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Numerical Investigation on the Transmission Loss of Skin Panels Based on the Intelligent PSO-CGA Algorithm

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ABSTRACT In the reported research, they only analyzed the impacts of restraint damping parameters on acoustic characteristics of skin panels, but failed to adopt advanced optimization algorithms to conduct an optimization design on restraint damping effects. In addition, they did not conduct further research on noises in cabins with skin panels as the basis. Aiming at these questions, according to the acoustic model and the PSO-CGA algorithm, the acoustic characteristics of the skin panel were conducted a multi-objective optimization, and a better structure with low noise and light weight was finally obtained. The computational model was also validated by its experimental test. In order to verify the effectiveness of the PSO-CGA algorithm after parameter selection, it was compared with the traditional CGA and PSO algorithm. Three kinds of algorithms adopted the same population to conduct a multi-objective optimization of transmission loss of skin panels. Optimized results showed that: the PSO-CGA model in the paper had a high clustering degree. Transmission loss of most iteration points was obviously more than those of other two kinds of algorithms. Noises in the cabin could be improved effectively.

INDEX TERMS Skin panels, transmission loss, CGA algorithm, PSO algorithm, novel PSO-CGA algorithm.

I. INTRODUCTION

During initial design of civil aircrafts at the earlier stage, cabin noises are very serious and do not affect safety performance of the aircrafts. Therefore, at that time, they do not draw enough attention of aircraft designers and manufacturers. However, it is shown in many researches that serious cabin noises will affect comfort of passengers and pilots and may lead to their fatigue, heartbeat acceleration and blood pressure rise. In addition, equipment and instruments in aircrafts will generate phenomena including instability and sensitiveness weakening due to cabin noises and vibrations [1]–[5]. Therefore, noises in passenger aircraft cabins gradually become an important index at the aircraft design stage [6]. In recent years, the tendency has been strengthened gradually. Transmission loss is also called as sound insulation amount which is an important parameter used to judge sound insulation abilities of aircraft structures. As an effective approach for noise reduction control in cabins, analysis and optimization of transmission loss characteristics of skin panels already draw attention of aircraft acoustics designers.

At present, a lot of research achievements have been obtained for acoustic characteristics of skin panels. Liu [7] proposed a novel method which predicts the sound radiation of aircraft panels. The method is the extension of an earlier deterministic approach, where the modal expansion and modal receptance methods were used to predict random noise transfer through curved aircraft panels with stringer and ring frame attachments. Aiming at determining the structural coupling loss factor (CLF) between two plates connected via vibration isolators. Campolina *et al.* [8] used a four-pole approach. And then a hybrid Experimental-SEA (statistical energy analysis) model has been developed by him for predicting the noise of the aircraft panels. However, in these researches, no measure was used to increase the transmission loss of skin panels and reduce cabin noises.

As for noise reduction of skin panels, traditional noise reduction measures mainly lay damping layers on skin panels to control mid-low frequency vibration and noise and lay sound absorption cotton to absorb mid-high frequency air noises. Damping material of a restraint layer is characterized in that a viscoelastic damping material is adhered between a metal plate and the restraint layer with high rigidity to increase efficiency of vibration energy of the dissipation of damping material. The material is widely applied to vibration restraining of engineering structures [9]. A lot of scholars

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have done a lot of work in modeling analysis and experimental test on dynamic characteristics of the restraint damping material, vibration restraint performance computation and optimization design. Specific methods mainly include analytical method [10], [11], numerical method [12]–[14] and experimental method [15]–[17]. These researches mainly involve analysis on system vibration restraining effects and structural vibration sound radiation performance before and after applying restraint layer damping of simple beams and plate-type structures. Researches on air sound insulation effects are still limited to transmission loss computation of damping composite plates of infinite restraint layers [18]. Only a few of researches systematically analyzed parameters including mass, damping and rigidity of the restraint layer damping material on noise reduction and vibration restraining effects of rib plate structures with actual boundary restraints, far from reaching the requirements for parameter optimization design. In order to rapidly predict sound insulation characteristics of aircraft panels with applying restraint damping, Feng *et al.* [19] took experimental results of transmission loss of uniform panels under acoustic impedance tube conditions as well as computational results of the finite element model as the basis to analyze impacts of restraint damping mass and damping loss factors on transmission losses. Bravo *et al.* [20] proposed a method for evaluating the absorption and transfer performances of multi-layer aircraft micro-perforated panels whose facings are excited by different noise sources is described here. The noise is studied by changing the combination type of the multi-layer panels. Arunkumar *et al.* [21] focused on the study of influence of core geometry on sound transfer characteristics of sandwich panels which are commonly used as aircraft structures. The present study has found that, for a honeycomb core sandwich panel in due consideration to space constraint, better sound transfer characteristics can be achieved with lower core height. However, they only analyzed impacts of restraint damping parameters on acoustic characteristics of skin panels, but failed to adopt advanced optimization algorithm to conduct optimization design on restraint damping effects. In addition, they did not conduct further researches on noises in cabins with skin panels as the basis.

