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# Comparative analysis of reverberation plate measurement methods for the purpose of tuning the numerical model

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**Abstract** Finite difference modeling is widely used to predict the behavior of plate structures, but its accuracy depends on validation with experimental data. Reliable measurements are crucial, yet accelerometer-based methods introduce challenges in model tuning. Acceleration values derived from displacement data lose constant components, whereas direct displacement measurements provide more accurate data but are less commonly used due to technical difficulties. This study compares displacement measurements using a laser sensor with acceleration measurements via an accelerometer on a reverberation plate. The findings indicate that displacement measurements yield accurate data without additional signal processing, making them valuable for model calibration. However, accelerometers remain more commonly used due to their ease of implementation, even though they may require additional processing steps to extract useful data. The study highlights the trade-offs between these methods in terms of measurement accuracy and practicality, providing insights for improving the calibration process of finite difference models of vibrating plate sensors.

**Keywords:** Finite Difference Modeling, plate structures, displacement measurement, reverberation plate.

## 1. Introduction

Reverberation, as one of the most important acoustic phenomena, is widely used in sound engineering, serving as a tool to create spatial impressions and enhance the attractiveness of an acoustic signal [1]. There are many methods for synthesizing artificial reverberation, including techniques that utilize the characteristics of physical structures such as springs or plates [2, 3]. One of the most significant roles in this field is held by plate reverbs, which were among the most popular effects of this type before the digital era. An example of one of the most important devices of this kind is the EMT 140 plate reverb by Elektromesstecknik [2, 3]. Although nowadays most plate reverb effects are implemented digitally [4, 5], research on physical devices remains a relevant topic [2, 6-8] since the literature lacks information on how exactly the vibrations of the object translate into the acoustic signal received from the plate. Such research requires numerous physical experiments. Therefore, there is a need to develop an accurate numerical model that allows for predicting how changes in plate vibrations will affect the received acoustic signal, which in turn can reduce the number of necessary experiments using a physical device. Although accelerometers are the de facto standard in vibro-acoustic measurements of reverberation plates, displacement sensing is rarely reported, likely due to practical and technical challenges. At the same time, finite difference models intrinsically operate on displacement variables, suggesting that displacement data may be more directly comparable than acceleration. While comparisons between displacement and acceleration measurements have been discussed in broader vibro-acoustic contexts, there is little evidence addressing their suitability for finite-difference modeling of reverberation plates. In response, we provide a systematic, experimentally supported validation of displacement versus acceleration data, demonstrating its relevance in the niche of tuning finite-difference models for sound synthesis.

This study attempts to create such a model after conducting an experiment by exciting the plate with impulses in two different testing points, followed by simulating such excitations in the model. Among the available methods, finite difference models stand out due to their ability to easily generate multiple simulations, including those from different readout points. Plate reverb measurements are typically performed by recording the acoustic signal with a microphone or measuring acceleration using an accelerometer attached to the plate[6]. However, tuning finite difference models based on acceleration is problematic due to the high-pass characteristic of the signal obtained at the model's output. This results from the fact that differentiating displacements to obtain velocity, and then acceleration, removes the signal's DC (direct current) component. Consequently, the obtained acoustic signal must undergo low-pass filtering with a characteristic that is difficult to define. Measuring displacements using a laser displacement sensor enables obtaining a signal that directly represents the plate's vibrations. Moreover, finite difference models typically operate on displacements in their calculations. Comparing experimental data with the signal predicted by the model offers hope for simpler tuning and adaptation of finite difference models for plate reverberators.

## 2. Measurements

Measurements were conducted to obtain sound samples for use in modeling with the finite difference method. To perform the measurements, a test stand was used that allowed for the excitation of the plate using impulse force, as well as the recording of its vibrations. The experiment utilized a thin steel plate with a thickness of 0.5 mm, commonly used for such applications [9]. The plate (Tab. 1) was placed in a wooden frame with hooks, allowing it to hang freely (Fig. 1). The excitations were performed using a modal hammer Brüel & Kjær 8206 with a mechanical impedance sensor PCB 288D01 attached, allowing to record force signals. The use of a modal hammer ensured similar force of the excitations, allowing to compare the results in a meaningful way.

