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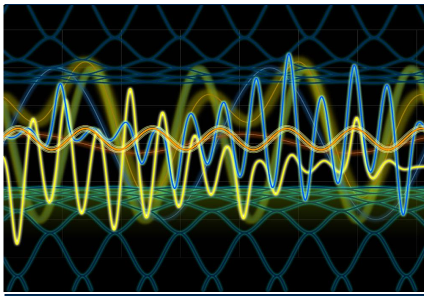

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Long radiation initial transient time (RITT) laser interferometry measurements of a Balinese *gender* bronze plate

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The lowest plate of a Balinese ***gender*** bronze percussion instrument, previously found to have additional modes due to its trapezoid shape (Bader 2009) is additionally measured using laser interferometry. Again, additional modes appear strongly within the initial transient of about 150 ms, clearly audible as found before using a Finite-Difference Time Domain (FDTD) calculation. The additional modes are not found in Finite-Element Method (FEM) eigenmode calculations. They are caused by internal boundaries within the plate at the connections between trapezoid sides and the middle plate section, as well as boundary conditions. These trapezoid parts show enhanced energy over the initial transient time and seem to store impact energy over about 150 ms. Although the fundamental frequency of the plate establishes within a few milliseconds, therefore making the initial transient of the instrument fast in terms of pitch, the radiation of the instrument considerably changes and only converges after about 150 ms. Therefore, a Radiation Initial Transient Time (RITT) is proposed to consider the spatial radiation development over an initial transient time no longer present in the steady-state and important for the spatial impression of musical instruments

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1. INTRODUCTION

Indonesian *gamelan* ensembles consist of bronze instruments like gongs or bronze plates, drums, and sometimes a dulcimer or bamboo flute instruments[3].[2] Ensembles of different kinds exist, like the large *gong gde*[96] or *gong kebyar*,[11] procession ensembles like the *semar pegulingan*, or smaller ones like the Balinese ensemble accompanying *wayang* shadow puppet theaters. In the latter, four *gender* instruments perform in two pairs.[3] Thereby, the Balinese *gender* is considerably different from the Javanese instrument of the same name in terms of shape, playing style, and ensemble use. The Balinese *gender* is played with a wooden hammer or a hard mallet and produces a loud and bright sound. Contrary, the Javanese *gender* is played with a soft mallet and therefore is also soft in sound. The present paper discusses the Balinese instrument only.

All *gamelan* ensembles are known to have a very precise tuning[8].[7] So e.g. the large gongs are carved slightly oval to form degenerate modes which are about 2 Hz apart, forming an amplitude beating known as *ombak*. The quality of the gong strongly depends on this beating. With the *wayang* ensemble consisting of *gender* instruments, also two neighbouring *gender* are expected to have their keys about 2 Hz apart to form such a beating.

The overall tuning of these instruments is very individual for each ensemble and is considerably different from Western tunings. Attempts to understand the reason for individual tunings have been suggested, following the inharmonic overtone structure of the instruments.[10] Artificial tuning a sampled Javanese *gamelan* ensemble into Western tunings showed a maximum of calculated roughness for the original tuning, but in listening tests with *gamelan* musicians, a least perceived roughness.[?] As the test subjects did all perform in differently tuned *gamelan* ensembles, this finding suggests a dependency of the tuning on the inharmonic overtone structure of the ensemble, leading to a typical '*gamelan*' sound.

Taking the complex and precise tuning of *gamelan* ensembles and the dependency to the inharmonic overtone structure into consideration, this investigation is trying to relate the shape of the *gender* to its sound. This especially holds for the trapezoid shape of the *gender* plates. In a previous investigation it was estimated that this shape causes additional frequency components in the sound and is responsible for the strong brightness of the instrument.[1] Using a Finite-Difference Time Domain model, the lowest plate of the *gender* was modeled as a trapezoid shape and as a flat plate. The trapezoid shape had more and much stronger higher harmonic content and was considerably brighter. Sound recordings of the *gender* plate were related to analytical solutions of bending, longitudinal, and torsional waves on the instrument. Thereby, many frequency components could be identified, still others appearing could not be associated. This might be caused by a missing analytical solution of a plate with free boundary conditions. Still this might also be caused by the trapezoid shape, the overall cured structure of the plate, as well as the carvings on its bottom which is used to tune the plate to a desired frequency.

As found before, the initial transient is complex in this instrument. Still, this complexity could only be estimated in terms of the recorded sound timbre. With the presence of mode shape measurements, performed in this paper, it is additionally possible to estimate the radiation of the plate with respect to time. Of course, as the *gender* is a percussion instrument, there is no perfectly steady-state, but only a quasi steady-state with a decay of partials. Still, as shown below, there is a considerable energy distribution change, way beyond a typical initial transient time for a percussion instrument, which usually is a few milliseconds. Therefore, a Radiation Initial Transient Time (RITT) is proposed, which is important for the establishment of a then decaying sound part, and therefore for the perceived spaciousness of the instrument.

Such complex energy distributions have already been found with Chinese gongs or tam-tams.[7] There, due to strong nonlinearities, energy is transferred from lower to higher modes over time, or a pitch-glide over time is produced. With the Fender Rhodes electric piano[4] it was found that the rod struck by the hammer first transfers the energy to a second plate, which, over time, gives its energy back to the rod, causing the long sustain of the instrument. With grand pianos, a complex distribution of energy over the piano top plate was found to collect energy within the round shape of the bridge.[5] All these energy transfers give way to a complex initial transient, as well as prolonged sound components, either of pitch, timbre, or radiation characteristics, often over a long time span.

