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AN EXPEDITIVE APPROACH FOR STRUCTURAL IDENTIFICATION THROUGH AMBIENT VIBRATIONS

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ABSTRACT

Structural control monitoring is by now widely used in engineering structural field as safety's control approach and is also employed in procedure's assessment for conservation of Cultural Heritage as well as historic constructions and monuments. By the way, the research proposes an optimization procedure through OMA approach and specific sensors (tromograph velocimeters) which transform ambient vibrations (wind, traffic, pedestrian noise, ground's microseismic effects, common urban sounds, etc etc.) in term of sensitive information. In detail, the results of a structural survey of an Italian UNESCO Baroque church are showed. The results, through experimental modal analysis, frequency peak, fundamental frequency and mode shapes, obtained by means Operational Modal Analysis approach, are discussed. The obtained information appear partially critical from the completion point of view, but very useful in presence of the need of a rapid assessment and a speditive analysis. Particularly, outcomes allow to understand the identification of macro-structural elements, with a focus regarding the Façade.

Keywords: SCM, OMA, heritage, AVMs, microtremor, ambient vibrations

1. INTRODUCTION

The structural control of any construction, and particularly of historic ones, has been always strategic and has become a highly significant topic over the last forty years [1]. Nowadays, non-destructive (ND) tests are of fundamental importance in structural health monitoring (SHM) practices, since they can provide valuable information about material and structural properties such as resonance frequency, modal shapes and damping of the historical building [2].

The aim of this work is to evaluate the different positioning of one or more sensors, synchronized or not, for a rapid structural diagnosis in existing historic construction with an OMA approach. The frequency peaks are defined to assess if the control scheme is optimal to obtain the correct information with the less number of sensors. For each measurement is possible to evaluate the value and the amplitude of the related peak, and correlate this information to the structural features of the building. In particular, the micro tremors are considered constant, this hypothesis accounts for the signal synchronization and allows for the recording of the correct relative displacements along the measuring points.

The case of study is the San Giorgio Church in Ragusa (Italy) (**Figure 1**), a UNESCO Cultural World Heritage site. The building investigated is one of the most important examples of Sicilian Baroque architecture, built by Rosario Gagliardi in XVIII century. It is located on the Hyblean Plateu, famous for one of the most powerful and destructive earthquakes in Italian history [3], which occurred in 1693[4] (Mw 7). The high seismicity of the area where the structure is located highlights the need to perform studies aimed at the dynamic characterization of the structure and the subsoil on which it is built [5]. In the present study, the horizontal to vertical spectral ratio (HVSR) and the standard spectral ratio (SSR) techniques have been used to identify the site and the building's fundamental frequencies respectively [6]. In particular, the masonry macro elements investigated with ambient vibration measurements (AVMs) in the current study are the Dome, the right lateral Nave and the Façade. Fundamental frequencies of each macro element were obtained to highlight the mutual interaction between them, following the typical features of masonry structure behaviour. Also, an in-depth analysis regarding the Façade is discussed to compare the results obtained through SSR technique with two of the most common dynamic identification algorithms (e.g. EFDD, SSI).

2. DESCRIPTION OF THE CASE STUDY

Figure 1. View of the Church of San Giorgio

The interior of the Basilica has a Latin cross layout and consists of three aisles divided by two rows of ten pillars each with a transept and a semi-circular apse. The main dimensions are approximatively 27x68m, and the highest point is located on the dome, which is 43m high (see **Figure2**). The dome has a diameter of almost 12m and is founded on 4 pillars with an octagonal plan. It culminates with a lantern on the top and has uniquely distinctive blue stained-glass. The Façade (**see Figure 2**) is of the "tower" type and consists of 3 levels separated by three orders of columns, with the central one slightly convex. The bell tower is incorporated, and ends at the top with a bulb cusp, typical of Capuchin churches.

3. ANALYTICAL APPROACH

In literature, OMA approaches provide many algorithms to identify the modal parameters, applied to masonry historic buildings [7]. Firstly, the eigenvalue problem need to be solved (Eq.1):

$$([K] - \omega^2[M])\{\phi\} = 0 \tag{1}$$

Where $[K]$ and $[M]$ are matrix of stiffness and mass of the system, ω is the circular natural frequency and $\{\phi\}$ is the eigenvector or mode shape. Basically, output-only identification methods to resolve the eigenequation work with an unknown input through a process of inversion, deriving the properties of the structure from experimental output.

