World Conference on Timber Engineering
Oslo 2023

ACTIVE MASS DAMPERS FOR TIMBER FLOORS

Thomas Hillberger[1], Thomas Furtmüller[2], Philipp Dietsch[3], Roland Maderebner[4]

ABSTRACT: Extensive modeling of timber slabs with active vibration elements has shown that, compared to passive vibration dampers, a significantly better effect is achieved with a fraction of the required mass. In this respect, it is obvious to intensify research in the field of active vibration control. These active damping systems are intended to positively affect the vibration properties of slender slab structures in particular. Fundamental for this research is that the requirements of the Eurocodes are met and the weight of the active elements is kept low. In the present work, the vibration properties, in particular the vibration response of cross laminated timber are addressed. The dynamic parameters determined for a simply line supported system define the following tests which are carried out with actively controlled damping elements. The tests with the cross laminated timber panel suggest that counteracting at certain times and with predefined levels of intensity causes a considerable reduction of the acceleration values. Based on controlling the acceleration response, tests are performed on a complex timber construction. Different excitation, including the random and dynamic motion of people moving on the slab, increase the difficulty to solve this task for slab systems using common control systems. Therefore, the purpose of this research is to verify the reduction of floor vibrations and to demonstrate its effectiveness in experiments with human-induced excitation. The results show a significant reduction in vibration acceleration for different types of excitation and highlight the possibilities of active vibration control.

KEYWORDS: Timber structures, cross laminated timber, active damper, vibrations, frequency

1 INTRODUCTION

A particular challenge in the design of timber floors are the requirements for the serviceability limit state (SLS). Fundamental research in the field of floor vibrations for different timber constructions was presented in [1]. Since then, the possible span of timber structures has evolved significantly due to improvements in timber products and fasteners.

If considering just the ultimate limit state (ULS), enormous advances in the realisation of slender floor elements are possible with currently executable constructions. However, this is accompanied by the fact that the SLS is becoming more and more relevant for the dimensioning of the components due to the large spans. In order to meet the noise reduction standards, appropriate masses are needed to ensure that the required sound insulations are achieved. This trade-off is solved with so-called heavy floor structures consisting of fillings, impact sound insulation boards and mineral floating screeds. These additional loads make it necessary to increase the structural heights and hence the material use of the timber slab to stay within the required limit value of the natural frequency.

The increasing number of publications regarding human-induced vibrations highlight the relevance of this topic for structural engineering [2,3]. Due to the dynamic properties of timber floors, experiments relating to the vibration behaviour are essential. The modal parameters such as natural frequencies and damping characteristics of floor elements depend on different design assumptions. The influence of support conditions of cross laminated timber (CLT) floors on the vibration properties has already been addressed in [4]. [5] deals with the effects of support conditions respectively plan aspect ratios on the natural frequencies and damping of the floor elements corresponding to the serviceability. By in-situ measurements but also in the laboratory, various research works have additionally examined the vibrational characteristics of the raw floor slab and furthermore differences between different floorings [4,6-8]. The tests presented in the current paper also provide measurement data for the human-induced excitation as well as additional experimental results for different floorings and support conditions. These experimental investigations are currently being performed as part of an ongoing research project at the Universität Innsbruck.

There are various approaches for improving the vibrational behaviour of floors. In [9] implementation examples of active vibration control with focus on seismic excitation are presented. Parallel-connected passive tuned mass dampers for slab elements have been examined [10]. The potential that active control systems can provide for floor constructions are discussed in [11]. Particularly active systems should enable to maintain the required serviceability limits despite the reduction in floor thickness. The effect of active vibration control (AVC) in a reinforced concrete slab is impressively shown in [12]

[1] Thomas Hillberger, Unit of Timber Engineering, Universität Innsbruck, Austria, thomas.hillberger@uibk.ac.at
[2] Thomas Furtmüller, Unit of Applied Mechanics, Universität Innsbruck, Austria, thomas.furtmueller@uibk.ac.at
[3] Philipp Dietsch, Chair of Timber Structures and Building Construction, Karlsruhe Institute of Technology, Germany, dietsch@kit.edu
[4] Roland Maderebner (Project leader), Unit of Timber Engineering, Universität Innsbruck, Austria, roland.maderebner@uibk.ac.at

https://doi.org/10.52202/069179-0251

(acceleration feedback control) and [13] (velocity feedback control). The tests in these publications are based on recorded accelerations of the vibrating structures. The values are converted according to the used method and provide the actuator data for the counteraction. A significant reduction of the acceleration values can be achieved with these methods.
The aim of this research work is to demonstrate, the effect of adaptive, actively controlled vibration dampers on the acceleration values of CLT panels caused by human-induced vibrations. With the current state of research on active mass dampers and the use of this knowledge to reduce vibrations, the possibilities for timber construction are presented in the course of this work.

