Revisiting the Schroeder Frequency: The Influence of Room Proportions and Subsequent Modal Distributions on the Validity of the Schroeder Cutoff Frequency

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I. Introduction

The present work involved investigating the Schroeder Cutoff frequency, which is a metric used for finding a lower limit to where high frequency theory can be applied in a given room. This metric is defined as 2000 times the square root of the reverberation time (T_{60}) divided by the volume of the space in cubic meters. When researching this metric, it was found that a frequency spacing index, Ψ, had been assumed by Dr. Manfred Schroeder to be equal to two [7]. This frequency spacing index concept had originally been created by R.H. Bolt in a 1946 paper, wherein Bolt created the index as a measure of the irregularity of mode spacing within a given room based off the given room proportions. Assuming that the parameter Ψ was equal to two was essentially a simplifying assumption made by Schroeder, as he found that most of the concert halls he was investigating fell relatively close to that number.

This is where the present research comes of interest, as while Schroeder clearly defined his Schroeder Cutoff Frequency as relative to large rooms *only*, there has been an interest in the years since in applying the Schroeder Frequency to smaller rooms as well. Relatively recent research by M. Skålevik has attempted to address the possibility of a crossover region relative the Schroeder Frequency in the presence of small rooms, implying that in theory, the Schroeder Frequency could potentially be as low as 0.45 times what the Schroeder Frequency equation implies [8]. This finding ultimately lead the author to Bolt's 1946 paper, wherein the previously mentioned frequency spacing index was found. See figure 1 for a nomogram featured in Bolt's paper.

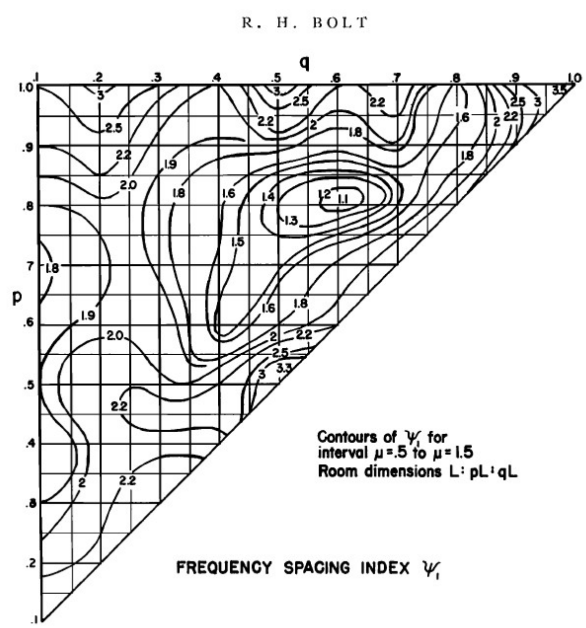

Figure 1: Bolt's nomogram for finding the spacing index based on the room proportions [2].

It is evident from the given nomogram that the spacing index could reasonably vary from approximately as low 1.1 to as high as 3.5, representing potential a 26% decrease and 29% increase to

Schroeder's cutoff frequency, respectively. These would evidently be vary drastic changes to Schoder's cutoff frequency at their most extreme.

The equation for the Schroeder Cutoff Frequency involving the frequency spacing index, as given in Schroeders 1954 paper, is as follows:

$$\boldsymbol{Fs = 2000\sqrt{(\frac{\psi}{2})(\frac{T}{V})}}$$

Wherein 'Ψ' is the frequency spacing index, 'T' is the reverberation time defined as the time to decay sixty decibels, and 'V' is the volume of the room in cubic meters.

II. Purpose

The present research examined this potential reformation of the Schroeder Cutoff Frequency in Riverbank Acoustical Laboratories' Room Zero, a highly reverberant chamber with decay times in excess of 4 seconds even at very low frequencies (below 100Hz). While this was initially the main goal of the research, ultimately assessing the validity of the Schroeder Cutoff Frequency relative to smaller rooms became a point of interest as well.

