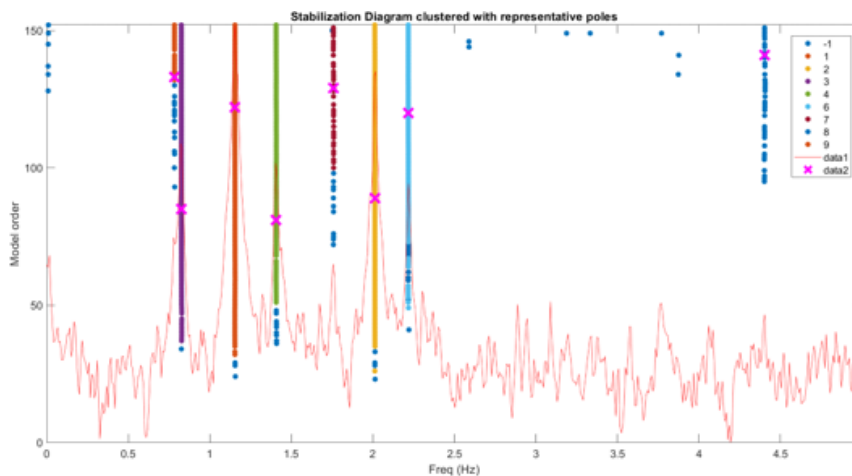
Figure 5 presents a stabilization diagram processed using the AMPS methodology. The measurement shown in this diagram corresponds to a rush hour period, specifically at 5:10 PM, with a sampling duration of 10 minutes. The stabilization diagrams were obtained using a model size of 152, time lags of 7168, and an exponential window of 1% to minimize leakage errors [15].

The stabilization diagram shows the thirteen prominent natural frequencies clearly identified by the method, in agreement with the modes previously analyzed in the following reference study [6]. Additionally, some noise points, identified by DBSCAN as -1, are present and do not represent a physical cluster. The resonance modes are highlighted with pink crosses, which indicate the selected representative poles.



**Fig. 5** Stabilization Diagrams of the bridge.

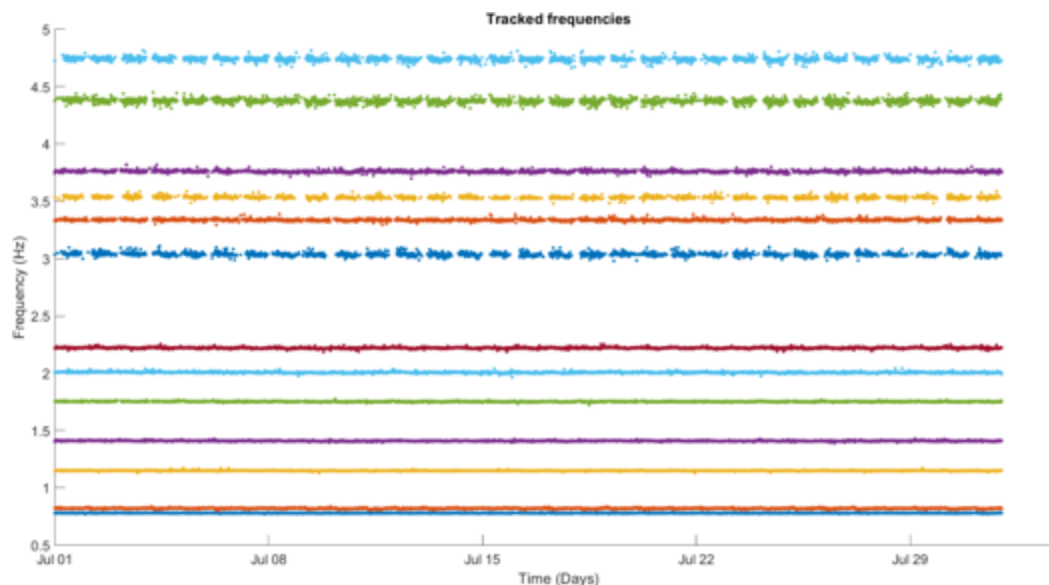
Due to the lower excitation during the night, the methodology is unable to identify all thirteen natural frequencies, particularly the higher frequencies, as shown in Figure 6, which represents a stabilization diagram from 2:30 AM. This issue is further compounded by the high noise levels from the accelerometers, which makes difficult the capture of higher frequencies. This is a limitation of the sensors adopted in this work (to explore a more challenging application), the use of force balance accelerometers allows a more continuous identification of the modal properties [6].