2 MATERIALS AND METHODS

2.1 GENERAL

Experimental tests are applied to verify the effectiveness of the active vibration elements. The vibration characteristics of the floor elements are essential. The experimental tests focus on CLT elements with different dimensions. The dimensions of the used plates can be found in Table 1. The excitation of the CLT panels is realized by different means, e.g. heel-drop or shaker. This is supplemented by experimental investigations of human-induced vibrations with the same test setup. In the experiments with active vibration control, the excitation is mainly imposed by a shaker, because initially reproducible vibration response is necessary.

Table 1: *Overview of CLT elements used in experimental investigations*

Type	Layer (mm)	Length (mm)	Width (mm)	Depth (mm)
CLT_01	5-Layer 40/20/40/20/40	7000	1222	160
CLT_02	3-Layer 30/30/30	4000	400	90
CLT_03	3-Layer 30/40/30	2000	970	100

2.2 EXPERIMENTS – VIBRATIONAL CHARACTERISTICS

For these tests, the element type CLT_01 from Table 1 is used. I-beams (HEB 300) with steel shaft ensure a hinged support (support distance of 5.80 m). In Figure 1 the test setup is visualized in addition to the two excitation modes (walking person and shaker). To determine the modal parameters, the plate is excited by an impulse hammer. The first natural frequency identified by these tests is 10.33 Hz. Furthermore, response data are recorded, which result from the excitation according to a heel-drop. Figure 2 and Figure 3 show the dynamic behaviour of the centrally placed sensors ACC-Sensor3 and ACC-Sensor4. These two sensors highlight the dominance of the first eigenfrequency. The acceleration values of a walking person are presented in Figure 2. Figure 3 shows the mid-section acceleration values according to the excitation mode heel-drop. All obtained experimental data are compared to results from fundamental literature [4-6] and used as basis to validate the computational models.

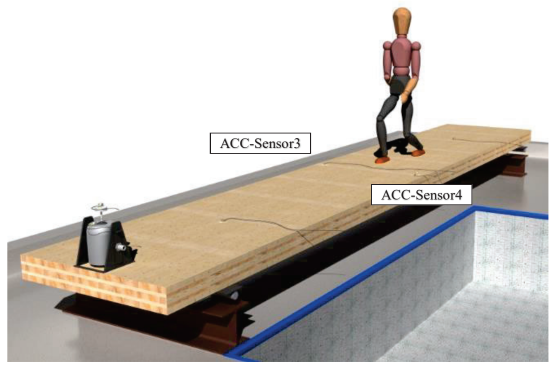

Figure 1: *Test setup for identifying vibrational characteristics with two different excitation (shaker and walking person) [14]*

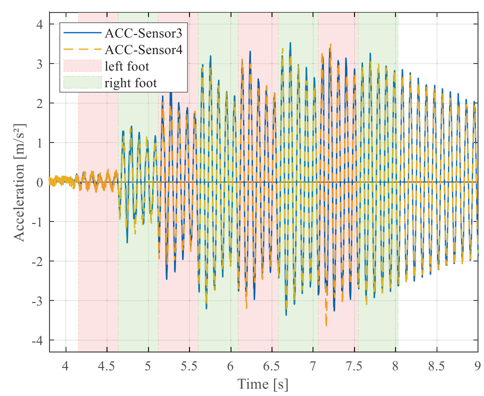

Figure 2: *Recorded response from walking tests*

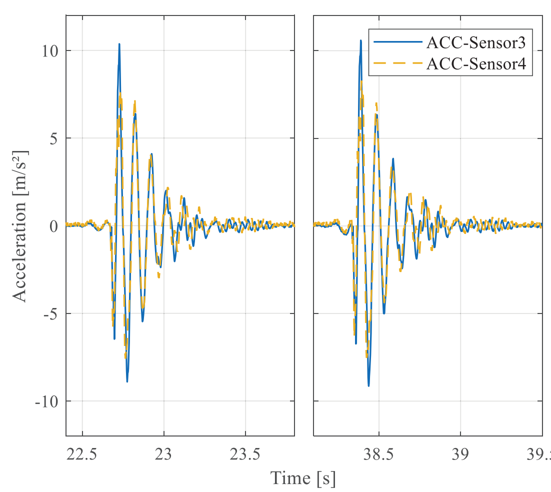

Figure 3: *Recorded response from heel-drop tests*

https://doi.org/10.52202/069179-0251

2.3 EXPERIMENTS – ACTIVE MASS DAMPER

The model of active vibration dampers in combination with slab elements corresponds to vibratory systems with two parts of force excitation. In Equation (1) M, C and K denote the mass, damping and stiffness matrices. The force excitation is on the one hand related to the excitation by a person $F_P(t)$ and on the other hand to the reaction of the active vibration elements $F_{AD}(t)$.

$$M \cdot \ddot{x}(t) + C \cdot \dot{x}(t) + K \cdot x(t) = F_P(t) + F_{AD}(t) \qquad (1)$$

The vibration response of the slab elements is reduced by defined force excitation in opposite direction to the load imposed by a walking person. Figure 4 depicts a possible reaction function of the active vibration elements. In fact, the diagram is an excerpt of an experimental test. It should clarify when the counteracting impulses of the vibration elements are needed and how the principle reaction of the active mass dampers (AMD) looks like.

