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Optimal Design of Multi-layered Radar Absorbing Structures (RAS) using Swarm Intelligence based Algorithm

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ABSTRACT

The steady progress in the fields of material science and processing technologies has made multi-layered Radar Absorbing Structures (RAS) an attractive option w.r.t. stealth technologies. They possess the ability to reduce radar cross-section with minimum thickness and is therefore most preferred in airborne applications. As far as their electromagnetic performance is concerned, the sequence of material layers and thickness profile plays a pivotal role. Optimisation of these two factors becomes complex in case of availability of large number of potential materials. Commonly used EM simulation software can be employed for the optimisation of thickness profile. However, selection of suitable material layer sequence is out of their scope. In this context, a Particle Swarm Optimisation (PSO) based algorithm is presented for sequencing of material layers and optimisation of thickness profile of multi-layered RAS configurations. The fitness function has been appropriately formulated to achieve maximum power absorption over broad band of frequencies and wide range of incident angles. Further, the efficacy of the algorithm has been demonstrated using a suitable case study.

Keywords: Stealth technologies; Multi-layered radar absorbing structures (RAS); Particle swarm optimisation (PSO); Power absorption

NOMENCLATURE

RCS	:	Radar cross section
EM	:	Electromagnetic
RAM	:	Radar absorbing materials
RCSR	:	Radar cross section reduction
RAS	:	Radar absorbing structures
PSO	:	Particle swarm optimisation
$\tilde{\Gamma}$	:	Overall recursive reflection coefficient
$\tilde{T}_{1M}$	:	Overall transmission coefficient
k	:	Phase constant
μ	:	Complex permeability
ε	:	Complex permittivity
Gbest	:	Global best
Pbest	:	Personal best

1. INTRODUCTION

The reduction of RCS of defense aircraft has become a stringent performance criterion with the rapid advancements in the area of airborne electronic warfare systems. The primary goal here is to increase the survivability of the vehicle by reducing the visibility from enemy radar systems which in turn will allow the operators to conduct surprise missions. The detectability of a target is determined by the strength of the radar signals reflected back from them towards the probing source. This can be quantified in terms of RCS which is basically the effective area contributing to the scattering of EM waves back towards the enemy radar. It depends on several factors like target shape, surface roughness, electromagnetic properties of the base material, wavelength and polarisation of the incident EM wave, aspect angle of the target etc. Based on these driving factors, several techniques like shaping, application of RAM, passive cancellation/impedance loading, active cancellation, etc. can be used to reduce RCS[1-2].

In shaping, the stealth platform is shaped in such a way so as to reroute the incident radar signals in directions away from the radar. The main surfaces and edges of the platform are therefore designed to reflect or diffract the incident signals accordingly. Low observable aircrafts like Lockheed F-117 nighthawk, Northrop Grumman B-2 Spirit etc. have used extensive surface faceting RCSR. But, the alteration of shape may adversely affect the aerodynamic performance and can also introduce maneuverability issues. In passive cancellation, RCSR is achieved by incorporating a secondary scatterer to cancel the reflections from the primary target. The core idea is to create reflected waves whose amplitude and phase can be adjusted to cancel out another set of reflected waves. This is applicable only for comparatively simple targets where a loading point can be clearly identified on the platform. Typical military platforms have numerous hotspots and thus it is not practical to have a secondary scatterer for each of these

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sources. With respect to active cancellation, active transmitters are introduced to generate new signals which would cancel the original radar signal reflected from the aircraft. This scheme requires detailed information regarding the incident wave like angle of arrival, intensity, waveform and frequency. It should sense these data accurately and then reproduce the wave with appropriate amplitude and phase. This is obviously a herculean task which requires complex avionics.

