Received: 16 October 2022 | Accepted: 1 November 2022

DOI: 10.1002/pamm.202200324

Vibration analysis on newly designed painting supports for the Cranach exhibition 2022 at Herzogin Anna Amalia Bibliothek

Eva Hartlieb[1,*], **Pascal Ziegler**[1], and **Peter Eberhard**[1]

[1] Institute of Engineering and Computational Mechanics, University of Stuttgart, Pfaffenwaldring 9, 70569 Stuttgart, Germany

The effect of vibration on the condition of sensitive works of art continues to be of great importance to museums. Vibrations contribute to irreversible changes in the complex materiality of art and cultural heritage. In cooperation with the Klassik Stiftung Weimar, the Institute of Engineering and Computational Mechanics at the University of Stuttgart accompanied an exhibition setup. The museum and partners designed free-standing columns in the exhibition hall to support valuable works of art. Due to their original design, these are susceptible to vibrations. Thus, the question arises as to what extent these columns should be modified in order to reduce these vibrations. In this study, measurements were taken on the floor and on the columns using a variety of measuring techniques. It was investigated which excitations from the environment propagate to the artwork. It was confirmed that vibrations from the environment, such as road traffic and museum visitors in the exhibition room, are sources of excitation.

Experimental modal analysis was used to identify the characteristic vibration behaviour of these columns. By using finite element methods, a simulation model was set up allowing to investigate modifications to the columns in order to predict the change in vibration behaviour. Based on the simulation modifications, structural changes were made to the system through stiffening of individual components and redistribution of masses.

1 Introduction

The effect of vibration on the condition of sensitive works of art continues to be of great importance to museums. Vibrations contribute to irreversible changes in the complex materiality of art and cultural heritage. Since works of art are documents of our history, it is urgent to preserve them. A safe environment must be guaranteed accordingly. Sources of vibration that excite the artwork are numerous. In addition to the transportation of art, sources such as construction work, heavy traffic in the immediate surroundings of a museum, machinery in the exhibition space or the building, and even the motion of museum visitors cause vibrations to work of art, [1–3]. The historical building of the Herzogin Anna Amalia Bibliothek is part of the Klassik Stiftung Weimar. The building keeps the Historical Library's famous Rococo Hall on the upper level, as seen in Figure 1. It is part of the "Classical Weimar" UNESCO World Heritage Site ensemble and receives some 100,000 visitors each year. On the lower level is the exhibition room in the Renaissance Hall, where works of art of exceptionally high value will be exhibited from the summer of 2022, see Figure 2. A modern concept for hanging the artworks is developed for this permanent exhibition. Traditionally artworks, mainly paintings, are hung on walls. For the permanent exhibition, a newly designed system was chosen where free-standing columns support the artworks.

This type of hanging is a novelty for the conservators in charge of the museum. Therefore, the question arises to what extent this hanging system is exposed to external vibrations and what excitation sources are relevant and reach the system. By visual inspection, it was already recognizable that the system moves in response to direct excitation. Certainly, this movement eventually reaches the original painting and might cause damage to the material structure of the original painting, [4–7].

This article describes the investigation of excitation sources from the surrounding environment and the vibration behaviour of the hanging system. Measurements were made of the floor and the free-standing columns to analyze the environmental influences. Acceleration sensors were used to measure vibrations from the surrounding conditions in different floor circumstances and time frames. An experimental modal analysis was used to investigate the vibration behaviour and allows the required parameters to be entered to represent the actual situation using the finite element method. Modifications were made to the simulation model in order to predict and modify the vibration behaviour. In this project, an existing hanging system for delicate artworks is systematically investigated, and a working simulation model is created using the obtained material parameters and finite element methods. It allows better understanding and fact-based decision-making in the design of such hanging systems.