The first tests for active damping are carried out with the test setup as displayed in Figure 5. The support conditions are defined in the same way as described for the preceding section. Figure 6 is intended to provide a better explanation of the measuring equipment and the entire experimental setup. Included are the input channels from the accelerometers (ACC-Sensor1 - ACC-Sensor6) to the measurement and control unit (MCU) and the output channel from the MCU to the shaker (LDS Shaker V400 Series with amplifier LPA 600). The CLT_02 is used in these test series.

With the previously determined eigenfrequencies, the structure can be excited at its first natural frequency (17.78 Hz). Such a reproducible excitation can be seen in Figure 7. In this diagram, the response recorded with the accelerometers (ACC-Sensor1 to ACC-Sensor4) and the output function for the exciter are displayed. After six periods, the shaker is switched off and the system can freely vibrate. The aim of these experiments is to demonstrate the effects on the vibration behaviour when the acceleration is counteracted by an active element at predefined times and with specified intensities. Figure 8 shows how the active counteraction can be realized in the experiments.

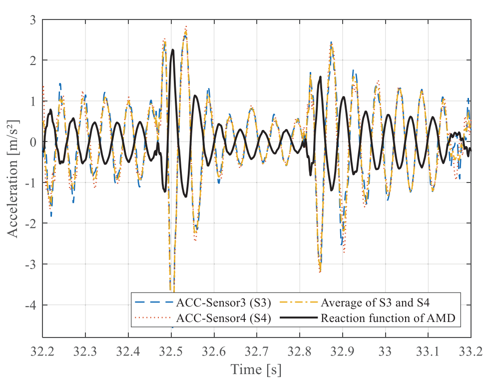

Figure 4: *Acceleration of measurement gauges and active mass damper (AMD) on a CLT element excited by a moving person*

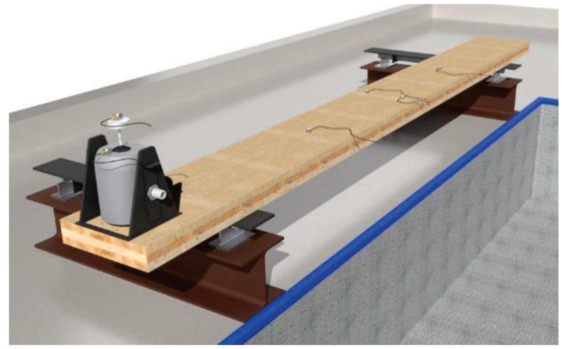

Figure 5: *Test setup for the first active damping tests with the shaker [14]*

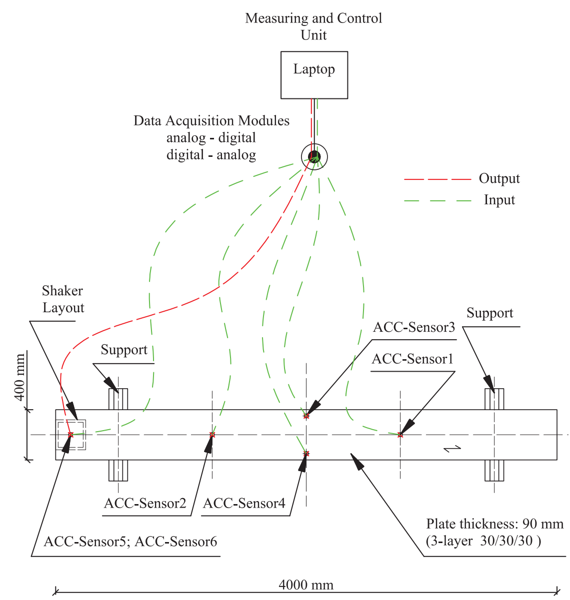

Figure 6: *Visualization of the measurement- and control systems*

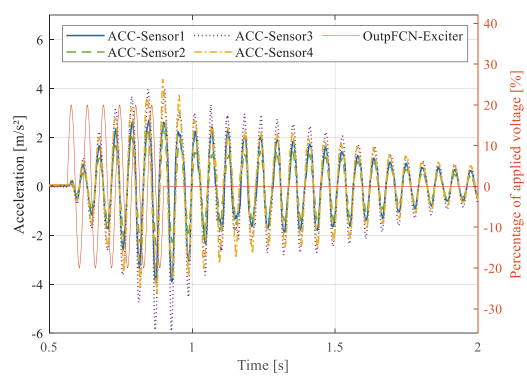

Figure 7: *Measured acceleration values for the reference test – free vibration after excitation by shaker*