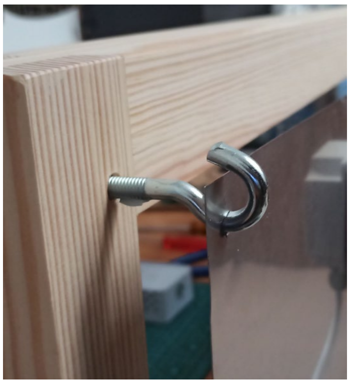

**Figure 1.** The suspension of the plate on hooks, in the test stand.

**Table 1.** Values of plate parameters used for measurements.

| Parameter | Symbol | Unit | Value |
|---|---|---|---|
| Plate width | $a$ | mm | 1300 |
| Plate height | $b$ | mm | 1000 |
| Plate thickness | $h$ | mm | 0.5 |
| Elastic modulus | $E$ | MPa | 200±10 |
| Poisson's ratio | $\nu$ | - | 0.3±0.03 |

To measure acceleration, a DYTRAN 3225F1 accelerometer was used. For displacement measurements, a MICRO-EPSILON ILD2300-50 triangulation laser displacement sensor was employed, paired with a MICRO-EPSILON C-Box/2A controller, which enabled the acquisition of an analog displacement signal. The signal recordings were made using an NI 9234 data acquisition card.

**Table 2.** Excitation and measurement localization.

| Session | x coordinate excitation position* | y coordinate excitation position* | x coordinate measurement position* | y coordinate measurement position* | Unit |
|---|---|---|---|---|---|
| 1 | 1000 | 300 | 300 | 700 | mm |
| 2 | 676 (0.52a) | 530 (0.53b) | 611 (0.47a) | 620 (0.62b) | mm |

* A right-handed coordinate system located in the bottom-left corner of the plate.

The point locations in Session 1 were chosen arbitrarily by the authors. The locations in Session 2 were determined based on the guidelines provided in the work of Ducceschi and Webb [9].

Two measurement points were selected for each excitation of the plate and the vibration recording, for two measurements for each vibration recording method:

- Points A(recording) and B(excitation) - points chosen considering pattern of nodal lines on the plate, choosing locations where, according to mathematical analysis, they do not appear, to get the output signals containing as many plate modes as possible, also keeping the points far from each other to get richer vibration data by capturing more wave modes.
- Points C(recording) and D(excitation) - whose positions were calculated relative to the plate length and width, based on research [10].

