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Review article

FROM ART TO ENGINEERING: A TECHNICAL REVIEW ON THE PROBLEM OF VIBRATING CANVAS PART I: EXCITATION AND EFFORTS OF VIBRATION REDUCTION

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Abstract. *Cultural assets are witnesses of past times with versatile worth. The irreplaceability of those treasures of art makes their protection our major task. This article reflects the commitment and results of 40 years of conservators' research to protect canvas - objects of cultural heritage - particularly from mechanical loads. It gives a classification of mechanical loads that act upon canvas during transport, exhibition and storing in depot. Furthermore, it gives an overview of different approaches which were used over years to protect canvas from various mechanical loads. This article tends to bridge the gap between restorers' knowledge and methods and concepts known from engineering dynamics. Restorers' first steps using engineers' methods are brought up and the necessity of theoretical modeling which has not started so far are pointed out.*

Key Words: *Canvas, Paintings, Transport, Shock, Vibrations, Elastic Isolation*

1. INTRODUCTION

Studying shock and vibration hazards in view of art and cultural objects has been an important topic during the last 40 years in conservation science. In spite of the long research period restorers and conservators are facing numerous unsolved problems.

Current research in the field of 'preventive conservation' is summarized by the term 'Green Museum', which '[...] brings together conservation science with the sustainable development for the preservation of art and cultural heritage [...]' [1]. Environmental influences like (a) temperature, (b) humidity, (c) UV radiation, (d) dust and (e) mechanical loads are discussed in different articles, papers and forums. References for the state-of-art are [2, 3] and the workshop [4]. In these, effects of the first four influences (a) – (d) are examined extensively. More recently, the effect of mechanical loads has been intensively discussed [5, 6].

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Cultural assets are exposed to mechanical loads during (i) transport, (ii) exhibition and (iii) storing in depots. However, it is just not clear yet which load level is critical and how art objects could be protected to avoid damages [7, 8].

The main contribution of this paper is a literature review. Restorers’ questions are summarized and transferred to engineering problems. Because of the huge range, this paper focuses on a particular class of cultural assets: paintings on textile carriers.

The article begins with the motivation of this topic (section 2), followed by the description of common excitation mechanisms (section 3). Relevant frequency ranges as well as amplitude levels are discussed. Afterwards in section 4, conservators’ efforts concerning shock and vibration reduction during transport, exhibition and storing in depots are discussed. Bridging the gap between restorers’ knowledge and the art of engineering is subject of section 5. The paper is closed by a summary, conclusion and outlook in section 6.

2. MOTIVATION

Nowadays the presentation of one’s own collection is insufficient for museums to keep pace with national and international competition [9]. The evolution of the number of attendees in German Museums in the period from 1996 until 2014 is shown in Fig. 1. As can be observed the total number is strongly influenced by the number of special exhibitions visitors.

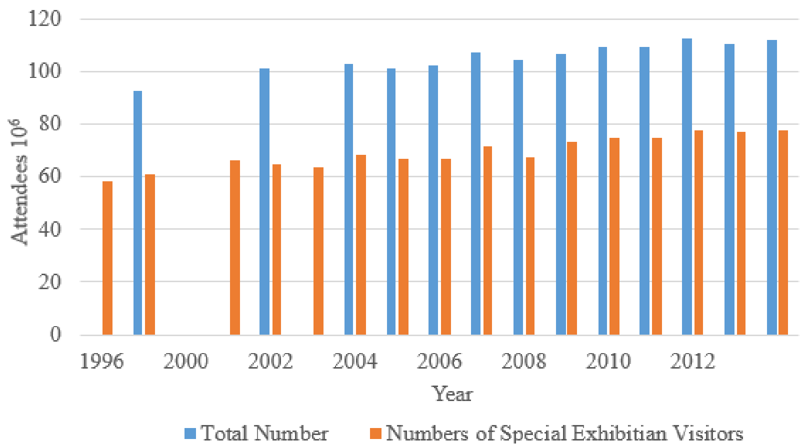

Fig. 1 Total attendees and special exhibition visitors’ numbers [10]

The evolution of the special exhibition numbers in German Museums in the period from 1996 until 2014 is shown in Fig. 2. With reference to 'Staatliche Museen zu Berlin' (SMB) [10], the German Museums stress an increased number of special exhibitions as one reason for the increased attendance. Among these, 'Blockbusters' like 'The MOMA in Berlin' (Berlin, 2004, 1.2 Million visitors), 'The Most Beautiful French Come from New York' (Berlin, 2007, 667.000 visitors) and 'Friedrich the Great' (Potsdam, 2012, 350.000 visitors) play a special role [10].

The number of special exhibitions seems to have reached a saturation point of approximately 9000 per year in Germany (Fig. 2). So, the attendance could be maximized by extended exhibitions with spectacular works of art, which are usually not loaned.

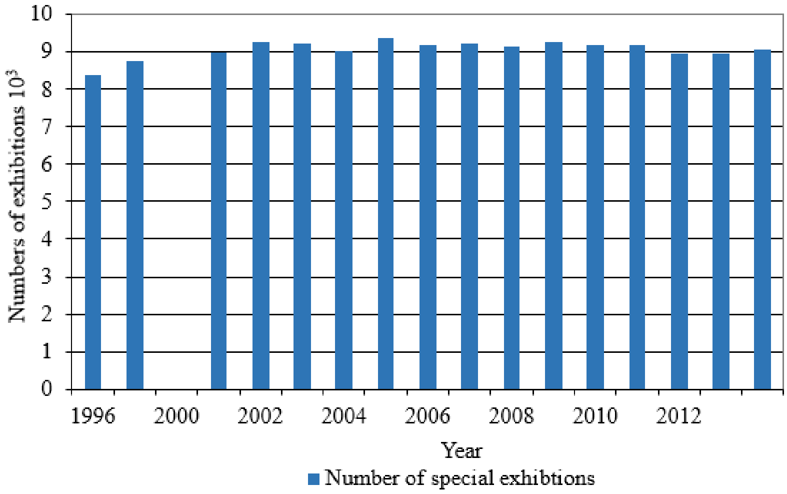

Fig. 2 Numbers of special exhibitions [10]

Summing up, the risk of damages during transport increases because of a constantly high number of special exhibitions with an increasing number of presented works of art especially in view of a keen demand for cultural objects with an endangered condition.

Furthermore, in-house and museum to museum/depot transports are caused by reorganization processes and building renovation. This should be acknowledged; the whole museum collections are moved [12].

Besides transportation, cultural objects are exposed to mechanical loads during exhibition and depot storage by visitors, construction works, concerts, public transportation systems and other kinds of environmental excitation. The different kind of excitation scenarios are discussed in the following section.

3. Excitation Scenarios of Canvas

The diversity of mechanisms requires a detailed consideration. The mechanical load during in-house and loan traffic transport is discussed in section 3.1. The examination of excitations during exhibition is discussed in section 3.2. Mechanical loads during depot storage are characterized in section 3.3.

