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PAPERS

Analysing the shielding effectiveness of rectangular enclosure by determining aperture dimensions with particle swarm optimization

Sunay Güler[1]

Electromagnetic shielding enclosure is used to protect electronic circuits against external EMI. Aperture on the enclosure, which is necessary for various reasons such as mounting connector, ventilation attenuates shielding effectiveness (SE) of the enclosure. Enlarging enclosure dimensions makes SE get better. Yet, they canot be designed so large due to weight and dimension considerations for EV. When the dimensions of the shielding enclosure remain fixed and the aperture is to have a particular area, it is essential to optimize aperture dimensions to increase SE. In this paper, an optimization methodology based on PSO is designed to obtain the optimal SE for a particular dimension range. The study also provides a comparative analysis between designed optimization methodology and the one based on genetic algorithm in the literature. Obtained SE results indicate that the optimization methodology establishes a very good agreement with the results in the literature. Moreover, it has faster convergence and higher calculation accuracy than GA and it utilizes a smaller number of parameters thanks to its simplicity. Finally, it is concluded that through designed optimization methodology in this study, SE of the enclosure can be raised by optimizing aperture dimensions when the dimensions of shielding enclosure remain fixed.

K e y w o r d s: electromagnetic shielding, shielding effectiveness, particle swarm optimization, genetic algorithm, electric vehicles

1 Introduction

The protection of electronic circuits against external electromagnetic interference (EMI) can be fulfilled by placing them into an electromagnetic shielding enclosure. The ideal shielding enclosure consists of perfect electric conductor and has no aperture on itself to prevent EMI leakage [1]. Yet, apertures are certainly necessary for the enclosures due to mounting connectors, ventilation, and heat dissipation etc. They attenuate the shielding performance of the enclosures by causing EMI leakage onto electronic circuits. The shielding effectiveness (SE) is a typical measurement of the shielding performance that is defined as the ratio of electric field strengths in presence and absence of the shield [2,3].

Shielding enclosures are widely used in complex electromagnetic environment such as electric vehicles (EV) to isolate electronic circuits inside [1]. Due to weight and dimension considerations, they cant be designed so large. Vehicle manufacturers mainly work with co-designer companies. They define dimension limitations for all enclosures to be mounted on the vehicle in which it is quite challenging to fulfil desired SE levels by co-designer companies. When the dimensions of shielding enclosure remain fixed and the aperture is to have a particular area, studies such as optimization of the aperture dimensions or changing the enclosure's material are required in order to increase SE. Changing the material of the enclosure may bring high cost of modification and processing difficulties, therefore the optimization of the aperture dimensions is taken into consideration in this study.

Different disciplines are being required to collaborate more closely in the development of new technologies and products. This situation brings new problems that are very difficult to solve and time-consuming to model mathematically. Various artificial intelligence and heuristic algorithms have been developed to obtain a reasonable solution to these difficult problems without dealing with the internal mathematical equations [1]. Approaches used in heuristic algorithms are derived from sciences such as biology, zoology and physics. The most popular of these algorithms are genetic algorithm (GA), differential evolution algorithm (DEA) and particle swarm optimization (PSO) algorithm [4-7].

GA obtains solutions by stochastic searching techniques based on mechanism of evolution and natural selection. GA searches the best chromosome that represents the solution for the problem in a randomly generated chromosome set called population after a number of iterations. By utilizing genetic operators such as reproduction, crossover, mutation the generational diversity inside the population is ensured, therefore GA can achieve optimal solution. GA has important advantages such as not requiring derivative information, investigating the best solution in a wide range and being able to perform searching with many parameters at the same time [1],[8].

