Available online at www.eccomasproceedia.org
Eccomas Proceedia SMART (2023) 817-828

ECCOMAS Proceedia

X ECCOMAS Thematic Conference on Smart Structures and Materials
SMART 2023
D.A. Saravanos, A. Benjeddou, N. Chrysochoidis and T. Theodosiou (Eds)

OPTIMAL SENSORS POSITION FOR STRUCTURAL HEALTH MONITORING OF STEEL JACKET OFFSHORE PLATFORMS

GIACOMO ZINI[*], MICHELE BETTI[*], OSTILIO SPADACCINI,[*] LUCIANO GALANO[*] AND PAOLO CASTELLI[†]

[*] Department of Civil and Environmental Engineering (DICEA), Florence, Italy
e-mail: giacomo.zini@unifi.it, michele.betti@unfi.it, ostilio.spadaccini@libero.it, luciano.galano@unifi.it

[†] Energean Italy S.p.A., Milan, Italy
email: pcastelli@energean.com

Abstract. The VEGA-A platform is an 8-legs fixed steel offshore structure that has been operating since 1988 in the Sicily channel (Italy). From its installation onwards, VEGA-A has been equipped with an environmental and structural (via above water accelerometers) monitoring system, and it is now time to consider an improvement of this system. Today the technological development makes it possible to consider additional underwater accelerometer measurements and this paper investigates on a possible optimal sensor position for new underwater accelerometers to improve - if any - detection of early damage in main structural elements. The final optimal sensor grid must be assessed to ensure a low-cost and sustainable dynamic monitoring system but, at the same time, to maximize the information contents for the identification of the mode shapes.

Key words: Offshore jacket platform, Structural health monitoring (SHM), Optimal sensors position (OSP), Fisher information matrix (FIM), Damage identification, Dynamic measurements.

1 INTRODUCTION

The control plan for offshore structures, or the verification of such facilities for use beyond their initial design life, requires the definition of an inspection plan aimed at the periodic examination of structural elements and/or joints ([1]). Frequency and typology of these investigations may represent a critical issue since it requires a proper selection of the elements and/or joints to be inspected and it may not always be feasible to inspect all critical components. In fact, the visual inspection of structural damage is in most cases difficult to carry out, taking into account of the depth of the water and seaweed hiding the structural element, and also increasingly expensive.

To overcome these issues monitoring techniques for damage identification through the analysis of the changes in the modal properties of offshore structures have been proposed since the early seventies. Provided that a reliable and sustainable monitoring system has been

Peer-review under responsibility of the organizing committee of SMART 2023.
doi: 10.7712/150123.9835.451254

designed and installed, results of previous research showed that the MAC (Modal Assurance Criterion), the COMAC (Coordinate Modal Assurance Criterion) and the MSF (Modal Scale Factor) are indexes capable to detect both offshore damage and mass change. It is however expected that the more the offshore platform is robust (i.e., damage tolerant), the less a structural damage can be detected through the changes in its first modal properties.

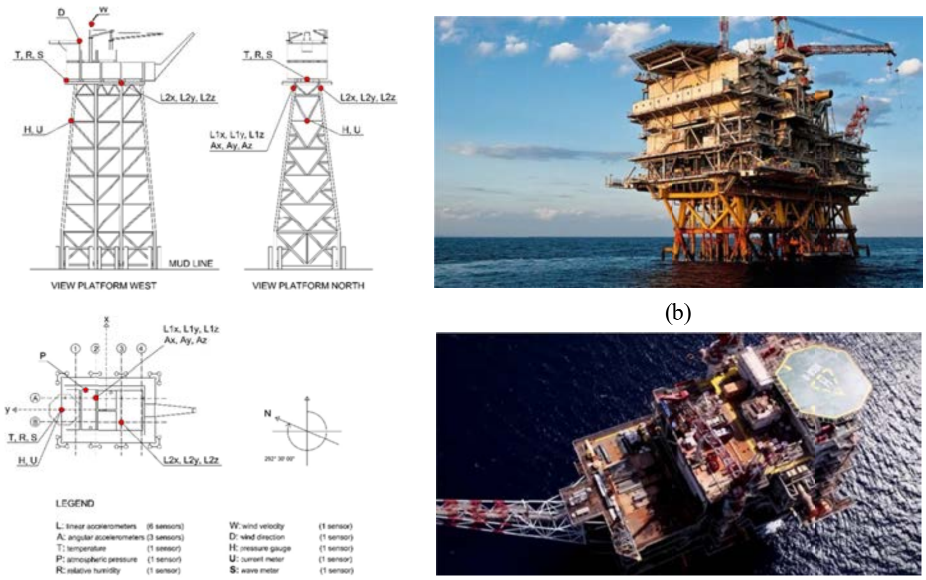
To deepen these aspects this paper discusses the experience acquired on a specific structure: the VEGA-A offshore platform. This structure is an 8-legs fixed steel structure that has been operating since 1988 in the Sicily channel (Italy). From its installation onwards, the platform has been equipped with an environmental and structural monitoring system. Wind, wave and current are hourly recorded. Accelerations of the two top skid-beams (above water) are continuously recorded by means of two triplets of linear accelerometers and one triplet of angular accelerometers. Last update of the monitoring system was performed at the end of 2015. The processing procedure of the acquired data was modified to increase both the number of hourly registrations and the frequency sampling of all the accelerometers. Over the past 30 years, the current VEGA-A monitoring system has proven to be an effective component of the inspection plan, useful for optimizing quantity and number of underwater inspections. It supported, in addition, the extension of the structure's design service life beyond the initial 25 years being able to verify safety and health of the platform using the main structural frequencies as a sound indicator for major damage occurrence.