2. METHOD

The investigated *gender* consists of ten bronze plates using a *sedeng* tuning which is in between the old *tiru* and modern *begbeg* tuning.[11] Over the course of the 20^{th} century Balinese tunings tended to make small intervals even smaller and therefore larger intervals larger. The ten bronze plates of the *gender dasa* used are tuned as 0, 136, 291, 670, 804, 1200 cent, referred to a fundamental pitch.

A. GEOMETRY OF PLATE

Fig. 1 shows the gender investigated and bought by the author at a *gamelan* instrument manufacturer in Savang, Northern Bali in 1999, as well as the lowest plate investigated. The lowest two figures shows the plate side with its trapezoid shape and its measures.

Below the plates, bamboo resonators are attached with frequencies close to the fundamental frequencies of the plates. The enhanced amplitude of these lowest frequencies allow for a pitch associated with the plates, allowing for a kind of pitch or melody perception of this percussion instrument.

B. PHYSICAL MODELING

In a previous investigation, the plate was modeled using Finite-Difference Time Domain Method (FDTD) calculating a sound, and Finite-Element Method (FEM), calculating eigenmodes and frequencies.[1] The FDTD was calculated for two shapes, a flat and a trapezoid-shaped plate. The trapezoid plate showed additional frequencies compared to the flat plate. The trapezoid plate was also much brighter in sound, supporting the salience of the trapezoid shape for the plates' sound. The FEM eigenvalues differed considerably in terms of the used boundary conditions. The FEM free case had free boundary conditions all over the plate. The FEM fixed case had two points fixed at each of the two holes where the rods hold the plate in place.

C. LASER INTERFEROMETRY

In the present paper, additional laser interferometry measurements were performed to clarify the role of the trapezoid shape and the instruments sound radiation. A commercial Digital SWIR Scanning Vibrometer from OptoMed was used. The system uses an impulse hammer to strike the plate at a driving point. A x=30 $\times$ y=20 point grid was defined over the plate top. The laser system points a laser at each grid point at adjacent time points and records the velocities $v_{x,y}$ of the plates' vibration with a sample frequency of 200 kHz using interferometry. Each point is struck three times and an average of the time-series of these three cases is calculated. The impulse hammer additionally records the impact impulse using a piezo sensor, and again averaging the three impulse time-series for each grid point.

During post-processing performed after the measurement, the recorded impulses of each grid point were deconvolved with the impulse hammer time-series. The time-series are then Fourier-Transformed and an automatic peak-picking algorithm determines the most prominent frequencies in the spectrum. For these frequencies the real, imaginary, and absolute amplitudes were picked for each grid point, and mode shapes were reconstructed by visualizing the grid. Additionally, a video of the strike was reconstructed.

Four Fourier-Transforms were performed with different time intervals and time offsets, to investigate the temporal development of modes, where the integration time started at impulse impact beginning:

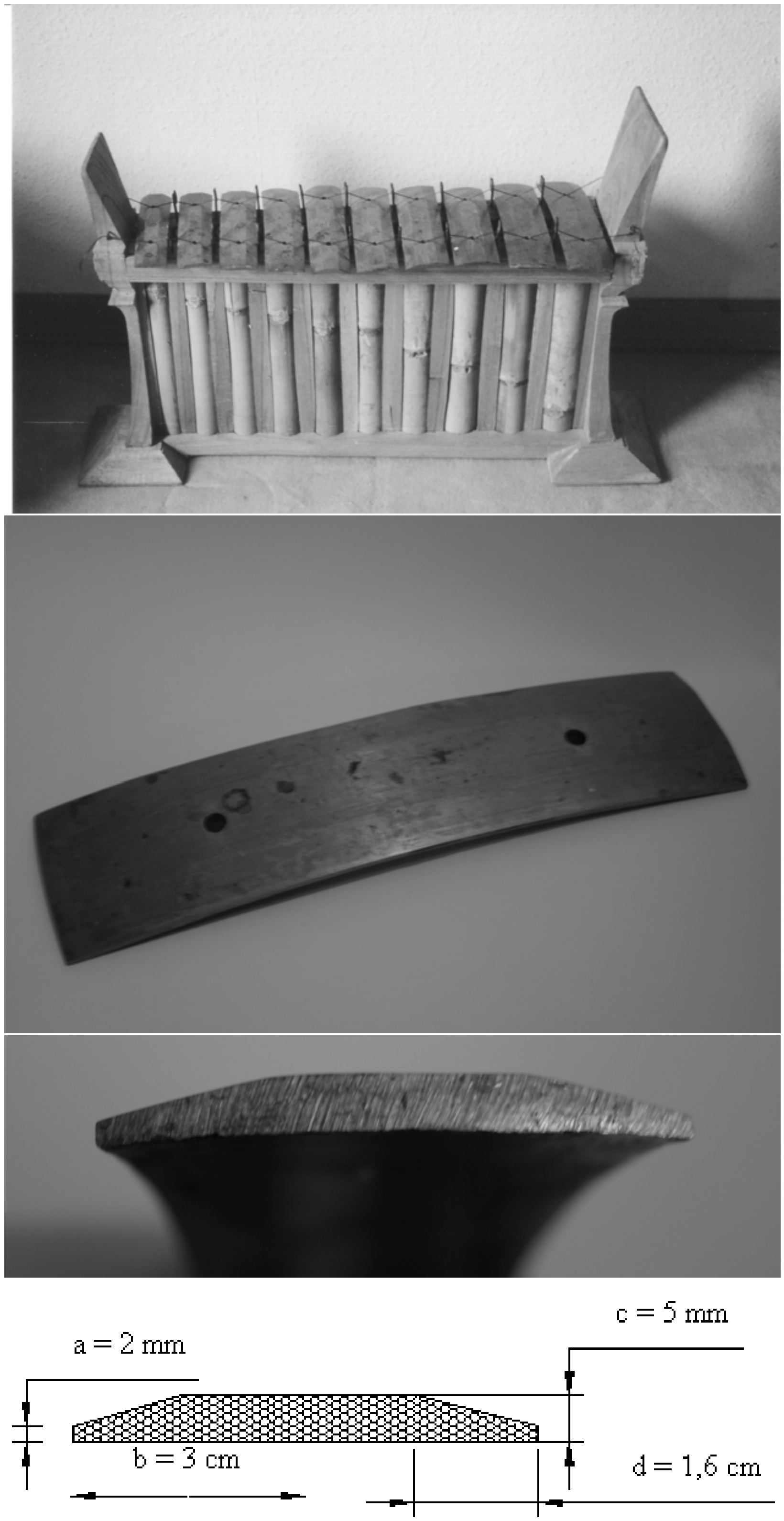

Figure 1: Top: The* gender dasa *investigated, Middle top: The lowest plate used in this investigation, Middle bottom and bottom: The trapezoid shape of the plate.

- 0-500 ms
- 0-50 ms
- 50-100 ms
- 500-550 ms

0-500 ms was used for an overview, 0-50 ms and 50-100 ms for the mode developments during the initial transient, and 500-550 ms for an estimation of remaining eigemodes.

Additionally, the energy distributions over the width

$$W_{y,t} = \sqrt{\sum_{x=1}^{30} v_{x,y}^2} \;, \tag{1}$$

and length

$$L_{x,t} = \sqrt{\sum_{y=1}^{20} v_{x,y}^2} \;, \tag{2}$$

of the plate were calculated for each time step t, to estimate the time needed for the plate to arrive at a steady-state of vibration and the energy distribution over this time.

D. SOUND RECORDING

In the previous investigation the sound of the instrument was recorded for different strike positions and strength, to arrive at a set of frequencies produced by typical strikes.[1]

E. ANALYTICAL CALCULATIONS

Analytical calculations solving the differential equations of a rod for its bending, longitudinal, and torsional waves have been performed in.[1] As there is no analytical solution for a plate with free boundary conditions, but for a rod with free boundary conditions, only modes of the form (x,0) and (0,x) can be calculated with this method. Results are shown below and indicated in terms of bending (B), longitudinal (L), or torsional (T) waves over plate length (l) or width (s), numbered according to its wave number.

3. RESULTS

First, the eigenmodes of the *gender* are investigated, and additional modes due to the trapezoid shape are estimated. Secondly, the energy distribution development during the initial transient is discussed, and a Radiation Initial Transient Time (RITT) is found as alternative to a Sound Initial Transient Time (SITT).

A. EIGENMODES AND THEIR TEMPORAL DEVELOPMENT

First, typical eigenmodes of the *gender* were identified in the laser interferometry measurements with integration time 0-500 ms. Fig. 2 shows 26 eigenmodes, from the lowest found at 270 Hz to up to about 19 kHz. Up to about 5 kHz they show typical (x,0), (x-1,1) patterns, where the amount of vertical nodes x=1,2,3,...,7. This pattern is strictly present with increasing mode frequencies. Above about 5 kHz, mode shapes become more complex with round or oval, broken, or curved nodal lines. Still, clearly, the amount of nodal lines horizontally and vertically increase steadily. All these peaks have strong amplitudes, with the lowest at -5.6 dB below the strongest peak at 0 dB.