PSO was developed after 20 years later than GA. When compared with other heuristic algorithms, PSO obviously provides robustness, efficiency and simplicity. Besides that, it may require much more effort to reach optimal solution for large-scale problems [5,6], [8]. The main

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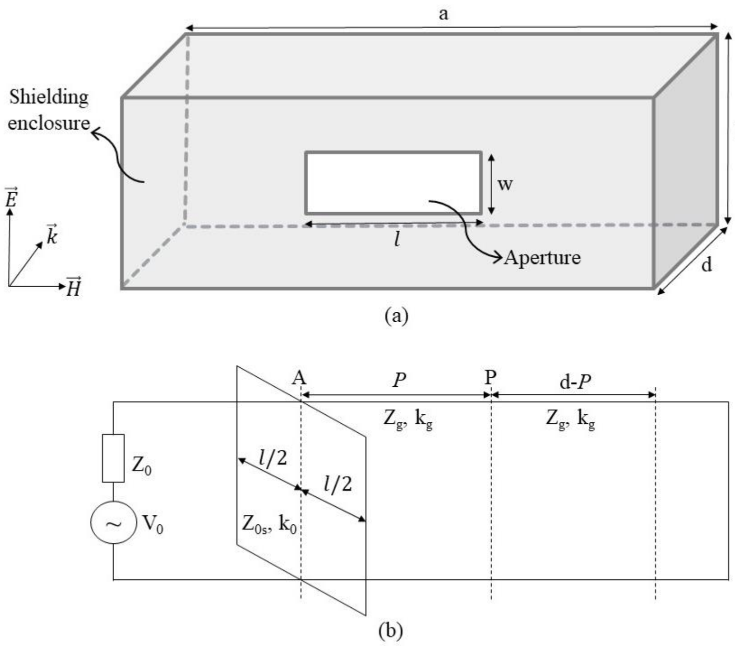

Fig. 1. (a) – rectangular enclosure with an aperture, (b) – its equivalent circuit

idea in PSO is that each particle in a swarm represents a potential solution and they are updated according to two important kinds of information for selection of the best particle. The first one is the cognitive behaviour which is gained by particle's own experience. The second one is the social behaviour which is gained from the neighbours. Particles keep the choices they tried by themselves and they have the knowledge which choices have outstand so far by their neighbours. This correlation provides the best choices in a swarm [9,10].

In the literature, there are many studies to calculate shielding effectiveness with deterministic methods [11-13]. Those analyses indicate the shielding performance of any structure without identifying the optimal solution in a particular design range. There is a small number of studies based on stochastic techniques to obtain optimal SE solutions. Genetic algorithm is reported to indicate that SE in multilayer design is higher than single layered counterpart of equal thickness [7],[14]. Particle swarm optimization is reported to determine the optimum effective mass of the bilayer electromagnetic shield that provides optimal SE [15]. PSO is also reported to arrange the hole array on a shielding enclosure to provide optimal SE [16]. Since there is only GA reported in a study which employs real dimensions of an enclosure used in electric vehicle and obtains optimal SE by optimizing aperture dimensions of the enclosure [1], this study determines aperture dimensions with an optimization methodology based on PSO and provides a comparative analysis with GA used in the literature. In this context, it is aimed to obtain optimal SE of a rectangular enclosure for a particular design range by determining aperture dimensions with a new optimization methodology based on PSO and present the advantages by comparing obtained results with the findings based on GA in the literature.

2 Problem formulation

Electric powertrain system inside electric vehicles is the major EMI source and potential EMI victim due to high switching speed inside inverter unit. Therefore, electromagnetic shielding performance of the enclosure of an inverter is analysed by determining its aperture dimensions with particle swarm optimization in this study.

Electromagnetic shielding performance of an enclosure is described with shielding effectiveness which indicates how the enclosure eliminates the effects of electromagnetic radiation from the interference source. There are various analytical and numerical methods to analyse SE. Since numerical methods need longer computation times and widely used for complex structures, an analytical method is employed to investigate SE of a rectangular enclosure [2]. Figure 1 shows the rectangular enclosure with an aperture and its equivalent circuit.

A plane wave acts as an interference source for the enclosure. Shielding effectiveness of a rectangular enclosure at the centre point P is given by the following equation, [2]

$$S_{\mathrm{E}} = -20\log\Big|\frac{v_p}{v_p'}\Big| = -20\log\Big|\frac{2v_p}{v_0}\Big|, \tag{1}$$

where the voltage at P in case of absence of the enclosure equals $v_{\mathrm{P}}' = v_0/2$ in which v_0 denotes the voltage of radiating source and v_{P} indicates the voltage in case of the presence of the enclosure which is governed by voltage phasor $\mathcal{V}_2$, equivalent impedance $\mathcal{Z}_2$ and load impedance $\mathcal{Z}_3$ in transmission line model expressed by the following equations respectively, [2]

$$\mathcal{V}_2 = \frac{\mathcal{V}_1}{\cos k_{\mathrm{g}}p + j(\mathcal{Z}_1/\mathcal{Z}_{\mathrm{g}})\sin k_{\mathrm{g}}p}, \tag{2}$$