3.1. Transportation

Several scenarios entail the transportation of art works. Examples are loan traffic, reorganization and renovation, as well as cleaning and restoration of objects. In principle, in-house movement and art in transit must be discussed in a different way.

Within the museum, objects are usually moved by hand or by using hard rubber tired trolleys. There are a lot of online tutorials for restorers on how to care for and handle art objects [13].

For a better understanding of the excitation mechanisms, a transport scenario is described for a special exhibition [14]:

The transportation route of cultural assets loan starts in the home museum. The canvas is taken by the restorer from the installation site and usually wrapped with wrapping film. Next the canvas is fixed in the transport case. The packed canvas is moved, usually by means of a hard rubber tired trolley, into a special truck, which is equipped with air springs. In a few publications canvas transportation by truck is discussed considering (i) the paintings' orientation [19] and (ii) its position on the platform (especially the closeness to the sideboard) [20]. Depending on the destination, transportation is continued by airplane – sometimes by ship and train. The last section of the journey requires the transportation by truck again. The canvas journey is completed by its unpacking and positioning at the new installation point. After the end of the special exhibition, the canvas travels back in the same way.

According to Marcon [15], measurements are the only option to characterize the shipping environment. Hence, vibration and shock measurements during transport are dealt with in a couple of papers and articles:

Important sources of past measurements are by Caldicott [16], Marcon [17] and Saunders [18, 19]. Recent investigations are done by Palmbach [20] and Läuchli [21] as well as Braun [22] and Kracht [23].

Palmbachs and Läuchlis data are acquired, analyzed and documented based on the German standard specification (DIN EN 30786). They investigate several different packaging systems during handling, trucking, shipping etc., considering route quality and the position as well as the orientation of the transport case. Läuchli and Bäschlin have pointed out that "shock immissions" occur mostly during handling in museums. Continuous vibrations, on the other hand, are rather generated during trucking and flight/shipping. Fig. 3 presents measurement results according to transportation processes by averaging the results of Palmbach [20], Läuchli and Bäschlin [21], Braun [22] and Kracht [23].

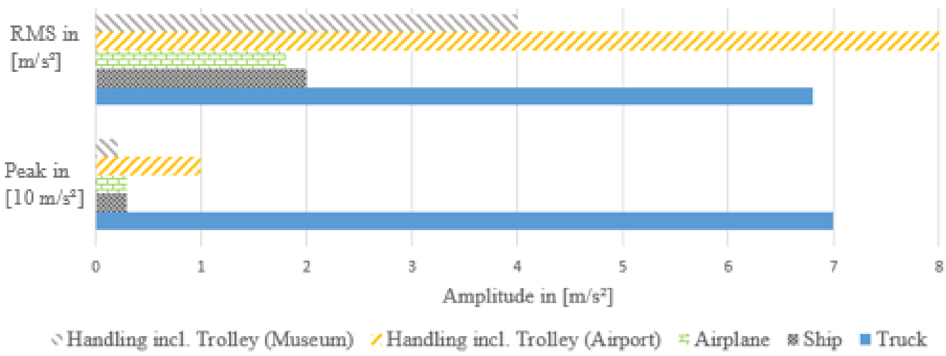

Fig. 3 Emission levels and frequency ranges of different vehicles [21]

Figure 3 represents emission levels from vehicle to packages and relevant frequency ranges of the excitation without specification of the measurement direction. The dimensions of the amplitudes and frequency ranges are similar in every direction, and the out-of-plane levels are greater than the levels in the in-plane directions. Precise values should be obtained from Palmbach [20], Läuchli and Bäschlin [21], Braun [22] and Kracht [23].

The increasing trend of measuring vibrations and shocks during transportation leads to the development of monitoring systems. By now there are several companies which sell or lend data loggers [22]. These small devices are frequently integrated on the bottom or at the side walls of transport cases. Some models enable their installation at the rear side of the canvas [24].

With such devices temperature, humidity, shocks and vibrations are recorded. Note that shocks are time discrete and dynamic events. In contrast, the changing of temperature and humidity are assumed to be quasi-static processes. As a consequence, the recording of mechanical vibrations is still a challenge due to a large memory space, permanent power consumption during permanent recording and a dynamic range of embedded sensors, mostly accelerometers [25].

As mentioned before, vibration and shocks of canvas during transportation are in most cases measured with embedded lightweight accelerometers, which are mounted at the frame or in the middle of the canvas. Non-contact measurements of the canvas using laser technology are also known [26]. Although the laser signal is proportional to the distance (triangulation) or to the relative velocity (vibrometer) between the laser and the canvas, the laser movement during the measurements has not been considered so far.

3.2. Exhibition

For most restorers and conservators, the ‘tight’ installation of cultural assets during an exhibition is the best preservation situation: the climate is controlled, UV and dust contamination is observed and the importance of shock and vibration immissions is much smaller compared to the transport problem. But the question remains whether the mechanical stress exposition is negligible.

In 2014, Gmach [12] introduces building dynamics in the context of damage scenario and risk estimation. She states that mechanical stress of canvas during exhibition is produced by vibrations of buildings, which are mostly excited by car traffic, railway dynamics, visitors’ footsteps (depending on footwear), construction works and earthquakes at certain locations. Gmach investigates shock and vibration emissions in several museums in Munich with different car traffic, railway and industry concentration. Four different construction types with three different materials (reinforced concrete, wood and brick) and subsoil are considered.

Gmach applied two different methods during her investigations. For executing the first method, the heel impact test, a person is standing at the center of the floor on his/her tiptoe and lets himself/herself tumble onto the heels. The resulting impact excitation allows us to draw conclusions related to the natural frequencies of the floors. The results of this test type are shown in Fig. 4. It has to be noted that Gmach measures the vibration of the floor with low-frequency-sensitive triaxial accelerometers (Deltatron Type 8340, Type 4506 B003 and Type 4507 B005 – all manufactured by Brüel & Kjaer). The velocities declared by Gmach are converted according to DIN 4150-4.

The main vibration response direction of the floor is an out-of-plane direction. The eigenfrequencies can be clustered into two groups. The natural frequencies of wooden floors with wooden parquet (8.5 – 40 Hz) are lower than the eigenfrequencies of steel-concrete bond with stone flooring (60 – 80 Hz).

