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Time and frequency domain analysis of Etruscan pottery magnified videos

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Abstract **– In the present study, the displacement time-series of ancient Etruscan pottery was analysed. The investigated pottery is exhibited within a museum display case and subjected to environmental vibrations induced by nearby urban transportation traffic. Some mathematical tools suited to non-linear and non-stationary analysis, namely the Recurrence Plot and the Stockwell transform, were used for the first time in this particular field. Even though the pottery displacements were small, the use of conventional high accuracy contact sensors should be discarded, due to the extreme fragility of the artefacts. Therefore, it was necessary to resort to a contactless methodology based on video recordings. In particular, the Motion Magnification method was applied to magnify the pottery displacements in order to increase the signal-to-noise ratio, facilitating the analysis of the vibrations. Moreover, it is shown that the Recurrence Plot is able to asses the presence of a real periodic dynamic, and therefore to confirm the frequency domain analysis results even for noisy, non-stationary signals.**

I. INTRODUCTION

This work aims to study the dangerous vibrations affecting pottery, jewelry, votive statuettes, and other small objects exhibited in museum display cases. These vibrations, sometimes visible even to the naked eye, are induced by vehicular traffic, trams, and an underground railway located in the immediate vicinity of the Etruscan Museum of Valle Giulia, Rome (Fig. 1).

Fig 1. View of the museum (on the left) and of the adjecent roads with tramways and urban traffic.

Such vibrations are largely transmitted through the ground, especially to the structure foundations, and turn out to be eminently non-stationary

Their dominant frequencies, which are those with the highest energy content, are mainly below 20 Hz and are the most dangerous. They cause significant oscillations that propagate within the building and thus also to the display cases. The mid-frequency band (20-100 Hz) also affects secondary structural elements, though to a lesser extent. This work has focused on the low-frequency band for the reasons mentioned above. The vibrations are omnidirectional with respect to the road plane, but the vertical ones have the greatest intensity. However, the horizontal motions, despite being of lower intensity, causes a risky dislocation of the objects within the display cases and deserves special attention.

Such dislocations are considered dangerous for the preservation of the artifacts. Therefore, in the past research has been conducted to characterize their frequency spectrum using the Motion Magnification (MM) [1, 2, 3, 4] compared with standard accelerometric measurements, which yielded interesting results [4].

Here, the displacements are analyzed as short, small-amplitude, non-linear, and non-stationary signals, employing both MM and other tools still largely new in the field of cultural heritage protection.

The above methodology was applied to a case study of a vase (see Fig. 2), representing a less critical dynamic situation than those investigated in [4], yet significant due to the large number of similar pieces exhibited in the museum.

Fig 2. The analyzed pottery (the photo is courtesy of the National Etruscan Museum of Valle Giulia).

The first step is acquiring videos of the studied object. Then a portion of the view, called Region of Interest (ROI), is selected so as to catch the average displacement of the studied object. We note that standard contact sensors (strain-gauges, accelerometers, etc.) are too large and heavy to be applied to such objects. Anyway, physical contact was avoided *a priori* for conservational reasons. Also LASER-based systems were considered unsuitable as measuring instruments because they could alter the remaining color on the terracotta of the vase. Therefore, a video-based technique, such as the MM, was preferred. MM can amplify small movements present in digital videos, even if they were not visible to the naked eye before processing. The amplification achieved by digital video through MM is considerable (and within linearity limits, arbitrary). Furthermore, it is possible to specify a frequency range to examine the object's motion within the chosen range. This allows for useful empirical analysis to determine which frequencies are most detrimental to the object, although the information obtained is evidently only qualitative. In the next step, the time series of the ROI are extracted from the magnified video, and a simple average is taken, as if they were signals from "virtual sensors." At this point, a single signal, representative of the vase's displacements, is available for processing with the Recurrence Plot (RP) and the Stockwell transform, described in subsequent paragraphs. Note that the calculations of the power spectral density (PSD) in the frequency domain could easily be altered by noise. Thus, any tool able to confirm the PSD results would be very much appreciated.

It should be noted that the detection of displacements through digital video processing could, in theory, be performed without MM. However, due to the very small values of these displacements, subsequent calculations would be compromised. Hence, the need to amplify the displacements using MM.