2 Measurement Setup

The hanging system examined consists of a base plate with eight rectangular vertical beams. The material used is steel. The base plate has the dimensions 170 cm x 100 cm and is 6 mm thick. It is placed on a gypsum concrete floor and underlaid with a rubber mat. The rectangular beams are firmly connected to the base plate, see Figure 3. They measure 3 cm x 3 cm with a wall

* Corresponding author: e-mail eva.hartlieb@itm.uni-stuttgart.de, phone +49 711 685-66388

Fig. 1: Ground measurements were taken on the wooden floor at the Historical Library on the upper level of the building.

Fig. 2: Setup in the Renaissance Hall of ground measurements and vibration analysis on the hanging system with an accelerometer and Laser Doppler Vibrometry.

thickness of 2 mm. The beams are arranged in pairs and welded together with two crossbeams. On top of them are wooden cases to which the corresponding paintings are mounted. These four painting supports are at various heights and widths: the highest support measures 197 cm and the lowest measures 179 cm. The differently sized wooden cases and weights of the original artworks are of diverse weights.

In the following, measurements are described to investigate the excitation from the environment and to analyze the vibration behaviour to provide the data for the corresponding simulation model. During the measurements, no original painting was harmed. In order to obtain a setup as realistic as possible, dummy paintings were made for the corresponding painting supports, resembling the original painting in terms of external dimensions and weight.

2.1 Ground Vibration Measurements

A seismic accelerometer (PCB, 393B04) was used to analyze the environmental excitation coming through the ground. Long-term measurements were carried out at different periods of the day covering different situations.

In the historical Herzogin Anna Amalia Bibliothek, a measurement of 150 min was recorded, starting 50 min before opening time and thus before the entrance of the first visitors but then also covering visitors in the Library. The floor is a historical wooden parquet floor with boards of different lengths and widths. The accelerometer was attached to the floor with non-residue double-sided adhesive tape. A side library corridor is chosen as the location for the investigation, which is not directly

Fig. 3: Hanging system with four painting supports before the start of the exhibition.

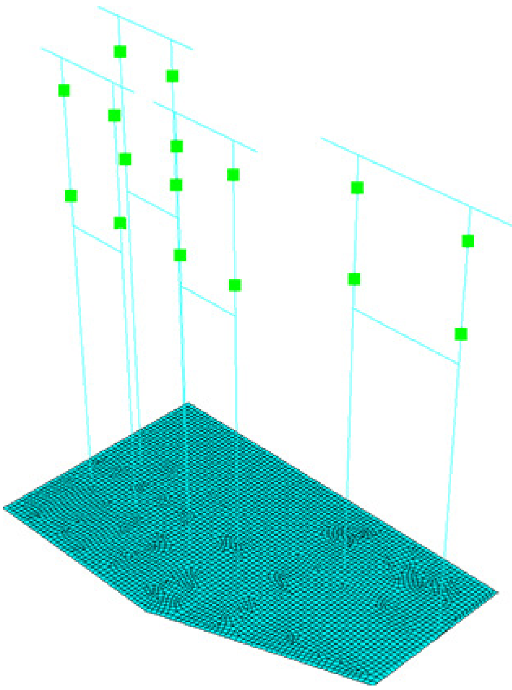

Fig. 4: FE model of the hanging system.

accessible to visitors. The same seismic accelerometer is also installed in the exhibition room, about 7 m from the hanging system. The floor is made out of gypsum concrete. The measurement there starts after the building is closed and measures a total of 10 h. In addition, three one-dimensional accelerometers (PCB, 333B30) have been installed on the ground plate. Further, in order to investigate the extent of the vibrations from the environment reaching the painting supports, i.e. close to the original paintings, another one-dimensional accelerometer (PCB, 333B30) is attached to each painting support which measures the acceleration in the direction toward the surface of the painting.

The signal of the seismic accelerometer is filtered with a hardware filter (KEMO VBF 44). As filter characteristics, an elliptic low-pass was chosen with a cut-off frequency at 1 kHz and an 80 dB stop band attenuation. The filtered output signals of all accelerometers are displayed and recorded on an oscilloscope (Yokogawa, DL850E). The results are then analyzed and processed with Matlab.