Cellular genetic algorithm is an advanced algorithm which combines the genetic algorithm and cellular automation principles. Therefore, this algorithm has inherited good quality of the genetic algorithm, and also had some characteristics of cellular automation [22]–[26]. However, the cellular genetic algorithm has a good global searching ability and insufficient local searching ability. Particle Swarm Optimization (PSO) is an optimization model established through simulation of bird group foraging behaviors [27]–[30]. It applies cooperation and competition of particles in a group to generate group intelligence in order to guide optimization search. The PSO model is simple and only has a few of parameters. Therefore, it is widely applied. Compared with other optimization algorithms: on one hand, during the search, the historical optimal value of each individual was used to guide the search track of the individual, but due to lack of a mutation operator, the group diversity is weakened continuously during the search and finally it will fall into local optimal points; on the other hand, information of the best individual in the group is used to guide search tracks of other individuals in the group, optimization information is shared effectively, convergence speed and accuracy of optimal solutions are increased, and thus the particle swarm optimization algorithm could more quickly converge to the good solutions of problems, but its global search ability is insufficient and it could easily converge to the local optimal solution. In the paper, regarding characteristics of the cellular genetic algorithm and the PSO algorithm were considered, the group information interaction of the PSO algorithm was used as the reference, and the PSO algorithm was mixed with the cellular genetic algorithm (PSO-CGA). According to the acoustic model and PSO-CGA algorithm, the acoustic characteristics of the skin panel were conducted a multi-objective optimization, and a better structure with low noise and light weight was finally obtained.

II. THE TRANSMISSION LOSS MODEL OF THE SKIN PANEL

Among panels of a large aircraft body, the main framework of a lateral panel is mainly composed of a common frame, where its rigidity is weaker compared with an upper panel or a lower panel. Meanwhile, its positioned deformation is more serious than that of panels at other positions, so obvious radiated noises would be caused. Therefore, the paper takes lateral panels as the studied object. The length and width of this structure are 1100mm and 1000mm, respectively. In the paper, the actual structure of lateral panels was simplified rationally; a front processor of ABAQUS software was used for modeling processing. Finally, the finite element model [31], [32] was obtained, as shown in Fig.1. The panel had 3 bulkheads and 3 stringers. Panel structures of an aircraft body mainly include thin wall parts. Therefore, some scholars often simplified them into a mixed model of beam elements and shell elements [33], [34]. However, beam elements often could not simulate real cross section shapes of parts, so computational results were not ideal. Simulation effects of shell elements were poor along the thickness direction. In order to accurately reflect impacts of each design parameter on transmission loss of skin panels, parts and components were modeled by non-conforming solid elements. The finite element model of the complete skin panel had 50892 elements. For the different parts, co-nodes were used to connect them. In this way, the structural vibration can be transmitted.

The finite element model of skin panels was input into Virtual.lab acoustic software to compute the transmission loss. At present, the finite element and boundary element were mainly used to compute transmission loss. However, both of them need formulas to obtain the transmission loss indirectly. Automatically Matched Layer (AML) is a new technology of Virtual.lab. The AML technology is a new technology developed based on acoustic infinity and Perfectly Matched

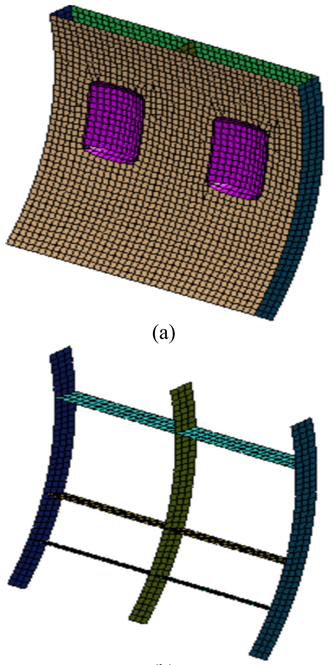

FIGURE 1. Finite element model of lateral panels at the aircraft body. a) Complete model. b) Local model.

FIGURE 2. Computational model of the transmission loss of skin panels. a) Anechoic chamber. b) Reverberation chamber. c) AML model.

Layer (PML) technology. It can directly extract transmission loss of the skin panel in the software. In addition, this method needs not to add artificial acoustic absorption layer meshes, and the absorption layer and the absorption coefficient can be defined automatically. In this way, computational accuracy can be increased, workloads can be reduced, and computational speed can be increased. Acoustic finite elements and boundary elements have different expressions for a computational model. Therefore, before specific computation, it is necessary to establish a computational model according to used methods. During acoustic computation, the size of acoustic elements is related to the computational frequency. Too rough acoustic elements will generate a very large error. In general, it is assumed that there are 6 acoustic elements in the minimum wavelength, namely the edge length of the maximum element is smaller than 1/6 of the minimum wavelength. In the paper, the analyzed frequency of skin panel noises was 0Hz-4000Hz, and the sound speed was 340m/s, so the element length should satisfy $L \leq 14.5$mm. With considering the computational accuracy and scale, the acoustic element size with 10mm was selected. Finally, the AML model of aircraft panels was established, as shown in Fig. 2. The model contained an anechoic chamber and a reverberation chamber. The reverberation chamber was used to simulate an excitation source, and the anechoic chamber was used to receive sound pressures from the panel. A reverberation sound source with 1Pa was applied in the reverberation chamber as the excitation.

