Electromagnetic Wave Absorber Optimal Design Based on Improved Particle Swarm Optimization

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***Abstract*— The optimal design of planar multilayered electromagnetic wave absorbers is presented. The optimization process is based on an improved particle swarm optimization (PSO). Assumed that the number of layers is given, in order to obtain an ideal absorber which is thin and has a low reflection coefficient within a wide band of frequencies, the thickness of each layer needs to be optimized as well that each layer needs to be chosen from a given material database. The problem is a classical optimization problem and the optimal design is to find the optimal solution. PSO in comparison with most of optimization algorithms such as Genetic Algorithms is simpler and faster. But the basic form of PSO may not obtain the optimal solution with complex problems. An improved PSO is applied to this design. Simulation results show the validity and effectiveness of this design method.**

Key words: Multilayered Structures; Electromagnetic Wave Absorber; Reflection Coefficient; Particle Swarm Optimization.

I. INTRODUCTION

Electromagnetic wave absorbers are often used to reduce radar echo from anechoic chambers, aircraft and so on. For many applications, the absorber must be built conformable to a complex surface, or must have a flat interface with the air. The most common of these conformable absorber types is the multilayer, which is composed of flat layers of different lossy materials [1]. Widespread applications of planar multilayered electromagnetic wave absorbers have inspired engineers to explore about optimal design with available algorithms. Ideally a thin, light weight and wide band absorber is an optimum one. But these features are inherently conflicting. For example it is possible to design an absorber with high reflection suppression, but high thickness or weight. On the other hand a thin and light absorber might have low reflection suppression [2]. Thus the design of a wide band absorber lies in minimizing the reflection coefficient of an incident plane wave in a multilayer structure. The reflection coefficient depends on the thickness and the electric and magnetic properties of each layer. Assumed that the number of layers is given, in order to obtain an ideal absorber which is thin and has a low reflection coefficient within a wide band of frequencies, the thickness of each layer needs to be optimized as well that each layer needs to be chosen from a given material database. Therefore, minimization of the reflection coefficient is a classical optimization problem.

The particle swarm optimization (PSO) is a population-based algorithm used to visualize the movement of a bird's flock [3]. Previous studies of electromagnetic wave absorber optimal design show that PSO in comparison with most of optimization algorithms such as Genetic Algorithms is simpler and faster [4]. But the optimal design of multilayered absorbers is a nonlinear optimization problem with a large number of local extreme values. Furthermore, both continuous variables such as thickness of each layer and discrete ones such as material types are involved in the problem. So it is difficult for traditional PSO to search the global or nearly global optimal solution of such a problem.

In this study the method based on improved PSO is applied for optimization in an absorber design problem. Numerical results show the validity and efficiency of the algorithm.

II. ELECTROMAGNETIC MODEL OF MULTILAYERED ABSORBER

Assuming a plane of infinite extent avoids diffraction effects, and with simplification of normal incidence of uniform plane wave, a multilayered coating absorber backed by a perfect electric conductor (PEC) is shown in Figure 1 [5].

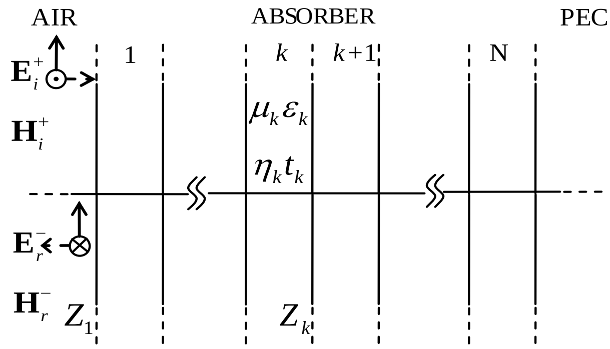

Fig. 1 A multilayer system of n layers, on which a uniform plane wave is normally incident from the left

Excited by the normally incident, time-harmonic wave ($\mathbf{E}_i^+, \mathbf{H}_i^+$) in region 1, each region acquires, in the sinusoidal steady state, the forward- and backward-traveling fields

($\mathbf{E}_i^+, \mathbf{H}_i^+$) and ($\mathbf{E}_r^-, \mathbf{H}_r^-$) except for the last region. The total electric field for each region becomes

$$\begin{aligned}\mathbf{E}_x(z) &= \mathbf{E}_i^+ e^{-\gamma z} + \mathbf{E}_r^- e^{\gamma z} \\ &= \mathbf{E}_i^+ e^{-\gamma z}[1 + \frac{\mathbf{E}_r^-}{\mathbf{E}_i^+} e^{2\gamma z}] = \mathbf{E}_i^+ e^{-\gamma z}[1 + \Gamma(z)]\end{aligned} \quad (1)$$

