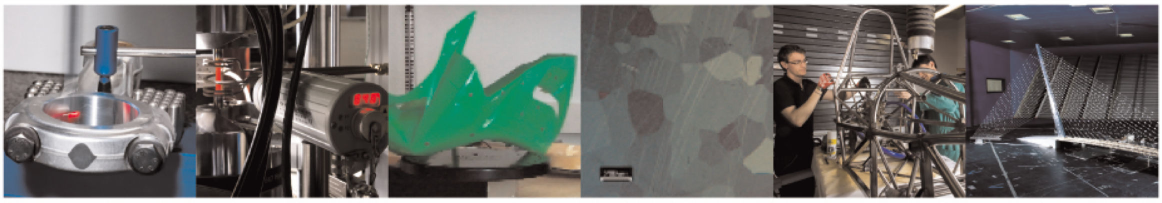

Protecting Pietà Rondanini against Environmental Vibrations with Structural Restoration Works

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This is an Accepted Manuscript of an article published by Taylor & Francis in International Journal of Architectural Heritage: Conservation, Analysis, and Restoration on 12/09/2021, available online: http://www.tandfonline.com/doi/full/10.1080/15583058.2021.1959674

Protecting Pietà Rondanini against environmental vibrations with structural restoration works

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Abstract

Michelangelo Buonarroti devoted the last years of his life to work on Pietà Rondanini. The statue reached Milano in the '50s and it became one of the most important pieces of the Castello Sforzesco collections. In view of Expo 2015, Ospedale Spagnolo was chosen as the new exposition space for the artwork. Subway lines under the new space was recognized as source of vibrations, not present to the same extent in the previous location. Since there is no consolidated knowledge about the effects of low and continuous vibrations on ancient marble, this type of excitation is discussed in this work, together with the peak vibration levels usually considered in scientific literature. In the case study of this work a conservative approach has been applied, reducing as much as possible both peak and mean excitation levels. This goal was achieved in the ambit of the restoration works with a proper selection of construction materials, a proper structural design and the selection of the best position of the statue relying on local vibration characteristics. The Pietà Rondanini project has been an important occasion to deal with both general problem of environmental vibrations in museum rooms and one possible way to solve it.

1. Introduction: the new museum and the new problems

Between the end of 2012 and the beginning of 2013, the municipality of Milan started a discussion about the possibility to move the Pietà Rondanini statue, a symbol of suffering and sorrow, from its position inside Castello Sforzesco in Milan, to the prison of Milan for some time. The project did not come to an end, but the idea to move the masterpiece to a new exposition place, to enhance its value, had started. The new room selected to host Michelangelo's masterpiece was the so called Ospedale Spagnolo, a wide space inside the Castle not yet properly exploited. It was the hospital of the Spanish troops occupying Milan during the plague of 1630, which killed one quarter of Milan inhabitants: again, a place reminding sorrow. It was soon recognized that while the old exposition hall faced a quiet park, Ospedale Spagnolo was more exposed to the city traffic. Apart from cars and buses, two subway lines run very close to the new exposition room, one having a very small radius curve (Figure 1 a), and prone to the creation of short pitch corrugation [1]. Especially the train transit causes both noise and vibrations. While noise can cause annoyance to people, very little is known about the effects of the environmental vibrations on museum artifacts: this aspect is analyzed in the first part of this work.

The vibration propagation path from the subway tracks to the statue to be protected is strongly affected by the characteristics of the underground tunnels (and the rolling stock), of the ground, as well as of the local structural response of the castle (see Figure 1 b). Moreover, the air heating and conditioning units often require installing fans and compressors that are additional vibration sources, often located in the basements. As a result, the perceived vibration level in different positions of the castle can be dramatically different. Moreover, any structural modifications can significantly alter the vibration transmission mechanism. All these aspects are analyzed in the second part of this paper.

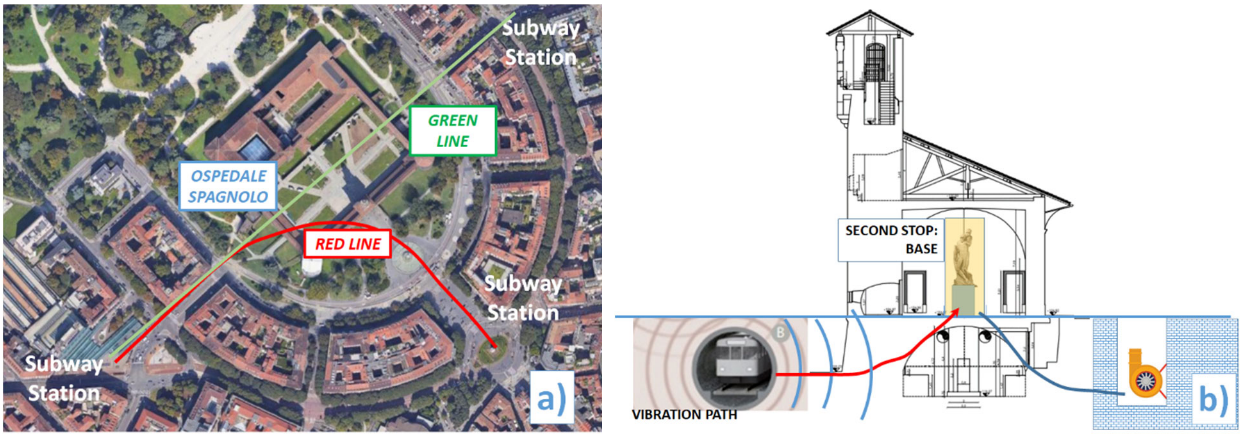

Figure 1: Top view of the Castello Sforzesco and Ospedale Spagnolo with subway line paths hihlighted a) and the elements involved in the vibration propagation b)

2. State of the art

Important expositions are often held in city centers, to attract more visitors, though this causes exposure to higher risks in terms of environmental pollution and traffic-induced vibrations. On the other hand, important events, like political meetings or concerts, demand big central plazas, again putting huge crowds and precious cultural heritage pieces in proximity.

Vibration problems and their effects on cultural heritage are considered a growing problem, not yet deeply investigated: most literature is devoted to the effects of earthquakes and some important papers on the topic of environmental vibrations came out during or after the Pietà Rondanini project. Seismic actions are not the main topic of this paper, though they have been considered too in the Pietà Rondanini project. The main aim of this work is the protection from vibrations produced by railway and road traffic. This problem can be faced with three different approaches: the reduction of the vibration source intensity, the mitigation of the propagation by means of structural modifications of the hosting structure and the creation of properly designed base to be installed below the object to be protected. Vibration source reduction is quite popular in the case of disturbances due to underground, mainly by means of substructures with filtering capabilities or by frequent maintenance, such as rail grinding, or with speed train reduction in the vicinity of the buildings to be protected. Structural modifications are not always possible, since the structure hosting the arti piece can be ancient buildings that cannot be modified. In the case of the Pietà Rondanini protection, the reduction of the vibration source was not possible, while the development of a protection base is discussed in [2-4]. This work focuses on the mitigation actions that can be obtained by means of structural modifications. The preliminary step consisted in gathering the available standards and limits, to prevent marble statues from damage. This was deemed a fundamental step though being conscious that each ancient object has different safety limits, mainly depending upon the material and the state of conservation.

The Italian Ministry of Cultural Heritage published a document [5], which is an official guideline about the technical and scientific standards for museum management. In this document limits about the thermos-hygrometric values, the maximum allowed light and the airborne pollution are given into details, while, about vibrations, this is listed among the risks worth being considered, especially for transportation, even though no limits are provided.

2.1. Seismic and ambient vibration

A literature survey clearly shows the main lacks encountered in the preliminary recognition phase: most literature is related to seismic assessment or to excitation due to transportation. Only a few papers and only in recent times deal with other vibration sources: most cases describe how restoration activities inside or in the surroundings of the museum have affected exposition objects. A growing attention is being devoted to what we term “environmental vibrations”, including in this cluster all sources other than the seismic ones (street traffic, footsteps, trains, restoration works…) which can reach an object in an exposition area. A review of scientific contributes on this topic follows.

If we compare environmental vibrations to seismic ones, the former are more predictable, usually being continuous (or almost continuous), their levels are lower than earthquake vibrations. Moreover, the frequency band of interest is different, as earthquakes span from 0.5 to 20 Hz (limits provided in the structural design [6]), while the typical bandwidth of environmental vibrations considered for damage can reach the upper limit of 80 Hz. That is why protection from environmental vibrations is different from protection against seismic actions. In some cases, the vibration band can excite one of the natural frequencies of the art piece to be protected. In these cases, the situation can be more severe since the vibration amplitude is amplified. In the case of Pietà Rondanini, the first natural frequency in a previous work has been estimated equal to 315 Hz (see [6]), which is out of the ambient vibration excitation. Unfortunately, both the source and the effects related to environmental vibrations are harder to foresee and to be known into details, while seismic shakes belong to a family of phenomena more similar among each other. Continuous vibrations produce effects at the material microscale, however the type and entity of these effects are only partially known [7]. In most of cases vibrations are analyzed in terms of velocity since its value is directly related to the kinetic energy. The Peak Particle Velocity (PPV) value is often used as a synthetic value to define limits for vibration in buildings; according to DIN 4150-3 [8], when the vibration is measured along three orthogonal directions, the PPV is the maximum amplitude of the resulting velocity vector.

Paper [9] describes an interesting project to control the vibration effects during restoration of the Neue Galery of New York, taking care of the safety of both the people and the works of art. G.R. Watts in [10] reports the effects of traffic induced vibrations on heritage buildings: three stone built and one timber-framed. Some authors have tried to concentrate on general requirements to mitigate the vibration problem: in [11] the Canadian government takes care about preventive conservation and the cultural heritage deterioration agents: after a general introduction about the vibration problems for cultural heritage, facing all possible sources, an attempt is proposed to provide some limits, taken from existing standards. In [12] the impact of continuous low-level vibrations is considered as a significant destabilizing mechanism: however, after providing a general guideline on vibration measurements, no limits are provided and just three real cases are shown as examples.

2.2. Environmental vibration limits in scientific literature and Standards

A series of interesting papers is from David Thickett ([13] [14]): he takes the occasion of the restoration works at the Great Court, British Museum, to define some limits which created damage to some artworks, with a discussion on damage examples observed on individual objects.

A second group of papers is from Greek authors, mainly written in the occasion of the excavations for the new subway in Athens and Thessaloniki. Some of these documents focus on numerical models and measurement techniques [15]. Another one, also starting from the excavations for the Athens subway [16], looks for possible limits, starting from those defined by the standard DIN 4150, dealing with the case of buildings, but then also tries to get a reference value for the vibration problem on statues or exposition artworks. The approach to work on already existing standards for buildings is rather widespread, as better explained in the following.