However, after 30 years of activities, it is now time to consider an efficient improvement of the current VEGA-A monitoring system. Today, the technological development (thanks for example to the availability on the market of fiber optic accelerometers), makes it possible to consider additional underwater accelerometric measurements at one or two levels of the jacket structure. This would make it possible to identify not only the structural frequencies but also the main mode shapes, thus possibly improving the capability of the monitoring system to control for damage in as many underwater elements as possible.

This paper, after summarising some of the results of the VEGA-A Structural Health Monitoring system from 2002 to 2022, discusses on a possible improvement of the current monitoring systems by investigating on an optimal sensor position for new underwater accelerometer sensors. The final optimal sensor grid must be assessed to ensure a low-cost and sustainable dynamic monitoring system but, at the same time, must maximise the information contents for the identification of the main mode shapes.

2 THE MONITORING SYSTEM

The VEGA-A operates in the Sicily Channel, 25 km offshore, in 122.3 m water depth. The structure comprises a steel jacket platform, which is 140 m high, having eight columns connected using horizontal bracings with four vertical bracings in the transversal direction and two vertical bracings in longitudinal direction (Figure 1). The dimensions of the jacket at the seabed are 70 m by 48 m, while at the top they are 50 m by 18 m ([2], [3]). Six horizontal bracing frames, spaced at approximately 24 m, are also used to support the well conductor guides. Above the platform skid-beams, structural modules hosting production and services are placed (Figure 1b-c). The steel jacket is supported by 20 vertical steel piles, 85 m long with a diameter of 2.6 m. These piles were driven to a depth of 65 m below the seabed by means of an underwater hammer. The whole VEGA field includes, apart the platform for the exploitation of the oil field, a 110,000-ton floating deposit obtained from the transformation of the former oil tanker Leonis in FSO (Floating - Storage - Offloading). The float is moored at a SPM (single point mooring) located about 1.5 miles from the platform and connected to it via pipelines.



(a) (b) (c)

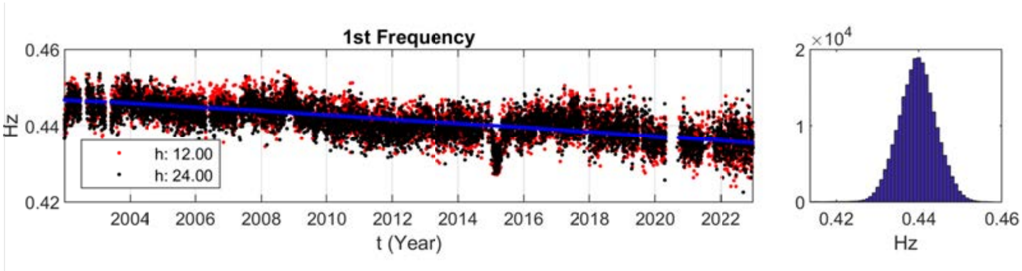
Figure 1: VEGA-A platform: (a) layout of the environmental and structural sensors, (b) view of the platform from the North side, and (c) aerial view.

The platform was settled in February 1987, and since March 1988 a Structural Health Monitoring system that records structural and environmental data is operating (Figure 1a). Over these 30 years, this system has been updated several times, until the actual configuration that dates back to the end of 2015.

