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Optimal Design of Slit Resonators for Acoustic Normal Mode Control in a Rectangular Room

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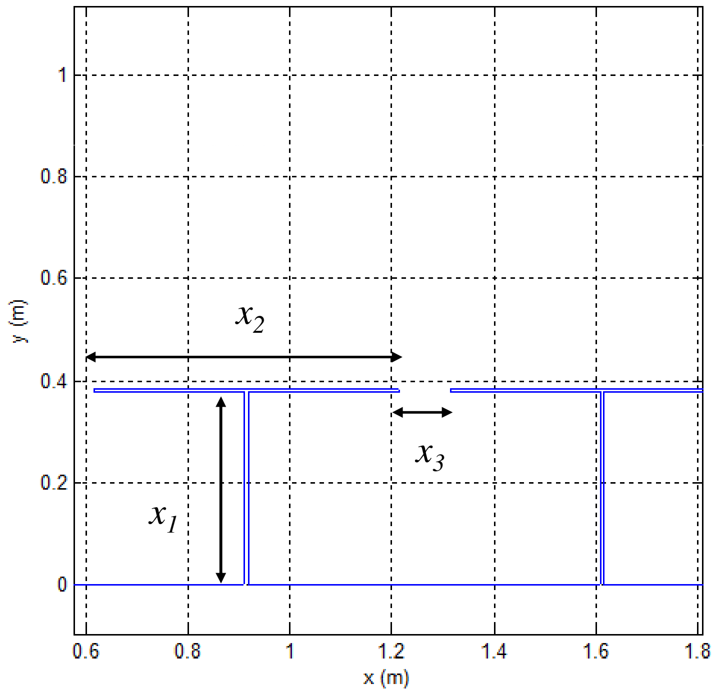
Introduction to the problem

- The sound field in a room is characterized by the interaction between the source and the acoustic properties of the room.
- The room's frequency response depends on the geometry and the materials.
- The objectives of this article are:
  - Decrease the effects of the resonances at low frequencies.
  - Distribute the normal modes of vibration using optimal slit resonators.
  - Compare optimization strategies based on decreasing the fluctuations of the sound pressure or loudness level.

Introduction to the problem

- Slit resonators are composed by a periodic structure of T-like plates. It can be described using three physical dimensions.



Dimensional characteristics of slit resonators

Introduction to the problem

- Two different optimization algorithms are considered
  - Genetic algorithm
  - Differential evolution algorithm.
- A cubical 5.1m-side enclosure with and without slit resonators is considered as a case of study.
- A point source is placed at one corner of the room. The reception point is located at the opposite corner.
- Vertically-oriented slit resonators are considered.
- The sound field is modeled for frequencies ranging from 20 Hz to 200 Hz.

Theory and Governing Equations

- The stationary solution in the frequency domain has been studied only.
- For harmonic solution, the governing equations is the Helmholtz's equation.

$$\nabla^2 P + k^2 P = 0$$

$$\nabla P \cdot \hat{n} = 0$$

$$P(x, y, z) = P_{xy}(x, y) P_z(z)$$

Formulation of the Problem and Application of the Method of Separation of Variables

$$\frac{\partial^2 P_z}{\partial z^2} + k_z^2 P_z = 0$$

$$\left(\frac{\partial P_z}{\partial z}\right)_{z=0} = \left(\frac{\partial P_z}{\partial z}\right)_{z=L_z} = 0$$

$$P_z(z) = A_{n_z} \cos(k_z z)$$

$$k_z = \frac{n_z \pi}{L_z}$$

$$n_z = 0,\ 1,\ 2,\ \cdots$$

$$\frac{\partial^2 P_{xy}}{\partial x^2} + \frac{\partial^2 P_{xy}}{\partial y^2} + k_{xy}^2 P_{xy} = 0$$

$$\nabla P_{xy} \cdot \hat{n} = 0$$

$$\mathbf{K}\boldsymbol{\varphi} = k_{xy}^2 \mathbf{M}\boldsymbol{\varphi}$$

$$\omega_{n_{xy} n_z} = c\sqrt{k_{xy}^2 + k_z^2}$$

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Formulation of the Problem and Application of the Method of Separation of Variables

- The sound pressure for any point $\vec{\mathbf{r}}$ inside the room enclosure produced by a point source located at $\vec{\mathbf{r}}_0$ of frequency ω

$$p\left(\vec{\mathbf{r}},\vec{\mathbf{r}}_0,\omega\right)=\sum_{n_{xy}}^{\infty}\sum_{n_z}^{\infty}\frac{A_{n_{xy}n_z}\left(\vec{r},\vec{r}_0,\omega\right)}{\omega^2-\omega_{n_{xy}n_z}^2}$$

$$A_{n_{xy}n_z}\left(\vec{\mathbf{r}},\vec{\mathbf{r}}_0,\omega\right)=jS_0\rho_0c^2\omega\left(\varphi_{r,n_{xy}}\cos\left(k_z z\right)\right)\left(\varphi_{r_0,n_{xy}}\cos\left(k_z z_0\right)\right)$$