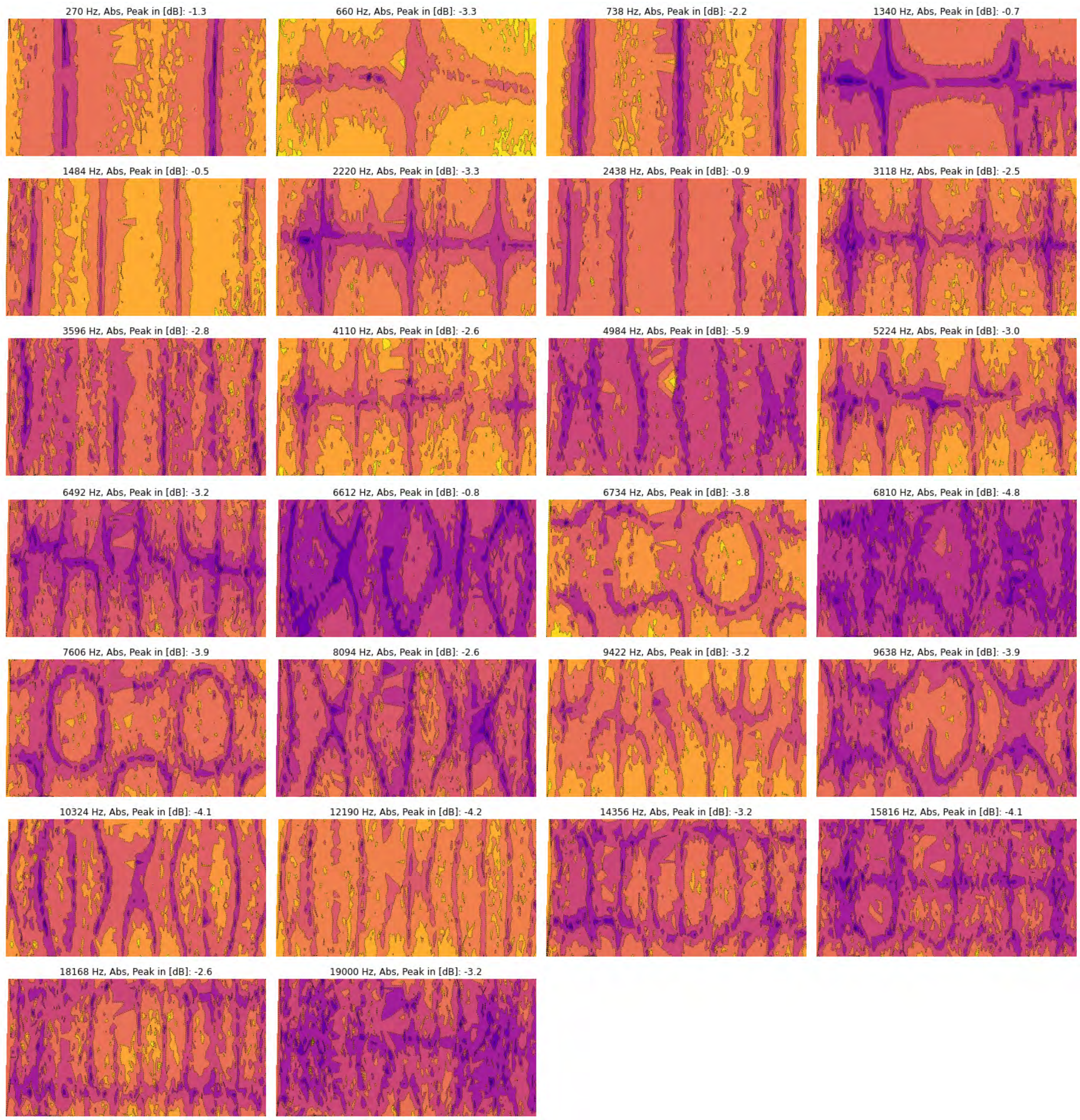

Figure 2: Absolute velocities of 26 strongest eigenmodes of the* gender *plate. Up to 5 kHz the regular pattern of (x,0) followed by (x-1,1) appears. Above 5 kHz modes are not clearly identifiable.

Still looking closer at these modes into their time developments strong deviations from the simple modal patterns found when integrating over 500 ms can be seen. In Fig.3 for six modes their shapes for 0-50 ms, 50-100 ms, and 500-550 ms integration times are shown.

The lowest (2,0) mode, in the sound recording at 273 Hz, is only establishing during 50-100 ms, and is blurred during the initial transient. This might be caused by an interaction with the bamboo resonator attached below the key. Also, the impact hammer point is visible at about the plate center within the first 50 ms plot. More astonishing is its left node. It is more prominent, and split into two, which is already visible during the first 50 ms. For 50-100 ms both left nodes have about the same strength, while at 500-550 ms the node at the far left is even stronger than its neighbour.

The (3,0) mode at 740 Hz is not detectable during the first 50 ms, becomes stable then, again more prominent during 50-100 ms and is vanishing, with also a split left nodal line at 500-550 ms. The (2,1) mode at 1340 Hz is clearly present during the first 50 ms, but starts to establish a new nodal line at the left, about the place where the (2,0) or (3,0) modes have their left nodal lines. The (4,0) mode at 1480 Hz is clearly present during 50 ms initial transient time, is vanished at 500 ms and in between also establishes a new nodal line at the left. The (5,0) mode at 2440 Hz is more stable throughout, with a slight additional nodal line on the left. Finally, the mode at 6060 Hz, which is no longer associated with a simple modal pattern, is stable throughout.

We see already a strong temporal dependency of the mode shapes over the first 500 ms of the tone. Taking into account that the *gender* is a percussion instrument, the length of this initial transient is astonishing. Still this is not a change in the frequencies. Of course the amplitudes decay. But what is striking is the change of the mode shape, which leads to a change in the sound radiation pattern of the instrument.

B. ADDITIONAL MODES

Fig. 4 shows eight additional mode shapes with strong amplitudes, the lowest in amplitude is -4.4 dB below the loudest of the sound at 0 dB. These modes are all below 5 kHz, up to where clear eigenmodes can be identified. In the 370 Hz and 2740 Hz modes, the hammer impact is clearly present. The others have blurred shapes, which are in between similar regular mode shapes near in frequency. Fig. 5 shows two modes at 1160 Hz and 1572 Hz. Above and below these two modes in the figure, regular modes with clear mode association are shown. The mode at 1160 Hz clearly has two nodes of the left of the plate, one also found at 738 Hz, and another one also found at 1340 Hz. The mode at 1572 Hz has two nodes on its right, the one also found at 1484 Hz and the other also present at 1340 Hz. The frequencies of the regular modes are that far apart from the additional mode that they do not merge due to large Q-values of their amplitude peaks. These modes are indeed additional modes, which seem to be caused by the complex shape of the *gender* plate.