Bill Wei in [17] focuses again on the problem of hall renovations and the possible damage to museum collections, addressing the specific case of the World Museum and Walker Art Gallery in Liverpool. From the same group, [18] is about the design of a damping system for sculpture pedestals: the paper relates to some heavy works on a museum building in Amsterdam, in 2006. The authors state that: “Except for limited studies on paintings (Staniforth 1984, Mecklenburg 1991, Saunders 2005, and Wei et al. 2005), no systematic scientific study has ever been conducted on the relationship between vibrations and damage to specific types of objects. This means that conservators, conservation scientists and curators have to set limits based on limited practical and anecdotal evidence and their own gut feelings and value judgements”.

The effort to define limits finds an interesting contribution in [19], aimed at defining a baseline for allowable vibrations of museum objects. This is managed through the adoption of Wohler curves, in which vibration levels are considered, together with their duration to evaluate the produced damage. In [19] the authors state that the limit of 1 mm/s can be considered safe according with their measures. This limit agrees with limits proposed by Domenichini in [20]. However in [19] the PPV limit of 2 mm/s is considered as reasonable compromise since the limit of 1 mm/s is hardly achieved.

It is also worth mentioning the important activities of Kerstin Kracht on museum vibration problems, which led to an important symposium held in 2018 (“Everything vibrates: strains on artworks and cultural artifacts through mechanical vibration and impacts”). Her most important papers, however, are on the protection of canvas [21], so, even providing important hints, they have less importance for the case of ancient statues.

Probably one of the milestones on both structural and not structural elements is the guide [22]. The authors work on an exhaustive research to define reasonable limits for both buildings and artworks, though in the foreword they write: “There is no commonly accepted standard for vibration limits to protect historic buildings, and vibration limits to protect artwork and other fragile objects within historic buildings are generally not addressed in the literature. This lack of definitive information is problematic for operators of historic buildings, such as museums, that are undertaking rehabilitations or expansions that could expose the building and its collection to vibrations”. This guide recalls again the big problem: the lack of shared limits. Anyway, it tries to provide some numerical values for limits, starting from the commonly adopted guidelines offered by international standards. They too mention the German standard DIN 4150 (again for buildings, in the case of “particular sensitivity to vibrations – class 3”) [8], the British standard BS 7385-2 [23], also adding the limits provided by USBM RI-8507 [24] and in the end those commonly adopted for artworks in the United States museums: it is noted that DIN 4150 provides a limit of 2.5 mm/s in case of long term vibrations.

In our review, we have also looked for some material related to the Orsay Museum, close to the RER subway train lines, in a similar situation to that of the Pietà Rondanini [25]. Though being aware that some work has been done about the vibration problem in that museum, only one paper has been found [26]. Trying to summarize the wide and spread proposed limits all data made available from literature have been graphically resumed in Figure 2.

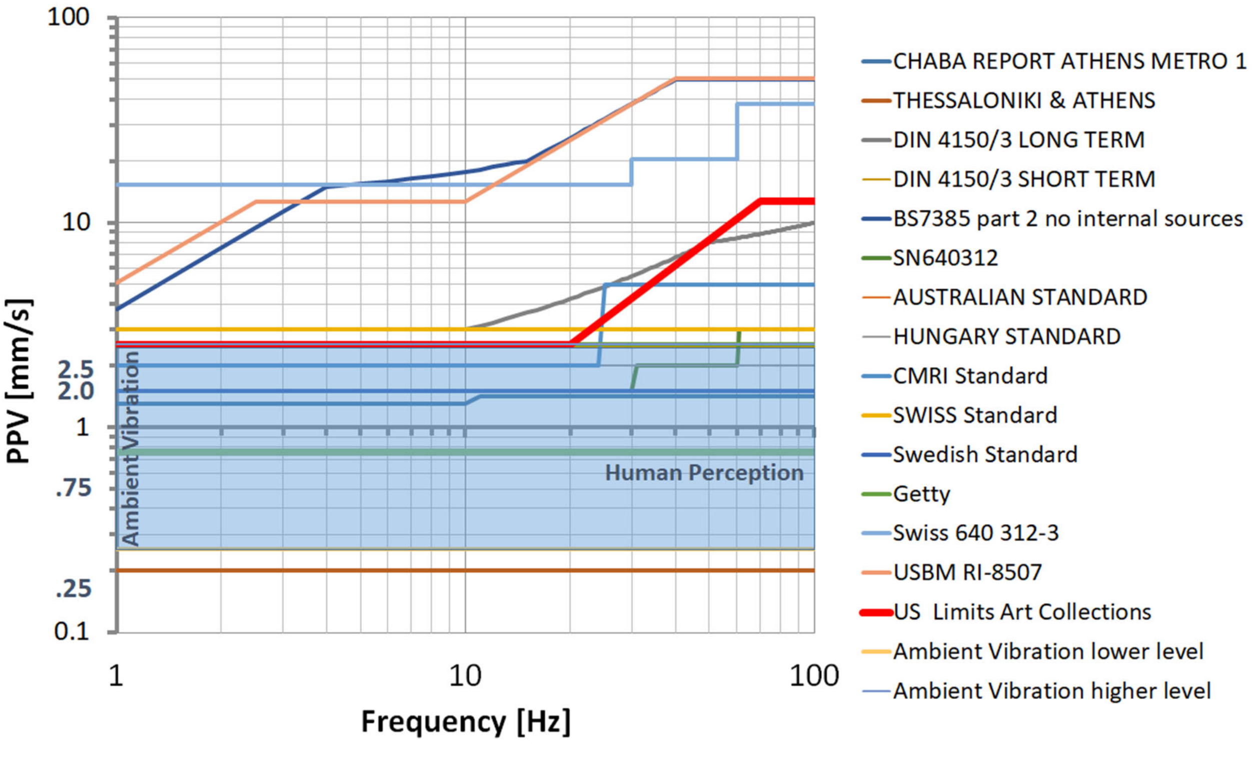

Figure 2: a summary of all limits given in literature

An analysis of Figure 2 confirms that both the values provided by Dr. Wei, a PPV of 2 mm/s and those defined by the US practice are not so far. These vibration limits can be considered a good starting point to assess a museum artwork safety, though being conscious that the piece condition still plays a fundamental role.

2.3. A proposal about new limits

In the analysed literature, vibration limits for museum artefacts are given as PPV. The authors of this paper consider this approach as a reference, which, however, could not be enough to assess a real damage level. The peak level strongly depends upon the considered bandwidth and, apart from limits given by standards, which apply a band-pass filter prior to any examination, there is not a common and shared viewpoint about the frequency limits to be considered. In addition, it is noted how even a high peak, having a very short duration, can have little or no effect on an artwork, while lower levels lasting more time can produce a higher damage. It is therefore thought that damage can be associated to a vibration dose, a parameter combining the magnitude of vibration and the time for which it occurs. This concept is also used in many standards, such as ISO 2631, and it is usually adopted to define comfort levels for humans. In this work the applicability of the vibration dose for art pieces is studied. In the following of this paper, a direct comparison against literature maxima will be carried out, and emphasis will be devoted also to the average energy content of the recorded signals, which represents an index of vibration dose. Energy vibration content is estimated as the running Root Mean Square (RMS) of the vibration values. This will help in a direct comparison among different situations analysed inside this research, all of them evaluated under the same conditions (among the others the considered frequency band).

3. Environmental vibrations at the original Pietà Rondanini location

The evaluation of the environmental vibration levels at the original location of Pietà Rondanini was carried out as a preliminary activity of the whole project, to get a target baseline for acceptable vibration levels. In fact, starting from the lack of standards and literature references, the original situation of the statue represented a safe condition. An important vibration source was the movement of visitors. For this reason, a first three-day measurement was carried out including a weekend, since the museum is more crowded during weekends. Vibration measurements were performed by means of accelerometers placed close to the Pietà Rondanini base, both on the floor and on the marble urn supporting the statue. A three-axes acceleration measurement allowed for a complete spatial vibration characterization. The adopted piezoelectric accelerometers were PCB 393A03 with a full-scale range of 5 g, a bandwidth 0.5 Hz to 2kHz and a sensitivity of 1 V/g. Acceleration signals were acquired by means of NI9234 modules by National Instruments, having a 24-bit Analog to Digital Converter and anti-aliasing filters. The sampling rate was 1024 Hz. The marble base is extremely rigid, so the acceleration measured on the floor and on the upper urn surface showed negligible differences. Hence, from here on, only the data measured on the floor will be shown.

In agreement with what stated by the international standards (see section 2), the effect of vibrations was primarily evaluated in terms of peak particle velocity (PPV). Vibration velocity was obtained by integration in the time domain of the acceleration signals. The integrated signal was then further filtered by a band-pass filter in the range 0.5-300 Hz, mainly to remove high frequency noise and to avoid the drift in numerical integration due to possible small bias in the signal. Figure 3 shows the Root Mean Square (RMS) of the velocity signal computed over temporal windows of 3 s, without overlapping. The choice of short windows of 3 s allows to maintain a good level of time resolution, giving the possibility to detect any high-energy-content event, for further analysis. Similar vibration levels are observed along all the three normal directions, without any significant variation during the three considered days. There is not a remarkable difference between day and night: this suggests that the movement of visitors near the statue has a negligible effect on the sensed vibration levels. In Figure 4 the same RMS time records are given in terms of acceleration. This representation allows to detect the presence of higher vibration levels during the day than during the night. This difference is not visible in the velocity plots since the higher acceleration peaks are associated with relatively high frequencies components corresponds to limited velocity peaks. In addition, the general vibration levels appear to be low, both in acceleration and in velocity. As already written, these data can be assumed as a safe condition for the following evaluations at the new Pietà Rondanini location.