In the case of RAM, the energy reflected back to the radar is reduced by enhancing the phenomenon of absorption. It can be done either by using radar absorbing composites as the base material for the platform or novel coatings at identified hotspots on the target body. Microwave absorption can be enhanced by tailoring the dielectric and magnetic properties of the materials with the help of suitable additives and processing techniques. The primary aim while doing so is to obtain a material with maximum absorption efficiency in a wide range of frequencies for any angle of incidence and arbitrary polarisation but with minimum thickness and payload burden[3-5]. Undoubtedly, it is difficult to achieve wideband polarisation-independent absorption with just a single layer of absorbing material. With the potential developments in the field of material science and process engineering, more importance is now being given to the development of multilayered RAS, which provides a viable solution for achieving broadband RCSR at reduced thickness. The design variables like number of layers, electric/magnetic parameters of each layer and thickness profile can be optimised to cater to specific EM performance requirements. However, optimisation of these parameters becomes complex in case of availability of large number of potential materials. Commonly used EM simulation software can be employed for the optimisation of thickness profile. However, the facility of selection of suitable material layer sequence is not available in such software packages.

In this context, an efficient PSO based algorithm is presented to optimise the sequence of material layers and thickness profile of a multi-layered RAS configuration, given a database of potential materials and specific range of feasible thicknesses. The fitness function has been intelligently tailored using a full wave formulation in order to achieve maximum power absorption over broad band of frequencies and wide range of incident angles. The theoretical formulation and description of algorithm is included in the subsequent sections.

2. COMPUTATION OF POWER ABSORPTION CHARACTERISTICS OF MULTI-LAYERED RAS

The schematic diagram of a multi-layered RAS model with *M* layers is shown in Fig. 1.

Each layer has its corresponding thickness (t), complex permeability ($\mu = \mu' - j\mu''$) and complex permittivity ($\varepsilon = \varepsilon' - j\varepsilon''$). Here, materials are layered in a particular sequence resulting in interfaces at which the electric/magnetic parameters change abruptly. The incident EM waves get reflected and transmitted at these interfaces and the overall reflection from a specific interface depends on the reflections from all the layers beneath it.

The overall recursive reflection ($\tilde{\Gamma}$) coefficient at the interface between j^{th} and $(j+1)^{th}$ layer in the RAS model can be expressed as[6],

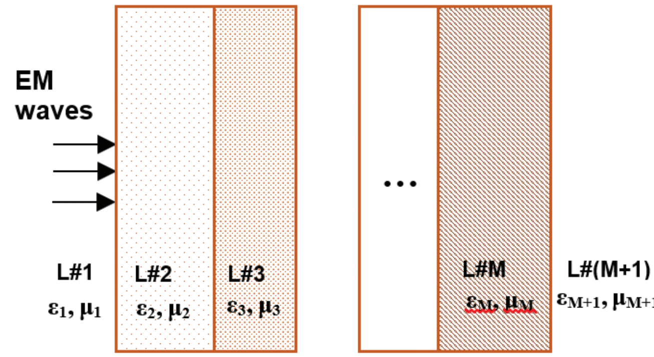

Figure 1. Schematic diagram of multilayered RAS.

$$\tilde{\Gamma}_{j,j+1} = \frac{\Gamma_{j,j+1} + \tilde{\Gamma}_{j+1,j+2}\, e^{2ik_{j+1,z}(t_{j+1}-t_j)\cos\theta_{tj}}}{1+\Gamma_{j,j+1}\,\tilde{\Gamma}_{j+1,j+2}\, e^{2ik_{j+1,z}(t_{j+1}-t_j)\cos\theta_{tj}}} \quad (1)$$

Where $\Gamma_{j,j+1}$, t_j, θ_{tj} and $k_{j+1,z}$ denote Fresnel (or intrinsic) reflection coefficient at the interface between j^{th} and $(j+1)^{th}$ layer, thickness of j^{th} layer, angle made by refracted ray with the normal to j^{th} interface and phase constant in $(j+1)^{th}$ layer along the direction normal to the RAS model respectively. Other notations with different subscripts can be interpreted in a similar manner.