Given the matrix $H(\omega)$ as the representation of the dynamic system and equivalent to the ratio between the system's response and the stress the excites (Eq.2):

$$[H(\omega)] = \sum_{i=1}^{n} \frac{(v_i)\langle l_i^t\rangle}{j\omega - \lambda_i} + \frac{(v_i^*)\langle l_i^H\rangle}{j\omega - \lambda_i} \tag{2}$$

The response of the system itself to a dynamic stress is represented in the domain of frequencies by the well-known matrix S_{yy} (Eq.3)

$$\left[S_{yy}(j\omega)\right] = [H\ (\omega)][S_{uu}(\omega)][H\ (\omega)]^H \tag{3}$$

and in operative conditions where the input spectrum is of unknown entity, the central term of Eq.3 is actually constant and is thus independent from the frequency (Eq.4):

$$\left[S_{yy}(j\omega)\right] = [H\ (\omega)][S_{uu}][H\ (\omega)]^H \tag{4}$$

The last equation allows for analytical definition of the relationship between the system's response spectrum and its modal parameters [8]. To solve these problems, a large number of algorithms have been developed such as Peak-Picking (PP), Enhanced Frequency Domain Decomposition (EFDD) [9], Stochastic Subspace Identification (SSI) [10]. Following the expeditious way of the entire method used in this work, PP algorithm has been performed to identify the frequency peaks present in the acceleration spectra. In addition, to validate the expeditive approach results, a comparison in term of peak frequency and mode shapes with the other two algorithms mentioned is present (e.g. EFDD, SSI).
The investigative technique adopted in this work is passive seismic single station, based on micro tremor recordings performed with a Tromino device in a range of frequency from 0.1 Hz to 1024 Hz [11]. As is currently performed in the OMA approaches, the signal's source is Ambient Vibration or Micro tremor. This type of noise is a combination of Rayleigh and body waves and its displacements are in the order of $10^{-4} – 10^{-3}$ cm [9]. The environmental noise may be caused by natural (e.g. microseisms, wind, marine waves) or anthropic origins (e.g. human activities, car, pedestrian traffic, industrial machinery): in the first case the value is less than 1 Hz, while in the second case one his value is above 1 Hz. This approach is used also to determine site effects, employs the Fast Fourier Transform (FFT) to obtain the spectrum [12], whose the mathematical function is expressed as follows (Eq.5,6) where *f* is frequency and *t* is time:

$$h(t) = \int_{-\infty}^{\infty} H(f)\, exp(i2\pi ft)\, df \, = F[H(f)] \tag{5}$$

With h(t): (t) variable function; (F) Fourier Transform Function and H (f):

$$H(f) = \int_{-\infty}^{\infty} h(t')\, exp(-i2\pi ft')\, dt' \tag{6}$$

Note that *h(t)* and *H(f)* represent a pair of particular variables, whose product is 1. This allows the Fourier Transform to be expressed as follows (Eq.7):

$$h(t) = \sum_{n=-\infty}^{\infty} c_n\, exp(i2\pi nf_0 t) \tag{7}$$

If the period *T* of such a function tends to infinity, this causes the frequency f_0 to zero and that the integral form of the Fourier series also applies to non-periodic functions. We can calculate, thus, the Fourier spectra of horizontal H and vertical V components of the signal and then the spectral ratio H/V, which gives us information about the site resonance frequency [13]. Basically, the H/V technique allows to eliminate the effect of noise from the recordings as to obtain a stable curve with the resonance frequencies of the ground. The Horizontal to Vertical Spectra Ratio (HVSR) is one of the most common approaches to study the relationship between the amplification of seismic waves and site effects, linked to the structural damage caused by earthquakes [14]. This method was proposed first by Nakamura [15] after preliminary studies by Nogoshi and Igarashi [16] and it uses the ratio of the geometric averaged horizontal-to vertical frequency spectrum to identify soil fundamental frequency [17]. The test was performed with a tromograph and Fast Fourier Transform (FFT) software, which allows for the evaluation of site effects and analysis of related spectra [18]. Recently, this technique, named Standard Spectra Ratio (SSR), has been used to obtain the fundamental frequency of buildings and identify different modal shapes [19]. The modal frequency response analysis of the structure was carried out using deconvolution, a process of subtracting from the motion occurring at the roof level. In SSR analysis the spectral ratio was computed between the ambient vibrations (Fourier spectra) of horizontal components, recorded at points located on the same vertical at both roof and floor levels, as well as the same components recorded at a reference or standard station (EXT1) located outside the church [20]. In this regard, it is noted that this procedure is only reliable over a long period [21] or if the noise source is the same for the stations in question, including reference (or standard) ones.