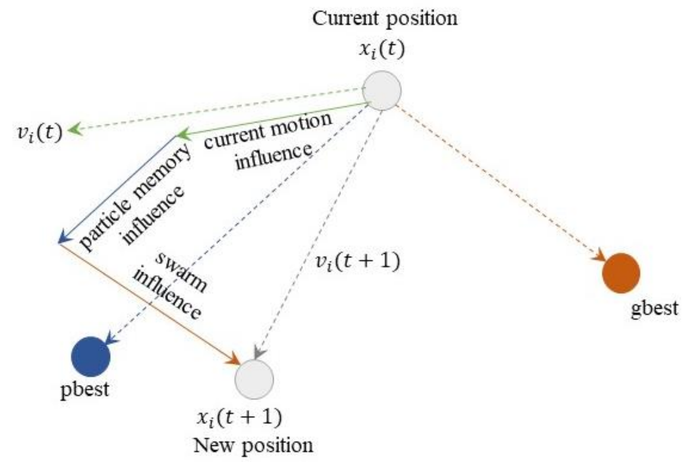

Fig. 2. The movement of a particle in a swarm based on velocity and position updates

$$\mathcal{Z}_2 = \frac{\mathcal{Z}_1 + j\mathcal{Z}_\mathrm{g}\tan k_\mathrm{g}p}{1 + j(\mathcal{Z}_1/\mathcal{Z}_\mathrm{g})\tan k_\mathrm{g}p}, \tag{3}$$

$$Z_3 = jZ_\mathrm{g}\tan k_\mathrm{g}(d-p), \tag{4}$$

where $\mathcal{Z}_\mathrm{g} = \mathcal{Z}_0/\sqrt{1-(\lambda/2a)^2}$, $k_\mathrm{g} = k_0/\sqrt{1-(\lambda/2a)^2}$, for TE_{10} mode of propagation. Here, $\mathcal{Z}_0 = Z_0 \approx 377\,\Omega$ is the wave impedance of free space and $k_0 = 2\pi/\lambda$ is the appropriate wave number.

The source voltage phasor $\mathcal{V}_1 = \mathcal{V}_0(\mathcal{Z}_\mathrm{ap}/(\mathcal{Z}_\mathrm{ap}+\mathcal{Z}_0))$ and the source impedance $\mathcal{Z}_1 = \mathcal{Z}_\mathrm{ap}\mathcal{Z}_0/(\mathcal{Z}_\mathrm{ap}+\mathcal{Z}_0))$ are obtained by $\mathcal{Z}_0$, $\mathcal{V}_0$ and $\mathcal{Z}_\mathrm{ap}$ which are source impedance, source voltage phasor and the equivalent impedance at point A respectively, [2]

$$\mathcal{Z}_\mathrm{ap} = \frac{jl}{2a}Z_\mathrm{0s}\tan\frac{k_0 l}{2}, \tag{5}$$

where Z_0S is characteristic impedance of the aperture of the rectangular enclosure

$$Z_\mathrm{0S} = \frac{120\pi^2}{\left[\ln\left(2\dfrac{1+Q}{1-Q}\right)\right]}, \tag{6}$$

with

$$Q = \left[1 - \frac{1}{b}\left(w - \frac{5t}{4\pi}\left(1+\ln\frac{4\pi w}{t}\right)\right)^2\right]^{1/4}$$

where w is the width of the aperture while the thickness and the height of the enclosure are denoted as t, and b, respectively.

SE can change depending on frequency, the dimensions of the shielding enclosure and aperture, [1]. While the frequency increases, the wavelength of the incident electromagnetic wave shortens and therefore higher amplitude of the incident field penetrates through the aperture which makes SE attenuate. Enlarging the enclosure dimensions provides better SE since the power of the electromagnetic wave propagating from the aperture to the depth of the enclosure attenuates depending on the increase of travelling distance. When the aperture dimensions are increased, the amplitude of the incident field penetrating into the enclosure increases which makes SE attenuate.