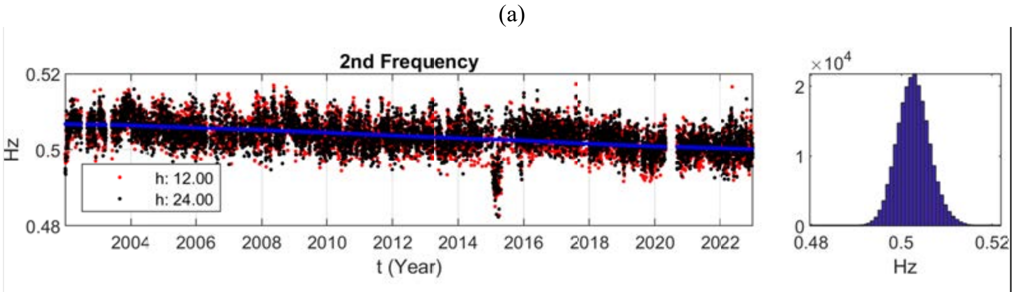
The current structural monitoring systems is constituted of 9 linear accelerometers (6 linear and 3 angular) disposed at the level of the skid-beams (i.e. above-water). The records collected by these sensors have a sampling rate of 16 Hz and a length of 20 minutes. The environmental monitoring system is constituted by a current meter and a depth gauge that allow to reconstruct wave characteristics (height and direction of sea waves) with a sampling rate of 2 Hz over 20 minutes. In addition, speed and direction of both wind and current are recorded together with the meteorological data (air pressure, temperature and humidity). The VEGA-A is continuously monitored by three acquisitions scheduled every hour.

2.1 Structural data

The last upgrade of the structural monitoring system was carried out, as previously reported, at the end of 2015. This upgrade did not affect the instruments (which remain the original accelerometers) but the data acquisition and processing system. The sampling frequency was increased to 16 Hz (from the previous 10 Hz), and the length of each individual accelerometer recording was set to 20 minutes (previously 10 minutes). Moreover, the number of acquisitions was increased from one to three per hour, thus leading to a continuous monitoring of the structure during all the environmental and operational conditions.



(a)



(b)

Figure 2: The main structural frequencies obtained by the system:
(a) first frequency, and (b) second frequency.

As an example, the first two structural frequencies in the period from the beginning of 2002 until the end of 2022 are showed in Figure 2. Some breakdowns recently occurred in the middle of 2020 due to maintenance works. At a first glance, the main frequencies extracted by the vibration signatures are quite stable over the time (except for the first mounts of 2015 where in the platform heavy maintenance work of the wells were performed).

3 FE MODEL OF THE PLATFORM

A numerical model of the VEGA-A platform was built using the finite element code ANSYS. Main columns and vertical and horizontal bracing elements have been modelled by means of beam elements assuming linear elastic behaviour (Figure 3). The final model consisted of 175 joints and 478 beam elements corresponding to about 1,000 degrees of freedom. This numerical model has been used to simulate damage scenarios and to assesses the optimal sensor position for new underwater accelerometer sensors capable to identify not only the structural frequencies but also the mode shapes. To do so, preliminarily, the numerical model has been identified in order to reproduce the experimental results, and the dynamic identification of the model was performed employing Genetic algorithms (GA).

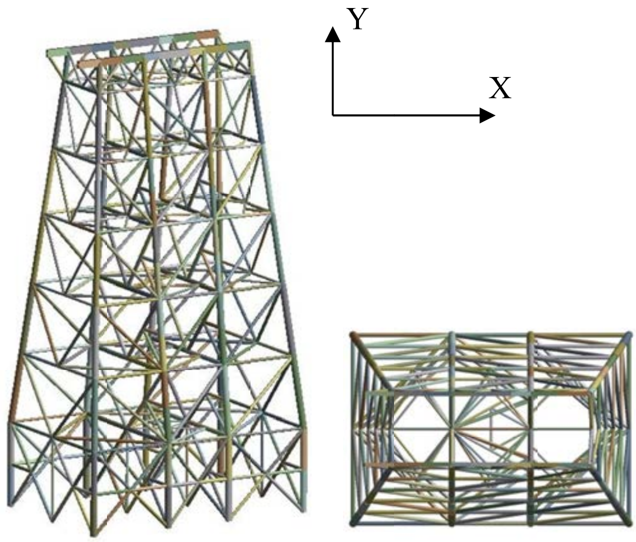


Figure 3: Vega A, the three-dimensional numerical model.

