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Plate reverberators with adjustable features – concept of study and test stand

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Abstract Mechanical vibration of plates have applications in many fields of science and industry including synthesis of artificial reverberation – one of the most important signal processors in audio engineering. The paper presents a concept for study and measurements of reverberating plates that contains an initial numerical solution with a goal of predicting behaviours of the vibrating plate as its response for physically affecting its vibration. The concept also considers experimental measurements of selected simplified solutions as well as their comparison with numerical simulation. In addition the paper contains evidence for perceptible differences between audio signals obtained from the initial experiments, which suggests the viability of adjustable mechanical reverberation mechanism. Moreover, the paper includes concept for test stand for experimental study of reverberating plates in order to achieve signals differing in perceptually significant way. The test stand and study will allow to increase knowledge of vibrating plates as parts of plate reverberation devices.

Keywords: vibrating plate, plate reverberation, audio equipment.

1. Introduction

Vibration of plates have been used for many applications including in audio engineering, where they can be used to apply a reverberation effect on a signal, which was helpful for audio engineers especially before the digital revolution [1]. Nowadays despite having an easy access to digital reverberation effects there is a trend for using hardware devices back again, because of characteristic features a processed signal using them can have.

Commercial plate reverberation producers describe their work usually without presenting measurement results and without describing what physical processes exactly occur in their devices. This includes one of the most popular devices of this type, the EMT140 plate reverberator from Elektromesstecknik [2]. Adjustable parameters of the plate reverberators are often given to a user without understanding how exactly the signal behaves and creating them is based purely on subjective impressions of the designer of the device.

Vibrating plates are among the most basic structures considered in mechanical engineering [3] and acoustics [4]. They are simple enough to study not only their numerical models, but also purely analytical solutions [5], and compare both to results obtained in experiments with actual physical objects [6]. The problem is well-researched, including discussions on boundary conditions [7–9], various modifications of studied objects, such as holes or connections of two materials, as well as variety of numerical methods applied for the purpose of their modelling [10–12]. Plates utilised as elements of reverberation devices have been studied as well [13–16]. However, the research concentrates on digital simulations of such devices [17, 18]. It is difficult to find reports on studies regarding the actual physical devices. Such devices are developed mostly as commercial solutions. Considering that a good model has to be based on, and compared to a physical object in order to reflect all relevant physical phenomena involved in production of the auditory effect of reverberation, there is a need to develop a test stand with a set of accompanying measurement and study procedures for plate reverberation devices. Due to a specific use case, regarding – in particular – excitation of plate using acoustic signal, and readout of acoustic signal as a result of plate vibration, study methods need to be adjusted to consider auditory phenomena and perceptual implications. Properly designed test setup can lead not only to advances in digital modelling, but also to designing new physical devices that will take advantage of studied phenomena.

The concept of the study assumes creating a numerical model as a tool for creating patterns that will be able to predict behaviours of the physical plate as a response for applied initial conditions. Concept of the test stand assumes having possibilities to affect vibrations of the plate in a way that the changes in the readout acoustic signal, being a result of the plate vibration, will be perceptually significant for a listener. There is described an initial experiment that shows changes in power spectral density of signals recorded from impulse excitations of the plate in different points on its surface, which shows differences in frequency and amplitude values of its components, which can modify the output signal from the plate reverberation system in perceptually significant way. This is a starting point for a research with different type of excitation force, which in this application of the vibrating plate will be an acoustic signal, which will excite the plate with values of its amplitude varying in time. This is followed by description of other features that the test stand could have, allowing a researcher to determine exact changes in the output signal when affecting the plate. The plate reverberation devices that can be created based on the target test stand can find an application as a part of signal path in audio processing systems.

2. Modelling approach

When proposing a concept for a test stand for reverberating plates, it would be useful to have a numerical model allowing to predict experimental results having simulation results first. In order to verify that the initial numerical approach is correct, there are calculated natural frequencies of the plate using analytical approach and then compared with numerical results.

