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Research Paper

Optimization of the Morphological Parameters of a Metal Foam for the Highest Sound Absorption Coefficient Using Local Search Algorithm

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Due to its unique features, the metal foam is considered as one of the newest acoustic absorbents. It is a navel approach determining the structural properties of sound absorbent to predict its acoustical behavior. Unfortunately, direct measurements of these parameters are often difficult. Currently, there have been acoustic models showing the relationship between absorbent morphology and sound absorption coefficient (SAC). By optimizing the effective parameters on the SAC, the maximum SAC at each frequency can be obtained. In this study, using the Benchmarking method, the model presented by Lu was validated in MATLAB coding software. Then, the local search algorithm (LSA) method was used to optimize the metal foam morphology parameters. The optimized parameters had three factors, including porosity, pore size, and metal foam pore opening size. The optimization was applied to a broad band of frequency ranging from 500 to 8000 Hz. The predicted values were in accordance with benchmark data resulted from Lu model. The optimal range of the parameters including porosity of 50 to 95%, pore size of 0.09 to 4.55 mm, and pore opening size of 0.06 to 0.4 mm were applied to obtain the highest SAC for the frequency range of 500 to 800 Hz. The optimal amount of pore opening size was 0.1 mm in most frequencies to have the highest SAC. It was concluded that the proposed method of the LSA could optimize the parameters affecting the SAC according to the Lu model. The presented method can be a reliable guide for optimizing microstructure parameters of metal foam to increase the SAC at any frequency and can be used to make optimized metal foam.

Keywords: Sound Absorption Coefficient (SAC); Local Search Algorithm (LSA); metal foam; optimization.

1. Introduction

Recently, metal foam has emerged as an attractive field of research in terms of science, industrial and acoustic applications (Azizan *et al.*, 2017). Porous metals are the most promising acoustical materials, mainly due to their high mechanical resistance and hardness, including resistance to heat, corrosion, and climatic conditions compared to non-metallic porous materials, such as fiberglass and polyurethane foam (Hakamada *et al.*, 2006a).

The sound absorption behavior of porous metal depends on the cellular structure, which is mainly divided into two types of open-cell structure and closed-cell structure (Gibson, Ashby, 1999). Open-cell porous metals have better sound properties than closed-cell structure due to the sound wave propagation inside the absorbent (Hakamada *et al.*, 2006a). The sound absorbs through the friction of air bonding on the boundary between the matrix and air by changing part of the acoustical energy to thermal energy (Hakamada *et al.*, 2006a). Therefore, the sound absorption in porous metal is related to intracellular air propagation behavior; hence, sound absorption in porous metal strongly depends on its cellular structure determined by production methods and conditions (Hakamada *et al.*, 2006a).

According to research studies, in metal foams, many factors, such as porosity, pore size, air flow resistance, thickness, and structure (morphology) of pore (open or close) affect the sound absorption coefficient (SAC) (Banhart, 2001; Han *et al.*, 2003; Jiejun *et al.*, 2003; Hakamada *et al.*, 2006a; Cox, D'antonio, 2009). Therefore, it seems that changing the microstructure of foams leads to enhancement of the SAC in them. The amount of sound attenuation is determined by optimizing the porous absorbent structure and its geometry (Otaru *et al.*, 2018). In typical laboratory conditions, it is often difficult to obtain the main acoustic parameters of the porous material with the metal frame (Zhang, Zhu, 2016). Although the reverse method accuracy mainly depends on the choice of acoustic models, it still provides an important reference for possible research studies regarding the acoustic absorption materials (Zhang, Zhu, 2016). It seems to be possible to use acoustic models to find the right type and size of the pores for higher sound absorption coefficient. In this regard, the sound absorption in a material depends on several variables, which is difficult to find the most appropriate one. Designers will be able to produce better designs to save time, material, and cost through optimization techniques. Optimization is a mathematical approach used to find answers of many questions about how to solve various problems (Haupt, Haupt, 2004; Pedregal, 2006).

Local search algorithms (LSA) are the most widely used algorithms in optimization (Stützle, 1999). Local Search is a meta-heuristic method of computing for solving hard optimization problems in which the solution for maximizing a criterion is used among a number of solutions (Jouya, Khayati, 2017). Local Search meta-heuristics are emerging techniques to deal with optimization problems and combinatorial search (Di Gaspero *et al.*, 2003). LSAs start with a suggested solution and try to find a‘ better solution within the defined neighborhood of the current solution (Stützle, 1999). If a better solution is found, it will replace the current solution and the process is continued from there (Stützle, 1999). LSAs have some advantages, including they (i) are the best performing algorithms used in practice for various problems, (ii) can test different possible solutions in short computation time, (iii) are often more easily adjusted to different types of problems and, thus, are more flexible, and (iv) are typically easier to understand compared to exact methods (Maniezzo *et al.*, 2009). They are also naturally suited for many practical applications to address the optimization criteria (Rossi *et al.*, 2006).

