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MONITORAGGIO STRUTTURALE VERSO ROBUSTEZZA DI PIATTAFORME OFFSHORE A BASE FISSA

STRUCTURAL MONITORING VERSUS ROBUSTNESS OF FIXED STEEL OFFSHORE PLATFORMS

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ABSTRACT

Since the early seventies, monitoring techniques for damage identification that analyze the changes in the modal properties of offshore structures have been developed. Results of previous researches showed that the MAC (Modal Assurance Criterion), the COMAC (Coordinate Modal Assurance Criterion) and the MSF (Modal Scale Factor) are indexes capable to detect not only the damages but also the mass changes (provided that a proper and reliable monitoring has been designed and installed). It is expected, however, that the more the offshore platform is robust and/or damage tolerant, the less a structural damage can be detected through the changes in its first modal properties. Within this framework, the paper investigates the ability of monitoring systems and damage measures to assess possible structural damage in conjunction with the robustness of such structures and, as a reference case study, the VEGA-A offshore platform (an eight-leg steel fixed jacket platform operating in the Sicily Channel, 25 km offshore in 122.3 m water depth), was considered. The aim of the paper is to discuss capability and limitation of the VEGA dynamic monitoring systems (a system that allow identifying mode shapes and main frequencies from above-water measurements) investigating possible improvements of the monitoring system (such as additional under-water measurements) aimed at the damage assessment.

SOMMARIO

Fin dai primi anni settanta sono state sviluppate tecniche per l'identificazione del danno basate sull’analisi delle modifiche nelle proprietà modali. I risultati di ricerche precedenti hanno mostrato che il MAC (Modal Assurance Criterion), il COMAC (Coordinate Modal Assurance Criterion) o il MSF (Modal Scale Factor) sono indici in grado di rilevare non solo l’eventuale presenza di danno, ma anche i cambiamenti di massa (a condizione che sia stato progettato e installato sulla struttura un sistema di monitoraggio affidabile). È ragionevole, tuttavia, ritenere che più la struttura è robusta e meno un danno strutturale sia rilevabile attraverso l'analisi dei cambiamenti delle sole prime forme modali. In questo ambito, ed in riferimento ad uno specifico caso di studio (la piattaforma offshore VEGA A), la memoria analizza, in parallelo ad appropriate misure di danno, la capacità di un sistema di monitoraggio come efficace ausilio per la valutazione di un potenziale danno strutturale.

1 INTRODUCTION

Verification of offshore structures for use beyond their initial life requires the proper design of an inspection plan aimed to constantly check-up the structural elements (members and joints). The amount of inspections, their frequency and their typology is still a critical issue since, for instance, it may not be feasible to inspect all critical component. In fact the visual inspection of structural damages is in most cases hard to perform (taking into account both the water depth and the marine growth plants that hides the structural member) and evermore economically demanding. For this reason inspection planning was, and still is, mainly based on probabilistic analysis (Risk Based Inspection, RBI) [1]. To overcome these problems, since the early seventies, monitoring techniques for damage identification through the analysis of the changes in the modal properties of offshore structures have been developed and the results of previous researches 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 damages and mass changes (provided that a proper and reliable monitoring system has been designed and installed). It is expected, however, 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 the paper investigates the ability of monitoring systems and damage measures to assess possible structural damage in conjunction with the robustness and damage tolerance of such structures. To characterize the platform robustness indexes such as the Structural Redundancy (SR) evaluated through pushover analyses are considered.

As a reference case study the VEGA A offshore platform, an eight-leg steel fixed jacket platform operating in the Sicily Channel, 25 km offshore, in 122.3 m water depth, was considered. 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. The dimension of the main columns ranges from 2000 OD × 35/50 WT at the three lower levels to 1700 OD × 35/50 WT at the higher ones, while the size of the main part of the vertical bracings is 1000 OD × 25 WT (with a length, in the longitudinal direction, of about 32 m). The dimensions of the jacket at the sea bed are 70 m by 48 m, while at the top they are 50 m by 18 m [2]. Six horizontal bracing frames, spaced at approximately 21 m, are also used to support the well conductor guides. EN S355 steel is employed for all structural elements. The jacket is supported by 20 vertical steel piles, 85 m long with a diameter of 2.6 m. These piles have been driven to a depth of 65 m below the seabed by means of an underwater hammer.