Verification of the numerical model with the analytical model was made for simply supported boundary conditions. Analytical calculations were made using the following equation for frequency of the plate [19]:

$$f_{mn} = \frac{1}{2\pi}\left[\frac{\pi^4 D}{\rho h}\left(\frac{m^2}{a^2}+\frac{n^2}{b^2}\right)^2\right]^{\frac{1}{2}}, \tag{1}$$

where: ρ – plate density, a – plate width, b – plate height, h – plate thickness, m and n – mode numbers;

$$D = \frac{Eh^3}{12(1-\nu^2)}, \tag{2}$$

is a flexural rigidity, where E – elastic modulus, ν – Poisson's ratio. Natural frequencies were calculated for the dimensions and material properties of a steel plate used for measurements in this paper (Tab. 1). In the initial modelling approach, natural frequencies for simulation of the considered plate were calculated in Ansys Workbench 2023 software and then compared with the analytical model (Tab. 2).

Table 1. Values of plate parameters used in natural frequency calculations.

Quantity	Symbol	Unit	Value
Plate width	a	m	0.5
Plate height	b	m	1.0
Plate thickness	h	m	0.001
Elastic modulus	E	GPa	200
Poisson's ratio	ν	-	0.3

Table 2. First five natural frequencies of the plate – analytical and numerical models' comparison.

Analytical calculation [Hz]	Numerical model [Hz]	Difference [Hz]	Difference [%]
12.00	12.00	0.00	0.00
19.19	19.20	0.01	0.05
31.19	31.22	0.03	0.06
40.79	40.86	0.07	0.17
47.99	48.06	0.07	0.15

3. Plate excitation surface location – experiment

To initialize measurements of vibration of a physical object – an actual steel plate, there were performed recordings of impulse responses from excitations in different points on the plate surface.

One of the factors that could affect a spectral characteristics of a plate impulse response is location of the excitation on its surface. In the initial experiment the plate was excited by an impulse force in various locations on the plate surface (Fig. 1) with the plate being fixed from its movement in its middle area in a 60 mm diameter. After the excitation, audio signal was recorded using a Zoom H4n device close to the plate (Fig. 1) in order to make a comparison between the responses from the plate and examine if they are perceptually different for a listener.

Initial analysis of the impulse responses spectra from the excitations in a single point shows similarity (Figs. 2, 3), which indicates that the performed experiment was repeatable. The similarities are especially noticeable in narrowed down frequency band (Fig. 3).

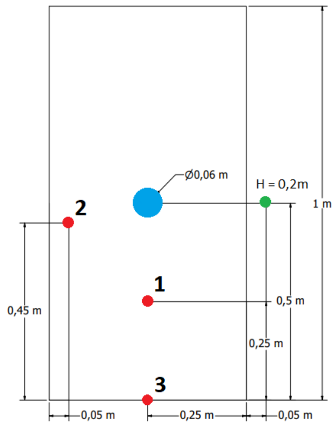

Figure 1. Location of excitations on the plate surface (red) with boundary conditions: fixed (blue) and free (plate edges), signal readout position (green).

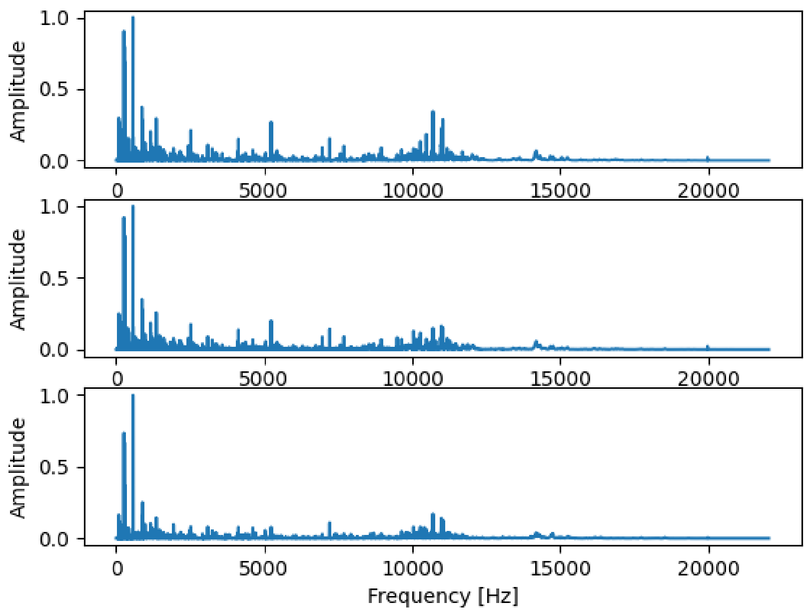

Figure 2. Power spectral densities of impulse responses from three excitations of the plate in a single point (point 2 – Fig. 1).