**Fig. 6** Representative stabilization diagram of a low rush hour.

## Modal tracking

Figure 7 shows the tracked frequencies resulting from the AMT methodology, applied to one month of data (July 2018).



**Fig. 7** Tracked frequencies for the Infante Dom Henrique Bridge in July 2018.

With the AMPS results for the entire month and a set of reference modes, the Automated Modal Tracking (AMT) procedure can be applied, using the modeset presented in figure 5 as the reference modeset.

For the AMT methodology, only the frequency distance, as explained in the subsection "Modal Tracking" was considered. The MAC value was excluded due to the simplicity of the monitoring system, which makes this value unreliable because of the spatial aliasing phenomenon. Additionally, an update of the reference modes was applied, based on the previous 10 points in the analysis, to account for small variations that may occur.

Analyzing figure 7, a clear definition of the first seven natural frequencies can be observed. However, noticeable gaps appear in the higher frequencies. These gaps are mainly due to the lower excitation during off-peak hours, as explained in the previous section. Conversely, in the higher frequencies, areas with a good concentration of poles are successfully tracked due to the high excitation present during rush hours, as shown in figure 5.

Overall, there was a good identification of the thirteen natural frequencies, despite the challenges associated with identifying the higher frequencies due to the constraints of the monitoring system.

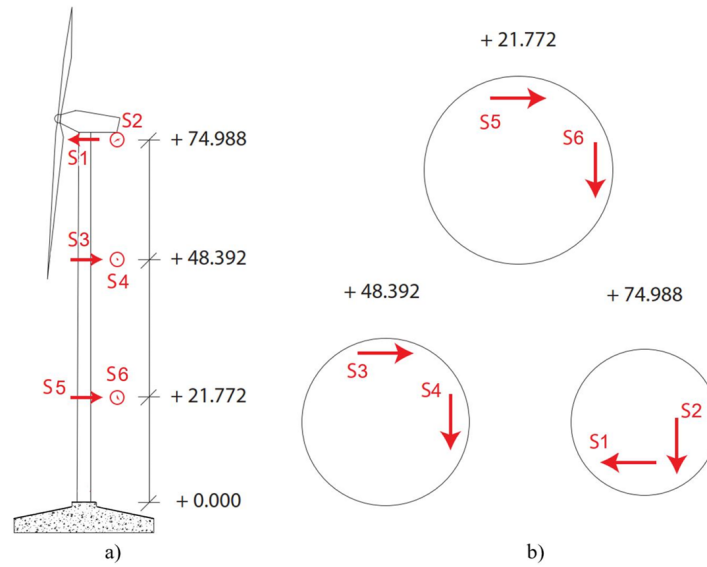
## Wind turbine 2.0 MW

In this section, the AOMA procedure previously explained in the section 'Automated Modal Analysis' is implemented to analyze the structural dynamics of a 2MW onshore wind turbine. These developments are reported in [16].

The wind turbine under study is located in northern Portugal. It has an up-wind rotor with a radius of 41 meters and three pitch-controlled blades. The tower is steel tubular with 80 meters in height and comprises three segments assembled by bolted flanged connections.

### Dataset characterization

Six uni-axial accelerometers were combined in duos to measure the accelerations in two orthogonal directions and distributed over three levels along tower height, as presented in Figure 8. The sensors have a range of 140 dB and can measure acceleration ranges from  $\pm 0.1$  g to 4.0 g. The acquisition system, composed of a computer and a digitizer, recorded acceleration data with a sampling frequency of 50 Hz within a 10-minute time series to pair with the SCADA data. 2401 data sets were recorded over a one-month measuring period.