After necessary parameters were set, material properties should be input. The skin panel was made of steel, so the elastic modulus was 2.11e11Pa; Poisson's ratio was 0.31; density was 7800kg/m3. Air was the sound transfer medium, so the density was 1.225kg/m3, and propagation speed was 340m/s. Finally, the 1/3 octave transmission loss of the aircraft panel could be obtained, as shown in Fig. 3. It is shown in the figure that when the analyzed frequency was lower than 315Hz, the transmission loss decreased sharply with the analyzed frequency. When the analyzed frequency was higher than 315Hz, the transmission loss increased gradually with the analyzed frequency until it tended to a stable state. The valley value of transmission loss of skin panels was 11.6dB. It was caused by the structural resonance. The valley value will seriously affect the noise level in the cabin. Therefore, this paper will optimize it later.

In order to validate the correctness of the computational model in this paper, the corresponding test should be conducted. As we all know, the noise test should be completed

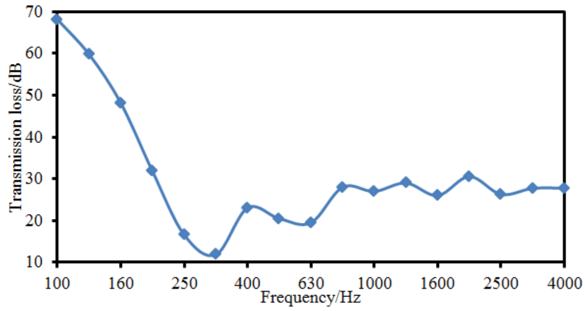

FIGURE 3. Transmission loss curve of skin panels.

in the anechoic chamber to avoid the environmental noise. Five microphones were used to collect the noise signals, and then the filter processing would be conducted on the collected signals [35]–[41]. In the experimental test, the applied sound source is 1 Pa. Finally, the experimental transmission loss can be obtained, and then compared with that of numerical simulation, as shown in Fig.4. Experimental results were not completely consistent with numerical simulation results as the skin panel in the experiment was fixed in a window between the reverberation chamber and the anechoic chamber, and the connecting gaps were sealed by plasticine. However, the transmission loss will be leaked inevitably, where numerical simulation was a completely ideal status and did not have sound leakage. In addition, numerical simulation is greatly affected by boundary conditions, so boundary conditions of experimental test could not be simulated completely. In addition, five microphones were arranged on the receiving side to test sound pressures. The average value of five microphones was considered as the tested result. In numerical simulation, the average sound pressure of all the element nodes on the transmission side was taken as the transmission sound pressure. However, as a whole, the numerical computation model still had high precision and could replace the experimental test.

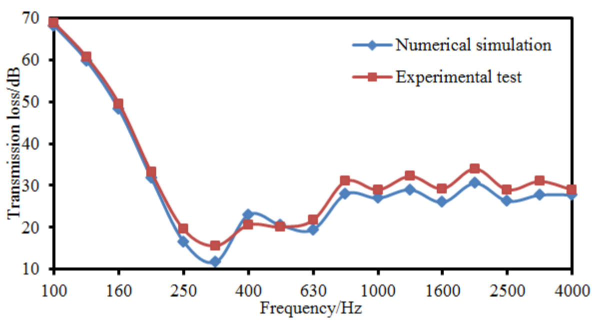

FIGURE 4. Comparison between experimental and simulation of the transmission loss.

III. NUMERICAL INVESTIGATION ON RADIATED NOISES IN THE CABIN

It was shown in computational results in Fig.4 that the sound insulation performance of skin panels was seriously insufficient and needed to be optimized. Structural vibration was always the source of noises. Therefore, it was necessary to recognize the part of panel structure which made obvious contributions to the cabin noise and then optimized it. The ATV (Acoustic Transfer Vector) method was a sound field computation method developed based on boundary element method. In the actual engineering, if the acoustic finite element method or acoustic boundary element method was used to analyze sound fields in the sealed cavity structure, the computation should be conducted again if the external excitation loads borne by the vibration structure were changed. For a mechanical system running under many working loads, the computational amount and time will be very large and amazing. ATV broke through the technology, making it possible to conduct acoustic optimization rapidly and conducted acoustic analysis and computation under multiple working load conditions. However, the reported acoustic software cannot obtain acoustic transfer vectors during computing transmission loss and could only obtain the acoustic transfer vector during separate computing cabin noises. As shown in Fig.5, a sound cavity model of the cabin was established. The shape of sound cavity model considered the shape of a suitcase, satisfying actual situations. The skin panel studied in the paper was coupled with the sound cavity model. In this way, the vibration response of the skin panel under the reverberation sound source was taken as the excitation. An observation point was set in the cabin. As shown in Fig.6, the observation point was used to simulate driver in the cabin.