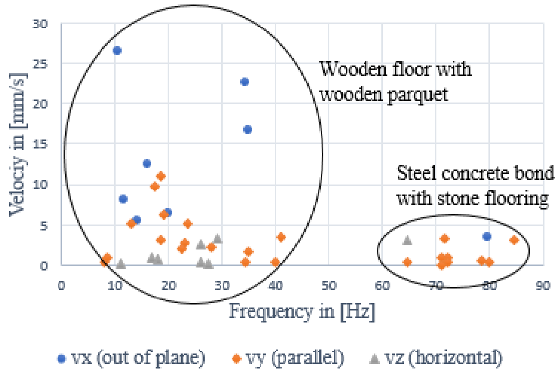

Fig. 4 Emission levels and frequency ranges of heel impact test in different exhibition halls of different museums [12]

Gmach's second method comprises the measurement of the vibration response of the floors caused by different excitation scenarios (construction work, rail traffic, visitors). The results are shown in Fig. 5.

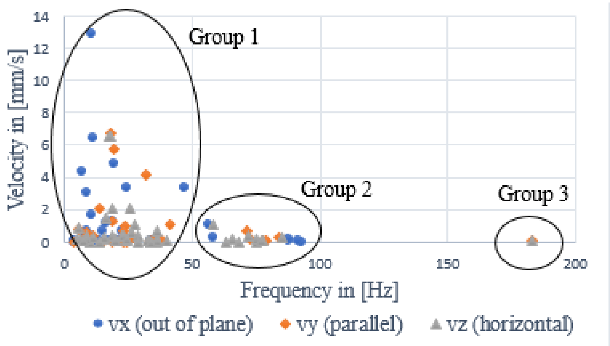

Fig. 5 Emission levels and frequency ranges of excitation scenarios (construction works, rail traffic, visitors) in different exhibition halls of different museums [12]

The results in Fig. 5 can be clustered into 3 groups [12]:

1. Vibration at low frequencies (5 – 40 Hz) and highest velocity amplitudes (6 mm/s – max. 13 mm/s), caused by visitors' footsteps on wooden truss floor.
2. Vibration at midrange frequencies (50 – 100 Hz) and velocity amplitudes (up to 2 mm/s), caused by railway traffic.
3. Vibration at high frequencies (150 – 200 Hz) and low velocity amplitudes (up to 0.064 mm/s), caused by construction work (especially drifter drills).

NOTE: Referring to DIN 4150-3, the velocity amplitudes of historic buildings in the frequency range up to 150 Hz should be permanently less than 3 mm/s. The allowable mechanical load level of canvas depends without doubt on its condition and on the properties of the load signal. However, Thickett [27] investigates the vibration and shock levels which cause damage(s) to museum objects.

Kracht [23] investigates the excitation of canvas during exhibition for two different suspension systems: steel hook and nylon rope. Fig 6 shows the setup for the measurement at the steel hook.

Fig. 6 Measurement setup for the investigations of the vibration excitation of the suspension system: steel hooks (oil painting “The Holy Family” by Luciano Podormo, Bode-Museum, Berlin) [23]

The measurement results are shown in Fig. 7. The clustering of Gmach’s results [12] are confirmed.

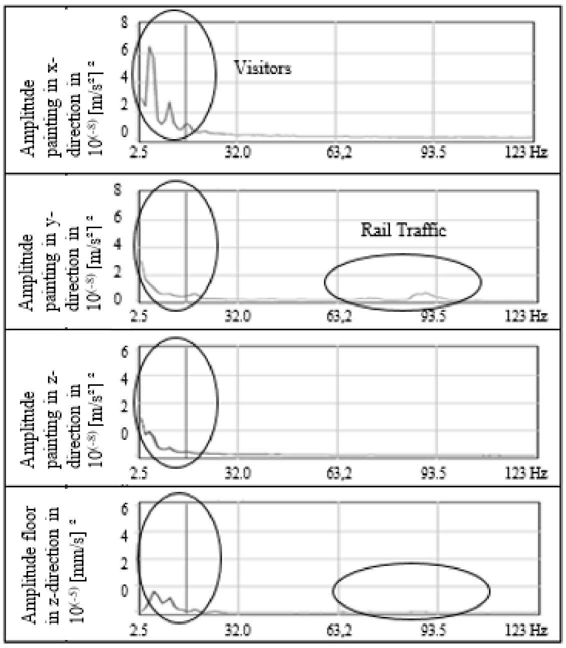

Fig. 7 Auto spectra of the signals of the measurements at the “Holy family” excited by rail traffic and visitors [28]

Bakker [29] and Weihser [30] highlighted another excitation mechanism. The attractive surroundings of museums and the special acoustics of museum buildings make them favored venues of different kinds of concerts.

3.3. Depots

Nearly 70% of a museum's collection is usually stored in depots [31]. Depots are excited by the same mechanisms as the exhibition halls – traffic, railway, etc. However, the initiation of mechanical vibrations inside the building depends on the in-house transfer paths. Mostly, depots are installed at the basement of the building, exhibitions usually at the higher floors. Furthermore, in contrast to exhibitions, canvasses are stored space-saving at moving grid walls.

Kracht [23] investigates three different kinds of moving grid walls and five different canvas mounting systems. An example of a usual grid wall, the sensor position and the measurement direction are shown in Fig 8.

Fig. 8 Storage of canvas at typical grid walls in the paintings' depot, Alte Nationalgalerie, Staatliche Museen zu Berlin [23]

The top edges of a grid wall are moveable since mounted in rails with ball-bearings. The rails of 20 up to 50 or more grid walls are parts of a huge steel rack. Furthermore, the front corners of the grid walls are often supported by a guiding hard rubber wheel on rough concrete or sometimes on tile flooring. As a consequence, if one grid wall is moved, the excited steel rack will hence induce vibrations to all the other grid walls. These design details are responsible for high excitation levels. The Peak and RMS values of three different types of moving grid walls are documented in Fig. 9.

The two grid walls in depots 1 and 2 have a hard rubber guide wheel in the front edge. The grid walls in depot 3 are mounted in a pending position. The stopping-systems are also different. The grid walls in depot 1 can be stopped by arm power or by a grid wall-to-rack-shock. The grid walls in depot 2 have a spring, which prevent shocks between grid wall and rack. The grid walls in depot 3 have a dashpot instead of a spring. Finally, only the ball-bearings of the depot 3-grid walls are free-moving.

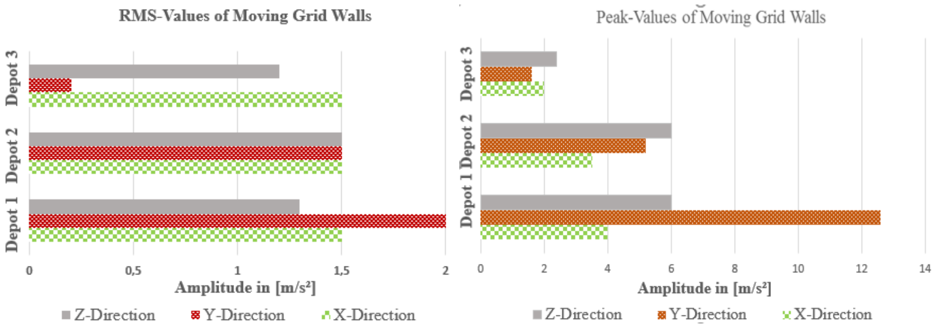

Fig. 9 RMS- and Peak-Values of three different moving grid walls [32]

These characteristics cause different vibration levels (RMS between 0.1 m/s² and 2 m/s²) and shock levels (peak values between 1.2 m/s² and 12.5 m/s²) levels. Kracht detects vibrations with a continuous excited frequency range between 3 and 150 Hz at all moving grid walls. The highest measured amplitudes are between 7 and 48 Hz.

