Virtual Structural Analysis of a Shaking Table for Earthquake Simulations

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Abstract: In modern engineering education, bridging the gap between theoretical knowledge and practical application is an important challenge. However, students often have limited access or no access to hands-on experiences, particularly with specialized equipment like shaking tables (devices that simulate how earthquakes can affect building structures), which are not always available in university teaching. Typically, students can only observe such devices during occasional demonstrations by lecturers, through scheduled appointments, or not at all. Consequently, most of the time they rely only on lectures or video material to understand how shaking tables work. In this project, Virtual Structural Analysis, we utilize immersive Virtual Reality (VR) technology to visualize and simulate real-world shaking table experiments. This project provides students with an interactive application in which they can experiment with shaking tables independently. Within the VR environment, students can input various simulation parameters, such as stiffness, frequency, amplitude, etc., to observe how these parameters affect building behavior during earthquakes. The project aims to deepen students' understanding of complex structural dynamics through active experimentation and immersion, as a complement to traditional teaching methods. The pilot testing with 11 students showed that the VR application helped them grasp the different parameters that influence building dynamics. Moreover, the students reported that the program improved their comprehension of the lecture content. A larger study using objective tests and comparisons with traditional instruction will be planned. Future updates will support more structural types and diverse input signals for learning analytics.

Keywords: Shaking Table Experiments, Virtual Reality, Structural Dynamics, Finite Element Analysis

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1 Introduction

Earthquakes are among the most destructive natural hazards and are capable of inflicting widespread damage to buildings and infrastructure [1]. For structural engineers, accurately predicting how buildings respond to seismic loading is essential to designing safe and resilient structures [2]. Achieving this requires not only theoretical understanding, but also observation of structural behavior under realistic dynamic conditions. [1].

One experimental tool for this simulation purpose is the shaking table. These devices reproduce ground motions by imposing controlled vibrations on scaled structural models, allowing engineers to observe how different systems respond to seismic excitation [1]. Regardless of complexity, from uniaxial to multiaxial, all shaking tables serve to test structural models under simulated earthquake loads. [3].

Despite their value in research, shaking tables are rarely accessible in typical engineering education [4]. Cost, large-footprints, and safety constraints often reduce their use to occasional demonstrations [4], [5]. This often forces students to rely on passive instruction, limiting their ability to visualize real seismic effects. [6].

To bridge this gap, we developed the Virtual Structural Analysis application: a free immersive Virtual Reality (VR) and desktop application that simulates the operation of a shaking table. The simulation replicates a physical 3.0 x 3.0 meter uniaxial seismic simulator from MTS Systems Corporation [7]. Within this virtual environment, users can manipulate stiffness, damping, and mass to see their effects on structural response. By enabling hands-on, parameter-driven experimentation, the system transforms passive observation into active learning [8], [9].

While a desktop version is provided, VR offers several pedagogical advantages. Unlike traditional screen-based tools, VR enables spatial immersion, free exploration of the experimental setup, and multi-angle observation of structural motion. Prior studies suggest that these features can enhance spatial understanding, engagement, and memory retention, particularly for complex three-dimensional phenomena [8], [9].

Our motivation is to offer a practical, engaging, and scalable learning tool that complements classroom instruction. To ensure accessibility, the application is free to download and use. For students without VR hardware, a desktop version is also available for Windows system. The application can be accessed at our *file server*.

Building on this foundation, this paper presents the system's design, educational integration, and initial evaluation.

2 Background and Related Work

Although the use of shaking tables in earthquake engineering is well established and has significantly advanced seismic design, their application in education remains limited due to high costs, space, and safety requirement [2], [5]. As a result, alternative approaches have been explored to improve accessibility, particularly in academic environments.

One direction involves low-cost physical setups, such as open-source uniaxial shaking tables like Namazu and Shakebot, which support programmable control and are compatible with tools like MATLAB or Python. Shakebot, for example, combines motion control with computer vision for real-time feedback, showing promise for classroom use [4], [10]. In addition to hardware solutions, VR systems simulate earthquake effects on building interiors using 360-degree imagery and pre-recorded seismic data [11]. However, most of these systems are limited to passive experiences, aimed more at public awareness than active engineering education.

In contrast, a VR-based digital twin enabled parameter manipulation and structural visualization in real time [12], while another system visualized nonstructural responses like ceiling failures [13]. These applications highlight the pedagogical potential of immersive interaction. Another study evaluates how VR labs help engineering students learn measurement techniques, finding them useful for concept learning but less effective for hands-on skill development [14].