In the years since the creation of the Schroeder Cutoff Frequency, there have been numerous attempts to apply it in a 'magic number' sense to a variety of rooms. As the Schroeder Frequency was intended as a lower limit to the validity of high frequency theory, it implies a heavy meaning when assessed in a space. That being that above this lower limit, the response of a room can be considered stochastic in nature, and analysis methods such as ray tracing are applicable. It also implies that below this Schroeder Frequency, the room geometry and modal characteristics of a room would dominate. A practical example of this concept would be the following: Consider a room with a Schroeder Cutoff Frequency of 120Hz, with a point source emitting a pure sinusoid of 80Hz. Now let us also say that a prominent mode of this room is found to be at 72Hz. In this previously described room, the 80Hz sine tone could potentially shift down to 72Hz in the reverberant field of the room, as the resonances of the space would dominate below the Schroeder. Such coloration of the original tone can often be undesired.

With all that is implied by the Schroeder Cutoff Frequency, it is easy to see why there is some desire to apply it to a wide range of spaces. This in particular is why previous research by M. Skålevik interested the author, as while a large range of spaces were investigated, there was also clearly some interest in applying the Schroeder Cutoff Frequency to small spaces as well.

III. Methods

Procedures for testing began with bringing a substantial amount of absorption to Riverbank Acoustical Laboratories Room Zero, so as to make the room less than completely reflective. 13 unique source/receiver configurations were then marked in the room. The speaker being used to excite the room was a QSC K10 loudspeaker, and a TEF 04 type 1 microphone was used as well. A Brüel & Kjær pistonphone type 1 microphone calibrator was used to calibrate the microphone on site. A Sound Designs audio interface was used to connect a computer with the Acoustics software Arta loaded, wherein Arta was used to perform a sine sweep with reverse integration to get the impulse response of the room for each source/receiver configuration. An impulse response was recorded three times at each source/receiver configuration to gather three decays from the impulse responses at each source/receiver configuration. A single burst decay and frequency response was also gathered at each source/receiver location. Olive Tree Lab 4.0 was used to model the room and verify results, as well as to assess the modal distributions of the room.

IV. Findings and Analysis

Measurements of the dimensions of the room with a Bosch laser measure gave a room ratio of 1:0.7:0.73, yielding a frequency spacing index of 2.2. Plugged into the revised Schroeder Frequency, this would yield a value of approximately 254Hz, whereas the current version of Schroeder's Cutoff frequency yields a value of approximately 242Hz. Decay times were very much as expected, being very close to published results by Riverbank Acoustical Laboratories – factoring in the extra absorption - as well as resulting from the simulation in Olive Tree Lab's Acoustics simulation software. See figures four and five on the next page for an illustration.

Figure 2: Picture depicting Riverbank Acoustical Laboratories' Room Zero, and experimental setup within the reverberant chamber. The walls, floor, and ceiling are a very dense concrete, and a number of diffusive panels made of corrugated fiberglass are placed within the space.