When the dimensions of the enclosure a, b, d and t remain fixed, S_E according to (1) can be changed by the aperture width w and the aperture length l of the enclosure, (5),(6).

3 Particle swarm optimization

Particle swarm optimization algorithm aims to find the optimal solution among the candidate solutions called particles in a swarm created randomly. These particles are moved around in the search space with respect to predefined rules. The movements of the particles are determined by their previous position and the best-known position of the particle in the swarm. When an improved position is being discovered, it will guide the movements of the swarm. The position and velocity of each particle is changed in such a way it moves towards particle's best position p^best and global best position g^best as depicted in Fig. 2. The process is repeated over a number of iterations until optimal solution is obtained.

When the dimensions of the enclosure shown in Fig. 1 remain fixed, then optimal solution for SE can be obtained by changing aperture width w and aperture length l of the enclosure.

In this study, a particle which generates a solution for SE consists of two elements such as aperture width w and aperture length l.

The first step in PSO is to have the position $x_i(t)$) for all particles randomly set in a swarm. The swarm is sized as $i \times d$, where i indicates the number of particles while d denotes the number of elements for a particle. Here $i = 1000$ is considered to be compared with the study in the literature [1], and $d = 2$ is defined due to reducing the solution parameters to the pairs of and which represent the particles. Initial positions of the particles are defined