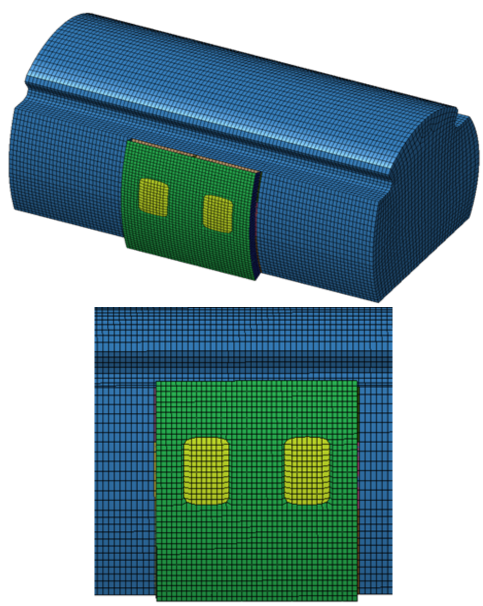

FIGURE 5. Sound cavity model of the aircraft cabin.

During computing cabin noises, the panel coupled with the sound cavity was divided into 9 panels. Each panel was divided according to the similarity principles. In this way, acoustic contribution of each panel at the observation point in the cabin could be obtained, as shown in Fig.7. According to the figure, the panels which had serious impacts on cabin

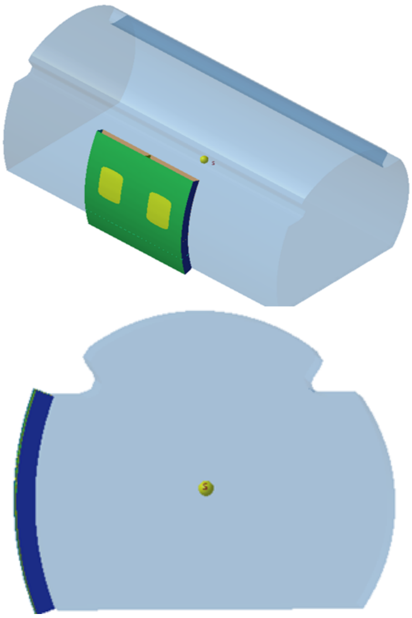

FIGURE 6. Noise observation point in the aircraft cabin.

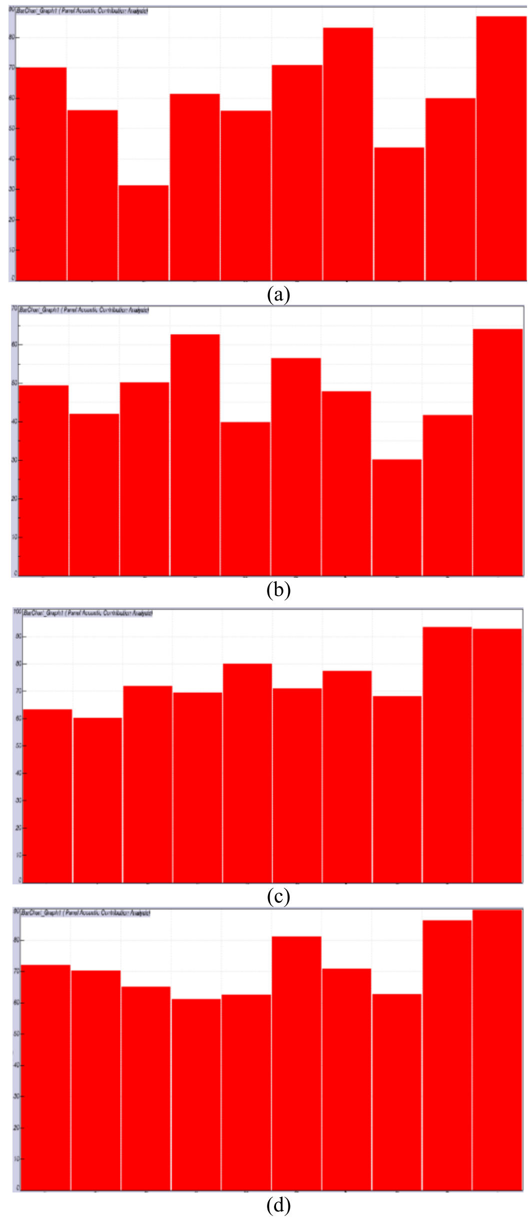

FIGURE 7. Panel contribution of the aircraft skin panel. a) 250Hz. b) 1000Hz. c) 2000Hz. d) 4000Hz.

noises could be found through analysis. Through improving these panels, noises at the observation point could be reduced effectively.

In order to further observe sound pressure distribution at each position in the aircraft cabin, an observation plane was set in the cabin, as shown in Fig.8. Sound pressure distribution of the observation plane was extracted, as shown in Fig.9. It is shown in the figure that: with the increase of the analyzed frequency, sound pressure distribution on the observation plane gradually became uniform. Wavelength of sound waves was shorter in the higher frequency. Therefore, the generated sound pressure was relatively more disperse and uniform. In addition, sound pressure distribution of the observation plane was basically symmetrical as the aircraft skin panel and the sound cavity structure were symmetrical. The reverberation sound source acting on the skin panel was also distributed symmetrically in the whole space.

