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MECHANICAL ENGINEERING | RESEARCH ARTICLE

Application of evolution strategy algorithm for optimization of a single-layer sound absorber

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Abstract: Depending on different design parameters and limitations, optimization of sound absorbers has always been a challenge in the field of acoustic engineering. Various methods of optimization have evolved in the past decades with innovative method of evolution strategy gaining more attention in the recent years. Based on their simplicity and straightforward mathematical representations, single-layer absorbers have been widely used in both engineering and industrial applications and an optimized design for these absorbers has become vital. In the present study, the method of evolution strategy algorithm is used for optimization of a single-layer absorber at both a particular frequency and an arbitrary frequency band. Results of the optimization have been compared against different methods of genetic algorithm and penalty functions which are proved to be favorable in both effectiveness and accuracy. Finally, a single-layer absorber is optimized in a desired range of frequencies that is the main goal of an industrial and engineering optimization process.

Subjects: Acoustical Engineering, Mechanical Engineering, Technology

Keywords: evolution strategy algorithm, single-layer sound absorber, one-fifth success rule, frequency band (range)

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PUBLIC INTEREST STATEMENT

Nowadays, public health is seriously threatened by different types of pollutions. Acoustic noise may be considered as one of the most important threats in this regard. More than 70% of mental disorders of workers in different fields can be related to noise pollutions emanating from their working environment, as reported by the World Health Organization in 1970. Accordingly, noise reduction/control is imperative to safeguard human life. One particular method of noise control is through utilization of different combinations of sound absorbers to attenuate reflection and transmission of acoustic waves. Hence, optimization of these combinations plays an important role in noise attenuation.

The current study focuses on optimization of noise attenuation of a perforated plate coupled by a porous media which is backed by an air layer, all as a single layer absorber on a rigid wall, through the use of Evolution Strategy as a novel approach in this particular field.

1. Introduction

In the present study, a new method is proposed for determining an optimum design of a single-layer absorber in a frequency band using evolutionary strategy (ES) algorithm. Genetic algorithm (GA), simulated annealing (SA), and Topology methods have been widely used as optimizing tools for sound absorption and transmission loss (Bolton, Shiau, & Kang, 1996; Chang, Yeh, Chiu, & Lai, 2005; Dühring, Jensen, & Sigmund, 2008; Krynkin & Tyutekin, 2002; Lee, Kim, Kim, Kim, & Kang, 2007; Meng, Wen, Zhao, & Wen, 2012; Ruiz, Cobo, & Jacobsen, 2011; Thamburaj & Sun, 2002; Tyutekin, 1998; Yoon, 2013; Chang, Yeh, & Chiu, 2005). The goal of maximizing the absorption property of single-layer sound absorbers using GA and SA methods was previously addressed by Chang, Yeh, Chiu, et al. (2005) and Chang, Yeh, & Chiu (2005). However, optimization of absorbers at a frequency band using ES method seems to be a new approach which is the goal of the present study. It is noteworthy that one of the main goals of acoustic science is to achieve an optimized absorber in a range of desired frequencies (Cox & D'antonio, 2009). A single-layer absorber consists of a rigid plate, an air gap, a layer of porous material, and a resonant absorber used as an absorbing cover sheet. The resonant absorber can be a type of perforated plate, membrane or micro-perforated panel. Application of this type of covering makes it possible to achieve favorable absorption at low frequencies which are hard to achieve using porous materials without these coverings. This is mainly due to the fact that thickness of the porous materials should be increased in order to obtain desirable absorption properties at low frequencies (Cox & D'antonio, 2009). In the present paper, a perforated plate is employed to cover the porous material. The arrangement of the absorption panel is displayed and discussed in Section 2. This type of absorber has varieties of applications for noise reduction in aviation industries, buildings, and factories. Thickness of an absorber is usually restricted because of various effective factors such as space limit. Hence, the design phase would be computationally expensive using trial and error techniques. As a result, optimization techniques are used in order to design an optimized absorber with the highest level of absorption based on the limited space constraint. While an optimized design of the absorbers is very important, only a limited number of works are reported in the literature. Furthermore, the application of ES algorithms for the optimal design of an absorber with maximum possible level of absorption in a frequency range seems to be new.

