Research Article

Open Access

Yonghua Wang, Shengfu Liu, Haiquan Wu, Chengchun Zhang, Jinkai Xu and Huadong Yu*

On-demand optimize design of sound-absorbing porous material based on multi-population genetic algorithm

<https://doi.org/10.1515/epoly-2020-0014>

Received October 19, 2019; accepted January 11, 2020.

Abstract: Porous material (PM) shows good sound absorption performance, however, the sound absorbing property of PM with different parameters are greatly different. In order to match the most suitable absorbing materials with the most satisfactory sound-absorbing performance according to the noise spectrum in different practical applications, multi-population genetic algorithm is used in this paper to optimize the parameters of porous sound absorbing structures that are commonly used according to the actual demand of noise reduction and experimental verification. The results shows that the optimization results of multi-population genetic algorithm are obviously better than the standard genetic algorithm in terms of sound absorption performance and sound absorption bandwidth. The average acoustic absorption coefficient of PM can reach above 0.6 in the range of medium frequency, and over 0.8 in the range of high frequency through optimization design. At a mid-to-high frequency environment, the PM has a better sound absorption effect and a wider frequency band than that of micro-perforated plate. However, it has a poor sound absorption effect at low

frequency. So it is necessary to select suitable sound absorption material according to the actual noise spectrum.

Keywords: multi-population genetic algorithm; parameter optimize; porous material

1 Introduction

Due to the sound-absorption performance of different sound absorbing materials in different frequency bands is not identical. In order to improve the efficiency, the application feasibility and to avoid blindness of noise control, we need to find a set of appropriate structural parameters to achieve satisfactory sound absorption performance within a given frequency range. On the other hand, the noise and vibration concerned in practical engineering are usually a certain (or several) fixed frequency or a certain range of (or several) specific frequency. Therefore, it is necessary to study the micro structure design of materials with the required acoustic properties in a specific frequency band.

There have been many studies so far on the sound absorption structures of micro-perforated plate (MPP) on-demand, Ma (1) presented an on-demand design method for a single aperture MPP sound absorber, Sui et al. (2) and Yang studied the simple genetic algorithm in the application of double-layer structure optimization design of MPP, Zhao et al. (3) adopted simple genetic algorithm to optimize three-layer MPP. However, the simple genetic algorithm cannot search for the global optimal value (4). Simulate annealing algorithm is applied by many scholars in a variety of sound absorption structure optimization design. For example, Chang et al. (5) optimized the design of composite sound-absorption material with plate thickness limitation, and Heidi et al. (6) realized the optimization design of sound-absorbing structure of multi-layer MPP. Although the simulate annealing algorithm has simple calculation process and strong robustness, There are disadvantages of slow convergence rate, algorithm performance related to initial

* **Corresponding author: Huadong Yu**, Ministry of Education Key Laboratory for Cross-Scale Micro and Nano Manufacturing, Changchun University of Science and Technology, Changchun 130022, China, email: yuhuadong@cust.edu.cn

Yonghua Wang, Ministry of Education Key Laboratory for Cross-Scale Micro and Nano Manufacturing, Changchun University of Science and Technology, Changchun 130022, China; Key Laboratory of Bionic Engineering (Ministry of Education), Jilin University, Changchun 130022, China

Shengfu Liu, Ministry of Education Key Laboratory for Cross-Scale Micro and Nano Manufacturing, Changchun University of Science and Technology, Changchun 130022, China

Haiquan Wu, COMAC Shanghai Aircraft Design & Research Institute, Shanghai 200120, China

Chengchun Zhang, Key Laboratory of Bionic Engineering (Ministry of Education), Jilin University, Changchun 130022, China

Jinkai Xu, Ministry of Education Key Laboratory for Cross-Scale Micro and Nano Manufacturing, Changchun University of Science and Technology, Changchun 130022, China

value and so on. In addition, Fackler et al. (7) based on Bayesian network inference algorithm to estimate the parameters of single-layer and multi-layer MPP sound absorption structure, and obtained satisfactory sound absorption performance. However, the calculation process of Bayesian network inference algorithm is complex, which is not conducive to practical application. Qian (8) optimized the acoustic absorption structure of multi-aperture MPP with multi-population genetic algorithm (MPGA). Based on Johnson-Champoux-Allard model, Bonfiglio et al. (9) obtained the optimal acoustic parameter values by using genetic algorithm respectively. Based on the Lafarge-Allard model, Sellen et al. (10) obtained the acoustic parameter values of PM by the method of inverse extrapolation. Zhou et al. (11) obtained the acoustic parameters of the felt by the reverse method. Based on Johnson-Champoux-Allard model, Zhang and Chen (12) deduced the acoustic parameters of metal fiber PMs by simulated annealing hybrid genetic algorithm and sequence quadratic programming method, meanwhile, the correctness of the reverse method was verified.