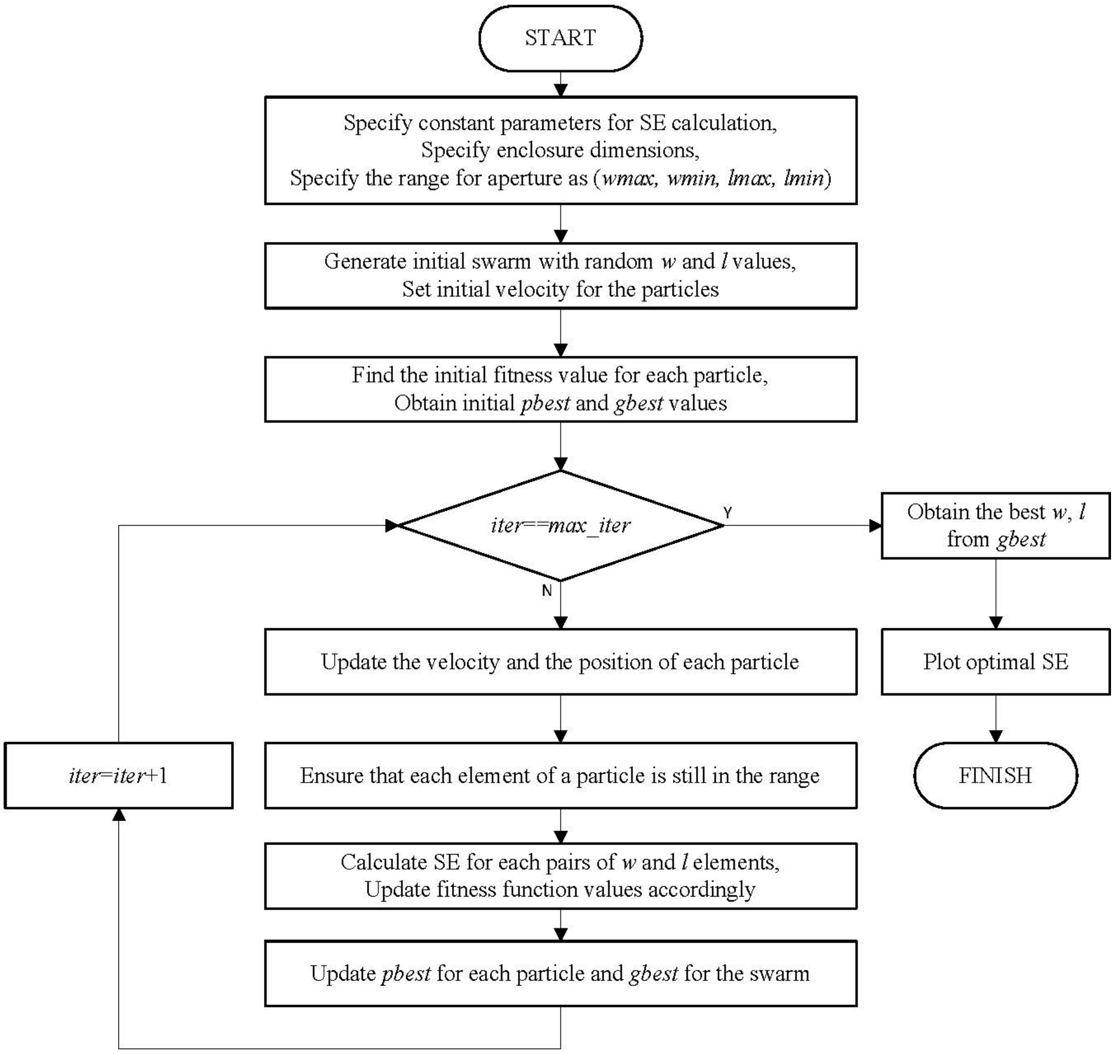

Fig. 3. The flowchart of optimization methodology based on PSO to provide optimal se

as

$$\begin{aligned} w_i|_{t=0} &= w_{\min} + \big(w_{\max} - w_{\min}\big) rs_i \,, \\ l_i|_{t=0} &= l_{\min} + \big(l_{\max} - l_{\min}\big) rs_, , \end{aligned} \tag{7,8}$$

where rs_i is a uniformly distributed random number that can take any value between 0 and 1 while $w_i|_{t=0}$ is the first element of the particle and $l_i|_{t=0}$ is the second one corresponding to the aperture width and the aperture length respectively. By $t = 0$ we denote the initial iteration step.

Second step in PSO is to update the velocity of each particle in the swarm at iteration step $[t+1]$ by, [17]

$$\begin{aligned} v_i[t+1] = \omega v_i[t] + c_1 rs_i \frac{(p_i^{\text{best}}[t] x_i[t])}{\Delta t} + \\ + c_2 rs_i \frac{(g_i^{\text{best}}[t] x_i[t])}{\Delta t} \end{aligned}, \tag{9}$$

where $v_i[t]$ represents current motion influence of a particle while $\omega = 0.8$ is an inertia factor. Initial velocity is set $v_i|_{t=0} = 0$ to update $v_i(1)$ with respect to the global best position in the swarm. Terms

$$c_1 rs_i (p_i^{\text{best}}[t] x_i[t]) / \Delta t \,,$$

and

$$c_2 rs_i (g_i^{\text{best}}[t] x_i[t]) / \Delta t \,,$$

represent particle memory influence and/or indicates the swarm memory influence. Values $c_1 = c_2 = 2$ are the learning factors of particle and swarm respectively [17,18].

The velocity of a particle $v[t]$ at an iteration step $[t+1]$ is updated with respect to fitness function value which depends on the particle current position in the swarm at an iteration step t. The fitness function value for each particle is obtained by calculating SE with the equation in (1). The best global position in the current swarm $g^{best}[t]$ and the best position of each particle over every iteration step $p^{best}[t]$ are determined by the fitness function values.

The third step is to update the position of each particle in the swarm by

$$x_i[t+1] = x_i[t] + v_i[t+1] \Delta t, \tag{10}$$

Table 1. Comparison of SE results with respect to frequency sample points

Result ID	Width (mm)	Length (mm)	Area (mm^2)	SE (dB) 200 MHz	SE (dB) 400 MHz	SE (dB) 600 MHz	SE (dB) 800 MHz
GA	9.9	51	504.9	57.33	43.74	34.71	41.08
PSO	10	50	500	57.65	44.06	35.04	41.39