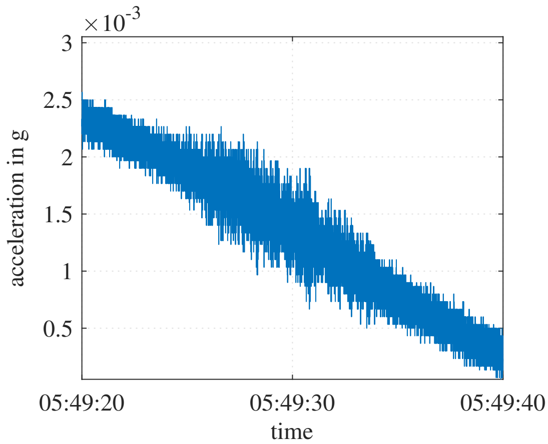

Fig. 5: A detail of the measurements taken in the exhibition room during the night.

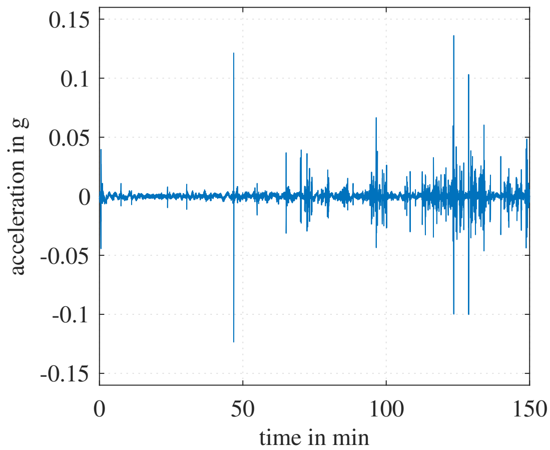

Fig. 6: Measurement in the Historical Library during the entry of the first visitors.

2.2 Vibration Analysis

An experimental modal analysis was carried out to describe the vibration behaviour of the suspension system by characterising the system's natural frequencies. Two different setups are excited by two methods. The different measurement setups aimed to obtain a maximum of information describing the vibration behaviour of the hanging system and to provide parameters to a model of the setup with a finite element model. One of the four painting supports is excited with an automated hammer. The chosen support is located in the centre of the base plate. It has a height of 188 cm and a dummy painting with a weight of 8,2 kg is mounted. The hammer is positioned below the centre of the support beams and allows a defined reproducible excitation with constant force. The contact force between the excitation point of the tested painting and the tip of the automatic impulse hammer is measured by an ICP force sensor PCB 086E80. A Polytec VibroGo Laser Doppler Vibrometer was used to measure the vibration response at 17 evenly spaced points. The experimental setup can be seen in Figure 2.

In a second setup, the system was detuned by removing the dummy paintings. The resulting change in natural frequencies was measured by using a manually operated impulse hammer. The response was measured at one point, located at the joint of the middle transverse beam. This detuned system provides additional information that can be used to parameterize the FE model. Also, an FE analysis that correctly predicts the response for the original as well as the detuned system, can be regarded to be verified to a higher level of confidence.

3 Results

Measurements on the ground, both in the historical library and in the exhibition room, give a solid impression of the measurable sources of excitation from the environment. In addition to the measurements on the ground, the vibrations that reach the painting supports are investigated. For this purpose, several measurement setups were prepared and used.

3.1 Environmental excitation

The Renaissance Hall is located levelling a busy cobblestone road in front of the building. It can be guessed that vibrations extend through the floor to the painting supports. To guarantee that no excitation sources inside the building conceal excitations from outside the building, the ground measurements were performed at night without traffic. The seismic accelerometer measured the excitation from passing cars, see Figure 5. However, compared to the measurements in the historical library originating from visitors, this excitation source has a much smaller influence on the painting supports. The measurements in the historical library produced a more severe result. The opening of the library leads to exaggerated peaks in the measurement. Figure 5 shows the increase in excitation from minute 50. The increase in visitors becomes visible with extended measurement duration.