The additional modes are also not symmetric over the plate width. Especially the lower trapezoid side has considerably more energy, which will also be found below to be only the case within the initial transient. This might be caused by the connections between the trapezoid sides to the middle plate section, acting as reflection points, where the trapezoid sides might store energy for a certain time. Also the holes, where the *gender* is held in place by two rods might cause distortions.

Such complex energy distributions are also found with Chinese gongs or tam-tams.[7] There, due to strong nonlinearities, energy is transferred from lower to higher modes over time. With the Fender Rhodes electric piano[4] it was found that the rod struck by the hammer first transfers the energy to a second plate, which, over time, gives its energy back to the rod causing the long sustain of the instrument. With grand pianos, a complex distribution of energy over the piano top plate was found to collect energy within the round shape of the bridge.[5]

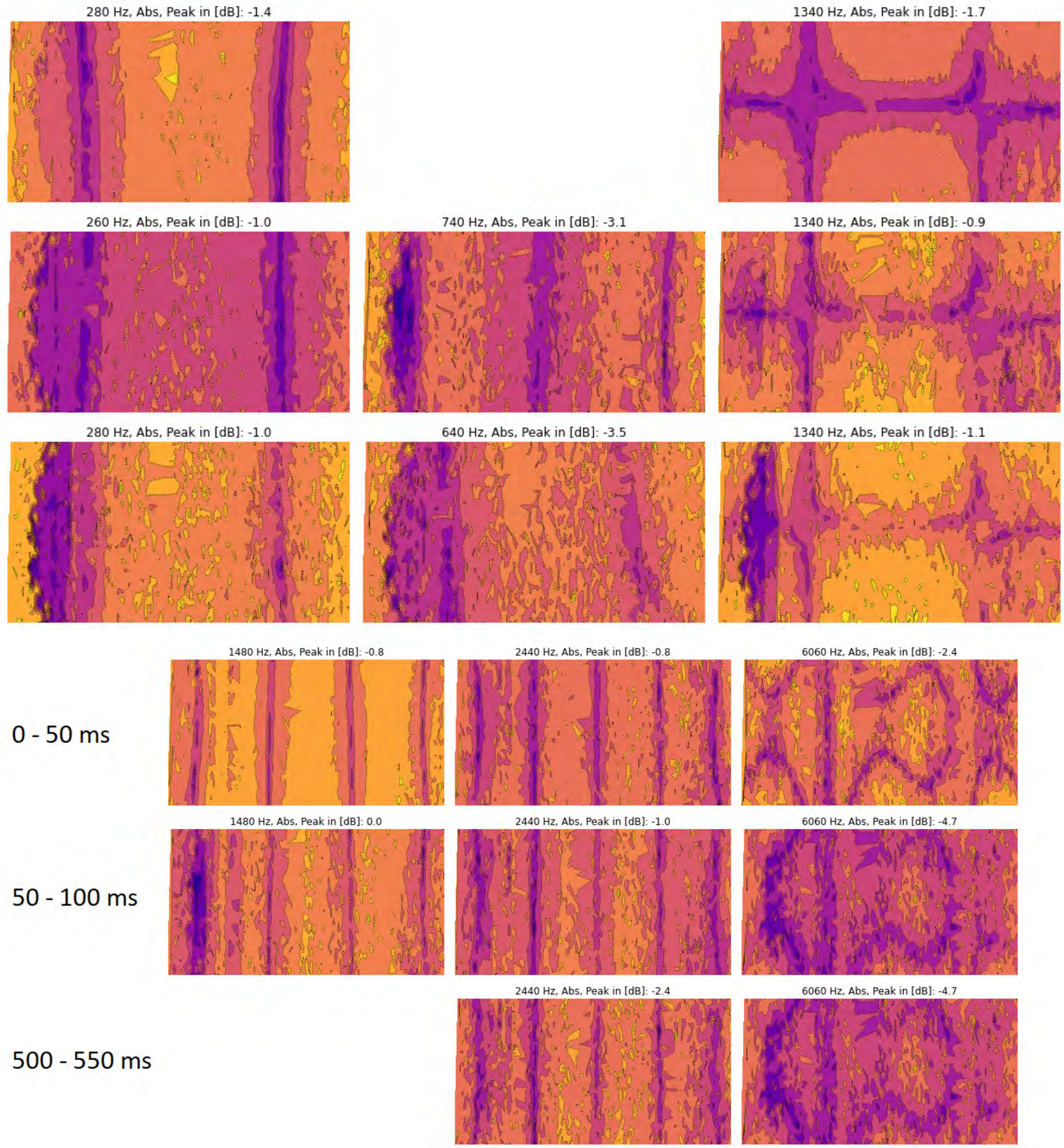

Figure 3: Temporal development of six example modes. Lower modes show considerable variation in terms of appearance and mode shapes, pointing to a complex radiation pattern developoment of the* gender *sound. Higher modes are much more stable, still also showing enhanced or additional nodal lines, mainly at the left of the plate.