Over the past few years, studies have focused on the characteristics of porous sound absorbent materials. It is particularly important for sound experts to predict the acoustic behavior of these materials and quantify the acoustic energy absorption (Egab *et al.*, 2014). Mathematical models of acoustic properties are powerful tools to examine these relationships. Several researchers have focused on development of theoretical models for acoustic behavior of the porous materials (Allard, Atalla, 2009). Currently, many authors have introduced different types of acoustic models to show the absorption properties of porous materials (Allard, Atalla, 2009; Zhang, Zhu, 2016).

Lu *et al.* (2000) designed an analytical model to describe sound absorption in semi-open cell (bottleneck) structures. They found a good logical agreement between predictions and experimental measurements, especially at lower frequencies (Otaru *et al.*, 2018). This model was compared with their experimental measurements for sound absorption in porous metals with bottleneck structures (Lu *et al.*, 2000; Neithalath *et al.*, 2005; Hakamada *et al.*, 2006a; 2006b; Li *et al.*, 2011; Otaru *et al.*, 2018). Lu model shows the relationship between porosity, thickness, pore size, and pore opening with the SAC in the metal foam (Lu *et al.*, 2000). This study aimed to optimize the parameters affecting the SAC, such as porosity, pore size and pore opening size in aluminum foam using the Lu acoustic model at each frequency.

2. Materials and methods

In this study, optimizing the effective parameters on the SAC was conducted according to Fig. 1. According to the study aims, a model would be used that indicates the correlation between SAC and morphological parameters, such as pore size, pore opening size, thickness, and porosity. In this case, these parameters can be optimized by local search algorithm. Nevertheless, the obtained material may not be adequately specified by previous theoretical models, due to the sudden change in cross-sectional area as the sound enters or exits the pore opening (Lu *et al.*, 2000). These effects

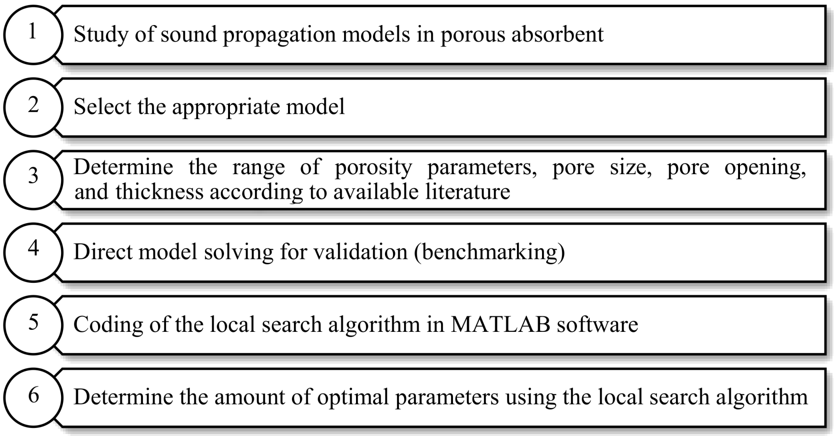

Fig. 1. The study flowchart.

have not been modeled by previous theories of those who mainly have dealt with homogeneous porous materials where the pores do not change suddenly in the cross-sectional area e.g., those of Allard *et al.*, Stinson, Champoux, and Wilson (Lu *et al.*, 2000). Moreover, no fitted parameter has been introduced in the present model, and it can be directly applied to non-homogeneous materials, such as a gradient of pore size and pore opening distribution (Lu *et al.*, 2000). In this study, the Lu model was chosen for optimization, since based on previous studies, the model has been approved numerically and experimentally (Hakamada *et al.*, 2006a; 2006b; Kuromura *et al.*, 2007; Li *et al.*, 2011). Lu *et al.* (2000) have proposed a model for describing the sound absorption behavior of aluminum foams with spherical cells. According to this model (Lu *et al.*, 2000), the air-specific acoustic impedance inside a cell Z_D can be calculated from Eq. (1)

$$Z_D = -i\rho_0 c_0 \cot\left(\frac{0.806D\omega}{c_0}\right), \tag{1}$$

where $\rho_0 = 1.184\ \mathrm{kg/m^3}$ is the air density, $c_0 = 346.5\ \mathrm{m/s}$ is the sound speed in air, D is the pore size, $\omega = 2\pi f$ is the angular frequency (f is the sound wave frequency), and i is the imaginary unit ($i^2 = -1$).