In addition to the sources of stimulation outside the building, it was investigated what kind of excitation may reach the supports from the exhibition room itself. The study examined two typical behaviours of museum visitors in the presence of artworks. Figure 7 shows how a conversation between two people at an average speaking volume stimulating the painting supports. This conversation took place at a distance of 2 m. Figure 8 shows the effect of one visitor walking past the painting supports. During the measurement, the visitor approached the support and walked away again. The obvious spikes are caused by the visitors steps.

Comparing the excitation sources from the environment, one gets different conclusions. The interpretation of specific excitation sources becomes complicated when they act simultaneously or overlap others due to their intensity. Thus, traffic outside the building can be measured with the measurement setup described here but is less relevant than the vibrations inside the building. For example, the increase in visitors to the library causes significantly higher peaks, as seen in Figure 5. Vibrations caused by the movement of museum visitors can also be measured.

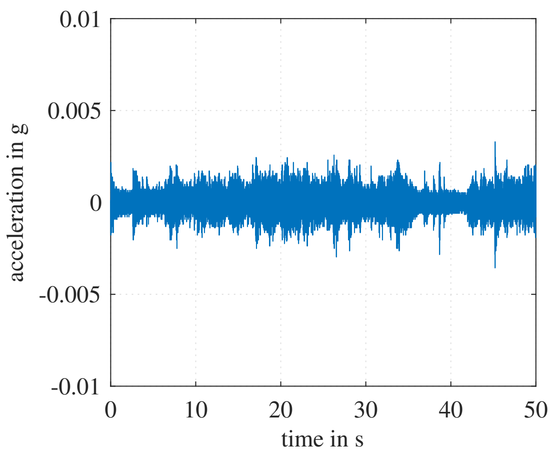

Fig. 7: Measurements show the vibration of the painting supports while visitors talk.

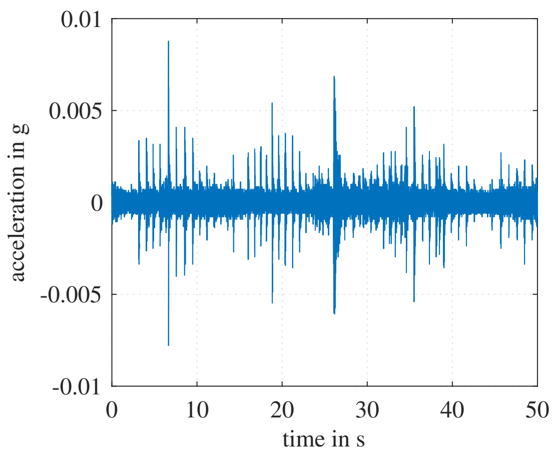

Fig. 8: Measurements show the vibration of the painting supports while visitors walk.

3.2 Modeling the FE-Model

The experimental modal analysis on the respective painting supports with different set-ups allowed the collection of different information about the vibration behaviour of the supports. Using the peak-fitting method [8], the natural frequencies were identified; see Table 1. Based on the existing parameters of the hanging system and the analysis of the natural frequencies of the system, a finite element model is created, as shown in Figure 4.

The FE model is created in Abaqus and consists of 5275 elements and about 15.000 nodes. For the base, linear shell elements (S8R) with 8 nodes and reduced integration are used. Euler-Bernoulli beam elements (B32) with quadratic interpolation are utilised for the beams. The inertia properties of the wooden cases and the dummy paintings are each represented by four mass points, highlighted as green dots in Figure 4. The rubber mat is modelled by a distributed stiffness of 10^8 N/m^2. For the material parameters, regular steel was applied with tuned Young's modulus and density of 7850 kg/m^3. For the rectangular beams a Young's modulus of 170.000 N/mm^2 and for the ground base 210.000 N/mm^2 were chosen.

In Table 1 the identified frequencies are compared to the eigenfrequencies calculated with FEM. The good agreement is obvious.

Table 1: First three eigenfrequencies of the four painting supports (blue) and the FE model (red) in Hz.