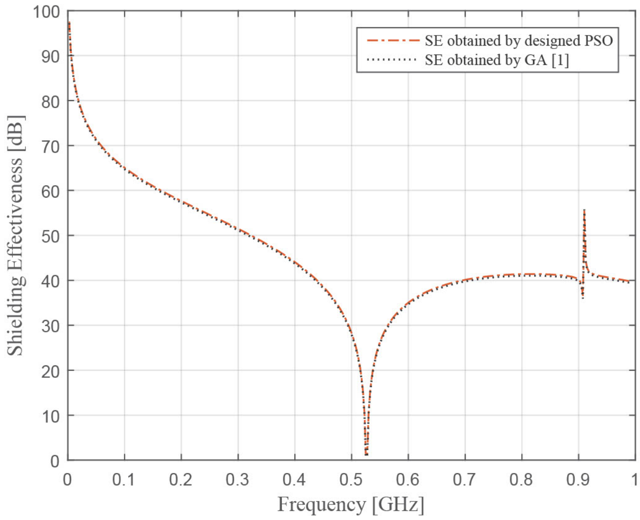

Fig. 4. Comparison of SE results obtained by PSO and GA

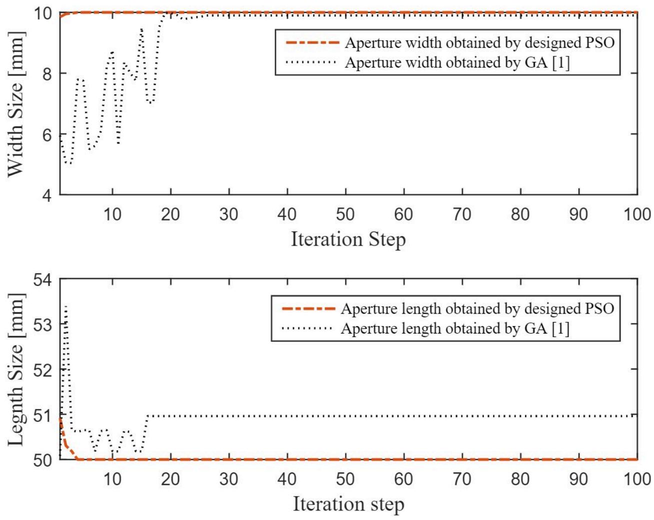

Fig. 5. The change on aperture dimensions during iteration steps

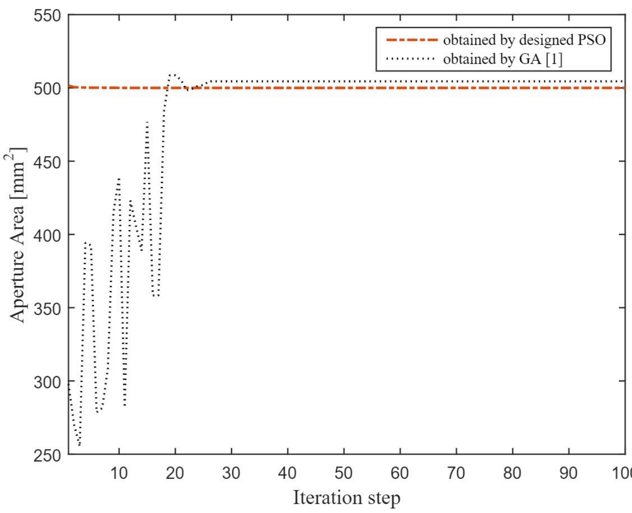

Fig. 6. The change on aperture area during iteration steps

where $x_i[t]$ is the actual position of the particle while $v_i[t+1]$ represents updating velocity towards the next position. is considered as the size of the iteration step $[t]$ which equals to 1. Therefore, updating position of a particle can be obtained as a sum of $x_i[t]$ and $v_i[t+1]$ values.

While updating the position of each particle, it is essential to verify that it does not exceed predefined range for the swarm. Since the particle has two elements such as the aperture width $w = x_{i,1}[t+1]$ and the aperture length $l = x_{i,2}[t+1]$ of the enclosure, both of them are checked for every iteration step. If $x_{i,n}[t+1] > x_{\max}$ then $x_{i,n}[t+1] = x_{\max}$ where $n = 1, 2$ and $x_{\max}$ equals to $w_{\max}$ or $l_{\max}$ depending on n value. Similarly, if $x_{i,n}[t+1] < x_{\min}$ then $x_{i,n} = x_{\min}$ where $n = 1, 2$ and $x_{\min}$ equals to $w_{\min}$ or $l_{\min}$ depending on n value.

