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Design Study of Sonic Crystal Technology as An Iconic Noise Mitigation Barrier in the Environment of Santa Maria Fatima Church in Magelang

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Abstract

Sacred buildings hold different significance for people based on their religious or spiritual beliefs. Many individuals use such buildings for personal or communal prayer, worship, and religious ceremonies. Silence is crucial in creating a peaceful environment that fosters introspection and spiritual connection. However, in recent years, the use of technology has become ubiquitous and has brought about concerns regarding noise pollution, especially from traffic. This has led to the development of new technologies, such as sonic crystals, proposed for use as acoustic barriers to mitigate this problem. Sonic crystals are structures that can manipulate sound waves, like how regular crystals manipulate light waves. They have unique acoustic properties that make them useful in various applications, such as noise reduction and filtering. However, sonic crystals require sufficient space for installation, and conventionally, the arrangement of sonic crystals are unappealing. This is a challenge for architects to incorporate aesthetically pleasing sonic crystals into the eco-design of sacred buildings without compromising on their values while providing a noise-free environment. Therefore, this paper aims to comprehensively examine the efficacy of Sonic Crystals as a noise attenuation method around sacred buildings, focusing on barrier designs that can also represent church values by using literature review, analysis, and simulation.

Keywords: Sonic Crystal, Noise Barrier, Icon

1. Introduction

The Santa Maria Fatima Church in Magelang faces a pressing issue of environmental noise that disrupts the comfort of its congregation during worship. The dominant source of noise originates from vehicular traffic, particularly from Ahmad Yani Street, a major arterial road traversing Magelang City and serving as a crucial transportation route for the local community. This noise disturbance can disrupt worship and congregation's concentration, calling for an effective solution. Possible remedies for this issue include closing all openings in the building or applying sound insulation treatments. However, these options may result in limited natural ventilation, which contradicts the church's concept of utilizing natural airflow. Another challenge arises from the church's limited visibility, as fast-moving vehicles make it difficult to identify the church's location due to the absence of a strong landmark. Thus, an eye-catching church icon is needed to serve as a recognizable symbol, elevating the values embedded within the church itself.

One potential solution to address these challenges is the implementation of a noise barrier at the building's transition area with the main road. To reinforce its effectiveness and visual appeal, an iconic object to represent the church is necessary. In this particular case, sonic crystals are effective elements for noise reduction while also serving as an iconic feature for churches [1]. Moreover, the availability of land for placing these elements makes it a feasible option.

The design study of barriers using Sonic Crystal technology aims to identify the optimal placement patterns to serve as both barriers and icons. This study involves testing the performance of various alternative barriers based on effectiveness, aesthetics, and cost criteria. The best alternatives will then be compared with traditional noise barriers without sonic crystals to assess the impact of these elements effectively. The results from this study of barriers using Sonic Crystal technology will offer effective and eye-catching design options for future architectural considerations. It will provide valuable insights for designing noise barriers that not only mitigate noise pollution but also create an iconic symbol for the Santa Maria Fatima Church, elevating its visual appeal and architectural significance.

2. Research Methods

2.1 Measurement of existing noise data

Noise level measurements will be conducted at critical locations, specifically the area in front of the church and inside the church premises. These measurements will follow the guidelines outlined in KEPMENLH No.48/MenLH/11/1996 [2] for noise assessment.

1) Measurement setup

Figure 1. Measurement point placement.

- The data collection was conducted on Sunday, March 26, 2023, at 08:10 WIB, during the weekly mass schedule. A Phonic PAA3 device was mounted on a tripod with a height of 1.2 meters and positioned at a predetermined location. facing towards the road area as the primary source of noise.
- The Phonic PAA3 was configured with a noise range setting of 30-90 dB, and a response time of 35 ms. Data from the Phonic PAA3 were recorded by taking screenshots from a connected laptop.
- Screenshots were captured every 5 seconds continuously for a duration of 10 minutes, resulting in the acquisition of 120 data points during a single experiment.

2) Measurement results

At Point A, the recorded noise levels ranged from a minimum of 49.9 dB to a maximum of 85.7 dB, with an overall Laeq value of 69.0 dB. The dominant frequency at this location was found to be in the range of 400-2000 Hz. At Point B, the noise levels ranged from a minimum of 41.7 dB to a maximum of 61.6 dB, resulting in an Laeq value of 49.6 dB. The dominant frequency at this point was identified in the range of 8k-16k Hz.