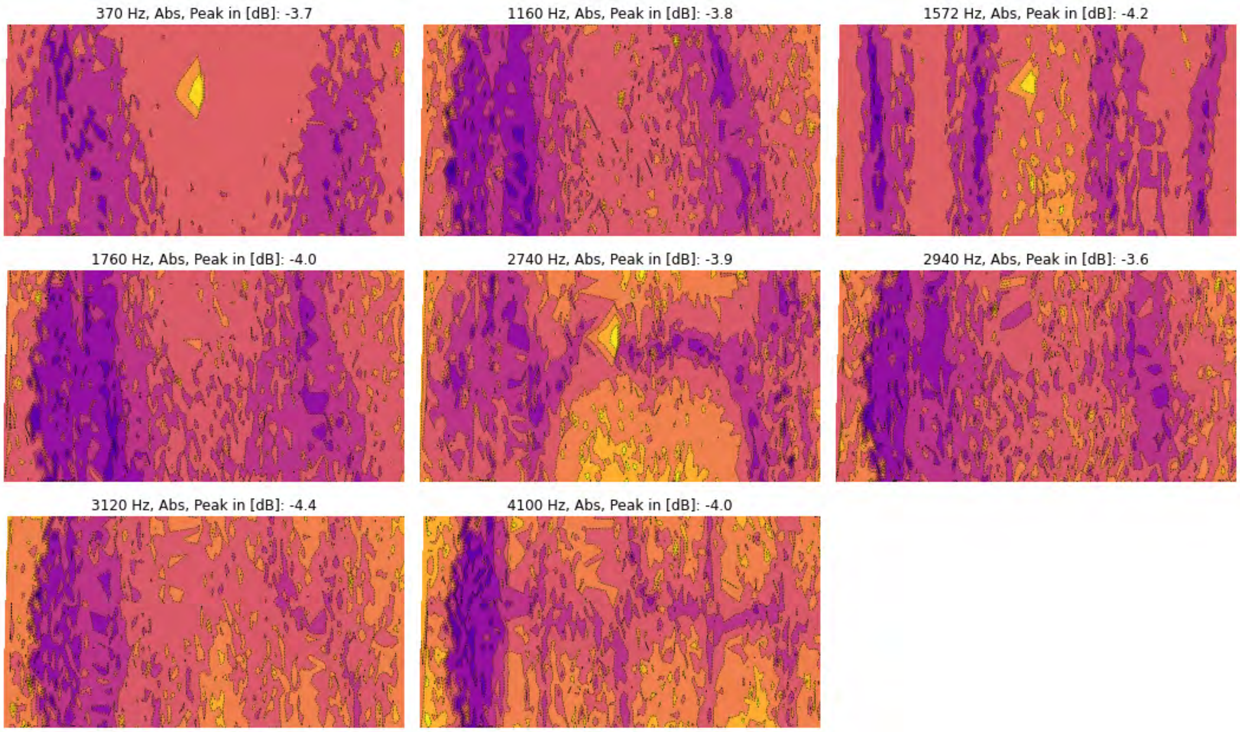

Figure 4: Additional modes, already found only examining the* gender *with microphone recordings before.[1] These modes are caused by the trepezoid shape and the boundary conditions. They are strong in amplitude, enhancing the overall brightness of the sound considerably.

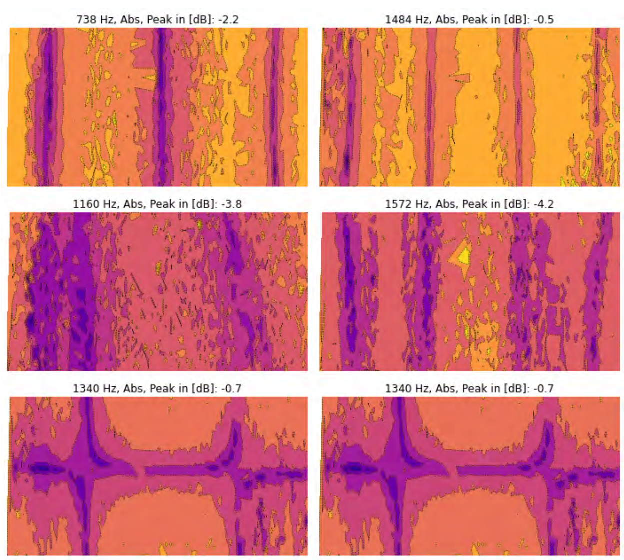

Figure 5: Two examples of additional modes at 1160 Hz and 1572 Hz, compared to regular modes at 738 Hz, 1484 Hz and 1340 Hz. Additional modes show mixtures of nodal lines taken from regular modes.