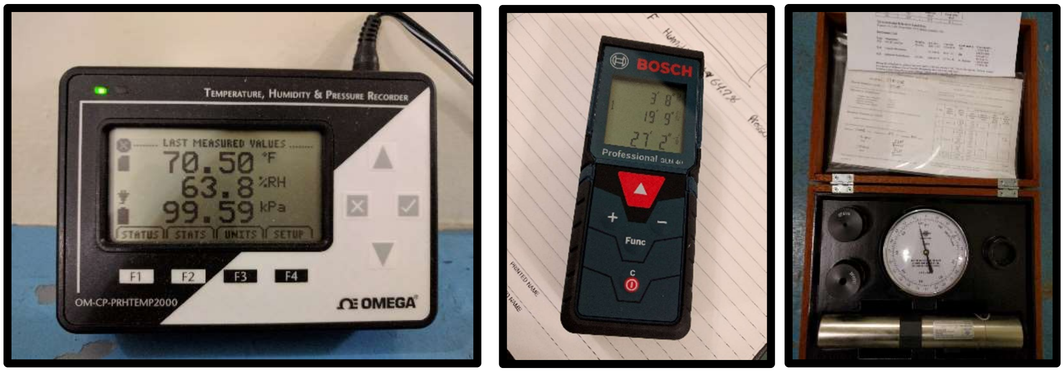

Figure 3: From left to right, the built in temperature and humidity monitor that Riverbank uses to keep the room within desired specifications (Room Zero is highly temperature and humidity controlled), the Bosch laser measure used to gather measurements of the room, and the Brüel & Kjær pistonphone type 1 microphone calibrator used to calibrate the type 1 microphone on site.

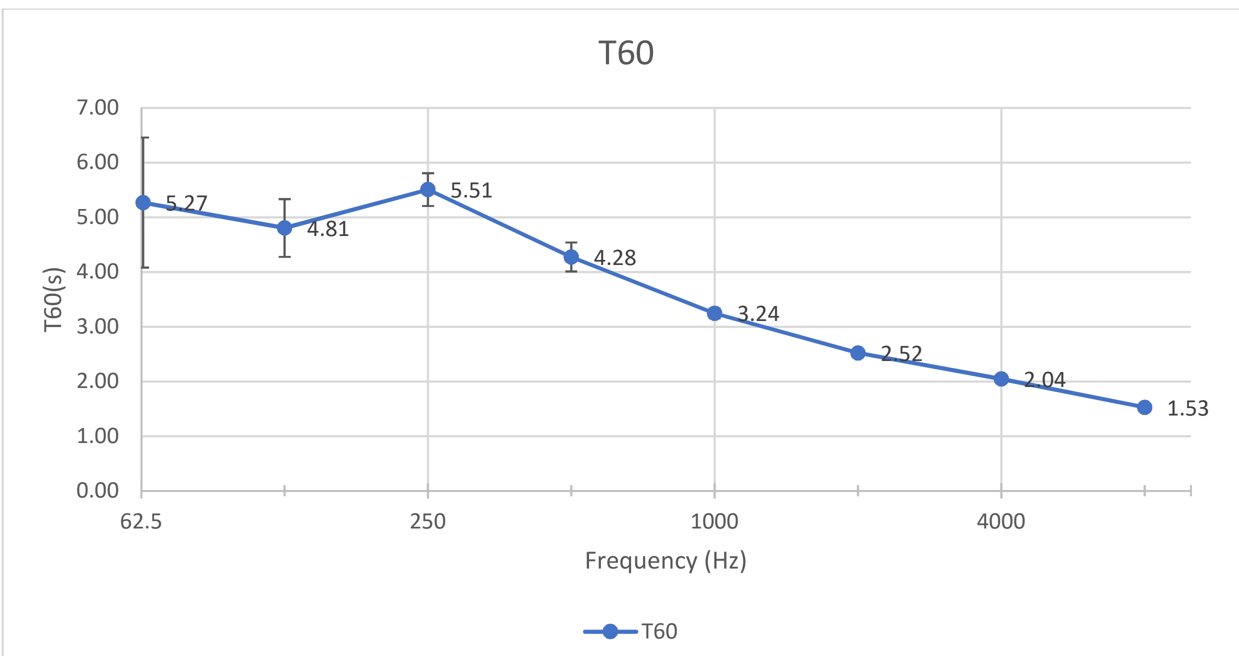

Figure 4: Graph of average T60 for all 13 source/receiver configurations, gathered from three distinct reverse integration sine sweep impulse responses of Riverbank Acoustical Laboratories Room Zero. Error bars correspond to the standard deviation of each octave band.