Further, the overall transmission coefficient ($\tilde{T}_{1M}$) of the RAS model with M layers can be written as[6],

$$\tilde{T}_{1M} = \prod_{j=1}^{M-1} e^{ik_{j,z}\left(t_j - t_{j-1}\right)\cos\theta_{tj}}\, S_{j,j+1} \quad (2a)$$

where,

$$S_{j,j+1} = \frac{T_{j,j+1}}{1-\Gamma_{j+1,j}\,\tilde{\Gamma}_{j+1,j+2}\, e^{2ik_{j+1,z}(t_{j+1}-t_j)\cos\theta_{tj}}} \quad (2b)$$

The Fresnel refection $(\Gamma_{j,j+1})$ and transmission $(T_{j,j+1})$ coefficients corresponding to TE as well as TM polarisations at the interface between j^{th} and $(j+1)^{th}$ layer can be evaluated using the following expressions[7]:

For TE polarisation,

$$\Gamma^{TE}_{j,j+1} = \frac{\mu_{j+1}k_j\cos\theta_{ij} - \mu_j k_{j+1}\cos\theta_{tj}}{\mu_{j+1}k_j\cos\theta_{ij} + \mu_j k_{j+1}\cos\theta_{tj}} \quad (3a)$$

$$T^{TE}_{j,j+1} = \frac{2\mu_{j+1}k_j\cos\theta_{ij}}{\mu_{j+1}k_j\cos\theta_{ij} + \mu_j k_{j+1}\cos\theta_{tj}} \quad (3b)$$

For TM polarisation,

$$\Gamma^{TM}_{j,j+1} = \frac{\varepsilon_{j+1}k_j\cos\theta_{tj} - \varepsilon_j k_{j+1}\cos\theta_{ij}}{\varepsilon_{j+1}k_j\cos\theta_{tj} + \varepsilon_j k_{j+1}\cos\theta_{ij}} \quad (3c)$$

$$T^{TM}_{j,j+1} = \frac{2\varepsilon_{j+1}k_j\cos\theta_{ij}}{\varepsilon_{j+1}k_j\cos\theta_{tj} + \varepsilon_j k_{j+1}\cos\theta_{ij}} \quad (3d)$$

Where θ_{ij} and θ_{tj} denote the angles made by incident ray and refracted ray respectively with the normal to the interface

j. k_j, μ_j and ε_j denote the phase constant, permeability and permittivity of j^{th} layer respectively. For normal incidence,

$$\Gamma^{TE}{}_{j,j+1} = \Gamma^{TM}{}_{j,j+1} \text{ and } T^{TE}{}_{j,j+1} = T^{TM}{}_{j,j+1} \quad (4)$$

In the present model, $\tilde{\Gamma}_{12}$ corresponds to the overall recursive reflection coefficient for the entire configuration. Once $\tilde{\Gamma}_{12}$ and $\tilde{T}_{1M}$ are computed, the amount of power absorbed (in %) by the RAS model can be calculated as,

$$Power\ \ absorbed\ (\%) = (1 - |\tilde{T}_{1M}|^2 - |\tilde{\Gamma}_{12}|^2) \times 100 \quad (5)$$

The main objective in the design of RAS is to achieve a power absorption (in %) greater than 90 per cent over the desired frequency band with the total thickness within the stipulated limits.

3. PSO BASED ALGORITHM FOR THE OPTIMISATION OF MULTI-LAYERED RAS

Well known approaches like Salisbury screen, Jaumann absorber, and Dallenbach layers have been used earlier to realise EM absorbers. They have been designed using fairly accurate closed-form expressions and optimised using relatively simpler schemes. As mentioned earlier, multilayered RAS are slowly replacing these conventional absorber models in view of their capability to achieve broadband RCSR at reduced thickness. The EM design of multi-layered RAS involves optimisation of a number of parameters so as to maximise power absorption over a broad band of frequencies and incident angles at the same time maintaining reduced thickness and weight penalty. Traditional optimisation algorithms like conjugate gradient method, simplex method, etc. take longer time for convergence and can easily settle down at local optimum. Nature inspired algorithms like genetic algorithm (GA), differential evolution, PSO, wind driven optimisation technique etc. are attractive alternatives in this regard. GA has been used in [8] for the optimisation of multi-layered dielectric media using a database of 16 materials. 500 cycles of iterations have been used here for converging onto an optimised model and it took approximately 10 minutes for the entire process. Different formulations of GA have been used in [9] to derive an optimised RAS model from a list of six lossy materials. It took 20, 8 and 4 minutes respectively for niched Pareto GA, non-dominated sorting GA (NSGA) and NSGA-II for 100 generations. However, implementation of GA is difficult owing to its inherent complexity[10] and large computation time[11]. Similar optimisation problems have also been dealt with using self-adaptive differential evolution algorithm[12] (DE), wind driven optimisation approach[13] and PSO[14-17]. In [17], PSO has been used for the thickness optimisation of multi-layered coatings for precision laser interferometry and the typical run times have been found to be in the order of 10 minutes. Amongst all, PSO is more efficient with comparatively minimal computational difficulties and high ease of implementation. In [18], the performance of PSO has been compared with that of bat algorithm and cuckoo search algorithm w.r.t the optimal design of a seven layered microwave absorber. It has been found that PSO is more efficient than others w.r.t computational time. On account of its attractive attributes, PSO has been used in the current paper for the optimisation of material layer sequence and thickness profile of multi-layered RAS. PSO is based on the intelligence of a swarm of bees which is in the pursuit of finding the location with maximum density of flowers. This concept can be extended to real life scenarios. The various steps involved in the implementation of PSO based algorithm are given as follows.