4. AMBIENT VIBRATION TEST DESIGN – OMA APPROACH

During the experimental campaign, a total of 18 measurements inside the building and 1 external measurement (EXT1) were performed to characterize the site by n.6 three-component velocimeter, known as tromographs (TROMINO®) (**Figure 2d**). Among the six devices, each one of them is a stand-alone portable unit (~10×14×7 cm) but only two of them can be linked each other through the built-in radio (red version). The first step is to designing the monitoring scheme and it is consisting of positioning through the most optimal way all the devices inside the building due the macro element to be investigated (**Figure 2a,b,c**) and the number of sensors for each typology (e.g. presence of radio channel). This last factor is considered to perform different expeditive approaches for each macro element. The sampling frequency adopted to characterize the macro elements and the site was 512 Hz, for a time length about 16 minutes. In particular, the internal recordings were carried out by positioning the instruments with the instrumental axis parallel to the longer dimension of the church. Grilla® software was used to process the acquired signal during a 20s window and 1% triangular smoothing, and to apply the FFT.

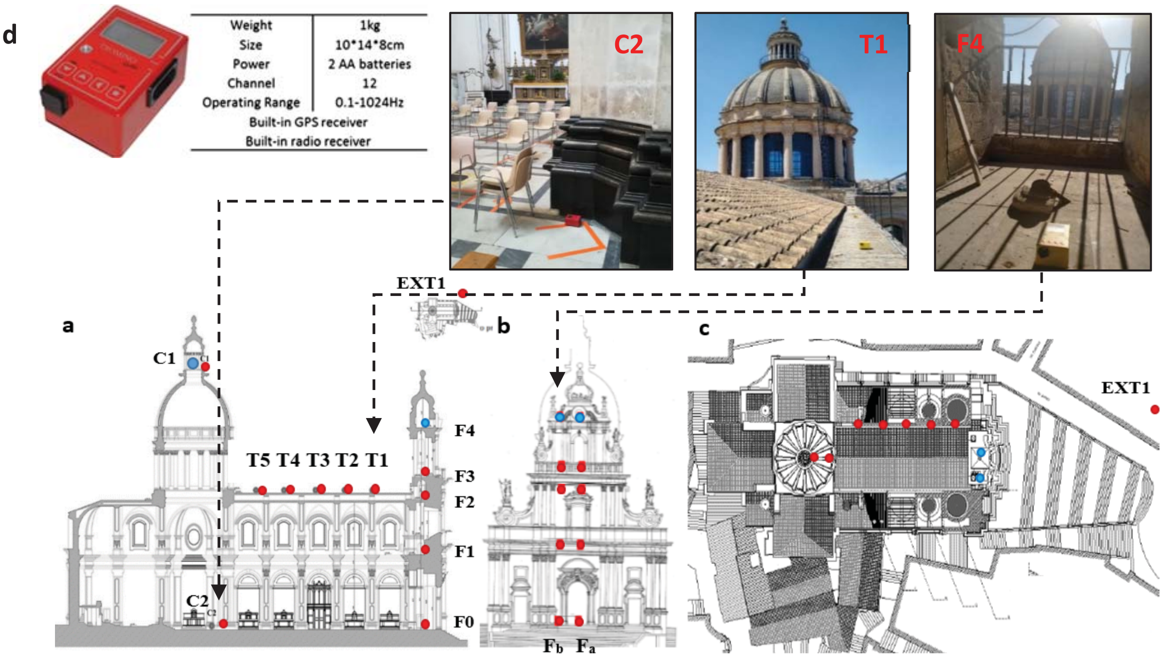

Figure 2. Monitoring scheme with combo Master (blue) and Rover (red) in longitudinal section a), in the facade b), on the roof c); TROMINO d) in location C_2, T_1, F_4.