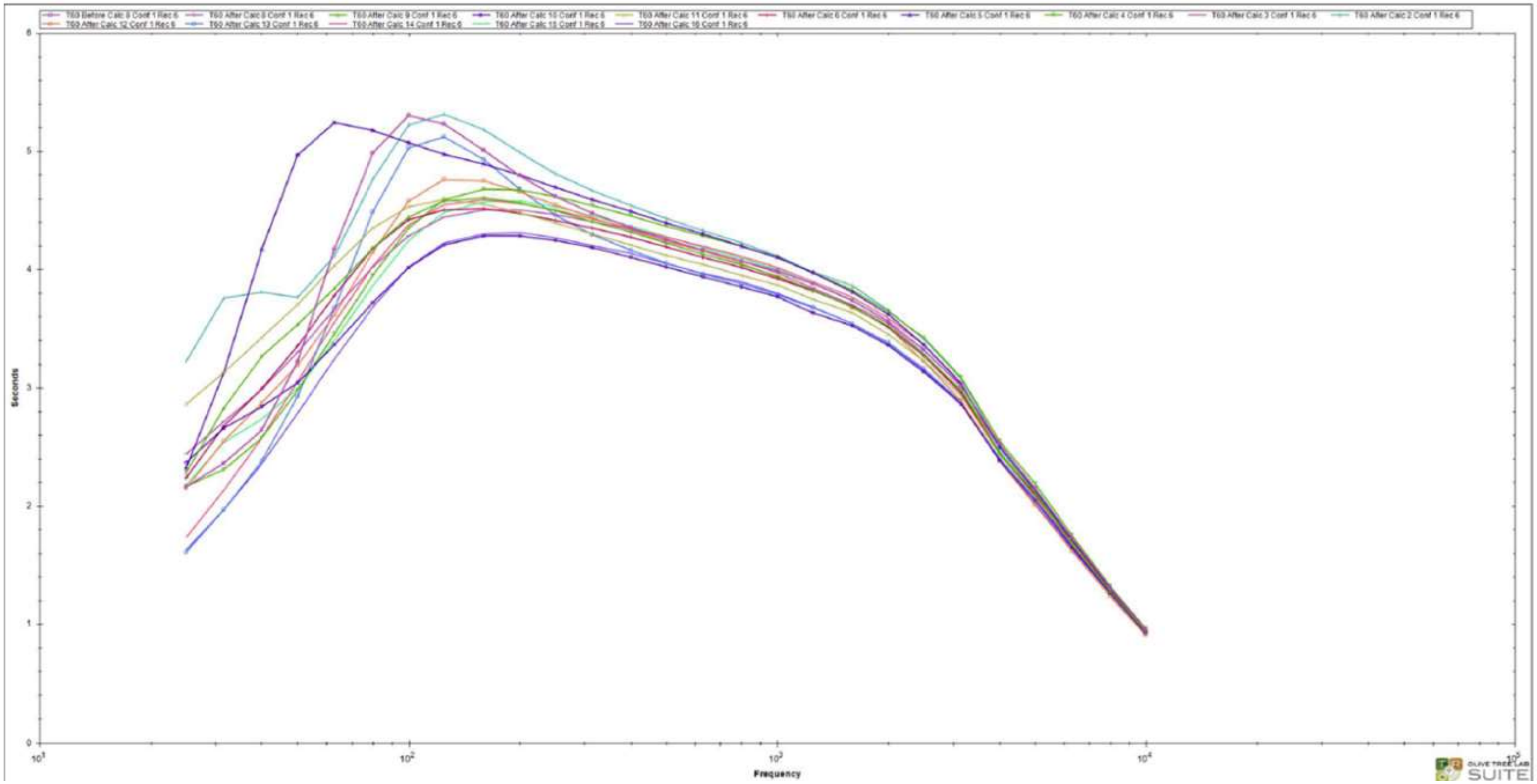

Figure 5: Results from OTL simulation of Riverbank Room Zero, showing individual responses for each source/receiver configuration. Results are very close to what was experimentally observed, with a strong convergence towards higher frequencies.