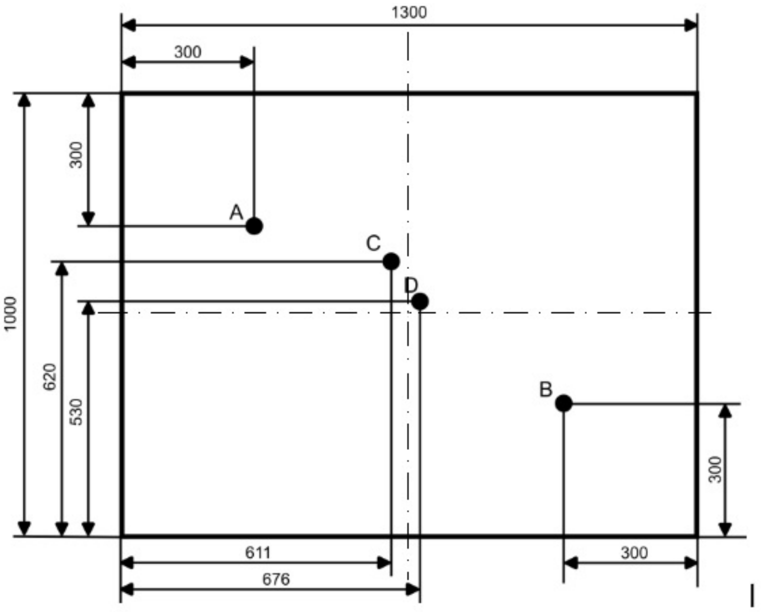


**Figure 2**. Location of excitation and recording points on the plate surface [mm] (plate thickness $h$=0.5 mm).

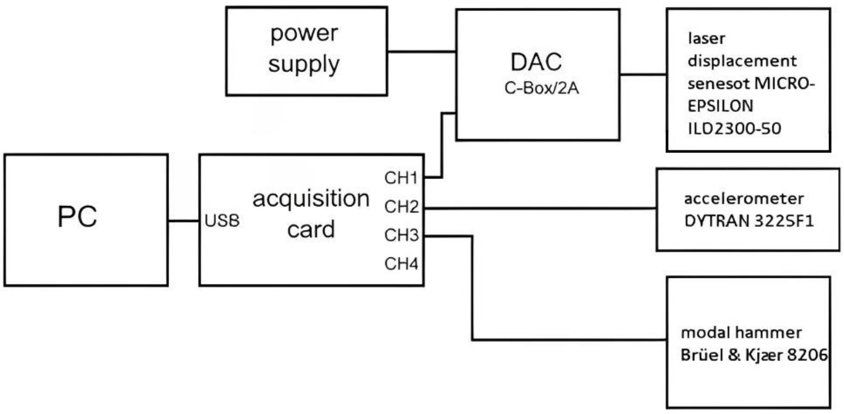


**Figure 3.** Schematic of the data acquisition system.

### 3. Finite difference model

The specific model used in this study is based on a code by Stefan Bilbao [11]. It employs a straightforward finite difference scheme for Kirchhoff plates, utilizing a five-point Laplacian approximation on a rectangular grid:

$$\sigma_{tt}u = -\kappa^2 \sigma_{\Delta\boxplus\Delta\boxplus} u\,, \tag{1}$$

where $\delta_{tt}$ is the second time difference operator equal to $\delta_{t+}\delta_{t-}$, $u$ is a grid function. $\kappa$ is stiffness parameter and $\sigma_{\Delta\boxplus\Delta\boxplus}$ is a biharmonic difference operator. Expanding the grid function $u_{l,m}^{n}$ with uniform spatial step $h$ in both dimensions, the scheme is written as:

$$u_{l,m}^{n+1} = (2-20\mu^2)u_{l,m}^n + 8\mu^2\left(u_{l,m+1}^n + u_{l,m-1}^n + u_{l+1,m}^n + u_{l-1,m}^n\right) - 2\mu^2\left(u_{l+1,m+1}^n + u_{l+1,m-1}^n + u_{l-1,m+1}^n + u_{l-1,m-1}^n\right) - \mu^2\left(u_{l,m+2}^n + u_{l,m-2}^n + u_{l+2,m}^n + u_{l-2,m}^n\right) - u_{l,m}^{n-1}, \tag{2}$$

where scheme parameter $\mu$ is defined as:

$$\mu = \frac{Kk}{h^2}, \tag{3}$$

where $k$ is the time step in seconds (s) and $h$ is grid spacing. To satisfy the von Neumann stability condition, $\mu$ must satisfy the following condition:

$$\mu \leq \frac{1}{4}. \tag{4}$$

Used implementation delivers a simulation for a thin plate with loss, impulse excitation and zero-level interpolation. The model code was modified to reflect the measurement setup. These modifications included adjustment of physical parameters of the model (dimensions, material properties), which enabled creation of basic finite difference spatial and time grids.

Excitation through a hammer-like object is approximated via the raised cosine condition in the location of defined width on the grid. An additional modification introduced in the process of model preparation is the reflection of the experiment set up via boundary conditions. Fixing the plate to the support frame by top corner was approximated by setting simply supported boundary conditions in top corners of the plate, represented by marginal indices of the first row of the spatial grid:

$$\mu = \sigma_{xx}u = 0. \tag{5}$$

As the model operates on predicting displacements, acceleration calculations were added by double differentiation displacements over time, providing insights into the dynamics of the structure and enabling comparison of those two parameters with the experimental data.

## 4. Results

The experimental results demonstrate consistency across both used measurement methods. Resonance frequencies and spectral peaks in the Fast Fourier Transform analysis appear at the same locations for both displacement- and acceleration-based measurements, as demonstrated on Figure 4. This consistency is crucial, as it indicates that model tuning can be guided by practical convenience rather than the need to determine a singular "true" or "better" parameter set. The analysis and corresponding graphs are presented in the frequency range of 1–5000 Hz, aligning with the frequency range of the acceleration sensor (±5%). However, to ensure the validity of the findings, the data was also examined across the full audible spectrum.