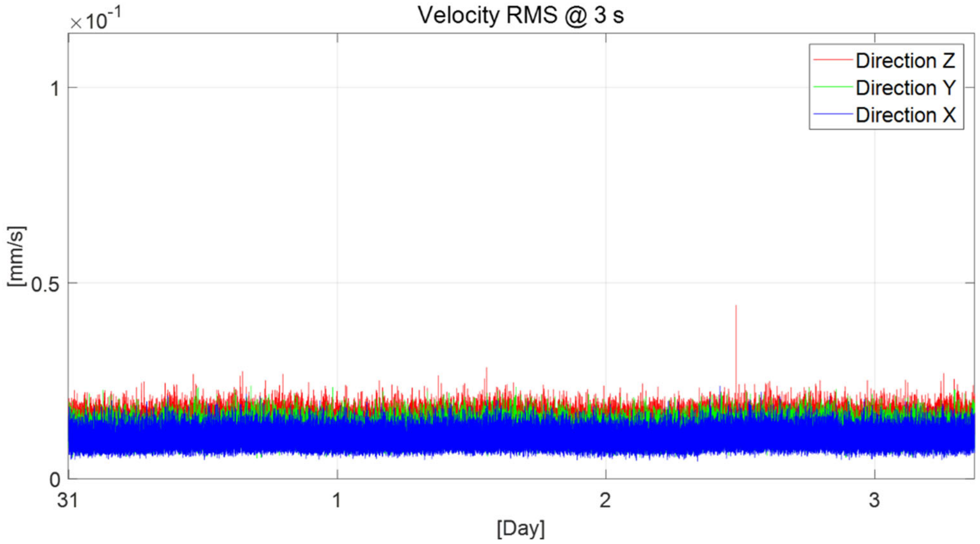

Figure 3. Time histories of velocity RMS on the floor in the original location of the Pietà Rondanini.

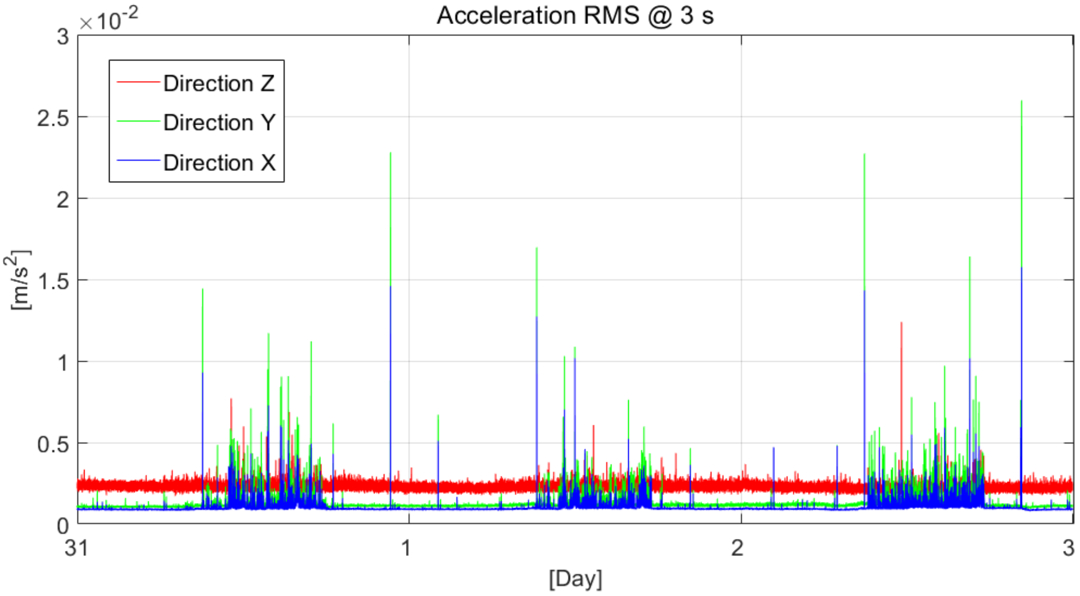

Figure 4. Time histories of acceleration RMS on the floor in the original location of the Pietà Rondanini

4. Preliminary vibration measurements to identify the best position for the Pietà Rondanini in the Ospadale Spagnolo

The new Pietà Rondanini museum is in an area inside Castello Sforzesco named Ospedale Spagnolo, a wide rectangular room close to the castle perimeter wall. As previously mentioned, the building is in the surroundings of two subway lines: vibrations were clearly perceptible in the room. It was hard, even for an experienced researcher, to separate ground borne vibration from the wall noise emission, without the aid of proper instrumentation. Since the floor of the room is not directly laid on the ground but is supported by vaults, sheltering a big basement, it was reasonable to assume that the building structure can have a crucial influence on the vibration transmission mechanism, producing different levels in different room positions. A prediction map of the floor behaviour was nearly impossible, due to the masonry structure of vaults, with sand fillings and the presence of hidden elements like tie rods in the floor or other reinforcements, in positions not exactly known. For this reason, a measurement campaign was carried out to get an estimation of the vibration levels in different points of Ospedale Spagnolo, with the final purpose to map those positions to be preferred or those to be avoided. Figure 5 shows a sketch of the Ospedale Spagnolo floorplan, with the possible statue positions, as given by the architectural design and from the need to follow the vibration path from the subway to the foundations, walls and then to the room floor. The three possible locations are along the dashed line in Figure 5. Position 3 was also selected for a complete structural characterization, though not acceptable to place the statue, because it was closer to the vibration source: the main wall.

Vibration measurements have been performed by means of the same type of accelerometers already used for the test described in Section 3 and with the same data acquisition hardware and software. The test set-up consisted of two units, measuring accelerations along three normal axes (6 sensors in total), thus getting the response of two points at the same time. One triad was always kept in a fixed position (named 0), while the second was moved to cover all the other points. Data acquired by the triads in each position were processed, following the procedure presented in section 3: acceleration signals have been filtered and numerically integrated to obtain velocity data, allowing to get values directly comparable to those measured at the original statue location and to the reference standards. RMS values every 3 s, without overlapping, were also computed. In Figure 6 the velocity RMS time records are shown for positions 0 and 1. Although the duration of these preliminary measurements is relatively short (about 30 minutes), it is possible to note that, as expected, the vibration levels at the Ospedale Spagnolo appear to be higher than those observed at the original statue position.

To compare the vibration levels in the four considered positions on the floor of Ospedale Spagnolo, the ratios among the RMS velocity values in each position and those recorded in position 0 have been computed. Figure 7 shows some examples. The ratios do not change significantly even for longer acquisitions. From these plots it is possible to see that on average the vibrational energy of position 0 is the lowest among all the considered positions. It appears how, moving from position 0 towards the room entrance (points 2 and 1) the vibration levels slightly increase. The subway tracks are just in front of the main door, so closer to position 1: this can explain the observed trends. Position 3 shows vibrations in the vertical direction similar to those of the corresponding point at the centre of the room (position 2), while vibrations in the two horizontal directions at position 3 appear to be much higher than the others. This could be due to the proximity to the room wall, which constitutes a preferential propagation solid path for these shear vibrations.

As known, RMS values represent the overall energy associated with a specific vibration, but they cannot provide any indication about the frequencies at which energy is concentrated. For this reason, a spectral analysis of the measured acceleration signals has been performed. Spectra were computed on 2 s time records and then averaged. In Figure 8 the magnitude of the acceleration spectra is shown for positions 0, 1, 2 and 3 in the frequency range 0-120 Hz (at higher frequencies vibration amplitudes are less prone to cause damage). It is therefore possible to see that also the frequency domain representation confirms that vibrations recorded in positions 1 and 2 are on average higher than those in position 0. Also vibration levels in position 3 are in general higher than in position 0, except for vertical direction at frequencies in the range from 21 Hz to 26 Hz, where a resonance that involves vertical movements is visible. For this vibration mode the centre of the room appears to be subject to higher amplitudes of motion than the point close to perimetral wall, resulting in a different dynamic response of the two regions.

In conclusion, among the three considered points for the placement of the statue inside Ospedale Spagnolo (point 3 is only for comparison), position 0, showing the lowest vibration levels along all directions, has been selected as the best: it is the furthest from the railway tracks and no relevant dynamic amplifications have been observed. The architectural design of the exposition has also accounted for this. In fact, the final statue position is close to point 0.

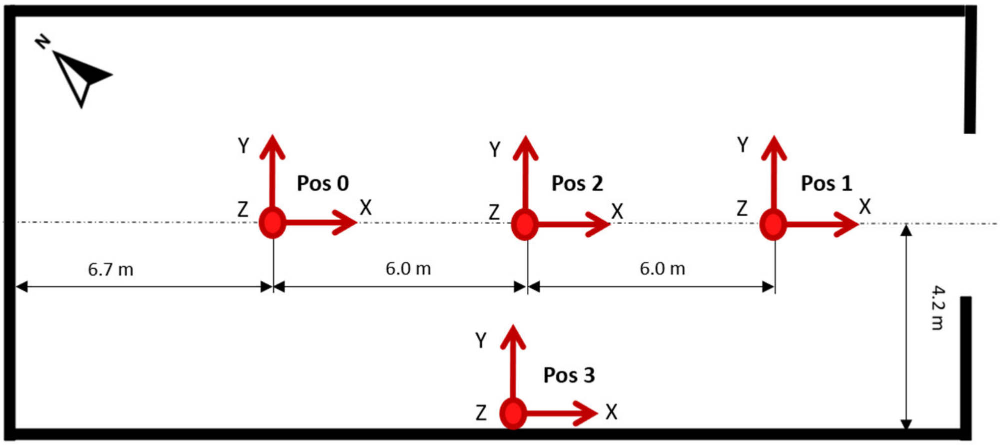

Figure 5. Floorplan of old Spanish Hospital and positions considered during preliminary investigation of levels of vibration. Rows indicate the placements of each triad of accelerometers.