Capability, limitation and possible improvements of the existing dynamic structural monitoring systems, that allow identifying mode shapes and main frequencies from only above-water measurements, are herein discussed.

2 THE MONITORING SYSTEM

Since March 1988 the structural behaviour of the platform has been object of analysis by the Department of Civil and Environmental Engineering of the University of Florence, and a system of vibration monitoring is still active that records structural and environmental data [3]. The actual VEGA A structural monitoring systems is constituted of 9 linear accelerometers (6 linear and 3 rotational) disposed at the level of the skid-beams (above-water). The environmental monitoring system is constituted by a current meter and a depth gauge that allow reconstructing the wave characteristics. In addition speed and direction of both wind and current are recorded together with the meteorological data (air pressure, temperature and humidity). Last updating of the monitoring system date back to 2001 and currently an improvement is expected. With the actual monitoring system, acceleration data are recorded with a sampling frequency of 10 Hz, instead the meteocean data are recorded with a sampling frequency of 2 Hz. The accelerometer data, the atmospheric pressure, the humidity and the wind and air temperature are acquired for a period of 10 min/h. The depth gauge and the current meter data are acquired for a period of 17 min/h.

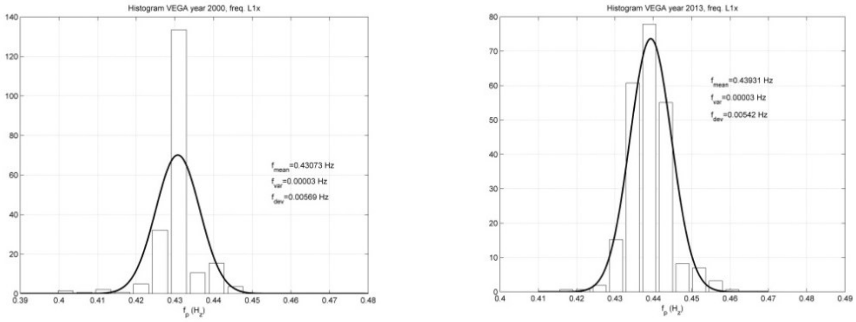

Fig. 1. Statistical analysis of the frequency: L1x year 2000 (left), L1x (right) year 2013.

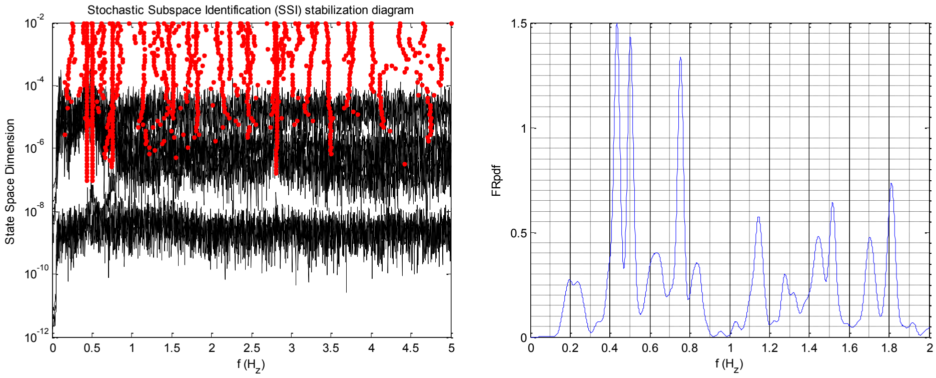

Fig. 2. SSI analysis: stabilization diagram and PDF (storm of 2014/01/25).

