Monitoring the mechanical behaviour of the weather vane-sculpture mounted atop Seville Cathedral's Giralda Tower

M. Solís*, A. Romero, P. Galvín
Escuela Técnica Superior de Ingenieros, Universidad de Sevilla, Camino de los Descubrimientos s/n, 41092 Sevilla, Spain
Corresponding author: Mario Solís
E-mail: msolis@us.es
Tel: 0034 954 48 72 93
Fax: 0034 954 48 72 95

Summary

This article presents the application of monitoring and detection of structural damage techniques to a historic monument. Seville cathedral's famous bell tower “La Giralda” is 96 metres tall and is crowned with a large 16th –century sculpture known as “Giraldillo”. The sculpture is supported with an internal bar structure which is fitted over the axis about which it rotates according to the wind direction, allowing it to function as a weathervane. Between 1999 and 2005 the Giraldillo was demounted and underwent an intensive restoration process, which included mechanical and structural repair work. As the sculpture is only accessible by means of complex and costly scaffolding systems, an instrumentation system consisting of different types of sensors was installed to study the assembly's mechanical response, its functioning as a weathervane and its state of conservation while it was being remounted atop the Giralda Tower. Different damage detection techniques aimed at detecting possible deterioration in the Giraldillo's support structure were employed as well. This article presents results obtained in two years of system

operation, showing how structural heath monitoring techniques can be applied to historical monuments.

Key words: historical monument – structural health monitoring – damage detection

1 INTRODUCTION

The Giraldillo, originally built in 1568, is a large bronze sculpture of tremendous historic, artistic and symbolic worth. The sculpture functions as a weathervane atop Seville cathedral's Giralda Tower, making it a unique combination due to its cultural value, its mechanical operation, and its position atop an architectural complex that was declared a World Heritage site by UNESCO in 1987.

Figure 1. The Giraldillo in the restoration workshop

Figure 2. Mounting of the Giraldillo atop the Giralda Tower

Due to the deterioration of the Giraldillo because of corrosion over its more than 400 years of history, it had to undergo of a thorough and meticulous restoration process from 1999 to 2005 [1] (Figure 1.), and in the meantime it was replaced with a replica. The restoration project culminated with its being mounted once again atop the Giralda Tower (Figure 2.).

Given the Giraldillo’s worth and the fact that observation would not be feasible once remounted atop the Giralda Tower, it seemed important to obtain information regarding its behaviour, state of conservation, etc. Therefore, the design, installation and start-up of an instrumentation system to monitor the Giraldillo’s functioning, in order to detect eventual deterioration, were included as part of the Giraldillo's remounting project.

The datalogging and control of the parameters associated with the conservation of works of art is widely employed in the world of restoration and conservation. In this field, the location of damage is usually known and the structure is accessible, so visual and localized experimental techniques can be used to detect and measure geometric discontinuities, cracks, etc. Methods based on X-ray, magnetic particles or Eddy-current examination, thermography, acoustic or ultrasonic waves, etc. can be used for this purpose. When monitoring the structural behaviour, only static magnitudes such as displacement strains and environmental conditions are usually measured.

However, in the particular case of this weathervane-sculpture, the response is mainly dynamic, since it is subjected to wind forces which make it rotate around its supporting axis and produce structural vibrations as well. Moreover, the structure is not accessible at all, unless complex and costly scaffolding systems are installed around the top of the Giralda Tower.

These difficulties may be overcome by using damage detection techniques based on the dynamic response of the structure. These techniques have received considerable attention in the literature [2]. The basic idea is that modal parameters depend on the physical properties of the structure. Therefore, changes in those properties can be detected from changes in the dynamic response of the structure. These damage detection techniques have no limitations due to the structure's accessibility, and global damage as well as local damage can be detected.

In addition to its ability to record static variables as temperature, humidity, galvanic potentials and the Giraldillo's position, the monitoring system also performs an exhaustive study of the sculpture’s dynamic behaviour, making it possible to apply different damage detection techniques, which are based on the sculpture’s modal parameters and aimed at tracking its state of conservation. These parameters are obtained using the structure’s response to service loads [3].

Not only is this instrumentation system interesting in terms of the control and study of the Giraldillo’s behaviour, but also in terms of the unique character implied by its location, purposes and diversity of measurements to be recorded, controlled and analysed. Accelerations, inclinations, forces, humidity, temperature, galvanic potentials, wind direction and wind velocity are measured to detect any damage that may occur in the structure.

This article will first provide a general description of the Giraldillo, placing particular emphasis on mechanical aspects, followed by a description of the instrumentation system installed on the Giralda Tower. The different measurements that can be taken will be enumerated along with the types of sensors used, their locations, and how the data provided by the system can be put to practical use. Finally, the most significant results and conclusions made after two years of system operation will be presented.

2 DESCRIPTION OF THE GIRALDILLO

The Giraldillo assembly consists of a cast-bronze sheet connected at various points to an internal bar structure, which rests on and rotates around an axis anchored to the Giralda Tower. The sculpture represents a female figure, holding a great standard in her raised right hand and a palm frond in her left hand. Its aerodynamic characteristics allow it to rotate with the wind, the palm frond indicating the direction from which the wind is coming. The sculpture is roughly 5m tall, with a frontal breadth of similar dimensions, and it weighs 1500kg approximately, not including the axis on which it rests, which is 5.4m long and weighs almost 500kg. The axis, which is anchored to the top of the tower, brings the Giralda Tower's total height to 96m, making it the highest point in the City of Seville. A schematic diagram of the Giraldillo and its structure is shown in Figure 3..