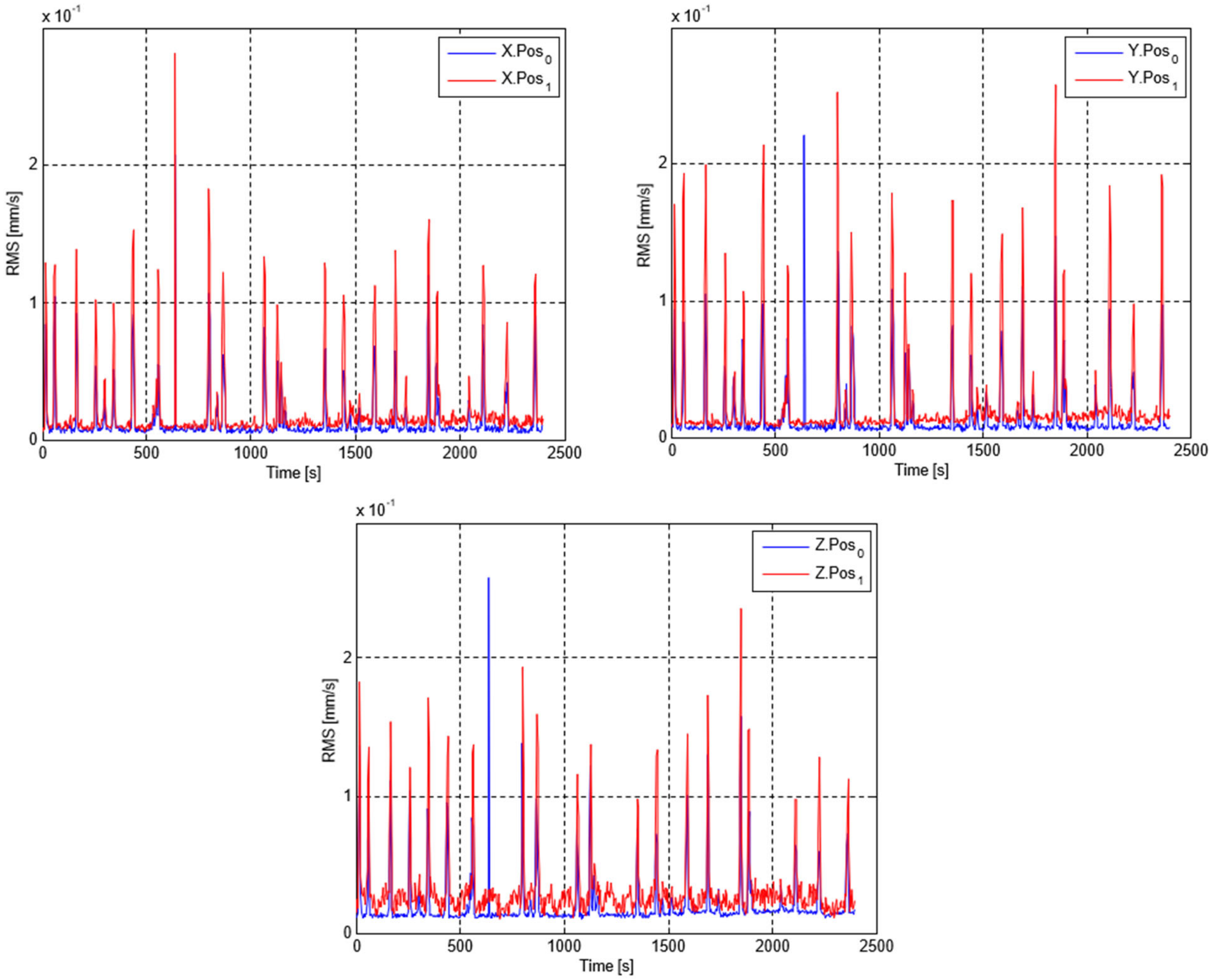

Figure 6. RMS velocity time records relative to position 0 and 1, in the three direction X, Y and Z (vertical to the floor)

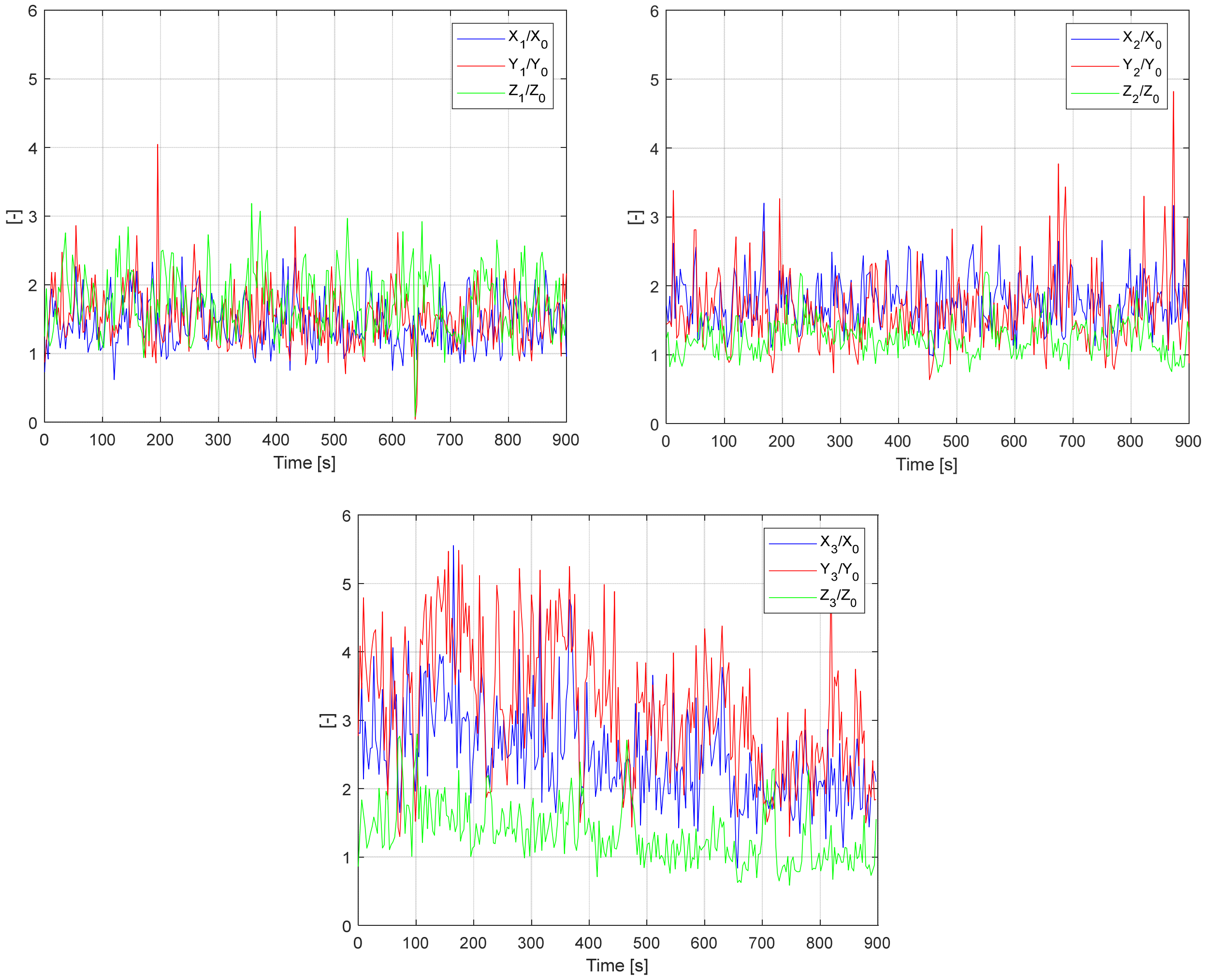

Figure 7. Ratio between velocity RMS in positions 1, 2 and 3 and the corresponding velocity RMS at the reference position 0.

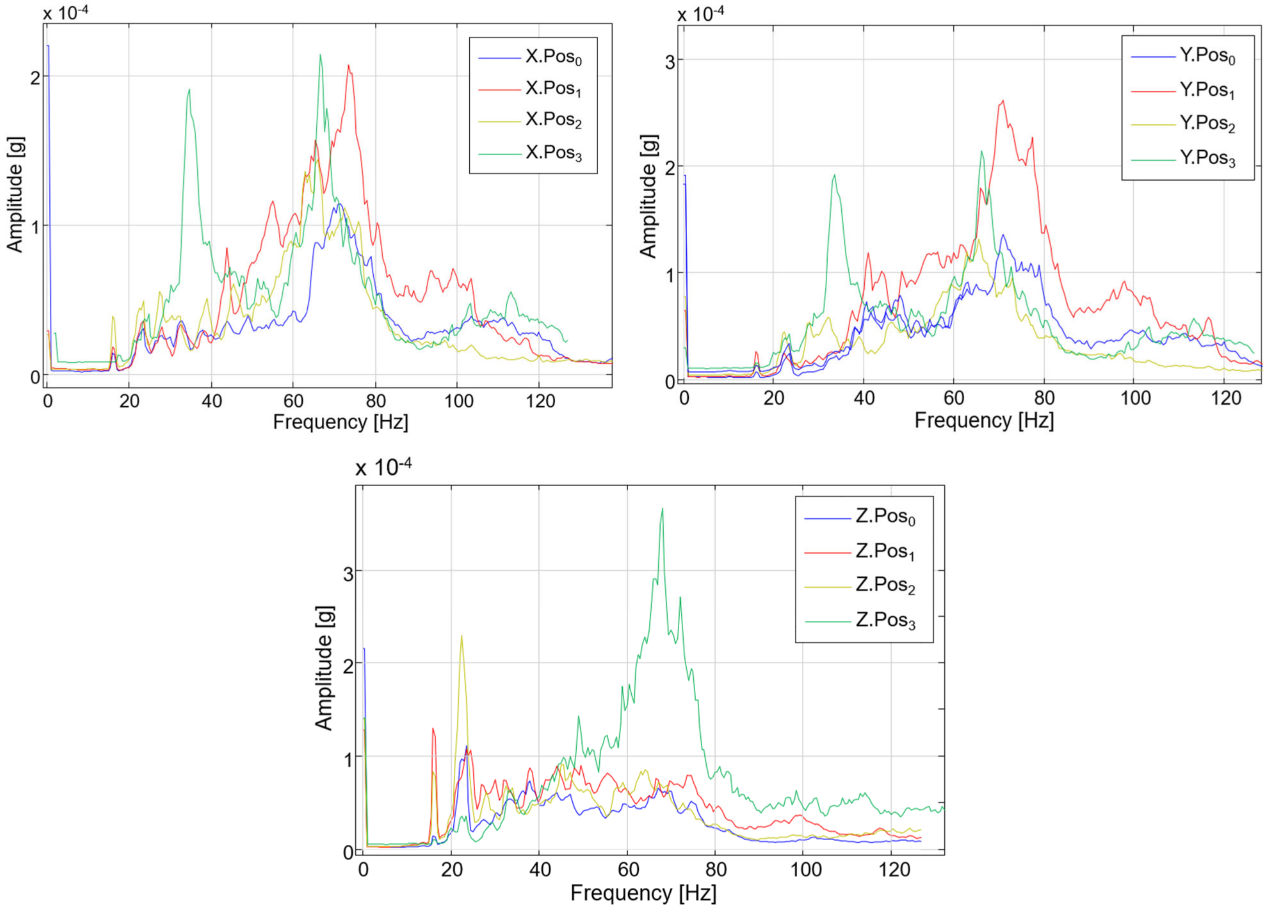

Figure 8. Amplitude spectra of the accelerations measured in positions 0, 1, 2 and 3 in the three directions X, Y and Z.

5. Influence of the structural response and the changing environmental conditions

Once completed the preliminary vibration survey, the best position to place Pietà Rondanini was pos 0 in Figure 5. A more complete vibration characterization was then carried out, with a longer test, lasting five days, some of them working days and then a complete weekend. This investigation followed the same approaches already adopted for the analysis of the vibrational levels at the original statue position. With reference to Figure 5, a triad of accelerometers, placed in position 0, was used to measure vibrations for a time record long enough to include different excitation conditions. The adopted accelerometers and data acquisitions system are the same already employed for the previously described measurements.