The paper aims to adopt MPGA to find out the optimal combination of parameters, within the given range of structural parameters to achieve the largest average sound absorption coefficient within the given range of noise frequency resulting in optimal sound absorption performance, and to expand the application range of on-demand design of sound absorption structure.

2 Test method

2.1 Acoustic model of PM

PM is composed of solid phase (skeleton) and liquid phase (usually air), and the liquid phase fills these skeletons to form an inter-connective sound absorbent of PM (13,14). Common porous acoustic models include empirical models and equivalent fluid models (15). However, the disadvantage of the empirical model is that there is only one parameter of flow resistance σ , which cannot comprehensively characterize the sound absorption performance of PM. Johnson-allard model and Lafarge-Allard model are the most commonly used equivalent fluid models under the premise that the PM skeleton is rigid, detailed introduction is as follows.

2.1.1 Johnson-Allard model

In Johnson-Allard model, effective density and dynamic compression can be characterized by five parameters,

including resistivity σ , porosity Φ , tortuosity α_∞ , thermal characteristic length Λ' and viscous characteristic length Λ .

Viscosity effect and inertia (16):

$$\rho_e(w) = \alpha_\infty \rho_0 \left(1 - \frac{j\sigma\Phi \left(1 + \frac{4j\alpha_\infty^2 \eta \rho_0 w}{\sigma^2 \Phi^2 \Lambda^2} \right)^{\frac{1}{2}}}{\rho_0 \alpha_\infty w} \right) \quad (1)$$

Thermal effect:

$$K(w) = \frac{\gamma P_0}{\gamma - (\gamma - 1) \frac{1}{1 + \frac{8\eta}{j\Lambda'^2 \rho_0 P_r w} \left(1 + \frac{j\Lambda'^2 \rho_0 P_r w}{16\eta} \right)}} \quad (2)$$

2.1.2 Lafarge-Allard model

Lafarge-Allard model represents the thermal permeability between the rigid skeleton and the hole k_0' , which is defined by viscous permeability similar to Darcy's law, and is more accurate at low frequency, expressed by trapping constant Γ :

$$k_0' = M' / \Gamma \quad (3)$$

while the trapping constant is expressed as $\Gamma = \frac{8}{\Phi \Lambda'}$ for cylindrical hole with circular section.

Effective density does not consider the viscosity and inertial coupling in saturated fluid and skeleton, so the thermal permeability introduced by thermal modeling has no effect on its expression, while dynamic compression generates a new expression containing M' :

$$K(w) = \frac{\gamma P_0}{\gamma - \frac{\gamma - 1}{1 - j \frac{w_0}{w} \left(1 + j \frac{M' w}{2 w_0} \right)^{\frac{1}{2}}}} \quad (4)$$

where: M' takes 1 to obtain the expression of dynamic compression in Johnson-Allard model.

For Johnson-Allard and Lafarge-Allard models, the effective volume is different. Lafarge-Allard model introduces static thermal conductivity k_0' , while static thermal conductivity does not have a definite expression when the hole section is not circular, so the scope of

application is narrow. Therefore, Johnson-Allard model is used in this paper to analyze the influencing factors of sound absorption performance of PM.

