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DESIGN OF MULTILAYER MICROWAVE BROADBAND ABSORBERS USING CENTRAL FORCE OPTIMIZATION

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Abstract—Central Force Optimization (CFO) is a new multi-dimensional search metaheuristic based on the metaphor of gravitational kinematics. In this paper, for the first time, a modified CFO algorithm is applied to the optimal design of multilayer microwave absorbers (for normal incidence) in a specific frequency range. Several numerical examples are presented, in which the CFO results are compared with those found by other evolutionary algorithms. It is shown that the CFO results are comparable to those found by the self-adaptive differential evolution (SADE) algorithm and better than those found by particle swarm optimization (PSO) and gravitational search algorithm (GSA).

1. INTRODUCTION

Multilayer microwave absorbers are important elements of many military and civil electronic systems. Absorbers employing ferrite, carbonyl iron and other new absorption materials can be used to minimize the electromagnetic reflection from the metal plate such as aircrafts, ships, tanks and electronic equipment [1]. Many parameters of the absorber can be varied in order to obtain its optimal characteristics by using an optimization technique. These parameters are the number of layers, dielectric constant, permeability, thickness of layers, frequency, angle of incidence and wave polarization [2]. The big challenge in designing an absorber is the minimization of the reflection coefficient of an incident wave on a multilayer structure for a range of frequencies and incidence angles [3, 4]. So, evolutionary

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optimization techniques such as particle-swarm optimization (PSO) [5–7], differential evolution (DE) [8–11], gravitational search algorithm (GSA) [12], central force optimization technique (CFO) [13–17], and genetic algorithms [18, 19] can be used to overcome this challenge.

Motivated by social behavior of animals, the particle swarm optimization (PSO) method is a stochastic, population-based adaptive optimization algorithm. In recent years, this technique has been widely applied in various disciplines in science and engineering such as applications to large-scale, highly nonlinear, and multimodal optimization problems. Recently, PSO has been applied to the problem of multilayer microwave absorber design [7].

Differential evolution (DE) was introduced by Kenneth Price and Rainer Storn in 1995 [8]. It is a simple metaheuristic and stochastic population-based evolutionary algorithm (EA) for global optimization problems. DE algorithm has gradually become more popular and has been used in many practical cases because it has good convergence properties. A new version of the DE algorithm is used in this paper; namely, the self-adaptive DE (SADE) [9]. In this algorithm, the setting of the control parameters is made adaptive through the implementation of a competition into the DE algorithm [9]. Very recently, SADE has also been successfully used in the design of microwave absorbers [10, 11].

Gravitational search algorithm (GSA) is a brand new optimization algorithm based on Newton's law of gravity [12]. In [12], it has been applied on several benchmark mathematical functions and it has been shown to give very good results compared to other optimization techniques.

Another recently proposed multi-dimensional optimization technique is the central force optimization (CFO) which is based on the metaphor of the gravitational kinematics [13, 14]. CFO searches a multi-dimensional decision space for the extrema of an objective function to be maximized or minimized. CFO starts with user-specified initial probes positions, which could be uniform (making it a fully deterministic optimization method) or random (making it a stochastic optimization method). CFO has been successfully applied on several antenna optimization problems [13–16]. In [17], a modified CFO algorithm (namely; CFO with acceleration clipping) has been proposed and successfully applied to the design of wideband microstrip patch antennas.

This paper is divided as follows: Section 2 presents the multilayer microwave absorber problem formulation. In Section 3, the results obtained using the modified CFO algorithm [17] are presented and compared to those obtained using other optimization techniques (specifically, PSO, DE and GSA). To our knowledge, both CFO and GSA have not been applied before on the optimal design of multi-layer microwave absorbers.

2. FORMULATION OF THE PROBLEM

Figure 1 shows the problem under consideration. It consists of N layers of different materials backed by a perfect electric conductor. The incident wave exists in free-space and is normally incident on the first interface. In general, the goal is to design a multilayer system that minimizes the overall reflection coefficient in a specific frequency range using an optimization technique. The generalized reflection coefficient at the interface between layer i and layer $i+1$ can be written as follows [3]:

$$\tilde{R}_{i,i+1} = \frac{R_{i,i+1} + \tilde{R}_{i+1,i+2} e^{-j2k_{i+1}d_{i+1}}}{1 + R_{i,i+1}\tilde{R}_{i+1,i+2} e^{-j2k_{i+1}d_{i+1}}} \tag{1}$$

where for TE (i.e., perpendicular) polarization:

$$R_{i,i+1} = \frac{\mu_{i+1}k_i - \mu_i k_{i+1}}{\mu_{i+1}k_i + \mu_i k_{i+1}} \tag{2}$$

while for TM (i.e., parallel) polarization:

$$R_{i,i+1} = \frac{\varepsilon_{i+1}\, k_i - \varepsilon_i\, k_{i+1}}{\varepsilon_{i+1}\, k_i + \varepsilon_i\, k_{i+1}} \tag{3}$$