A real-coded genetic algorithm (RCGA) was employed, and the chromosome was built in order to collect the unknown parameters of the model: the added masses (water and marine growth) and the stiffness of the 20 vertical steel piles. Consequently, the numerical model of the platform was parametrically built in order to accept as input these (the topside masses were assumed as fixed values). The fitness function was built based on the Modified Total Modal Assurance Criterion (MTMAC) ([4]), an improvement of the MAC with the introduction of the frequencies as penalty functions to account for differences between experimental and numerical results:

$$fit = 1 - MTMAC \; = \; 1 - \prod_{i=1}^{k} \left[MAC(i,i) / \left(1 + \left| \frac{f^2{}_{Num,i} - f^2{}_{Exp,i}}{f^2{}_{Num,i} + f^2{}_{Exp,i}} \right| \right) \right] \tag{1}$$

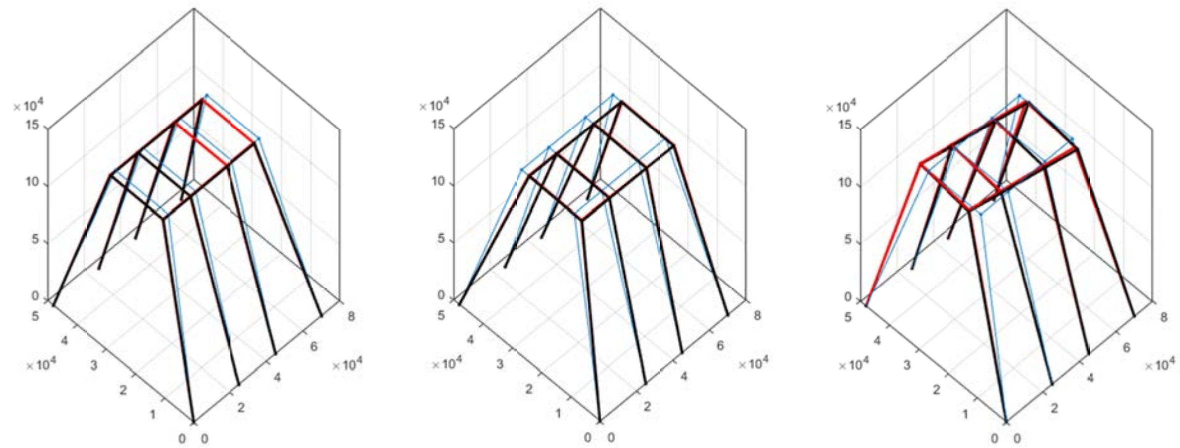
where k (=3) represents the number of frequencies employed in the identification process.

The updating procedure was set to reproduce the modal behaviour of the platform as recorded during the storm of 25 January 2014 (Table 1), and allowed to identify the first three frequencies although the reduced number of sensors does not allow to reproduce with the same accuracy the mode shapes.

Table 1: Environmental and structural parameter during the storm of 25 January 2014

Hs (m)	**Hmax (m)**	**Dwave (degN)**	**Wwind (m/s)**	**Dwind (degN)**	**f_1 (Hz)**	**f_2 (Hz)**	**f_3 (Hz)**
5.6	9.5	244	27.23	236	0.43	0.50	0.78

In fact, being the accelerometers positioned only at the skid-beams level the analysis of the experimental data allows for an approximate identification of the mode shapes. Nevertheless, despite these difficulties, the identified FE model reproduces quite accurately the modal behaviour of the platform since it is able to reproduce with good accuracy the experimental frequencies.

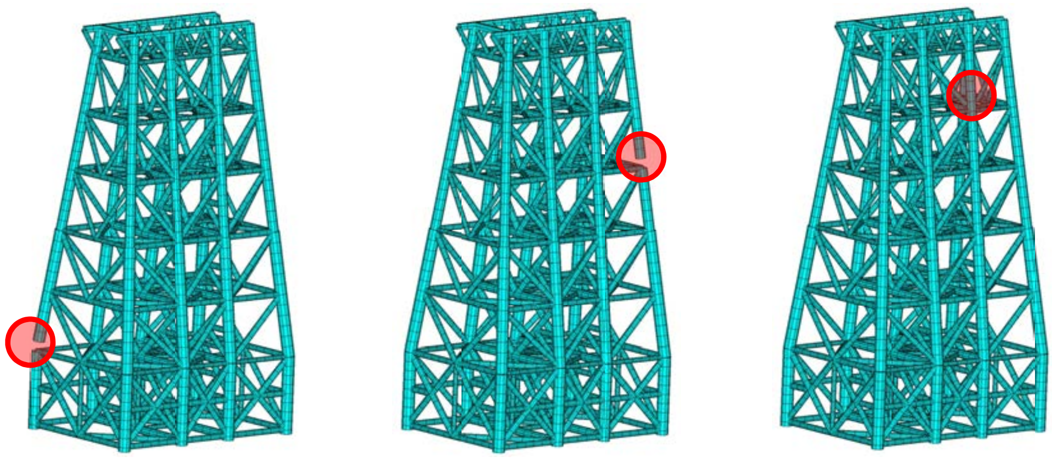


1st mode (f_{exp}=0.43 Hz – f_{num}=0.43 Hz) 2nd mode (f_{exp}=0.50 Hz – f_{num}=0.48 Hz) 3rd mode (f_{exp}=0.78 Hz – f_{num}=0.81 Hz)

Figure 4: Comparison between Experimental (black) and Numerical (red) mode shapes.