As is shown in the monitoring scheme in **Figure 2**, the Right Nave has been characterized with n.5 measurements (T1,T2,T3,T4,T5) not synchronized. However, all the five devices started to recording almost simultaneously by manual setting. Otherwise, in the Dome and in the Façade, a synchronized set-up of two instruments, named Master (on the Top) and Rover (at the bottom/correspondent level) is used to characterize the macro elements. In the first case the instruments with the radio option were aligned in the same vertical, and in particular, the Master was located on the Top (C1, blue) and the Rover (C2, red) also near the corresponding pillar at the ground level. Lastly, into the Façade, the couple Master and Rover was located at five levels (0m, 11m, 19m, 22m, 30m) and ten measurements distributed on two vertical alignments, one located in the centre and the second one in the left part, were carried out to obtain the modal parameters of the macro element.

5. EXPERIMENTAL RESULTS

The results are divided into two horizontal components, showing the different peaks for each axis, but regarding to the Nave, only graphs related to the point T1 and T5 are shown (**Figure 3**). Four different peaks are identified for each positioning and reported with the relative average values for each component in **Table 1.** In addition, interesting aspects are visible in the spectra of the Lateral Nave: all measuring points show one peak related to the N-S component (f_1=2,34Hz) and two peaks related to the E-W component (f_1=3,18 Hz and f_2=3,75 Hz). The macro element vibrates at higher frequency along the E-W axis because this is parallel to the axis of minor inertia [22]. Furthermore, in the spectra relative to the point T5, the nearest to the Dome, there are the same values of the peaks of the Dome (f_1= 1,86 Hz in N-S and f_1=1,94 Hz in E-W) because the Nave is affected by the influence of the cupola. In the same way, in T1, the nearest to the Façade, the amplitude of the peak in the E-W spectra at f= 4,74 Hz is larger than other points, this is probably due to the vibration effect of the façade to the aisle.

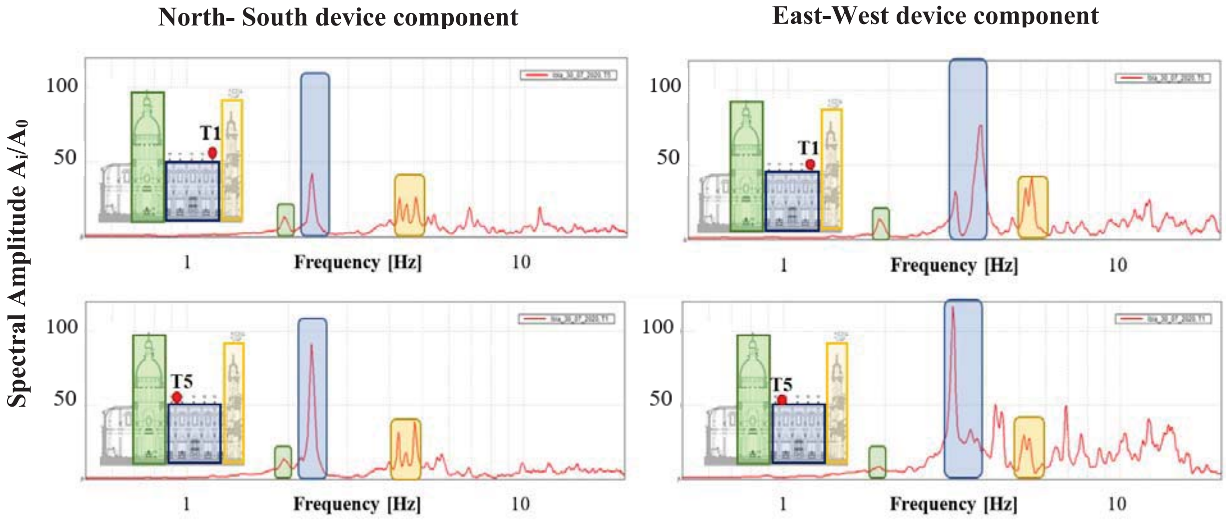

Figure 3. SSR analysis of Right Nave in point T1 and T5, and related spectra of N-S and E-W components