The acoustic impedance of the open cell Z_0 is obtained from the following relaxation-matching solution (Lu *et al.*, 2000)

$$Z_0 = R_0 + iM_0, \tag{2}$$

$$R_0 = \left(\frac{32\eta t}{d^2}\right)\left(\sqrt{\frac{1+\beta^2}{32}} + \sqrt{\frac{\beta d}{4t}}\right), \tag{3}$$

$$M_0 = \omega\rho_0 t\left(1 + \frac{1}{\sqrt{(9+\beta^2)/2} + 0.85d/t}\right), \tag{4}$$

where R_0 is the special acoustic resistance, M_0 is open cell reactance between the pores, $\eta = 1.849 \cdot 10^{-5}\ \mathrm{kg/m\cdot s}$ is the air dynamic (absolute) viscosity, t is cell wall thickness (Eq. (5)), Ω is porosity, d is pore opening size, and β can be defined as Eq. (6)

$$t = \frac{(1-\Omega)D}{3.55 - 6(d/D)^2}, \tag{5}$$

$$\beta = \frac{\sqrt{\Omega\rho_0\eta}d}{2}. \tag{6}$$

Acoustic impedance Z_1 is obtained as follows:

$$Z_1 = z_0 + Z_D, \tag{7}$$

where $z_0 = (0.909D/d)^2 Z_0$ is the relative specific acoustic impedance of the apertures. When the number of cells in the direction of sound propagation n is greater than 1, the acoustic impedance Z_n is computed from Eq. (8) (Lu *et al.*, 2000)

$$Z_n = z_0 + \frac{1}{1/Z_D + 1/Z_{n-1}} = R + iM. \tag{8}$$

Finally, the normal sound-absorption coefficient α (SAC) is calculated as (Lu *et al.*, 2000)

$$\alpha = \frac{4R/\rho_0 c_0}{(1 + R/\rho_0 c_0)^2 + (M/\rho_0 c_0)^2}. \tag{9}$$

2.1. Validation (benchmarking)

In this section, the benchmarking method was used to ensure that the code was correctly proposed in MATLAB software. Benchmarking is very relevant to verification and validation processes (Duncan, 1996; Bialek *et al.*, 2016). In benchmark validation, a valid model provides estimates and research results in accordance with a known actual effect (Bialek *et al.*, 2016). Benchmarking and validation are required to specify the aspects of real blackouts generated by different types of models, the results obtained from a particular tool, and the limitations of a specific methodology (Bialek *et al.*, 2016). Providing quantitative metrics is an important feature of a benchmarking/validation study allowing future analysts to compare the different studies statistics, and qualitative descriptions that facilitate the same comparisons (Bialek *et al.*, 2016). Accordingly, the results of the code proposed in this study were compared with the results of the code in Lu's article as well as the values measured by Lu. These results have been obtained for the case (a) in Lu's article and for a thickness of 20 mm (Lu *et al.*, 2000). To examine the prediction model, Fig. 2 shows the results of the comparison among current predictions, empirical data, and Lu's empirical model. A good agreement between the present coding and the results of the Lu model is shown in Fig. 2 and the deviation is less than 12%. The value of R squared (R^2) was also calculated which was 0.8042 for Lu's modeling and 0.9026 for present study.

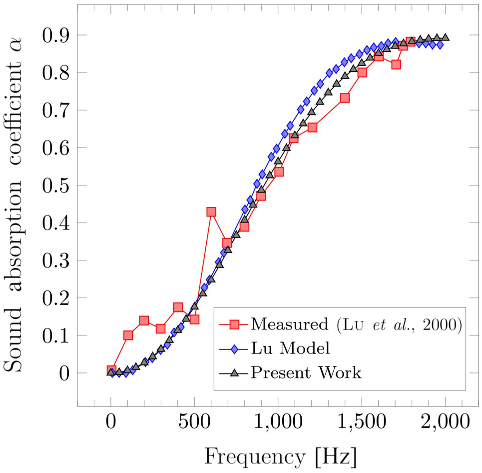

Fig. 2. Comparing the predicted results in this study with the predicted and measured results of the Lu model.

Finally, for further confirmation and validation, an example of the model f was solved in Lu's article, the results of which are shown in Fig. 3 (specification: D = 1.0 mm, d = 0.3 mm, Ω = 60% and L = 20 mm). Figure 3 indicates that it is impossible to obtain a clear pattern for the sound absorption coefficient changes. At one frequency, the rate of sound absorption coefficient is directly related to the porosity percentage. However, at another frequency, there is a reverse relationship. The same is true regarding the sound absorption coefficient, pore opening size, and pore size. Furthermore, the sound absorption coefficient is quasi-sinusoidal in frequency, indicating that the sound absorption coefficient graph has multiple peaks. These issues make it difficult to find the optimal point at a particular frequency. Using optimization algorithms would be a good solution to overcome this problem. In other words, an optimization algorithm can be used to find the optimal parameters. In this study, local search algorithm was used as a suitable tool for optimization and finding suitable parameters to optimize sound absorption coefficient.