2.2 Parameters influence of PM

The Johnson-Allard model of PM was established by MATLAB, and the effects of material thickness, flow resistance, porosity and tortuosity on the acoustic properties of PM were calculated respectively. Set a fixed number $\Lambda = 1.7 \times 10^{-5}$, $\Lambda' = 4.0 \times 10^{-5}$. When $\sigma = 30000$, $\alpha_{\infty} = 1$ and $\Phi = 85\%$ is constant, and e is taken as 10 mm, 20 mm, 30 mm, 40 mm and 50 mm, respectively. When $\alpha_{\infty} = 1$, $\Phi = 85\%$ and $e = 30$ mm is constant, the flow resistance σ is taken as 10000, 30000, 50000, 70000 and 90000, respectively. When $\sigma = 30000$, $\alpha_{\infty} = 1$, $e = 30$ mm is constant, the porosity Φ is taken as 55%, 65%, 75%, 85% and 95%, respectively. When $\sigma = 30000$, $e = 30$ mm, $\Phi = 85\%$ is constant, curvature α_{∞} was taken as 1, 1.1, 1.2, 1.3, 1.4, and the results were shown in Figure 1.

Figure 1 indicates that the thickness of PM has the greatest influence on its sound absorption performance. With the increase of plate thickness e , the maximum sound absorption coefficient rapidly moves to low frequency, but the value of the maximum sound absorption coefficient decreases slightly. Secondly, with the porosity increasing, the whole sound absorption coefficient increases. Then, as the flow resistance σ increases, the peak value of the sound absorption coefficient of the PM sound absorber gradually decreases, the sound absorption performance of the middle frequency band decreases, and the sound absorption bandwidth basically remains unchanged. With the increase of curvature α_{∞} , the sound absorption performance moves to low frequency and the sound absorption bandwidth remains basically unchanged. In conclusion, larger porosity and material thickness can improve the sound absorption coefficient and broaden the sound absorption band. The increase of flow resistance will lead to the decrease of sound absorption peak value of PMs, while the curvature has little effect on sound absorption performance. Therefore, in the parameter design of PMs, the function of each parameter should be considered systematically and comprehensively, to select the appropriate and effective parameter combination.

2.3 Multi-population genetic algorithm and feasibility verification

Multi-population genetical algorithm (MPGA) developed from the standard genetic algorithm by adding global

search strategy and migration strategy (17). The advantages of MPGA are as follows:

- (1) Introducing multiple populations for collaborative optimization search; as a result, search efficiency is improved, convergence accuracy is increased, and the monotony of standard genetic algorithm can be overcome.
- (2) Introducing Migration: as a matter of fact, Migration means simple the additions of new operators based on the standard genetic algorithm to form an exchange relationship between multiple population and make good individuals Shared between populations, speed up the convergence speed and the precision of the optimal solution significantly.

The basic principle of MPGA is shown in Figure 2a. the evolutionary mechanism of population 1~N adds two control parameters including migration operator and manual selection based on the selection, crossover and mutation of standard genetic algorithm to avoid premature convergence of the optimization process. Most scholars set the genetic algebra as the condition for the termination of the genetic algorithm. In this way, the difficulty of the program can be reduced and the accuracy of the optimal solution can be improved, but the calculation amount and solution time can be increased to a certain extent. Similarly. The larger the population size, the higher the accuracy of solution and the longer the time. The crossover probability P_c is generally takes 0.7~0.9, and the probability of variation P_m is usually 0.001~0.005.

Optimization design steps of porous sound-AM based on MPGA are as follows:

- (1) Establish an optimization model
Firstly, establish the objective function to maximize the average sound absorption coefficient of PM within a certain frequency range:

$$\max(Y) = \int_{f_1}^{f_2} \alpha(f) df \quad (5)$$

In the formula, f_1 and f_2 represent the given lower and upper limit frequency, respectively, and $\alpha(f)$ are sound absorption coefficients.

- (2) Determine the decision variables and constraints
The Johnson-Allard model of PM has 6 parameters (5 acoustic parameters and 1 structural parameter thickness), among which two thermal characteristic constants have little influence on the sound-absorbing coefficient. The fixed value is set as $\Lambda = 1.7 \times 10^{-5}$, the constraint conditions of thermal characteristic length

Figure 1: Influence of various parameters on sound absorption coefficient of PM: (a) thickness e , (b) flow resistance σ , (c) porosity Φ , (d) curvature α_∞ .