Peak	Macro Element	$f_{N\text{-}S}$ [Hz]	$f_{E\text{-}W}$ [Hz]
No.1	Dome	1,93	1,86
No.2	Nave	2,34	3,18
No.3	Façade/Dome	4,24	3,75
No.4	Facade	4,74	4,43

Table 1. Average frequencies of macro-elements in N-S and E-W direction

In the spectra related to the Dome (**Figure 4**) there are two main vibration modes. The first value is 1,90 Hz in both directions. The second value is 2,50 Hz, and it is shown clearly in the E-W spectra. However, the amplification of the first mode is higher in the N-S axis with respect to the other direction because the Dome is constrained to the short arm of the Latin Cross.

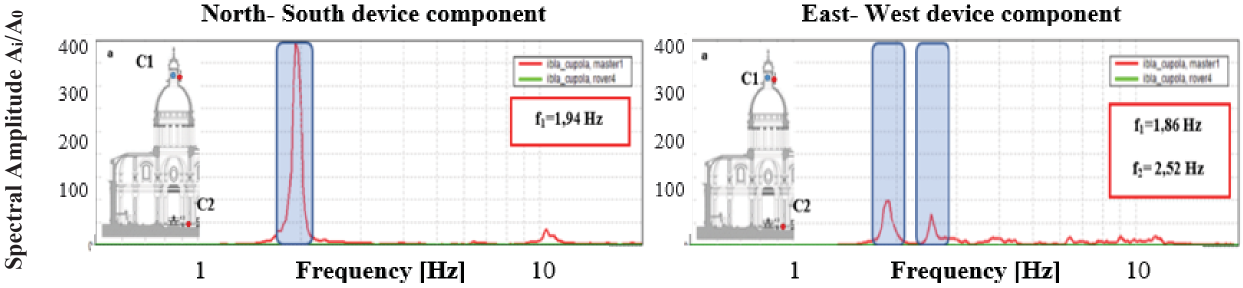

Figure 4. SSR analysis of Dome in point C1 (top) and C2 (base ground floor) and related spectra

Regarding the Façade, we obtained five couple of synchronized measurements (F1 - F5), for each alignment. Then, as an example, only results with centred vertical are shown in **Figure 5.**

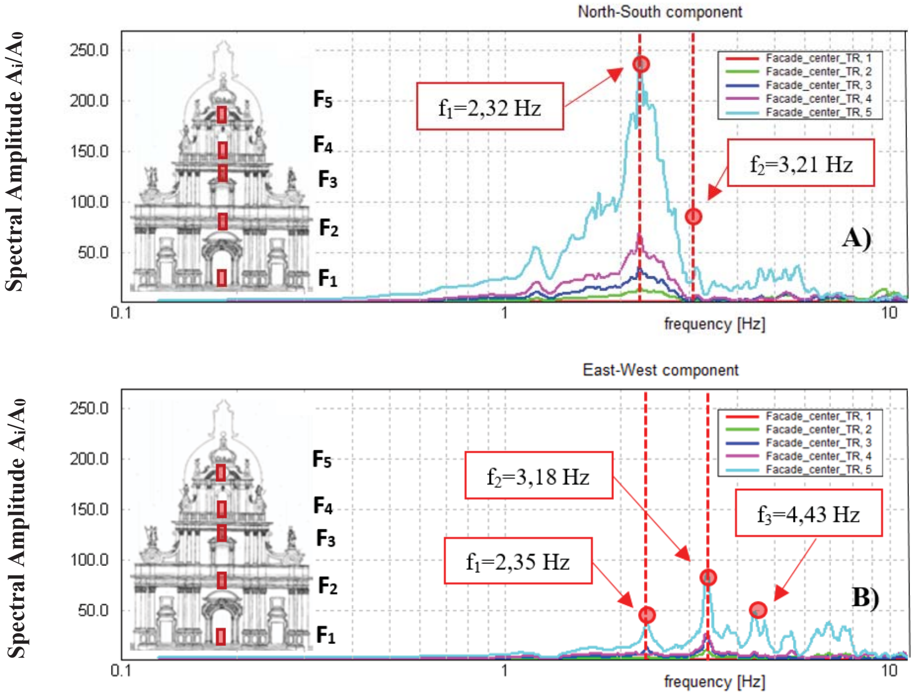

Figure 5. SSR analysis of Façade with the centred alignment, in N-S (a), E-W (b)