4 DAMAGE SCENARIOS

After tuning the FE model, three damage scenarios were simulated by simply removing some ending element with the aim to reproduce a joint failure of one or more elements of the platform. The three damage scenarios considered were as follows: i) DAM01, the damage of one of main legs at a lower level was assumed; ii) DAM02, the damage of one of the main legs at a higher level was assumed; iii) DAM03, the damage of two elements of the vertical bracing was assumed. The damage location for each scenario is showed in Figure 5.



DAM01 DAM02 DAM03

Figure 5: Assumed damage scenarios for the Vega-A platform.

The simulated damage scenarios aim to represent major or minor damage with the only purpose to evaluate the capability of an updating of the current structural monitoring system to read a damage state. They have been selected, at this level of the study, regardless of their probability of occurrence and their consequences in terms of residual life of the platform. The next steps of this study will correlate the analysed damage states with the robustness of the platform and the consequences of the damage in terms of platform residual capacity ([5]).

Table 2: Geometric information about the levels of the platform.

Level	z [m]	Plan [m]
Skid-beams (SK)	+16.00	18.00×56.70
Above water (AW)	+7.00	19.88×51.26
Under water 1 (UW1)	-13.00	25.34×54.90
Under water 2 (UW2)	-33.00	30.80×58.53
Under water 3 (UW3)	-54.00	36.53×62.36
Under water 4 (UW4)	-75.00	42.27×66.18
Under water 5 (UW5)	-96.00	48.00×70.00
Mud line (ML)	-122.30	48.00×70.00

4.1 Selection of the damage sensitive features

The selection of the damage sensitive features is a key point in the Structural Health Monitoring approach. According to the Rytter's scale, the first level is here addressed, both considering the main frequencies and the mode shapes.

The first investigated damage sensitive features, d_1, is the relative distance in terms of main frequency between damaged and undamaged configuration:

$$d_1 = \frac{[f_{dam} - f_0]}{f_0} \tag{2}$$

where f_{dam} and f_0 denote the main frequencies with and without damage, respectively.

The second damage sensitive features, d_2, is the Modal Assurance Criterion (MAC) between the damaged and undamaged state:

$$d_2 = 1 - MAC(\Phi_{dam}, \Phi_0) \tag{3}$$

where Φ_{dam} and Φ_0 denote the mode shapes with and without damage, respectively. According to the damage scenarios introduced before,

The above damage sensitive features have been evaluated from the frequencies and the mode shapes numerically calculated with by the calibrated FE model previously discussed.

The third damage sensitive feature, d_3, is inspired by the Mode Match Index (MMI) [6] and represents a weighted linear superposition of the two previous damage sensitive features:

$$d_3 = (1 - \gamma)d_2 + \gamma d_1 \tag{4}$$

where γ denotes a weighting coefficient of d_1 and d_2 that allows to gather the information about the frequency and mode shape shifts due to the simulated damage scenario.

In particular, if γ is assumed equal to 1, $d_3 = d_1$, otherwise if γ is assumed equal to 0, $d_3 = d_2$. Thus, a value equal to 0.5 is here assumed to have a balanced combination of d_1 and d_2.

A preliminary evaluation of the performance of the selected Damage Indexes (DI) was performed by using the modal parameters as extracted from the identified FE model.

The modal coordinates employed to characterize the *k-th* mode, $\Phi_i^{(k)} \in \mathbb{R}^{56\times 1}$, are the horizontal components at the corner vertexes of each level (apart the mud line level that was not considered). In Table 2 all the levels of the platform are reported.