IV. NUMERICAL OPTIMIZATION FOR THE TRANSMISSION LOSS OF THE SKIN PANEL

Serious deficiency of transmission loss of skin panels will affect riding comfort and will also cause acoustic fatigue of the skin panel structure. Therefore, it is very necessary to take measures to optimize transmission loss of the skin panel. Through the above panel contribution analysis, these panels which obviously affected the cabin noise can be obtained. At first, a composite structure formed by that the restraint damping material was laid on these panels. The composite system is composed of three parts including a skin panel, a damping layer and a restraint layer, as shown in Fig.10. Related physical parameters of the restraint layer were as follows: density was 2700kg/m3; Young modulus was 69GPa; Poisson's ratio was 0.3; damping loss factor was 0.001; thickness was 0.3mm. Related physical parameters of the damping layer were as follows: density was 1300kg/m3; Young modulus was 5.5MPa; Poisson's ratio was 0.4; damping loss factor was 0.3; thickness was 1.4mm. After the restraint damping layer was laid on some panels of the skin panel, the transmission loss of the skin panel was optimized. Design variables in the paper included thicknesses of framework, stringer, restraint layer and damping layer of the skin panel. In this way, only the thickness needed to be changed during numerical optimization, and the structures needed not to be designed again. Transmission loss of the skin panel was insufficient, so the maximization of transmission loss and valley value was taken as the objective and set as max(f).

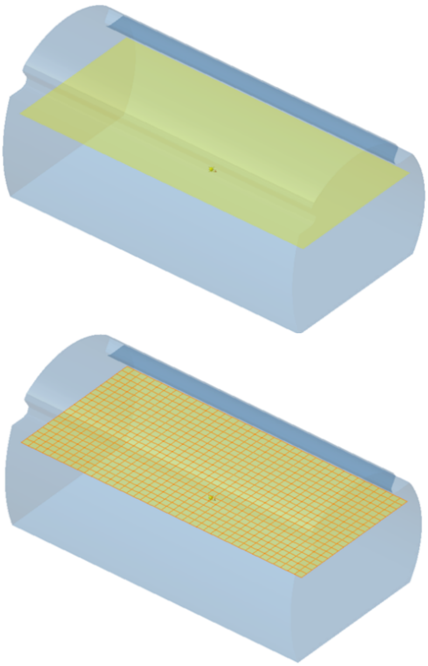

FIGURE 8. Observation plane in the cabin.

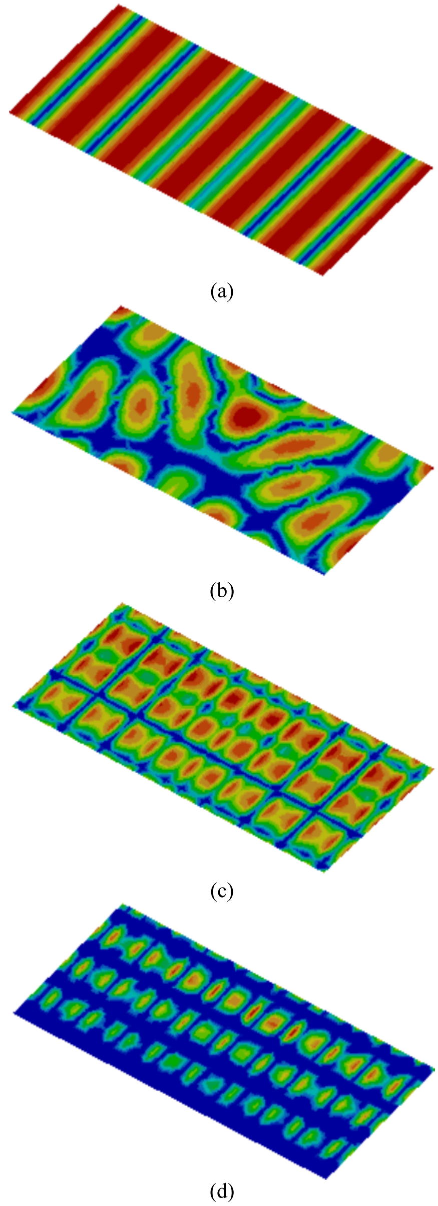

FIGURE 9. Distribution contours of sound pressures in the aircraft cabin. a) 250Hz. b) 1000Hz. c) 2000Hz. d) 4000Hz.

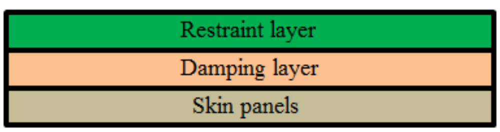

FIGURE 10. Schematic diagram of composite system laid on skin panels.

Noises in the cabin should be reduced, and meanwhile the mass should not be increased, so that materials and cost could be reduced. Therefore, the mass of skin panels was taken as the restraint function and set as $m(f)$. Its mathematical model was as follows:

$$\begin{cases} \max(f_1) = f(x_1, x_2, \ldots x_{12}) \\ \max(f_2) = f(x_1, x_2, \ldots x_{12}) \\ s.t. m(x_1, x_2, \ldots x_{12}) \leq 20 \\ x_i^{(l)} \leq x_i \leq x_i^{(u)} \quad i = 1, 2, .., 12 \end{cases} \tag{1}$$

Where: f_1 is the average transmission loss of the skin panel, and it can be obtained through the related frequency points and transmission loss; f_2 is the valley value of transmission loss of the skin panel; x_i is a designed variable; m is the original mass of the skin panel, which should be less than 20kg; $x_i^{(l)}$ is the lower limit values of designed variables; $x_i^{(u)}$ is the upper limit values of designed variables.