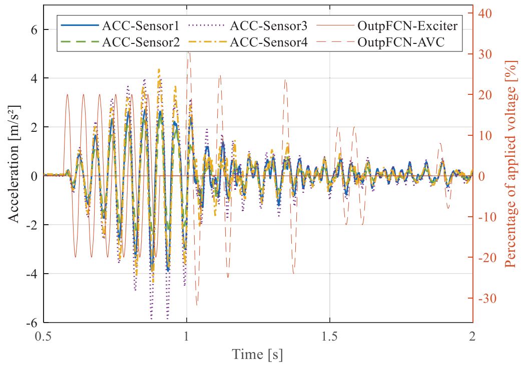

Figure 8: *Measured acceleration values for the active damping – counteracting damper after excitation by shaker*

2.4 EXPERIMENTS – ACCELERATION FEEDBACK

For the tests with active vibration control (AVC), the measured acceleration is used as measure for the intensity during counteraction (according to [12]). The experimental investigations are carried out with the test type CLT_03. A complex setup (see Figure 9 and Figure 10) is planned for this test series. In the lower left area, the CLT element has a fixed support. Due to the defined placement of additional masses (seen upper left and lower right), the first two eigenfrequencies of the system are close to each other (15.5 Hz respectively 18.2 Hz). The used shakers of type APS 400 (Shaker I and Shaker II) act on the system at the corner points. In addition, 800VA amplifiers of type APS 145 are used. Shaker I acts as exciter and Shaker II as active element for vibration control. Accelerometers ACC-Sensor1 and ACC-Sensor2 are placed next to the connection between the shakers and the CLT element. The records from ACC-Sensor2 are used for acceleration feedback.

Three different excitation modes are examined in these tests. On the one hand, as mentioned before, Shaker I serves as exciter (sweep and impulse) and on the other hand, a human-induced excitation by fist drop is performed. The voltage values for the two excitation by Shaker I can be seen in Figure 11. The linear sweep is performed between 5.0 Hz and 35.0 Hz over a duration of 30.0 s. The voltage amplitude is kept constant at a value of 3.7 V. The pulse is generated by a sine half-wave. The voltage amplitude is approx. 13.7 V and the periodicity is 0.5 s. In this test the data are recorded over a period of 10.0 s. The used equipment is from National Instruments. Data is collected and delivered by CompactDAQ and with Field Programmable Gate Array (FPGA) Target from CompactRIO the control of Shaker II is carried out. A Siglent SDG1032X function generator produces the sweep and pulse excitation.

During the tests, the measured acceleration of the plate at ACC-Sensor2 is transferred to the ComactRIO of the Control Unit (CU). Shaker II can also be switched on through this CU. The acceleration value is multiplied by a gain factor and the resulting voltage is sent to the Shaker II via the amplifier.

Figure 9: *Test setup for the active damping tests with acceleration feedback control [14]*

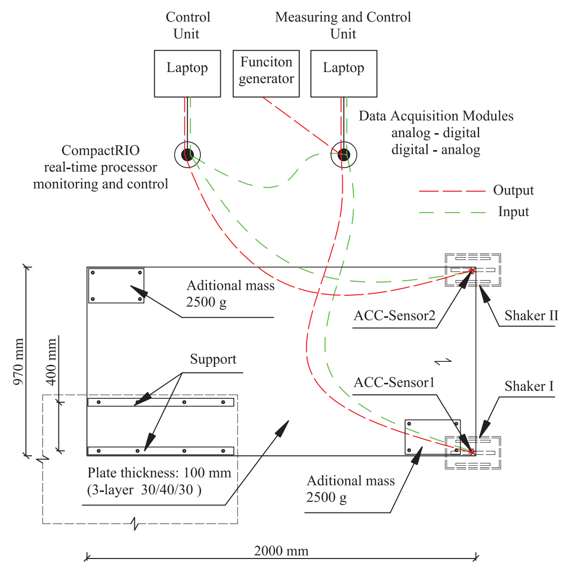

Figure 10: *Visualization of the measurement- and control systems (active damping with acceleration feedback control)*

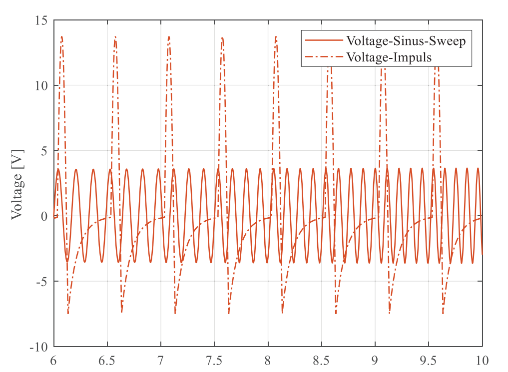

Figure 11: *Measured voltage of the exciters as a result of linear sweep and generated pulse*

https://doi.org/10.52202/069179-0251

2.5 COMPUTATIONAL MODELS

First preliminary calculations are performed with the program *RFEM Release 5.24.01* [15]. The load functions of a moving person on a slab are based on the research work of Bachmann and Baumann [16]. The computational model and the loading method are illustrated in Figure 12. For realistic outcomes different walking paths are simulated.