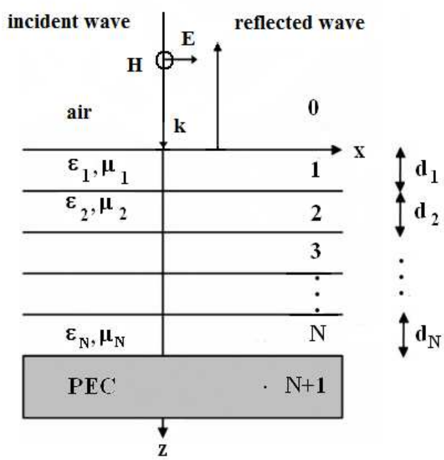

Figure 1. General structure of multilayer microwave absorber.

In the above, ε_i and μ_i are the complex permittivity and permeability, respectively, for the ith layer, and k_i, is the wave-number in the ith layer given as follows:

$$k_i = \omega\sqrt{\mu_i \varepsilon_i} \tag{4}$$

The above equations are recursive relations that express $\tilde{R}_{i,i+1}$ in terms of $\tilde{R}_{i+1,i+2}$. The total reflection coefficient of the multilayer structure, shown in Figure 1, is obtained by evaluating the above equations recursively starting from $\tilde{R}_{N-1,N}$ to $\tilde{R}_{0,1}$, where $\tilde{R}_{0,1}$ is the overall reflection coefficient of the multilayer structure. Since normal incidence is only dealt with here, either Equation (2) (TE polarization) or Equation (3) (TM polarization) can be used. Both polarizations should have the same magnitude of the reflection coefficient for normal incidence. Because of the existence of the perfect electric conductor, one has to set: $\tilde{R}_{N,N+1} = -1$ if Equation (2) is used (TE polarization) and $\tilde{R}_{N,N+1} = +1$ if Equation (3) is used (TM polarization). Here, it is emphasized that the above equations correspond to the reflection coefficient for the electric field for the TE case, while they correspond to the reflection coefficient for the magnetic field for the TM case [3, 11]. This leads to the setting of $\tilde{R}_{N,N+1} = +1$ (not -1) for TM polarization. Since normal incidence case is dealt with here, one may also use simple transmission line theory to obtain an expression for the overall reflection coefficient of the multilayer absorber, instead of the above recursive formula. This option has been checked and it gives the same results as the above expressions, whether TE or TM formulas are used in the calculations.

Generally, the goal of the absorber design is to find a set of layers that minimizes the reflection coefficient for a set of frequencies. This can be expressed as minimizing the overall reflection coefficient of the multilayer absorber $\tilde{R}_{0,1}$ (within a specific range of frequencies). Moreover, a condition on the total thickness of the absorber can be set while searching for the optimum solution [7, 10, 18, 19].

3. NUMERICAL RESULTS

In this section, the results of applying the modified CFO algorithm (i.e., the CFO with acceleration clipping [17]) to find optimal designs for multilayer microwave absorbers are presented. The CFO results are compared against those obtained using other evolutionary algorithms: the Gravitational Search Algorithm (GSA), the Self-Adaptive Differential Evolution (SADE) algorithm [11], and the Particle Swarm Optimization (PSO) algorithm. The maximum thickness for each layer is set to 2 mm. All algorithms are run for

20 independent trials. The number of iterations is set to 1000 for all algorithms. For each algorithm; the best, worst, mean and standard deviation values are presented. The values of the used CFO run parameters depend on the initial probe distribution. For random initial probe distribution, the values were as follows: $N_t = 1000$, $A_{\max} = 0.1$, $N_p = 20$, $G = 1.7$, $\alpha = 0.6$, $\beta = 0.9$ and $F_{rep} = 0.9$. For uniform initial probe distribution, the values were as follows: $N_t = 1000$,

Table 1. Pre-defined materials database used in the optimal design of the microwave absorber.