After the optimization model of the transmission loss was obtained, an advanced optimization algorithm should be used to conduct a multi-objective optimization. Cellular genetic algorithm was an advanced algorithm which combined the genetic algorithm with cellular automation principles. Therefore, this algorithm has inherited good quality of the genetic algorithm, and also had some characteristics of cellular automation. In the cellular genetic algorithm, the cellular model simulated evolution of nature with individuals as the starting point. Main ideas of the model were as follows: in general, an initial population in the cellular genetic algorithm was distributed in a topological structure. In the structure, individuals in the population were placed on points of the mesh; each individual communicated with neighboring individuals; crossover operations were only conducted between neighbors, as shown in Fig.11. By the algorithm, individuals in the population were isolated based on distances [42]. Similar individuals were clustered to create ecological niches [43]–[46].

The cellular genetic algorithm had a good global searching ability and insufficient local searching ability. Particle

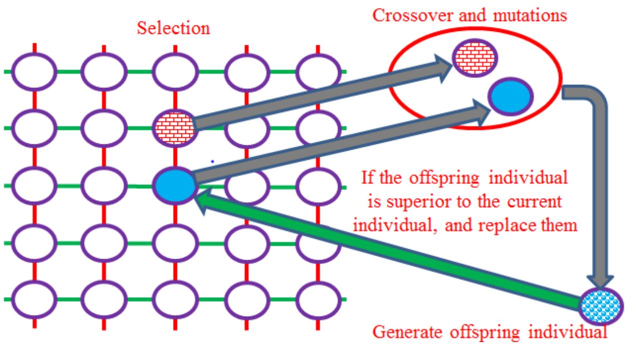

FIGURE 11. Basic topological structure of the cellular genetic algorithm.

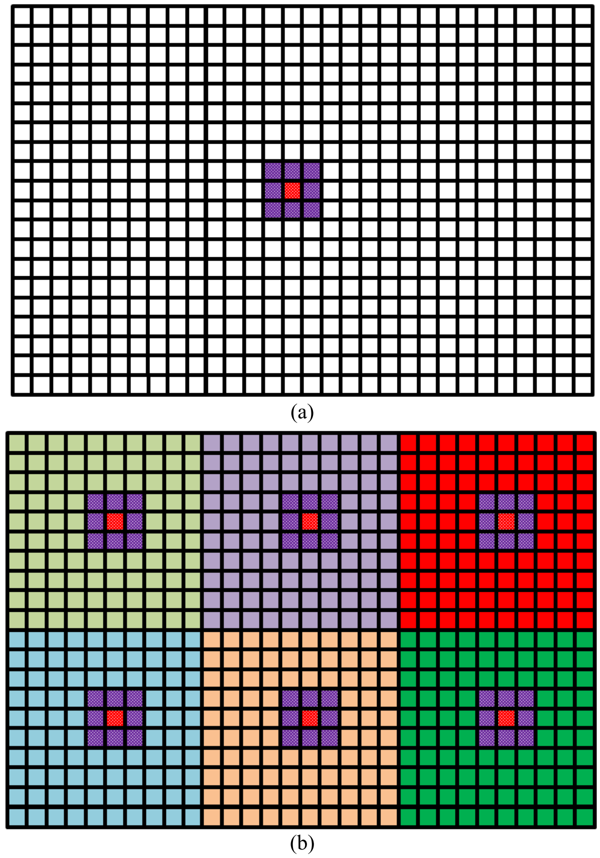

FIGURE 12. Schematic diagram of two kinds of CGA models. a) Original CGA. b) Improved PSO-CGA.

Swarm Optimization (PSO) was an optimization model established through simulation of bird group foraging behaviors. It applied cooperation and competition of particles in a group to generate group intelligence in order to guide optimization search. The PSO model was simple and only had a few of parameters. Therefore, it was widely applied. The PSO could more quickly converge to the good solutions of problems, but its global search ability is insufficient and it could easily converge to the local optimal solution. In the paper, regarding characteristics of the cellular genetic algorithm and the PSO algorithm were considered, the group information interaction of the PSO algorithm was used as the reference, and the PSO algorithm was mixed with the cellular genetic algorithm (PSO-CGA). Specifically, the population in the CGA algorithm was uniformly divided into several cellular sub-populations, as shown in Fig.12. Each cellular sub-population evolved independently; individual migration took place at an interval of certain evolution generations, so evolution information between cellular sub-populations could be exchanged. It aimed to prevent formation of unrelated evolution islets caused by division of the cellular population, so as to achieve mutual communication and parallel evolution of each sub-population as a whole.