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Determination of the Loudness Levels Using Neuronal Networks

- Inputs: Frequency and sound pressure level
- Output: Loudness level (the sensation that corresponds most closely to the sound intensity of a stimulus)
- A loudness model has been built from equal-loudness-level contours data using an artificial neural network:
  - Quasi Newton Back-propagation (3000 epochs and an objective goal of 10e-5)
  - Three layer feed-forward neural network: 5 hidden neurons and 1 output neuron.
  - Transfer functions: sigmoidal hyperbolic tangent (hidden layer) and linear function (output layer)

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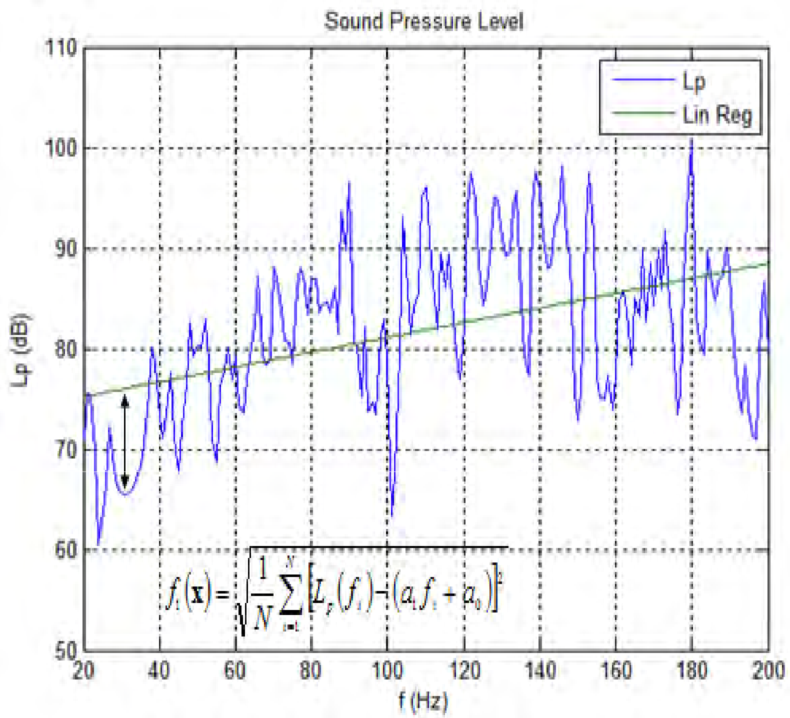
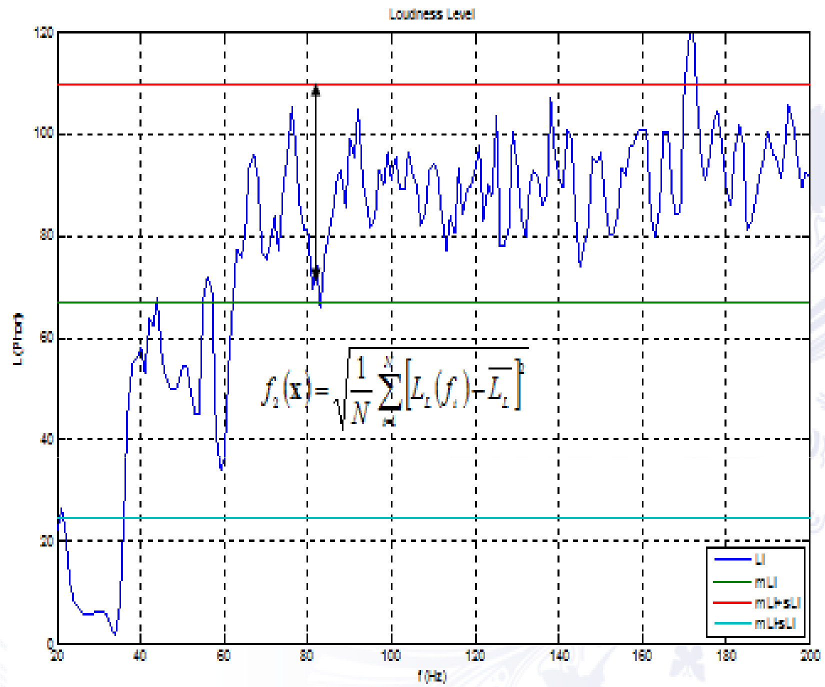
Objective Functions



SPL-based objective function



Loudness level-based objective function

$$f_1(\mathbf{x}) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[L_p(f_i) - (a_1 f_i + a_0)\right]^2}$$

$$f_2(\mathbf{x}) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[L_L(f_i) - \overline{L_L}\right]^2}$$