4. Efforts to Reduce Shock and Vibration – State-of-the-Art

In most cases, damages caused by continuous vibrations are neglected in the literature. The low amplitude of mechanical vibrations (compared to shock levels) makes a high cumulative number of vibration cycles necessary to make damages visible [7, 8]. For this reason, efforts to protect canvas during transport are focused on shock absorbing treatments. Moreover, restorers and conservators usually assume that shocks do not occur to canvas during storing in depots as well as during exhibition. Hence, the efforts of vibration and shock reduction by conservators and restorers are focused on the field of transportation.

In the following three subsections, the state-of-the-art of: (a) transport utility design, (b) mounting systems during exhibition and (c) storing for depots are discussed.

4.1. Transport utility design

Since the 70's '[...] the technologies of packing and transporting paintings have been the subject of extensive investigations. [...].' [11]. A report is given by Hackney and Green [34]. Among other findings they state: '[...] None of the respondents incorporate any specific vibration protection in their case [...]' because '[...] vibration specifically has not been shown to cause damage [...]' (ref. p. 74). This position still influences the design of transport utilities in such a way that mainly shocks are considered during the design process, and continuous vibrations are neglected [15].

Based on the properties of cushioning materials, the fragility rating of objects [42] and expected shock loads, a 'circular slide rule' [43] and a computer program 'padcad' is developed by the Canadian Conservation Institute for supporting package designer [15, 17]. A description of the cushion design procedures with examples using measurement curves and notes about cushion material behavior like buckling as well as creep is given by Richards [11]. Last but not least chemical and bio-chemical material properties are discussed in [35].

Green, one of the few engineers in the field of heritage preservation, presents in [44] the idea of a vibration isolation transport utility. Herein he suggests: '[...] The low natural frequencies of canvas make the successful application of vibration isolating materials difficult. [...]'. Building on this, Green develops 'Performance criteria for packing' in general [36]. Green also develops a transit frame for paintings with cushioning material which isolates canvas from most shocks during handling and transit [37].

Various packages from simple slides to expensive box-in-box systems are used. The art of packaging differs from museum to museum and from country to country. Restorers [21] consider the actual best solution for vibration reduction and shock absorbing is the box-in-box transport case. Canvasses shipped in such crate are damaged least [45].

Figs. 10 and 11 show a typical case and a close-up of the elastic support between inner and outer case.

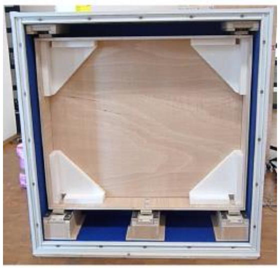

Fig. 10 Box-in-box transport case [38]

Fig. 11 Support between inner and outer case [38]

In their project, Bäschlin, Läuchli and Palmbach [39] have investigated five different package systems in a number of transports over years. The key motivation of the measurements is the understanding of the damage potential for assessing risks and developing preventive strategies [13]. They establish that most efforts of vibration reduction amplify the input instead of reducing the incoming noise in a frequency range up to 40 Hz. The research group names the stiffness of the elastomer support as a reason for amplification [21].

In 2016 Kracht analyzes the vibration behavior of a transport crate and the interaction between transport crate and canvas [40]. As an example, Fig. 12 shows the absolute value of a transfer function between the response of the midpoint of a canvas and the excitation force signal (chirp 0 to 500 Hz, average 10 N) at the outer case measured near the right lower corner.

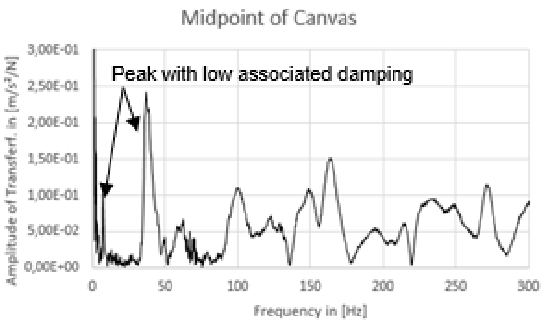

Fig. 12 Amplitude of transfer function between midpoint of canvas and outer case [40]

In Fig. 13 four absolute values of the transfer functions between the corners of a test canvas and the excitation force signal (chirp) at the outer case are shown.

The magnitude of the two most dominant modes of this particular canvas during this test is approximately 4 mm at the midpoint. The corresponding resonance frequency modes are 5 Hz (tilting of the rigid case) and 45 Hz (torsion mode of the case). These measurement results are fundamental for vibration isolation design and optimization.

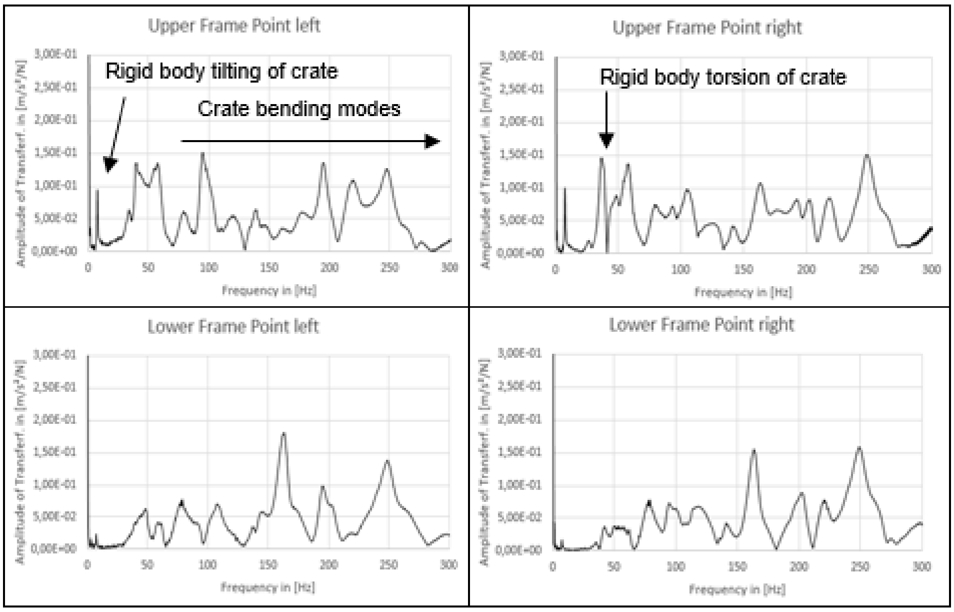

Fig. 13 Amplitude of transfer function between canvas frame and outer case [40]

4.2. Mounting and support systems in exhibition halls

During exhibition, canvasses are presented in an upright position. They are mounted at steel hooks or with nylon/steel ropes or standing at pedestals. In Fig. 14, left, a steel hook as a coupling element between wall and canvas frame is shown. Fig. 14, right, presents the mount system based on Nylon rope.