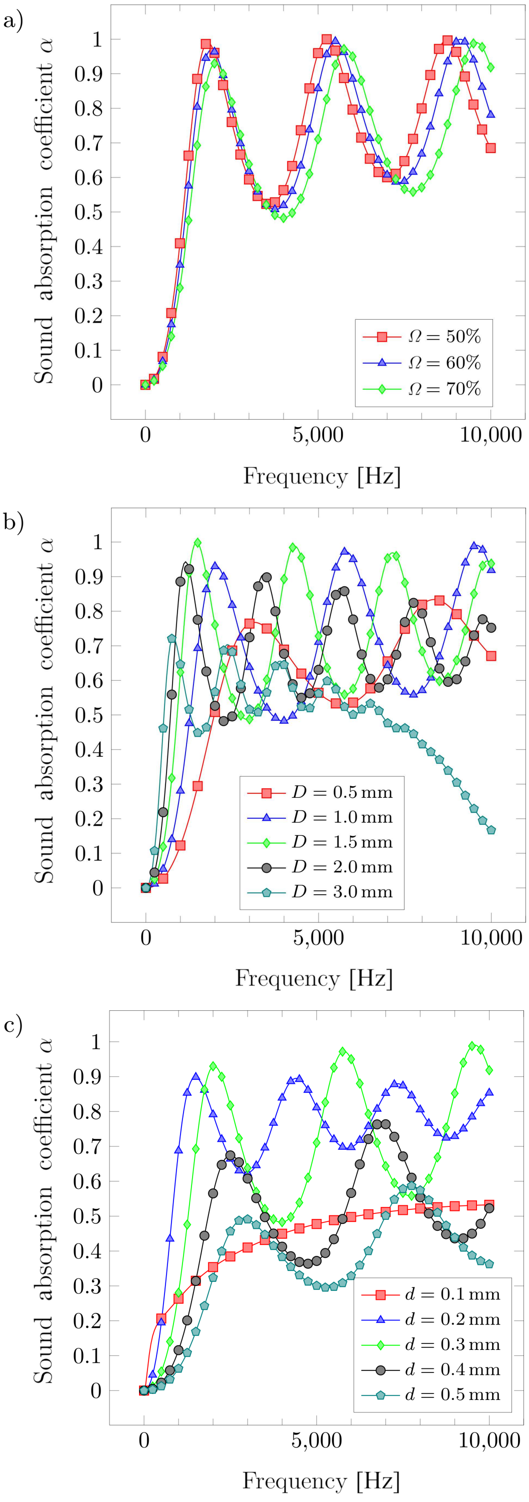

Fig. 3. SAC in terms of: a) porosity, b) pore size, and c) pore opening size according to the Lu model for a thickness of 20 mm.

2.2. *Optimization (local search algorithm – LSA)*

In this study, to calculate the SAC from the Lu model and to determine a trail system design, the LSA was used to find optimal values. In other words, the

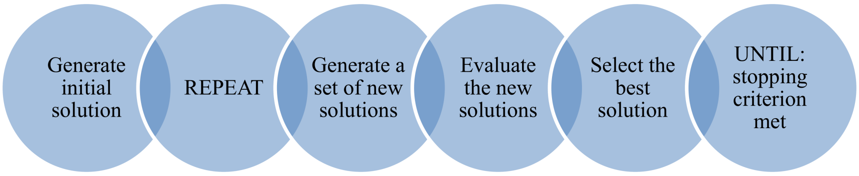

Fig. 4. Structure of the local search (Fränti, Kivijärvi, 2000).

Lu model and LSA method were linked together to find optimal values (d, D, and Ω). For this purpose, different modes were tested using the Lu model.

The number of tests was determined using the LSA method. In the Lu model, the values of the variables were changed in the specified range to find the optimal value of unknown parameters. In fact, the Lu model was numerically solved using the proposed codes for all possible values of the parameters in order to find the best answer. Local search can be used on issues considered as finding a solution to maximize a benchmark among a number of upcoming solutions (Arya *et al.*, 2004; Hoos, Stützle, 2004). LSAs move from one solution to another in the search space using limited variations to find a desirable solution or spent time (Arya *et al.*, 2004; Hoos, Stützle, 2004).

This algorithm can be considered as an innovative mechanism in which the neighbors of the current answer are investigated as its potential alternatives (Fränti, Kivijärvi, 2000). If one of the neighbors of the current answer is accepted, the movement will begin to the new answer and the neighbors of the new answer are taken into consideration (Sastry *et al.*, 2005). LSAs are widely used in a large number of computational issues, including computer science (Arya *et al.*, 2004; Hoos, Stützle, 2004). They are also useful in solving optimization problems in addition to finding the target (Hoos, Stützle, 2004). The structure of a local search algorithm is shown in Fig. 4. Local search starts with an initial solution, which is constantly improved with the use of neighborhood search and selection (Fränti, Kivijärvi, 2000). A set of candidate solutions is provided in each repetition by slightly correcting the existing solution (Fränti, Kivijärvi, 2000). Then, the best candidate is selected as the new solution (Fränti, Kivijärvi, 2000). Using multiple candidates makes the search to be improved in the optimization function (Fränti, Kivijärvi, 2000). The search is repeated as long as a stopping criterion is guaranteed (Fränti, Kivijärvi, 2000). In present study the search continued until the value of the absorption coefficient reached the maximum possible value. Since the maximum amount of SAC was not specified for some frequencies (i.e. absorption did not reach number one) there for, so much smaller search interval had a range of size zero (a point) approach. In this case, the point value would be optimized.