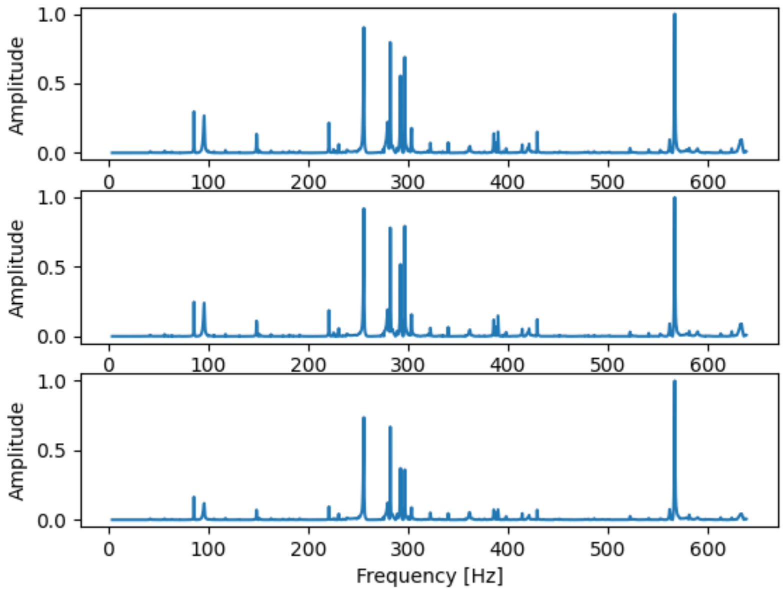

Figure 3. Power spectral densities of impulse responses from the excitations of the plate in a single point, in a in narrowed down frequency band (point 2 – Fig. 1)

The spectra from excitations in different points on the plate surface (Fig. 4) differ because of different patterns of nodal lines on the plate after the excitation. During the excitation, in the location of the excitation on the plate surface there is a wave antinode created, which defines the plate behaviour forcing it to have a specific pattern of nodal lines excluding some of the modes from being active. This is reflected in the readout acoustic signal containing the plate vibration.

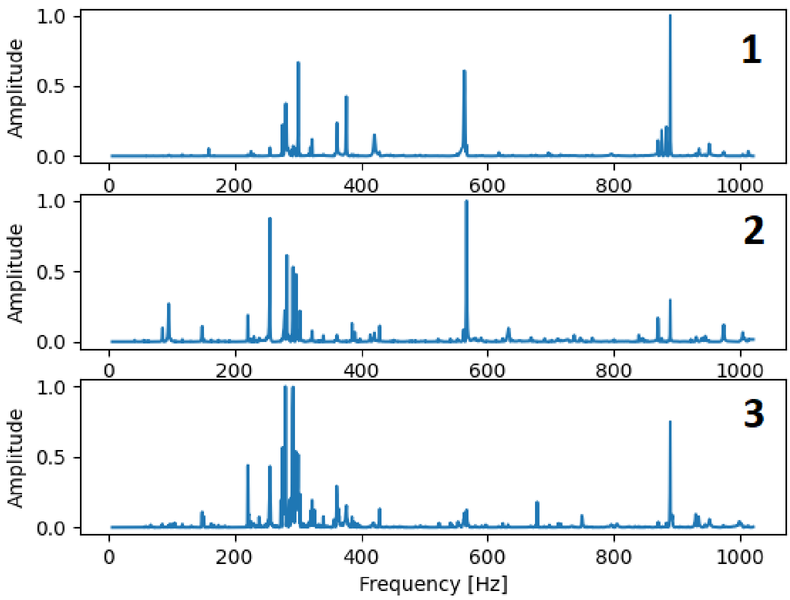

Figure 4. Power spectral densities of impulse responses from the plate excitations in three different points (Fig. 1).

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Plate excitation in different points on its surface can be perceptually significant for a listener. Smallest change in a stimuli human can detect is a just noticeable difference (JND), which for pure tones is around 1 dB [20]. The most important change in spectra from the plate excitations, that is predicted to affect the perceptual impressions, is presence of spectral components in a specific frequency or their lack as well as differences in amplitude. Research of perception of more complex spectra than a pure tone shows [21] that for sounds with more than ten frequency components, lack of one can be audible for a listener. Similar situation occurs in power spectral densities of plate excitations in different points (Fig. 5), where in every frequency band in audible range there are frequency components that are not present in one of the spectra, or its amplitude decrease is significant. This indicate that the changes can be perceptually significant for a listener.