Painting Support #1	Painting Support #2	Painting Support #3	Painting Support #4
2.7 | 2.77	2.7 | 2.77	2.6 | 2.64	2.7 | 2.74
16.3 | 16.23	16.4 | 16.24	15.2 | 15.22	10.8 | 10.57
26.8 | 25.32	25.0 | 25.28	22.7 | 22.76	22.6 | 22.39

3.3 Coupling of the painting supports

During the measurements, an effect known as coupling was detected. Exciting one of the four painting supports, the other three are excited via the base plate. The effect becomes visible in Figure 9, where the dynamic behaviour of the central painting support is shown. The system can be seen to resonate again and again. This occurs due to the back and forth transmission of the excitation energy between the individual painting supports.

In order to reduce this effect, an experiment to separate eigenfrequencies was carried out, the result of which is shown in Figure 10. In the experiment, the mass distribution is changed by adding mass. A sandbag with a weight of approximately 7 kg is placed on the central painting support. This mass distribution or weighting on the support changed the dynamic characteristics. The system is excited once and can now resonate isolated and reduce its vibration amplitude according to its damping.

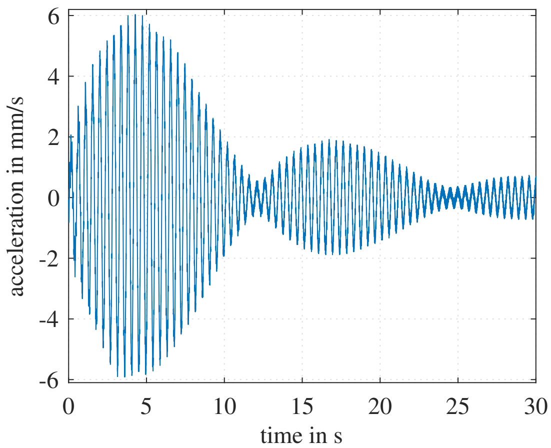

Fig. 9: Vibration behaviour of painting support Nr 2 by excitation. Coupling is seen clearly.

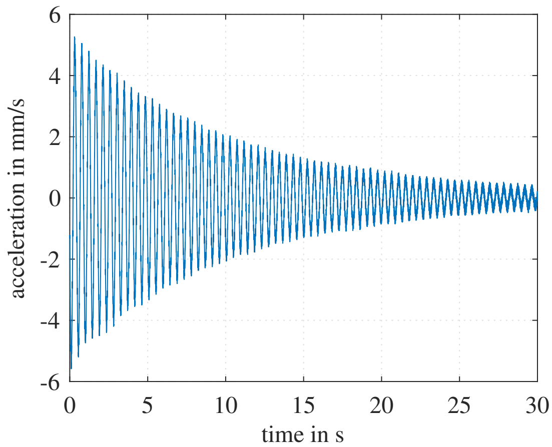

Fig. 10: A different vibration behaviour of painting support Nr 2 is analysed after adding mass. Now no coupling with other points of the structure is visible

3.4 Modifications

Using the FE model, it is now possible to modify the virtual system and predict the change in vibration behaviour. To adjust the hanging system, different methods are chosen to stiffen the system, as seen in Figure 11. A base was simulated that can not be statically deformed. Furthermore, triangular plates at the base of the beams with a height of 30 cm are modelled, which stiffen the painting supports on the base plate. A third modification shows the combination of those two. Finally, the model shows that the most effective way to stiffen the painting supports is to use a lever arm as large as possible, connecting the vertical beams to the base.

To evaluate the modification a static investigation is carried out. The modified painting support is loaded with a force of 100 N at a defined point, at the centre of the middle horizontal beam, as shown in blue in Figure 3. The displacement at the point of force application is measured and compared. According to the above-described order and as shown in Figure 11, the following values resulted in displacement: 9.01 mm, 7.03 mm, 5.14 mm and 0.97 mm