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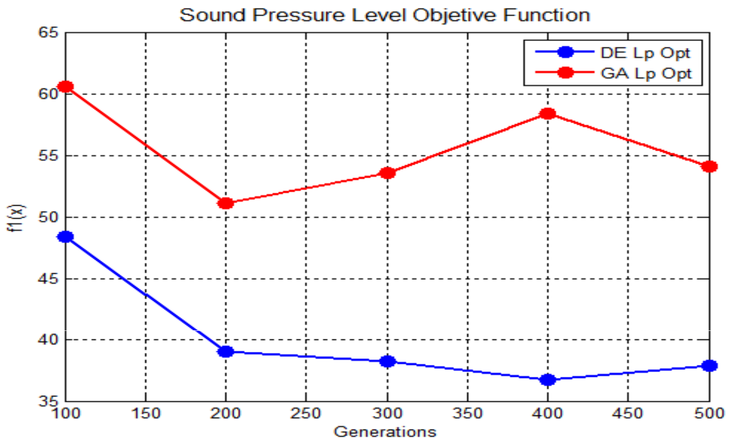
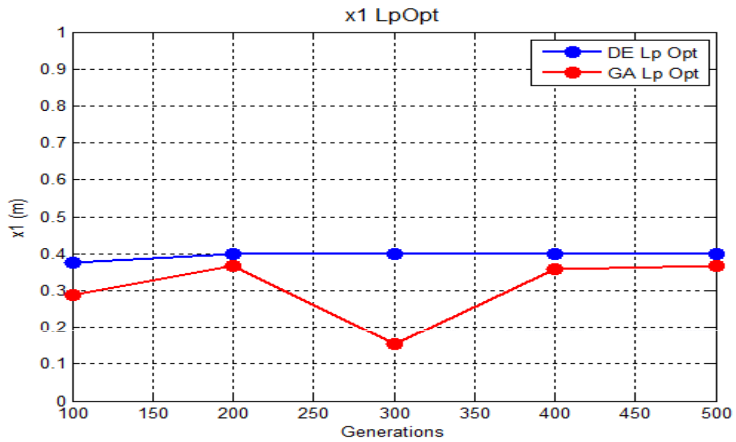
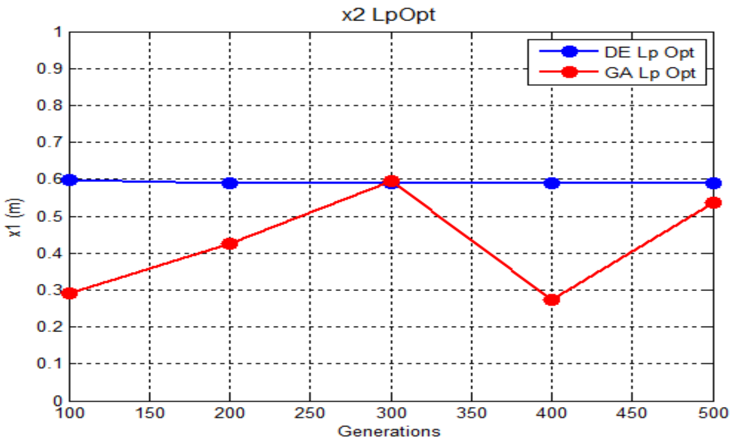
Comparison between GA and DE – optimization using SPL-based Objective Function