3. Results

Three morphological parameters were optimized at various frequencies and thicknesses. The results of optimized parameters predicted by LSA for 5, 10, 20, 30, and 40 mm thicknesses are presented in Tables 1 to 5. The range of all parameters were first determined from previous studies conducted based on the Lu model and their results were consistent with the model either numerically or experimentally (Wang, Lu, 1999; Lu *et al.*, 2000; Neithalath *et al.*, 2005; Hakamada *et al.*, 2006a; 2006b; Wang *et al.*, 2011).

For all thicknesses and at all frequencies, the ranges of parameters were first searched with the following steps for coarse tuning

$$\Delta D = 0.05\ \text{mm}, \qquad \Delta d = 0.005\ \text{mm}, \qquad \Delta\Omega = 5\%.$$

Then, each neighborhood of the approximate result obtained in the previous step was searched by the following smaller steps for fine tuning to find the exact answer

$$\Delta D = 0.005\ \text{mm}, \qquad \Delta d = 0.0005\ \text{mm}, \qquad \Delta\Omega = 1\%.$$

It was observed that there was a possibility of having an optimal amount at a point outside this range. Ensuring this issue was determined by including the boundary values in the searching ranges. In other words, when the optimal value is set to the specified boundary, it creates the possibility that the optimal value may be specified outside the range. Therefore, optimal values were obtained in an open space using the LSA as well. These values are specified in Tables 1 to 5 in gray color (second row). The predicted value of the sound absorption coefficient increased by searching the optimal values outside the ranges specified from other studies which are shown in last row of each table. Table 1 shows that searching for the optimal values of the parameters outside the range of other studies for an absorber with 5 mm thickness, increases the value of the SAC by 0.03% at 6 kHz up to 125.51% at 2 kHz. Table 2 indicates the results of optimal values of the main parameters in a thickness of 10 mm at each frequency.

Table 2 shows that higher sound absorption coefficients were obtained especially at low frequencies in an absorber with 10 mm thickness. The sound absorption coefficients at different frequencies are almost 1.

Table 1. The optimized morphological parameters for the highest SAC in a sound absorber with 5 mm thickness.

Frequency (f) [Hz]	500	1000	2000	3000	3500	4000	6000	8000
Prosity (Ω) [%]	50	50	80	95	95	95	95	85
	50	50	80	70	50	90	92	86
Pore size (D) [mm]	1.0	1.0	1.0	1.0	1.0	1.0	0.6	0.35
	3.1	3.1	4.55	2.5	2.1	2.1	0.61	0.31
Pore opening size (d) [mm]	0.08	0.1	0.1	0.095	0.1	0.1	0.095	0.09
	0.178	0.235	0.4	0.3	0.295	0.215	0.105	0.085
Sound absorption coefficient SAC (α)	0.1023	0.2125	0.4434	0.7062	0.8353	0.9001	0.9997	0.9992
	0.1644	0.4200	0.9999	0.9999	1.000	0.9951	1.000	1.000
Increase of SAC (α) [%]	60.70	97.65	125.51	41.59	19.72	10.55	0.03	0.08

White row: the optimal values from inside range search, gray row: the optimal values from outside range searching.

Table 2. The optimized morphological parameters for the highest SAC in a sound absorber with 10 mm thickness.

Frequency (f) [Hz]	500	1000	2000	3000	3500	4000	6000	8000
Prosity (Ω) [%]	65	90	95	95	95	95	95	95
	50	50	93	95	91	93	95	95
Pore size (D) [mm]	0.95	0.95	0.88	0.6	0.55	0.4	0.15	0.1
	4.13	4.13	2.37	0.88	0.67	0.45	0.14	0.09
Pore opening size (d) [mm]	0.1	0.095	0.1	0.1	0.1	0.09	0.06	0.07
	0.288	0.425	0.242	0.135	0.133	0.104	0.058	0.063
Sound absorption coefficient SAC (α)	0.1870	0.3781	0.7638	0.9556	0.9910	0.9987	0.9994	0.9951
	0.3406	0.8827	1.000	1.000	1.000	1.000	1.000	0.9999
Increase of SAC (α) [%]	82.14	133.46	30.92	4.65	0.91	0.13	0.06	0.48

White row: the optimal values from inside range search, gray row: the optimal values from outside range searching.

Table 3. The optimized morphological parameters for the highest SAC in a sound absorber with 20 mm thickness.