Now, what is interesting to look at in regards to the Schroeder Frequency is the amount of standard deviation observed in the results at each band. One would expect to see substantially less deviation of results above the Schroeder Cutoff frequency, as opposed to below it. See figure 4 below.

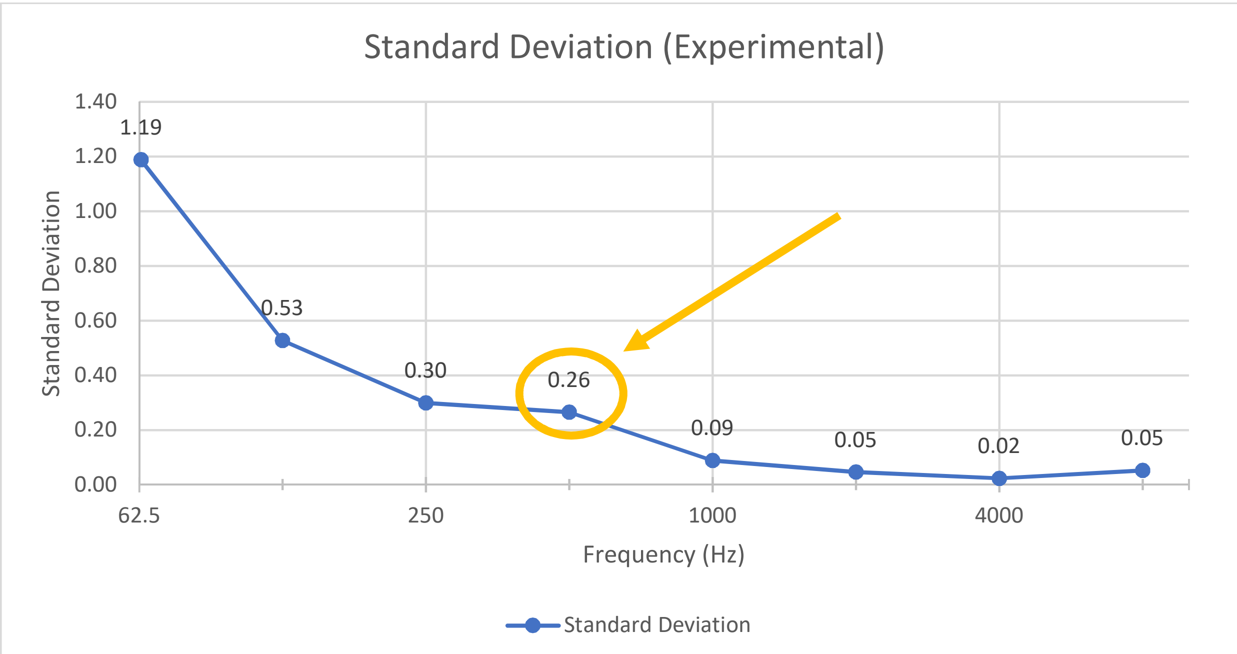

Figure 6: Standard deviations of each octave band reverb time. A standard deviation of 0.3 corresponds to an uncertainty of 0.3 seconds for the 250Hz octave band.

While most of the data is as expected, it is of particular interest the results in the 500Hz octave band. By definition, the 500Hz octave band would encompass all frequencies from 355Hz to 710Hz, and yet the standard deviation is only marginally lower than the 250Hz octave band. This is of particular interest as both the older version of the Schroeder Frequency and the proposed revision of the frequency lie approximately in the very middle of the 250Hz band, (242Hz and 254Hz, respectively). Ultimately this raises many questions regarding the applicability of the Schroeder Frequency to smaller spaces. Perhaps a greater amount of modal overlap, rather than the current 3x modal overlap, should be used to assess smaller spaces? For example, if one were to use Schroeder's unrevised equation from his 1954 paper, accounting for a 10x modal overlap, a Schroeder Frequency of approximately 625Hz would result. As can be observed in figure 4, this would seem a reasonable number, as the standard deviation is much lower in the 1kHz band and beyond as compared to the 500Hz band.