Compared to these approaches, our project introduces a fully interactive VR shaking table simulation grounded in real experimental setups. Unlike most passive or hardware-limited systems, it supports real-time parameter control, offers both VR and desktop access, and mirrors authentic test procedures, thereby bridging the gap identified in the literature.

3 Material and Methodology

3.1 Physical Shaking Table

The simulation is based on a uniaxial shaking table and structural testing system located at the Chair of Structural Analysis and Dynamics (LBB) at RWTH Aachen University [3]. Developed by MTS Systems Corporation, the physical system, shown in figure 1, served as the reference for digitally replicating both the table's mechanical behavior and the dynamic response of a full-scale test structure [7]. The goal is to enhance accessibility and interactivity in structural dynamics education.

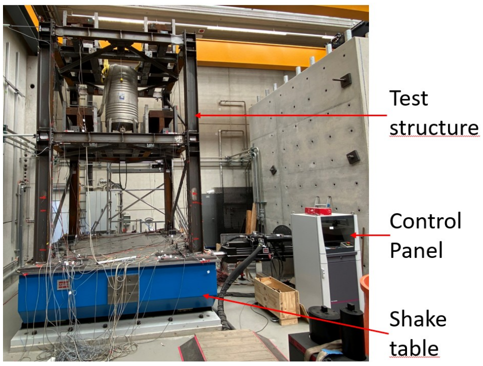

Figure 1: Physical shaking table

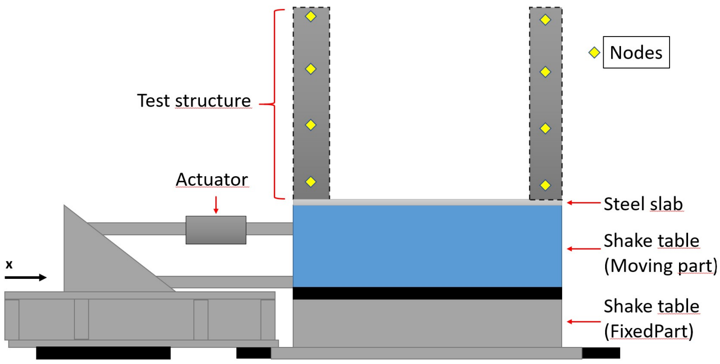

Figure 2: Schematic of a shaking table

The shaking table features a 3.0 × 3.0 meter platform, supports specimens up to 10 metric tons, and operates with a maximum actuator stroke of ±250 mm. It can reach velocities of ±1 m/s, accelerations of ±1g at rated load, and frequencies between 0 and 50 Hz, while withstanding overturning moments up to 30 meter-tons.

Figure 2 illustrates the uniaxial setup used for dynamic testing. A hydraulic actuator drives the platform horizontally to reproduce ground motion. The test specimen is a multi-storey steel frame fixed to the top of the shaking table. The frame columns are instrumented with multiple accelerometers, shown in figure 2 as yellow diamond symbols. These sensors are installed at discrete nodes along the height of the structure. Each node represents a measurement point corresponding to a specific floor level or elevation within the structural model. The sensors capture acceleration profiles and structural response during seismic loading. The blue platform represents the shaking table itself, which transmits the input motion directly to the base of the specimen. The entire setup is mounted on a stiff foundation to ensure minimal energy loss and accurate reproduction of input dynamics. This setup serves as the reference for the virtual simulation.

3.2 Virtual Shaking Table

The virtual shaking table simulation was developed using the Unity game engine. All 3D models and the virtual environment were created in Blender. The simulation's structural and shaking table responses are computed using EasyFEM, a finite element library developed by LBB. The virtual scenario is placed in a minimalistic laboratory space devoid of unnecessary visual elements. Figure 3 shows the appearance of the virtual simulation, including the digitally reconstructed shaking table and its surrounding interface.