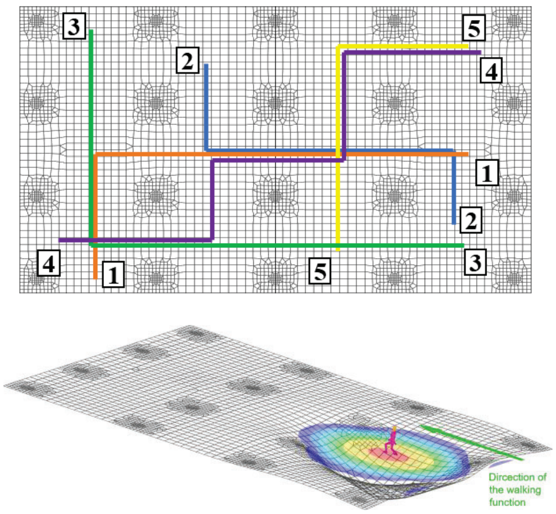

Figure 12: *Computational model of a point supported flat slab with the walking person*

3 RESULTS AND DISCUSSION

3.1 GENERAL

The following section focusses on the results of active damping with counteraction at specific times and control with acceleration feedback. There is always a comparison between reference system and the actively controlled tests. The so-called root-mean-square acceleration (a_{RMS}, see Equation (2)) is used as a reference value for the measurements. a_{RMS} is calculated with the acceleration $a(t)$ over the period T from an initial time T_1 to the end of duration T_2 ($T = T_2 - T_1$). For comparability, these values are shown in the diagrams as constant lines over the calculated period.

$$a_{RMS} = \sqrt{\frac{1}{T} \cdot \left(\int_{T_1}^{T_2} (a(t)^2 \cdot dt) \right)} \tag{2}$$

3.2 ACTIVE MASS DAMPER

In the first tests defined intensities at specific times are used to counteract the vibrating structure. For this purpose, those times are determined at which the lowest value for a_{RMS} is reached over the period T of 1.0 s (Equation (2)) after the excitation phase by means of a given counterimpulse. Due to the programming it is possible to run these tests several times with different time steps t_1 to t_n and the corresponding time increment Δt between the impacts (see Equation (3)). The aim is to identify the extremal values with respect to the minimum of a_{RMS}. In the current experiments, values between 2 and 30 milliseconds are used for Δt (depending on the sampling frequency f_{sample} = 2560 Hz and vibration behaviour of the plate).

$$\begin{aligned} t_1 &= t_0 + \Delta t \\ t_2 &= t_1 + \Delta t \\ &\dots \\ t_n &= t_{n-1} + \Delta t \end{aligned} \tag{3}$$

For each pulse this procedure is performed repeatedly. In the present case, this results in a process with six impacts at different times. Figure 13 shows the acceleration values of the reference measurement and the test with the active element switched on. The data refer to the sensors ACC-Sensor3 and ACC-Sensor4. For ACC-Sensor3, there is a reduction of the a_{RMS} of approx. 58 % and for ACC-Sensor4, the reduction is 62 %.

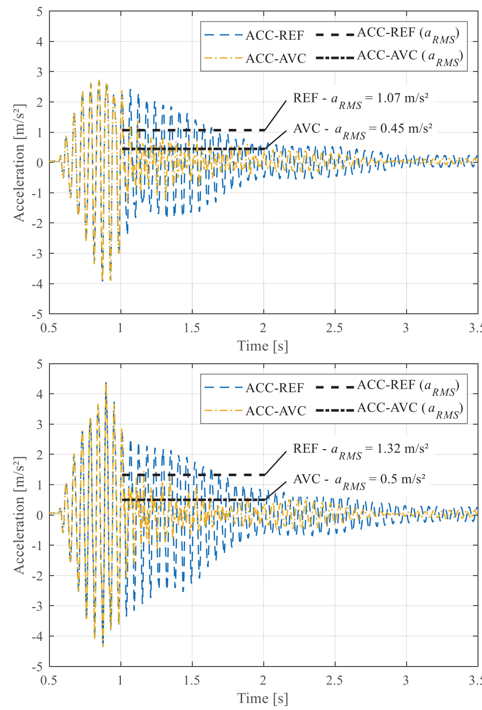

Figure 13: *Acceleration values of sensors ACC-Sensor3 (top) and ACC-Sensor4 (bottom) – reference test ACC-REF and test with active vibration control ACC-AVC*

3.3 ACCELERATION FEEDBACK CONTROL

Figure 14 to Figure 16 display the tests with a linear sweep over a defined frequency band of 30 Hz. Figure 14 shows the reference values (ACC-REF) and the test with active counteraction respectively active vibration control (ACC-AVC). At the local maxima in the area of 15.5 Hz and 18.2 Hz, the first two eigenfrequencies of the system are excited. Especially the response related to the first natural frequency can be controlled very well which is shown in Figure 14.