Frequency (f) [Hz]	500	1000	2000	3000	3500	4000	6000	8000
Prosity (Ω) [%]	95	95	95	94	95	92	95	95
	75	95	94	93	92	95	95	92
Pore size (D) [mm]	0.99	0.67	0.4	0.205	0.14	0.15	0.4	0.22
	6.2	4.29	0.64	0.22	0.16	0.14	0.56	0.25
Pore opening size (d) [mm]	0.0965	0.1	0.1	0.087	0.074	0.1	0.1	0.086
	0.475	0.351	0.142	0.093	0.089	0.101	0.134	0.102
Sound absorption coefficient SAC (α)	0.3496	0.6577	0.9732	0.9999	0.9999	0.9980	0.9733	0.9999
	0.7648	1.000	1.000	1.000	1.000	0.9997	1.000	1.000
Increase of SAC (α) [%]	118.76	52.05	2.75	0.01	0.01	0.17	2.74	0.01

White row: the optimal values from inside range search, gray row: the optimal values from outside range searching.

Table 3 reveals the optimal values of the morphological parameters in order to have the highest SAC in an absorber with a thickness of 20 mm.

Table 3 indicates that even higher sound absorption coefficients were obtained in an absorber with 20 mm thickness. Table 4 represents the results of optimal morphological parameters for a proposed absorber with a thickness of 30 mm.

Table 4 shows that at different frequencies, the SAC is close to 1 when the porosity is between 80 and 95%, pore size is between 0.1 and 1.8 mm, and pore opening size is between 0.09 and 0.25 mm. In most cases, the pore opening size is 0.1 mm. Table 5 gives the results of determining the optimal morphological parameters based on a LSA for a proposed absorber of 40 mm thickness.

Table 5 indicates that at different frequencies, the sound absorption is close to one when porosity is 95%, pore size is 0.1 to 0.9 mm, and pore opening size is 0.09 to 0.1 mm. In the thickness of 40 mm, the porosity is up to 95 percent, and the pore opening size is constant at 0.1 mm. Thus, the main role of LSA seems to be the

Table 4. The optimized morphological parameters for the highest SAC in a sound absorber with 30 mm thickness.

Frequency (f) [Hz]	500	1000	2000	3000	3500	4000	6000	8000
Prosity (Ω) [%]	95	95	95	95	95	95	95	95
	95	95	85	95	95	95	93	80
Pore size (D) [mm]	0.7	0.4	0.25	0.15	0.8	0.4	0.2	0.3
	1.45	1.8	0.3	0.16	1.1	0.6	0.21	0.5
Pore opening size (d) [mm]	0.1	0.1	0.1	0.1	0.1	0.1	0.095	0.1
	0.15	0.25	0.145	0.111	0.205	0.145	0.104	0.195
Sound absorption coefficient SAC (α)	0.4818	0.8131	0.9991	0.9909	0.9604	0.9336	0.9998	0.9846
	0.5377	0.9999	0.9998	0.9919	0.9999	0.9943	1.000	0.9995
Increase of SAC (α) [%]	11.60	22.97	0.07	0.10	4.11	6.50	0.02	1.51

White row: the optimal values from inside range search, gray row: the optimal values from outside range searching.

Table 5. The optimized morphological parameters for the highest SAC in a sound absorber with 40 mm thickness.

Frequency (f) [Hz]	500	1000	2000	3000	3500	4000	6000	8000
Prosity (Ω) [%]	95	95	95	95	95	95	95	95
	95	95	95	95	95	95	95	93
Pore size (D) [mm]	0.5	0.3	0.15	0.15	0.3	0.25	0.15	0.15
	2.15	0.9	0.2	0.8	0.5	0.3	0.45	0.2
Pore opening size (d) mm]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.09
	0.235	0.195	0.145	0.19	0.155	0.12	0.15	0.115
Sound absorption coefficient SAC (α)	0.5902	0.9034	0.9888	0.9241	0.9608	0.9882	0.9821	0.9937
	0.7944	0.9997	0.9995	1.000	0.9992	0.9986	0.9993	0.9999
Increase of SAC (α) [%]	34.60	10.66	1.08	8.21	4.00	1.05	1.75	0.62

White row: the optimal values from inside range search, gray row: the optimal values from outside range searching.

optimization of the pore size. Moreover, at a low frequency of 500 and 1000 Hz, there is an increase in SAC relative to the thickness of 5 mm. At low frequencies, by increasing thickness, the SAC increases.

Since the absorption coefficients at low frequencies are the main concern, therefore the highest SACs at the range of 0.5 to 3 kHz are shown in Fig. 5.