II. THE MOTION MAGNIFICATION

The MM technique acts like a microscope for micro-motions present in digital videos unveiling patterns hardly visible to the naked eye, while saving the topology of the image. So, tiny movements present in the video are magnified to become clearly visible. The algorithm works on the pixel intensity value along all the video frames, forming a large number of time-series since each pixel may produce a single time-series, and therefore a large number of contactless "virtual sensors" are made available.

Theoretically, with our resolution of 720 x 1280 pixels, we could have 921,600 "virtual sensors", meaning that each pixel provides a time history of intensity variation, from the first frame to the last one. These time series contain the information about the displacements of the physical points related to the pixels (although they are not real displacements) and are averaged to obtain a single signal that may be analyzed as a conventional one, for example in the frequency domain. Of course, it is not necessary to use all the "virtual sensors", because only a small area of the image is actually interesting, the region of interest. Importantly, the magnification can be operated in arbitrarily selected range of frequencies [1, 2, 3, 4]. Measurements with conventional velocimeters and accelerometers are surely more precise and accurate, but are also expensive and much less practical [5, 6].

Usually, a limitation of the MM algorithm is represented by the frame rate of the processed video. In fact, the frame rate (frame-per-second or fps) represents the sampling frequency of the acquired data.

According to the Nyquist sampling theorem, the maximum frequency of interest (f_{max}) that can be analyzed is the half value of the fps speed of acquisition. Therefore, since most common video camera acquire at around 29 fps, the highest frequency of the studied object that can be analyzed is f_{max} = 14.5 Hz. It is worth observing that many structures have their fundamental frequency below 14.5 Hz, as in our case study. Further limitations in the application of MM methods are related to the physical conditions during video acquisition, such as low or instable lightning conditions, cam-era instability, improper distance or angle of view from the object, etc.

We also should note that recorded videos must avoid large motions such as people passing by in front of the camera and swinging objects. The presence of large motions is one of the most important sources of noise for the MM, often requiring to isolate part of the video.

The measurement procedure follows some steps: the video camera records a footage possibly after a tram as passed by. Then, the video was magnified by a software tool [1, 2] from the Computer Science and Artificial Intelligence Lab of the MIT (CSAIL), entering a frequency range and the level of amplification. An excessive amplification or a too large range will produce disturbing noise into the MM video. There is no simple way to determinate the correct values *ex-ante*, therefore, the procedure may require several attempts.

Finally, the pixel time-series are extracted from a selected region of interest of the magnified video, averaged and processed just as the usual standard signals in the frequency domain.

III. THE MATHEMATICAL TOOLS

The RP is a dedicated time-series tool. It is based on Recurrence described as a point in a state-space x of a multidimensional dynamic system is "similar" to another point at time $t+\Delta t$ up to a distance ε [7, 8, 9, 10].

This situation is expressed by the recurrence matrix **R**:

$$\mathrm{R}_{ij} = 1 \;\text{ if }\; x_i \approx x_j,\;\text{ with }\; i,j = 1 \cdots N \tag{1}$$

$$\mathrm{R}_{ij} = 0 \;\text{ if }\; x_i \neq x_j,\;\text{ with }\; i,j = 1 \cdots N \tag{2}$$

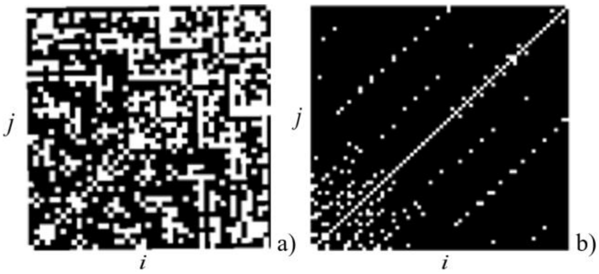

Fig. 3. Examples of RP of a random (a) and a periodic (b) time series.