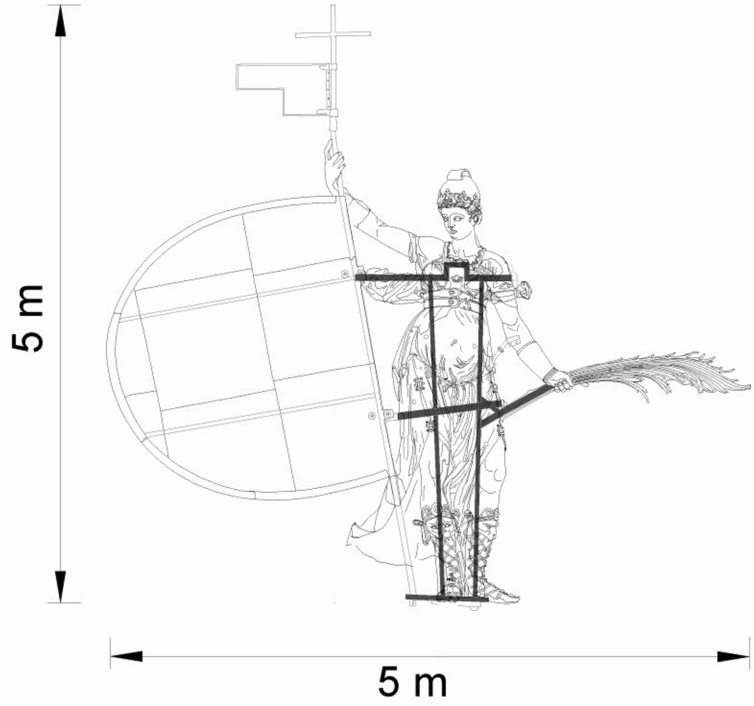
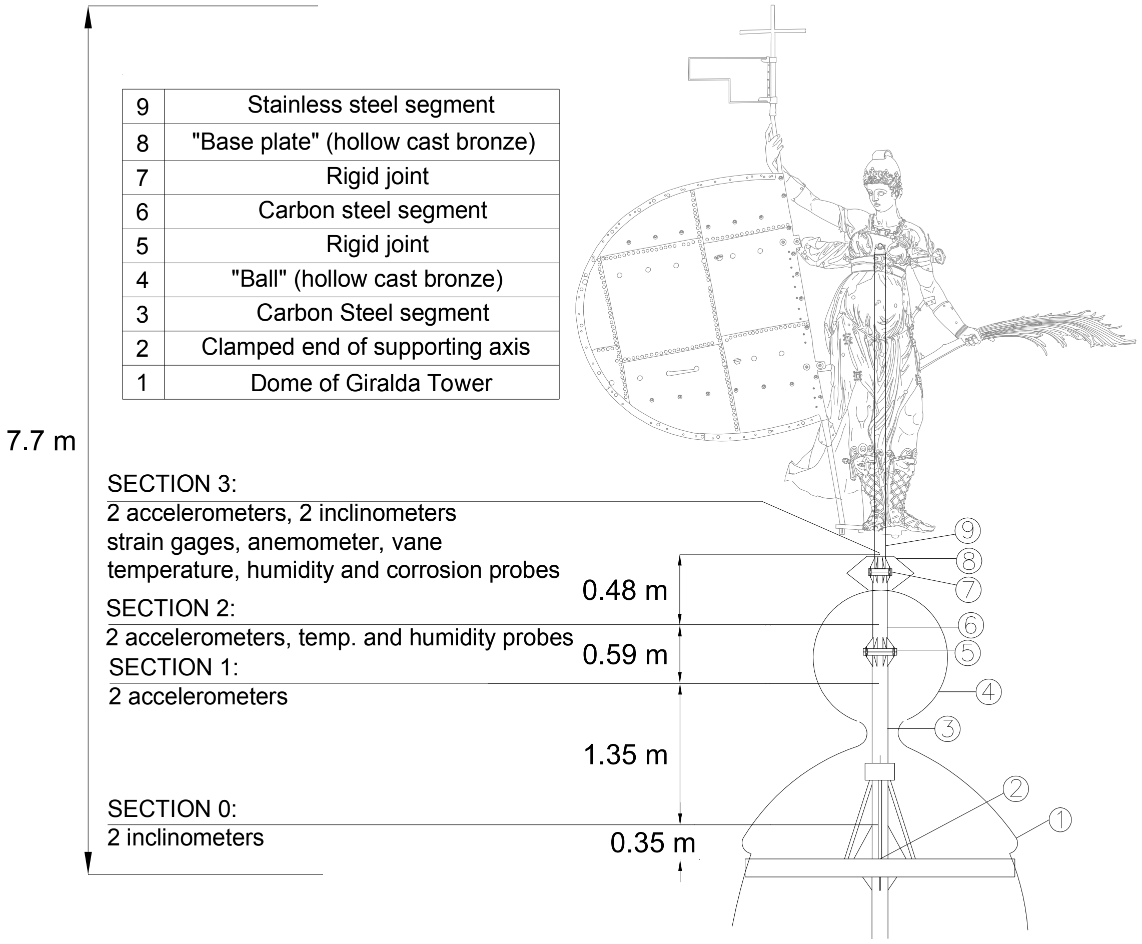


Figure 3. Schematic diagram of the Giraldillo's internal structure.

The Giraldillo's rotation and support axis passes through two hollow cast bronze components known as "ball" and "base-plate" collars and into the sculpture. Its pointed-arch tip fits into the upper brace of the internal structure (at the height of the chest) and is the only point of contact for support and rotation on the axis.



9	Stainless steel segment
8	"Base plate" (hollow cast bronze)
7	Rigid joint
6	Carbon steel segment
5	Rigid joint
4	"Ball" (hollow cast bronze)
3	Carbon Steel segment
2	Clamped end of supporting axis
1	Dome of Giralda Tower

SECTION 3:
2 accelerometers, 2 inclinometers
strain gages, anemometer, vane
temperature, humidity and corrosion probes

SECTION 2:
2 accelerometers, temp. and humidity probes

SECTION 1:
2 accelerometers

SECTION 0:
2 inclinometers

Figure 4. Schematic diagram of the Giraldillo’s support structure and location of attached sensors.

The Giraldillo’s original axis was taken to pieces when the original Giraldillo was temporally replaced with its replica. The design of the axis is essential for ensuring the stability of the assembly as a whole and its functioning as a weathervane: it must allow for mounting and demounting of the Giraldillo, be compatible with internal structure, be corrosion resistant and of course provide sufficient strength and stiffness. The axis on which the Giraldillo is supported after restoration consists of three segments, of different cross-sections and materials, connected with rigid joints made of blind flanges and gussets. Figure 4. shows a schematic representation of the Giraldillo’s support shaft and location of the sections where sensors are attached to.

3. DESCRIPTION OF THE INSTRUMENTATION SYSTEM

Most of the sensors used are located on the support shaft, as it is the element most responsible for the Giraldillo's stability. Furthermore, its mechanical response can be used to analyse the Giraldillo’s functioning. The idea placing sensors on the sculpture as well was dismissed, given the high costs and complexity that would be implied by the sculpture’s inaccessibility and rotating nature. Thus, the inconvenience of the cables getting tangled together would be avoided and no wireless sensors would be necessary. Summarised below are the various readings taken by the system and the different types of sensors employed (Figure 4. and Figure 8.).

Velocity and wind direction: Among the system devices there is an anemometer and a vane for recording speed and direction of the wind striking the Giraldillo at any given moment, wind being the main mechanical force to which the Giraldillo is subjected. The recording of such data is indispensable for evaluating proper operation, as all mechanical response data measured for the study will be directly related to wind-induced forces.

The vane and anemometer sensors are installed on the lightning rod support installed under the Giraldillo and oriented towards the southeast. One of the reasons for choosing this location was to make them visually less conspicuous. For similar reasons, small-sized sensors were selected and were coated with a greyish matte finish.

Figure 5. Sensors on the lightning rod support

Figure 6. Mounting of sensors inside the "ball" (referred to as sections 1 and 2 in Figure 4.)

The measurements taken with these sensors will inevitably be subject to a certain margin of error or erratic functioning due to the fact that the movement of the Giraldillo itself creates air currents that will affect the data taken from the anemometer and vane. This effect is expected to be almost negligible when the sensors are in an upwind position, but considerable when they are in a downwind position. Given the prevailing wind directions for Seville (southwest and northeast), it seemed appropriate to locate the sensors on the southeastern leg of the lightening rod support structure.

Figure 7. Mounting of inclinometers inside the dome of the Giralda Tower (referred to as section 0 in Figure 4.).

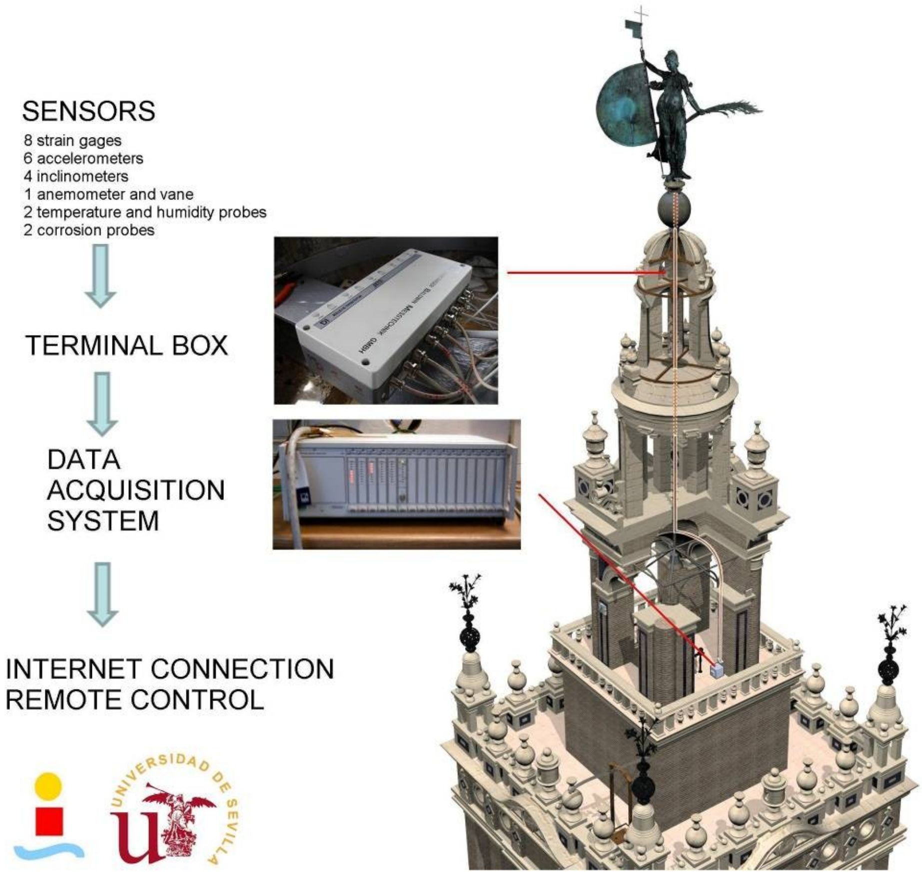


Figure 8. Schematic diagram of the instrumentation system installed on the Giralda Tower

Measurement of forces in the support shaft: Strain gages are installed on one section of the support shaft, creating two full-bridge assemblies, two of which can be used to obtain bending moments in two perpendicular directions, making it possible to determine bending forces acting on the shaft, which are the main forces exerted by the wind on the Giraldillo, as well as possible seismic activity.