Since the main concern for an optimal design is to increase the level of noise reduction and sound absorption and not necessarily find two- or three-dimensional details, a sound absorber is usually analyzed in one dimension (Lee et al., 2007). Chang, Yeh, Chiu, et al. (2005) optimized a single-layer sound absorber using different techniques of GA, Gradient and SA methods. In another attempt, a micro-perforated panel was optimized by Ruiz et al. (2011) using SA optimization technique. Yoon (2013) studied the acoustical properties of porous materials using topology optimization method, based on the empirical formulas of Delany and Bazley (1970).

In the framework of sound absorbers, current methods for the analysis of absorption are categorized into three modeling groups: Empirical, Phenomenological, and Microstructure models. The first two models are based on the assumption of cylindrical tubes, while the latter uses the theory of sound waves propagating via a set of cylinders with air passing through them. A common example for empirical models is the formulas introduced by Delany and Bazley (1970), while Phenomenological models are used by some authors (Allard & Daigle, 1994; Attenborough, 1982, 1983; Biot, 1956; Champoux & Stinson, 1990, 1992; Lafarge, Lemarinier, Allard, & Tarnow, 1997; Stinson, 1991; Wilson, 1997; Zwikker & Kosten, 1949) and various works are presented using Microstructure models (Attenborough & Walker, 1971; Dupère, Dowling, & Lu, 2004; Kawasima, 1960; Tarnow, 1996, 1997).

Formulation and mathematical modeling for the calculation of impedance and the absorption coefficient using transfer matrix method are presented in the following section. In Section 3, the evolution strategy (ES) approach is explained and different parameters and steps of the algorithm are described. This method is later used for the optimization of a single-layer sound absorber at a frequency band which is presented in Section 4.

2. Mathematical formulation

In this section, transfer matrix method which is used to study the absorption property is presented. Transfer matrix method is a powerful tool for modeling sound propagation through porous materials with or without resonant absorber coverings. This method uses the plane wave assumption as illustrated in Figure 1.

In most of the porous absorbers, sound speed is far less than the speed of sound in the air which makes it is possible to assume $\phi \approx 0$ and $k_{xi} \approx k_i$. As a result, impedance of the surface is calculated using the formula

$$z_{si+1} = \frac{-jz_{si}z_i\frac{k_{xi}}{k_i}\cot(k_{xi}d_i) + \left(z_i\frac{k_i}{k_{xi}}\right)^2}{z_{si} - jz_i\frac{k_i}{k_{xi}}\cot(k_{xi}d_i)} \tag{1}$$

where z_{si+1} and z_{si} are the impedances at X_{i+1} and X_i, respectively. k_i is the wave number at the ith layer and locations of X_i and X_{i+1} are shown on Figure 1.

In the presence of a rigid plate behind the absorber layer, Equation 1 will be modified as follows:

$$z_{si+1} = -jz_i\frac{k_i}{k_{xi}}\cot(k_{xi}d_i) \tag{2}$$

Figure 1. Transfer matrix model for multi-layered absorber.

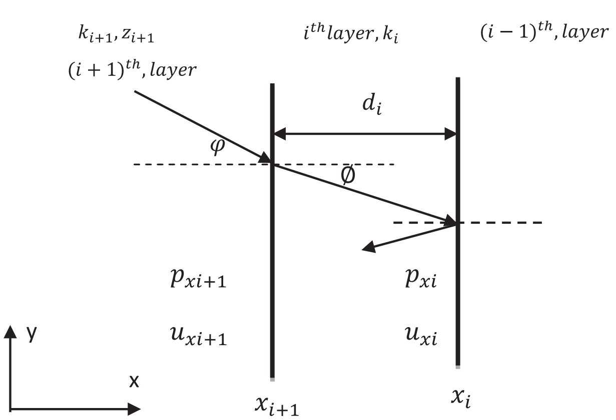
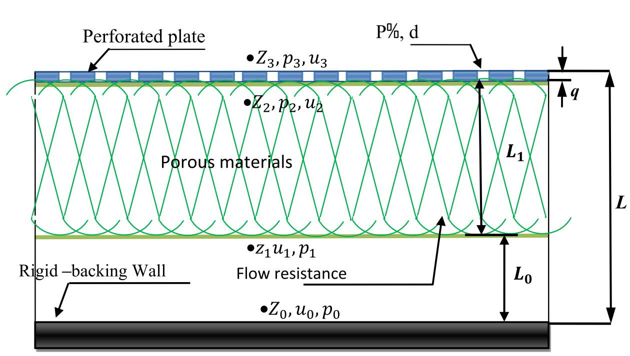


Figure 2. Absorption mechanism for a single-layer absorber.