Lossless Dielectric Materials ($\mu' = 1,\ \mu'' = 0$)				
No.				ϵ'
1				10
2				50
Lossy Magnetic Materials ($\epsilon' = 15,\ \epsilon'' = 0$)				
$\mu = \mu' - j\mu''$		$\mu'(f) = \frac{\mu'(1\text{GHz})}{f^a}$	$\mu''(f) = \frac{\mu''(1\text{GHz})}{f^b}$	
No.	$\mu'(1\text{GHz})$	a	$\mu''(1\text{GHz})$	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 ($\mu' = 1,\ \mu'' = 0$)				
$\epsilon = \epsilon' - j\epsilon''$		$\epsilon'(f) = \frac{\epsilon'(1\text{GHz})}{f^a}$	$\epsilon''(f) = \frac{\epsilon''(1\text{GHz})}{f^b}$	
No.	$\epsilon'(1\text{GHz})$	a	$\epsilon''(1\text{GHz})$	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 ($\epsilon' = 15,\ \epsilon'' = 0$)				
$\mu = \mu' - j\mu''$		$\mu'(f) = \frac{\mu_m f_m^2}{f^2+f_m^2}$	$\mu''(f) = \frac{\mu_m f_m f}{f^2+f_m^2}$	
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

$N_p = 20$, $G = 1.2$, $\alpha = 0.5$, $\beta = 0.8$ and $F_{rep} = 0.5$. N_t and N_p are, respectively, the number of iterations and the number of probes. The values of the classical PSO run parameters that have been used in all the coming examples were as follows: $c_1 = 2$, $c_2 = 2$, swarm size = 100, $w_{\max} = 0.95$, $w_{\min} = 0.4$ and $\text{iter}_{\max} = 1000$; where c_1 determines the relative influence of the cognitive component, c_2 determines the relative influence of the social component, $w_{\max}$ is the initial weight, $w_{\min}$ is the final weight, and $\text{iter}_{\max}$ is the number of iterations. The values of the SADE run parameters were as follows [9]: $\varepsilon = 10^{-7}$, $N = 1000$ and $h = 18$; where ε is a small positive value for stopping criterion, N is the maximum number of iterations, and h is the number of settings in competition (different combination of F and CR), where F is the differentiation factor that takes any value between [0.5–1] and CR is the crossover constant that could be any number between [0–1]. The values of the GSA run parameters were as follows [12]: $N = 20$, $G_0 = 100$, $\alpha = 20$, $R_{norm} = 2$ and the maximum number of iterations is 1000; where N is the number of agents, G_0 and α are the initial gravitational constants, and R_{norm} is the Euclidian distance between any two agents. Table 1 shows the pre-defined materials database used in the optimization [7, 10, 11, 18].

3.1. First Example

In this example, a five layers absorber ($N = 5$) is optimized to minimize the reflection coefficient in the frequency range of 2–8 GHz, with a frequency increment of 0.5 GHz. In this case, the optimization involves 10 design parameters: the thicknesses and the materials numbers. The maximum total thickness of the absorber is set to 5 mm. Table 2 shows the best CFO results obtained from 20 trials along with the best results obtained using other algorithms. It can be seen that CFO offers slightly less total thickness than other algorithms and it gives the best maximum reflection coefficient in the desired frequency band. Figure 2 shows the reflection coefficient as a function of frequency for this design. Table 3 presents the statistical results of the reflection coefficient (best, worst, mean and standard deviation values) for each algorithm. It can be seen that the CFO gives results that are comparable to those obtained using the SADE method. Moreover, the CFO gives results that are better than those obtained using PSO and GSA.

In the above, the initial probe position was chosen to be random. However, they could be chosen to be uniform which makes CFO to be a deterministic algorithm. Tables 4 and 5 show the results obtained using uniform initial probe distribution in CFO with acceleration clipping ($A_{\max} = 0.1$) and without acceleration clipping ($A_{\max} = 1$). The obtained results in Table 4 are comparable to those found by

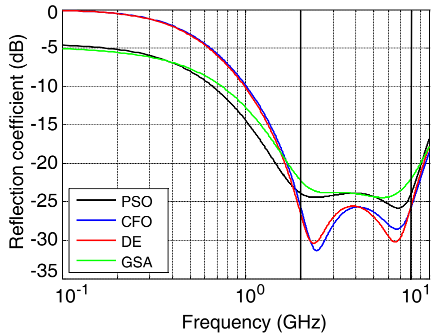

Figure 2. Five-layer absorber optimized for 2–8 GHz frequency range (first example).

Table 2. Design parameters for the first example.