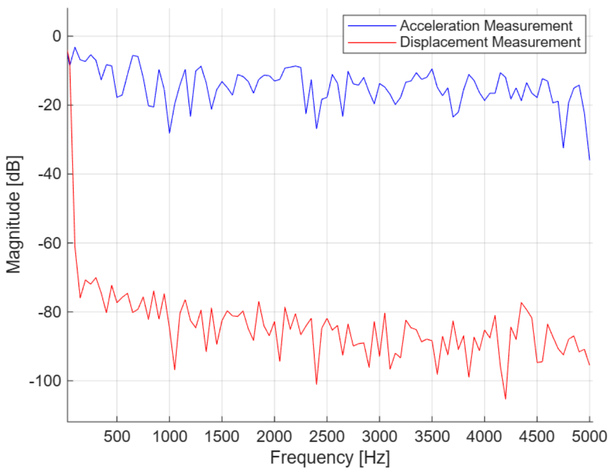


**Figure 4.** Power spectrum at Point A (measurement).

Figure 5 shows that both the displacement measurement and the displacement model (Fig. 5a) exhibit similar spectral shapes. This is not the case for the accelerometer (Fig. 5b), as double differentiation introduces a high-pass characteristic into the signal.

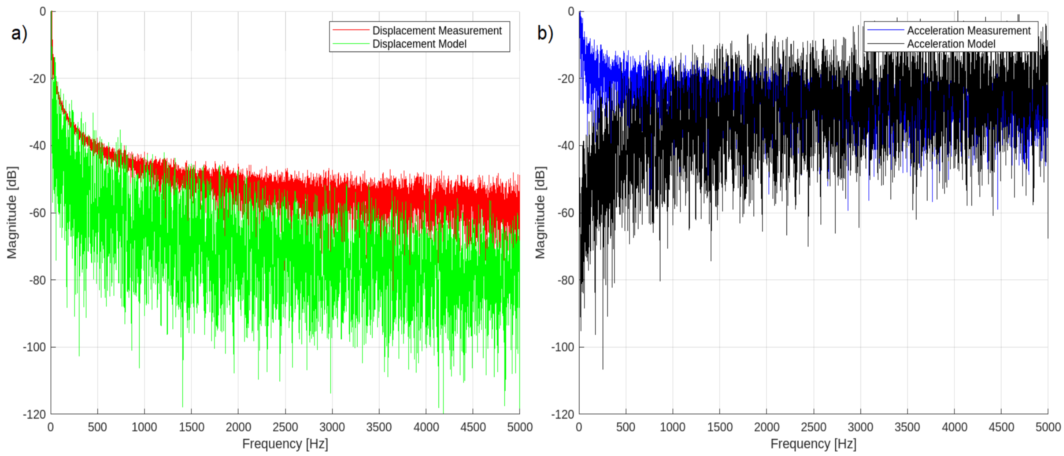


**Figure 5.** Comparison of normalized spectra from measurement and finite difference (FD) model: a) displacement signals, b) acceleration signals.

The initial model aligned quite well with the measurements right from the start after inputting the physical parameters, highlighting both the quality of the measurements and the accuracy of the model. Final tuning was refined by adjusting parameters such as the plate stiffness, the scheme-free parameter or the excitation width on the model's grid (the impulse application point).

Overall, the displacement-tuned model provided a better match (Fig. 6), as it more accurately captured the presence of lower frequencies in the spectrum. In contrast, the acceleration-based model would ideally require low-pass filtering, though determining the appropriate filter characteristics remains a challenge. After tuning, the obtained results were satisfactory, demonstrating an agreement between the model and experimental data. To further support this observation, we performed a quantitative comparison between measured and modeled spectra using two metrics: the Pearson correlation coefficient of spectral magnitudes and the Mean Absolute Error (MAE) in dB. These were calculated over the frequency range 50–5000 Hz using an FFT size of 8192 samples. For the raw displacement measurement and model output comparison, the spectral correlation coefficient was 0.63, and the MAE was 7.3 dB, indicating a moderate-to-strong match. In contrast, the raw acceleration measurement vs. model yielded a correlation of −0.20 and an MAE of 8.7 dB over the whole analyzed spectrum. However, when the analysis was limited to higher frequencies (above 1000 Hz), the correlation improved to 0.42, reflecting a more consistent alignment. This supports the earlier observation of the high-pass characteristic introduced by double differentiation in the model. These results further support the conclusion that displacement sensing provides a more reliable basis for tuning finite difference models, especially in the context of sound synthesis.