In the Façade, analysing E-W spectra, there are three fundamental frequencies values well-defined: f_1 =2,35 Hz, f_2 =3,18 Hz and f_3= 4,43 Hz. Otherwise, in the perpendicular direction, the frequencies obtained are f_1= 2,32 Hz and f_2= 3,21 Hz. In both directions, the peak related to f_1 confirms the presence of the first flexional mode.

In addition, in **Figure 6**, through SSR technique, the mode shapes relative to the first flexional mode in both directions are clearly defined. Moreover, the displacements relative to pt. 4 and 5 are higher in respect to the previous, because from pt. 3 the macro element is not constrained to the Church, in particular to the Central Nave. In this regard, three locations could be named “vital” to define an optimal configuration and describe the modal features of the element with the less number of sensors as possible; i.e. one located at the bottom (TR1), the second one on the top (TR5) and the last in correspondence of the linking with the Nave (TR3). The experimental mode shapes are also compared with them obtained by SSI technique elaborated with ARTeMIS Modal pro software.

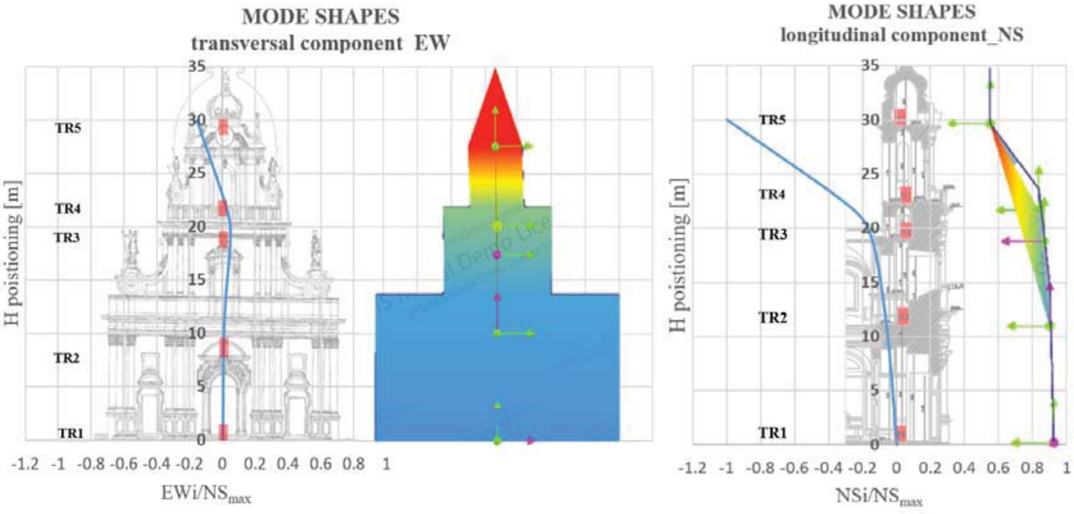

Figure 6. Modal Shapes of Facade in N-S a) and E-W b) direction regarding first mode

6. DISCUSSION

During the experimental survey, basically, three different type of set-up were performed: 1) Multiple-Single station along the Lateral Nave; 2) Single couple (Master and Rover synchronized by radio) into the Dome; 3) Multi-Single couple into the Façade.

The easiest set-up is made using only one device and two recordings, one located in the point of interest (T1-T5) and the second one external near the Church (EXT1). The device used is not provided of the built-in radio and the synchronization in not allowed. However, with the SSR procedure, it has been possible obtain the frequency peaks of the macro-elements, changing the position of the instrument along the Lateral Nave, for five different positions. As is notable in both T1 and T5 points, the proximity to the Façade (T1) or the Dome (T5) is confirmed by the presence of peaks related with interactive effects.