Acceleration measurements: The response of the Giraldillo and its support shaft is essentially dynamic, so acceleration measurements are taken on three different sections of the axis. Two accelerometers are placed on each section to record movements in the Southwest-Northeast (SW-NE) and Southeast-Northwest (SE-NW) directions, which are the predominant wind directions in the city of Seville. The accelerometers used are of the multi-purpose ICP type with a sensitivity of 50mV/g.

Shaft inclination: Four inclinometers have been installed to detect shaft inclination in two different sections. Two have been applied to each section, one to measure the inclination corresponding to the SW-NE direction and the other for measurements corresponding to the SE-NW direction, coinciding with the movements detected by the accelerometers. The inclinometers have a range of ±5.75º with an output voltage of ±5V.

Corrosion: Connections between the sculpture and its supporting structure imply interfaces between different metals. The bronze of the sculpture is in contact with the stainless steel of the internal structure, while in the shaft there is a carbon steel-stainless steel interface. The contact between these materials can produce different degrees of deterioration due to galvanic corrosion. A corrosion detection probe, employing samples of different materials that come into contact with one another and between which measurements of existing galvanic potential are taken constantly, can be used to measure the tendency for corrosion at these interfaces. The probe is positioned inside the bronze collar located just below the sculpture’s feet, where the temperature and humidity conditions are similar to those at the interfaces between different materials.

Temperature and humidity: Two temperature and humidity detection probes were installed so that the Giraldillo’s ambient conditions could be known. One of the probes is on the outside and the other one is on the inside of the “ball”, where prevailing ambient conditions are similar to those of the sculpture’s interior. Fluctuations in these measurements and differences between exterior and interior ambient conditions can be useful for assessing the possibility of condensation forming in the sculpture’s interior, temperature gradients, extreme temperature variation, correlation with signals emitted from the corrosion detection probe, etc. This information proved to be useful for the preservation and restoration experts working on the Giraldillo's restoration project. Further analysis of this information, however, would have to be considered beyond the scope of this article.

Altogether, in total, 21 different instruments are used to take the various measurements. All of the sensor cables, with the exception of those attached to the accelerometers, descend to the Tower's dome where they are connected to a terminal box through which they are fed into a conduit of 44 braided cables, which are in turn connected to power sources and to the data acquisition system (Figure 8.). Sensors are 35 to 40 meters away from the data acquisition system and located at the highest point on the tower that can be safely accessed for programming or performing maintenance tasks on the equipment, and to which an internet connection is available for remote control. Locating the data acquisition system any higher was deemed impractical, as access above this point would entail climbing the shaft centred on the tower’s axis or using scaffolding systems.

4 RESULTS

This section presents the most significant results obtained along two years of the monitoring system's operation. The values obtained in the various studies will serve as a reference for the future, as the type of analysis employed would also be applicable in the long-term. Thus, it seemed reasonable to establish yearly study sessions in order to make comparisons with past experiences and be able to detect behavioural tendencies and variations in the Giraldillo.

So that the quantity of data collected did not become unmanageably large and given the fact that wind is the main agent of mechanical force to which the Giraldillo is subjected, the sampling frequency was determined as a function of wind speed, i.e., when the wind speed stays below a certain threshold level its influence is very small and thereby requires a low sampling frequency, one which is sufficient to obtain the quasi-static values of temperature, humidity, galvanic potential, wind speed and direction; as other measurements have been considered unessential. Data would thus be taken every 200 seconds.

However, in the cases where the wind speed becomes significantly high, a sampling frequency that permits a subsequent analysis of the Giraldillo's dynamic response using the records taken with the accelerometers, inclinometers and strain gages is required. In this case, given that the system's first natural frequency is approximately 1 Hz, ten samples per second and per channel are sufficient.

The threshold wind speed at which the Giraldillo's dynamic response becomes more critical and at which the sensors become notably agitated is 5 m/s. The data recorded at this wind speed are the data that will be used in the analysis of the Giraldillo’s dynamic response. Given the statistical probability density of wind speed, this threshold value gives a reasonable number of data sets for analyzing the Giraldillo's dynamic response and monitoring its state of conservation. Moreover, there is a good signal to noise ratio from that threshold value, so clear and precise spectral analysis results can be obtained.

4.1 Forces produced by the wind

By measuring bending forces in the support shaft while recording wind speed, it is possible to establish a correlation between these magnitudes. Changes in this correlation over time could indicate deterioration of the Giraldillo’s rotation system resulting from the stronger forces produced by the wind when the Giraldillo is not properly aligned with the direction of the wind. This correlation will also allow to quantify the effect that this deterioration would have in terms of the forces to which the Giraldillo is subjected.

Figure 9. shows the correlation between average wind speed and average amplitude of the resultant bending force for different wind speed intervals, obtained from auto-spectra of bending force data. For every record, the mean value of wind speed and the amplitude of the bending force-corresponding to the first natural frequency is obtained (forces corresponding to the first mode shape are dominant). Since these bending moment values are obtained from a spectral analysis, they are not influenced by any unbalance in the strain gage circuits.

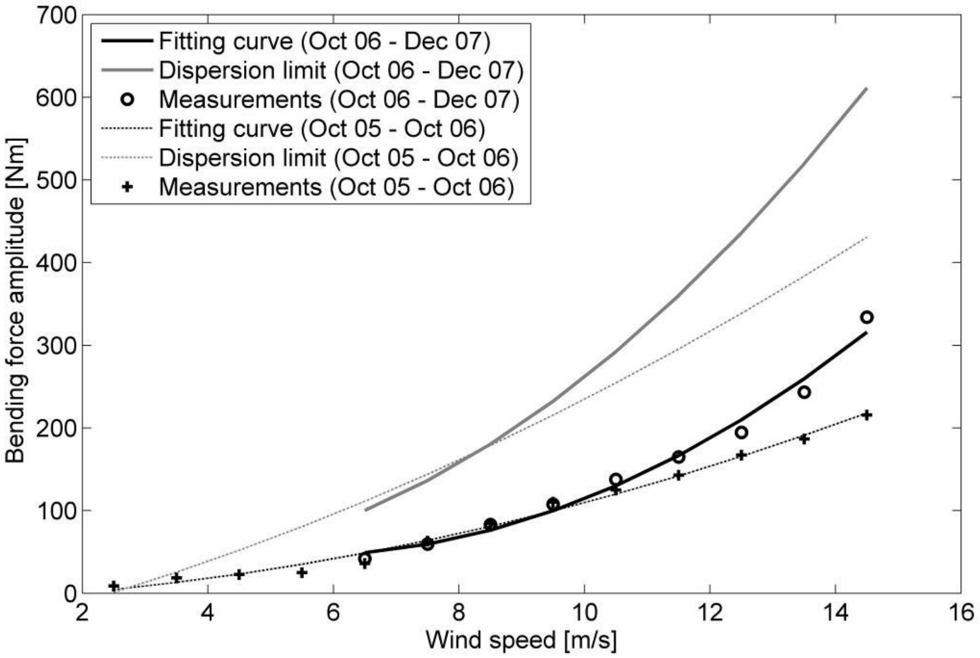


Figure 9. Correlation between the load cycle amplitude in the support shaft and wind speed for two different periods

Variance in the results obtained is relatively high due to the fact that in every record taken into consideration wind speed and direction may change significantly. Thus, Figure 9. shows - in addition to the parabolic fitting curve - a curve representing three times the standard deviation from the mean value for each velocity range.