It is now possible to rewrite the above equation based on the single-layer absorber shown in Figure 2 as in

$$z_1 = -jz_0 + \cot(k_0 L_0) \tag{3}$$

$$z_0 = \rho_0 c_0$$

$$k_0 = \frac{w}{c_0} \tag{4}$$

where z_0 and k_0 are impedance and wave number for air medium, respectively (Cox & D'antonio, 2009).

$$z_2 = \frac{-jz_1 \times z_c \times \cot(kc \times l_1) + z_c^2}{z_1 - jz_c \times \cot(kc \times l_1)} \tag{5}$$

Adding z_2 and z_p gives the impedance of the absorber's surface (Cox & D'antonio, 2009):

$$z_3 = z_2 + z_p \tag{6}$$

Using the empirical formulas, the impedance and wave number of a porous material can be calculated using Equations 7 and 8.

$$k_c = \frac{w}{c_0}\left[1 + c_1\left(\frac{\rho_0 f}{R}\right)^{c_2} + c_3\left(\frac{\rho_0 f}{R}\right)^{c_4}\right] \tag{7}$$

$$z_c = \rho_0 c_0\left[1 + c_5\left(\frac{\rho_0 f}{R}\right)^{c_6} + c_7\left(\frac{\rho_0 f}{R}\right)^{C8}\right] \tag{8}$$

Equation 9 may also be used for calculation of the impedance of the perforated panel (Beranek & Ver, 1992):

$$z_p = \frac{\rho_0}{\varepsilon}\sqrt{8\vartheta}\left(1 + \frac{q}{2d}\right) + j\frac{w\rho_0}{\varepsilon}\left[\sqrt{\frac{8\vartheta}{w}}\left(1 + \frac{q}{2d}\right) + q + \delta\right] \tag{9}$$

in which

$$\delta = 0.85(2d)\left(1 - 1.47\sqrt{\varepsilon} + 0.47\sqrt{\varepsilon^3}\right) \tag{10}$$

Finally, the absorption coefficient will be measured using the following set of equations:

$$\alpha(f, \varepsilon, R, q, L_1, L_0, D) = 1 - \left|\frac{z_3 - \rho_0 c_0}{z_3 + \rho_0 c_0}\right|^2 = \alpha(f, p\%, d, R, q, L_1, L_0) \tag{11}$$

$$p\% = \varepsilon \times 100 \tag{12}$$

$$L = L_0 + L_1 + q \tag{13}$$

It is noteworthy that the absorption coefficient of unity implies maximum possible absorption.

3. ES algorithm

The algorithm of ES, as an innovative method, was first introduced by Rochenberg (1973). In most of the ES algorithms, following steps are performed:

(1) Determination of population size, maximum number of generations, and mutation rate,

(2) Generation of the initial population (as parents) using random numbers (which gives a set of chromosomes),

(3) Calculation of the fitness function for each chromosome,

(4) Evaluation of the termination criterion and moving to Step 5 in case the criterion is not satisfied

(5) Production of next generation using following methods:

   (i) Using elitism (selection of a particular number of elite chromosomes from the community)

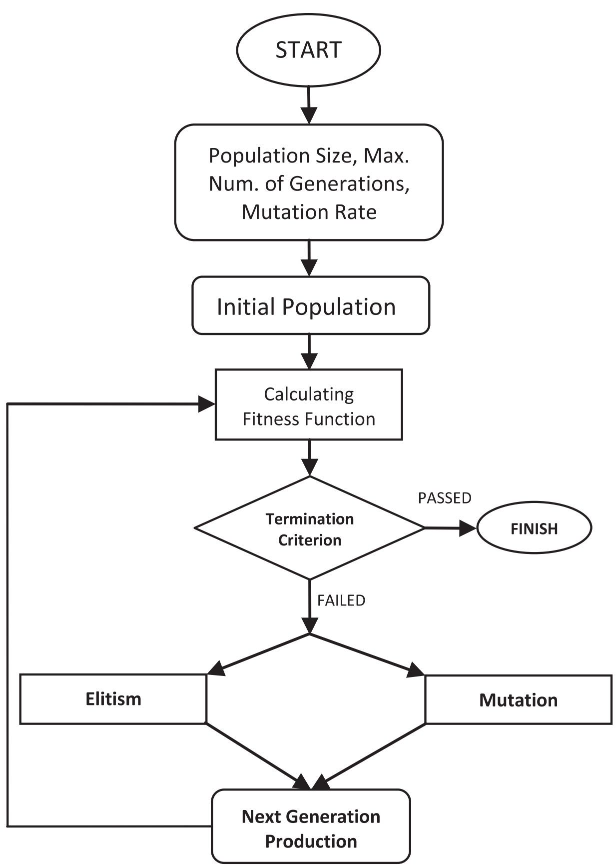
   (ii) Applying mutation to a particular set of community members (mutants) and the generation of children for the next generation, and