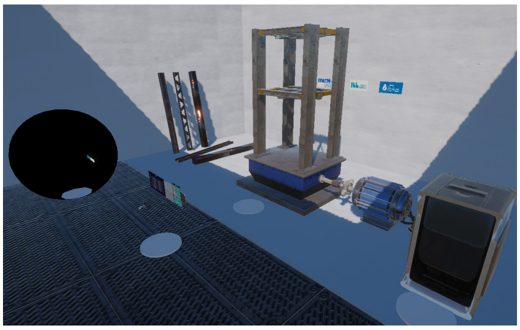

Figure 3: VR shaking table scene overview

As shown in figure 4, users interact with the shaking table via the main control panel, where (in the current version) they can adjust the following parameters:

- Emodul (Elastic Modulus): This input defines the material stiffness (kN/m^2).
- Flächenträgheitsmoment (Moment of Inertia): This parameter influences the resistance of beams and columns to bending (m^4).
- Punktmasse 1 and Punktmasse 2 (Point Mass 1 and 2): These fields define concentrated masses (kg) located at discrete heights within the structure.
- Rayleigh Systemdämpfung 1 and 2 (Rayleigh Damping Coefficients): These inputs correspond to the damping ratios associated with specific vibration modes ($\%$). They are used in Rayleigh damping formulations to simulate energy dissipation mechanisms in the structure.
- Sinusanregung (Sinusoidal Ground Excitation Amplitude): This field sets the amplitude (m) of the sinusoidal ground motion applied by the virtual shaking table.
- Frequenz (Frequency): This parameter determines the frequency of the sinusoidal input (Hz). It allows users to investigate frequency-dependent behavior and resonance phenomena by exciting the structure at various rates.

- Amplitude: This output field displays the calculated response amplitude of the system based on the selected input parameters.

While the current version does not restrict input ranges, future updates will introduce suggested value limits based on typical engineering scenarios, to help users avoid unrealistic configurations and ensure meaningful simulation results.

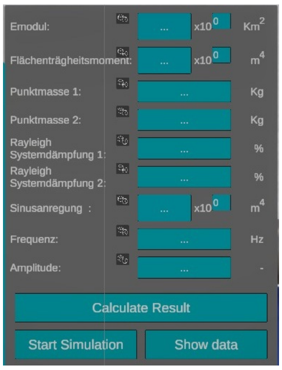

Figure 4: User menu

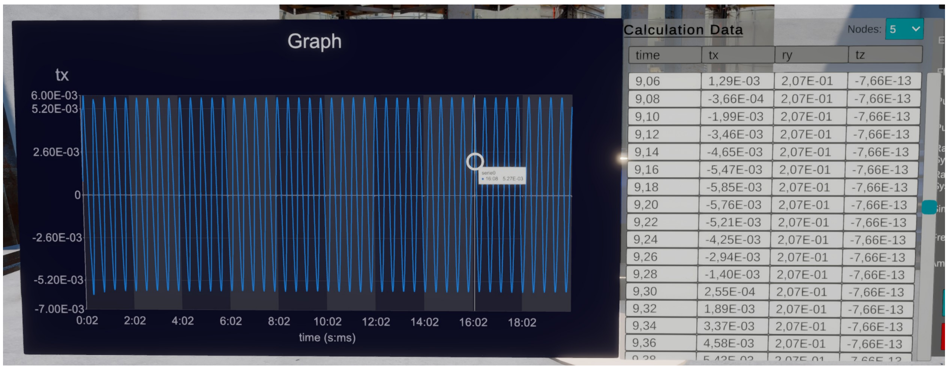

Figure 5: Extended user menu: data and graph visualization

After defining the parameters, users begin the simulation by clicking *Calculate Result*, which computes the displacement of each structural node based on the input values. Pressing *Start Simulation* animates the structure's real-time response on the virtual shaking table as shown in figure 6.

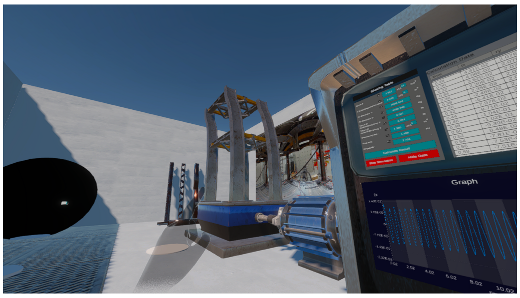

Figure 6: The VR shaking table performs simulations based on user-defined parameters

Users can also choose the *Show Data* to view X, Y, and Z displacement values in a structured table. They can also inspect displacement at individual nodes. Data is sampled every 0.2 seconds for 20 seconds and visualized in table and graph form (figure 5).

To bridge the gap between simulation and reality, a video of the corresponding physical shaking table test is displayed behind the virtual setup (figure 7), allowing direct comparison between simulated and real-world behavior.