In the tests which are affected by switching on Shaker II, these two distinct maximum values are no longer visible.

https://doi.org/10.52202/069179-0251

A single peak at about 12.4 s is now clearly apparent. For clarification of this effect and the possible reduction of the vibration acceleration in this section, see also Figure 15 and Figure 16. Displayed are also the measured values of the applied voltages of Shaker I and Shaker II. In the period between 10.0 s (15.0 Hz) and 11.0 s (16.0 Hz), the reduction of a_{RMS} is 77.5 % and between 11.9 s (16.9 Hz) and 12.9 s (17.9 Hz) it is 48.9 %.
The tests excited by the pulses can be seen in Figure 17. With a periodicity of 0.5 s, a pulse with a vibrating duration of the sine half-wave T_{SHW} = 0.1 s is generated. The resulting accelerations are again measured by the reference test and the actively controlled system. The calculation is made with the duration T of 1.0 s (Equation (2)) to get comparative values of acceleration. For the reference system a_{RMS} = 0.39 m/s², with the active vibration control a_{RMS} = 0.26 m/s². This corresponds to a reduction of 33.1 %.
Of great interest, however, are the human-induced excitation. In the tests presented, the interaction between a person and the CLT element always takes place in the same way by a fist drop, but important is the possibility to generate comparable values. Care is taken to ensure that in both the reference system and the actively controlled system, two impacts are compared which have the same maximum value in the first 30 milliseconds. Although it must be considered that this peak is already damped to a certain extent (controlling in real-time). Therefore, the given comparison values are conservative. Figure 18 shows the raw data of both test series. The values from the reference system are compared with the values from actively controlled system. a_{RMS} is calculated over the time span T of 0.5 s (Equation (2)). For clarification, these tests are shown in detail in Figure 19. The time axis is taken from the reference system. The a_{RMS} is reduced by 53.2 % when comparing fist drop 1 (FD1) with fist drop 2 (FD2), and a reduction of 52.4 % is obtained when comparing the tests fist drop 3 (FD3) and fist drop 4 (FD4).

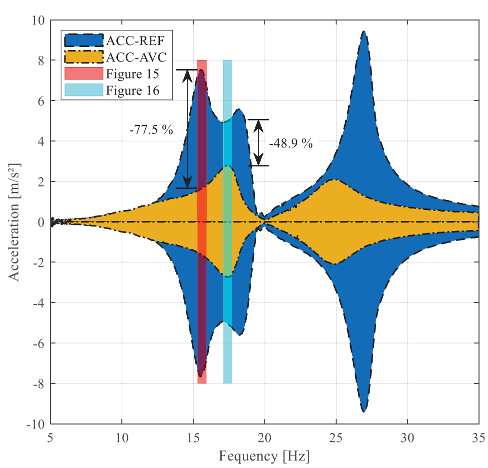

Figure 14: Measured acceleration values of ACC-Sensor2 as a result of excitation by a linear sweep – reference test ACC-REF and test with active vibration control ACC-AVC

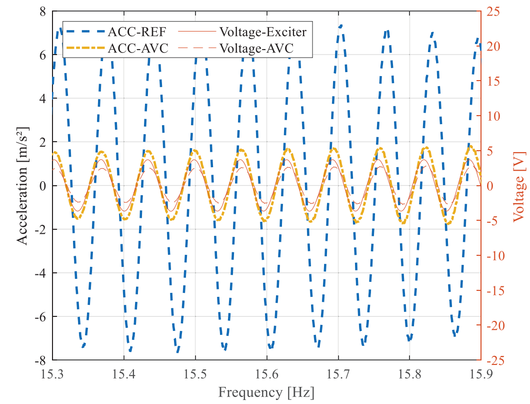

***Figure 15:** Measured acceleration and voltage values of the frequency band with included first natural frequency of the reference system*

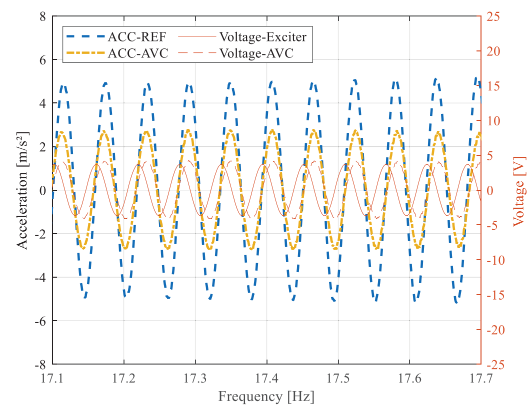

***Figure 16:** Measured acceleration and voltage values of the frequency band with included first natural frequency of the active controlled system*