2.1 Signal analysis

The main structural frequencies of the platform were first evaluated through the FFT technique. In 2001 one of the superstructures (the Derrick, approximately 2800 ton taking into account additional structures) was removed during a reconfiguration of the platform. The statistical analysis of the first frequency over the period 2000-2013 is reported in Fig. 1. It is possible to read clearly the frequency shift: before the removal of the Derrick the first two frequency of the platform were $f_{1mean,\ 2000} = 0.431$ Hz and $f_{2mean,\ 2000} = 0{,}483$ Hz; after the removal they become $f_{1mean,\ 2013} = 0.439$ Hz (+1.85%) and $f_{2mean,\ 2013} = 0.504$ Hz (+4.35%).

A more efficient identification of the frequencies was also performed by means of the Subspace Stochastic Identification (SSI) technique, analysing the data recorded at the midnight of each day over the years 2000-2013. Subsequently, the identified eigenfrequencies were employed to evaluate the corresponding modal shapes by means of a Singular Value Decomposition (SVD). The Probability Density Function (PDF) was built by means of a Gaussian base and Fig. 2 shows the stabilization diagram and the PDF of structural resonance (the identified mode shapes are reported in Fig. 5). Despite the ability of the SSI to evaluate exactly the main frequencies of the platform, the SVD allows for a poor identification of the corresponding modal shapes (Fig. 5) since the actual monitoring system record only above-water acceleration.

Table 1. Main characteristics of few significant events.

Event	Hs (m)	Ts (s)	Dm (°)	W (m/s)	Dw (°)	f1 (Hz)	ξ1 (%)	f2 (Hz)	ξ2 (%)	f3 (Hz)	ξ3 (%)
2014-01-06 h23	1.1	6.6	131	8.47	23	0.437	2.02	0.503	2.16	0.756	1.45
2014-01-30 h04	1.0	5.3	248	9.21	141	0.435	2.08	0.508	2.20	0.749	1.88
2013-12-27 h01	3.5	8.4	337	8.22	288	0.439	3.00	0.495	2.74	0.771	3.63
2014-01-25 h02	5.6	9.3	244	27.23	236	0.437	4.31	0.484	3.37	0.761	8.04
2013-03-14 h22	6.7	9.8	307	n.a.	n.a.	0.432	5.83	0.508	3.52	0.755	13.87

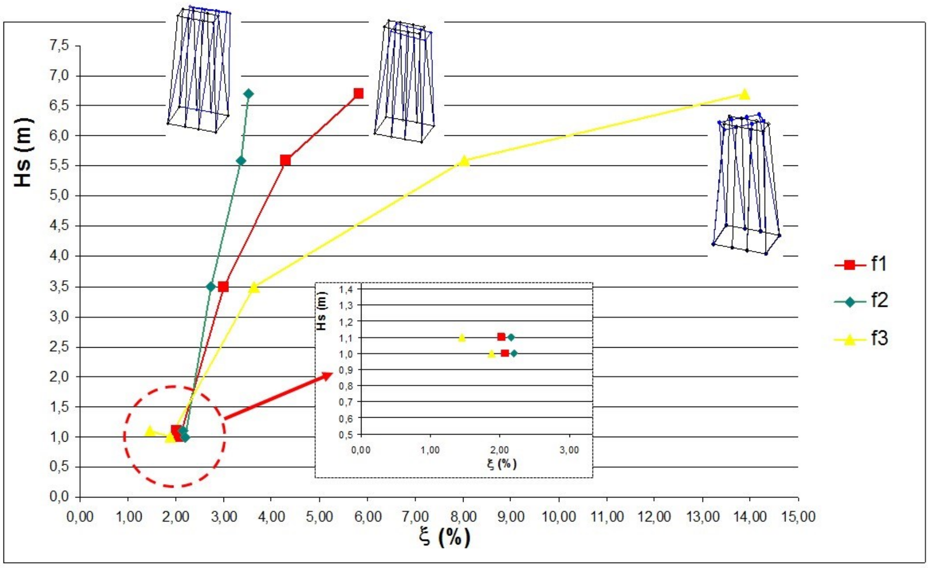

Fig. 3. SSI analysis: damping evaluation.