Moreover within the VR environment, students have the option to explore a 360° video recording of a real shaking table experiment. The "bubble view," shown in figure 7 allows immersive observation of the real lab.

For accessibility, a desktop version is available for users without a VR headset. VR users may interact using standard controllers or hand tracking for a more natural experience.

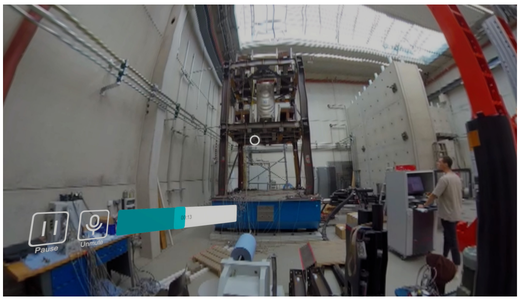

Figure 7: 360° bubble view of a physical shake table

4 Application Testing

In order to evaluate both usability and instructional effectiveness of the VR-based shaking table simulation, a standardized questionnaire was distributed after the user testing session. The survey included seven Likert-scale statements and six open-ended questions. Participants ($n = 11$) responded on a six-point scale (1 = strongly agree, 6 = strongly disagree).

Overall, feedback was highly positive, particularly for learning and ease of system use. The simulation helped students understand how structural parameters affect dynamic behavior ($\mu = 1.64$). Similarly, the ability to understand how vibrations get transferred through a structure was rated positively ($\mu = 1.82$). Participants reported improved understanding of lecture and exercise content after using the simulation ($\mu = 2.0$) which shows its effectiveness as a complementary instructional tool.

The simulation was rated visually realistic ($\mu = 1.25$). Although user experience was positive, about half reported motion sickness. ($\mu = 3.0$). Though teleportation and vignette were included, many users missed or avoided them, suggesting a need for clearer access or better defaults. Notably, most participants stated they would recommend the simulation as part of the lecture ($\mu = 1.5$). These results show that the simulation is informative, engaging, and user-friendly. The findings support integrating immersive technologies into structural engineering courses and provide a strong foundation for future improvements.

In addition to the rating-based feedback, participants answered six open-ended questions:

- *What did you find particularly helpful or informative in the program?* Many students highlighted the freedom to walk around the setup, observe vibrations from various angles, and adjust parameters in real time. This interactivity was frequently cited as essential for deepening conceptual understanding.
- *What did you find unclear or difficult to understand?* Some users noted unclear parameter labels and missing units; a few were unsure about specific interface elements.
- *Which features would you like to see improved?* Common suggestions included movable/closable input windows, tooltips, and clearer navigation instructions.
- *What additional features would you find helpful in future versions?* Participants expressed interest in including multiple structural configurations, support for various excitation types (e.g., impulse or real earthquake data), and functionality to compare different simulations side by side.

- *What was your impression of the 360° bubble view?* Most found the 360° video view immersive and informative for understanding real-world shaking table experiments. However, a few users felt it slightly affected their spatial orientation in VR.

While these initial results are encouraging, the study has clear limitations. The sample size was small and based on volunteer participation, and the evaluation relied primarily on subjective feedback. To establish learning effectiveness more rigorously, a follow-up study is planned that will involve a larger cohort of students, a control group using traditional media (e.g., lecture slides or videos), and objective measures such as pre- and post-tests or delayed retention quizzes. Additionally, the feedback provides clear direction for future improvements, especially in usability, simulation options, and user guidance.

5 Conclusions and Future Work

This study introduced a Virtual Reality (VR) simulation to replicate shaking table experiments for structural dynamics education. The tool allows students to adjust structural parameters and observe seismic responses interactively. Unlike passive or hardware-limited systems, it offers an immersive, scalable, and accessible platform to bridge theoretical knowledge and practical understanding.

Preliminary testing with 11 participants indicated its potential effectiveness. Quantitative results showed strong agreement on learning impact and usability, while qualitative feedback praised its interactivity, visualization clarity, and ease of use. Most users recommended its integration into coursework.

Despite being early-stage, users welcomed the tool's potential. Future improvements include support for biaxial simulations and custom structural models. Planned research will evaluate long-term learning outcomes and compare results with a control group using traditional materials. Broader testing across diverse academic settings is also planned to validate the tool's effectiveness and adaptability.

6 Acknowledgement

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7 Conflict of Interest

The authors declare that this research was carried out without any commercial or financial interests that could be perceived as a potential conflict of interest.

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