The measurements show that the Church has a problem with noise reduction, as the recorded noise levels exceed the recommended standard of 55 dB set in KEPMENLH No.48/MenLH/11/1996. The dominant frequencies detected also indicate that the Church struggles to reduce noise effectively in the higher frequency ranges.

2.2 Sonic Crystal unit model search

To enhance the effectiveness of the Sonic Crystal model, we employed the precedent specifications of the Sonic Crystal unit, with slight modifications to the absorption material by incorporating coconut fibers, in response to the availability of local materials.

Specifications of the Sonic Crystal:

- Casing, perforated metal with a thickness of 3mm and a diameter of 20cm
- Inner casing, iron plate with a thickness of 3mm and a diameter of 10cm
- Filler, composite of coconut fibers

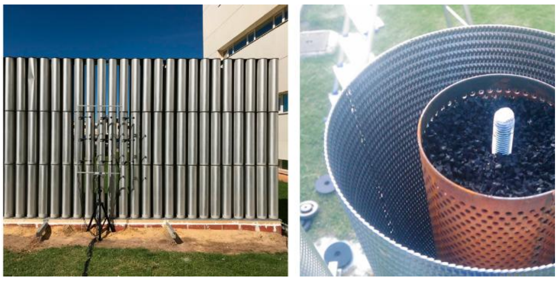


Figure 2. (a) SC appearance; (b) SC section.

Research data by Saggita [3], shows the absorption coefficient data of the coconut fiber composite with 1.25cm thickness as follows: 0.80 (500 Hz), 0.78 (1k Hz), 0.81 (2k Hz), By using this data as a reference, it is assumed that the composite's coefficient at other frequencies can be estimated using percentage-based calculations of coefficient addition/reduction with materials having similar characteristics.

TABLE I. ASSUMED VALUE OF SOUND ABSORPTION COEFFICIENT OF COCONUT FIBER COMPOSITE

Material	Frequency (Hz)					
	125	*250*	*500*	*1k*	*2k*	*4k*
Rockwool 50mm, 80 kg/m3	0.22	0.60	0.92	0.90	0.88	0.88
addition	-	*+172%*	*+53%*	*-2%*	*-2%*	-
Coconut fiber composite (assumed)	**0.19**	**0.52**	0.80	0.78	0.81	**0.81**

The exploration of sonic crystal arrangement patterns is approached through the lens of church icon criteria, aiming to discover forms that embody a strong conceptual alignment with its spiritual value and architectural locality.

Spiritual Value

The Cross symbolizes the suffering, death, and resurrection of Jesus Christ, as well as the atonement of sins and the salvation of humanity, representing the identity of the building as a place of Catholic worship.

Local Value

The temple's architectural form, with its wide base and body, reflects the proportions and grandeur of Borobudur Temple, a UNESCO World Heritage site, representing the architectural identity of Magelang.

Design guideline

The combination of the cross and temple icons represents Catholic values and local heritage, while also symbolizing interfaith harmony. The background is added to enhance the effectiveness of the sonic crystals.

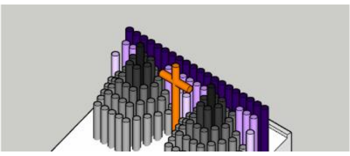


Figure 3. Basic Arrangement scheme of sonic crystals.

The combination of the cross and temple icons represents Catholic values and local heritage, while also symbolizing interfaith harmony. The background is added to enhance the effectiveness of the sonic crystals.

2.3 Design Alternatives

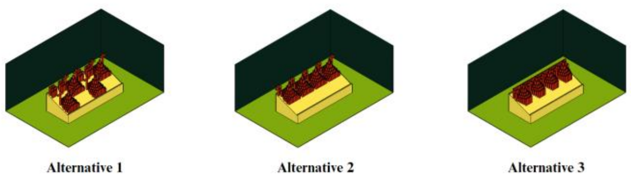


Figure 4. 3 Alternative designs based on the design guideline.

Utilizing AHP as a quantitative method for selecting the best solution among multiple options based on various criteria, it helps assess the effectiveness of diverse sonic crystal arrangements by weighing the importance of each factor and comparing their relative values:

• Effectiveness, with the primary research goal being noise reduction (5 points).

• Aesthetics, evaluating how well the arrangement of the SC can clearly represent church values (3 points).

• Cost, assessing the investment value of the sonic crystal construction (2 points)

Star Rating System for Each Alternative

To facilitate the assessment, each alternative design can be rated using a star system for each criterion. These star ratings are then multiplied by the respective weights to determine the overall score for each design.