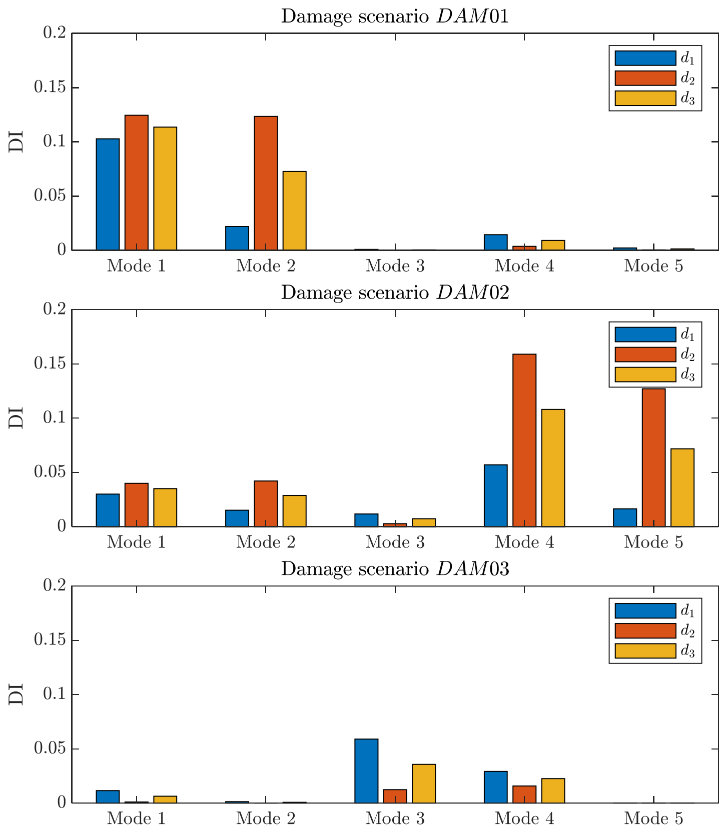


Figure 6: Results of the damage indexes d_1, d_2 and d_3 for each damage scenarios

Figure 6 reports the results obtained with the three indexes reported in Eqs. (2), (3) and (4) for the three investigated damage scenarios. To calculate the indexes d_2 and d_3 it assumed that the displacement of the modal shapes are known on a full grid (i.e. it was assumed that the modal displacements are known at each of the platform levels).

By analysing the results, it is apparent that the DAM01 scenario is clearly assessed (as expected), by all the damage features thus meaning that the first two modes (bending modes) can recognize the DAM01 scenario with good results. A similar results is obtained with the damage scenario DAM02, with good performance for the index d_2. In this case, higher bending modes contribute to assess the occurrence of a damage. The third scenario (DAM03) is recognised by all the indexes with the contributions of mode #3 and #4.

From these results it is clear how d_3 can successfully capture every kind of damage scenario, confirming that it can be used as synthetic parameter for the damage assessment. It is worth to notice how this damage indicator stand between 0.1-0.2 (Figure 6).

4.2 Optimal sensor position (OSP)

The results reported in the previous section, highlights how some additional underwater sensors are needed in order to identify higher modes with a good resolution. Currently, only two measuring stations are installed at the top level of the platform, with triaxial and angular accelerometers. Theoretically, eight possible sensor locations are available at each of the levels reported in Table 2, for a total of 256 nodes.

Not taking into account the vertical component, and hence considering only the horizontal components of the accelerations, a total of 512 DOF can be measured with monoaxial accelerometers. To simplify the problem, the possible locations of each sensor are represented by the modal coordinates $\Phi_i^{(k)} \in \mathbb{R}^{56\times1}$ described above.

The optimal sensor position (OSP) problem can be approached by calculating the radius norm of each elementary Fisher Information Matrix (FIM), by adding each possible sensor position and excluding those sensors with higher values of the redundancy. Hence the set of sensors that maximize the FIM norm can be considered the best option to retain the maximum information from the available data.

The method, originally introduced by Kammer in [7] and improved by Zini et al. [8] can find the OSP of a limited number of sensor N_s over the possible sensor positions N. The number of identified modes N_m was set equal to 5 as reasonably assumed in the previous section.

Starting from the existing accelerometers that are approximatively located at two opposite corner of the upper level (1x,1y,3x and 3y), the reduced set of possible locations N was limited to the levels UW1 and UW2.

The FIM matrix is calculated according to Eq. (5):

$$I_k = \sum_{k=1}^{N_S} I_{el,k} \tag{5}$$

where $I_{el,k}$ denotes the elementary FIM of the *k-th* sensor position calculated with Eq. (6):

$$I_{el,k} = \phi_k^T \phi_k \tag{6}$$

where $\phi_k \in \mathbb{R}^{1\times N_m}$ denotes a sub-partition of the modal matrix $\mathbf{\Phi} \in \mathbb{R}^{56\times N_m}$, corresponding to the *k*-th DOF where an additional sensor can be positioned.