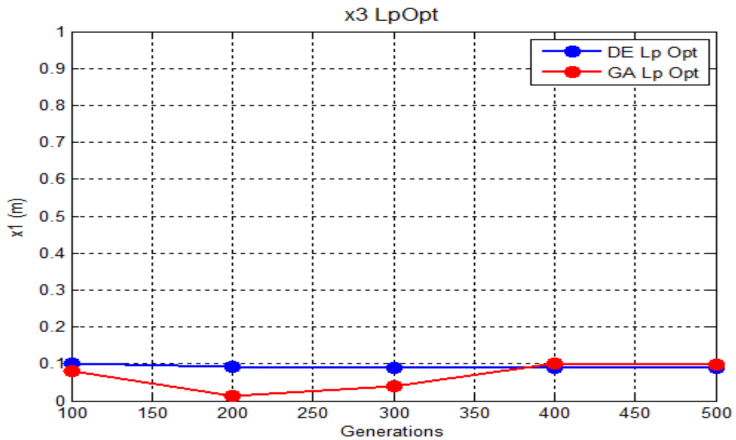




x_1

x_2





x_3

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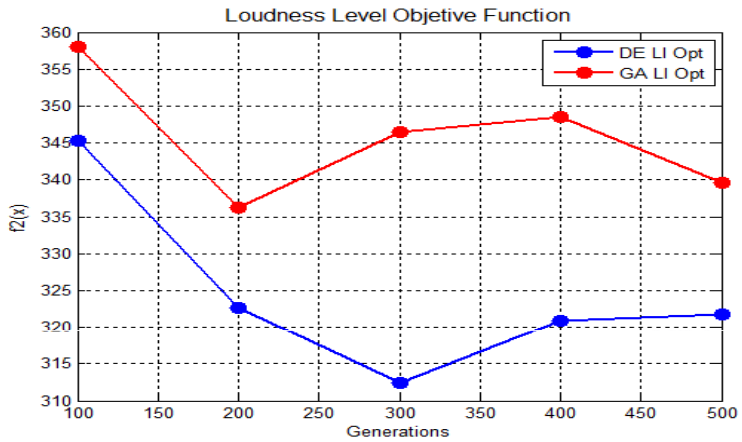
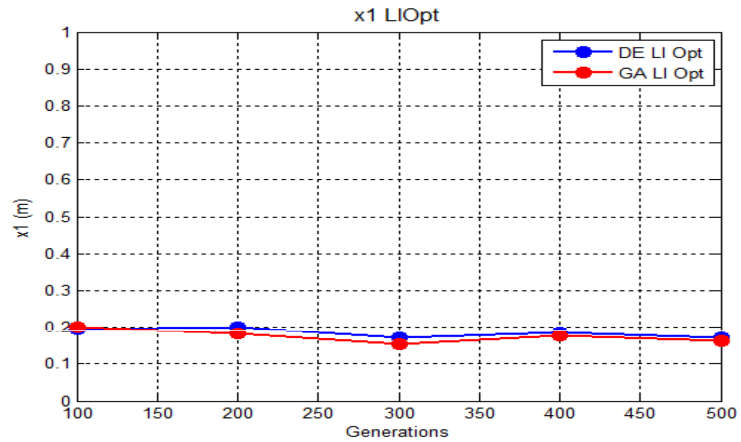
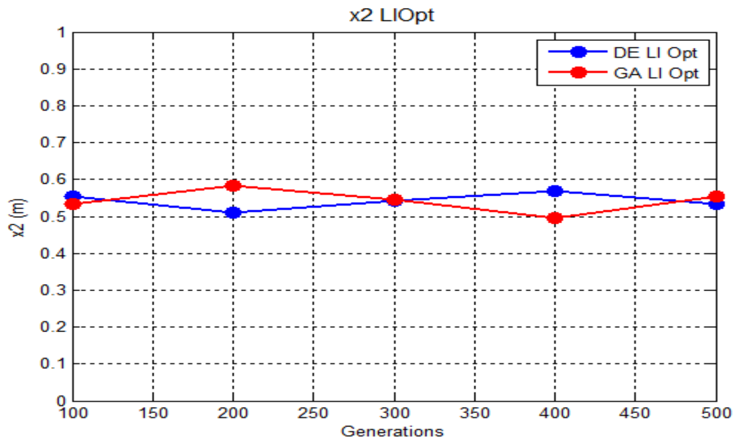
Comparison between GA and DE – optimization using Loudness Level-based Objective Function

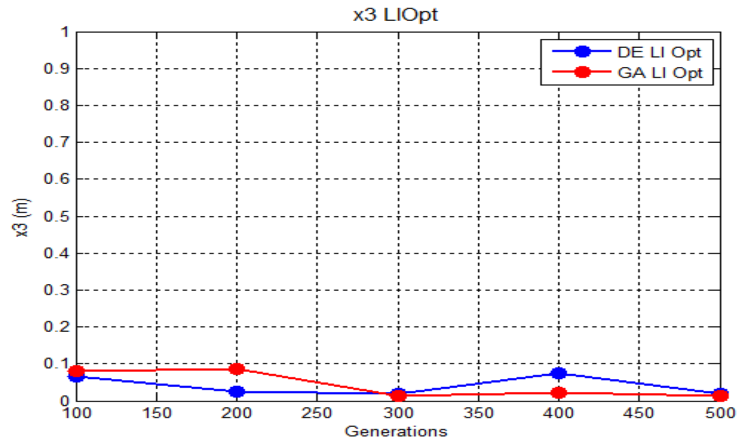




x_1

x_2





x_3

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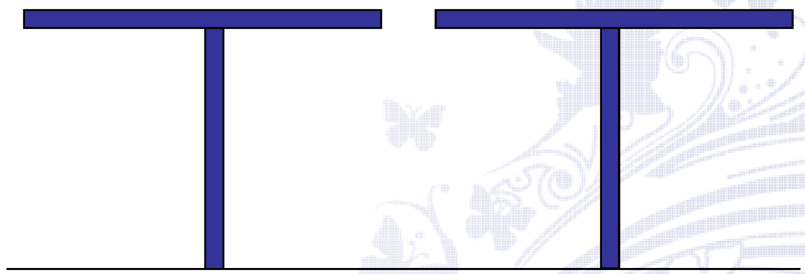
Optimal dimensions and comparison between objective functions – DE – 1000 generations