Steps to Implement the Star Rating System:

Assign Star Ratings to Alternatives:

Each alternative design is rated on a scale of 1 to 3 stars for each criterion based on its performance.

Convert Stars to Numerical Values:

Each star corresponds to a numerical value (e.g., 1 star = 1 point, 3 stars = 3 points).

Multiply by Weights:

The star rating for each criterion is multiplied by its respective weight:

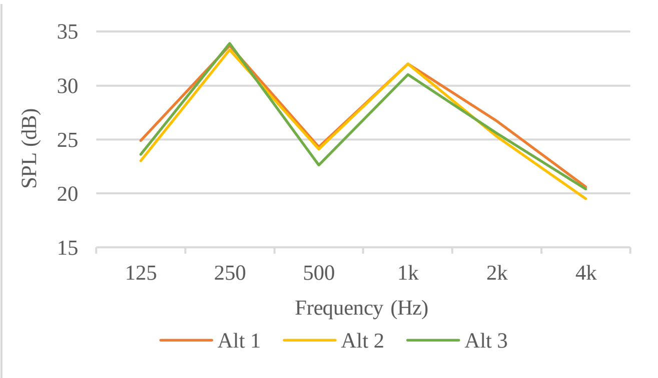
• Effectiveness: Star rating * 5
• Aesthetics: Star rating * 3
• Cost: Star rating * 2

Calculate the Total Score:

Sum the weighted values for each alternative to get a total score.

1) Effectiveness

The analysis is conducted using a method based solely on SC barrier simulation results



Graph 1. The data above represents the SPL (Sound Pressure Level) received by the receiver. A smaller SPL value indicates a more effective alternative sonic crystal configuration.

In the context of a church, frequencies between 500 Hz and 1000 Hz are important to ensure that messages, teachings, and hymns can be clearly understood by the congregation [4].

- Alternative 1 *(1 star)*

It is only effective at reducing noise at the 250 Hz frequency; for other frequencies, it is less effective.

- Alternative 2 *(2 stars)*

It is highly effective at reducing noise across the entire frequency range, but it is not effective at reducing noise in the 500-1000 Hz frequency range.

- Alternative 3 *(3 stars)*

It tends to reduce noise overall effectively, with the highest efficiency in reducing noise in the 500-1000 Hz frequency range (most important in church context).

2) Aesthetics

Aesthetics are evaluated based on comments from 10 respondents as a simple assessment method, and conclusions are drawn from their feedback.

- Alternative 1 *(1 star)*

Asymmetric shape, unclear arrangement, and ambiguous hierarchy of elements, with the cross-shaped columns giving a visual resemblance to graves.

- Alternative 2 *(2 stars)*

The background appearance appears more dynamic with the height variations in SC. However, the positioning of the cross in the background makes the visual representation of the cross as a church symbol less clear. The front arrangement looks rigid.

- Alternative 3 *(3 stars)*

The front arrangement appears dynamic, compact, and effectively represents the church's values (cross and temple) with suitable proportions. The background provides clarity regarding the use of SC technology but may make the design appear busy.

3) Cost

Cost considerations are assumed to be based on the volume calculation of the Sonic Crystal. Volume = L x t, Using the formula $L = \pi \times r^2$, with the same L for each alternative, volume comparison can be done by comparing the height of the SC.

- Alternative 1 *(1 star)*

Total height = 360,4 meters

- Alternative 2 *(3 stars)*

Total height = 323,3 meters

- Alternative 3 *(2 stars)*

Total height = 354,3 meters

From the sum of points for each criterion, following the established hierarchy of criteria, the following results were obtained:

Alternative 1 1x5 + 1x3 + 1x2 = 10 points

Alternative 2 2x5 + 2x3 + 3x2 = 22 points

Alternative 3 3x5 + 3x3 + 2x2 = 28 points

So, it can be concluded that alternative 3 is the best alternative overall, considering various aspects of the assessment criteria.

2.4 Proposed Design

1) Shape

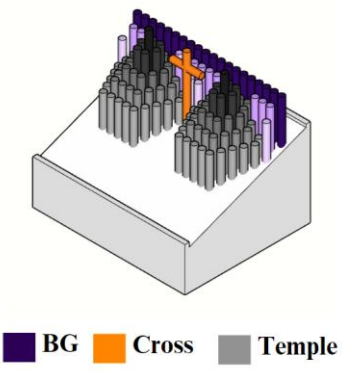


Figure 5. Shape of Sonic Crystals Arrangement.