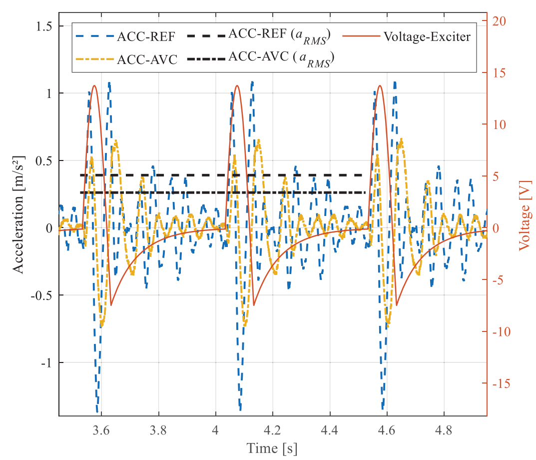

***Figure 17:** Measured acceleration, voltage values and a_{RMS} of ACC-Sensor2 as a result of excitation by impulse function – reference test ACC-REF and test with active vibration control ACC-AVC*

https://doi.org/10.52202/069179-0251

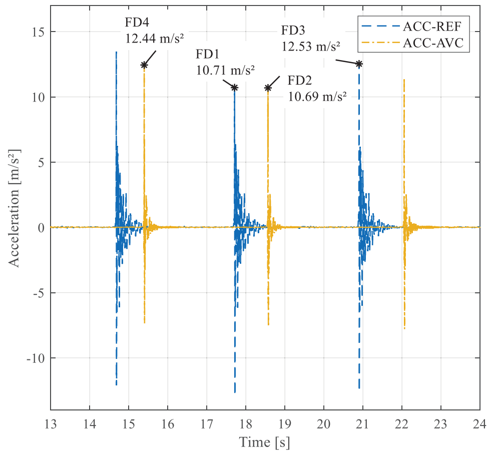

Figure 18: *Measured acceleration values of ACC-Sensor2 as a result of excitation by fist drop – reference test ACC-REF and test with active vibration control ACC-AVC*

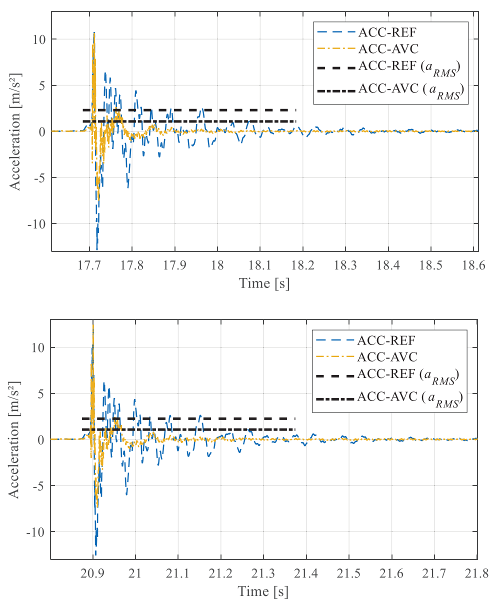

Figure 19: *Measured acceleration and a_{RMS} of the comparable fist drops FD1 and FD2 (top); FD3 and FD4 (bottom) – reference test ACC-REF and test with active vibration control ACC-AVC*

3.4 RESULTS OF CALCULATION MODELS

Research on point supported flat slabs [17] and solutions for edge connections [18] at the Universität Innsbruck highlight the importance of the floor's vibrational characteristics. In the course of these studies, the relevance of investigations in active counteraction, to control the vibrations of such slabs, increased. By using active vibration dampers and intelligent control systems, a considerable improvement of the vibration behaviour based on the slab structure can be achieved. Figure 20 shows the results of the calculation models. Despite the low natural frequency, values in the range of higher demands for floor structures can be achieved. The example of a point supported flat slab in Figure 20 shows that two active mass dampers are sufficient to achieve the vibration verification of the calculated floor construction even for higher demands according to EN 1995-1-1.

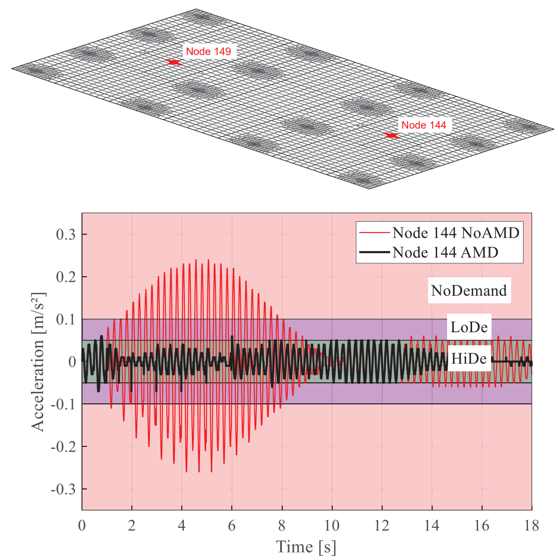

Figure 20: *Results of the calculation models; AMD ... active mass damper, LoDe ... low demands and HiDe ... high demands*

4 CONCLUSION AND OUTLOOK

The results for damping by active elements demonstrate an enormous improvement compared to the reference measurements in terms of the recorded vibration accelerations. Challenges like generating reproducible measurements as well as reacting in real-time could be solved with the available equipment. The reproducibility can be realized by means of shakers. The use of the CompactRIO enables the reaction to accelerations in real-time. Due to the encouraging results by active vibration control both in the area of impulsive counteraction and acceleration feedback control, further tests with the active elements are planned. For this purpose, the measurement and control equipment will be integrated into the experimental setup presented in Section 2.2. Human-induced vibrations, such as those caused by walking occupants, should also be significantly damped despite different setups, support distances and hence varying natural frequencies.