3.1 Specification of Feasible Range for Design Parameters

At this step, the parameters to be optimised are chosen and their solution space is clearly outlined. In the present optimisation problem, the maximum and minimum values of individual layer thicknesses and the total number of materials in the database defines the solution space.

3.2 Formulation of Fitness Function

A fitness function denotes the quality of a particular position in a single value. In the present case, in order to have maximum power absorption over a frequency range specified by f frequency points and over a range of incident angles defined by a points, the fitness function (FIT) has been formulated as,

$$FIT = \sum_{p}^{f} \sum_{q}^{a} \left(|\tilde{\Gamma}|^r + |\tilde{T}|^r \right) \quad (6)$$

Where $|\tilde{\Gamma}|$ and $|\tilde{T}|$ denotes the absolute value of overall recursive reflection and transmission coefficients respectively at p^{th} frequency and q^{th} incident angle. Based on the polarisation of incident wave, the coefficients corresponding to TE and TM polarisation have to be appropriately substituted. The variable r has been used to shift the area of optimisation to those frequency points where reflection and transmission is higher. Here, r has been assigned a value of 2.

3.3 Definition of Initial (Random) Positions and Velocities

In PSO terminology, an individual bee in the swarm is referred to as a particle. In the search for optimal location, each particle begins from an initial random location and flies initially with a random velocity. These parameters have to be specified at this step. The locations with the best value of fitness function personally come across so far by the bee and that encountered by the swarm of bees are referred to as personal best (*Pbest*) and global best (*Gbest*) respectively. These parameters will also be evaluated using initial position at this step.

3.4 Tracing the Trajectory of Particles in the Solution Space

PSO based algorithm moves each particle by a small amount and repeats this for a pre-defined number of iterations. During each iteration, the fitness function corresponding to the current position of a particle is evaluated and compared with the values at its *Pbest* and *Gbest*. If the value corresponding to the current position is better than that at *Pbest* and *Gbest*, the appropriate positions are substituted with the current position.

In order to move the particle further in a direction influenced by both *Pbest* and *Gbest,* the velocity (VL) needs to be updated as[14],

$$VL_{iD}^{j} = q \times VL_{iD}^{j-1} + Pbest\_term + Gbest\_term \quad (7a)$$

where,

$$Pbest\_term = k_1 \times rand\,1_{iD}^{j}() \times \left(Pbest_{iD}^{j-1} - X_{iD}^{j-1}\right) \quad (7b)$$

$$Gbest\_term = k_2 \times rand\,2_{iD}^{j-1}() \times \left(Gbest_{iD}^{j-1} - X_{iD}^{j-1}\right) \quad (7c)$$

where i and j corresponds to particle number and iteration number respectively. VL_{ID} and X_{ID} denote the particle velocity and particle co-ordinate in the D^{th} dimension respectively. q corresponds to the inertial weight and (k_1, k_2) represent the acceleration constants which decide the relative pull of *Gbest* and *Pbest*. *rand1* and *rand2* are random number functions which generates uniform random numbers between 0 and 1. Once the velocity is updated, the new position of particle can be evaluated as,

$$X_{iD}^{j} = X_{iD}^{j-1} + VL_{iD}^{j} \quad (8)$$

Once new positions are found, appropriate boundary conditions (absorbing walls, reflecting walls or invisible walls) have to be applied to confine the particles within the solution space.