(6) Returning to Steps 3 and 4.

In order to use the ES algorithm for optimization of the absorber, it is vital to first introduce the operators of the absorption problem as discussed below.

A chromosome in the ES algorithm is given as a set of ($x_1, x_2, \ldots, x_n, \sigma$) in which x_i are the problem variables which are given as real numbers and σ is the step length for the mutation. The value of σ is determined using the one-fifth success rule during the execution of the algorithm. Rochenberg (1973) mathematically proved that when the number of successful mutations accounts for one-fifth of the unsuccessful mutations, the speed of convergence to the optimum solution will be increased. Based on this role, in the present study, five variables are introduced. Each chromosome of the population has five genes which stand for the different parameters; Gene 1 for the porous material

Figure 3. ES algorithm flowchart.



thickness (L_1), Gene 2 for the specific resistance of the porous material (R), Gene 3 for the diameter of the holes on the perforated panel (d), Gene 4 for the porosity of the perforated panel (ϵ), and Gene 5 for the total thickness of the absorber (L). Continuous random numbers are used for production of the initial generation (parents). It has to be noted that these random numbers should not violate the limitations of the problem at hand. After production of the initial generation, a fitness function should be assigned to each chromosome. Based on this fitness function, some elite chromosomes will be chosen as new parents in order to be used for the mutation process which leads to the production of children for the next generation. In the present study, normal mutation method is applied to the parent chromosomes to produce mutants. In this way, a random and normalized number is added to all genes as shown in Equation 14.

$$X_i' = x_i + N(0, \sigma) \tag{14}$$

It is noteworthy that after this mutation process, no impossible chromosome should be generated. This basically means that the generated genes should not violate the limitation of the problem. If this situation occurs, the respective chromosome should be repaired. In order to repair the chromosome, the value of the violated gene should be set as the allowable limit for that parameter.

In order to generate the next generation, the elitism is used. In other words, a particular number of elite chromosomes are chosen which will be transferred to the next generation. The rest of the required chromosomes for the next generation will be selected randomly from the chromosomes of the previous generation and the newly generated chromosomes resulting from the mutation process. The ES algorithm will continue until the termination criterion is met. The flowchart of the ES algorithm is shown in Figure 3.

4. Results and discussion

4.1. Single-layer absorber optimization at a particular frequency

In order to validate the present method, results of the optimization of a single-layer absorber at a particular frequency is compared against the results of Chang, Yeh, Chiu, et al. (2005) which uses different method of optimization. The parameters of optimization for the absorber including the design limitations are given as follows:

$$L_1 \le .19; \quad d \le .015; \quad 1000 \le R \le 50000; \quad p\% = 50$$

Thickness of the perforated panel q is kept constant and fixed at $q = .1$. The single-layer absorber gets optimized at a particular frequency of $f = 350$ Hz.

Results of optimization using the ES algorithm is validated against the results of different optimization methods used by Chang, Yeh, Chiu, et al. (2005) based on GA, exterior and interior penalty

Table 1. Comparison of the obtained results of ES method against different methods used by Chang, Yeh, Chiu, et al. (2005)

	L_1	R	d	p%	q	α
GA (Chang, Yeh, Chiu, et al., 2005)	.1286	39673	.015	24.7	.01	.999943
Exterior penalty function method (Chang, Yeh, Chiu, et al., 2005)	.036	17459	.0019	4.6	.01	.999998
Interior penalty function method (Chang, Yeh, Chiu, et al., 2005)	.050	7000	.015	15	.01	.870331
Feasible direction method (Chang, Yeh, Chiu, et al., 2005)	.038	7563	.015	14.9	.01	.879046
Evolutionary strategy	.090264	5793.038	.015	3.6164	.01	.9999999