After the optimization algorithm was selected and set, the mathematical model in formula (1) was combined with the optimization algorithm in commercial software Isight. In this software, there is one mature genetic algorithm. Therefore, we can only write one simple program to obtain the improved genetic algorithm. As a result, the optimization model in equation (1) is parameterized and imported into the commercial software. In this way, the numerical optimization can be completed. In order to verify effectiveness of the proposed PSO-CGA algorithm after parameter selection, it was compared with the traditional CGA model and PSO model. CGA, PSO and PSO-CGA adopted the same population to conduct a multi-objective optimization of transmission loss of skin panels. Optimization iteration process of three kinds of algorithms was shown in Fig.13. It was shown in Fig.13 that the PSO-CGA model proposed by the paper had a high clustering degree. Transmission loss of most iteration points was obviously more than those of other two kinds of algorithms. The average transmission loss of the original skin panel was 30.6dB, and the valley value was 11.6dB. The average transmission loss obtained by the traditional CGA algorithm was 35.0dB, and the valley value was 18.7dB; compared with the original structure, the average transmission loss increased by 14.4%, and the valley value increased by 61.2%. The average transmission loss obtained by the traditional PSO algorithm was 37.1dB and the valley value was 17.3dB; compared with the original structure, the average transmission loss increased by 21.2%, and the valley value increased by 49.1%. The average transmission loss obtained by the PSO-CGA algorithm proposed in the paper was 39.5dB, and the valley value was 26.2dB; compared with the original structure, the average transmission loss increased by 29.1%, and the valley value increased by 125.8%. Obviously, through using the PSO-CGA algorithm proposed by the paper, high average transmission loss could be obtained; meanwhile, the valley value was increased greatly; noises in the cabin could be improved effectively. In addition, experimental results showed that: aiming at the same computer resources, 256min, 198min and 125min were needed for optimization of the transmission loss using CGA, PSO and PSO-CGA models. Therefore, the PSO-CGA model proposed by the paper had obvious advantages in optimized results and time.

According to optimization parameters of the skin panel, acoustic computation models were established again.

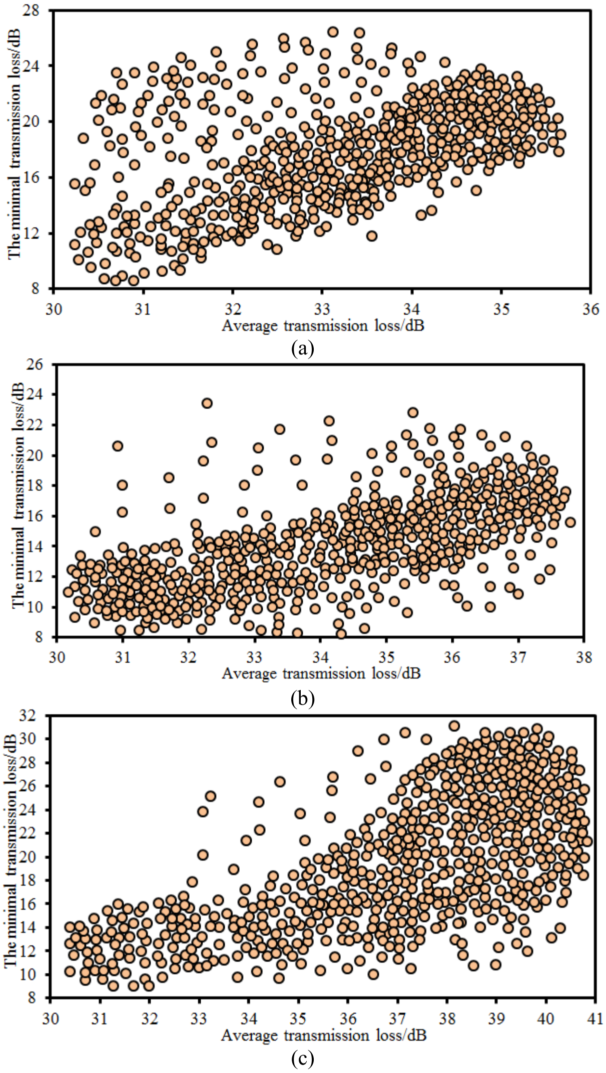

FIGURE 13. Population iteration process of three kinds of optimization models. a) Traditional CGA model. b) Traditional PSO model. c) Novel PSO-CGA model.

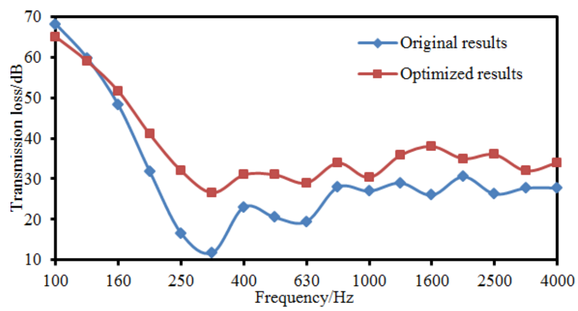

FIGURE 14. Comparison of transmission loss before and after optimization.