With this correlation and the statistical probability density of wind speed, an estimation of the load cycle history on the supporting axis and a fatigue analysis have been carried out. As it was expected from the numerical analysis that had been carried out during the restoration project, values of the measured forces are very low and there is no risk of fatigue failure for these values. However, the main issue here for monitoring the operation of the Giraldillo is not the values of the forces but their increase along time due to the deterioration of the Weathervane rotation mechanism. If this happens, as the Giraldillo is not correctly positioned according to wind direction, higher bending forces will be induced by wind action. During the first two years of the system's operation, an increase of these forces can be observed for high values of wind speed from the first year to the second year. Nevertheless, there is a good agreement between results for these two years for a wind velocity interval between 6 and 10 m/s, for which most of the dynamic analysis data have been obtained. However, two years is not a sufficient period of time and the data dispersion is too high, so no deterioration can be noticed from the observed variation.

~~Increasing values of the bending force produced by the wind in future years may indicate some deterioration of the Giraldillo’s rotation system.~~

4.2 Giraldillo's position

The Giraldillo assembly is not perfectly centred on its axis, which means that it produces a bending moment that can be measured by the strain gages glued to the support shaft. This bending moment is evidently constant, but when the Giraldillo changes its position, changes in bending force values measured in two different directions are detected. Thus, the Giraldillo’s position can be estimated using these average value variations (disregarding wind-produced oscillations).

Estimating position using this method is somewhat difficult due to the fact that the Giraldillo and its support shaft had to be installed simultaneously, so an initial balance of the strain gage full bridges could not be done. Thus, zero level estimates had to be based on average values for the Giraldillo’s different positions. Nonetheless, with the method developed, it is possible to determine quite accurately the Giraldillo's position and correlate it with wind direction and speed, so that its functioning as a weathervane can be analysed over time.

The full-bridge circuit is supposed to be very stable, and no influence of any unbalance in the circuit has been noticed in this application. However, the zero level estimates have been updated several times due to required maintenance operations of the data acquisition system.

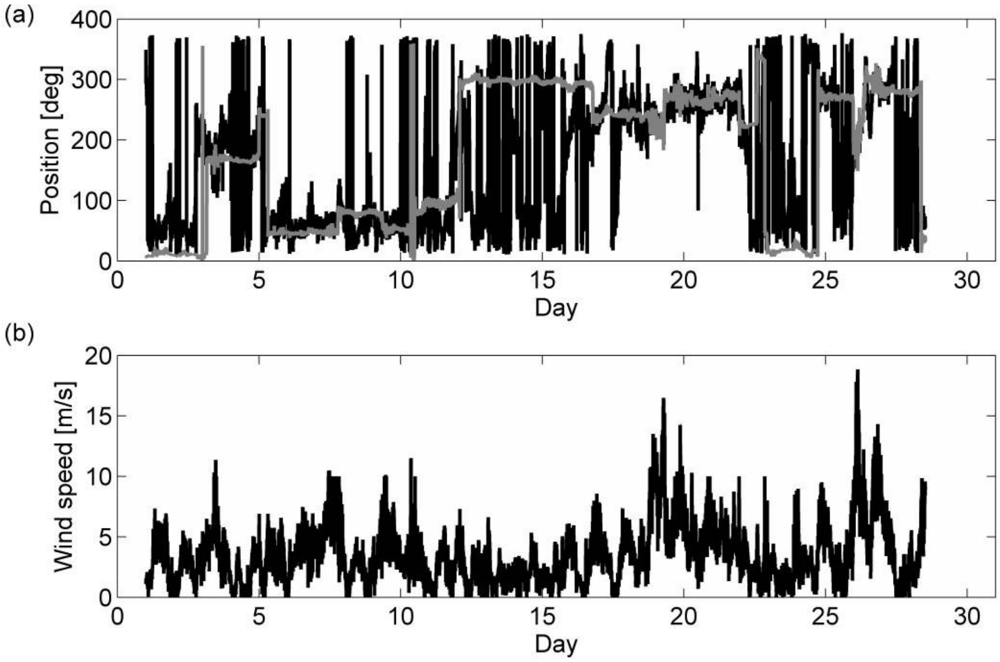


Figure 10. ~~Sample of recorded data for the wind direction and Giraldillo's orientation~~ a) Sample of recorded data for the wind direction (black line) and Giraldillo's orientation obtained with the proposed methodology (grey line). b) Wind speed for the same period.

Applying this methodology, the value of the moment produced by the imbalance of the Giraldillo assembly over the support shaft is 1774 Nm, which is in agreement with the value of 1983 Nm obtained with the numerical model generated during the Giraldillo's restoration process to analyse its mechanical behaviour [4]. This imbalance results from the right side's being heavier than the left side (the palm frond does not adequately balance the weight of the standard).

Figure 10. presents a sample graph showing the wind direction measured by the vane and the predicted orientation of the Giraldillo by the proposed method for a period of time. As would be expected, fluctuations in the Giraldillo's position are less frequent than fluctuations in the wind direction itself due to the fact that certain wind intensity is required to change its position. Figure 11. shows the agreement between the statistical distribution of the Giraldillo's orientation and the wind direction.

Figure 12. presents statistics on phase difference between wind direction and the Giraldillo's orientation for two periods of time, showing that the Giraldillo ~~accurately~~ indicates wind direction most of the time~~, provided that wind speed is sufficiently high~~. The probability of the orientation of the Giraldillo to be in agreement with wind direction can be obtained for different wind speed ranges from the correlation of the phase difference with wind speed. This probability values are presented as a function of wind speed in Figure 13. for two different periods of time, considering the Giraldillo's orientation to be correct when the phase difference between its orientation and wind direction is less than 20º. The Giraldillo usually functions adequately

as a weathervane at wind speeds higher than 6m/s, while at speeds over 10m/s, there is a nearly 100% probability that it will correctly indicate wind direction. These values are similar to those obtained through instrumental monitoring of the Giraldillo Replica's behaviour, which served as a substitute for the original for six years [5].

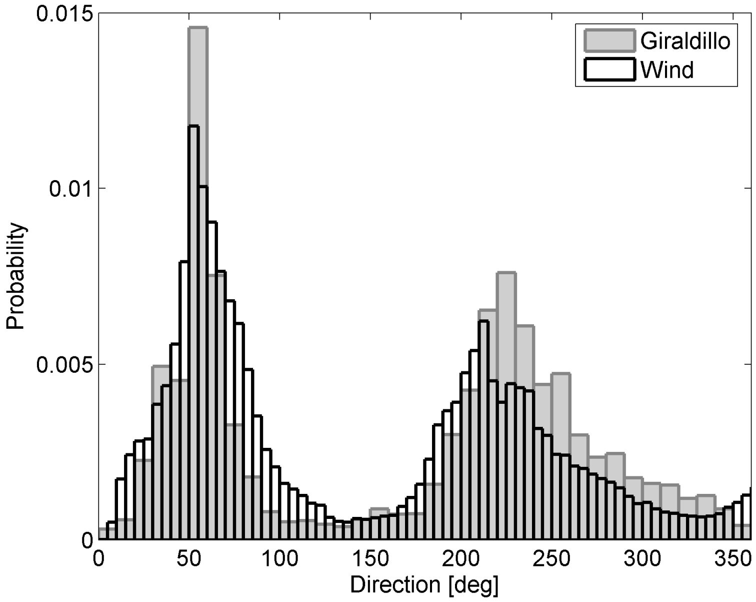


Figure 11. Statistical distribution of the Giraldillo's orientation and wind direction