By means of the SSI technique, analyzing events with increasing intensity (Table 1), it is possible to evaluate not only the main frequencies and modal shapes but also the corresponding damping. As is known the damping of offshore structures can be evaluated as the sum of several factors [4]: the structural damping, the aerodynamic, the hydrodynamic and the one connected to the behavior of foundations:

$$\xi = \xi s + \xi a + \xi w + \xi f \tag{1}$$

It is interesting to observe that events of increasing intensities are associated with higher damping values (Fig. 3). In case of events of moderate intensity, the damping value is stable and close to 2%; while with the growing of the intensity of' event it reaches values around 14% (for the third mode shape). Intensities of the event modify also the modal displacements. This behavior is due to the nonlinear behavior of the platform, in particular to the nonlinearity of its foundations.

3 THE NUMERICAL SENSITIVIY ANALYSES

A 3D numerical model of the VEGA A platform was built with the finite element code ANSYS (Fig. 4) modelling main columns and vertical and horizontal bracing elements by means of 1D beam elements with elasto-plastic behaviour. The numerical model was first employed to assess robustness and damage tolerance of the platform. Subsequently, after dynamic identification, modal analyses were performed to assess sensibility of frequencies to damages with the aim to discuss improvement of the actual monitoring system to allow identifying of the modal shapes.

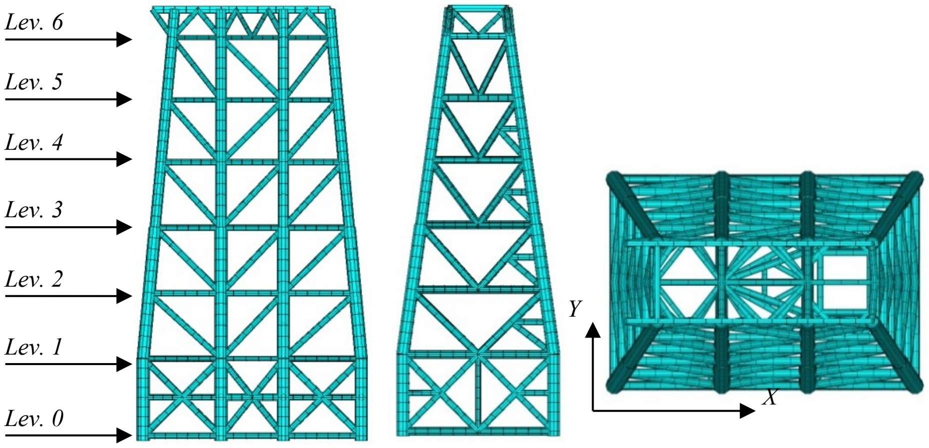

Fig. 4. Vega A, numerical model.

3.1 Modal assessment and model sensitivity

The dynamic identification of the model was performed employing Genetic algorithms (GA). The basic flowchart of a GA works as follows: 1) Start with a randomly generated population of n chromosomes (candidate solutions to a problem); 2) Calculate the fitness $f(x)$ of each chromosome x in the population; 3) Generate a new population selecting the chromosomes according to their fitness value and recombining new chromosomes through crossover and mutation; 4) Replace the current population with the new population; 5) Step 2 to step 4 are repeated (iteration) until a termination criteria is verified.