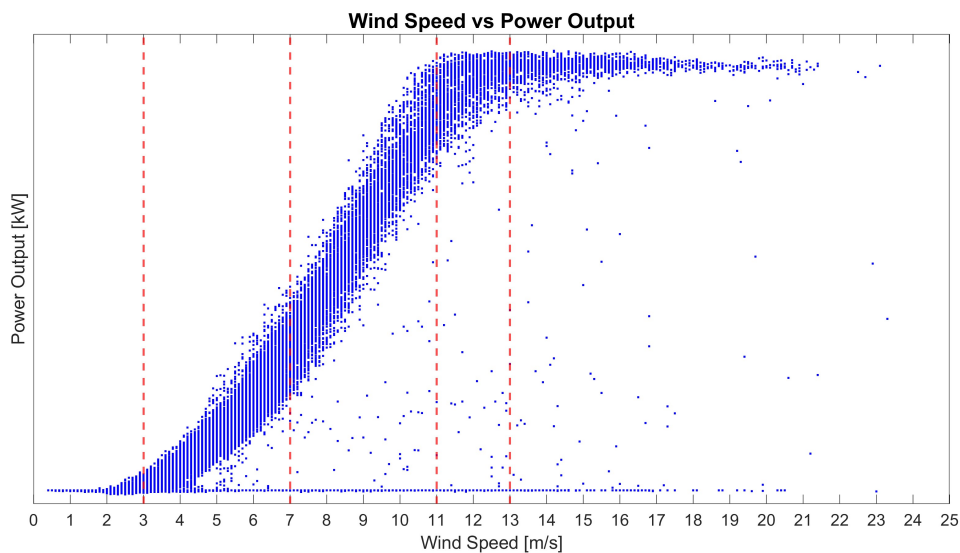


**Fig. 8** Accelerometers located at three levels of the wind turbine: a) front view; b) cross-sectional views.

### *Different operating conditions*

Figure 9 presents the wind turbine power curve defined with measured data. Five main regions were defined according to the operating conditions and are further described.

The rotor is parked or idling for wind speed inferior to 3 m/s while the environmental conditions are evaluated to determine whether the operation is feasible. The second region corresponds to the initiation of power production, if the rotor torque is consistent, and a rotor speed augmentation is observed. In this region and the following one, the pitch angle is minimal to optimize the power generated, while maximizing the lift force. The rotor torque rated value achievement defines the end of the third region. In the following region, for enhanced wind speed, the blade's pitch angle decreases to maintain the rotor torque within operation limits while the power production enhances. The last region observed in the operational data, for wind speed above 13 m/s, corresponds to the increasing blades pitch for enhanced wind speed maintaining the rotor torque and power production at rated values. These limits ensure the wind turbine's operational safety and structural integrity, preventing mechanical and electrical overloading.



**Fig. 9** Wind turbine power curve based on real measured data over one year.

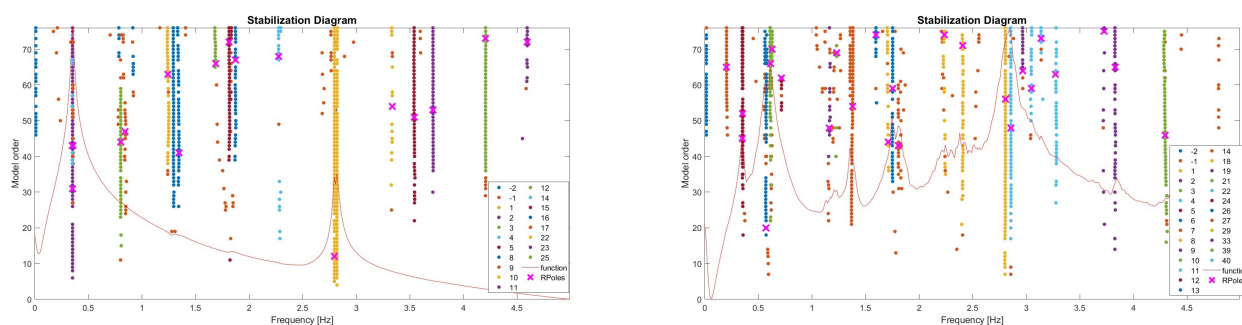
## Automated Modal Analysis results

In this section, the impact of the wind turbine rotating conditions is observed in the stabilization diagrams. Therefore, the Automated Modal Parameter Selection (AMPS) is applied to the complete dataset for February 2014, followed by the implementation of the Automated Modal Tracking methodology, presented in the section titled 'Modal tracking'.