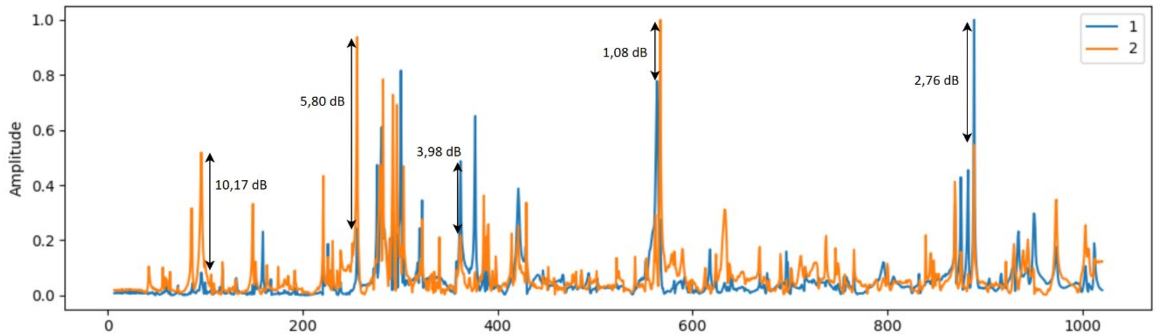

Figure 5. Power spectral densities of impulse responses from excitations in two different points (Fig. 1.) with highlighted example differences in amplitude.

4. Numerical model

The numerical model should allow to have possibilities to design changes in the readout acoustic signals obtained from plate vibration in physical experiments. The model should be able to indicate how affecting the vibrating plate system will affect the output acoustic signals. In order for the reverberating plate to fulfil its role, differences between the output signals should be perceptually significant for a listener.

To begin a work leading to achieving it, in the initial model the Finite Element Method, widely used for vibration of plates [22–24], has been used in order to be able to evaluate physical parameters of the vibrating plate and its surrounding in any point. To calculate natural frequencies of the plate, the plate geometry was divided into 20 mm size elements and simple supported boundary conditions were defined on the edges of the plate in order to make a verification with the analytical model for these conditions (Sect. 2). There was a modal analysis performed, which led to achieving the natural frequencies of the plate (Tab. 2). Then, there was a harmonic response analysis performed with plate excitations in locations on the plate surface considered in Sect. 3. To obtain results of the plate excitation that could be compared with the described physical experiment, there was a harmonic acoustics simulation performed. There was an air volume created around the plate and divided into 50 mm size elements. Boundary conditions of the plate were attempted to be made as close as possible to the conditions from the physical experiment – free at the edges, but instead of fixed support in the centre area of the plate (Fig. 1), the best results were achieved for elastic support with a stiffness value of 10^9 N/m with the same geometry that in the physical experiment (Fig. 1). The plate was excited with sinusoidal signals in a 1-1000 Hz range with a 1 N force and for each frequency (with a frequency step of 0.5 Hz) there was a sound pressure value recorded numerically in the same location as the audio signal recording in the physical experiment, relative to the plate. There are differences between plate responses obtained from different points of excitation in the numerical model (Fig. 6), but they also differ from responses from the performed experiment, which may have many reasons, including anisotropy of real plate as opposed to the simulation where calculations are being made for an isotropic body, as well as simplified model of the geometry and boundary conditions, which may have not exactly reflected real conditions from the performed experiment and can be improved in further iterations of the model. The model requires being adjusted with results from the experiment, which would be desirable for future work in order to predict further experimental results by using the numerical model.

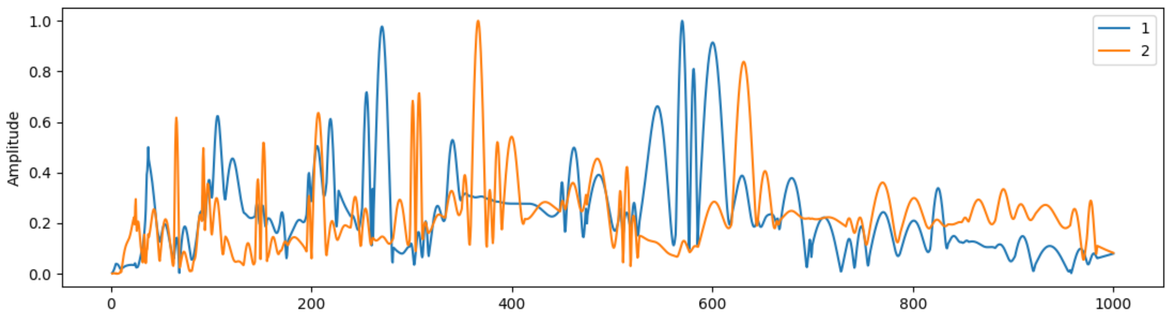

Figure 6. Spectra of sinusoidal excitations responses in two different points on the plate surface (Fig. 1.) from the initial numerical model