On completion of steps (3.1) through (3,4), the algorithm has to be repeated from (3.4) until a specific termination condition is satisfied or when pre-defined number of iterations are completed. The choice of various constants in Eqn. (7) has been done as per criteria mentioned in[16].

4. PERFORMANCE EVALUATION OF DEVELOPED ALGORITHM

The developed PSO based algorithm has been implemented in FORTRAN. In view of aerospace applications, the base material has been taken as carbon fibre reinforced plastic (CFRP) of thickness 3.0mm in all the cases considered in the present paper. The full wave formulation developed for the computation of reflection/transmission coefficients has been framed as a sub-routine. To validate the code, the computed frequency dependent power absorption characteristics of a two layered RAS at angle of incidence of 60° has been compared with that obtained from FEKO, as shown in Fig. 2. The details of RAS configuration are given below:

Top-layer:

$\varepsilon = 5 - j0.10,\ \mu = 1 - j0.01$ (at 10 GHz)
Maximum thickness = 1.0mm

Middle layer:

$\varepsilon = 0.16 - j0.6,\ \mu = 2.7 - j1.00$ (at 10 GHz)
Maximum thickness = 1.0mm

Bottom layer:

CFRP; Thickness = 3.0mm.

It is apparent that the computed results for both TE and TM polarisations match with those simulated using FEKO.

Once accuracy of formulation has been confirmed, the indigenously developed algorithm has been used for the optimisation of a two layered RAS given a database of 30 materials. The frequency dependent material parameters of potential absorbing materials have been measured using waveguide setup. For illustration, the variation in the constitutive parameters (at 10 GHz) of materials in the pre-defined database is presented in Fig. 3.

The number of particles and number of iterations have

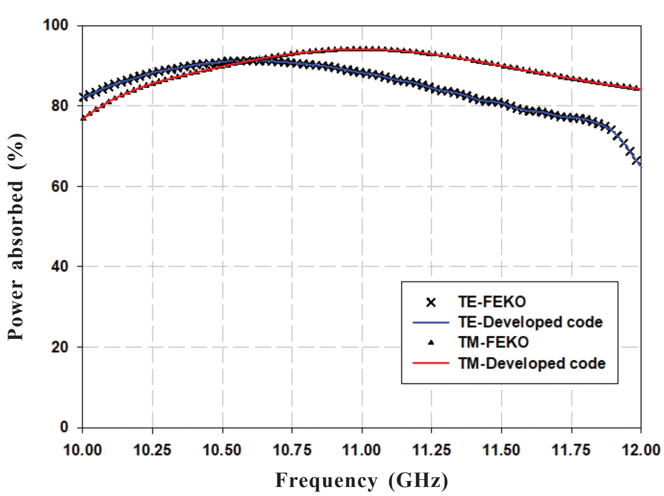

Figure 2. Comparison of power absorption characteristics of two-layered RAS computed using developed sub-routine and FEKO.