### Stabilization diagrams

Polymax is applied to each 10-minute acceleration dataset to estimate the modal parameters, followed by the AMPS implementation to define accurately the resonance modes. The first algorithm considered 4096-time lags, 1% exponential window, and was applied to a frequency range between 0 and 5 Hz for a maximum model order of 76.

Referring to Figure 10, two stabilization diagrams are presented, the first while the wind turbine is parked and the second while the rotor is rotating at 12 rpm. The structural modes identified have positive integer identifiers, with pink crosses signaling each reference pole. The poles labeled '-1' were classified as spurious by the DBSCAN clustering algorithm and the clusters designated '-2' correspond to spurious modes defined by the second verification step. The red function represents the sum of the cross-power spectral densities.



**Fig. 10** Wind Turbine Stabilization Diagrams: Parked Condition (left) and Operating at 12 rpm Rotor Speed (right).

The stabilization diagram in parked conditions presents a modal model graph with greater stability, with the identified modes appearing cleaner and more distinctly defined compared to when the rotor is in operation. In rotating conditions, a higher number of modes are identified due to the aerodynamic rotor excitation. Additionally, the rotor speed variation over the 10-minute time series analyzed introduces greater complexity, leading to more dispersed poles in the stabilization diagram.

### Modal tracking

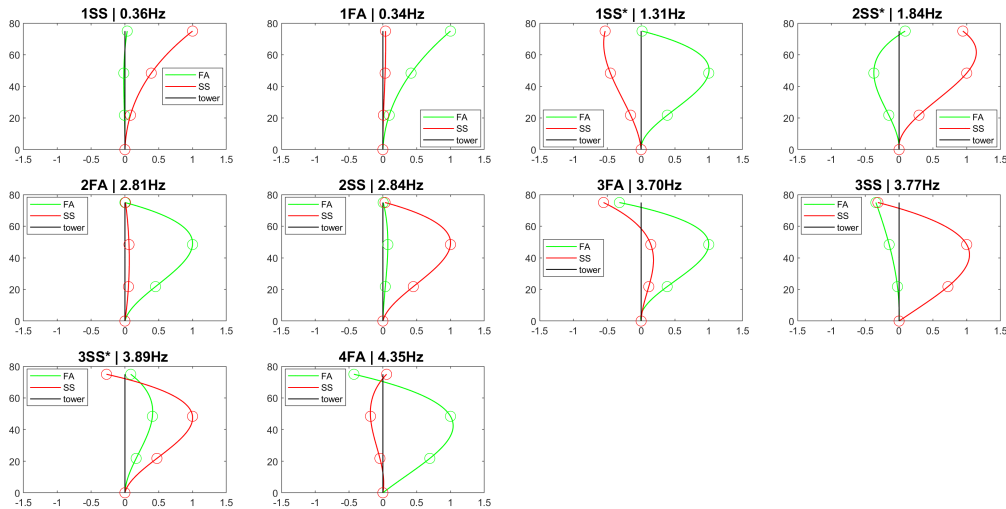
Posterior to obtaining the stabilization diagram for each 10-minute acceleration dataset, the resulting resonance modes identified were subjected to the tracking procedure to evaluate their correspondence with the reference modes defined.

Random measurement setups were investigated, and the planar mode shapes corresponding to the expected were identified to establish the reference, presented in Figure 11. This method leads to ten reference modes defined mainly while the rotor is close to its maximum speed.