The combination of the cross and temple icons serves as a representation of Catholic values and local culture, simultaneously depicting interfaith harmony. The background is utilized to enhance the SC effectiveness

2) Pattern

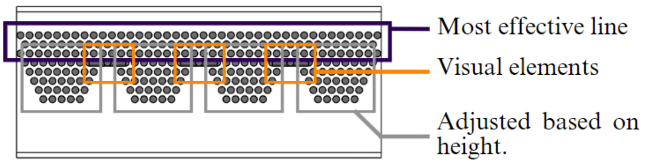


Figure 6. Pattern of Sonic Crystals Arrangement.

3) Meaning of the number of temples

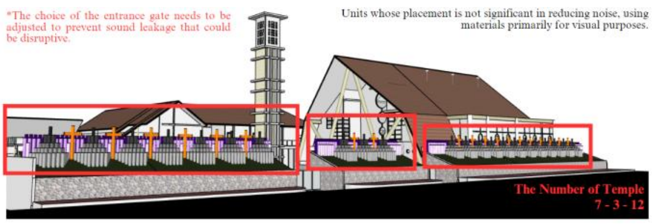


Figure 7. Number of temples.

The number 7 holds the meaning of perfection and is interpreted as the seven Catholic Sacraments.

The number 3 carries the meaning of the concept of the Holy Trinity, which represents Father, Son, and Holy Spirit.

The number 12 also represents structural completeness, like the 12 Apostles chosen by Jesus and the 12 stars on the crown of the Virgin Mary.

4) Preliminary Design Illustration

Figure 8. Front View.

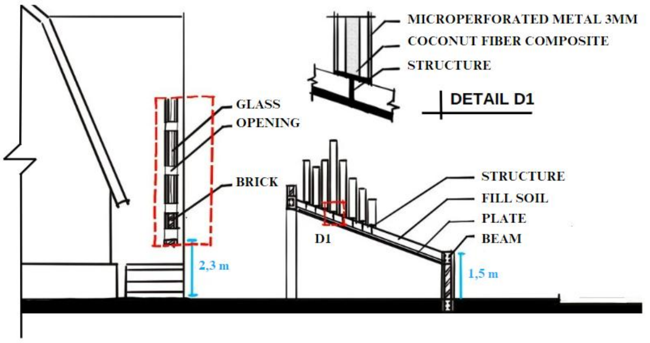


Figure 9. Schematic Section.

2.5 Proposed Design Simulation

1) Materials Absorbtion Coefficient

TABLE II. SOUND ABSORPTION COEFFICIENTS OF COMMON BUILDING MATERIALS

Material	Frequency (Hz)					
	125	*250*	*500*	*1k*	*2k*	*4k*
Asphalt	0.02	0.03	0.03	0.03	0.04	0.07
Free Air	0.99	0.99	0.99	0.99	0.99	0.99
Coconut fiber composite (Sonic Crystals)	0,19	0,52	0,80	0,78	0,81	0,81
Walls, hard surfaces average (brick walls, plaster, hard floors, etc.)	0.02	0.02	0.03	0.03	0.04	0.05
Glass window, 0.68 kg/m2	0.10	0.05	0.04	0.03	0.03	0.03
Grass	0.50	0.43	0.37	0.38	0.44	0.52

The data is derived from assumption-based calculations and journal sources [3][5].

2) Source and Receiver Placement

• Source

Placed at the midpoint of the road surface with a height of 1m (assuming the height of the sound source in vehicles), directed straight towards the receiver.

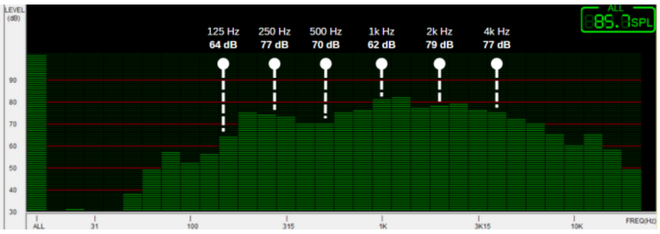


Figure 10. The data represents noise measurements in the church area.

The noise source data was extracted from the highest sample during the site noise data collection using the Phonic PAA3 hardware, resulting in values:

TABLE III. NOISE SOURCE DATA

Frequency (Hz)	*125*	*250*	*500*	*1k*	*2k*	*4k*
SPL (dB)	64	77	70	82	79	77

• Receiver

Placed 1 meter from the church building, assuming the noise experienced by the congregation walking around the church. The receiver's height is set at 2.3 meters (the height of the eaves on the church building).