Figure 3 shows the flowchart of optimization methodology based on particle swarm optimization which intends to provide optimal SE for the shielding enclosure by determining its aperture width w and length l.

4 Optimization results and findings

Electromagnetic compatibility (EMC) is one the critical topic for electronic units inside the propulsion system of electric vehicles. In this study, SE analysis of a shielding enclosure of an electronic unit is performed by determining its aperture dimensions with an optimization methodology based on particle swarm optimization. It is aimed to obtain optimal SE in a predefined range for the dimensions of aperture as 5 mm $\le w \le$ 10mm, 50 mm $\le l \le$ 150mm while the dimensions of the enclosure are considered as a = 490 mm, b = 240 mm, d = 350 mm to compare the results with the study in the literature, [1]. The wall thickness of the enclosure is t = 2.5 mm while the material of the enclosure is aluminium.

Table 2. Comparison of SE values obtained for each iteration step

Iteration step	Width (mm)	Length (mm)	Area (mm^2)	SE (dB) 200 MHz	SE (dB) 400 MHz	SE (dB) 600 MHz	SE (dB) 800 MHz
1	9.85	50.92	501.56	57.24	43.65	34.62	40.95
2	9.95	50.31	500.58	57.56	43.97	34.94	41.28
3	9.97	50.18	500.29	57.6	44.01	34.98	41.33
4	10	50	500	57.65	44.06	35.04	41.39
5	10	50	500	57.65	44.06	35.04	41.39

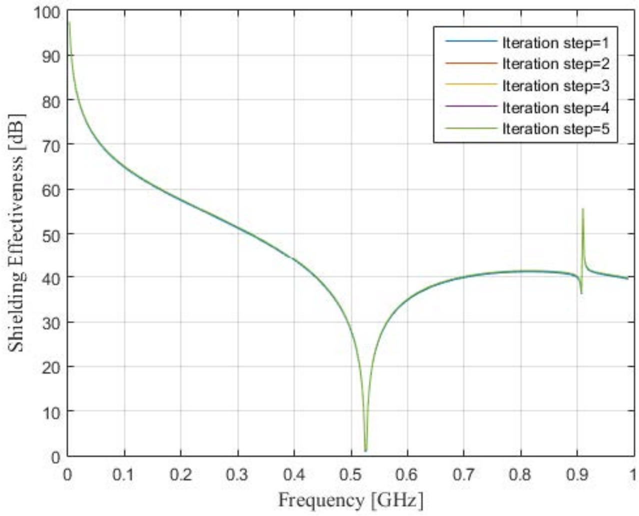

Fig. 7. The change on SE during iteration steps

Figure 4 depicts the comparison of SE result obtained with designed optimization methodology based on PSO and the one obtained with genetic algorithm in [1]. The results clearly show the effectiveness of designed optimization methodology which also establishes a very good agreement with the result in the literature.

The comparison of SE results with respect to frequency sample points is shown in Tab. 1 which indicates that obtained result with the optimization methodology based on PSO is similar to the one in [1]. Maximum 0.33 dB difference is calculated between two SE results.

Figure 5 shows the change of aperture width and aperture length l during iteration steps to get optimal SE result. The optimization methodology based on PSO is superior in term of speed to reach the optimal solution. It is observed that the optimization methodology reaches to the final w and l values by 4th iteration step while GA reaches to its final ones by 19th iteration step. The change on aperture length l has bigger impact on SE than changing of aperture width due to the vertical polarization of the incident electric field. Thus, the optimization methodology based on PSO intends to increase aperture width w while decreasing aperture length l in order to provide optimal SE.

Figure 6 depicts the change of aperture area during obtaining optimal SE result. It is observed that the optimization methodology reaches to the final aperture area as 500 mm^2 by 4th iteration step while GA reaches to the final one as 504.9 mm^2 by 19th iteration step.

Thanks to reaching smaller aperture area with the optimization methodology based on PSO, it provides better SE than GA. Figure 7 illustrates the change on SE during iteration steps of the optimization methodology. SE values with respect to frequency sample points obtained for each iteration step is shown in Tab. 2. Due to the optimization methodology reaches to the final and values by 4th iteration step, the comparison of the first 5 iteration steps is presented. Since lower aperture area is reached for the next iteration steps, SE gets better accordingly. The optimization methodology converges quickly to the final values and therefore very small difference such as ≤ 0.44 dB is calculated between initial and final iteration steps.