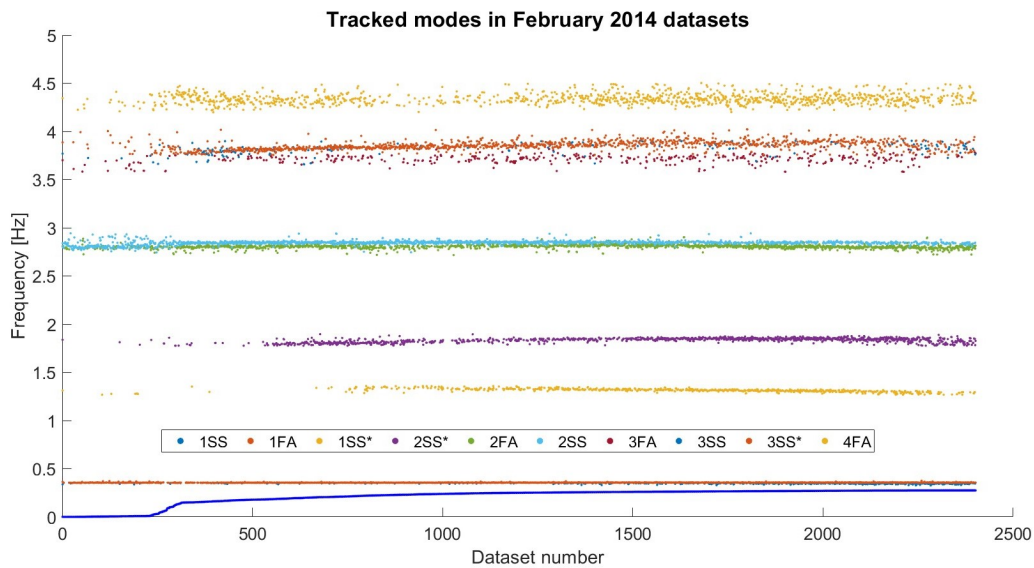
To track a resonance mode, the frequency variation must not exceed 3.5%, and the mode must maintain a maximum 30% MAC deviation from the reference mode. If multiple modes meet these criteria, the mode with the smallest distance is selected for tracking. The results are visually presented in Figure 12, where the datasets are organized in ascending order of rotor speed, emphasizing their effect on mode frequency response.

The majority of modes are successfully tracked in more than half of the datasets analyzed. However, the mode 3SS is detected in less than 10% of the datasets, and three other modes—1FA, 3FA, and 1SS\*—show success rates below 50%.

The procedure encounters challenges in tracking the modes when the wind turbine is either parked or idling. Although the reference modes were defined based on near-maximum rotor speed, two factors may explain the reduced tracking success rates observed at zero or low rotor speeds. First, certain modes—specifically, 1SS\*, 2SS\*, and 3SS\*—rely on rotor motion for excitation. Second, as noted in [17], both frequency and mode shape vary with changes in rotor speed. This is observed for modes 1SS\* and 2SS\* once the frequency of the first one tends to decrease with enhanced rotor speed and the opposite trend is verified for second mode 2SS\*.



**Fig. 11** Wind turbine reference mode set, regarding frequencies and mode shapes. The following abbreviations are FA - fore-aft vibration mode, SS - side-side vibration mode, and SS\* - side-side vibration mode dependent on rotor motion.



**Fig. 12** Tracked frequencies for the 2MW wind turbine in February 2014. The continuous blue line at the bottom of the graph represents the rotor speed corresponding to each measurement.

On average, the MAC between each tracked mode and its reference counterpart exceeds 85% and the frequency variation is generally inferior to 7%. These results suggest a high level of similarity between the tracked and reference modes, indicating strong overall performance, despite the lower success rates for certain modes.

## Conclusion

In this work, an automated modal analysis methodology was developed by combining the DBSCAN, density-based clustering algorithm, with mode verification steps inspired on modal analysis expert judgement. This methodology was applied to automatically calculate the resonance modes from the stabilization diagrams obtained with the Polymax modal parameter

estimator, for the Infante Dom Henrique bridge and a 2MW wind turbine. Both these structures were monitored across time by coupling the AMPS methodology with a modal tracking procedure based on statistical comparisons between modes obtained for a given measurement and a set of reference modes for each structure. For the Infante Dom Henrique bridge, the modal tracking was successful in tracking the reference modes, though for low excitation periods mostly during the night, some of the high-frequency modes were not excited enough to be obtained in the stabilization diagrams. For the wind turbine, the same procedure managed to track ten reference modes. Due to the variability of some modes with respect to different operational conditions of the wind turbine, the modal tracking procedure has difficulties in tracking the more susceptible modes.

**Acknowledgments** André Tavares is supported by a VLAIO Baekeland PhD mandate [nr. HBC.2020.2300]. This work is financially supported by national funds through the FCT/MCTES (PIDDAC), under the project 2022.08120.PTDC (M4WIND) and Base Funding - UIDB/04708/2020 with DOI 10.54499/UIDB/04708/2020 (<https://doi.org/10.54499/UIDB/04708/2020>) of the CONSTRUCT - Instituto de I&D em Estruturas e Construções.

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