	CFO		DE [11]		GSA		PSO	
Layer	Material	Thickness(mm)	Material	Thickness(mm)	Material	Thickness(mm)	Material	Thickness(mm)
1	16	0.377	16	0.384	16	0.418	14	0.455
2	6	1.572	6	0.433	6	1.593	6	1.995
3	6	0.991	6	1.143	8	0.485	8	0.322
4	6	0.377	6	1.446	13	1.366	5	0.986
5	15	1.425	15	1.454	4	0.986	11	1.128
6	Ground plane		Ground plane		Ground plane		Ground plane	
Total thickness (mm)	4.744		4.860		4.850		4.888	
Max. relfection coefficient (dB)	−25.698		−25.485		−21.955		−23.889	

Table 3. Maximum reflection coefficient (in dB) comparative results after 20 trials for the first example.

Algorithm	Best	Worst	Mean	Standard Deviation
PSO	−23.889	−19.838	−22.495	1.133
GSA	−21.955	−10.222	−15.552	2.802
DE	−25.485	−22.760	−24.001	0.784
CFO	−25.698	−21.848	−23.154	0.988

random probe distribution. The main problem in using a uniform initial probe distribution is the difficulty in choosing the proper CFO run parameters. As shown in Tables 4 and 5, the CFO with acceleration clipping gives better results than those obtained without using acceleration clipping. The CFO results for the next coming

Table 4. Design parameters of the first example using uniform probe distribution and acceleration clipping ($A_{\max} = 0.1$).

Layer	Material	Thickness (mm)
1	16	0.365
2	6	1.843
3	6	1.203
4	14	1.119
5	11	0.441
6	Ground plane	
Total thickness (mm)	4.972	
Max. reflection coefficient (dB)	−25.903	

Table 5. Design parameters for the first example using uniform probe distribution without acceleration clipping ($A_{\max} = 1$).

Layer	Material	Thickness (mm)
1	14	0.398
2	6	0.695
3	6	1.301
4	6	0.651
5	11	1.801
6	Ground plane	
Total thickness (mm)	4.847	
Max. reflection coefficient (dB)	−22.773	

examples are obtained using random probe initial distribution and employing the acceleration clipping scheme with $A_{\max} = 0.1$.

3.2. Second Example

This design is similar to the first one except that a thinner absorber is considered here. Specifically, the maximum total thickness of the absorber is set to 2.57 mm. Table 6 shows the CFO results along with those obtained using the other optimization methods. Figure 3 shows the frequency response for this design, while Table 7 presents the statistical results of the maximum reflection coefficient for each algorithm. As in the previous example, the CFO gives results that are comparable to those obtained using the self-adaptive DE and better than PSO and GSA results in the desired frequency band.

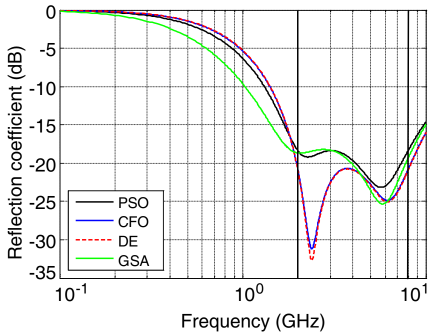

Figure 3. Frequency response for the second example.

Table 6. Design parameters for the second example.

	CFO		DE [11]		GSA		PSO	
Layer	Material	Thickness(mm)	Material	Thickness(mm)	Material	Thickness(mm)	Material	Thickness(mm)
1	16	0.561	16	0.562	16	0.575	16	0.397
2	7	0.850	7	0.897	1	0.574	14	0.201
3	2	0.393	2	0.408	2	0.345	2	0.658
4	13	0.158	15	0.592	9	0.355	13	0.524
5	15	0.605	15	0.111	9	0.699	11	0.353
6	Ground plane		Ground plane		Ground plane		Ground plane	
Total thickness (mm)	2.569		2.57		2.550		2.134	
Max. relfection coefficient (dB)	−20.825		−20.910		−18.292		−18.373	

Table 7. Maximum reflection coefficient (in dB) comparative results after 20 trials for the third example.