3) Results

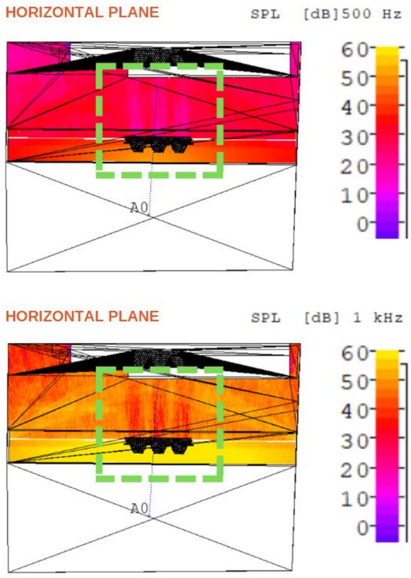


Figure 11. Sound distribution map for 500 Hz and 1 kHz frequencies on a horizontal plane (1 meter above ground level).

On the horizontal plane, after the sound passes through the barrier, there is a noticeable color difference between the barrier with sonic crystals and the barrier without sonic crystals. The color difference reaches 10 to 15 dB. However, we can observe gaps between the sonic crystals (between the temples) that are still ineffective in reducing noise.

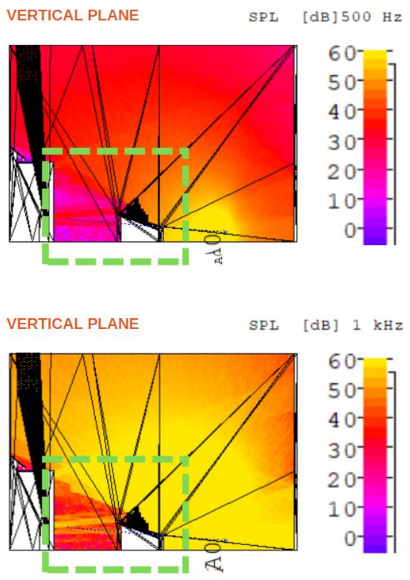


Figure 12. Sound distribution map for 500 Hz and 1 kHz frequencies on a vertical plane parallel to the line from the sound source to the receiver.

On the vertical plane intersecting the temple, it can be seen that the sound is reduced after passing through the barrier and sonic crystals. Additionally, there are line-shaped areas where sound energy is still less effectively absorbed.

The simulation results show the noise levels received by the listener as follows:

TABLE IV. SPL RECEIVED BY THE LISTENER

Frequency (Hz)	***125***	***250***	***500***	***1k***	***2k***	***4k***
SPL (dB)	35	47	37	51	48	42

Based on the data above, we can conclude that the implementation of the sonic crystal barrier effectively reduces roadway noise to the listener's level. It is evident that the noise levels reaching the receiver at each tested frequency consistently remain below 55 dB, in accordance with the established standard [6]. We can observe a relatively constant reduction of approximately 30 dB across all tested frequencies.

I. Conclusion

The study of implementing sonic crystal barriers at the Santa Maria Fatima Church in Magelang demonstrates significant advancements in noise reduction technology. Through detailed analysis and simulations, it is evident that these barriers effectively mitigate noise from vehicular traffic, ensuring that the noise levels received by listeners consistently remain below the 55 dB threshold, in accordance with established standards. This reduction is relatively constant at approximately 30 dB across all tested frequencies.

The chosen design, Alternative 3, was selected based on its superior performance in reducing noise, particularly within the critical frequency range of 500-1000 Hz, essential for clear communication during church services. Furthermore, this alternative successfully integrates aesthetically pleasing elements that symbolize the church's values and local heritage, making it a practical and visually appealing solution. This research underscores the potential of sonic crystals not only as an effective noise attenuation method but also as a means to enhance the architectural and spiritual significance of sacred buildings. Future applications could explore similar integrations in other noise-sensitive environments, offering both functional and symbolic benefits.