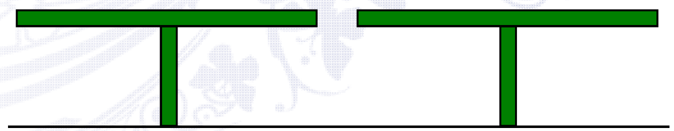
SPL-based objective function

$f_1(\mathbf{x})Opt$	x_1 (m)	x_2 (m)	x_3 (m)
37.254	0.399	0.591	0.091

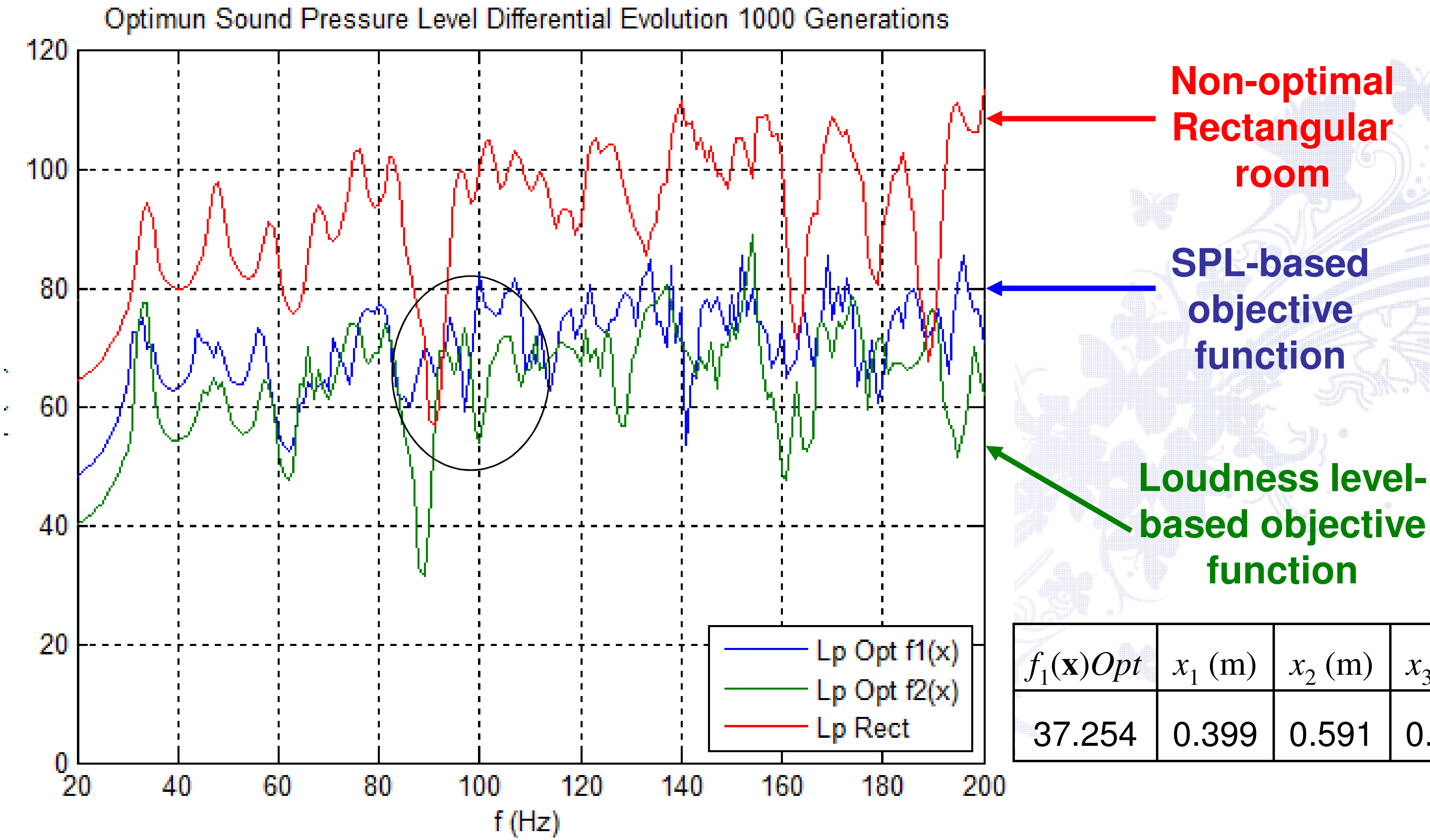


Loudness level-based objective function

$f_2(\mathbf{x})Opt$	x_1 (m)	x_2 (m)	x_3 (m)