Algorithm	Best	Worst	Mean	Standard Deviation
PSO	−18.373	−11.775	−14.205	1.653
GSA	−18.292	−6.082	−12.778	2.697
SADE	−20.910	−17.687	−19.204	0.725
CFO	−20.825	−15.388	−19.115	1.226

3.3. Third Example

In this example, a five layers absorber ($N = 5$) is optimized to minimize the reflection coefficient in a wider frequency range of 0.5–8 GHz. The maximum total thickness of the absorber is set to 5 mm and the frequency step is taken as 0.5 GHz. Table 8 shows the CFO results along with those obtained using the other algorithms. Figure 4

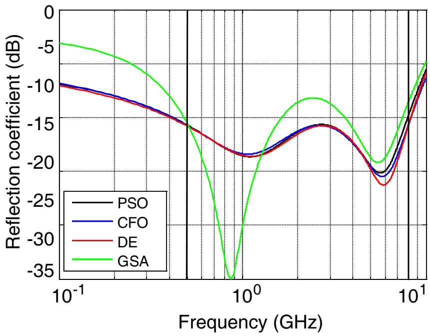

Figure 4. Five-layer absorber optimized for 0.5-8 GHz frequency range (third example).

Table 8. Design parameters for the third example.

	CFO		DE [11]		GSA		PSO	
Layer	Material	Thickness(mm)	Material	Thickness(mm)	Material	Thickness(mm)	Material	Thickness(mm)
1	16	0.327	16	0.484	16	0.490	16	0.478
2	14	0.142	6	1.314	6	1.128	6	0.944
3	6	1.210	5	0.517	4	2.000	5	1.356
4	5	1.844	4	1.529	10	0.979	4	1.793
5	4	1.426	5	1.149	5	0.363	7	0.426
6	Ground plane		Ground plane		Ground plane		Ground plane	
Total thickness (mm)	4.950		4.993		4.961		5.000	
Max. relfection coefficient (dB)	–20.753		–20.796		–18.188		–20.704	

Table 9. Maximum reflection coefficient (in dB) comparative results after 20 trials for the second example.

Algorithm	Best	Worst	Mean	Standard Deviation
PSO	−20.704	−11.218	−17.341	2.858
GSA	−18.188	−9.827	−13.210	2.413
SADE	−20.796	−19.305	−20.337	0.372
CFO	−20.753	−16.579	−19.576	1.218

shows the frequency response for this design, and Table 9 presents the statistical results of the reflection coefficient for each algorithm. In this example, the CFO gives reflection coefficient comparable to self-adaptive DE and PSO and better than GSA in the desired frequency range.

3.4. Fourth Example (Seven-layer Design)

In this example, a seven layers absorber ($N = 7$) is optimized to minimize the reflection coefficient in the very wide frequency range of 0.1–20 GHz using only the CFO algorithm with acceleration clipping ($A_{\max} = 0.1$). Table 10 shows the best results obtained from 20 trials. In addition, for the same design, data from [7], obtained using a modified PSO, are included in the same table. Using CFO, the obtained maximum reflection coefficient in the desired frequency band is −17.924 dB as compared to −18.5 dB in [7]. However, the CFO design is thinner than the one presented in [7] which makes it more

Table 10. Design parameters for the fourth example.

Layer	CFO		Data from [7]	
	Material	Thickness (mm)	Materia	Thickness (mm)
1	16	0.2102	14	0.21267
2	6	1.8485	6	2.1786
3	14	0.5678	14	0.50102
4	5	1.6820	6	1.1592
5	4	1.2007	5	1.7043
6	4	0.2630	6	2.1965
7	3	0.0894	5	1.6561
8	Ground plane		Ground plane	
Total thickness (mm)	5.861		9.6	
Max. reflection coefficient (dB)	−17.924		−18.5	

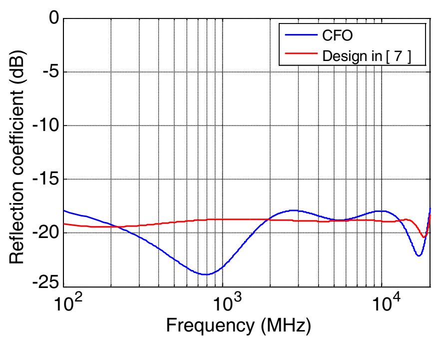

Figure 5. Seven-layer absorber optimized for 0.1–20 GHz frequency range (fourth example).

attractive practically. Specifically, the CFO design has a total thickness of 5.861 mm as compared to 9.6 mm in [7]. Figure 5 shows the frequency response of the CFO design along with the frequency response of the design from [7].

4. CONCLUSION

CFO is a new optimization method whose performance has been studied on the problem of designing broadband multilayer microwave absorbers. The CFO results were compared to those found by other well-developed algorithms such as PSO and DE. Moreover, the newly proposed GSA optimization technique has been applied to the same problem. It has been found that the results of CFO are comparable to those obtained using the self-adaptive DE and better than those found by PSO and GSA.

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