The optimization methodology generates results less than a minute to provide a design decision in case of the dimensions of shielding enclosure remain fixed. Designed optimization methodology is very flexible that can be modified easily to process more data by increasing the particle number i, iteration number $i_{\max}$. It can be applied to obtain optimal SE for any rectangular enclosure by determining the aperture dimensions in a predefined range.

It is observed that designed optimization methodology based on PSO can allow faster convergence than GA in this study. Besides that, it provides greater diversity and exploration over a single initial population since it does not utilize any operator such as crossover, mutation for changing the diversity of the population as GA did. Both of them start with randomly generated population and both calculate fitness value to evaluate the population. The evaluation mechanism in designed optimization methodology based on PSO and the optimization based on GA in the literature are carried out differently. Global best g^{best} obtained by each iteration in PSO gives out the information to the other particles in the swarm while chromosomes share information with each other in the population of GA. PSO has an information sharing mechanism from one particle to the others which may make the optimization methodology to converge a local minima or

Table 3. Summary of the comparison of the optimization methodology based on PSO and the one based on GA

Indicator	Optimization methodology based on PSO	Optimization based on GA, [1]
Complexity	Easier to be implemented compared to GA	Needs additional operators such as crossover, mutation
Parameters	Less number of parameters compared to GA	More parameters are needed for operators
Iteration	Less iteration step thanks to faster convergence	More iteration step due to replacing whole population
Accuracy	High resolution provides the optimal solution	Large variables result in feasible solutions coptimal one

maxima quickly, but it is more computationally efficient than GA.

The decrease in accuracy of GA is caused by the increase of the number of variables. Changing the diversity of the population by applying genetic operators such crossover, mutation requires much more variables than PSO. Besides that, PSO has more stable condition in finding the optimal SE since no need to add several techniques to elect elite chromosomes or to improve genetic operators. Table 3 shows summary of the comparison of the optimization methodology based on PSO and the one based on GA in the literature.

5 Conclusions

Ideal protection of electronic circuits against external EMI is achieved by placing them into an electromagnetic shielding enclosure which has no aperture on itself. However, the aperture on the enclosure is strictly needed due to mounting connectors, ventilation etc. Unless the aperture is designed carefully, it attenuates shielding effectiveness of the enclosure significantly. Enlarging enclosure dimensions makes SE get better. Yet, they cant be designed so large due to weight and dimension considerations. For the enclosures in electric vehicles, there are dimension limitations which force to investigate alternative solutions to increase SE. When the dimensions of shielding enclosure remain fixed and the aperture is to have a particular area, it is essential to optimize aperture dimensions to increase SE of the enclosure.

In this paper, analysis of shielding effectiveness by determining aperture dimensions of a rectangular enclosure with particle swarm optimization has been performed. An optimization methodology based on PSO is designed to obtain the optimal SE for a particular dimension range. The study provides also a comparative analysis between designed optimization methodology and the optimization with genetic algorithm carried out in the literature.

Obtained SE results clearly show that the optimization methodology based on PSO establishes a very good agreement with the one based on GA in the literature. Moreover, designed methodology provides faster convergence to the final values thanks to the information sharing mechanism of PSO and very small difference such as $\leq 0.44\,\mathrm{dB}$ is calculated between initial and final iteration steps. It is obtained that the change on aperture length has bigger impact on SE rather than changing of aperture width due to the vertical polarization of incident electric field. Thus, the optimization methodology intends to increase aperture width while decreasing aperture length to obtain the optimal SE.

Consequently, the optimization methodology based on PSO is easier to be implemented compared to the one based on GA since it does not require any genetic operators. It utilizes less number of parameters thanks to its simplicity. The best particle in PSO gives out the information to the rest of the particles in the swarm while chromosomes share information with each other in the population of GA. Thus, the optimization methodology has higher calculation accuracy and faster convergence than GA. As a future work, changing the material of the enclosure to increase SE will be proposed.

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