In which $\Gamma(z)$ is called the reflection coefficient at any location z in the region, defined as the complex ratio of the reflective wave to the incident wave as follows

$$\Gamma(z) = \frac{\mathbf{E}_r^-}{\mathbf{E}_i^+} e^{2\gamma z} \quad (2)$$

The corresponding total magnetic field is

$$\begin{aligned}\mathbf{H}_y(z) &= \mathbf{H}_i^+ e^{-\gamma z} + \mathbf{H}_r^- e^{\gamma z} \\ &= \frac{\mathbf{E}_i^+}{\eta} e^{-\gamma z}[1 - \frac{\mathbf{E}_r^-}{\mathbf{E}_i^+} e^{2\gamma z}] \\ &= \frac{\mathbf{E}_i^+}{\eta} e^{-\gamma z}[1 - \Gamma(z)]\end{aligned} \quad (3)$$

A total-field impedance $Z(z)$ is defined at any z location by the ratio of the total electric field (1) to the total magnetic field (3)

$$Z(z) = \frac{\mathbf{E}_x(z)}{\mathbf{H}_y(z)} = \eta \frac{1 + \Gamma(z)}{1 - \Gamma(z)} \Omega \quad (4)$$

A converse expression for $\Gamma(z)$ in terms of $Z(z)$ is obtained from (4) by solving for $\Gamma(z)$

$$\Gamma(z) = \frac{Z(z) - \eta}{Z(z) + \eta} \quad (5)$$

A form convenient for finding $\Gamma(z)$ whenever $Z(z)$ is known.

The reflection coefficient R at the interface (z=0) between air and the absorber is

$$R(f) = \frac{Z_1 - \eta_0}{Z_1 + \eta_0} \quad (6)$$

According to the transmission-line equations, we obtain the total-field impedance Z_1 [6]

$$Z_1 = \eta_1 \frac{Z_2 + j\eta_1 \tan(\beta_1 t_1)}{\eta_1 + jZ_2 \tan(\beta_1 t_1)} \quad (7)$$

and we can express Z_k using the iteration formula as follows:

$$Z_k = \begin{cases} \eta_k \dfrac{Z_{k+1} + j\eta_k \tan(\beta_k t_k)}{\eta_k + jZ_{k+1} \tan(\beta_k t_k)} & k < n \\ j\eta_n \tan(\beta_n t_n) & k = n \end{cases} \quad (8)$$

where η_k is the wave impedance of the k^{th} layer and β_k is the phase constant, given by

$$\eta_k = \sqrt{\frac{\mu_k}{\varepsilon_k}} \quad (9)$$

$$\beta_k = \omega\sqrt{\mu_k \varepsilon_k} = 2\pi f \sqrt{\mu_k \varepsilon_k} \quad (10)$$

The design of the absorber is defined as the minimization problem of the quantity R (expressed in dB), given by

$$RL = 20\log\{\max|R(f)|, f \in B\} \quad (11)$$

where $\max|R(f)|$ is the maximum reflection coefficient over the desired frequency, $B = \{f_{\min}, f_2, f_3, \cdots, f_{N-1}, f_{\max}\}$ is the desired set of frequencies. The samples are shown in figure 2.

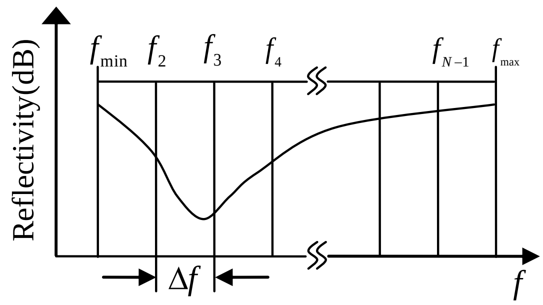

Fig. 2. Grating of samples in a frequency range.

III. Particle Swarm Optimization

A. Traditional PSO

PSO is a population-based stochastic optimization algorithm proposed by Eberhart and Kennedy in 1995 [3], inspired by the social behavior of birds. In a PSO algorithm, a swarm of particles fly through an N-dimensional search space where each particle represents a potential solution to the optimization problem. Each particle flies around in the N-dimensional search space with a velocity, which is constantly updated by the particle's own experience and the experience of the particle's neighbors or the experience of the whole swarm. Each particle has a fitness value calculated by a fitness function, and the position of each particle is updated by following two optimum values. One is the best solution (fitness) that has been achieved so far, which can be regarded as the particle's own experience. This value is called *pbest*. The other important parameter for PSO is the global best value obtained so far by any particle in the swarm, which can be regarded as the experience of the whole swarm. This best value is called *gbest* [7].