318.960	0.189	0.567	0.078



Sound pressure level – DE – 1000 generations



$f_1(\mathbf{x})Opt$	x_1 (m)	x_2 (m)	x_3 (m)
37.254	0.399	0.591	0.091

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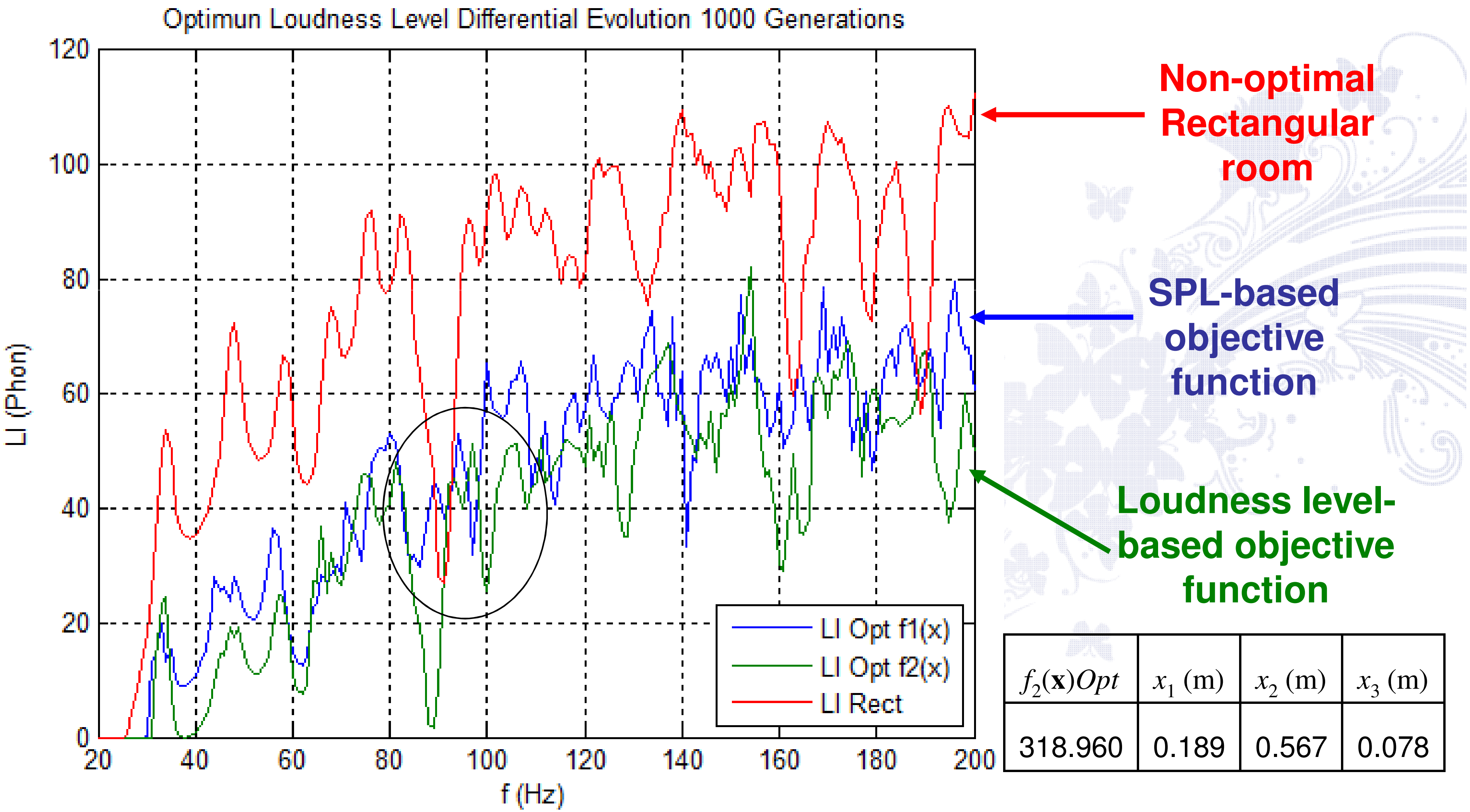
Loudness level – DE – 1000 generations