In Figure 7 are shown the norm of the elementary FIM matrices for each possible sensor position along the x and y directions. Excluding the sensors that share the same information (e.g. a redundancy values above 0.5), three different set of sensors are considered to quantify the benefits in the assessment of the three damage scenarios previously discussed (DAM01, DAM02, DAM03).

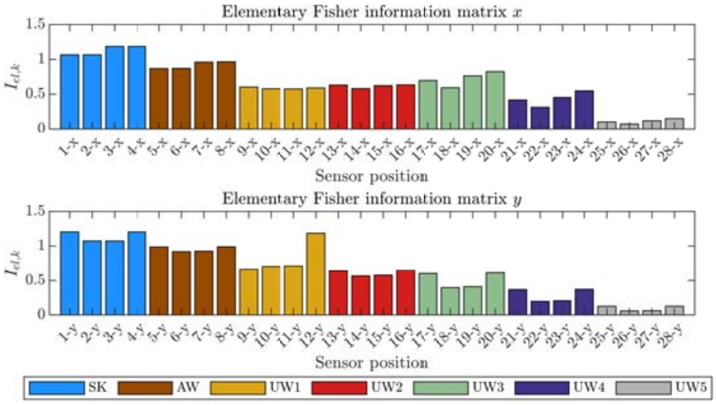


Figure 7: Elementary FIM norm considering the first five modes for each sensor position

Table 3: The assumed sensor configurations

Sensor configuration	Abbreviation	Monitored levels
Two biaxial stations (1x,1y,3x,3y)	SEN01	SK
Four biaxial stations (1x,1y,3x,3y,10x,10y,12x,12y)	SEN02	SK, UW1
Six biaxial stations (1x,1y,3x,3y,14x,14y,16x,16y)	SEN03	SK, UW2

The configurations reported in Table 3, consider two extra sensors for each the two considered underwater levels (UW1 and UW2). To minimize the installing cost of the extra sensors, only biaxial stations measuring both in x and y directions are considered. As damage sensitive feature the d_3 introduced with Eq. (4) is considered.

4.3 Discussion of the results

The results show that while major damage (DAM01 and DAM02) can be detected with the current sensor configuration, to obtain detection of the minor damage (DAM03) it is useful to have extra sensors able to improve definition of the mode shapes (Figure 8).

It is worth noting that even if in some cases the damage can be apparently assessed only considering d_1, since the environmental effects can hide the frequencies variations (Figure 2), the adoption of mode shapes that are less sensitive to the environmental changes can provide a more robust damage assessment.

With respect to the optimal sensor position, to obtain a better resolution of the higher bending modes (namely modes 4 and 5) , Figure 9 provides an indication of the positions that give a highest contribute of information to the definition of such mode shapes. The positions at UW3 give more information, but similar results can also be found at the level UW2.

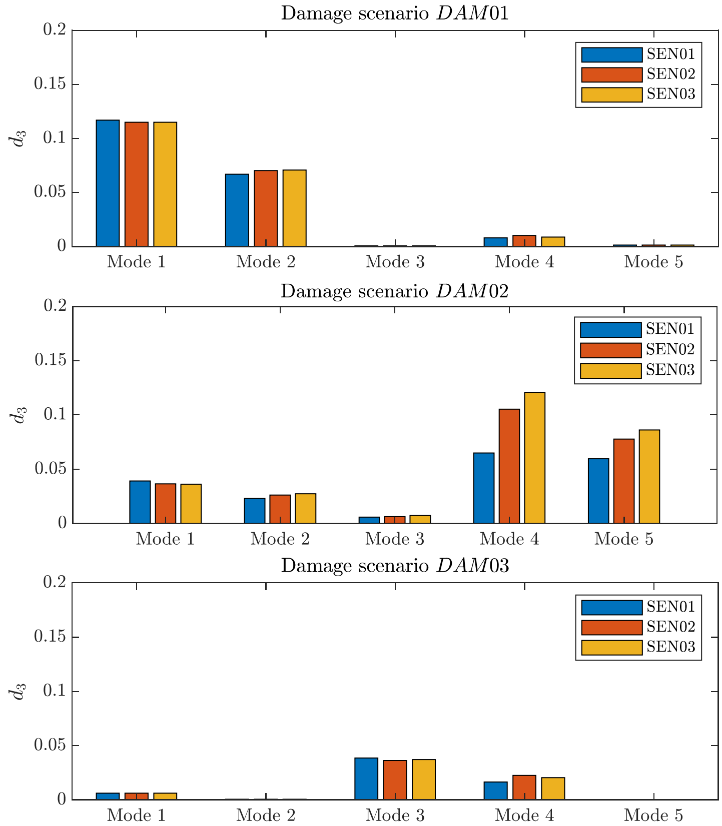


Figure 8: d_3 results for the selected sensors layout in the damage scenarios.