$\Lambda' = 4.0 \times 10^{-5}$, flow resistance σ , porosity Φ , curvature α_∞ and material thickness e are set as follows:
 $10000 \leq \sigma \leq 50000$, $0.80 \leq \Phi \leq 0.98$, $1 \leq \alpha_\infty \leq 1.5$, $5 \text{ mm} \leq e \leq 50 \text{ mm}$,

- (3) Determine the operation parameters of the MPGA
- Number of population $MP = 20$, number of individuals $NIND = 50$.
 - Cross probability $P_c = 0.7 + (0.9 - 0.7) \times \text{rand}(MP, 1)$, randomly generated probability within 0.7~0.9.
 - Probability of variation $P_m = 0.001 + (0.05 - 0.001) \times \text{rand}(MP, 1)$, randomly generated within 0.001~0.05.
 - Termination condition: the minimum retention algebra of the optimal individual in the elite population MAXGEN is set as 80.

Firstly, MPGA was used to solve the optimal value of a simple function $y = -x^2 + 3$, and the range of x

was set to $-10 \sim 10$. The optimization results are shown in Figure 2b. Which illustrates that the number of individuals keeps increasing with the evolutionary algebra, and individuals were constantly gathering at the vertex of the function to obtain, the optimal value $y = 3$, the feasibility of the algorithm could be identified preliminarily.

3 Validation of PM model

The most commonly used PM is polyurethane foam, which has the advantages of light weight, abrasion resistance, corrosion resistance, low processing cost, cutting resistance, tear resistance, high bearing capacity (18) and loss resistance. It is widely used in household, construction, aviation and other fields (19,20). So take

Figure 2: Flow diagram of MPGA (a) and function optimization result diagram (b).

a polyurethane foam with thickness $e = 40$ mm as an example, the flow resistivity and porosity are tested with self-made equipment, and then tortuosity, thermal and viscosity characteristics constant are got by the reverse method. Finally, based on these parameters, Johnson-Allard model was used to calculate the sound absorption coefficient, and compared with the experimental values.

3.1 Flow resistance determination of PM

To measure the flow resistance of PM based on the direct method (21-23), the equipment needed for flow resistance measurement are shown in Table 1. The device connection and PM sample are shown in Figure 3. As can be seen from the SEM, PM presents interconnected holes with diameters between 0.1 mm and 2 mm.

First, measured the bottom diameter d of PM and calculated its surface area S . Placed the PM specimen in a container and injected distilled water into the u-shaped manometer. The water column at both ends was of moderate height and placed the u-shaped manometer vertically. Then, opened the air supply source, adjusted the flow control valve above the air compressor and air flowmeter, and waited for the float in the air flowmeter to be stable, the height of the water column in the u-shaped manometer will not change. Δh is the height difference

of the water column on both sides of the u-shaped tube, Q is the air flowmeter. The linear velocity of air flow is $u = \frac{Q}{S}$, the static pressure difference between two sides of PM is $\Delta p = \rho g \Delta h$.

The flow resistance can be obtained by the following equation:

$$\sigma = \frac{1}{D} \cdot \frac{\Delta p}{u} \quad (6)$$

where: D is the thickness of the sample, and then the base area S is calculated; ρ is the density of the pressure gauge liquid (kg/m^3); g is the acceleration of gravity (m/s^2).

Finally, all the tests were repeated five times and results were averaged.

3.2 Determination of PM porosity

To begin with, mass-volume method, the most commonly used with higher accuracy (24), was used to measure porosity of PM. When measuring the diameter, select at least 5 positions for each size and get the average of such values. The density of the polyurethane foam corresponding to the dense solid is 500 kg/m^3 . The calculation formula is as follows:

$$\Phi = \left(1 - \frac{M}{V \rho_s} \right) \times 100\% \quad (7)$$

where: M is the quality of the sample, V is the volume of the sample and ρ_s is the density of the dense solid corresponding to the PM.

The measured material thickness was $d = 40$ mm, air flow was $Q = 5125 \text{ L/h}$, and height difference of water column was $\Delta h = 8$ mm. According to the calculation the flow resistance of PM was $\sigma = 10800$, the porosity was $\Phi = 0.87$.

Table 1: Equipment and model of flow resistance measuring device.

Serial number	Equipment name	Amount	Model
1	Air compressor	1	QTS-550
2	U-type pressure gauge	1	BYJU
3	Air flow meter	1	LZB-15
4	Test piece placement container	1	
5	Rubber hose	3	
6	Vacuum seal, tape, etc.	Several

Figure 3: SEM of sample PM (a) and physical drawing of flow resistance measurement equipment (b).