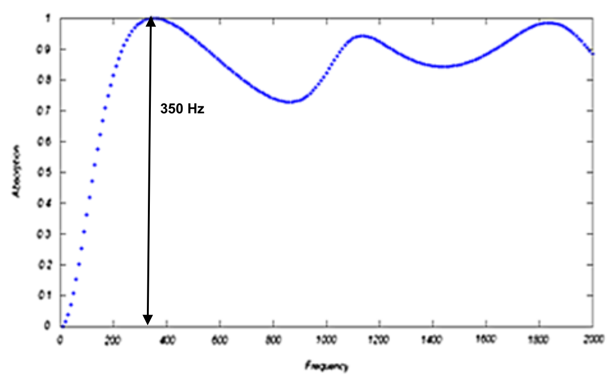


Figure 4. Absorption coefficients for the single-layer absorber at different frequencies after optimization, using the ES algorithm.

function, and feasible direction methods. A comparison is made between the obtained results and that of (Chang, Yeh, Chiu, et al., 2005) in Table 1.

It is clear that the ES algorithm gives favorable results for the optimization of a continuous medium. It is also worth mentioning that the obtained results using the ES method achieve highest possible absorption coefficient merely near unity (full absorption). Absorption coefficients for the single-layer absorber at different frequencies are depicted on Figure 4.

4.2. Optimization at a frequency band

As stated earlier, one of the main challenges of engineers is to optimize an absorber in a desired frequency range. By demonstrating the validity of the obtained results which was shown in the previous section, it is now possible to have optimization in a range of frequencies which will be desirable in engineering and industrial applications.

This time, a frequency band of 325 Hz < 375 Hz is chosen as the goal of optimization using the ES algorithm. The frequency is increased by steps of .1 Hz in order to achieve a continuous optimization in the desired range. After the optimization by ES algorithm, the absorption coefficients are calculated and the results for different design parameters are given in Table 2 and also illustrated in Figure 5.

Table 2. Design parameters for the single-layer absorber after optimization at a frequency band using ES

	f **(HZ)**	L_1 **(m)**	***R*** **(MKS rayls m⁻¹)**	***p*%**	***d*** **(m)**	***q*** **(m)**	α
Evolutionary strategy	325–375	.18	4296.3265	.015	.29991	.01	.9998

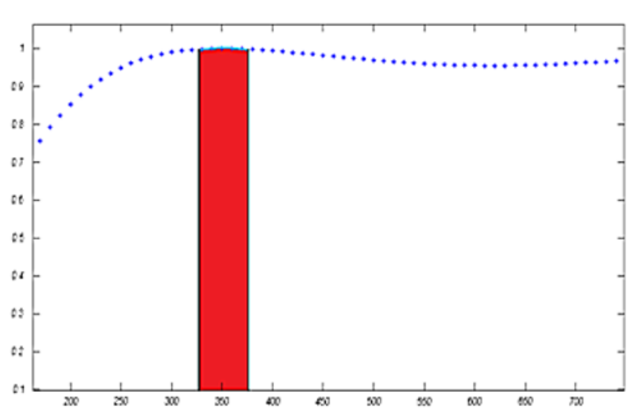


Figure 5. Absorption coefficient for optimization of the single-layer absorber in a frequency band.

4.3. Statistical significance

As mentioned before, the evolution algorithm is a stochastic optimization technique. Therefore, to ensure the statistical significance of the results, it is more convenient to implement a statistical test on the algorithm. Here, a two-sample *t*-test is used in the Excel program.

For this purpose, the same optimization has been repeated 40 times and two data-sets of 20 optimized absorption coefficients have been extracted randomly. Mean values and variances of the two data-sets are presented in Table 3.

These two data-sets have been analyzed by a *t*-test function in Excel and the results of the *t*-test are presented in Table 4.

High probability of similarity of the given data sets in a *t*-test implies statistical significance of the data sets. Accordingly, as evident in Table 4, the high probability of .959 obtained in the current study confirms the statistical significance of the implemented algorithm.