In comparison with Fig. 7, the results of the measurements at the nylon rope fixation in Fig. 15 show that the steel hook causes no vibration isolation – in contrast to the nylon rope support. It must be also noted that the

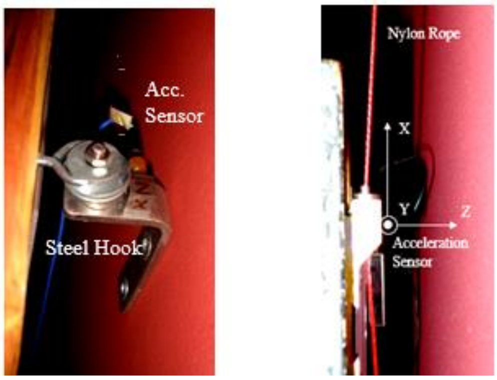

Fig. 14 Attachment of the work “The Holy Family” by Luciano Podormo (Fig. 6) with a steel hook (left) and with a nylon rope (right) [23, 28]

auto spectra of the measurement at nylon rope support shows one peak in X-direction at 20 Hz with a magnitude of 0.75 $(m/s^2)^2$. In contrast, the auto spectra of the measurements at the steel hook support show a broad band with a maximum magnitude of 6×10^{-5} $(m/s^2)^2$ at 5 Hz in X-direction.

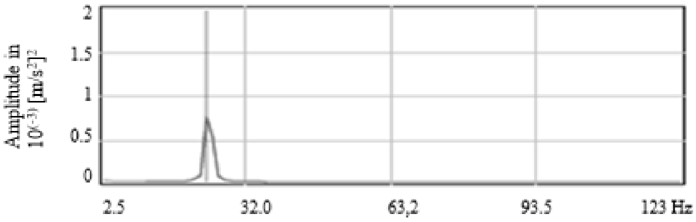

Fig. 15 Auto spectra in X-direction of the vibration measurements at nylon rope fixation excitation, which is excited by visitors (magnitude of the Auto Spectra in the other directions are approx. 10^{-6} $(m/s^2)^2$) [28]

Canvas painted from both sides is often presented on pedestals (Fig. 20 left) or in a free hanging position (Fig. 20 right). The pedestal of the canvas in Fig. 20 is a wooden box. In [41] the operational vibration behavior of the system, shown in Fig. 16, left, is analyzed. Tab. 1 contains the measurement results: peak values and relevant frequency ranges. For these measurements 6 visitors excited the floor around the system.

Fig. 16 Presentation solutions of canvas painted from both sides: on pedestals (left) [41] and hanging at four steel ropes (right) [38]

Tab. 1 Vibration measurement results of the system shown in Fig. 16 (left) excited by 6 walking visitors [41]

Sensor direction (Fig. 16)	Peak in [mm/s]	Frequency range in [Hz]
x	0.03	4 to 65
y	0.035	10 to 35
z	0.13	4 to 25
y_{floor}	0.04	n. s.
z_{canvas}	0.2	3 to 10

4.3. Mounting and support systems in depots

In contrast to restorers' and conservators' assumptions, the results of vibration measurements at moving grid walls prove that vibrations and shocks (dependent on the moving grid walls design) can occur in practice. Thus, the mounting system of the canvas should be able to absorb and to neutralize shocks as well as to isolate the system from incoming vibrations. In Fig. 17 common suspension systems, which have no elastic or energy absorbing elements, are shown.

Fig. 17 Suspension systems at moving grid walls [32]

The vibrations of five different steel hook-grid wall-combinations are analyzed by [32]. RMS and Peak values are shown in Figs. 18 and 19.

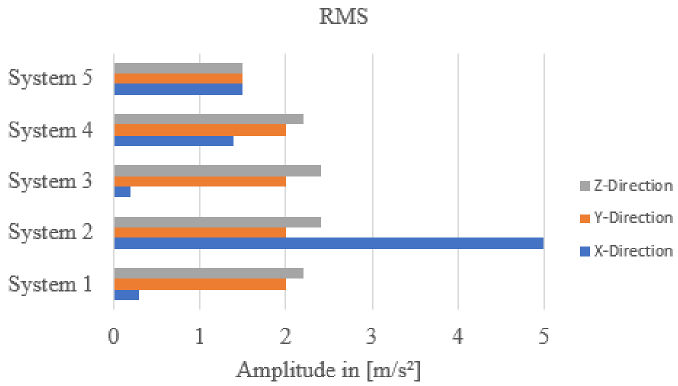

Fig. 18 RMS-Values of different moving grid walls and mounting systems [32]

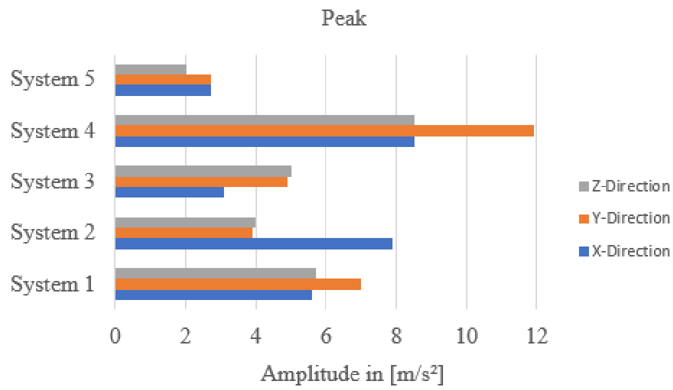

Fig. 19 Peak-Values of different moving grid walls and mounting systems [32]

Hanging systems 1, 2 and 3 in Figs. 18 and 19 are mounted in a hanging position at grid walls in depot 1. Hanging system 4 in Figs. 18 and 19 is mounted in a hanging position at a grid wall in depot 2 and hanging system 5 in Figs. 18 and 19 is mounted in depot 3. Compared to the results shown in Fig. 9 it can be observed that the excitation of the moving grid walls in depot 1 is the most significant one, but the peak values of the canvas' mounting points in depot 2 are larger than in depot 1.

It can be concluded that the low-level excitation of the moving grid walls in depot 3 causes a low-level excitation of the canvas' mounting points.