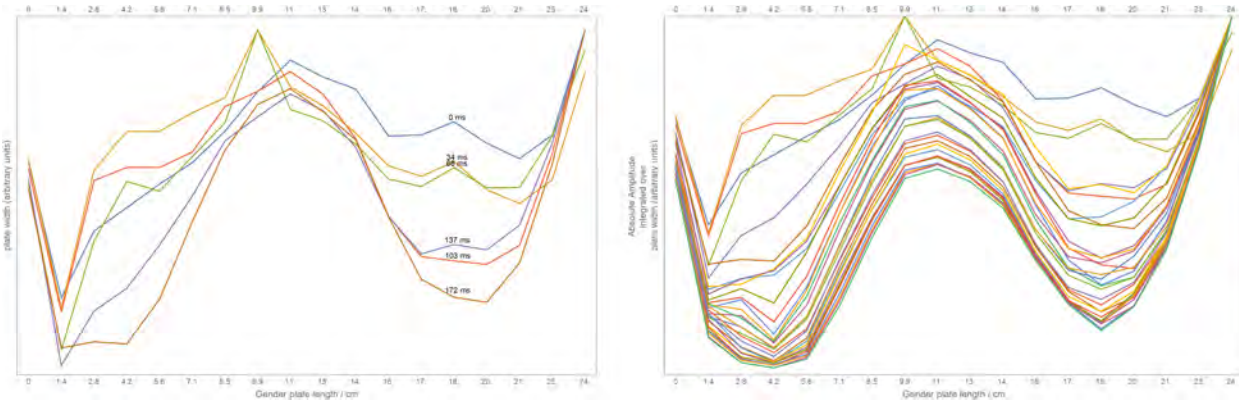

Figure 6: ***Energy distribution*** $L_{x,t}$ ***of the plate, integrated over its width, for different time points. Left: Until convergence, Right: Up to 500 ms. The convergence time is very long for a percussion instrument, taking about 160 ms.***

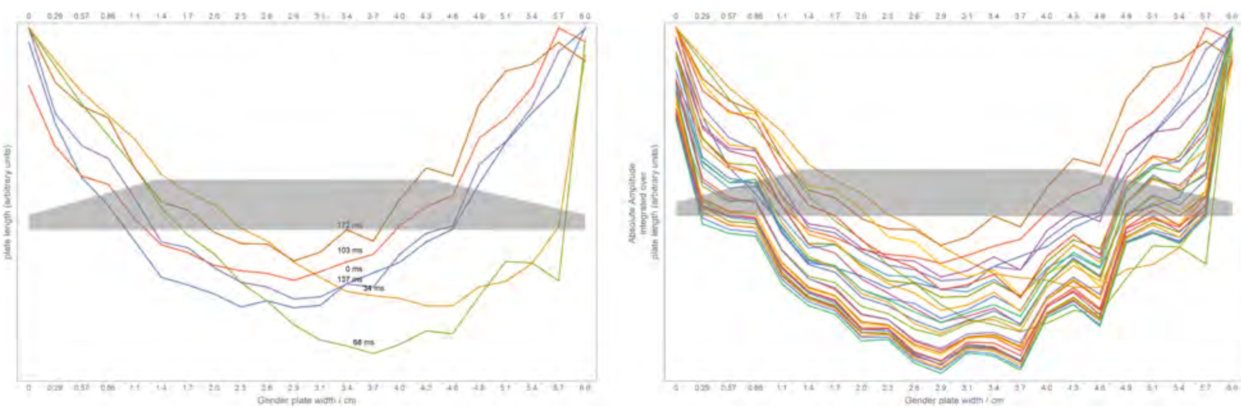

Figure 7: ***Energy distribution*** $W_{t,y}$ ***of the plate, integrated over its length, again showing a large initial transient time of about 100 ms.***

C. TRANSIENT ENERGY DISTRIBUTION AND RADIATION INITIAL TRANSIENT TIME (RITT)

The Radiation Initial Transient Time (RITT) is here defined as the time it takes for the overall energy distribution of a vibrating body to converge to a steady-state, while after convergence the energy distribution is only decaying.

To estimate the RITT, $L_{x,t}$ and $W_{y,t}$ are displayed in Fig. 6 and Fig. 7 respectively. The left plots show the development from 0 ms to 172 ms, the lower plots that from 0 ms to 500 ms. Note that the integrations have been performed over the squared velocities, therefore are proportional to energy, and therefore all values are positive. So the minima correspond to regions of low energy, close to nodal points.

Along the plates' length, the converged shape shows two minima, therefore the main radiation is basically a (2,x) mode shape. This corresponds also to the boundary conditions of the plate, where the holes the plate is held by the rods are placed at the minima of the converged plot. The radiation over the plates' length therefore is tripole-like. Still, the shape is clearly asymmetric with more energy at the right side. This corresponds to enhancement of the left node discussed above.

Examining the initial transient, for the 34 ms and 68 ms plots the hammer impact slightly left from the middle can clearly be seen. This is astonishing because of two reasons. First, the impact point does not appear at 0 ms. Secondly, 68 ms is way beyond the hammer impact time which is about 2 ms. Also, during the initial transient, the right side of the plate has considerably more energy than the left side, which is only balanced at about 172 ms. When considering the time development over 500 ms it appears that only at about 150 - 170 ms the overall energy distribution on the plate has converged. Therefore, for the width integration we find a RITT   160 ms.

When integrating over the length of the plate, shown in Fig. 7, an overall (x,1) shape appears, with least energy at the plate midline. This shape converges at about 100 ms. Here, RITT   100 ms. Before, a strong enhancement of the lower side is present.

The overall energy distribution over the plate width is clearly caused by the trapezoid shape, where the thinner sides are more flexible and therefore have larger velocities, causing radiation. This leads to a dipole-like radiation over the plate width.

D. COMPARISON OF METHODS AND MODE ASSOCIATION

Tab. 1 shows a comparison between the measured modes using a microphone recording at the left, the analytical calculations for bending, longitudinal, and torsional modes of a rod, the FEM calculations with free and fixed boundary conditions, and the laser interferometry measurements. The first four rows are from.[1]

The bold cases of the measured frequencies are those still present one second after striking the plate. Both, from laser measurements and FEM calculations they correspond to the modes 273 Hz: (2,0), 751 Hz: (3,0), 1486 Hz: (4,0), 2450 Hz: (5,0), 3606 Hz (6,0), and most probably 5407 Hz: (3,2). Clearly, the FEM with free boundary conditions performs better than that with fixed conditions.

