Defence Science Journal, Vol. 73, No. 4, July 2023, pp. 394-401, DOI : 10.14429/dsj.73.17889

Aero-structural and Electromagnetic Design Optimisation of Maritime Patrol Aircraft Radome Using Direct Search Algorithms

M.R. Shankar[#,*], A.C. Niranjanappa[#] and B. Dattaguru[$]

[#]*DRDO-Centre for Airborne Systems, Bengaluru - 560 037, India*
[$]*IIAEM, Jain (Deemed-to-be University), Bengaluru - 562 112, India*
[*]*E-mail: mrsankar.cabs@gov.in*

ABSTRACT

Airborne surveillance systems such as Maritime Patrol Aircraft are deployed by armed forces to collect surveillance information on airborne and sea surface enemy targets. Airborne Electronically Scanned Array Radar is an electromagnetic sensor integrated on this aircraft. The antenna of this radar is installed generally in belly of a turboprop aircraft. An electro-magnetically transparent cover, called radome, protects this antenna to protect it from various environmental effects, like rain, dust, etc. Installation of the radome results in additional drag, weight and electromagnetic signal loss. The Pareto optimality involving three design disciplines of structure, aerodynamics and electromagnetics is attempted with direct search optimisation algorithm NSGA II.

Keywords: Radomes; MDO; Structures; Electromagnetics; A-Sandwich

1. INTRODUCTION

Maritime Patrol Aircraft (MPA) is used for scanning sea surfaces for getting real-time data about enemy threats i.e., low flying aircraft. Turboprop aircraft are generally modified as MPA since they fly at low altitudes. RAdio Detection And Ranging system, or RADAR, in short, is an electromagnetic sensor integrated on this aircraft. Radar antenna of MPA is mounted under the belly of the aircraft to scan sea surface in Air-to-Sea mode. The antenna is protected by a structural cover called radome (a portmanteau for Radar DOME). Radome should withstand air loads in flight and protect the antenna from environmental effects like rain, ice, dust, etc.

As stated, a radome is a necessity to protect the antenna. However, it introduces certain unwanted side effects like additional weight, drag force, and distortion of the electromagnetic signals transmitted and received by the antenna. The increase in the weight due to radome, drag forces introduced and distortions of electromagnetic signals due to their presence should be minimum.

In this study, multi-disciplinary design and analysis of MPA radome is carried out by integrating three important disciplinary analyses on an MDO software framework. Multi-objective optimisation of three conflicting design objectives, weight, drag and electromagnetic loss, is carried out using direct search algorithm. Pareto optimality condition for such MDO problem is established.

2. LITERATURE REVIEW

Profile of maritime patrol radar airborne radome[1] was modeled and CFD analysis was carried out with ANSYS software to estimate radome's drag. Single objective optimisation i.e., minimisation of the drag due to this radome, was demonstrated by integrating aerodynamics discipline on MDO software framework with a proprietary algorithm PilOPT by the authors.

In continuation to the above, the same study was expanded by the authors[2] for optimisation of maritime patrol radar airborne radome involving two disciplines, namely, aerodynamics and structures. Two objectives, drag and weight of radome were optimised subject to design constraints with additional design variables introduced due to structural design. In the current paper, the study is further expanded to include electromagnetics discipline in addition to structural and aerodynamics disciplines. MDO is carried out with a GA technique, NSGA II.

The design steps for ground surveillance radar on a transport aircraft were brought out by Pulvirenti*, et. al.*[3]. The electromagnetic analysis, selection of materials for such radomes, structural analysis for air loads, and bird strike are elaborated. The size of the radome is limited by aircraft size. This study has dealt with a similar radome for which present optimisation is attempted. Although in this paper in literature, it was remarked that radome design is multi-disciplinary, such analysis was not carried out.