Then the sound absorption performance of the polyurethane foam at 50-1600 Hz was tested with acoustic impedance tube, backed with an cavity $D = 30$ mm. The material used and impedance tube test equipment were shown in Figure 4, and the test was repeated five times and results were averaged. On the basis of the flow resistance and porosity of the test, then the least square method was used to fit the calculated value with Johnson-Allard model with experimental test values, Results showed that the optimized tortuosity was 1.8, the viscosity characteristic constant was 7.8×10^{-4} and the thermal characteristic constant was 3×10^{-4} . Finally, the theoretical sound absorption efficient results of Johnson-Allard model was compared with test results (25), and shown in Figure 5.

Figure 5 revealed that the experimental results were basically consistent with the theoretical predictions. It can be seen that the sound absorbers of PM had one sound absorption peak, which had a good sound absorption effect at high frequency and a relatively large frequency band. This experiment proves the correctness of the theoretical model of PM and improves theoretical support for the subsequent optimization of double-layer sound absorbers.

4 On-demand optimized design of PM

4.1 Optimized results

On-demand optimization design was carried out at low frequency band (200-500 Hz), middle frequency band (500-1000 Hz), high frequency band (1500-5000 Hz), as well as fixed point frequency ($f_1 = f_2 = 1000$ Hz), respectively. The parameters optimization results were shown in Table 2 and the sound absorption coefficient curve was shown in Figure 6 which reveals that the sound absorption coefficient curves obtained under different optimization conditions were basically consistent with the set conditions. For low-frequency optimization, the peak value is 0.94 at 550 Hz. The sound absorption effect is best at low frequency while worse at the middle frequency. For the mid-band optimization, the sound absorption effect is the best in the mid-band and the sound absorption peak value is 0.97 at 820 Hz. In the range of 500 ~ 1500 Hz, the sound absorption coefficients of PM are all higher than 0.6. For high-frequency

Figure 4: Impedance tube for the test of sound absorption coefficients.

Figure 5: Comparison of experimental and simulation results.

optimization, the sound absorption coefficients of PM are above 0.8 at 1500–5000 Hz, and the sound absorption peak value is close to 1 at about 2000 Hz. For the fixed frequency optimization of 1000 Hz, the sound absorption peak value is exactly at the place where $f = 1000$ Hz, and the sound absorption coefficient can reach 0.98. On the whole, different parameters of PM have great differences in sound absorption performance, which indicates that on-demand optimization plays a good guiding and promotion role in avoiding noise control blindness.

The evolution process of the optimal value of sound absorption coefficient is shown in Figure 7, which shows that in the low-frequency optimization, the maximum sound absorption coefficient of PM tends to the optimal value of 0.92 after 60 iterations. In the middle-frequency optimization, the maximum sound absorption coefficient tends to the optimal value of 0.962 after 40 iterations. In the high-frequency optimization, the maximum sound absorption coefficient tends to the optimal value of 0.995 after 10 iterations, and the maximum sound absorption coefficient can be taken as 1. For the fixed point frequency optimization, the calculation amount is small, so the evolution process of sound absorption coefficient of single-layer PM is relatively stable when $f = 1000$ Hz.

Table 2: On-demand optimization parameters of PM at different frequency bands.

Conditions	σ	Φ	α_{∞}	e (mm)
low frequency band	10234.56	0.969	1.1421	49.79
middle frequency band	10003.7	0.976	1.0287	37.466
high frequency band	10035.553	0.979	1.0002	18.803
fixed point frequency band	10145.6834	0.977	1.0001	32.738

The evolution process of the optimal average value of the maximum sound absorption coefficient is shown in Figure 8. In low-frequency optimization, the average value gradually increases with the increase of the number of iterations, The average value tends to be stable and fluctuates between 0.7 and 0.8 after 15 iterations. In middle-frequency optimization, the average value tends to be stable and fluctuates around 0.85 after 25 iterations. In high-frequency optimization, the average value of the maximum acoustic absorption coefficient of the PM fluctuates greatly, and it tends to be stable after 60 iterations. In the process of fixed-frequency point optimization, it tends to be stable after 15 iterations.