$f_2(\mathbf{x})Opt$	x_1 (m)	x_2 (m)	x_3 (m)
318.960	0.189	0.567	0.078

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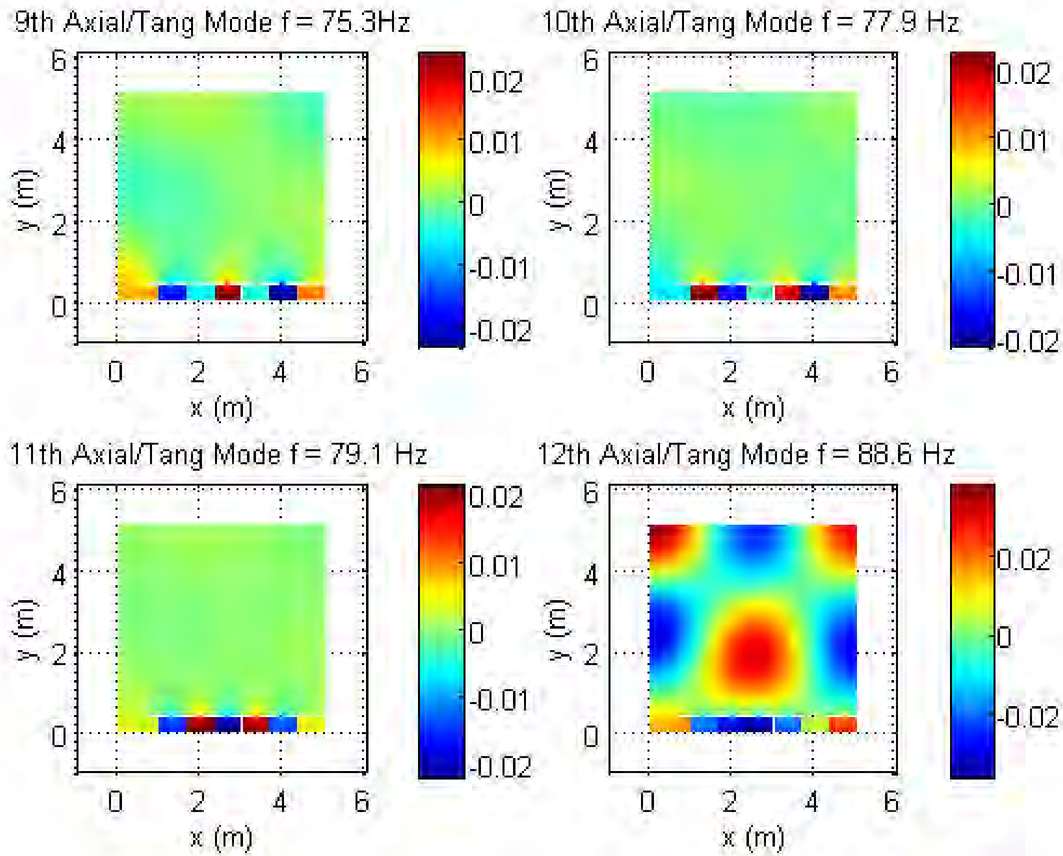
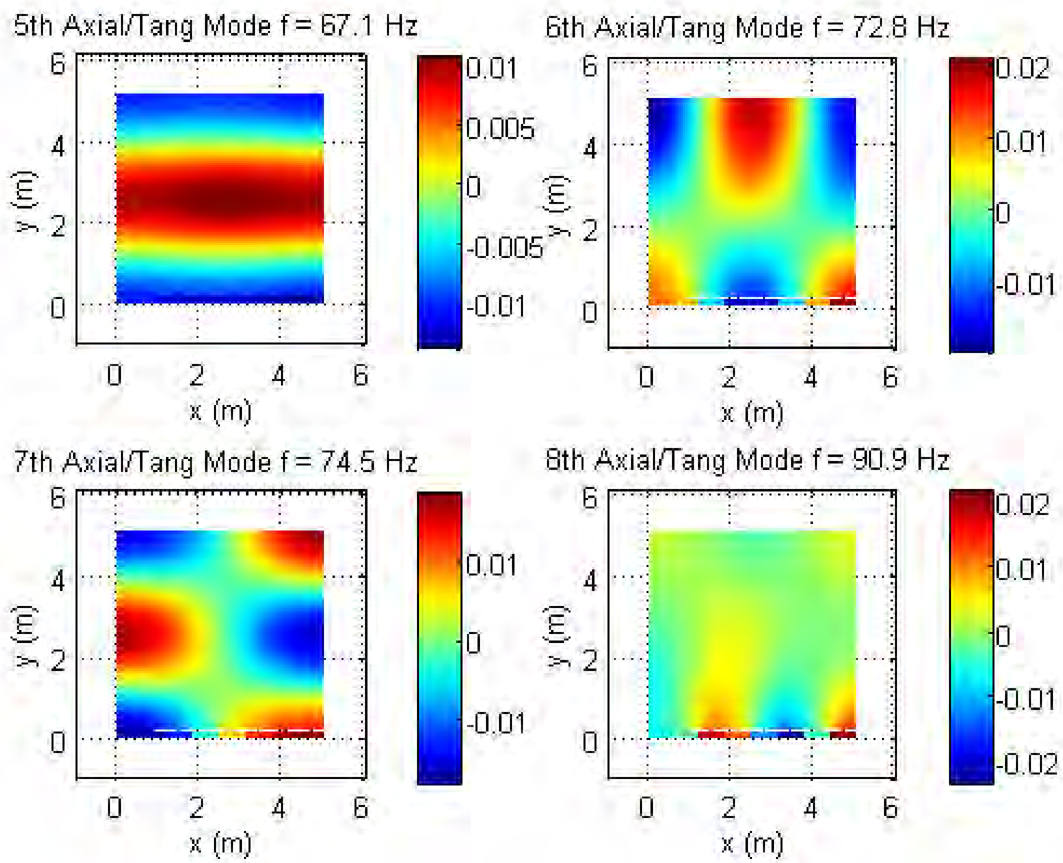
Sound pressure distribution – optimization using SPL-based objective function – DE – 1000 generations