Transmission loss of the optimized skin panel was computed and compared with the original structure, as shown in Fig.14. It was shown in the figure that the valley value at 315Hz was improved obviously, while transmission losses at other

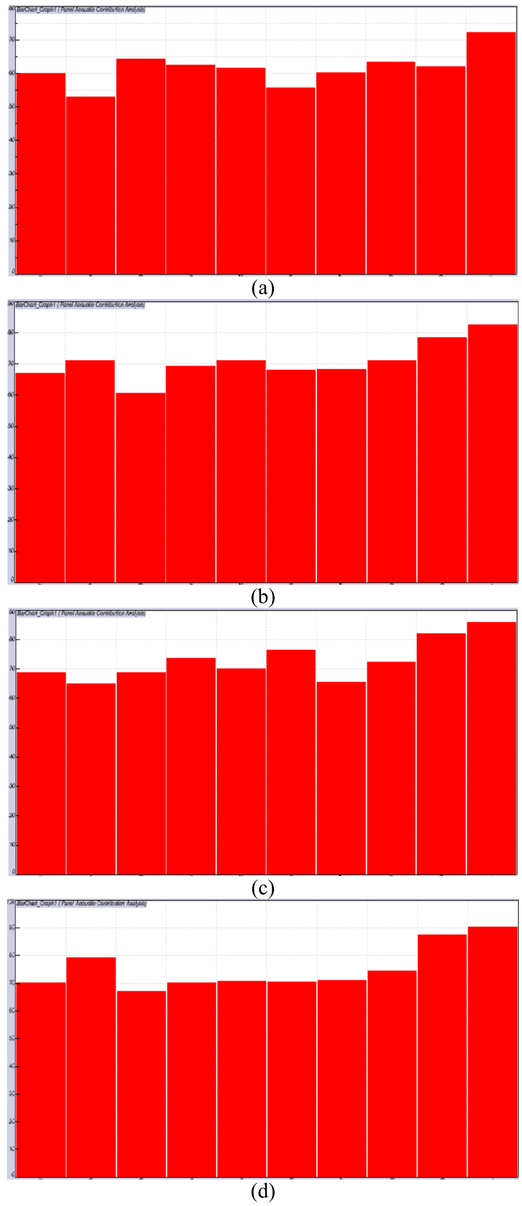

FIGURE 15. Panel contributions of the optimized skin panel. a) 250Hz. b) 1000Hz. c) 2000Hz. d) 4000Hz.

frequency points also increased. Obviously, optimization effects were very significant. However, when the analyzed frequency was lower than 125Hz, the transmission loss of the optimization model was lower than that of the original structure as the low-frequency band was very sensitive to model boundary conditions, and improper setting of boundary conditions would seriously affect computational results. In order to further observe noise reduction effects of the optimization measure in the cabin, panel contributions of the skin panel at observation points in the cabin were extracted, as shown in Fig.15. Compared with Fig.7, the panel contributions of the optimized skin panel were basically consistent at the observation points. Obviously, the optimization measure proposed by the paper could significantly improve noises in the cabin.

V. CONCLUSIONS

According to the acoustic model and PSO-CGA algorithm, the acoustic characteristics of the skin panel were conducted a multi-objective optimization, and a better structure with low noise and light weight was finally obtained. The computational model was also validated by its experimental test. More specifically, the addressed conclusions can be achieved:

1) When the analyzed frequency was higher than 315Hz, the transmission loss increased gradually with the analyzed frequency until it tended to a stable state. The valley value of transmission loss of skin panels was 11.6dB. It was caused by the structural resonance. The vibration displacement contour of skin panels was distributed symmetrically. Positions with serious vibration will radiate serious noises to the cabin.

2) With the increase of the analyzed frequency, sound pressure distributions on the observation plane gradually became uniform. In addition, sound pressure distributions of the observation plane were basically symmetrical as the aircraft skin panel and the sound cavity structure were symmetrical. The reverberation sound source acting on the skin panel was also distributed symmetrically in the whole space.

3) The PSO-CGA model proposed by the paper had a high clustering degree. Transmission loss of most iteration points was obviously more than those of other two kinds of algorithms. Using the traditional CGA algorithm, the average transmission loss was increased by 14.4%, and the valley value was increased by 61.2%. Using the traditional PSO algorithm, the average transmission loss was increased by 21.2%, and the valley value increased was by 49.1%. Using the novel PSO-CGA algorithm in the paper, the average transmission loss was increased by 29.1%, and the valley value was increased by 125.8%. Obviously, through using the PSO-CGA algorithm in the paper, high average transmission loss could be obtained; meanwhile, the valley value was increased greatly; noises in the cabin could be improved effectively. In addition, experimental results showed that: aiming at the same computer resources, 256min, 198min and 125min were needed for optimization of the transmission loss using CGA, PSO and PSO-CGA models. Therefore, the PSO-CGA model proposed in the paper had obvious advantages in optimized results and time.

4) Transmission loss of the optimized skin panel was computed and compared with the original structure. The valley value at 315Hz was improved obviously, while the transmission losses at other frequency points were also increased. Obviously, optimized effects were very significant. In order to further observe noise reduction effects of the optimization measure in the cabin, panel contributions of the skin panel at observation points in the cabin were extracted. The panel contributions of the optimized skin panel were basically consistent at the observation points. Obviously, the optimization measure proposed by the paper could significantly improve noises in the cabin.

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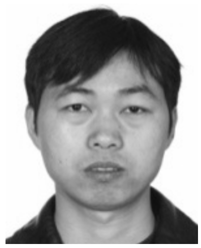

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