Modal mapping from OTL shows a similar picture, with significant ripples and modal spacing evident up to the 630Hz Octave band. See figures six, seven, eight, and nine below.

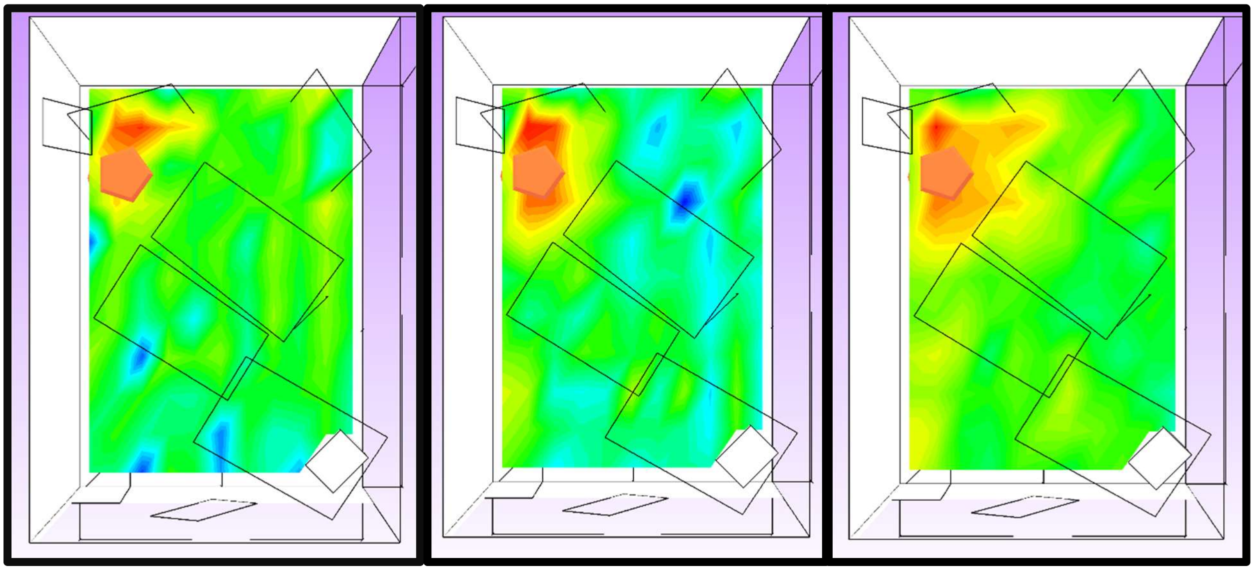

Figure 7: From left to right, the 200Hz, 250Hz, and 315Hz modal mappings that OTL generated for source 3. Blue color indicates areas of less amplitude, while red and yellow indicate areas of stronger amplitude.