Table 3. Data-sets produced by solving the same problem 40 times

	Data-set 1	Data-set 2
Absorption coefficients	.99996	.81249
	.99613	.95921
	.96116	.98357
	.8344	.99992
	.9927	.84098
	.8881	.84098
	.97386	.87401
	.99518	.99999
	.89388	.99993
	.9999	.97649
	.79388	.96206
	.97183	.99999
	.92922	.87448
	.99733	.97119
	.99477	.96991
	.7727	.81867
	.99641	.86907
	.97049	.95842
	.99357	.99999
	.81638	.99885
	.91241	.99803
Mean	.937346	.938487
Variance	.005668	.004766

Table 4. Results obtained by the *t*-test

t Stat	−.051207833
t Critical	2.02107537
$P(T \leq t)$	.959414782

5. Conclusion

In the present paper, ES algorithm is used for optimization of a single-layer absorber at a particular frequency and also in a desired frequency range. The obtained results are compared against the results of optimization using different methods of GA, exterior and interior penalty function, and feasible direction in order to validate the present algorithm. This comparison confirms the robustness and validity of the present technique which can be further used for the optimization in a frequency band. It is therefore concluded that application of ES algorithm for optimization of the single-layer absorbers in a frequency band is of high importance which should gain more attention and can be further extended to the optimization of various absorbers used in engineering and industrial applications.

Nomenclature

C_0	sound speed (m s^{-1})
d	diameter of perforated hole on the front plate (m)
L	total thickness of absorber (m)
L_0	thickness of gap air (m)
L_1	thickness of fibrous acoustic materials (m)
k_0	wave number of air
k_c	wave number of fibrous acoustic material
q	thickness of the perforated plate (m)
R	acoustic flow resistance of acoustic fiber material (MKS rayls m^{-1})
z_c	characteristic impedance of acoustic fiber
z_i	specific normal impedance at point *i*
z_p	characteristic impedance of perforated plate
ε	porosity of the perforated plate
ϑ	kinematic viscosity of air ($=15\times10^{-6}\,m^2/s$)
δ	viscous boundary layer thickness of the perforated plate (m)
f	frequency (Hz)
$p\%$	porosity of perforated plate ($\varepsilon\times100$)
ρ_0	air density($kg\,m^{-3}$)

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References

Allard, J. F., & Daigle, G. (1994). Propagation of sound in porous media: Modeling sound absorbing materials. *The Journal of the Acoustical Society of America, 95*, 2785. http://dx.doi.org/10.1121/1.409801

Attenborough, K. (1982, February). Acoustical characteristics of porous materials. *Physics Reports, 82*, 179–227. http://dx.doi.org/10.1016/0370-1573(82)90131-4

Attenborough, K. (1983). Acoustical characteristics of rigid fibrous absorbents and granular materials. *The Journal of the Acoustical Society of America, 73*, 785–799. http://dx.doi.org/10.1121/1.389045

Attenborough, K., & Walker, L. (1971). Scattering theory for sound absorptionin fibrous media. *The Journal of the Acoustical Society of America, 49*, 1331–1338. http://dx.doi.org/10.1121/1.1912505

Beranek, L. L., & Ver, I. L. (1992). *Noise and vibration control engineering-principles and applications* (Vol. 1, 814 pp.). New York, NY: Wiley.

Biot, M. A. (1956). Theory of propagation of elastic waves in a fluid-saturated porous solid. I. Low-frequency range. *The Journal of the Acoustical Society of America, 28*, 168–178. Retrieved from http://dx.doi.org/10.1121/1.1908239.

Bolton, J. S., Shiau, N. M., & Kang, Y. J. (1996, April 4). Sound transmission through multi-pannel structures lined with elastic porous materials. *Journal of Sound and Vibration, 191*, 317–347. http://dx.doi.org/10.1006/jsvi.1996.0125

Champoux, Y., & Stinson, M. R. (1990). Experimental investigation of models of sound wave propagation in air-saturated porous media. *The Journal of the Acoustical Society of America, 88*, S121–S121. http://dx.doi.org/10.1121/1.2028552

Champoux, Y., & Stinson, M. R. (1992). On acoustical models for sound propagation in rigid frame porous materials and the influence of shape factors. *The Journal of the Acoustical Society of America, 92*, 1120–1131. http://dx.doi.org/10.1121/1.405281

Chang, Y.-C., Yeh, L.-J., & Chiu, M.-C. (2005, March). Optimization of constrained composite absorbers using simulated annealing. *Applied Acoustics, 66*, 341–352. http://dx.doi.org/10.1016/j.apacoust.2004.07.003

Chang, Y.-C., Yeh, L.-J., Chiu, M.-C., & Lai, G.-J. (2005, September 22). Shape optimization on constrained single-layer sound absorber by using GA method and mathematical gradient methods. *Journal of Sound and Vibration, 286*, 941–961.