5.1.1. RMS values analysis and comparison with the original position

Following the same procedure already presented in the previous sections, the acquired data have been converted into velocity values first, and then analysed in terms of RMS, computed over 3 s windows. In Figure 9 the velocity RMS time histories for the three considered directions are shown. A clear difference is seen in the comparison of the vibration levels between days and nights public transportation is stopped for around 5 hours during the night (only some service trains are passing). If a time record is extracted during daytime (Figure 10), a train pass-by is clearly visible. According to the RMS estimates, it is also possible to state that anomalies are not seen: a spread in the peak value distribution is observed, but this shows a random variability without extreme events. In addition, considering the three measurement directions, values are of the same order of magnitude, with a slightly higher level observed for the vertical direction.

Once analysed the relationship between the recorded vibrations and the train passages, these data have been compared to the same quantities measured at the original Pietà Rondanini position. The comparison between Figure 3 and Figure 9 allows confirming that the vibration levels at Ospedale Spagnolo during a train pass-by is much higher than the values recorded in the original position, where the effects of train transits are not perceived.

To evaluate vibrations in a comparison against the available limits, the velocity peak values have been extracted. The peak values for each of the three measurement axes do not necessarily correspond to the same train passage (i.e. peaks are not synchronous). Figure 10 shows the selected segments of time histories and the peak values are highlighted. The peaks values, not being synchronized, cannot be composed to calculate the PPV. However, to make a comparison with the available literature values in a worst-case scenario, a PPV value can be obtained from the highest peak, assuming the same value also in the other two directions: this leads to an overestimation of the real PPV: in favour of safety. As shown in Figure 10, the maximum recorded velocity component was about 0.6 mm/s, giving a PPV in the order of 1 mm/s. Comparing this value with the limits given by literature, shown in Figure 2, we can infer that the new position selected for Pietà Rondanini can be considered safe. Maintenance of underground trains and track can play an important role in changing the source vibration levels, given by the interaction between the infrastructure and the rolling stock. Short pitch corrugation as well as bad rail joints can meaningfully increase the measured values. Not knowing the maximum spread in the sensed values, the adoption of some means, to reduce the vibrations reaching the statue, has been considered a primary need. This could have been achieved in several ways, including structural modifications for restoration, which is the opportunity analysed in the following of the paper (though not being the only one: another paper will deal with the design of a specific base).

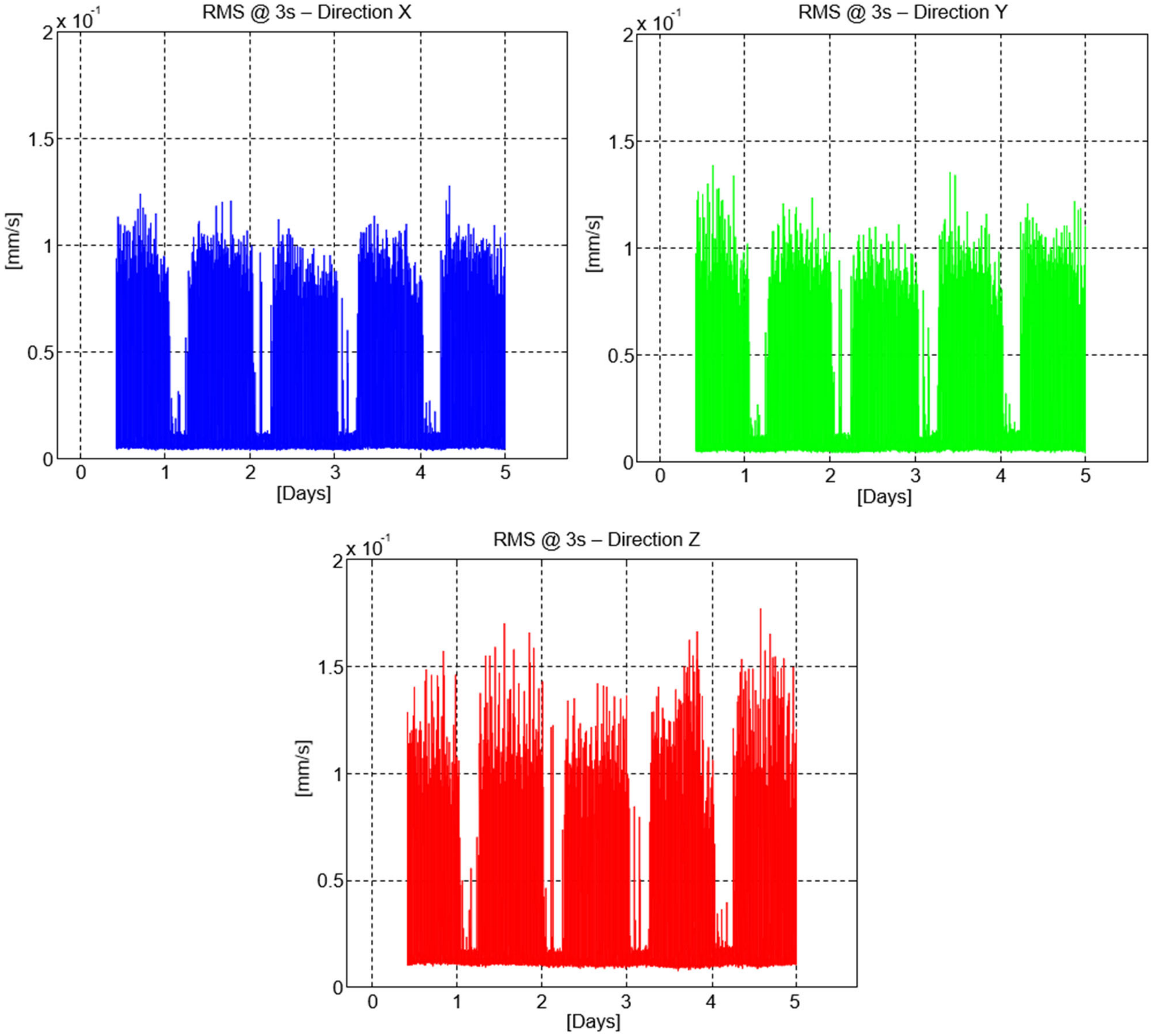

Figure 9. Time histories of velocity RMS on the floor of Ospedale Spagnolo (pos0).

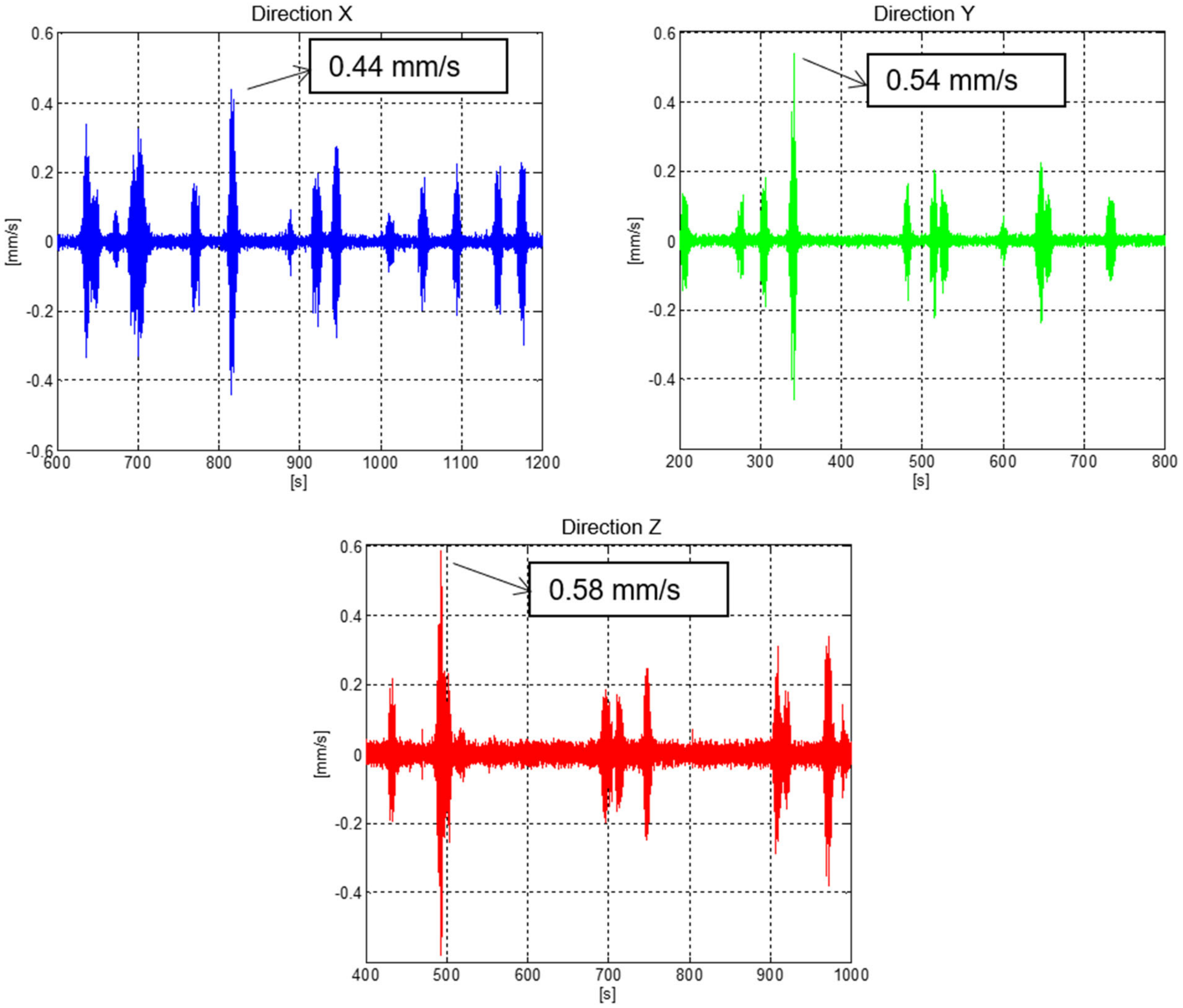

Figure 10. Velocity peaks extracted from segments of time history in correspondence of maxima RMS values. Peaks in the three directions do not correspond to the same instant of time.