5. Test stand concept

The initial concept of the test setup assumes excitation of a thin plate using an acoustic signal and readout of an output signal being a result of the plate vibration. The concept assumes having multiple possibilities to affect the plate vibration in a way that it will affect the output signal which will be audible for a user. In the concept, the plate is assumed to be excited with an input acoustic signal varying in time, sent from an audio interface, that will force the plate to vibration. Then the vibration will be picked up by piezoelectric transducers from the plate or alternatively air pressure close to the plate will be recorded by a microphone. The output reverberation signal will be brought back to the audio interface (Fig. 7).

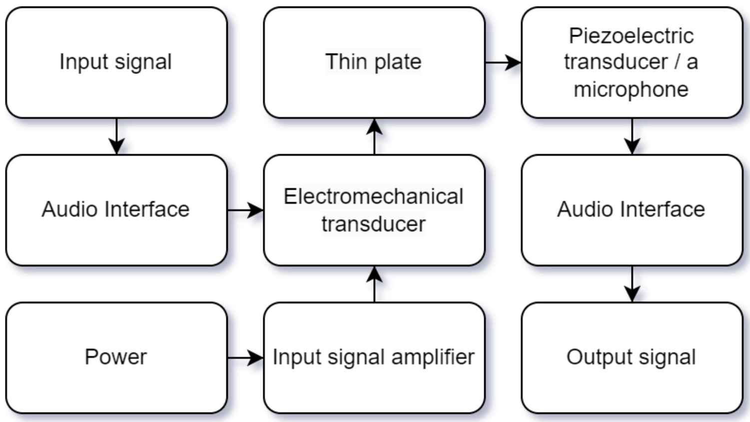

Figure 7. Signal path in the concept test stand.

The example ways to a potentially affect an output signal in perceptually significant way are:
a) Plate excitation. The position of the excitation with an input audio signal requires having a possibility to adjust a position of the transducer on the plate. This could be made possible by applying in the test stand stepper motors in two axis that would be able to move the transducer on the surface on the plate, which would allow a user to modify the output reverberation signal, or alternatively a Cartesian robot used for similar applications [25].

Apart from the changes in impulse response's spectra caused by position of the excitation force on the plate surface, there are other factors that can affect the plate impulse response and the output signal from the plate reverberation system. In the presented concept, as a force used for the plate excitation it is considered an audio signal from an electromechanical transducer, which is a typical way of excitation in plate reverberators [2]. Hence the force $F(t)$ will be time variant with its values based on amplitude values of the audio signal. Potential ways of further changes in the output signal are:

- Transducer mass – the concept assumes the plate being placed horizontally, which will distribute inertial forces evenly across the plate surface. In horizontal placement of the plate, the simplest way to insert the transducer is to place it on its surface. Having an audio signal as an excitation force, the transducer needs to stay on a surface of the plate continuously, which adds a boundary condition that depends on the transducer's mass and geometry. Every boundary condition affects vibration of the plate, which can also affect the recorded output signal.

- Transducer type – apart from having different masses and geometries every type of electromechanical transducer processes an audio signal differently. The differences are related to their different frequency responses but also their electromechanical and mechano-acoustical efficiencies, frequency region of resonance, electrical power factor, transfer parameter and many others [26].

b) Signal recording. There are two main ways of recording plate vibrations in plate reverberation systems – recording the audio signal close to the plate after the excitation or using transducers that are attached to the plate to pick up the vibrations [1, 2]. Depending on the method the output signal can be different in terms of frequency content, as there will occur attenuation or enhancement of different frequency bands of their impulse responses, which is confirmed in listening tests to be audible for musical instruments [27], this might occur also for the vibrating plate. These changes are desirable from a user point of view, to have a possibility to choose the way of signal recording depending on needs.