4.2 Limits

As we know, the sound absorption performance of MPP is directly related to its structural parameters (aperture, perforation rate and plate thickness). After obtaining the optimized structural parameters, it is easy to produce MPP completely consistent with the optimized parameters through mechanical processing, so as to guide practical application. While for PM taking polyurethane foam as an example, the preparation parameters involves the mix ratio of each component such as polyol, modified MDI, catalyst, silicone oil. As PM prepared with different parameters have different pore sizes, porosity, density, etc., the corresponding sound absorption properties varies greatly. On the other hand, the acoustic model of PM is an idealized equivalent model and its acoustic absorption performance is related to the acoustic parameters (resistivity, porosity, tortuosity, characteristic length, etc.) of bubbles with different structural parameters.

Figure 6: On-demand optimization results for PM at different frequency bands and fixed point frequency.

Figure 7: Sound absorption coefficient evolution process of PM at different frequency bands and fixed frequency points: (a) in low frequency band, (b) in middle frequency band, (c) in high frequency band, (d) at fixed point frequency.

What we obtained by the algorithm is only the acoustic parameters of PM and how to establish the relationship between the acoustic characteristic parameters and the preparation parameters is the most critical step to guide the on-demand optimization of PM for the practical applications. The relationship between different types of PM (such as polyurethane foam, fiberglass, glass wool, etc.) is definitely quite different. It is still feasible to establish the relationship between the acoustic parameters and preparation parameters in the case of the same kind of material and preparation method. The author has previously published an article, in which the optimal acoustic characteristic parameters were obtained through identification of characteristic parameters based on polyurethane foam materials with different mixing proportions (26). However, due to the limited sample size, if a large number of experimental verification statistics can be carried out in the future, the practical application of PM on-demand optimization will be promoted.

5 Conclusions

Based on Johnson-Allard acoustic model, this paper adopts MPGA to optimize the sound absorption performance of PM at low, middle and high frequency bands as well as fixed points frequency as needed respectively. The validity of the MPGA is verified in terms of the feasibility of the algorithm and the validity of the acoustic model. The results show that the acoustic absorption coefficient peak and the bandwidth of the absorption materials optimized by MPGA are better than those of the standard genetic algorithm. Moreover, the optimization results of different frequency bands are in good agreement with the requirements. For the optimization of fixed points frequency, although the sound absorption peak can be obtained at fixed frequency points, the acoustic performance of other frequency bands may be sacrificed, and appropriate acoustic optimization needs to be carried out according to the noise spectrum of specific occasions.

Figure 8: Maximum sound absorption coefficient variation process of PM at different frequency bands and fixed frequency points: (a) in low frequency band, (b) in middle frequency band, (c) in high frequency band, (d) at fixed point frequency.

Acknowledgement: All support is greatly acknowledged and appreciated, especially the constructive discussion and criticism from colleagues. Thanks are due to Project supported by the National Natural Science Foundation of China (Grant No. 51705033, U19A200125), the Education Department of Jilin Province (Grant No.: JJKH20190560KJ), the Science and Technology Department of Jilin province (Grant No.: 20190103001JH and 20180101324) provide financial support for this article.

References

1. Ma D.Y., Theory and design of sound absorption structure of micro-perforated plate. *Sci. China*, 1975, 18(1), 40-52.
2. Sui L.Q., Zhao X.D., Zhu R.Y., Application of genetic algorithm in optimal design of double-layer micro-perforation structure. *Noise Vib. Control.*, 2006, 26(2), 49-52.
3. Zhao X.D., Zhang X.J., Jiang Z., Optimum Design and Characteristic Analysis of Three-layer Microperforated Plate. *Acta Acust.*, 2008, 33(1), 84-87.
4. Qu Z.J., Zhang X.W., Cao Y.F., Liu X.H., Feng X.H., Research on genetic algorithm based on adaptive mechanism. *Appl. Res. Comput.*, 2015, 32(11), 3222-3225.
5. Chang Y.C., Yeh L.J., Chiu M.C., Optimization of constrained composite absorbers using simulated annealing. *Appl. Acoust.*, 2005, 66(3), 341-352.
6. Ruiz H., Cobo P., Jacobsen F., Optimization of multiple-layer microperforated panels by simulated annealing. *Appl. Acoust.*, 2011, 72(10), 772-776.
7. Fackler C., Dieckman E., Xiang N., Porous material parameter estimation: A Bayesian approach. *AIP Conference Proceedings (American Institute of Physics)*, 2012, 1443(1), 314-321.
8. Qian Y.J., Study on broadband single-layer Micro-perforated panel sound absorber. PhD thesis, University of Science and Technology of China, 2014, 1-50.
9. Bonfiglio P., Pompili F., Inversion Problems for Determining Physical Parameters of Porous Materials: Overview and Comparison Between Different Methods. *Acta Acust. United Ac.*, 2013, 99(3), 341-351.
10. Sellen N., Gall M., Hilbrunner O., Identification of the characteristic parameters of porous media using active control. *American Institute of Aeronautics and Astronautics*, 2013.