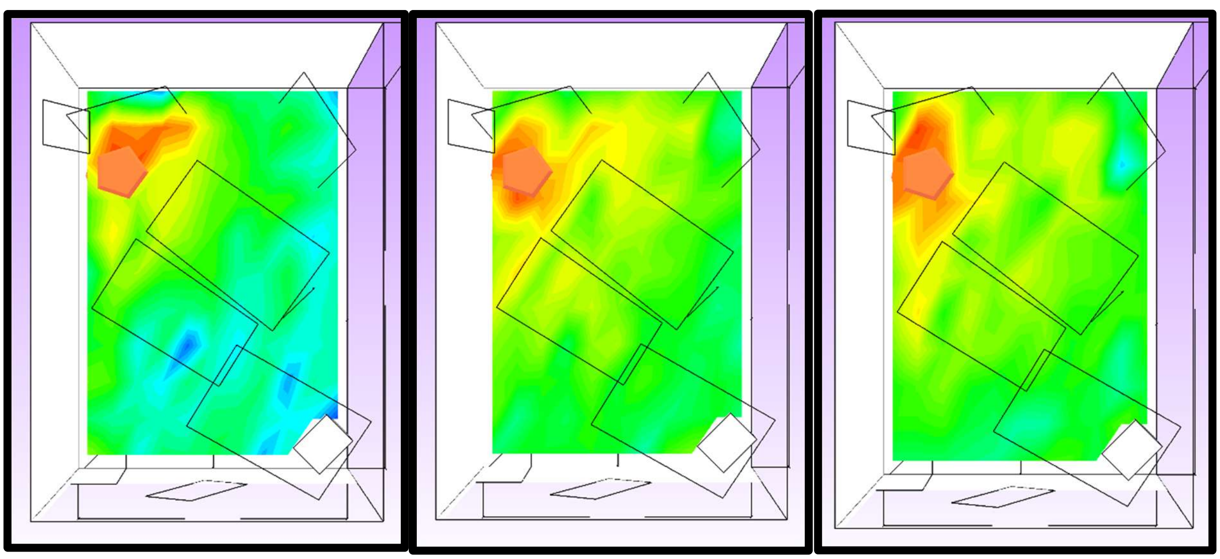

Figure 8: From left to right, the 400Hz, 500Hz, and 630Hz modal mappings generated by OTL. Significant presence of antinodes is evident in the 400Hz band, while less modes are present at 500Hz and 630Hz.

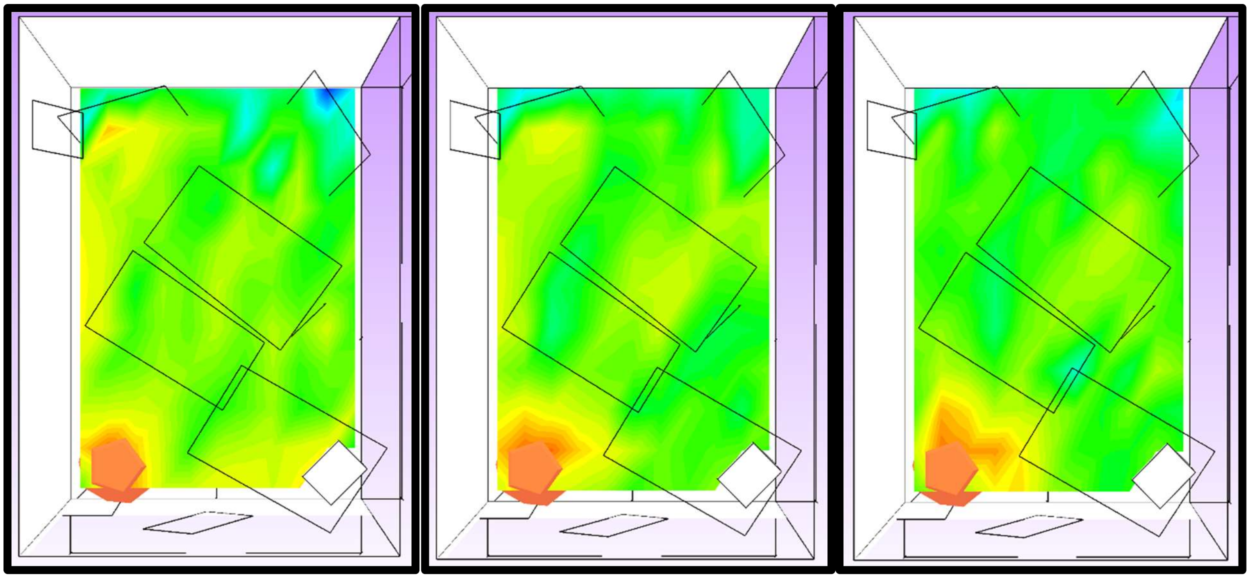

Figure 9: From left to right, the 200Hz, 250Hz, and 315 Hz modal mappings generated by OTL for source location 2.