II. Appendix

1) *Cost Calculation*

Alternative 1

TEMPLE

0,4 x 6 = 2,4
0,5 x 6 = 3,0
0,6 x 2 = 1,2
0,7 x 2 = 1,4
0,8 x 2 = 1,6
0,9 x 10 = 9,0
1,0 x 10 = 10,0

1,1 x 12 = 13,2
1,2 x 4 = 4,8
1,3 x 8 = 10,4
1,6 x 2 = 3,2
1,7 x 4 = 6,8
2,1 x 1 = 2,1
1 Unit = 69,1

CROSS

1 unit = 2,3 + 1

BACKGROUND

1,1 x 4 = 4,4
1,2 x 4 = 4,8
1,3 x 4 = 5,2
1 unit = 14,4

4 Temples = 276,4

8 crosses = 26,4

4 backgrounds = 57,6

Totals = 360,4

Alternative 2

TEMPLE

0,4 x 6 = 2,4
0,5 x 6 = 3,0
0,6 x 2 = 1,2
0,7 x 2 = 1,4
0,8 x 2 = 1,6
0,9 x 10 = 9,0
1,0 x 10 = 10,0

1,1 x 12 = 13,2
1,2 x 4 = 4,8
1,3 x 8 = 10,4
1,6 x 2 = 3,2
1,7 x 4 = 6,8
2,1 x 1 = 2,1
1 Unit = 69,1

CROSS

1 Unit = 2,3 + 1

BACKGROUND

0,9 x 4 = 3,6
1,0 x 4 = 4,0
1 Unit = 7,6

4 Temples = 276,4

5 crosses = 16,5

4 backgrounds = 30,4

Totals = 323,3

Alternative 3

TEMPLE

0,8 x 2 = 1,6
0,9 x 10 = 9,0
1,0 x 10 = 10,0
1,1 x 12 = 13,2
1,2 x 4 = 4,8

1,3 x 8 = 10,4
1,6 x 2 = 3,2
1,7 x 4 = 6,8
2,1 x 1 = 2,1

1 Unit = 61,1

CROSS

1 Unit = 2,3 + 1

BACKGROUND

1,1 x 2 = 2,2
1,3 x 6 = 7,8
1,5 x 10 = 15,0
1 Unit = 25,0

4 Temples = 244,4

3 crosses = 9,9

4 backgrounds = 100,0

Totals = 354,3

Figure 13. Details of Sonic Crystal Height Calculation as Cost Comparison Assumption for Each Alternative.

2) Design Optimization Recommendations

Based on the simulation results and literature research, to reduce costs, High-Density Polyethylene (HDPE) material is used for sonic crystal units that are considered less efficient.

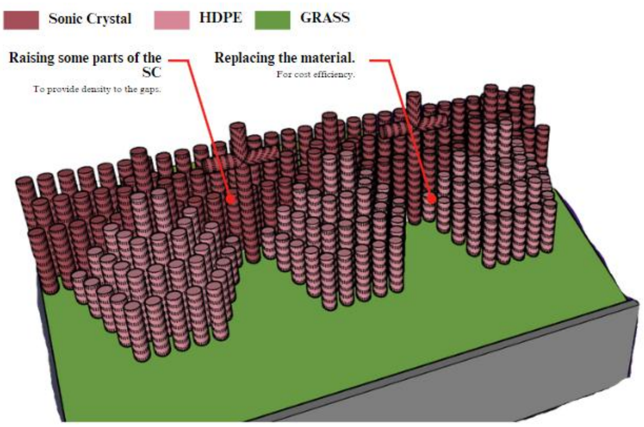


Figure 14. Material replacement for cost optimization.

Considerations for using this material include:

- Durable and long lasting
- Ressistant to corrosion
- Ease of manufacturing
- Recycleable

Simulation results:

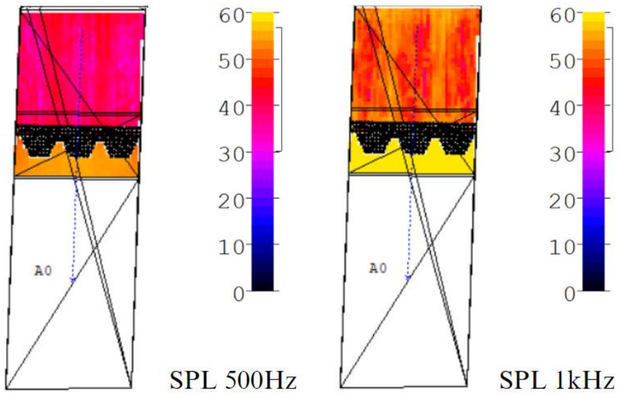


Figure 15. Simulation Results After Design Optimization.

Conclusion:

Improving the gaps in the sonic crystal configuration resulted in a more even 5 dB gap compared to the previous configuration. However, changing the material led to a 5 dB reduction in overall effectiveness compared to the previous material. This is still considered good because it meets the standards.

Acknowledgements

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