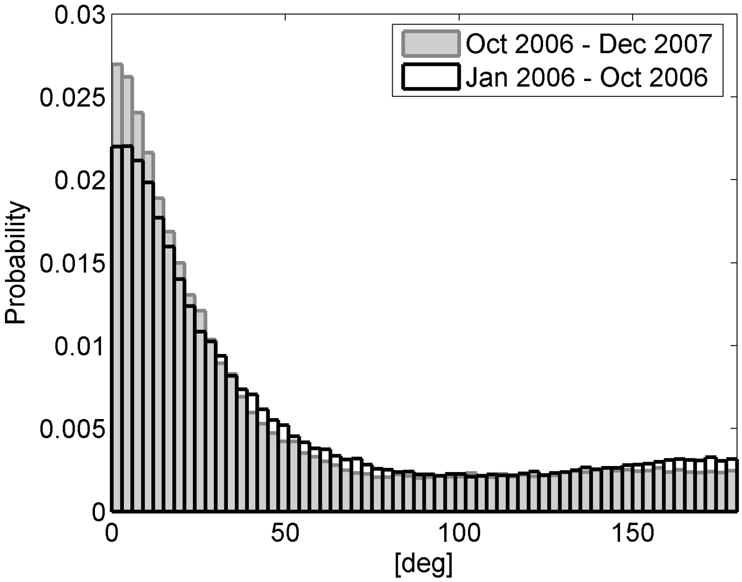


Figure 12. Statistical distribution of the phase difference between wind direction indicated by the weathervane sensor and Giraldillo’s orientation

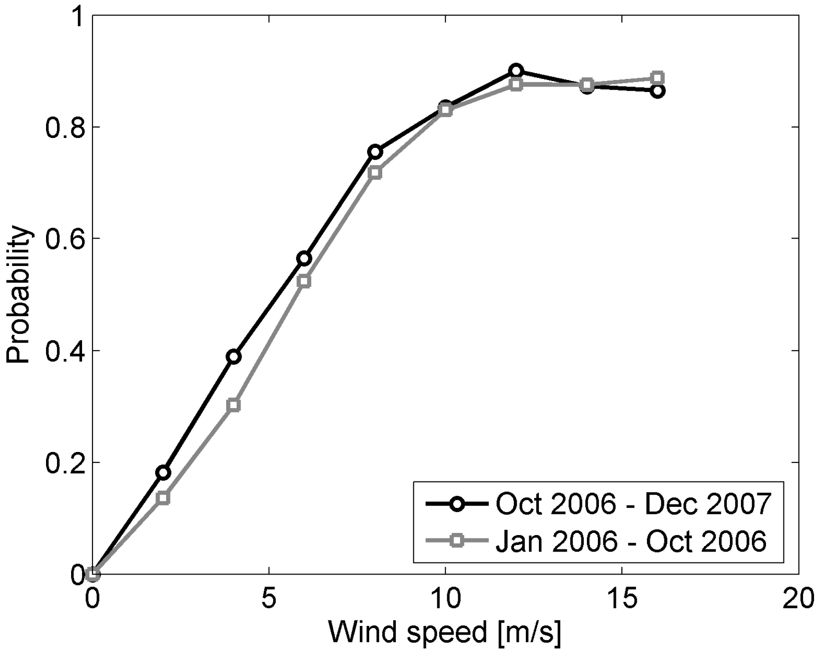


Figure 13. Probability of the Giraldillo to be properly positioned for different wind speed ranges

Figure 11., Figure 12. and Figure 13. can be used to analyze the operation of the Giraldillo as a weathervane and to notice any deterioration on its rotational mechanism.

4.3 Wind speed and direction

Figure 11. presents a graph showing a statistical distribution of wind direction together with the Giraldillo's orientation, which is measured as explained before. The data collected confirmed that northeast (45º) and southwest (225º) wind directions are predominant in Seville. Figure 14. presents a statistical distribution of wind speed, where a typical wind speed of about 2m/s is observed.

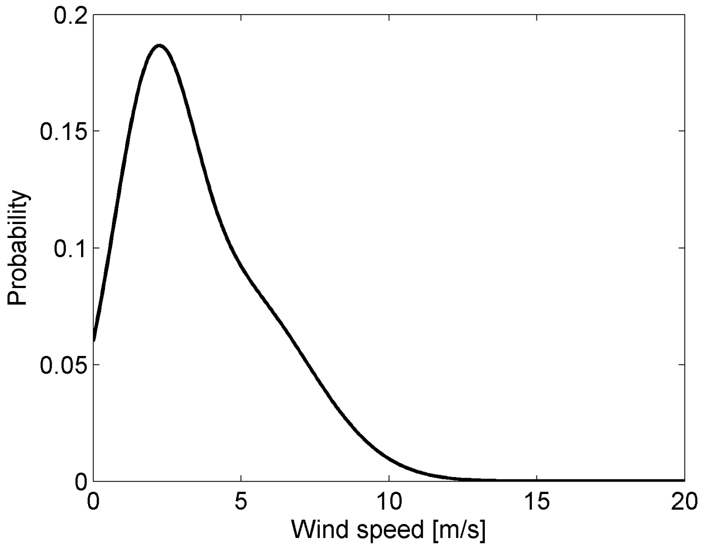


Figure 14. Statistical distribution of wind speed

4.4 Modal Parameters

Using recordings measured with accelerometers and inclinometers installed on the Giraldillo's support shaft, a modal parameters identification was conducted by Operational Modal Analysis (OMA) [[3], [6], [7]. These parameters have been used for the implementation of different damage detection techniques based on the variation of the dynamic properties of the structure. The study of these changes over time, beginning with an original reference state, can indicate the presence of some type of deterioration in the structure and can even be used to identify where the deterioration has occurred.

The natural frequencies and mode shapes are obtained applying peak-picking [3] and frequency domain decomposition techniques [6]. In the first case, information provided by the accelerometers and the inclinometers is employed, while in the second case, only data provided by the accelerometers are used. In some cases, more elaborate modal parameter identification techniques have been employed [7].

Applying this analysis, it was determined that the first natural frequency of the Giraldillo on its support shaft was 1.025 Hz. These results correspond quite closely to the predictions made with the numerical model formulated and analysed during the Giraldillo's restoration process [4]. At that time, a frequency value of 1.09 Hz was estimated.

One curious aspect about the spectra obtained with the accelerometer records was the unequivocal connection between support shaft movements and the movement of the Giralda Tower itself, which vibrates with a fundamental frequency of 0.68 Hz obtained experimentally. This was subsequently corroborated by experimental data of the tower’s dynamic response recorded at other positions, and the value obtained is in agreement with that calculated numerically in previous work [4].

The structure type called for a study of the effect of oblique models [8]. Very similar values were obtained for the natural frequency and for the corresponding mode shape in each of the instrumentation-equipped movement directions (SE-NW and NW-SE directions), and using any of the two techniques employed for their identification (peak-picking and frequency domain decomposition).

4.5 Damage detection

Given the Giraldillo’s difficult access, the application of experimental techniques for remote detection of possible deterioration or property changes in the structure seems particularly advantageous [2]. These techniques are based on changes in the structure modal parameters and have already been applied successfully in other ~~singular~~ structures [9-11].

Using the natural frequencies and mode shapes obtained with the techniques mentioned above, it is possible to obtain some features that can be useful in studying the state of conservation of the Giraldillo's support structure over time. This section details the damage detection techniques employed in this project. For all of them, an undamaged or original condition point of reference is established from the values obtained at the beginning of the project.

The following graphs show a pair of reference lines corresponding to the values $\mu \pm 3\sigma$, where μ is the average of the representative parameter obtained in the first six months of system operation, and σ is the standard deviation of the parameter for that time period, assuming a normal statistical distribution. These references are also useful for gaining an appreciation of the random nature of the data and afford an analysis of possible increases or decreases in the values obtained. The use of more advanced control charts is an issue for ongoing work [13].