5. Bridging the Gap: Roads to the Art of Engineering

This section aims to arbitrate between restorers' mind and engineers' abstract conceptions. On the one hand, restorers' first steps using engineers' methods are brought up and, on the other hand, the advantages and the necessity of theoretical modeling which has not started yet are pointed out. The challenges of saving canvasses from shocks and vibrations will be shown by means of a minimal model of the canvas-in-crate-system in Fig. 10. Furthermore, an excursus to environmental testing and the fact that canvasses are complex fiber-matrix-composites with a very complex dynamic behavior will show the wide research potential:

Observation and monitoring are the basis of conservators' and restorers' work. As shown in sections 3 and 4, principles of canvas' excitation as well as effects of elastomer mounts [46] are analyzed phenomenological by case studies during real transportation and storage scenarios.

A fine step forward using engineers' methods is checking the capability of transport cases especially cushioning materials based on environmental testing [48]. State-of-the-art is the simulation of an aircraft flight or the conditions during a truck ride by electrodynamic or hydraulic/pneumatic shakers. Therefore, the vibration and shock transmission has to be considered:

Based on the engineers' Input-Output-assumption [33], Fig. 20 shows the vibrations and shocks transmission exemplary from the rolling truck wheels by road roughness through the wheels, platform and package to the shipped canvas considering the reaction of each subsystem.

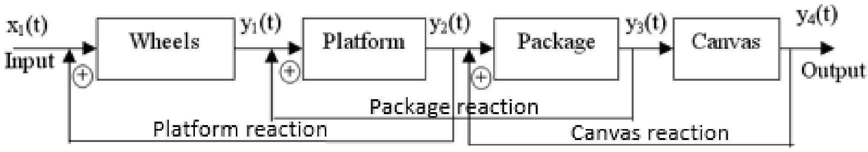

Fig. 20 Path of shock and vibration transmission with considered reactions

The determination of load profiles for shaker tests are common due to DIN EN 61373 and DIN EN 60721-2-9. Recorded data for example at the package are clustered and smoothed with filter function. The results in terms of Power-Spectral-Densities (PSD) serve the target value of a control loop. Exemplary the PSDs (target value, actual value and control limits) of a mid-range air spring truck transportation simulation are shown in Fig 21.

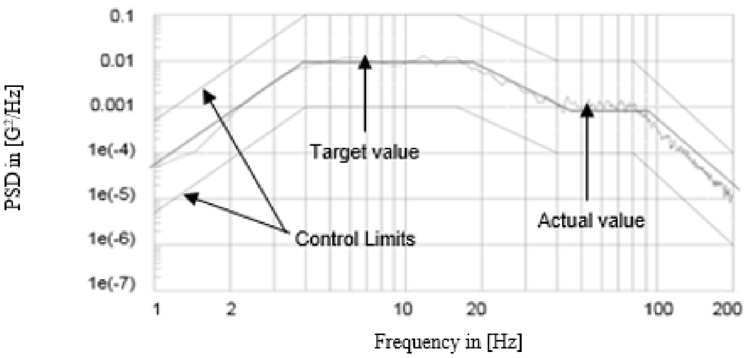

Fig. 21 Desired and actual values of Power-Spectral-Density (PSD) within the break-off limits referring to air spring truck level II [49]

The practical approach of case studies and environmental testing is limited in terms of finding feasible solutions by the uniqueness of each canvas, the great number of canvasses as well as the complexity of vibration isolation together with shock absorption. The challenge of vibration and shock reduction of canvasses during transportation can be shown with an engineers' basic: 1-degree-of-freedom minimal model:

Thinking of the vertical movement of the box-in-box transport crate shown in Figs. 10 and 11, the dynamic of the canvas-frame-system can be modeled as shown in Fig. 22 – abstracting the canvas and frame as rigid body (approximation zero order) and introducing parameters k (spring stiffness), d (damper constant), m (mass) and the coordinates of movement x(t) and u(t).

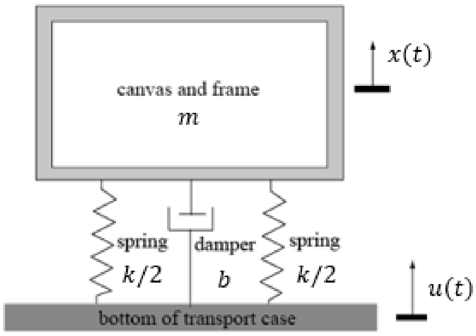

Fig. 22 Simplified model of the base support of the box-in-box transport crate in vertical direction

The complex transfer function is given by

$$H(j\eta) = \frac{F\{x(t)\}}{F\{u(t)\}} = \frac{j2D\eta + 1}{-\eta^2 + j2D\eta + 1} \tag{1}$$

with introducing $\omega_0 = \sqrt{k/m}$ (natural frequency), $D = b/(2\sqrt{km})$ (damping ratio) and $\eta = \Omega/\omega_0$ (frequency ratio between excitation frequency and natural frequency) of the system in Fig. 22 [47].

Mostly, the excitation of canvas can differ regarding continuous random vibration and discrete shock events. The plot of absolute value of *H(jη)* in Fig. 23 shows the remarkable characteristics of vibration isolation:

i. The higher damping factor *D*, the lower the amplitude during resonance (η=1),

ii. The higher damping factor *D*, the lower the effect of vibration isolation ($\eta > \sqrt{2}$).

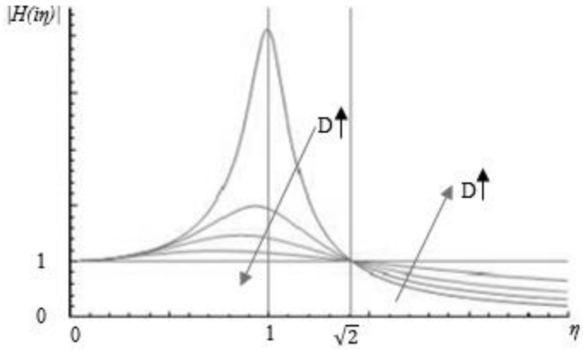

Fig. 23 Absolute value of transfer function *H(jη)*

This means that a high damping factor is necessary to avoid resonance, but a high damping factor reduces the vibration isolation effect.

Furthermore, the springs of the isolation system must be weak, because the first natural frequency of paintings on textile carrier is generally very low (< 4 Hz) [23] and various excitations occur from also very low frequencies, e.g. truck excitation from 1 Hz (Fig. 3). The consequence of weak springs becomes obvious in Fig. 24.