5.1.2. Frequency domain analysis

Changes in environmental conditions, including lack of maintenance, not only can increase the measured levels, but it also produces a wider band spectral input. To analyse this aspect, some portions of signals, corresponding to train transits producing high vibration levels, have been extracted from the overall record. In Figure 11 the vibration spectra along the three measurement axes, relative to two different train passages are considered. The plots show that for both passages the frequency content of the recorded vibrations is concentrated in the range from about 20 Hz to about 70-80 Hz, while outside this range amplitudes appear lower. Comparing the two considered passages, the spectra are overlapped in some regions, indicating that the amplitudes of some frequency components are independent from the single train producing the input. These components probably identify the dynamic response of the structure. Conversely some other components only appear in one of the two transits and may be associated to different characteristics of the primary source: the frequencies of the spectral maxima can change, depending on the track over which the train is passing. We recall that there are four tracks (lines 1 and 2 have different sub-structures), the train features are different (rolling stock maintenance of wheels, loading conditions, age and time of construction, bogie design, …) and the speed can vary: this approach has been replicated on different transits, always leading to similar results.

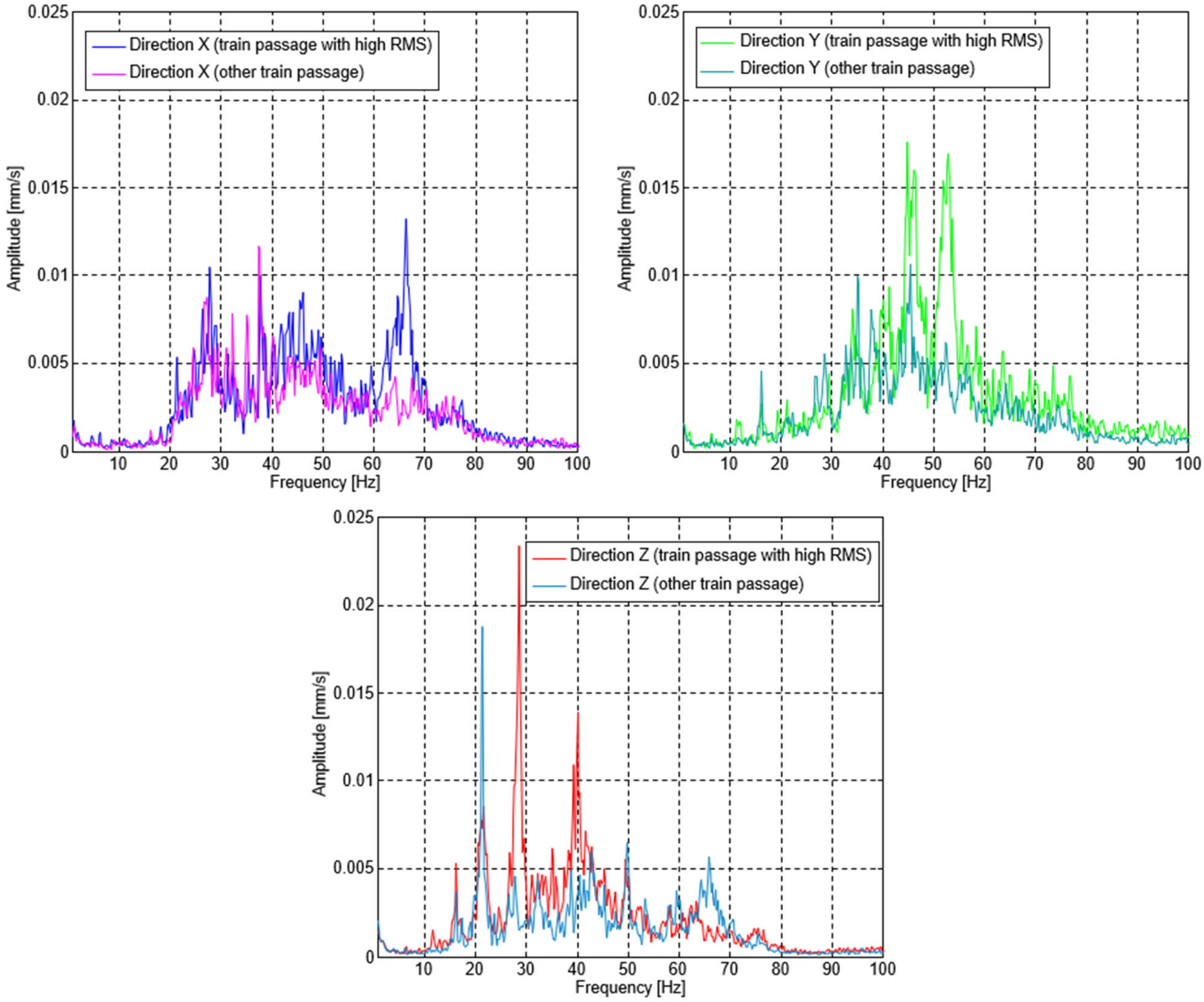

Figure 11. Amplitude spectra of two different train passages.

5.2. The influence of the structural dynamics and of auxiliary machines

5.2.1. The influence of the structural dynamics

As mentioned in chapter 4, the main room of Ospedale Spagnolo is not directly laid on the ground, but it is supported by vaults, which allow transferring the load from the floor to the perimetral walls. A room having the same dimensions is at the lower floor. Figure 1 (right) schematically represents a vertical section of the building, showing Ospedale Spagnolo and the whole building structure. The room at the lower floor is employed as a warehouse. With such a structure, vibrations coming from the subway through the ground are modified by the transmissibility of the structure. Therefore, to understand whether and how the primary vibrations from the ground can undergo dynamic amplification or mitigation, a simultaneous measurement of the vibration entry point to the building (input) and the vibration at the points of interest (output) must be carried out. Provided that in the present case the most important source of vibrations is the subway close to Castello Sforzesco, it seemed reasonable to estimate the input vibration at the warehouse floor, directly laid on the ground, and closeto the subway tunnel walls. Two measurement positions were considered: the one selected for the new Pietà Rondanini exposition (pos0 in Figure 5) and the corresponding point at the warehouse floor. Measurements have been carried out in both points along three normal directions, including the vertical to the ground. The used sensors have been piezoelectric accelerometers PCB 393B12 (full scale of 0.5g, sensitivity of 10V/g and bandwidth from 0.15 to 1000 Hz). To obtain data for different subway traffic conditions, the test lasted 24 hours, with a sampling frequency of 2048 Hz.

Data from these tests have been analysed in the frequency domain, first in terms of Welch PSDs. Figure 12 shows the PSD computed on the data collected for the entire day, while in Figure 13 segments of the time records without any train passage are being considered. From the comparison of the two figures it is possible to get interesting information. Considering the vibration levels recorded at the basement floor, most power is concentrated in the range 50-80 Hz during train passages, while, without transits, the vibrations significantly decrease: this confirms that, as widely expected, the trains are the most important vibration source, mainly acting in the 50-80 Hz range. In this same frequency range, a clear amplitude reduction is observed in passing from the basement, closer to the subway, to the upper floor, thanks to the structural damping properties along the vibration path. Considering the range 15-40 Hz, the vibration level at Ospedale Spagnolo is higher than at warehouse floor; in addition, without trains, narrow peaks at 16Hz, 22Hz, and 32Hz appear, with magnitudes about two orders of magnitude higher at the ground floor than under-ground. This suggests the presence, in this range, of frequencies due to both the dynamic amplification of the structure and to some external sources associated to narrow peaks. The nature of these external sources will be better investigated in Section 5.2.2.

The dynamic behaviour of the structure can be summarized by means of a transfer function between the vibrations at the basement floor and those measured at Ospedale Spagnolo. Figure 14 shows the multi-input-multi-output (MIMO) transfer function that relates the vibrations in the vertical direction at Ospedale Spagnolo with those along all the three directions in the basement, downstairs. Note that the MIMO computation was considered since, due to the complexity of the structure, the three measurement directions cannot be considered mutually independent, therefore a function capable to consider the cross effects among all vibration directions has been considered fundamental (for instance the effect of an out-of-plane wall vibration on the floor behaviour). Looking at the plots obtained through this approach, it is possible to see a dynamic amplification of the structural behaviour starting around 20 Hz and then progressively decreasing above 30 Hz: this can be explained with the presence of one or more structural resonances in the range 20-30 Hz. Conversely, above about 50 Hz the structure seems to filter out every vibration coming from the ground.

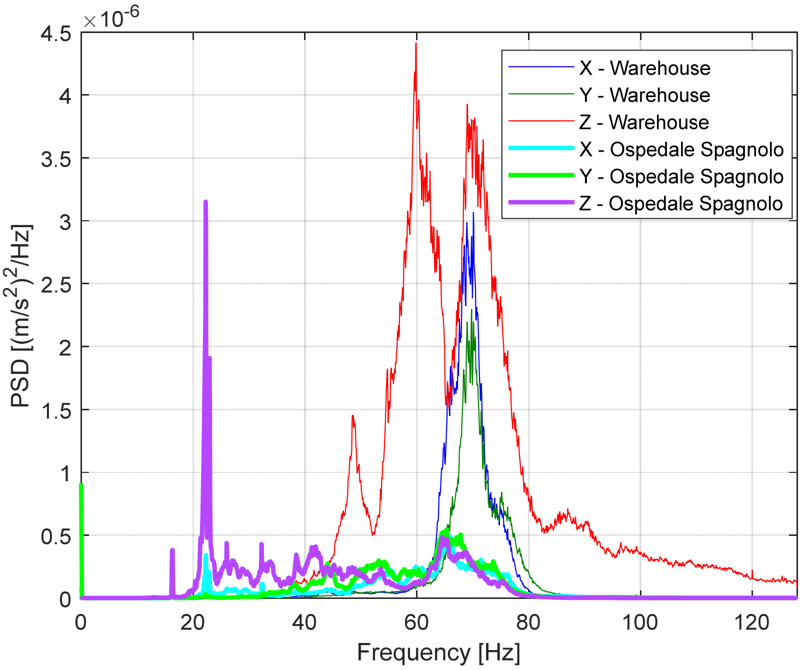

Figure 12. PSD of accelerations at warehouse and Ospedale Spagnolo floors. The entire time history of data is considered.