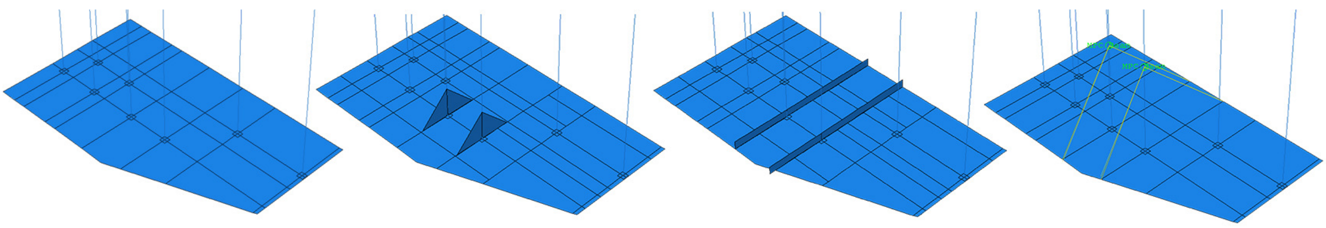

Fig. 11: Four modifications were carried out and compared to each other throughout a static examination.

4 Conclusion

It was possible to detect that some external influences, such as road traffic, are minor and presumably negligible. A significantly stronger excitation is measured during the visitors' approach. The excitation from the building through the painting supports to the exhibits is supposedly less critical. There is a measurable transfer of vibrations from the support to the dummy paintings. However, no statement can be made about the damage potential to the original paintings. Further investigation is needed here. An FE model allows the reproduction of the vibration shapes and, based on modifications, permits estimations of vibration properties. The results show that the supports should be stiffened. In addition, the relocation of the mass showed promising results in terms of modifying the vibration characteristic to avoid coupling.

The investigation of these hanging systems and the methods used to analyse the system and build an FE model provided a profound basis for decision-making guidance for the museum's staff.

Acknowledgements Special thanks to the conservators Mrs Levin and Mr Katzer of the Klassik Stiftung Weimar, for their cooperation and the extraordinary opportunity to accomplish such a unique project. Open access funding enabled and organized by Projekt DEAL.

References

[1] A. Gmach, Erschütternde Umstände - Schwingungsbelastung von Kunst- und Bauwerken, Diplomarbeit, Technische Universiät München, (2010).
[2] W. Wei, W. Kragt, A. Visser, Non-contact measurement of vibrations in paintings using laser doppler vibrometry, Proceedings of 8th Inter- national Conference on Non-Destructive Investigations and Microanalysis for the Diagnostics and Conservation of the Cultural and Environmental Heritage, Lecce, Italy, (Italian Society of non-destructive testing monitoring diagnostics AIPnD, Brescia, 2005).
[3] W. Wei, S. Watts, T. Sedodn and D. Crombie, Protections Museum Collections from Vibrations Due to Construction: Vibration Statistics, Limits, Flexibility and Cooperation, Studies in Conservation, **63** (S1) (Taylor & Francis, 2018), pp. 293–300.
[4] N. Hein, Die materielle Veränderung von Kunst durch Transporte – Monitoring und Transportschadensbewertung an Gemälden durch das Streifenprojektionsverfahren, Dissertation, Staatliche Akademie der bildenden Künste Stuttgart, (2015).
[5] M. Läuchli, N. Bäschlin, C. Palmbach, M. Ryser, T. Fankhauser and A. Hoess, Vibrationen - kleine Erschütterungen millionenfach, Zeitschrift für Kunsttechnologie und Konservierung, **29** (2), (Wernersche Verlagsgesellschaft mbH, 2015), pp. 223–236.
[6] C. Heinemann, P. Ziegler, N. Hein, C. Krekel and P. Eberhard, Objektiviertes Gemäldetransportmonitoring unter Berücksichtigung mechanischer Einflussfaktoren, Zeitschrift für Kunsttechnologie und Konservierung **33** (1) (Wernersche Verlagsgesellschaft mbH, 2019), pp. 178–198 .
[7] W. Wei, L. Sauvage, J. Wölk, Baseline limits for allowable vibrations for objects, Preprints ICOM-CC 17th Triennial Conference, Melbourne, Australia (International Council of Museums, Paris, 2014), pp. 7–14.
[8] D. F. Ewins, Modal Testing: Theory, Practice and Application, (Wiley, 2000).