Lee[4]*, et al.* proposed a simple design equation for A-sandwich radome design for aircraft, missiles as well as fixed ground installations. Radomes are proposed as thin or multiple half-wavelengths (λ/2). Radomes with good EM transmission properties are with a thickness of λ/20. This radome will not be able to sustain harsh environmental conditions and is

Received : 07 February 2022, Revised : 18 January 2023
Accepted : 13 April 2023, Online published : 11 July 2023

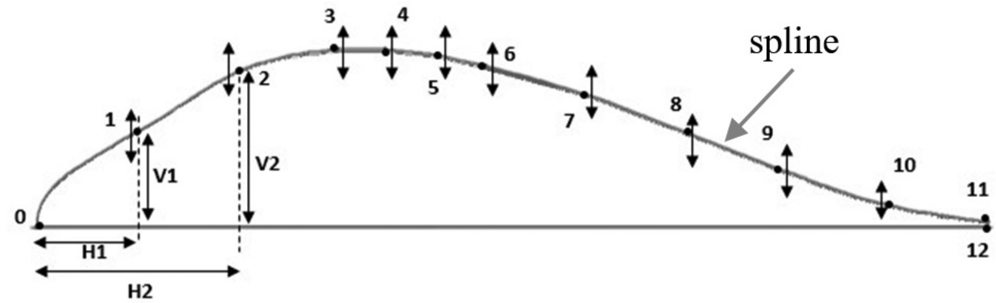


Figure 2. Radome shape.

structurally weak. Half-wavelength radomes are sturdy but have very narrow band characteristics. This paper arrives at the empirical formulae to arrive at the skin thickness (d) and core thickness based on the operational frequency.

Nair[5], *et al.* have studied various requirements for the electromagnetic design of airborne radomes. Various techniques for EM design include Transmission Line Transfer Matrix method (TLTMM), Method of Moments (MoM) techniques, etc and antenna-radome interface analysis using Low Frequency (LF), High Frequency (HF) and hybrid methods. An elaborate survey has been made on each of these techniques, their applicability and the state-of-the-art.

Sheret[6], *et. al.* discuss optimisation of a Von Karman ogive shaped aerodynamically ideal radome for its thickness. 2D ray-tracing techniques are used with MATLAB implementation with HFSS simulation. The thickness of the radome is optimised with the Quasi Newton method as a function of the beam angle of the incident ray. 2D ray-tracing with unit EM and full EM simulation are compared and gave results that are very close.

Application of GA for simultaneous optimisation of Bore Sight Error (BSE) and power transmittance of an A-sandwich radome is attempted by Meng & Dou[7]. Local uniform thickness radome which is easier in terms of fabrication compared to variable thickness radome is proposed and analysed with ray-tracing technique. The thickness of the radome is defined using a piecewise function. The best thickness for each zone is found by minimising maximum BSE and maximizing the minimum power transmitted. Von Karman curve is used to define the radome shape. The results of optimised local uniform thickness radome are compared with globally uniform thickness radome.

Deng[8], *et al.* concentrated on the multi-disciplinary approach required for designing an airborne composite radar considering the EM and Structural aspects. Since the presence of radome can degrade the performance of the radar antenna, it is necessary to minimise two important EM parameters of radome namely BSE and Transmission Loss (TL). Besides, radome has to withstand the air-load and other environmental

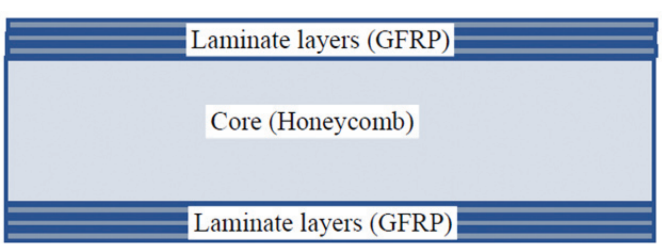


Figure 1. A-sandwich construction.

effects. Structural aspects considered are material failure (Material is composite and so Tsai Wu index and maximum stress criteria), deformation, and stability. Multi-island GA is used to optimise twin objectives of BSE and TL with constraints on material failure and structural stability.

In the literature, there are very few cited studies that involve optimisation involving EM and structure or EM and aerodynamics. This study could be the first possible effort of combining all three disciplines and that too for an industrial problem.