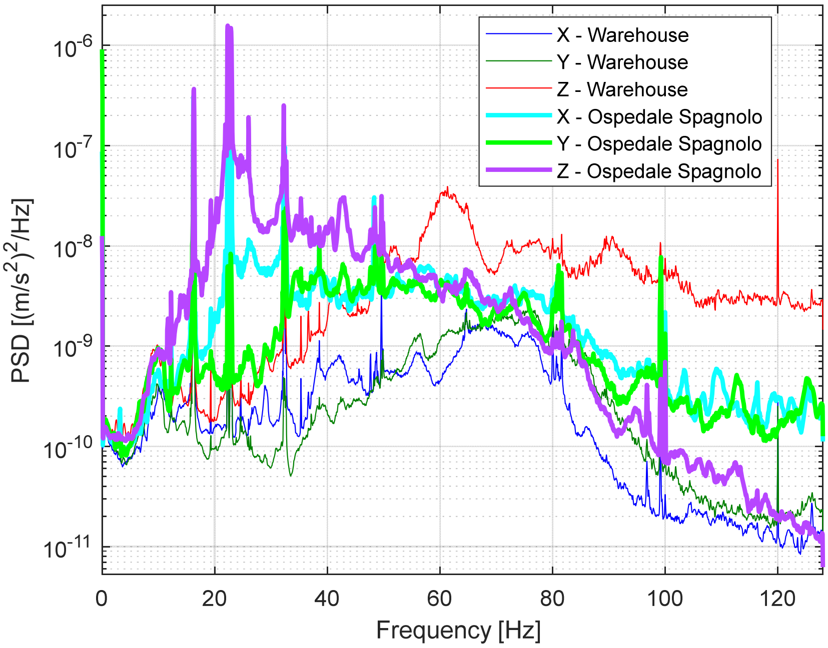

Figure 13. PSD of accelerations at warehouse and Ospedale Spagnolo floors, obtained considering only segments of time history in absence of train passages.

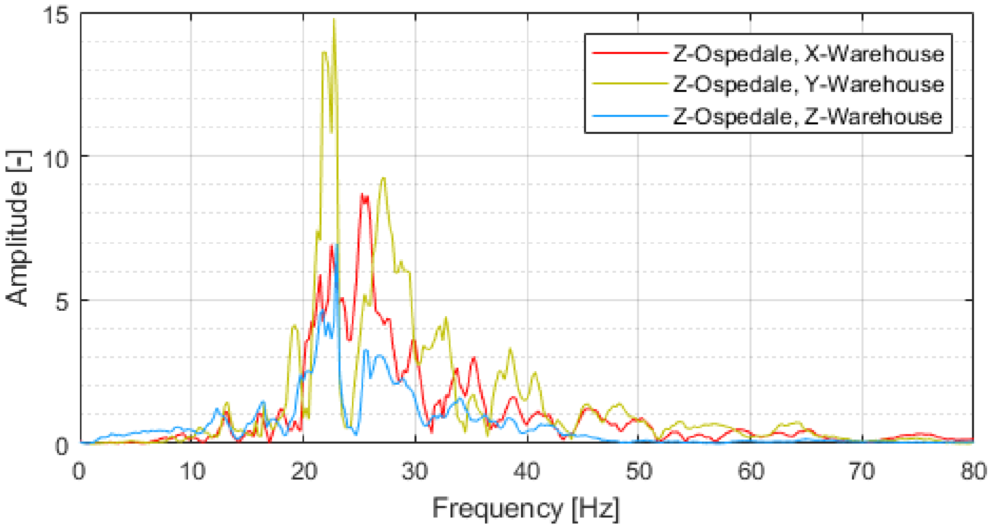

Figure 14. Multi-input-multi-output transfer function between vibration in all direction at warehouse floor (input) and vibration in vertical direction at old Spanish Hospital floor (output).

5.2.2. Measurements to detect sources other than the subway

In the case of vibrations due to auxiliary devices (i.e. fans, refrigerators or air conditioning units) vibration mitigation can be more easily obtained by dynamically isolating the source than by isolating the statue. Specific tests allowed to evaluate the potential vibration reduction that could be obtained by isolating these auxiliary sources. As an example of this analysis, in this subsection the effects of the vibration generated by an air handling units (AHU) installed in the basement is analysed. In Figure 15 the PSD of the acceleration recorded at the Ospedale Spagnolo floor are presented, showing, on separate plots, the conditions of AHU turned off and on. It is possible to see that, when the AHU is active, some narrow peak components (22Hz, 33Hz, 44Hz, 66Hz in the range of our interest) appear. This analysis allows to mark some peaks visible in Figure 12 and Figure 13 as the effect of the AHU. Since the statue will be installed on a new base, these vibrations could be mitigated thanks to the system vibration isolation capabilities. As an alternative, a modification of the AHU support stiffness can be considered a solution to reduce the AHU vibration source.

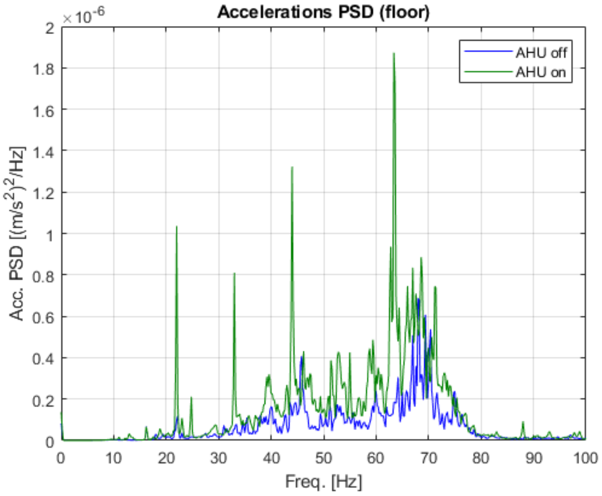

Figure 15. Acceleration PSD measured on the floor of the Ospedale Spagnolo with the AHU on and off

6. Effect of the structural restoration on vibrations transmissibility

As already written, the analysis of the vibration levels described in the previous Sections, contributed to select the best position for the Pietà Rondanini exposition (position 0 in Figure 5) and created a baseline to check the effectiveness of any further structural restoration. In this Section the effects of structural restoration on the vibration transmissibility are analyzed.

The new exposition has a crude wood floor laid over the old terracotta tiles: this elevation of the floor level (around 40 cm) was accomplished using lightweight concrete, with added damping properties, to contribute to the vibration mitigation, exploiting the opportunity of already undergoing restoration activities. The seat for the new base was in a pit, whose bottom had to be perfectly flat to properly host the new base. The described situation had for sure an important impact on the expected vibration amplitude reduction, due to the increased damping. In addition, the modal masses had for sure an increased value, due to the increased floor thickness, therefore changing the overall dynamic structural behavior. That is why, after the room was completely restored, it was necessary to analyze the vibration levels again, both at Ospedale Spagnolo and at the basement, since important structural modifications had been carried out not just in the new museum, but also downstairs. To analyze these effects in a quantitative way, new measurements were needed, as any numerical modelling forecast was nearly impossible, due to the complex structural design and to the presence of different materials. The sensors and the acquisition systems used for these tests were the same used in the tests described in Section 5.

The collected data were analyzed following the same procedure adopted in the previous Sections. A comparison in terms of velocity peaks and RMS values before and after the structural restoration was considered at a first stage. In Figure 16 the RMS values after the restoration, computed on 3 s windows, for about 25 min, are shown. Comparing these values with those from Figure 9, it is possible to see that, after restoration, a reduction in the vibration levels was present for all directions. Similarly, also the velocity peaks presented in Figure 17 show a reduction with respect to those presented in Figure 10. This confirms that restoration operations had a global positive effect on the environmental vibration minimization. It is noted that in both cases, for the considered time record, the PPVs are well lower than those provided by the most recognized limits discussed in Section 2.2.

A comparison between the vibrations before and after restoration was performed also in the frequency domain. A first check was aimed at understanding if the frequency bands with the highest vibration levels had changed significantly after the restoration activities. To this aim, acceleration power spectral densities at the basement floor have been monitored and compared to the data taken in the same position before restoration. Since most of the observed vibrations are due to the train transits, for this analysis the full acquisition has been automatically segmented, to consider only time slots corresponding to the underground train transits. As it can be seen in Figure 18, the vibration band did not change significantly after the restoration works.

The dynamic response of the structure and its capability to filter or amplify the vibration levels has been deeply investigated; the transfer function between the vibrations at the basement floor and those in new the position of Pietà Rondanini have been estimated. The multi-input multi-output (MIMO) transfer function has been computed again, using the same approach described in Section 5.2. Comparing the MIMO transfer function before (Figure 14) and after (Figure 19) restoration, the modifications of the structural response can be analyzed. Into details, we can see that the dynamic amplification due to the response of the structure is similar in the two conditions: larger amplitude values are visible in the frequency band between 20 and 30 Hz. However, after the restoration activities, the dynamic amplification in the range between 25 and 30 Hz, has lower amplitudes than before restoration. The amplitude of nearly all the transfer function peaks along the three directions has lower amplitudes after restoration, pointing at a good effectiveness of the adopted solutions. These response changes are considered good facts for the protection of the statue, since they represent a slight reduction of the vibrations transmitted to the Ospedale Spagnolo floor. It is obvious that these changes are by far too limited to ensure by themselves a safe conservation of the statue: the solution to work on the building has been adopted, as restoration was already planned, otherwise the ratio between costs and benefits would have been too unfavorable. To make the overall system effective, in addition to the attempt to reduce the input excitation, it was also necessary to design a base, capable of significantly cutting the vibrations reaching the statue. However, the analysis carried out in this paper allowed to verify that the restoration activities can play an important role in the dynamic response of a structure, and therefore in the improvement of the health environment of cultural heritage artifacts.