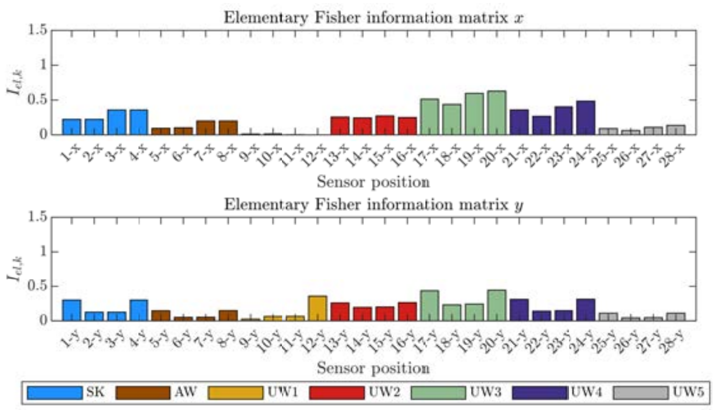


Figure 9: Elementary FIM norm considering the modes 4 and 5 for each sensor positions

5 CONCLUSIVE REMARKS

This paper reported on the dynamic behaviour of the VEGA-A summarizing some of the results provided by the current structural monitoring system over the last 20 years. With the aim to investigate on an updating of this system, a numerical model of this offshore platform was first tuned to reproduce the experimental modal behaviour and subsequently used to simulate damage scenarios. Three damage sensitive measures have been considered as damage index and, among them, the one inspired by the Mode Match Index (MMI) which account for the mode shapes resulted capable to detect the simulated damage scenarios with good confidence. This highlighted the need to improve the grid of measurements for the definition of the mode shapes (currently the accelerometric sensors allow to characterize the mode shape only at the upper level).

Based on this results a possible optimal sensor position (OSP) for new underwater accelerometers was investigated with the goal to ensure a low-cost and sustainable dynamic monitoring system and, at the same time, to maximize the information contents for the identification of the mode shapes. The results show how the simulated damage scenarios can be detect with the use of the damage index d_3, that exhibits variations about the 0.1-0.2. It is hence demonstrated that an upgrading of the current structural monitoring system with the addition of a supplementary level, apart from providing relevant instantaneous dynamic information, can improve detectability of damage correlated to significant events (and eventually for the selection of proper warning thresholds and alarms).

REFERENCES

[1] J. Goyet, D. Straub, and M.H. Faber, “Risk-Based Inspection Planning of Offshore Installations,” *Structural Engineering International*, Vol. 3, 2000, pp. 200-208, 2000.

[2] M. Rizzo, M. Betti, O. Spadaccini, and A. Vignoli, “Structural dynamic monitoring of VEGA-A platform: 30 years of data,” In Proc. 9th European Workshop on Structural Health Monitoring (EWSHM 2018), 2018, pp. 1-13.

[3] M. Betti, P. Castelli, L. Galano, O. Spadaccini, and G. Zini, “Long-Term Structural Monitoring of a Steel Jacket Offshore Platform. Validation of Meteo-Marine Data and Implications for Maintenance,” *Lecture Notes in Civil Engineering*, vol. 254, pp. 1038-1047, 2023.

[4] M. Betti, L. Facchini, and P. Biagini, “Damage detection on a three-story steel frame using artificial neural networks and genetic algorithms,” Meccanica, vol. 50, no. 3, pp. 875-886, 2015.

[5] M. Betti, M. Rizzo, O. Spadaccini, and A. Vignoli, “Offshore platform structural damage identification versus robustness,” In Proc. IABSE Workshop Safety, Robustness and Condition Assessment of Structures, 2015, pp. 86-93.

[6] B.T. Svendsen, O. Øiseth, G.T. Frøseth, A. Rønnquist, “A hybrid structural health monitoring approach for damage detection in steel bridges under simulated environmental conditions using numerical and experimental data,” *Structural Health Monitoring*, vol. 22, no. 1, pp. 540-561, 2023.

[7] D.C. Kammer, “Sensor Placement for On-iOrbit Modal Identification and Correlation of Large Space Structures, “ *J. Guid., Control, and Dynamics*, vol. 14, pp. 251-259, 1991.

[8] G. Zini, M. Betti, G. Bartoli, “A pilot project for the long-term structural health monitoring of historic city gates,” *Journal of Civil Structural Health Monitoring*, vol. 12, pp. 537-556, 2022.