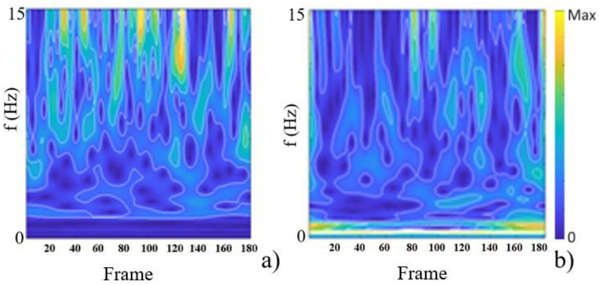

Fig. 4. Examples of the S-transform for a random (a) and a periodic (b) time-series.

In Fig. 3, examples of RP of time-series generated from a random phenomenon and a periodical (single frequency) are depicted. In substance, the matrix compares the states of a system at times *i* and *j*: if they are close, this is indicated by a 1 in the matrix, otherwise we have a 0, displayed in black and white colors respectively (Fig. 3).

Since usually we have only the time-series evolution of one variable of the dynamic system, to calculate the matrix **R** we need to reconstruct the state-space of the dynamic system, that is called a Takens pseudo state-space [8, 9, 10].

The importance of the RP lies in the fact that it is suitable to analyze short time series produced by non-linear, non-stationary systems, which is exactly the kind of temporal data sequence available in our case study.

In the example of Fig. 3b the segments parallel and symmetrical to the main diagonal indicate a clear periodicity. On the contrary, the random signal of Fig. 3a does not show any recognizable diagonal alignments.

This tool is very useful to assess the deterministic nature of a signal, if there is any, even if it is embedded in noise and disturbances. Moreover, it is also possible to quantify the deterministic degree of the signal, although the procedure is quite longer.

The many short diagonal lines in the Fig. 3 represent epochs when the phase-space trajectories runs parallel to later sequences of the trajectories, meaning the dynamics is similar.

The next tool is the Stockwell transform, also known as *S*-transform (see Fig. 4). The *S*-transform is a time-frequency generalization of the Fourier transform [11, 12].

With respect to the Fourier decomposition, the S-transform handles better non-stationary and short time-series, however it may be difficult to interpret. This disadvantage is evident in Fig. 4, where the noise masks the regular pattern much more than the case of the recurrence plot of Fig. 3.

Nevertheless, the distinction with regards to the random pattern is clear, also in the *S*-transform test.

IV. RESULTS

Fig. 5 shows a frame of the pottery magnified video after a tram is passed by close to the Museum. The blue box indicates the studied ROI to obtain the analyzed time series. The arrow indicates the prevailing direction investigated through MM.

The displacements detected by MM are mapped in false color in Fig. 6. In particular, an example of time series of displacements from the pixels in the studied ROI is illustrated in Fig. 7. From such displacements an Averaged/differenced time-series was also obtained.

The PSD of the averaged time-series is displayed in Fig. 8. Significant peaks were detected at 5.4 Hz, 8.2 Hz and 9.4 Hz. Although they are embedded in the noise, which distorts the peak shapes and adds spurious ones, they are quite recognizable.

Fig. 5. Magnified video frame. The studied ROI and the investigated motion direction of are indicated in blue.

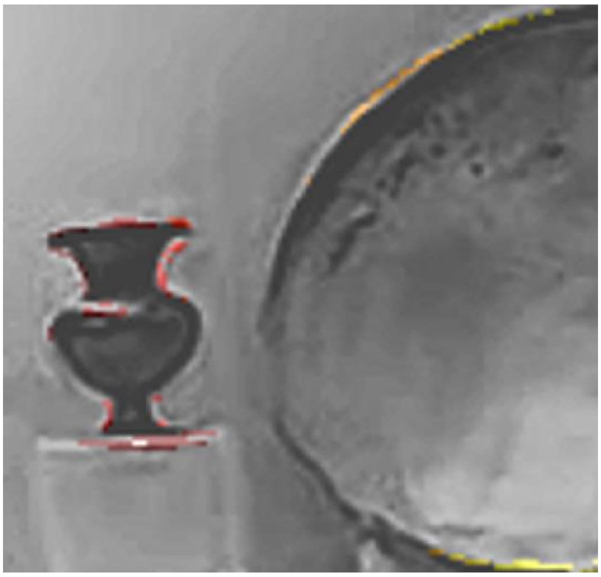

Fig. 6. A frame of the magnified pottery video, indicating the displacements by a color code (yellow-red for the largest displacements, brown for the lower ones).