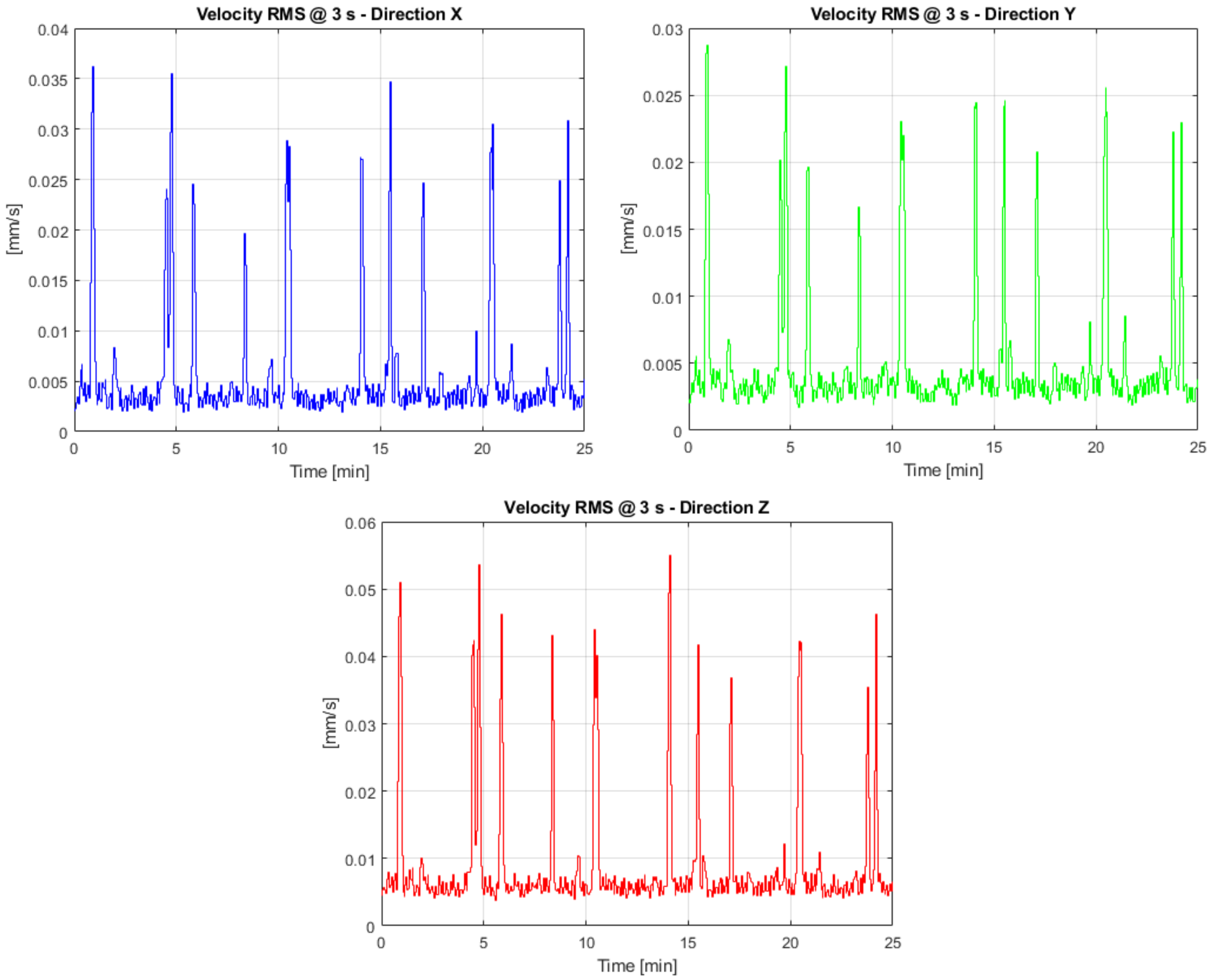

Figure 16. Velocity RMS values measured after structural restoration.

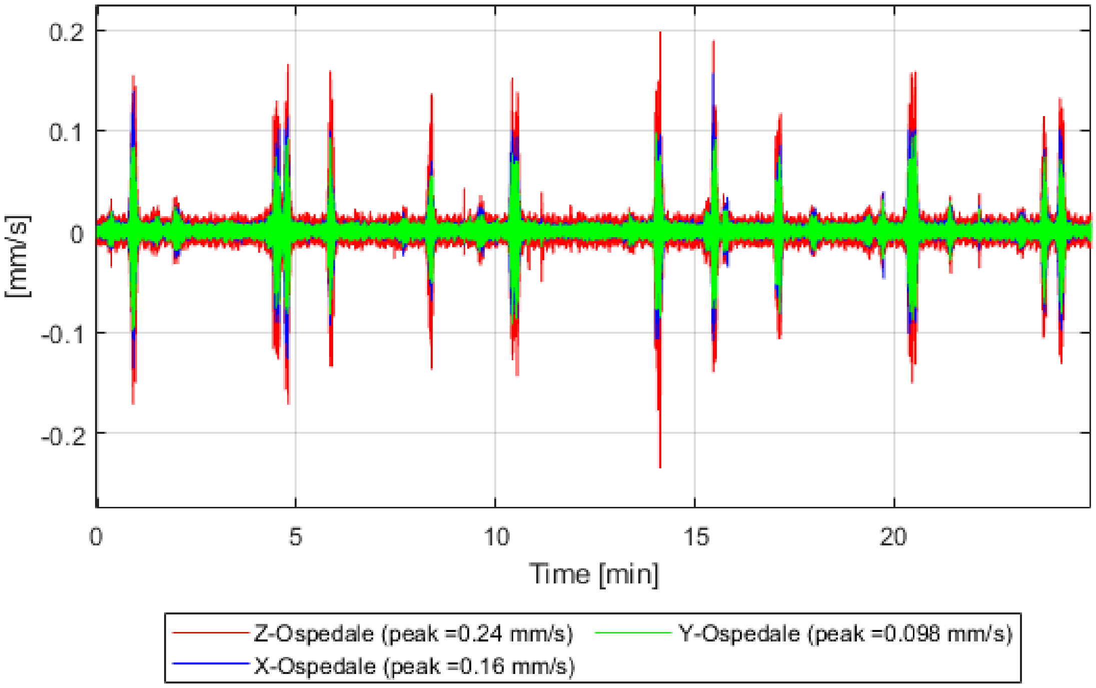

Figure 17. Velocity time history and peaks measured after the structural restoration.

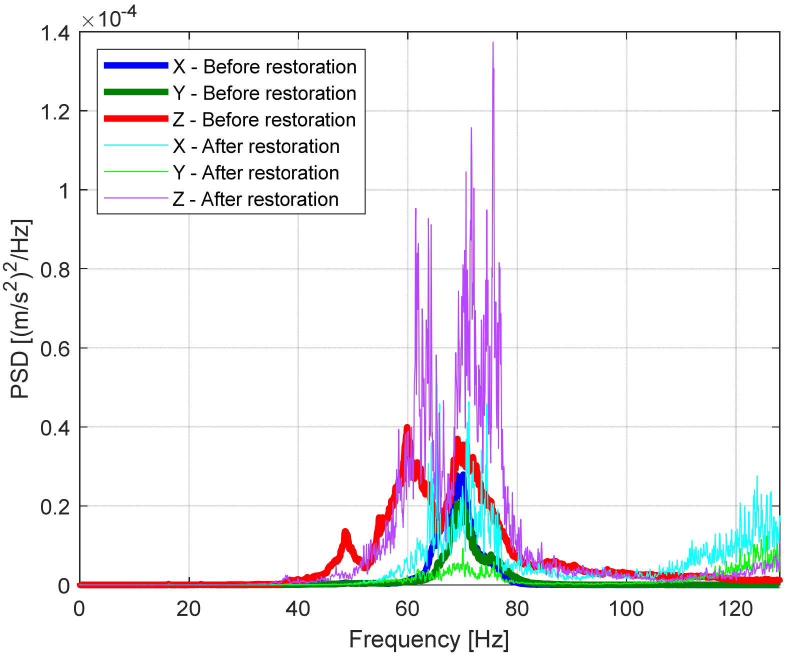

Figure 18. Comparison of the acceleration PSD at the floor of the warehouse before and after the restoration of the structure. PSDs are obtained considering only segments of time history during train passages.

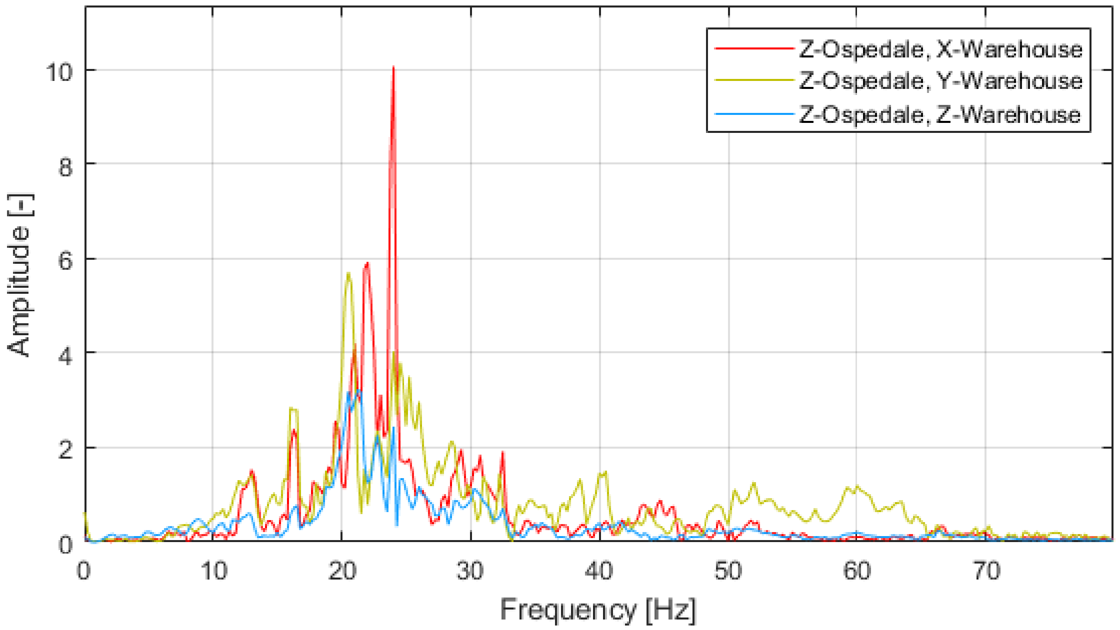

Figure 19. Transfer functions between the warehouse and the selected position of the Pietà Rondanini, after the restoration activities

7. Concluding remarks

The effects of environmental vibration on the safety of ancient statues is still mostly unknown; by environmental we mean continuous or quasi continuous low-level excitations which can be produced by traffic, footsteps, nearby machinery. The eventual damage strongly depends on the main characteristics of the statue and both the level and frequency distribution of the input vibration. Seismic actions have not been the main focus of this paper. In the first part of this work, we have collected a database of the available recommendations provided by both International Standards and best practices, expressed in terms of maximum allowed velocity levels, or PPV. To mitigate the effects of such vibrations it is possible to work on the building, whenever possible, or, alternatively, it is possible to think of an insulation system, interrupting the excitation flow: this paper is mainly devoted to the structural modifications and a proper evaluation of the environmental conditions. The case study analyzed in this paper is the testing and restoration of the new exposition area chosen for the new museum of Michelangelo's Pietà Rondanini, at Castello Sforzesco, with the aim to protect the statue from the vibration due to the underground lines located close to the museum. The peak vibration levels due to the train pass-by are safe if compared against the literature limits, though the train passages are quite frequent. Together with the peak vibration values recommended by literature, the vibration root mean square values have been considered, proposing the idea that damage can be associated to a "vibration dose" (i.e. a certain level is considered unsafe if it is higher than a certain threshold for at least a given time). For sure a peak value is easier to evaluate, even though probably it is not sufficient to describe and detect damage conditions. In the second part of the work, the transmissibility of the structure (walls and vaults) has been analyzed before and after the restoration works, providing relevant information about the possibility to mitigate the transmitted vibrations by means of structural restoration.

8. Acknowledgements

The authors gratefully acknowledge the Municipality of Milano and Direzione Castello Sforzesco, namely Claudio Salsi and Giovanna Mori, for the strong impulse given to the project and its coordination, and also for the funding provided to the development of the research presented in this paper.

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