For the determination of modal parameters, further tests are scheduled in addition to the presented ones. The focus is on different support conditions and the variation of flooring. The comparison with existing literature and the possible validation of future calculation models will deliver an important input to the serviceability of timber floors. The calculations show promising results in terms of a better behaviour with regard to the vibrational characteristics and the possibilities in the reduction of construction materials. However, the calculations have to be confirmed by laboratory tests and parameter studies. Another important issue is the optimization (dimensions, control, etc.) of the active damping systems. Experimental investigations with the AMD's complement the modeling and calculations.

In addition, the possibilities of machine learning to control the AMD's will be tested. Large-scale field experiments are then used to train the AMD's and make them able to react on numerous movement sequences.

5 ACKNOWLEDGEMENT

The authors would like to thank the partners of the research project "Good Vibrations" – the research funding association of Austria (FFG), Technical Laboratory for Research and Testing (TVFA) and the company SIHGA GmbH from Ohlsdorf, Austria.

6 REFERENCES

[1] Hamm P., Richter A., Winter S.: Floor vibrations – new results. In *Proc. World Conference on Timber Engineering (WCTE 2010)*. Riva del Garda, Italy, 2010.

[2] Mohammed A., Pavic A.: Human-structure dynamic interaction between building floors and walking occupants in vertical direction. Mech. Syst. Sig. Process. 147, 107036, 2021.

[3] Ussher E., Arjomandi K., Smith I.: Status of vibration serviceability design methods for lightweight timber floors. J. Build. Eng. 50, 104111, 2022.

[4] Zimmer S. E.: Ein Beitrag zur Aufarbeitung der Schwingungsthematik für die Holz-Massivbauweise in Brettsperrholz. Masterarbeit, Technische Universität Graz, 2013.

[5] Weckendorf J., Ussher E., Smith I.: Dynamic response of CLT plate systems in the context of timber and hybrid construction. Compos. Struct. 157, 412–423, 2016.

[6] Winter S., Hamm P., Richter A.: Schwingungs- und Dämpfungsverhalten von Holz- und Holz-Beton-Verbunddecken. Schlussbericht Juli 2010. TU München, Lehrstuhl für Holzbau und Baukonstruktion, 2010.

[7] Kreuzinger H., Mohr B.: Gebrauchstauglichkeit von Wohnungsdecken aus Holz; Abschlussbericht Januar 1999. TU München, Fachgebiet Holzbau, 1999.

[8] Kawrza M., Furtmüller T., Adam C.: Experimental and numerical modal analysis of a cross laminated timber floor system in different construction states, submitted for publication. Constr. Build. Mater., 344, 128032, 2022.

[9] Meinhardt C.: „Smart Structures" – aktive und passive Schwingungsreduktion von Bauwerken – Stand der Technik und Erfahrungen bei der praktischen Realisierung. Bautechnik 98, H. 12, S. 930–937, 2021.

[10] Billmaier M., Bamer F.: Tilger-Systeme zur Verbesserung des Schwingungsverhaltens von weitgespannten Bauteilen. In *Proc. 16. D-A-CH-Tagung: Erdbebeningenieurwesen und Baudynamik*. Innsbruck, Austria, 2019.

[11] Hudson M.J., Reynolds P.: Implementation considerations for active vibration control in the design of floor structures. Eng. Struct., 44, pp. 334–358, 2012.

[12] Díaz I.M., Reynolds P.: Acceleration feedback control of human induced floor vibrations. Engineering Structures, 32(1): 163–173, 2010.

[13] Nyawako D., Reynolds P.: Response-dependent velocity feedback control for mitigation of human-induced floor vibrations. Smart Mater. Struct. 18 (7), 2009.

[14] Hillberger T.: Schwingungsreduzierung bei Flachdecken aus Brettsperrholz (working title). Dissertation. Universität Innsbruck, manuscript under preparation.

[15] RFEM 5. Finite element program for design of spatial structures. Dlubal Software GmbH. Release 5.24.01

[16] Baumann K., Bachmann H.: Durch Menschen verursachte dynamische Lasten und deren Auswirkungen auf Balkentragwerke. Bericht/Institut für Baustatik und Konstruktion ETH Zürich, 7501(3), 1988.

[17] Maurer B., Maderebner R.: Cross Laminated Timber under concentrated compression Loads – Methods of Reinforcement. Eng. Struct. 245:112534, 2021.

[18] Stieb T., Maurer B., Bestler M., Dietsch P., Maderebner R.: Solutions for edge connections to build two-way spanning cross laminated timber slabs. In *Proc. World Conference on Timber Engineering (WCTE 2023)*. Oslo, Norway, 2023.

https://doi.org/10.52202/069179-0251