4.5.1 Variation of natural frequencies

This technique is based on the decrease in the resonance frequencies of a structure due to a damage-produced loss in stiffness. It serves as a preliminary phase in the study of structural integrity, in which values of natural frequencies of the support shaft are compared with the original (undamaged) state reference values established at the beginning of the project.

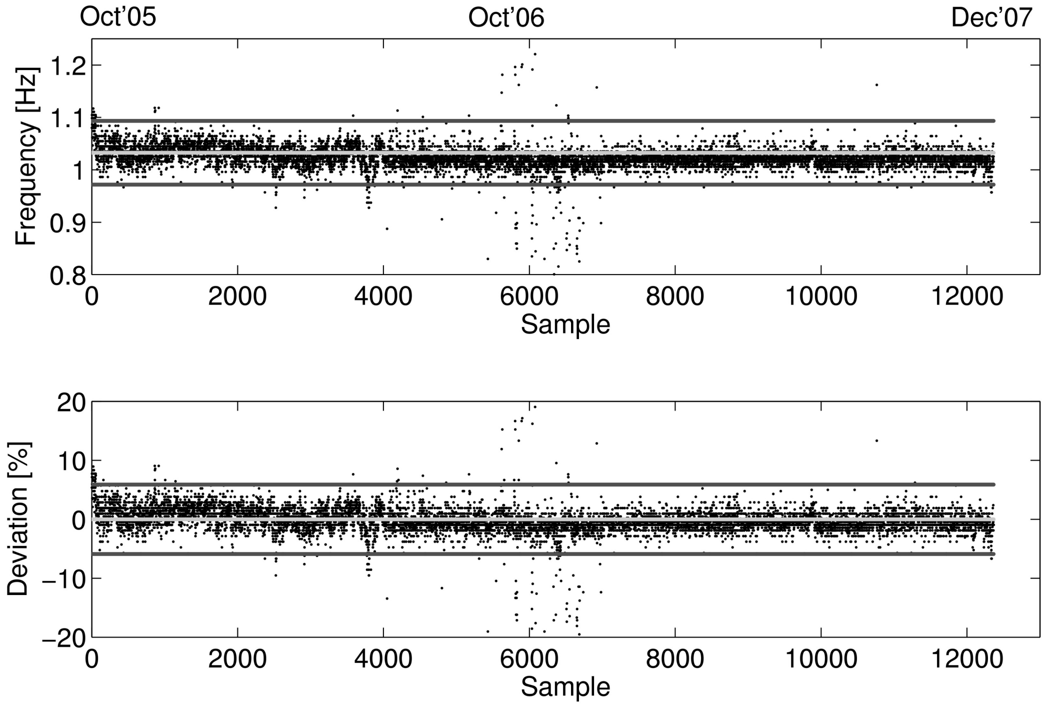


Figure 15. Fluctuations in the first natural frequency obtained for every analyzed recording

It is important however to analyze that this technique, which is based on changes in natural frequencies, has considerable practical limitations in terms of its ability to detect damage, due to the low sensitivity to damage-induced variations in frequency, requiring either very precise measurements or high levels of damage [2]. Moreover, due to the fact that natural frequency is a property of the entire sculpture, variation in this parameter can only indicate the possible existence of damage, but cannot provide specific information as to any structural changes.

Figure 15. shows the variation of the first natural frequency observed in the structure during the period considered. It can be observed that there are no indications of loss of stiffness in the structure.

Changes on temperature might affect the natural frequency values of a structure [9]. However, the influence of temperature in this application is negligible. Figure 16. shows the measured frequency values and temperature for which they have been obtained.

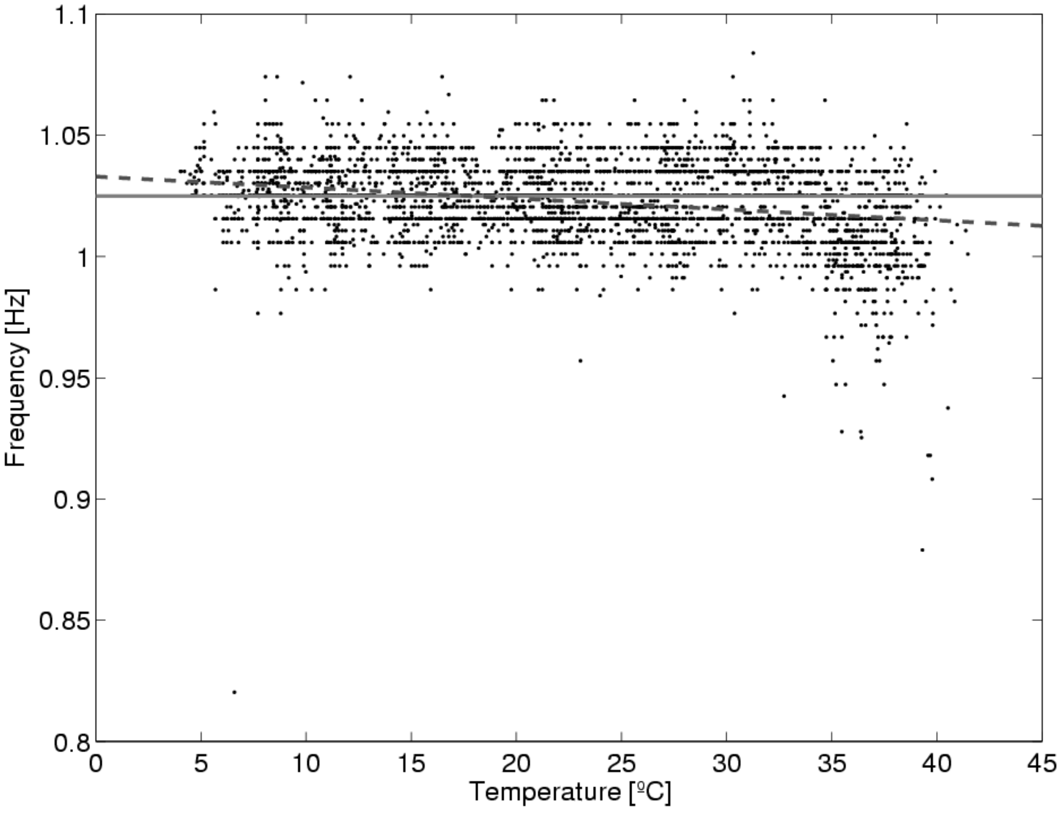


Figure 16. First natural frequency value vs. temperature. Reference value of frequency (1.025Hz) is also plotted with a solid line.

4.5.2 Variation in the mode shape

The presence of damage in the structure can result in changes of the mode shape as well as in the possible appearance of new modes. In this study, in order to detect a change in the shape of the first mode, the Modal Assurance Criteria (MAC) [14-15] was employed, making it possible to quantify the existing deviation among the obtained mode shape and the reference one. MAC values are defined as

$$MAC(\phi_u, \phi_d) = \frac{\left(\phi_u^T \cdot \phi_d\right)^2}{\left(\phi_d^T \cdot \phi_d\right) \cdot \left(\phi_u^T \cdot \phi_u\right)} \qquad (1)$$

where Φ_u and Φ_d represent the mode shape for the original reference and the present situations, respectively.

The MAC values vary between zero and one; a value of one implies a perfect correlation of the two mode vectors (one vector is proportional to the other); while a value close to zero indicates that there are no correlated modes (orthogonal modes). A MAC index lower than 0.9 may indicate the presence of damage. In Figure 17., it can be observed that only a few MAC values under 0.9 have been obtained. They can be attributed, however, to the random and uncertain nature of the experimental results, and do not necessarily indicate the presence of any damage.