A real-coded genetic algorithm (RCGA) was employed, and the chromosome was built in order to collect the selected unknown parameters of the model: the added masses (water and marine growth) and the stiffness of the 20 vertical steel piles. The numerical model of the platform was hence built parametrically in order to accept as input these parameters (the topside masses were assumed as fixed values). The fitness function was built based on the Modified Total Modal Assurance Criterion (MTMAC) [5], an improvement of the MAC with the introduction of the frequencies as penalty functions to account for differences between experimental and numerical results. The optimization procedure allowed identifying the first three frequencies although the reduced number of data does not allow reproducing with the same accuracy the modal shape. 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 modal shape. In this respect additional underwater measurements can offer effective data to substantially improve experimental modal identification through the monitoring of level #3 (Fig. 4). A comparison between the experimental and the numerical modal shape is reported in Fig. 5 (without Derrick). Despite the difficulties in identifying the modal shape, the identified FE model reproduce quite accurately the modal behaviour of the platform since it is able to reproduce with great accuracy the frequency changes produced by the removal of the Derrick masses occurred in 2001 as summarized in Table 2.

Table 2. Experimental (Exp.) and Numerical (Num.) frequencies.

Frequency	2013 (without Derrick)		2000 (with Derrick)	
	Exp.	Num.	Exp.	Num.
f_1 (Hz)	0.44	0.441	0.43	0.429
f_2 (Hz)	0.50	0.498	0.48	0.479

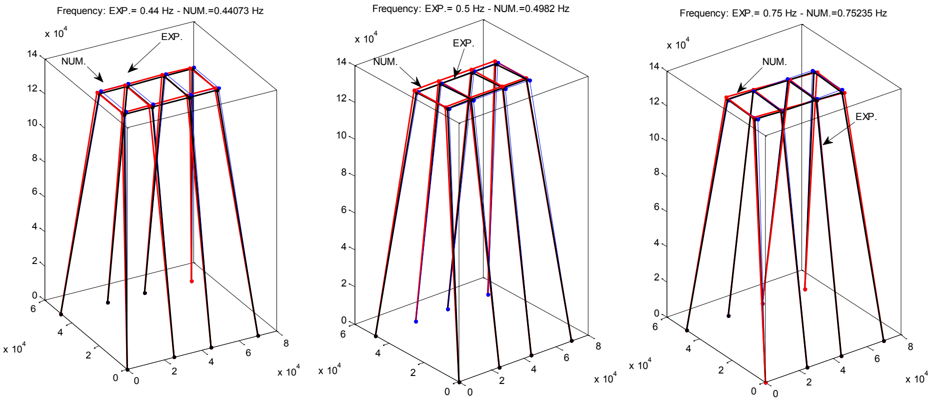

Fig. 5. Experimental and numerical modal shape: first three frequencies (without Derrick).

The identified numerical model was subsequently employed to estimate the changes in frequencies due to a possible damage. Damages of structural primary (columns, the main legs) and secondary (vertical bracings) components were assumed and the main three frequency of the structure were evaluated. Results of the analyses are illustrated in Fig. 6.

It is possible to observe that the damage of one element of the main columns can affects directly and significantly the first two frequency. On the contrary, damage of one of the element of the vertical bracings interests mainly the third frequency (the torsional one). This result shows that even though a major damage can be detected by a change of the two main frequencies, an improvement of the monitoring system in order to better characterize higher modal shapes is needed to detected damage of secondary elements.

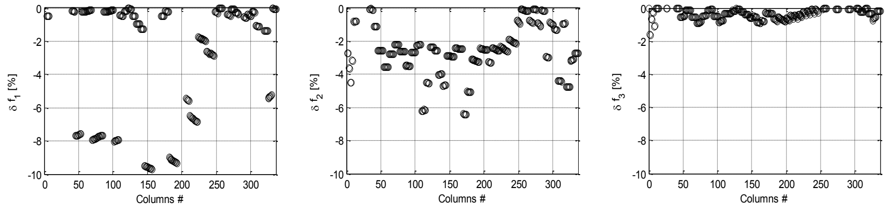

Fig. 6. Sensitivity of frequencies due to possible damage of main legs.