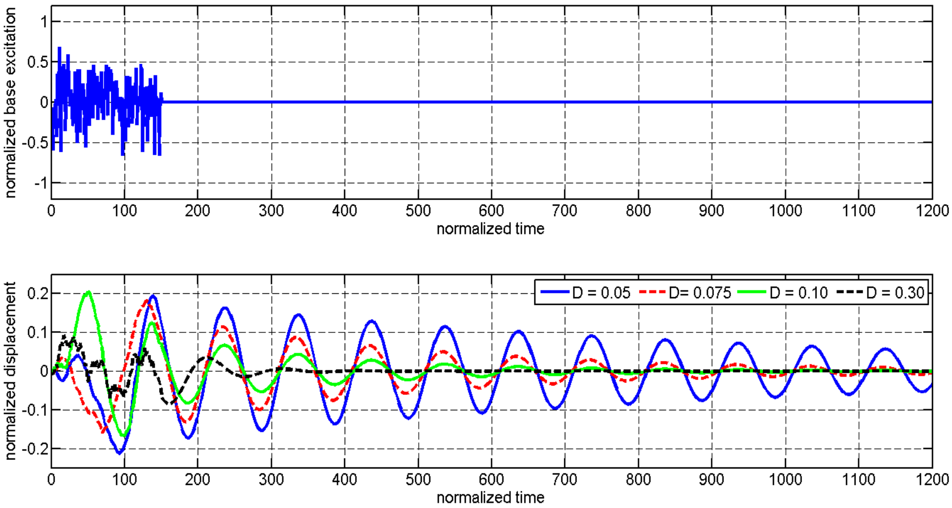

Fig. 24 Base excitation and responses of the system in Fig. 22

Fig. 24 shows an excitation time signal, which includes random vibration and an abort, as well as the responses of the dynamic system in Fig. 22 with different damping factors *D* in the time domain, which is calculated by numeric integration of the normalized (with $t \mapsto \tau := \omega_0 t$ and $x \mapsto \xi_x := x/x_0$) differential equation second order (dynamic force equilibrium of the system in Fig. 21):

$$\xi_x''(\tau) + 2D\xi_x'(\tau) + \xi_x(\tau) = 2D\xi_u'(\tau) + \xi_u(\tau) \tag{2}$$

Regarding the first maximum absolute amplitude of the diagram in Fig. 24 dependent on the damping factor, the third characteristic of the vibration isolation - shock absorption - problem can be figured out:

iii. The lower damping factor D, the higher the deflections of the canvas.

Thus, fact iii. requires also a high damping factor to avoid high deflection of canvas.

The question about the prevention of resonance and about shock absorption seems to have been answered. The simultaneous reduction of vibration excitation of canvas is up to now an unresolved problem.

6. Summary, Conclusion and Outlook

This paper gives a summary of the 40 years of conservators’ research on canvas vibration caused by various excitation scenarios and restorers’ efforts to reduce mechanical load. To this end, this paper contains a summarized data collection, which compresses the huge data volume in restorers’ literature.

It is acknowledged that the customary solutions for transporting, presenting and storing canvas in matters of vibration reduction are improvable. These utilities are not designed in consideration of modeling and analyzing the dynamic behavior of each subsystem. Until nowadays restorers themselves establish most of vibration reduction solution. It is figured out that most of these solutions amplify the input instead of reducing the incoming noise. In this context, the practice and methods of environmental testing are suggested.

The difficulties of reducing the mechanical loads of canvas during transportation are shown by means of a minimal model. Generally very low natural frequencies of paintings on textile carriers (first natural frequencies often < 4 Hz) and the excitation of canvas from 1 Hz in many cases require a vibration isolation system with weak springs. As a consequence, a high damping factor to avoid the resulting high deflections of canvas after shock loads and during resonance is necessary. In contrast to this, the high damping inhibits the reduction of the excitation caused by continuous vibrations. Furthermore, in the context of the very low natural frequencies of canvas, it is noteworthy that transport crates tend to rigid body tilting modes at frequencies lower than 10 Hz (ref. Fig. 17).

Scopes to solve the problem of vibrating canvas are 1. the reduction of load levels, 2. the development of passive or active adjustable spring damper elements and 3. the stiffening of canvas. Therefore, the systematic investigation and modeling of each subsystem are required. Engineering literature provides several approaches in terms of excitation reduction and spring damper elements design. The transfer to the preservation of paintings poses the challenge. Contrary to this, the dynamic behavior of canvas as well as the damage mechanism of canvas itself is very complex and hardly examined. A review on the condition analysis techniques and the investigation of the dynamic behavior of canvas is subject of an upcoming paper (Part II).

REFERENCES

1. Kunz, S., Röhrs, S., Simon, S., 2013, *Heritage Science and Sustainable Development for the Preservation of Art and Cultural Assets - On the Way to the GREEN Museum,* Conference Booklet, Berlin, 11.-12. Apr. 2013.
2. Waentig, F., Dropmann, M., Konold, K., Spiegel, E., Wenzel, C., 2015, *Leitfaden Präventive Konservierung*, Report, ICOM Deutschland e.V.
3. Michalski, S., 2013, *Stuffing everything we know about mechanical properties into one collection simulation*, Technical Report, Canadian Conservation Institute.
4. Kracht, K., v. Wagner, U., 2013, *Vibration behavior of paintings and the consequences*, Poster presentation at the conference on heritage science and sustainable development for the preservation of art and cultural assets – on the way to the GREEN Museum, Berlin, 11.-12. Apr. 2013.
5. Wei, W., 2006, *Art in transit – The need to reconsider the problem of vibrations in the transport of cultural heritage*, Presentation at the international seminar: Impact of loan traffic on works of art, Berlin, 4.-5. Sept. 2006.
6. Wei, W., 2008, *Zijn trillingen erg? Onderzoek naar her cumulatieve effect*, CR: interdisciplinair tijdschrift voor conservering en restauratie, 9, pp. 24-27.
7. Läuchli, M., Bäschlin, N., Palmbach, C., Hoess, A., Ryser, M., Fankhauser, T., Sautter, K., 2015, *Der Teufel steckt im Details – Zur Praxisanwendung der Forschungsergebnisse Transport fragiler Gemälde,* Zeitschrift für Kunsttechnologie und Konservierung 29 (2), pp. 211 – 222.
8. Läuchli, M., Bäschlin, N., Palmbach, C., Ryser, M., Fankhauser, T., Hoess, A., 2015, *Vibrationen – kleine Erschütterungen millionenfach,* Zeitschrift für Kunsttechnologie und Konservierung 29 (2), pp. 223 - 236.
9. Eichmüller, G., 2016, *Schwingungsbelastungen und das daraus resultierende Risikopotential für keramische Objekte - Eruierung des Schädigungspotentials anhand von keramischen Prüfkörpern ausgelöst durch ein innerstädtisches Belastungsprofil,* Master-Thesis, HTW Berlin.
10. Graf, B., 1996 - 2014, *Statistische Gesamterhebung an den Museen der Bundesrepublik Deutschland,* Jährliches Heft, Berlin.