After finding the *pbest* and *gbest*, the velocity and position of each particle for every problem dimension are updated with the following equations:

$$\begin{aligned}v_i^{t+1}(d) &= \omega \times v_i^t(d) + \\ &c_1 \times rand \times (pbest_i^t(d) - x_i^t(d)) \\ &+ c_2 \times rand \times (gbest^t(d) - x_i^t(d))\end{aligned} \quad (12)$$

$$x_i^{t+1}(d) = x_i^t + v_i^{t+1}(d) \quad (13)$$

where the velocity and position are regulated as follows:

$$\left.\begin{array}{ll} if\ v_i > V_{\max} & v_i = V_{\max} \\ if\ v_i < V_{\max} & v_i = -V_{\max} \end{array}\right\} \quad (14)$$

and

$$\left.\begin{array}{ll} if\ x_i > X_{\max} & x_i = X_{\max} \\ if\ x_i < X_{\max} & x_i = -X_{\max} \end{array}\right\} \quad (15)$$

where d is the dimension, t is the current iteration number, c_1 and c_2 are positive constants, called learning factors, rand is a random number between (0,1) and ω is the inertia weight and can be linearly decreased from 0.9 to 0.4 with the following equation:

$$w = w_{\max} - \frac{(\omega_{\max} - \omega_{\min}) \times t}{T} \quad (16)$$

Above equations represent traditional PSO. In the following sections, an improved PSO that are applied to the optimal design of planar multilayered electromagnetic wave absorbers is introduced.

B. *An Improved PSO*

In general, PSO can converge to the global optimal solution with a considerable probability when stochastic initial solutions are distributed over the search space. However, if the search space is quite large and stochastic initial solutions exist in some corner of the search space, PSO can be easily trapped into the local optimal solution. Although the problem can be solved by increasing the swarm size, it will cost much time. Therefore, in order to improve the global searching ability of PSO and reduce searching time, we need to monitor the changes of iteration results and change the searching strategy if the iteration result keeps invariant [8].

The specific procedures are as follows:

Step 1: Initialize population in hyperspace and set a fixed window W for recording the times of the iteration results which are continuously invariable, and set two parameters: $T_w = 1$, $T_{iter} = 1$.

Step 2: Evaluate fitness value of individual particle.

Step 3: For each particle, if the fitness value is better than the best fitness value (*pbest*) in history, set the current value as the new *pbest*. Choose the particle with the best fitness value of all the particles as the *gbest*.

Step 4: Calculate particle velocity according to the formula (12). Update particle position according to the formula (13).

Step 5: Monitor the changes of iteration results.

If the iteration results have changed, change T_w and T_{iter} by the following formulas: $T_{iter} = T_{iter} + 1$, $T_w = 1$.

If the iteration results keep invariable, change T_w and T_{iter} by the following formula: $T_w = T_w + 1$, $T_{iter} = T_{iter} + 1$. Record *gbest* generated by the last iteration and initial population again if T_w equals to *W*.

Step 6: Loop to step 2 and repeat until a criterion is met.

IV. Simulation Results

In the following simulation we attempt to demonstrate the validity of the model and algorithm. In our design, a 5-layer absorber is optimized for the range of frequencies (0.2- 6.0) GHz, and the thickness of each layer varies in the range [0, 2] mm. The material database is shown in Table I [9].

TABLE I
MATERIALS DATABASE [9]

Lossless Dielectric Materials ($\mu' = 1$, $\mu'' = 0$)				
No.	ε'			
1	10			
2	50			
Lossy Magnetic Materials ($\varepsilon' = 15$, $\varepsilon'' = 0$) $\mu = \mu' - j\mu''$ $\mu'(f) = \frac{\mu'(1GHz)}{f^a}$ $\mu''(f) = \frac{\mu''(1GHz)}{f^b}$				
No.	u' (1GHZ)	a	u'' (1GHZ)	b
3	5	0.974	10	0.961
4	3	1.000	15	0.957
5	7	1.000	12	1.000
Lossy Dielectric Materials($u' = 1$, $u'' = 0$) $\varepsilon = \varepsilon' - j\varepsilon''$ $\varepsilon'(f) = \frac{\varepsilon'(1GHz)}{f^a}$ $\mu''(f) = \frac{\varepsilon''(1GHz)}{f^b}$				
No.	ε' (1GHZ)	a	ε'' (1GHZ)	b
6	5	0.861	8	0.569
7	8	0.778	10	0.682
8	10	0.778	6	0.861
Relaxation-type Magnetic Materials ($\varepsilon' = 15$, $\varepsilon'' = 0$) $\mu = \mu' - j\mu''$ $\mu'(f) = \frac{\mu_m f_m^2}{f^2 + f_m^2}$ $\mu''(f) = \frac{\mu_m f_m f}{f^2 + f_m^2}$ f and f_m in GHz				
No.	μ_m		f_m	
9	35		0.8	
10	35		0.5	
11	30		1.0	
12	18		0.5	
13	20		1.5	
14	30		2.5	
15	30		2.0	
16	25		3.5	