3.2 Platform robustness assessment

Robustness and structural redundancy were evaluated through non-linear collapse analyses. Damages (or deteriorations) of structural primary and secondary components were assumed in order to evaluate their effects on the robustness of the structure. The nonlinear analyses were developed through a pushover approach where load distributions derived by waves were modelled using the Stokes 3th order theory. The analyses were developed assuming the environmental load distribution acting in the two main direction of the offshore platform (the *x*-direction, the longitudinal one, and the *y*-direction, the transversal one, Fig. 4). More details about the pushover analyses are reported in [6], [7]. A similar approach has been recently employed in [8].

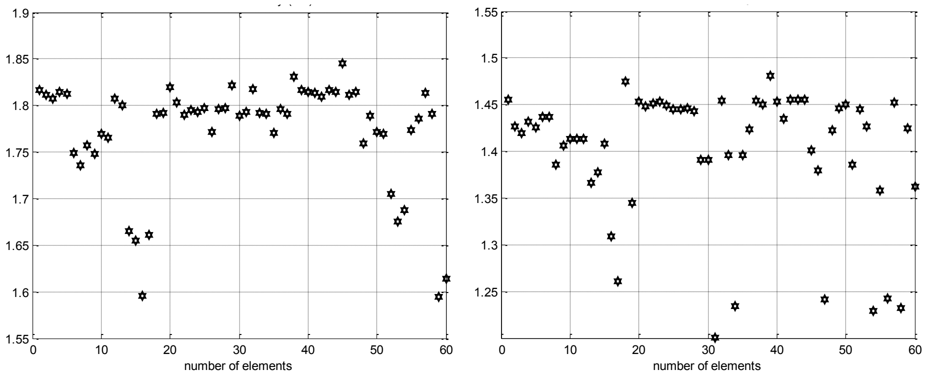

Fig. 7. Pushover analysis: SR *x*-direction (left); SR *y* -direction (right).

In this context the non-linear redundancy analysis was regarded as a possible sound method to be combined with the dynamic monitoring to ensure proper future safety of the structure beyond its original design life. In fact, taking into account that changes in stiffness are reflected in changes in main frequencies, a dynamic monitoring system able to evaluate the structural frequencies and the corresponding modal shapes can be used as a sound indicator for major damage of the structure. The redundancy, strictly related with the concept of robustness, is analysed on the basis of the results of the pushover analyses by evaluating the Structural Redundancy (SR). The Structural Redundancy (SR) index is a measure of the load level at first member failure with respect to the collapse load of the structure. Fig. 7 reports the SR evaluated for the case of load acting in *x* and *y*-direction. The ratio between the numerical collapse load and the first member failure was found to be in the range between 1.6 and 1.8. This denotes a significant redundancy in the structure, as the structural collapse does not occur until the loading is increased of about 80% from the load level at first member failure. In the case of load acting in *y*-direction the SR was found to be in a range between 1.2 and 1.5, less than the previous according to the fact that the strong direction is the *x*-direction. The analysis of the indexes shows high values of SR denoting in addition that a (single) member damage, thanks to the structural redundancy (and damage tolerance), does not affect the whole safety of the platform.

4 CONCLUSIVE REMARKS

The paper, with the aim to evaluate the ability of the monitoring systems to detect damage in structural members, investigated the aspects of robustness and damage tolerance of a steel jacket platform in conjunction with the data obtained by a structural monitoring system.

The analysis of the Structural Redundancy (SR) shows that single member damage does not affect the whole safety of the platform. From a point of view this shows that the structural redundancy is a key factor in design of such typology of structure. From another point of view the result shows that, due to the robustness of the structure, the dynamic monitoring system in order to check-up the presence of a failure in secondary elements should be improved to allows to identify the modal shapes of higher modes.

In this respect additional under-water measurements, made now possible by the technological development, can offer effective data to substantially improve experimental modal identification. Nonetheless the actual monitoring system is able to identify damage in main elements and hence it can be considered an effective component of an inspection plan helpful to optimize the amount of inspection.

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