The Master and Rover combo has been essential to a rapid and correct evaluation of the main modes of the Dome. The synchronized recordings show clearly the first flexional mode and, as like the previous case, the influence of the transept in term of displacements. However, only one couple is not enough to consider the possible presence of torsional modes. In symmetric structures like the present one, torsion modes are characterized by having the same spectral amplitude in two measurements at the opposite corners but with opposite phase [23]. Unfortunately, the shape of the elements and his collocation inside the Church does not allow to positioning the instrument to produce this additional consideration.

The last set-up provides as many couple of synchronized recordings as many positions at different levels are available. The rapid mode shapes obtained shows that the number of points available is enough to produce satisfactory results and the matching between the expeditive results and the numerical ones can be easily observed. However, more detailed analyses should be made, including the whole masonry complex to assess the dynamic behaviour of the other macro elements, since the facade in the reality is not isolated.

It is also noteworthy that the OMA approach used in this work even if it is expeditive, is not lacking in precision. SSI and EFDD algorithms were performed to validating the experimental peaks defined with SSR technique. The first mode is correctly identified with the other two analyses (**Figure 7**), and they match with the previous one**,** but using a larger computational borden.

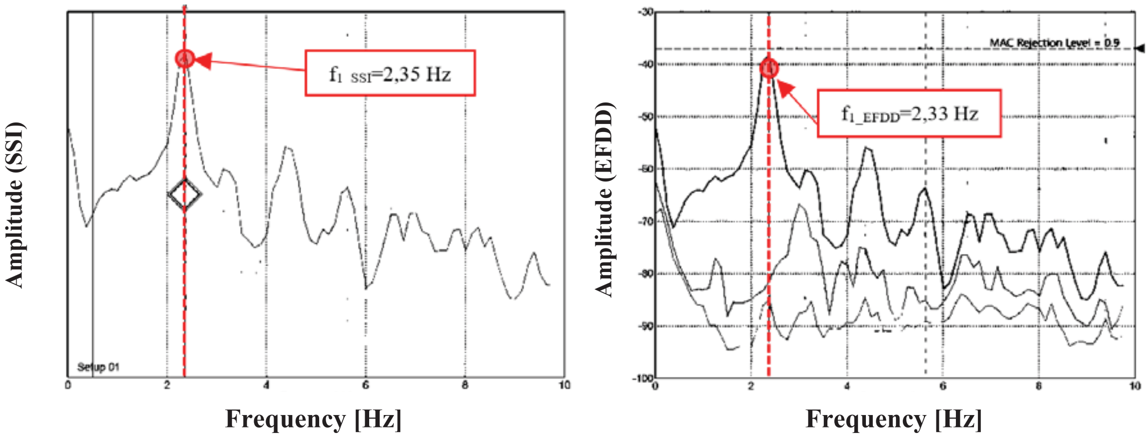

Figure 7. Peak Frequency Identification with SSI and EFDD

Regarding the possible presence of torsional modes, although the instruments were located along two alignments 3 meters apart, this distance is not enough to obtain satisfactory results. Further analyses with different tools will be performed to analyse the phase of the signal and the possible existence of torsional effects.

7. CONCLUSION

The object of this work was to performing an expeditive dynamic characterization in operative conditions of a UNESCO world heritage site through AVMs.
The following results were obtained:

- the fundamental frequencies of the Dome are: 1,90Hz and 2,50 Hz. Regarding the Nave, the values are: 2,34 Hz in longitudinal N-S direction and 3,18 Hz, 3,75 Hz in the transversal E-W component;
- The different set ups show that the synchro option is essential to do not miss the phase of the signal and to obtain the correct mode shapes of the element investigated. However, the SSR technique allows to identify the frequency peaks even with only one instrument.
- For a rapid structural identification of the buildings, the information regarding the modal parameters provided by two points for each macro element and the external one among eighteen (C1,C2, F1,F3, T1,T5, EXT1) are satisfactory.
- Indeed, if we consider just 30 minutes of recording for each couple of measurements the total length of the recordings is less 2 hours, including the instrumental placing.
- The eigenvalues calculation can be guaranteed by four positioning, (EXT1,C1,T5,F5). It should be noted that this is allowed by just one sensor located on the top of the macro element investigated, without any synchronization mode and it provides a huge gain in term of time and costs.

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