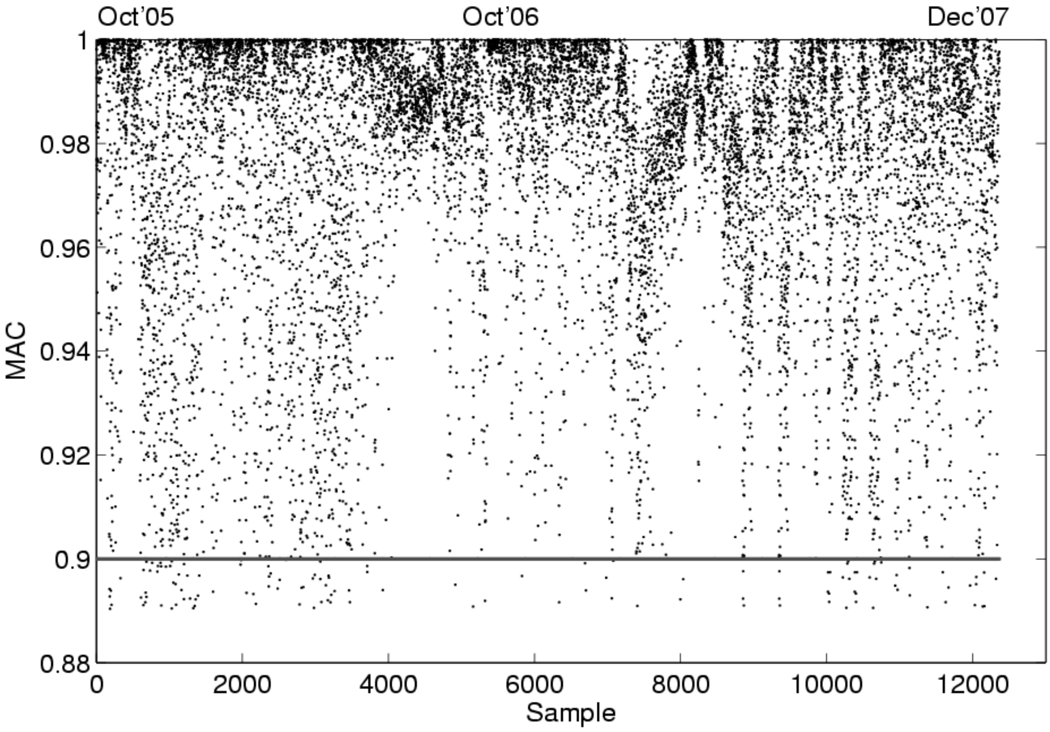


Figure 17. MAC index variation over time

4.5.3 Variation of mode curvature

Another damage detection method employs an analysis of mode curvature changes over time [16]. Curvature values can be calculated with the mode shape using the expression of differences centred for the mode i and degree of freedom (dof) q

$$\ddot{\phi}_{q,i} = \frac{\phi_{q-1,i} - 2\phi_{q,i} + \phi_{q+1,i}}{h^2} \qquad (2)$$

where h is the length of the segment between dof $(q-1)$ and $(q+1)$.

The method derived from this is based on a decrease in the deformation modal energy. A damage index β is defined, where values higher than one correspond to elements where the possible damage is located [17].

$$\beta = \frac{\mu_p^d}{\mu_p^u} \qquad (3)$$

$$\mu_p^u = \frac{\int_{l}^{l_2} \left[(\phi^u (x))'' \right]^2 dx + \int_{0}^{L} \left[(\phi^u (x))}{\int_{0}^{L} \left[(\phi^u (x))'' \right]^2 dx}$$

(4)

$$\mu_p^d = \frac{\int_{l}^{l_2} \left[(\phi^d (x))'' \right]^2 dx + \int_{0}^{L} \left[(\phi^d (x))}{\int_{0}^{L} \left[(\phi^d (x))'' \right]^2 dx}$$

(5)

Figure 18. and Figure 19. show mode curvature changes over time and the parameter β in the three sections equipped with accelerometers. As may be observed in these figures, there are many recordings for which no values are obtained for section 3. This is due to the fact that the accelerometers located at this section have not always worked properly so no information can be obtained for this section in some of the recordings.

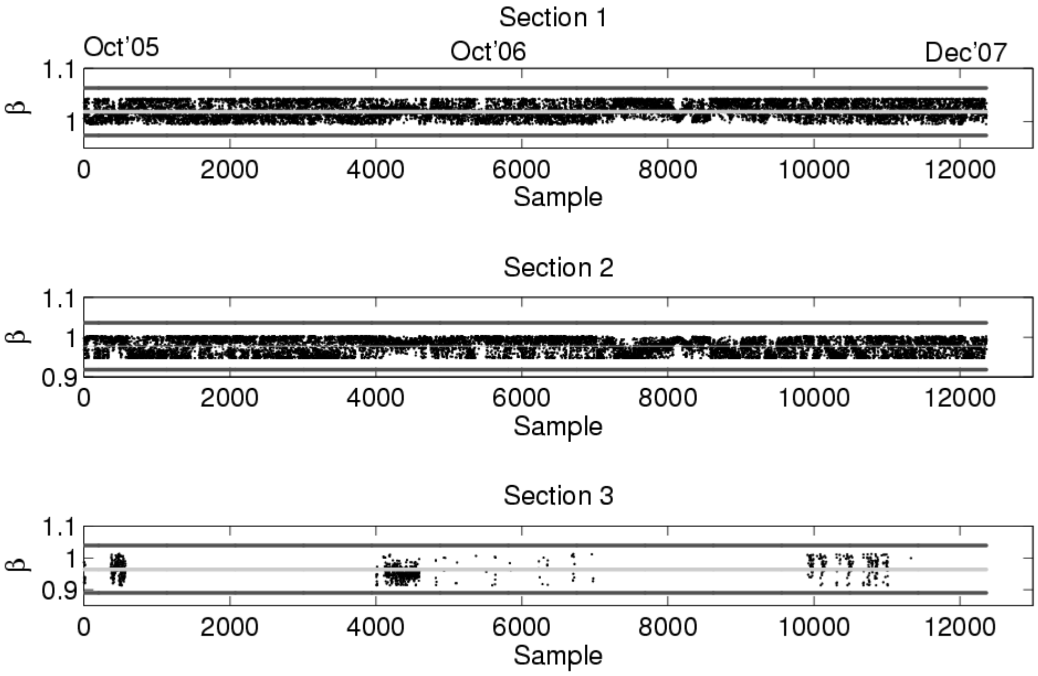


Figure 18. Evolution of variation in mode curvature in the three sections equipped with accelerometers

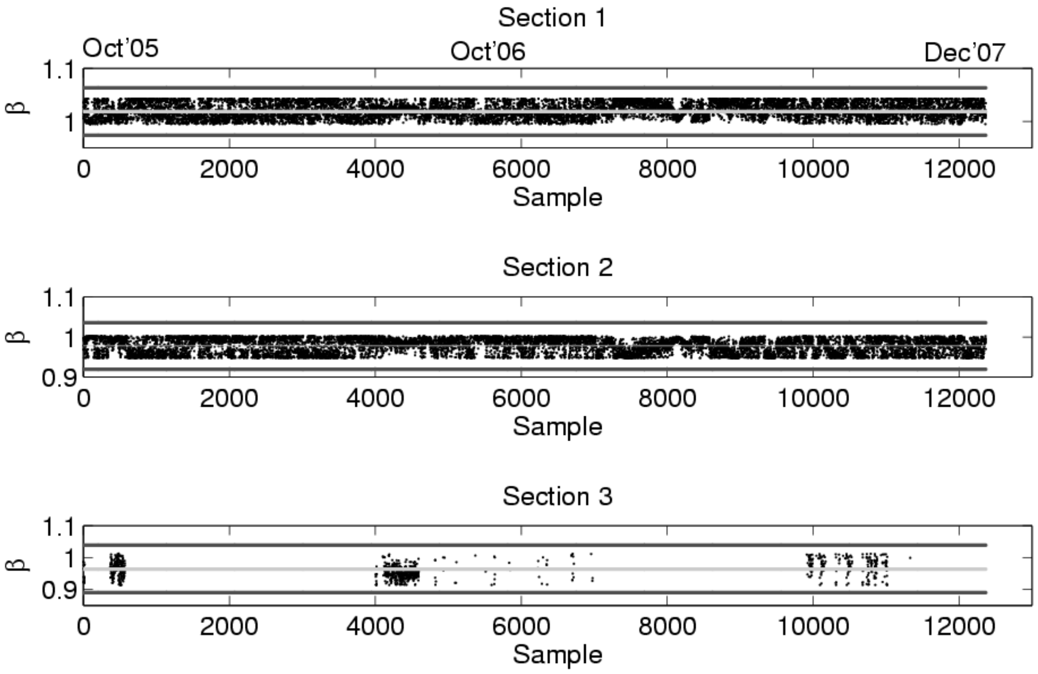


Figure 19. Evolution of changes in parameter β over time in the three sections equipped with accelerometers