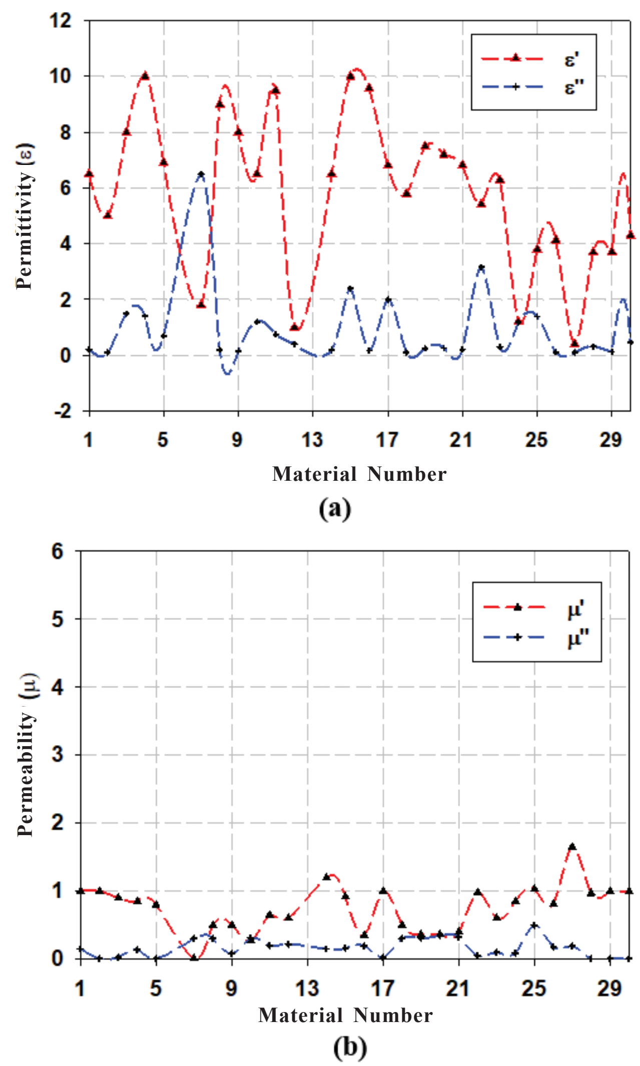

Figure 3. Constitutive parameters of materials in the predefined database: (a) Permittivity (ε) (b) Permeability (μ).

been fixed as 30 based on convergence studies. The maximum possible thickness for top layer and middle layer has been taken as 1.5mm and minimum thickness for all layers has been fixed as 0.1mm. On execution of code, the following profile has been obtained as the global best solution for X-band:

Top-layer:

$\varepsilon = 7.5 - j1.1,\ \mu = 0.2 - j\ 0.4;\ (\text{at 10 GHz})$

Thickness = 1.3mm.

Middle layer:

$\varepsilon = 6.4 - j1.15,\ \mu = 1.05 - j0.01;\ (\text{at 10 GHz})$

Thickness = 1.49mm.

Bottom layer:

CFRP; Thickness = 3.0mm.

Total thickness of RAS = 2.79mm.

Figure 4 presents the power characteristics of the optimised two layered RAS configuration and it is clear that the percentage of power absorbed is greater than 95 per cent over X-band thereby clearly establishing the efficiency of fitness function.

In order to visualise the effect of optimisation, the power absorption characteristics of the RAS model corresponding to the initial randomly generated parameters as well as the optimised parameters is compared in Fig. 5. It is clear from Fig. 5 that the percentage of power absorbed has increased significantly with the optimised thickness profile and material sequence.

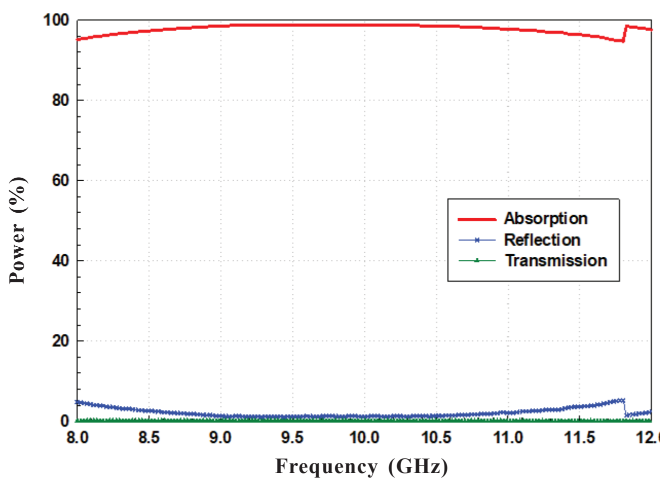

Figure 4. Power characteristics of optimized two layered RAS in X-band.