11. Richards, M., 1990, *Art in Transit: Studies in the Transport of Painting,* Conference Book, National Galery of Art, Washington.
12. Gmach, A., 2014, *Erschütternde Umstände. Schwingungsbelastung von Kunst- und Bauwerken,* Master-Thesis, TU München.
13. Website: http://www.museumoflondon.org.uk/Resources/e-learning/handling-museum-objects/ (last access: 17.Mar. 2017)
14. Nicolaus, K., 2001, *Handbuch der Gemälderestaurierung,* Könemann, Köln.
15. Marcon, P. J., 1991, *Shock, vibration and protective package design*, in: Mecklenburg, M. F. (Ed.) *Art in Transit – Studies in the transport of paintings*, National Gallery of Art, Washington.
16. Caldicott, P. J., 1991, *Vibration and shock in transit situations*, in: Mecklenburg, M. F. (Ed.) *Art in Transit – Studies in the transport of paintings*, National Gallery of Art, Washington.
17. Marcon, P. J., 1991, *Shock, vibration and the shipping environment*, in: Mecklenburg, M. F. (Ed.) *Art in Transit – Studies in the transport of paintings*, National Gallery of Art, Washington.
18. Saunders, D., 1998, *Monitoring Shock and Vibration during the Transport of Paintings,* National Gallery Technical Bulletin, 19, pp. 64-73.
19. Saunders, D., 2005, *The effect of painting orientation during air transportation*, Presentation at ICOM-CC 14th Triennial Conference Preprints, The Hague. 12.-16. Sep. 2005.
20. Palmbach, C., 2013, *Transportmonitoring bei Gemäldetransporten - Neue Datensammlung zur Charakterisierung der Schock- und Vibrationsimmisionen*, Presentation at 23. Tagung des Österreichischen Restauratorenverbandes Konservieren Restaurieren Kunst unterwegs, Wien, 30.-01.Dez. 2012.
21. Läuchli, M., Bäschlin, N., 2014, *Packing systems for paintings: Damping capacity in relation to transport-induced shock and vibration*, Presentation at ICOM-CC 17th Trienniel Conference, Melbourne, 15.-19. Sep. 2014.
22. Braun, N., 2013, *Transport von Gemälden – Grundlegende Aspekte und Vibrationsmessungen während eines Kunsttransports*, Master-Thesis, TU München.
23. Kracht, K., 2011, *The investigation of the vibration behavior of canvas dependent on weathering,* PhD Thesis, TU Berlin.
24. Website: http://artguardian.com/ (last access: 17.Mar. 2017)
25. Palmbach, C., 2012, *Risk assessment for shock and vibration immissions with new preventive strategies for transporting fragile paintings,* Test report, MSR Data Loggers.
26. Lasyk, L., Lukomski, M., Bratasz, L., Kozlowski, R., 2008, *Vibration as a hazard during the transportation of canvas paintings,* Studies in conservations, 53, pp. 64-68.
27. Thickett, D., 2002, *Vibration damage levels for museum objects*, Presentation at ICOM-CC 13th Triennial Meeting, Rio de Janiero, 22.-27. Sep. 2002.
28. Kracht, K., 2010, *Schadensdetektion an Gemälden auf Leinwand mit Hilfe von mechanischen Schwingungen*. Presentation at öffentliche. Vortragsreihe des Rathgen - Forschungslabors im Schloss Charlottenburg, Berlin, 27. Apr. 2010.
29. Bakker, K., 2008, *Gecraqueleered canvas - Concerten veroorzaken trillingsschade aan schilderijen*, De Ingenieur, 5, pp. 34 - 35.
30. Website: http://www.zeit.de/online/2008/27/eremitage-rock-konzerte (last access: 17.Mar. 2017)
31. Kracht, K., von Wagner, U., 2016, *Schwingungsbelastung von Kunst- und Kulturgut,* Presentation at Arbeitskreis Forschung im Museum, München, 03. May 2016.
32. Kracht, K., 2010, *Untersuchung des Schwingungsverhaltens von Ölgemälden*, Presentation at Annual Meeting European Modal Analysis Users Group, Berlin, 11.-12. Mar. 2010.
33. Natke, H. G., 2013, *Einführung in Theorie und Praxis der Zeitreihen- und Modalanalyse: Identifikation schwingungsfähiger elastomechanischer Systeme,* Springer, Berlin.
34. Hackney, S., 1991, *Packing case design*, in: Mecklenburg, M. F. (Ed.) *Art in Transit – Studies in the transport of paintings*, National Gallery of Art, Washington.
35. Erhardt, D., 1991, *Art in transit: material considerations*, in: Mecklenburg, M. F. (Ed.) *Art in Transit – Studies in the transport of paintings,* National Gallery of Art, Washington.
36. Green, T., 1991, *Performance criteria for packing*, in: Mecklenburg, M. F. (Ed.) *Art in Transit – Studies in the transport of paintings*, National Gallery of Art, Washington.
37. Green, T., 1991, *A cushioned transit frame for paintings*, in: Mecklenburg, M. F. (Ed.) *Art in Transit – Studies in the transport of paintings,* National Gallery of Art, Washington.
38. Kracht, K., 2012, V*ibration measurements at Museum Ludwig*, Test report, TU Berlin.
39. Website: www.gemaeldetransport.ch (last access: 17.Mar. 2017).
40. Kracht, K., 2016, *Vibration measurements at different transport crates for canvas,* Test report, paconsult Hamburg.

41. Kracht, K., 2016, *Schwingungsbelastung von Kunst- und Kulturgut*, Presentation at Restaurierungskolloquium Technoseum Mannheim, Mannheim, 18. Sep. 2016.
42. Richards, M., 1991, *Foam cushioning materials: Techniques for their proper use*, in: Mecklenburg, M. F. *Art in Transit – Studies in the transport of paintings*, National Gallery of Art, Washington.
43. Richards, M., 1991, *A circular slide rule for protective package design*, in: Mecklenburg, M. F. (Ed.) *Art in Transit – Studies in the transport of paintings*, National Gallery of Art, Washington.
44. Green, T., 1991, *Vibration control: paintings on canvas supports*, in: Mecklenburg, M. F. (Ed.) *Art in Transit – Studies in the transport of paintings*, National Gallery of Art, Washington.
45. Website: http://www.3sat.de/mediathek/?mode=play&obj=46414 (last access: 18. Mar. 2017).
46. Smyth, A. W., Brewick, P., Greenbaum, R. Chatzis, M., Serotta, A., Stünkel, I., 2016, *Vibration Mitigation and Monitoring: A Case Study of Construction in a Museum*, Journal of the American Institute for Conservation, 55(1), pp. 32 – 55.
47. Hagedorn, P., Hochlenert, D., 2012, Technische Schwingungslehre, Frankfurt am Main, 230 p.
48. Website: http://www.gemaeldetransport.ch/category/publikationen/messungen (last access: 17.Mar. 2017).
49. Website: ftp://185.72.26.245/Astm/2/01/Section%2015/ASTM1509/PDF/D4169.pdf (last access: 17.Mar. 2017).