Cox, T. J., & D'antonio, P. (2009). *Acoustic absorbers and diffusers: Theory, design and application*. London: CRC Press.

Delany, M. E., & Bazley, E. N. (1970, April). Acoustical properties of fibrous absorbent materials. *Applied Acoustics, 3*, 105–116. http://dx.doi.org/10.1016/0003-682X(70)90031-9

Dühring, M. B., Jensen, J. S., & Sigmund, O. (2008, November 11). Acoustic design by topology optimization. *Journal of Sound and Vibration, 317*, 557–575. http://dx.doi.org/10.1016/j.jsv.2008.03.042

Dupère, D., Dowling, A. P., & Lu, T. J. (2004, January). The absorption of sound in cellular foams. In *ASME 2004 International Mechanical Engineering Congress and Exposition* (pp. 123–132). doi:10.1115/IMECE2004-60618

Kawasima, Y. (1960). Sound propagation in a fiber block as a composite medium. *Acustica, 10*, 208–217.

Krynkin, S. V., & Tyutekin, V. V. (2002, July 01). Optimization of the parameters of sound-absorbing materials made on the basis of rubberlike media with heavy inclusions. *Acoustical Physics, 48*, 458–466. http://dx.doi.org/10.1134/1.1494026

Lafarge, D., Lemarinier, P., Allard, J. F., & Tarnow, V. (1997). Dynamic compressibility of air in porous structures at audible frequencies. *The Journal of the Acoustical Society of America, 102*, 1995–2006. http://dx.doi.org/10.1121/1.419690

Lee, J. S., Kim, E. I., Kim, Y. Y., Kim, J. S., & Kang, Y. J. (2007). Optimal poroelastic layer sequencing for sound transmission loss maximization by topology optimization method. *The Journal of the Acoustical Society of America, 122*, 2097–2106. http://dx.doi.org/10.1121/1.2770541

Meng, H., Wen, J., Zhao, H., & Wen, X. (2012). Optimization of locally resonant acoustic metamaterials on underwater sound absorption characteristics. *Journal of Sound and Vibration, 331*, 4406–4416. http://dx.doi.org/10.1016/j.jsv.2012.05.027

Rechenberg, I. (1973). Evolution strategy optimization technical systems according to principles of biological evolution. Stuttgart: Verlag Frommann-Holzboog.

Ruiz, H., Cobo, P., & Jacobsen, F. (2011, October). Optimization of multiple-layer microperforated panels by simulated annealing. *Applied Acoustics, 72*, 772–776. http://dx.doi.org/10.1016/j.apacoust.2011.04.010

Stinson, M. R. (1991). The propagation of plane sound waves in narrow and wide circular tubes, and generalization to uniform tubes of arbitrary cross-sectional shape. *The Journal of the Acoustical Society of America, 89*, 550–558. http://dx.doi.org/10.1121/1.400379

Tarnow, V. (1996). Compressibility of air in fibrous materials. *The Journal of the Acoustical Society of America, 99*, 3010 –3017. http://dx.doi.org/10.1121/1.414790

Tarnow, V. (1997). Calculation of the dynamic air flow resistivity of fiber materials. *The Journal of the Acoustical Society of America, 102*, 1680–1688. http://dx.doi.org/10.1121/1.420079

Thamburaj, P., & Sun, J. Q. (2002, June 27). Optimization of anisotropic sandwich beams for higher sound transmission loss. *Journal of Sound and Vibration, 254*, 23–36. http://dx.doi.org/10.1006/jsvi.2001.4059

Tyutekin, V. (1998). Optimization of the characteristics of a sound absorber synthesized from mechanical resonators. *Acoustical Physics, 44*, 581–584.

Wilson, D. (1997). Simple, relaxational models for the acoustical properties ofporous media. *Applied Acoustics, 50*, 171–188. http://dx.doi.org/10.1016/S0003-682X(96)00048-5

Yoon, G. H. (2013, March 4). Acoustic topology optimization of fibrous material with Delany–Bazley empirical material formulation. *Journal of Sound and Vibration, 332*, 1172–1187. http://dx.doi.org/10.1016/j.jsv.2012.10.018

Zwikker, C., & Kosten, C. W. (1949). *Sound absorbing materials*. New York, NY: Elsevier.