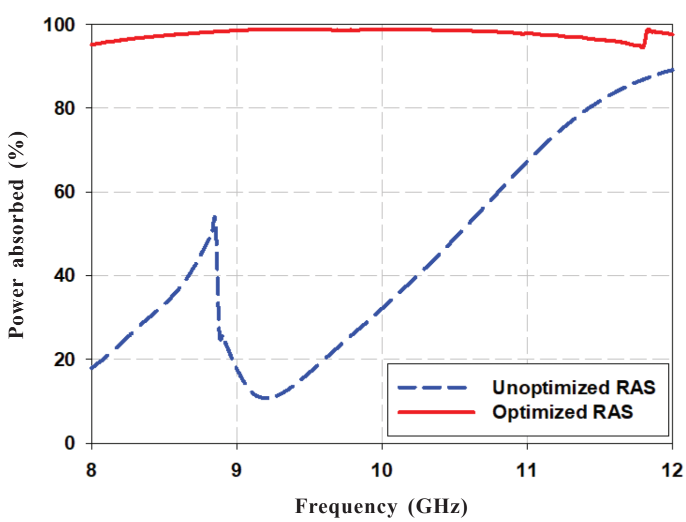

Figure 5. Comparison of power absorption characteristics between initial randomly generated parameters and optimised parameters.

Further, the computational efficiency of the developed PSO based algorithm has been compared with that of full wave simulation software like FEKO. FEKO does not have option for automatically choosing suitable materials for different layers. Therefore, all possible material combinations have to be chosen manually and the corresponding thickness profiles have to be optimised in FEKO. Considering a database of 30 materials as in the present case, the number of material sequences possible for a two layered RAS configuration will be 30 × 30, i.e., 900. In order to optimise the thickness profiles of all these 900 models, the PSO based optimisation option in FEKO has to be run 900 times. Once all results are available, the best option amongst them have to be selected. FEKO takes approximately 2.5 hours for PSO based thickness optimisation (step size = 0.01mm) of a two layered RAS configuration over X-band (number of frequency points = 201) using a Dell precision tower 7810 workstation. This implies that FEKO would take $900 \times 2.5 \approx 2250$ hours for completing the entire optimisation problem. However, the developed PSO based algorithm completed the entire process in less than a minute in turn establishing its computational efficiency. The computational performance of the present work is compared with other reported algorithms in Table 1.

Table I. Performance comparison with previously reported algorithms

Reference	Optimisation technique	Number of materials	Computational time (in minutes)
Michielssen, E. *et al.*[8]	GA	16	10
Jiang, L. *et.al.*[9]	Niched Pareto GA	6	20
	NSGA	6	8
	NSGA-II	6	4
Roy, S. *et.al.*[18]	PSO	16	16
	BAT	16	22
	Cuckoo search	16	25
Present work	PSO	30	<1

5. CONCLUSION

Multi-layered RAS are potential options for reducing the scattering from hotspots on airborne platforms on account of their superior power absorption characteristics achievable with reduced thicknesses. Hotspots like air intake cavity, leading wing edge, corner reflectors, exhaust cavity, etc. are some of the identified hotspots on military aircraft whose RCS can be effectively reduced using multi-layered RAS. In this direction, RAM synthesis has gained a lot of research attention resulting in the availability of a huge number of potential materials. However, the selection of suitable material layer sequence and optimisation of corresponding thickness profile of a multi-layered RAS configuration is a challenging task. In this regard, a computationally efficient PSO based algorithm has been presented in this paper for material layer sequencing as well as thickness optimisation of multi-layered RAS models. The fitness function has been intelligently tailored using a full wave formulation in order to achieve maximum power absorption over broad band of frequencies and wide range of incident angles. The accuracy and efficiency of the developed algorithm has been established by carrying out the design of a two layered RAS using a database of 30 potential materials. The optimised design suggested by the code, in less than a minute, achieved greater than 95 per cent power absorption over the desired frequency range. On the other hand, FEKO would take approximately 2250 hours for the same problem. Therefore, the indigenously developed PSO based optimisation methodology can be used for the realisation of efficient multi-layered RAS configurations which can be used on stealth platforms. However, since the algorithm is tailored for multi-layered configurations, it cannot handle frequency selective surface (FSS) and metasurface based RAS. The algorithm needs to be elaborately modified to incorporate the same.

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In the present study, she reviewed the work and consistently provided valuable guidance as well as critical inputs.