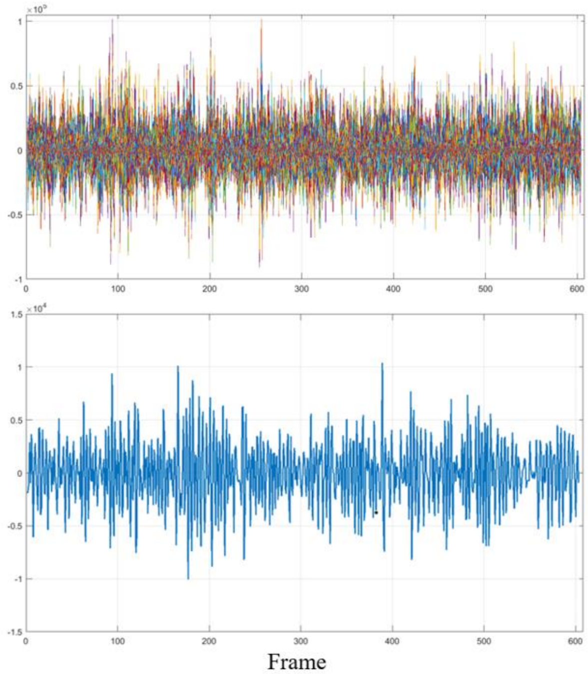

Fig. 7. Displacements time series from the pixels of the studied ROI (top). Averaged/differenced time-series (bottom).

Results show that the use of RPs and the *S*-transform offers added value to traditional analyses, along with some disadvantages. In particular, the RP allows for an instantaneous assessment when the signal is contaminated by noise, in order to reveal a deterministic periodic dynamic.

The Stockwell transform of the studied signal can be seen in Fig. 9. It is to be compared with Fig. 3. It is worth noting the absence of the linear substrate at the bottom of the image, a clear indicator of periodicity, as for Fig. 4 b.

In our case, even though the signal is non-stationary, the periodic components are well identified by the segments parallel to the main diagonal (Fig. 10). Here, we see diagonal segments parallel and symmetrical to the main diagonal, which indicate a periodic deterministic dynamic, even if amidst noise. The three (dotted blue) segments indicate an equal number of peaks in the frequency domain. For the quantitative analyses to identify the parallel segments and the related periodicities, see [7, 8]. Quantitative evaluations related to the PSD frequency values can be obtained from the RP as distance between the parallel segments, but they were not taken into consideration in this paper.

V. DISCUSSION

As noise may well introduce many spurious peaks in the frequency domain analysis, questioning the very *determinism of the dynamic* producing the examined signal, it is useful to have tools revealing any periodic behavior even when the signal is non-stationary and amid strong noise. A periodic RP indicates that frequency peaks are genuinely due to a deterministic vibrational dynamic.

In the context of the MM, this is even more necessary, as the magnification procedure itself is prone to producing a large amount of noise in the magnified video.

On the other hand, the *S*-transform, although much more difficult to interpret than the classic *F*-transform, is better at isolating disturbances and analyzing responses to impulsive stresses, which are common in road traffic.

However, in our case its performance is not satisfactory, since the periodicity of the signal is not clearly highlighted, (see Fig. 10) because of the absence of the linear substrate at the bottom of the image, a major indicator of periodicity.

From the perspective of protecting the pottery, the frequencies detected and verified by the RP provide guidance for the design of isolators for the display cases.

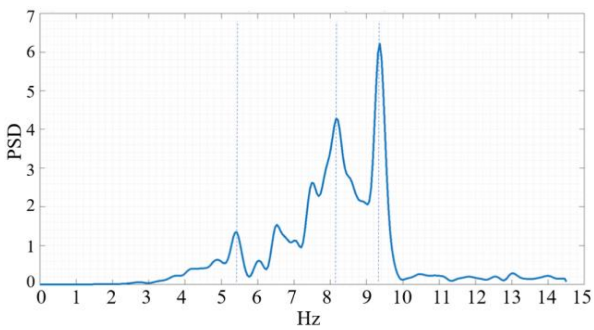

Fig. 8. Power spectral density of the averaged time-series in Fig. 7. Identified peaks at 5.4 *Hz,* 8.2 *Hz and* 9.4 *Hz are indicated by the dotted lines.*