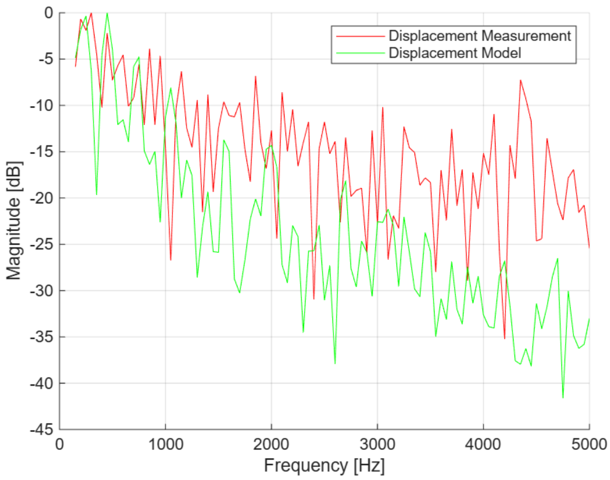


**Figure 6.** Comparison of measured and model-predicted displacement.

It is important to acknowledge that perfect alignment between the model and experimental results is not expected. Discrepancies arise due to factors such as the experimental setup, material imperfections, the presence of mounting holes in the corners of the plate, and the additional mass of the attached measurement device. An important consideration in finite difference modeling of thin plates, as noted by Bilbao [11], is that the thinner the plate, the less control the model has over frequencies in the audio range. For typical reverberation plates, which are often quite thin, this can reduce simulation accuracy at higher frequencies compared to lower bands. This effect is evident in our results (Fig. 7), where the model aligns with the experimental data in the lower frequency bands, but the consistency deteriorates as frequency increases.

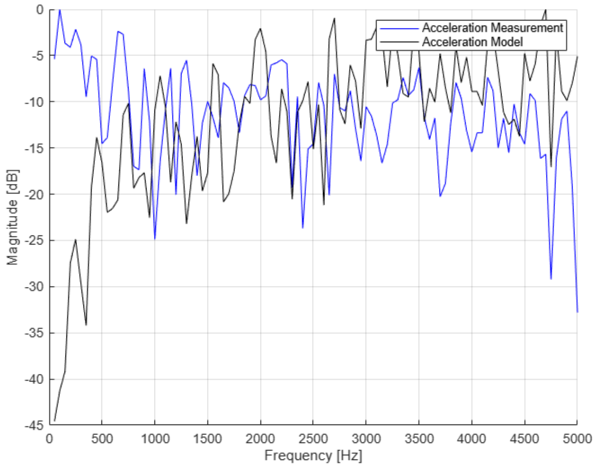


**Figure 7.** Comparison of measured and model-predicted acceleration.

## 5. Conclusions

This study compared finite difference model tuning for reverberation plate measurements using displacement and acceleration data. Both approaches yielded consistent results, with resonance frequencies aligning across methods. However, displacement measurement offers several practical advantages. It provides a direct match to the model predicted values without requiring numerical differentiation, making it a straightforward "plug-and-go" approach. Additionally, it does not introduce external physical elements into the system, unlike an accelerometer, which has mass and must be attached to the plate, potentially influencing the measurement. While careful choice of acceleration sensor can alleviate this problem, using laser displacement measurement completely eliminates such interference.

The main advantage of the accelerometer is that it remains an accessible and widely available tool. However, reliance on double differentiation in the model in order to compare results introduces a high-pass filtering effect in the signal. While this did not significantly impact the tuning process in this case, displacement measurement proved to be the more convenient choice due to its simplicity and direct compatibility with the model.

In summary, displacement measurement-based tuning should be preferred when accurate spectral alignment is required. Compared to acceleration, displacement signals provide better agreement with model predictions without requiring additional filtering or signal processing. This makes displacement sensing a more efficient choice for model calibration. While accelerometers remain practical and widely accessible, displacement measurements offer superior compatibility with numerical models and deliver cleaner data for direct comparison.

The findings of this study have practical applications in various fields involving plate vibration analysis. In musical acoustics and instrument design, accurate modeling of metal reverberation plates can improve the tuning and creation of digital instruments and audio plugins. While the resulting models could, in principle, be used as artificial reverberation effects, perceptual evaluation lies beyond the scope of the present work. Displacement measurement can also be beneficial for analyzing similar thin plate-like structures, such as those used in certain mechanical components. Additionally, by providing a comparison with acceleration-based measurements, this study helps in selecting appropriate measurement tools depending on the specific requirements of a given application. By demonstrating the reliability of different measurement approaches and highlighting the advantages of displacement-based tuning, this study contributes to the broader field of vibration analysis and numerical modeling of thin plates.

**Additional information**

The authors declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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