11. Zhou G.J., Tian X.J., Zhu K.D., Huang W., Study on the influence of material parameters to acoustic performance. *Sea Technical Papers*, 2015, 2015(1), 1-17.
12. Zhang B., Chen T.N., Research on Acoustic Parameters of Porous Metal Materials. *Ningxia Eng. Technol.*, 2009, 8(1), 43-47.
13. Liu Y.G., Wang X.L., Effect of skeleton parameters of viscoelastic foam porous material on sound absorption performance of materials. *J. Vib. Shock*, 2016, 35(20), 137-141.
14. Wang X.L., Optimization model of sound absorbing panels for porous metal materials. *Acta Acust.*, 2007, 32(02), 22-27.
15. Wang Y.H., Zhang C.C., Wang J., Shi L., Zhang X.P., Sound Absorption Properties of Biomimetic Porous Materials. *J. Jilin Univ.-Technol. Ed.*, 2012, 164(6), 1442-1447.
16. Allard J.F., Atalla N., Propagation of sound in porous media. *Modelling sound absorbing materials* (2nd ed.). John Wiley & Sons, Ltd, 2009, 243-281, DOI:10.1002/9780470747339,
17. He W.H., Wang J.L., Hu L.S., Improvement and application of real-coded multi-population genetic algorithm. *Chin. J. Geophys.*, 2009, 52(10), 232-239.
18. Wang J.J., Lui Z.W., Qian Z.H., Ren L.Q., Soft tissue artifact evaluation of the cervical spine in motion patterns of flexion and lateral bending: a preliminary study. *PeerJ.*, 2016, 4(3), e1893, DOI:10.7717/peerj.1893.
19. Howard G.T., Biodegradation of polyurethane: a review. *Int. Biodeter. Biodegr.*, 2002, 49(4), 245-252.
20. Murphy J.G., Rogerson G.A., A method to model simple tension experiments using finite elasticity theory with an application to some polyurethane foams. *Int. J. Eng. Sci.*, 2002, 40(5), 499-510.
21. Fellah Z.E.A., Fellah M., Sebaa N., Lauriks W., Depollier C., Measuring flow resistivity of porous materials at low frequencies range via acoustic transmitted waves. *J. Acoust. Soc. Am.*, 2006, 119(4), 1926-1928.
22. Brown R.J.S., Connection between formation factor for electrical resistivity and fluid-solid coupling factor in Biot's equations for acoustic waves in fluid-filled porous media. *Geophysics*, 2012, 45(8), 514-514.
23. Wang L.W., Chen S.M., Analysis and Optimization of Sound Absorption Properties of Automotive Porous Materials. *MSc thesis*, Jilin University, China, 2017.
24. Liu X., Hu Y.F., Xiong J.J., Study on the determination method of porosity of graphite porous materials. *Lubricating Oil*, 2012, 35(10), 99-101.
25. Doutres O., Salissou Y., Atalla N., Panneton R., Evaluation of the acoustic and non-acoustic properties of sound absorbing materials using a three-microphone impedance tube. *Appl. Acoust.*, 2012, 71(6), 506-509.
26. Wang Y.H., Wu H.Q., Zhang C.C., Ren L.Q., Yu H.D., Galland M.A., et al., Acoustic Characteristics Parameters of Polyurethane/Rice Husk Composites. *Polym. Composite.*, 2019, 40(7), 2653-2661.