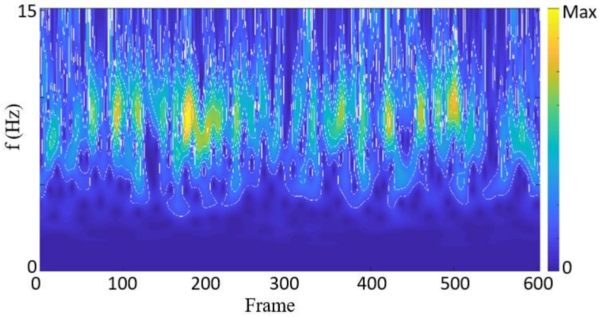

Fig. 9. Stockwell transform of the signal in Fig. 7.

As already mentioned, our analysis stops at low frequencies, but it must be kept in mind that this is the band with the greatest energetic impact.

Now, a few words on the issue of filtering: it would be natural to object that, instead of using tools like the RP to limit the effects of noise, one could simply perform filtering to eliminate the problem itself.

Unfortunately, a band-pass filter is unable to act on in-band noise, while the Wiener filter requires good *a priori* knowledge of noise, and filters based on neural networks or similar methods need numerous training patterns and long elaborations.

Non-linear filters transfer the listed difficulties to the choice of their own functional parameters and are computationally intensive. Actually, also the RP needs the fine-tuning of a couple of Takens parameters, but their algorithms are quite fast, if the time-series is short.

One should also consider that filtering typically eliminates useful components of the signal. Consequently, this option requires a careful evaluation.

A. Main outcomes

Reassuming the main findings of the work, we emphasize the low-frequency peaks of Fig. 8. Should an external vibrational stress match exactly one of these frequencies, the consequences for the pottery's stability would be dangerous.

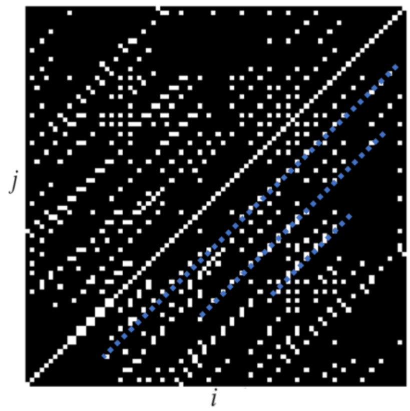

Fig. 10. RP of the signal in Fig. 7.

Therefore, an isolation system for the show case should probably address the issue as a priority.

Moreover, the use of the RP helped greatly to distinguish the effect of noise on the signal. Briefly, the RP proved to be an economical, simple, effective choice for the purpose, and more importantly, it can be employed in any situation where noise is a relevant factor.

Finally, MM confirms as a fundamental methodology for the study of museum artifacts subjected to environmental vibrations.

VI. CONCLUSIONS

An innovative methodology based on unusual mathematical tools for analyzing the vibrations of cultural heritage assets was explored. It was applied to the characterization of the displacements produced by the traffic vibrations to the Etruscan pottery of the National Museum of Valle Giulia in Rome, recorded by digital videos of commercial cameras, in order to provide suggestions for the design of an isolator.

We suggest that the described procedure is not limited to our case study, but is easily extendable to other sectors of the cultural heritage protection. Indeed, all ancient artifacts, whether they are stored indoors or protected outdoors, face the same problems: it is impossible to use minimally invasive monitoring, they are extremely fragile and sensitive to even small vibrations. This makes the protection of cultural heritage a complex activity, which justifies the use of advanced strategies

Due to the very small amplitude of the displacements present in the videos, it was necessary to magnify them by means of the MM methodology. Then, the RP and the *S*-transform were applied to reveal and identify the periodic dynamic of the signal produced by the vibration of the pottery. This is of the outmost interest when noise is so pervasive to cast doubt on the correctness of the analysis in the frequency domain. It turned out that our contactless, low-cost procedure provided promising results and proved to be very effective to study short, non-stationary and noisy displacement time-series.

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