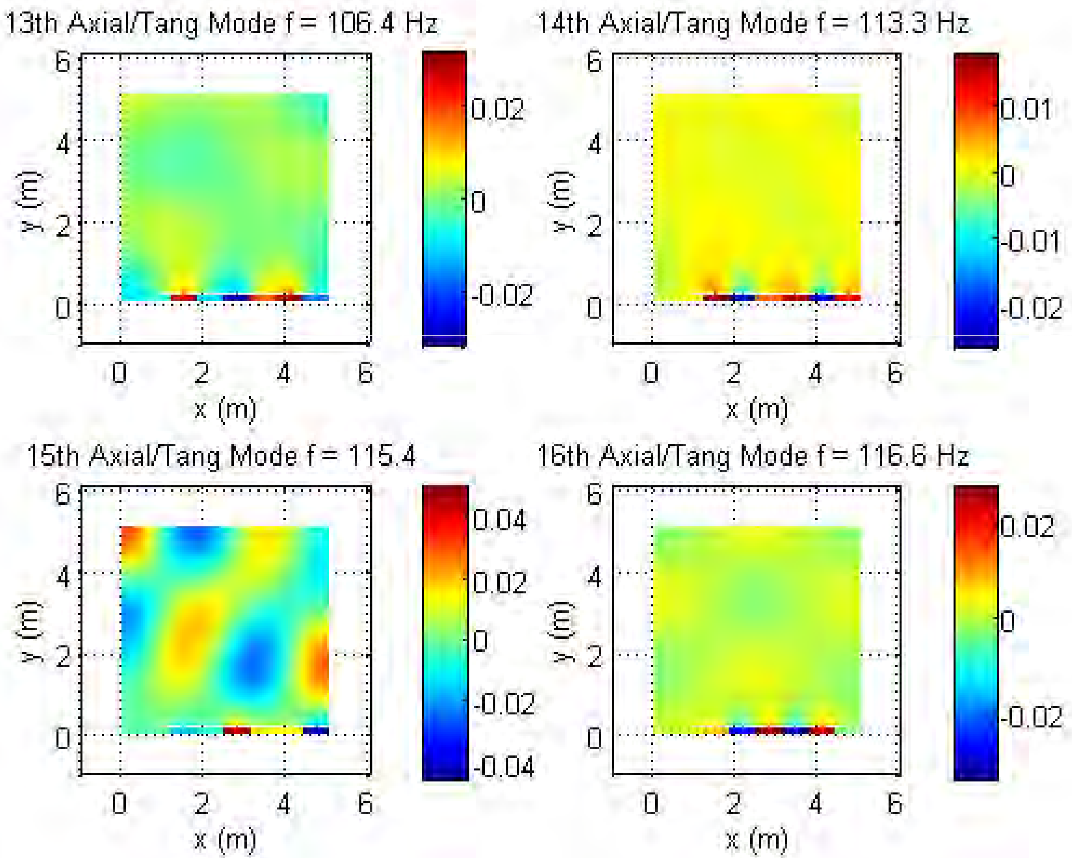
Sound pressure space distribution, for axial/tangential modes $f(n_{xy}, 0)$ - Optimized with objective function based on Lp, $f1(\mathbf{x})$ - Frequency band between 70 Hz and 90 Hz

Sound pressure distribution – optimization using Loudness level-based objective function – DE – 1000 generations



Sound pressure space distribution, for axial/tangential modes $f(n_{xy}, 0)$ - Optimized with objective function based on L_L, $f_2(\mathbf{x})$. - Frequency band between 70 Hz and 90 Hz -

Sound pressure distribution – optimization using Loudness level-based objective function - DE – 1000 generations



Sound pressure space distribution, for axial/tangential modes $f(n_{xy}, 0)$ - Optimized with objective function based on L_L, $f_2(\mathbf{x})$. - Frequency band between 100 Hz and 120 Hz

Conclusions

- The SPL-based objective function:
  - is more efficient at simultaneously decreasing the fluctuations of both sound pressure and loudness levels.
  - tries to eliminate the resonant frequencies lower than 100 Hz.
- The loudness level-based objective function
  - tends to better control the resonances at higher frequencies. In this range, however, the effect of these resonances is less noticeable.

Conclusions

- The spatial distribution of the sound pressure level is more homogenous when optimizing with respect to sound pressure level.
- The results of this paper indicates that the SPL-based objective function is more efficient.
- An investigation on the influence of overall enclosure dimensions and the design restrictions on sound pressure and loudness level distribution is being carried out.

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Acknowledgments

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Thank you very much for your attention. Suggestions and comments are more than welcome!

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