In order to compare the improved method with traditional PSO, we run the two methods independently for 50 times and analyze statistical characteristics of fitness values respectively. In the experiment, the fitness function is formula (11) and the fitness value is *RL*. The object is to find the minimum value of *RL*. The parameters chosen for the above experiment are: 20 particle swarm size, 1000 iterations and set W equals to 60.

The comparison diagram of the statistical characteristics is shown in Fig 3. Record the number of the minimum *RL* falling into the interval (-∞,-20], [-20,-18],……,[-12,-10], [-10,+∞)

and mark each interval with serial number 1,2,3,4,5,6,7 respectively.

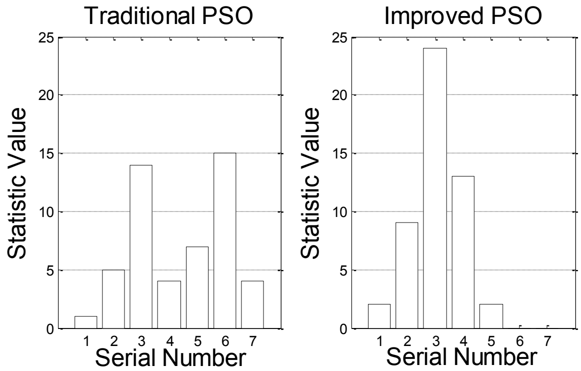

Fig.3 Statistical characteristics of fitness values obtained by the two methods.

Because the design in this paper is to find the minimum value of *RL*, as seen from Fig 3, the improved PSO shows better character than traditional PSO in the successful rate of finding the optimal solution and precision of the optimal solution.

When the particle swarm size is set at 100 or even larger, the optimal solution can be easily found. But it is not appropriate by increasing the particle swarm size when the material database is too large. So it is indispensable to make the above improvement to traditional PSO. The frequency response of the absorber designed by above method is shown in Figure 4. The design parameters for the novel absorber are given in Table Ⅱ.

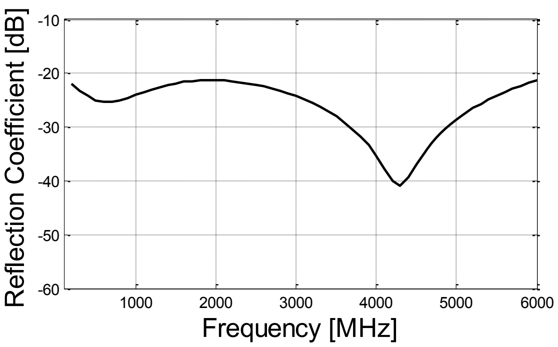

Fig. 4 Five-layer broadband absorber optimized for normal incidence with uniform plane wave for f =0.2–6 GHz.

TABLE Ⅱ
DESIGN PARAMETERS FOR FIVE-LAYER BROADBAND ABSORBER OPTIMIZED FOR NORMAL INCIDENCE WITH UNIFORM PLANE WAVE

Layer	Material	Layer Thickness[mm]
1	16	0.60000
2	6	1.07337
3	5	0.60000
4	4	1.96735
5	4	0.69749

V. CONCLUSION

In this paper, a planar absorber design method using improved PSO was presented. In order to obtain better solutions and reduce running time, we make an improvement with the traditional PSO. Numerical simulation results show that the improved PSO can avoid trapping into the local optimum effectively and obtain optimal solution.

It is effective and easy to implement in designing planar multilayered electromagnetic wave absorbers using PSO algorism. Particularly, when the swarm size is large enough, this method shows better character in finding the optimal solution. But when the size of the material data is too large, it will cost much time in designing planar absorber using traditional PSO by increasing the swarm size. Compared with tradition PSO, the improved PSO is easier to obtain the optimal solution. A problem worthy to be pointed out is that the size of the fixed window *W* is important. A suitable value of *W* can improve the performance of this method obviously. The selection of the fixed window *W* is a problem to be solved.

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