4.5.5 Analysis of damage detection results

~~Employing damage detection techniques throughout the period considered, no trends that would be cause for alarm – in terms of support structure behaviour – were observed,~~

During the first two years of operation of the monitoring system, no increasing or decreasing trends in damage detection parameters have been noticed, so it can be asserted that the support shaft structure's state of conservation remains unaltered from the time of its installation. This is not surprising given that the period considered was extremely short compared to the expected functional lifespan for a structure with these characteristics. This type of analysis will become more valuable with time, making certain trends or structural changes easier to detect, thereby allowing for more prompt intervention as needed.

At this point, only the detection and location of damage can be done (which is usually referred to as level two damage detection). In order to quantify the damage, a numerical simulation would be necessary in order to analyze the sensitivity of the damage detection parameters, and more advanced control charts would also be necessary in order to reduce the influence of the random nature of data. Future work will be focused on these two issues.

4.6 Relative humidity, temperature and corrosion

As stated above, a thorough analysis of these variables does not fall within the scope of this article, as this study is geared towards preservation/restoration and materials experts. Daily temperature and humidity fluctuations on the interior and exterior surfaces of the sculpture were however clearly observed, with those on the exterior being more significant. As for temperature, the typical difference between the internal and external surfaces is 5ºC. In the case of the corrosion detection probe, a certain correlation between readings of internal humidity and galvanic potential was observed, which would suggest that ambient humidity conditions may accelerate the corrosion process.

5 CONCLUSIONS

Despite the difficulty on the installation and set up of the instrumentation system described in this article, it can be said that its operation has proven to be satisfactory.

The system has made it possible to obtain relevant information and has proven to be particularly useful for the study of the Giraldillo's behaviour and its state of conservation. Furthermore, the techniques implemented have provided a long-term tool for diagnosing any type of deterioration in the Giraldillo's structure and indicate when it is necessary to undertake remedial intervention.

These techniques have been successfully applied by the authors in previous work [10], [20]. This application shows how structural health monitoring and damage detection techniques based on the dynamic response of the structure are very powerful tools than may be very useful for monitoring complex and inaccessible structures, historical buildings and works of art.

~~The techniques implemented to detect possible defects in the structure have been successfully implemented and have proven to be satisfactory to date.~~

Results obtained up to date indicate that the Giraldillo has not suffered any damage during the last two years, as it was expected since deterioration of this type of structure is a long term phenomenon. In this particular case, the Giraldillo was built in 1568 and its first restoration was carried out in 1770, and a second restoration process took place from 1999 to 2005. Thus, significant damages in the Giraldillo have been historically noticed every two hundred years approximately, therefore a period of two years of operation of the monitoring system is too short a period.

However, given the natural tendency for deterioration in the life of any type of sensor, which is even greater under severe climatic conditions, ~~it is recommended that~~ maintenance operations of the instrumentation system will be necessary more frequently than the restoration of the Giraldillo. ~~that a revision of the installation be conducted at least every five years~~. Moreover, these operations need a complex scaffolding system to be mounted to access wires and sensors, so it entails a significant economic and social cost that needs to be taken into account. Therefore, they should be carried out coinciding with scheduled revision and maintenance operations of the Giraldillo and regardless of whether or not the monitoring system has detected any particular malfunctioning. The multidisciplinary team that was responsible for the restoration of the Giraldillo decided that *in situ* revision should be carried out every five years, which seems also to be a reasonable period of time for the maintenance of the instrumentation system.

ACKNOWLEDGEMENTS

This project is financed by the Andalusian Historical Heritage Institute (IAPH).

REFERENCES

[1] Various authors, (2003). El Giraldillo: Proceso de una Restauración, Consejería de Cultura de la Junta de Andalucía, Sevilla.

[2] Doebling, S.W., Farrar, C.R. and Prime, M.B. and Shevitz, D.W. (1996). Damage Identification and Health Monitoring of Structural and Mechanical Systems From Changes in their Vibration Characteristics: A literature Review. Los Alamos National Laboratory report LA-13070-MS.

[3] Bendat, J.S. and Piersol, A.G. (1980). Engineering Applications of Correlation and Spectral Analysis. John Wiley & Sons, New York.

[4] Solís, M. and Domínguez, J. (2002). Modelo laminar para la recuperación de una escultura de bronce del siglo XVI: el Giraldillo, Proceedings of the Fifth Latin American Conference of Numerical Methods in Engineering (SEMNI-APMTAC), Madrid, 2002, (CD-ROM).

[5] Various authors, (2000). Giganta de Sevilla. Fundación El Monte, Sevilla

[6] Brincker, R., Zhang, L. and Andersen, P. (2001). Modal Identification of Output-Only System using Frequency Domain Decomposition. Smart Material and Structures, 10: 441-445.

[7] Peeters, B. and De Roeck, G. (1999). Reference based stochastic subspace identification for output-only modal analysis. Mechanical Systems and Signal Processing, 13 (6): 855-878.

[8] Ewins, D.J. (2000). Modal testing. Research Sudies Press Ltd.

[9] Peeters, B. and De Roeck, G. (2001). One-year monitoring of the Z24-Bridge: environmental effects versus damage events. Earthquake Engineering and Structural Dynamics, 30:149–171.

[10] Galvín, P. and Domínguez, J. (2007) . Dynamic analysis of a cable-stayed deck steel arch bridge. Journal of Constructional Steel Research, 63:1024–35.

[11] Wu, Z.R. and Su, H.Z. (2003). Diagnosis and evaluation of dam health. In Proc. SHMII-1, Structural Health Monitoring and Intelligent Infrastructures, vol. 1 (ed. Z. Wu & M. Abe), 79–86. Swets & Zeitlinger.

[12] Sohn, H., Zarnecki, J.A. and Farrar, C.R. (2000). Structural Health Monitoring using statistical control process. Journal of Structural Engineering, 126(11): 1356 – 1363.

[13] Kullaa, J. (2003). Damage detection of the Z24 Bridge using control charts, Mechanical Systems and Signal Processing, 17(1): 163-170.

[14] Allemang, R.J. and Brown, D.L. (1993). Correlation coefficient for modal vector analysis, Proceedings of International Modal Analysis I, 110-116.

[15] West, WM. (1984). Illustration of the Use of Modal Assurance Criterion to Detect Structural Changes in an Orbiter Test Specimen. Proc. Air Force Conference on Aircraft Structural Integrity: 1–6.

[16] Pandey, AK., Biswas, M. and Samman, M.M. (1991). Damage Detection from Changes in Curvature Mode Shapes. Journal of Sound and Vibration, 145: 321–332.

[17] Stubbs, N., Kim, J.T. and Topole, K. (1992). An Efficient and Robust Algorithm for Damage Localization in Offshore Platforms. Proc. ASCE Tenth Structures Congress: 543–546, 1992.

[18] Pandey, A.K. and Biswas, M. (1994). Damage Detection in Structures Using Changes in Flexibility. Journal of Sound and Vibration, 169: 3–17, 1994.

[19] Yan, A. and Golinval, J.C. (2005). Structural damage localization by combining flexibility and stiffness methods, Engineering Structures, 27: 1752-1761.

[20] Galvín, P. and Rojas-Diaz, R. (2008). Detección de fallos en estructuras mediante la medida de la variación de sus propiedades dinámicas. Anales de Ingeniería Mecánica, 16: 1147-1154, 2008.