These modes are maintaining, while the (2-6,1) modes are weaker in amplitude and decay faster. This seems to contradict the finding from plate width integration at first, namely that the side of the plates are vibrating stronger, pointing to an enhancement of the (x,1) modes with one nodal line over the middle of the plate along its length axis. Still, as both findings are there without any doubt, we need to conclude that the enhanced vibrations of the plate sides over its width mainly are caused by the (x,0) modes rather than the (x,1) modes.

The additional modes found in the laser measurements were also found when recording the *gender* sound. Still, they never appear in the analytical or the FEM solutions. Some show the impact hammer point, nearly all have additional, enhanced nodal lines at the left or right over the plate length. Such additional nodal lines might be caused by an interplay of modes, an interaction of modal nodes with boundary conditions of the rods holding the plate in place, or the trapezoid shape, which might be the cause of the very long RITTs, where the lower trapezoid side store energy due to reflections at the connections between the thicker middle and the thinning sides of the trapezoid shape, as discussed above. Such a behaviour could also work with the two holes where the rods hold the plate in place. During the initial transient, the outer parts could store energy for a while and act as de-coupled plates to a certain extend. As the additional modes found in the laser measurements and microphone recordings all show strong asymmetries in both directions and additional nodal lines, additional modes seem to be caused by both, the trapezoid shape and the boundary conditions.

4. CONCLUSIONS

The enriched spectrum during the initial sound transient, clearly audible in the comparison between a FDTD simulation comparing a flat from a trapezoid-shaped *gender* plate, is therefore found to be caused by the trapezoid shape in connection with the boundary conditions of the rods holding the plate in place. Also, additional modes are found not appearing in the analytical solutions or the FEM eigenmode calculations. These modes appear during the initial transient most probably because of the trapezoid shape in the plate. Still they also appear only after some time, pointing to an influence of the boundary conditions. These are, both, the connections between the trapezoid sides and the middle section over the plate width and the holes

Measured f (Hz)	Analytical	FEM free	FEM fixed	Laser
273	Bl1 288	(2,0) 281	(2,0) 277	(2,0) 270
(350?)			(3,0) 451	**(2,0)? IH 370**
			(2,1) 660	
		(1,1) 726	(1,1) 726	
751	Bl2 802	(3,0) 764	840	(3,0) 738
980	hammer-click			
1230				**(2,0)? 1160 AL**
1341		(2,1) 1464	1464	(2,1) 1340
1486	Bl3 1571	(4,0) 1486	1902	(4,0) 1484
				1572 (4,0)? AR IH
1756				**1760 (2,0)? AL**
2218		(3,1) 2302	2303	(3,1) 2220
2450	Bl4 2598	(5,0) 2452	2535	(5,0) 2438
2750				**2740 (2,1)? AL**
2824		(in-plane) 2865	2700	
			2864	
				2940 (2,0)? AL
3113		(4,1) 3242	3239	(4,1) 3118
3606	Bl5 3881	(6,0) 3624	3717	(6,0) 3596
4116	Bs1 4469	(5,1) 4253	4254	(5,1) 4110
4860	just with strong longitudinal struck T1 4440 or Bs1	(7,0) 4928		(7,0) 4984
5232		(6,1) 5367	5234	(6,1) 5224
5407	Bl6 5421			(3,2)? 5396
5694				5546
				5688
6077				6060
6188				
6491				6492
6539	Ll1 7159?			6612
6731				6734
				6810
7604	Bl7 7218			7606
8086				8094
8756	T2 8880			
				9422
9633	Bl8 9271			9638
10002	Bl9 11581			10324
11043	just with strong longitudinally struck			
12601	Bs2 12415			12190
14624	Bl10 14147 or Ll2			
14319				14356
				15816
16901	Bl11 16970			
				18168
				19000

Table 1: Strongest measured frequencies compared to the calculated frequencies. Bl is bending along the longer side l, Bs is bending along the shorter side s, Ll is longitudinal wave along the side l, T is torsional wave. The numbering refer to the theoretical values of eigenmodes. The bold frequencies are still present in he sound one second after the struck. FEM: mode associations with two boundary conditions. Laser: Laser interferometry associations, bold are additional modes, IM = Impact Hammer, AL, AR = Additional nodal line left or right.

where the rods holds the plate in place. As the FDTD simulations in both the flat and the trapezoid case have the rod holding positions unchanged, the trapezoid shape seems to be necessary to enhance the sound brightness during its initial transient.

This energy storage is clearly found when examining transient energy distribution integrated over plate length and width respectively. With respect to a percussion instrument, and taking into account the fast establishment of a fundamental frequency within a few milliseconds, this transient phase is very long. Aurally, this makes the sound of the instrument much more interesting, both in terms of enhanced brightness and of a more differentiated tone development. But it also mean a long transient time for establishing a quasi-stable radiation characteristics, which has a Radiation Initial Transient Time (RITT) of about 160 ms to converge. In terms of spatial audio, such long initial transient times need to be taken into consideration when discussing radiation from musical instrument.

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