Another factor deciding what frequency content the output signal will have is location of recording relative to the plate. Using a microphone to record air pressure changes around the plate will have different results depending on location of the microphone relative to excitation point, due to attenuation of high frequencies with distance, but more importantly to phase changes. In near field, for low frequencies the recorded plate response will depend on the wave phase. Hence, having a possibility to change microphone position during the signal processing may be significant for listener's auditory perception. If determined that position of the microphone affects the output signal in perceptually significant way, in the test stand there could be applied a system allowing to move the microphone in the same way that the input transducer – with stepper motors or a Cartesian robot allowing to move the microphone in two (or even three) axis, above or below the plate. On the other hand, location of signal recording using the piezo-electric transducers may also be significant, but in a different way, as the phase effects will occur there in less significant way and picking the plate vibration from its surface will depend more on nodal lines present in the pickup location depending on the excitation location and the excitation signal frequency.

c) Housing. Plate excitation causes vibration of the plate itself, but also the air around it, which can be used as an advantage having more reverberating signal to use. Having a surface close to the reverberating plate, the acoustic wave from the plate vibration could be reflected or absorbed in specific frequency ranges, depending on physical parameters of a material of the surface. Regardless of the surface type it is worth to measure how a surface or set of surfaces around the plate affects the recorded output signal. The additional air pressure changes caused by reflections from the added surfaces may be especially useful when recording the signal using a microphone as opposed to surface transducers attached to the plate, however it is worth to measure potential changes in the signal when recording using the surface transducers as well.

d) Boundary conditions. Different boundary conditions in any mechanical system serve different purposes. Limiting vibration in any part of the plate will affect its frequency response due to fewer or more modes being present in the plate vibrations after an excitation, which may also be a factor affecting spectral content of an audio signal recorded from the plate. Common boundary conditions met in existing plate reverberator are not fully described [2], however, in digital implementations there are attempts to simulate different types of boundary conditions, like free, pointwise clamping including in the corners of the plate [1, 28]. In hardware devices as well as digital implementations boundary conditions may serve role of a signal modifier if determined that their effect on a signal is audible for a user.

Initial concept assumes measuring plate vibration with simply supported, clamped and rotational spring supports. These are the most commonly researched boundary conditions in other branches of mechanics [28, 29] and may also find an application in the plate reverberation research.

Having a rectangular frame of a size of at least the vibrating plate, a spring support could be applied in the corners of the plate, which would limit its vibration in these areas. The spring support could also help with suppressing natural frequencies of the plate below 20 Hz which are unneeded from the output acoustic signal point of view. Also, stiffness of the springs is a factor that will affect the vibration of the plate that will result in differences in the readout signal. The spring support can be extended with higher number of springs if there is a need from the construction reasons, but might have an effect on the output signal, which if it is a case, can be as an advantage as an adjustable feature of the reverberation signal.

The rectangular frame can be also used to apply adjustable boundary conditions on the edges of the plate. Various materials elements can be mounted in the frame next to the edges of the plate and could be used as a simple support if having an option to be brought up closer to the edges so they collide with them, which will cause the plate to change its way of vibrating. A value of the force used for bringing the elements together as well as materials of the supporting elements will also affect the way the plate vibrates.

5. Conclusions

An important usage of plate vibration is an artificial reverberation synthesis, which nowadays is still a valid topic to research and develop. Many different factors can affect plate vibrations and the audio signal in the output of the plate reverberation system.

An experiment was performed to test a potential effect that location of the plate excitation on its surface has on the output signal and its perceptual significance. The experiment shows that differences in modal content between signals from excitations in different points might have a perceptual significance for a user. Further tests are planned to evaluate this occurrence in more details.

There has been a work on a numerical model initiated, which is needed in order to have possibilities to design changes in the readout acoustic signals obtained from plate vibration in physical experiments. The model requires being adjusted with results from physical experiments, which is needed for future work in order to predict further experimental results. The future study will include experimental measurements along with improvements of the numerical model.

To be able to perform measurements allowing to evaluate the output acoustic signal and plate vibration results with different configurations, a test stand is needed to be created. The concept of the test stand assumes having possibilities to measure how a way of plate excitation, signal recording, presence of plate housing and different boundary conditions affect output acoustic signal being a result of plate vibration. Some of planned measurements are to evaluate mechanical and signal effects of common ideas, met in commercial plate reverberators, but not fully described in literature. However, more important is to measure original and new ways of influencing the plate and their effect on the reverberation signal.

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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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