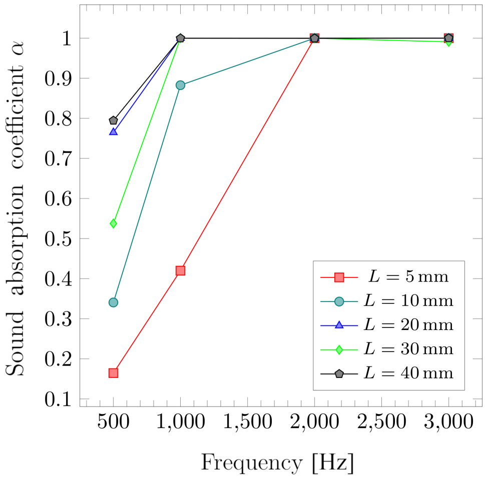

Fig. 5. The highest values of SAC obtained for optimized morphological parameters at lower frequencies and thicknesses.

According to Fig. 5, by increasing the thickness, the SAC increases at low frequencies, and at a frequency higher than 1000 Hz, with the optimization of pore size, porosity, and pore opening size, the SAC can be approximated to one. At the results reveal that at low frequencies, thickness has a significant effect on the SAC.

4. Discussion

This study showed that the application of Local Search Algorithm is a novel approach to predict the optimized morphological parameters in order to have the highest sound absorption in metal foams. This approach seems to be applicable to optimize other interested physical parameters to have the highest sound absorption in sound absorbers. The novelty of the work is that by having these optimized parameters of the metal foam, it is possible to produce foams with highest sound absorption coefficient. At present, the sintering technology lets to produce the metal foams with desired morphological sizes. The production of metal foams with the highest SAC using LSA approach along with sintering is not far from the reach. If this approach is experimentally approved, then it is expected to have intelligent metal foam sound absorbents. This is important particularly at low frequencies where at the present it is very difficult to have reasonable absorbents for them. The present tedious method of try and error will also be deleted to build the most desirable metal foam absorbents.

In this study, a Local Search Algorithm was applied to obtain the optimal pore size, pore opening size, porosity, and thickness for the highest sound absorption coefficient in a metal foam absorbent, according to the Lu model. The proposed computer codes written in the MATLAB were validated through benchmark data. According to the results the amplitude of the parameters in order to obtain the highest SAC (close to one) at the frequency range of 500 to 8000 Hz include a porosity of 50 to 95%, a pore size of 0.09 to 4.55 mm, and a pore opening size of 0.06 to 0.4 mm.

Moreover, based on the results of this study the SAC increases by increasing porosity, which indicates that highly porous materials are good absorbent materials. This is in line with the results of previous studies (Lu *et al.*, 2000; Xie *et al.*, 2004a; 2004b; Hakamada *et al.*, 2006a). Hakamada *et al.* (2006a) found that the SAC increases with porosity, which is also in line with the present study. Wang *et al.* (2007) showed that the SAC is affected by the structure of the cavity and pores. They also found that in the open cell aluminum foam, by increasing the porosity and reducing the pore diameter, the SAC increases which is consistent with the present study. The experimental results of Jin *et al.* (2015) showed that the sound absorption coefficient of foam gradually increases by decreasing pore size. In addition, when the porosity of the foam increases, the SAC increases which is in line with the current study. The results revealed that with a maximum porosity value of 95%, it is not possible to determine the constant value for pore size and pore opening size by increasing or decreasing frequency, which requires optimization at any frequency and thickness. However, Azizan *et al.* (2017) determined that at high frequencies, aluminum foams with bigger pores have higher acoustic absorbing properties than smaller pores. Wang and Lu (1999) stated that the optimal pore size for the best sound absorption is about 0.1 mm.

According to the results, for each maximum SAC, the optimal pore size was necessary and its range was from 0.09 to 4.55 mm. In Ke *et al.* (2011) study, the effect of particle size distribution (with an air gap) in semi-open cell metals on sound absorption was investigated. They found that grading particle size increases the sound absorption properties (Ke *et al.*, 2011). In Navacerrada *et al.* (2013) focused their study on aluminum foam with pore sizes of 0.5, 1, and 2 mm. The aluminum foam with 0.5 mm pore diameter showed the best absorption capacity, which is in line with the optimizing pore size range of 0.1 to 4.55 mm in the present study. In Raut *et al.* (2016) argued that by increasing foam thickness, the maximum sound absorption would change to low frequencies, which is consistent with the current study. They also stated that the sound absorption capacity depends on the pore size and the pore opening size. In this study, by considering a maximum porosity of 95%, the morphological parameters of pore size and pore opening size were optimized. Raut *et al.* (2016) stated that by reducing the pore opening size, the maximum absorption of sound moves to lower frequencies. This is not in line with the present study and a constant amount cannot be defined. Furthermore, by increasing the pore size, the maximum absorption moves down to low frequencies, which is consistent with this study only in the thickness of 10 mm. In Li *et al.* (2011) concluded that the SAC increases by increasing the number of pore openings in the unit region or by decreasing the pore opening size in the range of 0.3–0.4 mm. Their results are in the optimization range of the present study. However, the optimum SAC in this study is at the pore opening size of 0.1 mm (Li *et al.*, 2011).