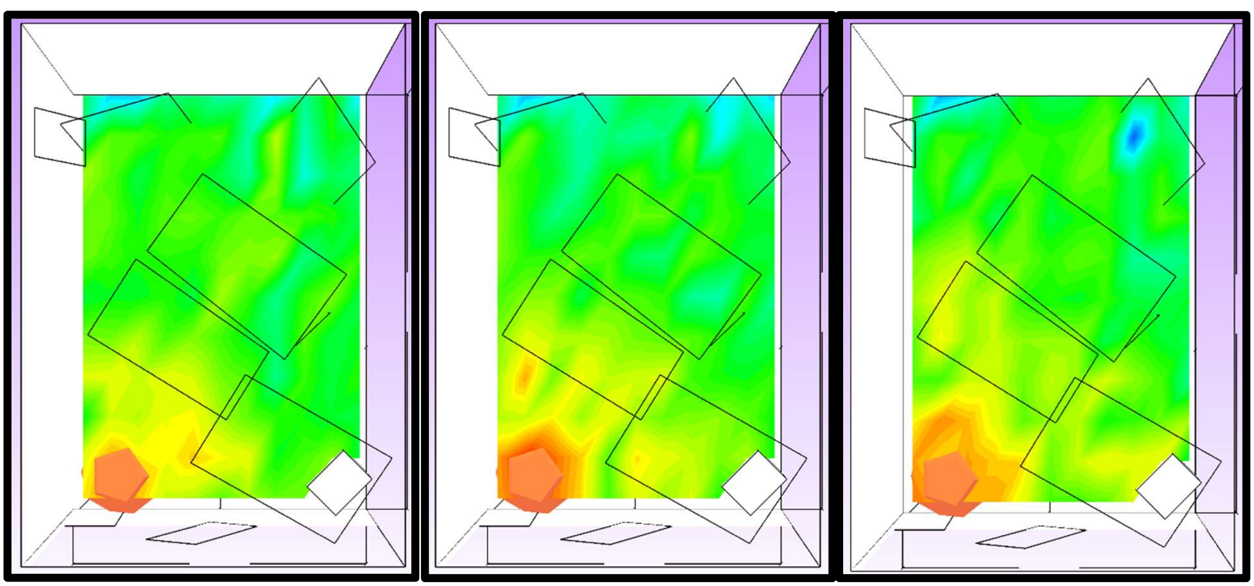

Figure 10: From left to right, the 400Hz, 500Hz, and 630Hz modal mappings generated by OTL for source location two.

V. Conclusions

The previous work has shown that use of the Schroeder Cutoff Frequency in small rooms should be exercised with some degree of caution, as it this use challenges some of the fundamental theory behind Schroeder's equation. It is important to note the underlying condition for Schroeder's theory of a diffuse, isotropic reverberant field. This condition is perhaps never perfectly met, but it is much more difficult to achieve in a small room than in a building as large as a concert hall. Also of concern, and perhaps debate, is whether or not the decay measured in a small room then qualifies as reverberation. This brings to attention the lack of proper vocabularly for describing small rooms acoustically, as the author's research did not yield even a clear consensus on the definition of reverberation from multiple sources. Summarily, the argument is made that some effort should be made to define a difference between reverberation, and a measurable decay that can perhaps often give a sense of reverberance.

With regards to the previous paragraph, a new metric is needed if there is a desire to define a lower limit to high frequency theory in small rooms. It simply does not suffice to apply the Schroeder Cutoff Frequency in a 'magic number' manner, as this often ignores the underlying assumptions of Schroeder's theory.

There may also be some desire to explore reintroducing the room spacing index into Schroeder's equation, as this has been shown to theoretically represent a potential 26% decrease and 29% increase to the Schroeder Frequency for a particular room.

VI. Acknowledgements

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