Studies have confirmed that there is a correlation between SAC and flow resistance (Lu *et al.*, 2000; Hakamada *et al.*, 2006a). Pore opening size plays a significant role in the flow resistance of porous metals (Despois, Mortensen, 2005; Hakamada *et al.*, 2006a). Recent studies clearly show the importance of controlling the pore opening size for absorbing sound (Hakamada *et al.*, 2006a). In this study, this parameter varies at each frequency and thickness. The Lu model which exactly explains the sound absorption of porous metals, expresses the significance of the pore opening size effect (Hakamada *et al.*, 2006a).

Li *et al.* (2014) showed that pore opening walls play an important role in determining the foam sound absorption behavior, which is due to the significant effect of resistance to airflow. By decreasing pore opening size, the airflow resistance increases and the maximum absorption moves to lower frequencies, while its value decreases. According to the results, a constant value cannot be expressed for it. Hakamada *et al.* (2006a) stated that the presence of a pore opening size smaller than 100 μm, (which is special for porous metals produced by the Spacer method) greatly improves the absorption properties. This is also about 0.1 mm in present study (Hakamada *et al.*, 2006a). It is definitely shown that pore opening size greatly affects the sound absorption behavior of porous Al produced by the method.

Therefore, controlling of the pore opening sizes to obtain high sound absorption capacity is important (Hakamada *et al.*, 2006a). The small pore openings that connect the large pores let the sound waves to enter the pore structure. When the air moves from the large pores into the much smaller pore openings, the air speed increases leading to high pore surface friction. This can broke down the sound waves entered the pore structure (Li *et al.*, 2011).

According to the results of this study, in all frequencies and thicknesses, the pore opening size is 0.06 to 0.4 mm. Li *et al.* (2011) stated that the SAC increases with an increase in the number of pore openings in the unit area or with a decrease of the diameter of the pore openings in the range of 0.3 to 0.4 mm. Wang and Lu (1999) suggested that optimum cell size is about 0.1 mm for optimal sound absorption, which is in accordance with this study. Therefore, the airflow speed will change a little by passing through the pores when the pore opening size is too large. Moreover, the resulting loss from the friction will not be high (Hakamada *et al.*, 2006a; Li *et al.*, 2011). However, when the pore opening size is too small, the airflow resistance will be too high. Therefore, most of the sound waves will not enter to the materials and will be reflected from the sample surface. Moreover, it leads to weak sound absorption (Wang, Lu, 1999; Chen *et al.*, 2001; Hakamada *et al.*, 2006a; Li *et al.*, 2011). Regarding aluminum foams with the same porosity and pore shape, the pore opening size and the sample thickness are very important for the air flow resistance (Lu *et al.*, 2000; Li *et al.*, 2011). This shows that the contribution of friction (enhanced by the pore openings) in sound wave energy loss is more important compared to those of viscous and thermal losses by the large pores (Lu *et al.*, 1999; Han *et al.*, 2003; Li *et al.*, 2011). Therefore, the pore opening size strongly affects sound absorption behavior, and controlling of the pore opening size to achieve high SAC is important (Hakamada *et al.*, 2006a).

Figure 5 shows that, at low frequencies (of 500 and 1000 Hz), by increasing thickness from 5 to 40 mm, the SAC increases from 0.4 to 0.99, respectively, which is similar to the study of Hakamada *et al.* (2006a). Furthermore, in Wang *et al.* (2011) stated that the SAC was low due to the relatively thin sample thickness and open porosity of 90% or more at low frequencies. As the frequency or sample thickness increases, sound absorption increases significantly (Wang, Lu, 1999). Han *et al.* (2003) included that increasing in sample thickness also increases the resistance to flow as well as the absorption capacity. Li *et al.* (2011) stated that increasing sample thickness increases the absorption peak and moves it toward the low frequencies. They also noted that the effect of sample thickness on sound absorption is understandable due to long propagation distance in relatively thick specimens. This leads to an increase in the interaction of the sound wave with the pores walls (Li *et al.*, 2011). It has been shown that sound absorption coefficients predicted using the optimized morphological parameters were much higher than hose obtained through conducting empirical or numerical studies.

5. Conclusions

In this study, an optimization tool was applied to predict the optimized morphological parameter of porous metal materials. The optimized morphological parameters including porosity, pore size and pore opening size were predicted in order to have the highest sound absorption coefficient. The optimized parameters can be used to produce metal foams with a considerable high sound absorption capacity. The method presented in this study can be a reliable reference and guide for future studies to optimize micro-structural parameters and increase the SAC at any frequency, and can also help to produce the optimized metal foam. The results of this study were compared with other studies carried out using the Lu model, and the results are roughly the same. Production and examination of Al metal foam based on this study in undergoing in order to validate the results experimentally. The results of the study will be the title of another article in the near future. Local search algorithm' makes the Lu's original model easier/faster to use, or more efficiently to obtain the absorption evaluation result. The application of this method helps to decrease tedious laboratory try and error tests to have an optimized metal foam as sound absorbent.

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