3. AIRBORNE RADOME AND ITS DESIGN ASPECTS

3.1 General Aspects

Radome design is a multidisciplinary effort involving structural, aerodynamics, and EM disciplines. The interactions between these disciplines have to be captured to be able to get optimality in terms of all three disciplines involved. Optimum design of radome has to be arrived at analysing various radome shapes and associated structural and electromagnetic characteristics. Radomes for airborne applications are generally of “A-Sandwich” or “C-Sandwich” construction. “A-sandwich” radome (Fig. 1) with a core with faceplates on both sides is considered in this study.

3.1 Radome Geometry and Construction

The radome profile is modeled as a spline with several control points (Fig. 2). By revolving the resulting spline by 180° about the X-axis, the radome shape is obtained. Different profiles can be generated by varying the coordinates of these control points. By adding thickness to the radome shape, its geometric model is realised. As stated previously, A-sandwich has got a core with skins inside and outside. The core material is Aramid Honeycomb and faceplates are considered to be made of GFRP laminae. The thickness of each lamina is kept constant (0.25 mm). The core thickness, number of laminae in outer and inner skins and shape control points are design variables. The length of the radome is varied from 1.5 m to 3.0 m. ‘X’ coordinates of control points are varied as a percentage of ‘L’ (L is length of radome)

3.2 Aerodynamic and Structural Design

In the previous work[2] aerodynamic and structural disciplines were integrated on the MDO framework. As a first step aerodynamic optimisation is carried out. ANSYS Fluent® software was used to carry out CFD analysis for finding out the drag for a given profile by modifying an adaptive mesh which is refined as the profile of radome is changed. Drag is calculated by integrating the pressure values over the surface of the radome by the software and provided as an output parameter. The optimised radome had a drag value of 33N for a flow velocity of 103 m/s and 2438m (8000 ft) altitude. In the present study, the flow conditions have been changed, as explained in section 4.1.

Structural discipline is added to the above model as the next step. The radome is modeled with four layers of laminae (GFRP) on either side with a central core (honeycomb) in ANSYS software. Default values of material properties in ANSYS ACP module are used for the analysis. Radome surface is meshed with an automatic meshing algorithm in ANSYS Workbench with quad-dominated (shell) elements. This mesh is adaptive and it is refined every time the size & shape of the radome is changed. The pressure load from the CFD analysis is imposed on the surface of the radome. Pareto front involving aero-structural disciplines, which has non-dominated designs, is established with MOGA II and PilOPT algorithms.

3.3 Electromagnetic Design

Wavelength of EM waves in radome material, λ_m is given by Eqn. 1. This plays key role in deciding the optimal thickness of radome.

$$\lambda_m = \frac{\lambda_o}{\sqrt{\varepsilon_r}} \tag{1}$$

In eqn. 1, λ_o is the wavelength in free stream and ε_r is the relative permittivity of the material. Optimum thickness of monolithic radomes, t_m, is given by Eqn. 2. When radome thickness is $n*\frac{\lambda_m}{2}$, the radome almost becomes transparent to microwaves.

$$t_m = \frac{\lambda_o}{2*\sqrt{\varepsilon_r}} = \frac{\lambda_m}{2} \tag{2}$$

The electrical performance of A-sandwich radome depends on the distance between skin and its core material. Lee*, et. al.*[4] proposed skin and core thicknesses as per eqns. 3 & 4 for A sandwich radomes.

$$t_{skin} = \frac{c_o}{20*f*\sqrt{\varepsilon_{r,skin}}} \tag{3}$$

$$t_{core} = \frac{c_o}{2*f*\sqrt{\varepsilon_{r,core}}} \tag{4}$$

Maritime patrol radar operates in the X band and the radome is designed for a spot frequency of 9.5 GHz. The optimal thickness (half wavelength) for 9.5 GHz considering monolithic radome is about 15.7 mm.

Three-dimensional EM analysis is carried out using CST Microwave Studio software® to find out the signal losses for one operational spot frequency of 9.5 GHz. Finite Integration Technique (FIT) is used for solving the problem, which is suitable for high-frequency problems. Hexahedral mesh is used to discretise the computational domain. The mesh size is determined based on the wavelength which is a function of operational frequency.

Asymptotic Solver, a ray-tracing solver, is chosen as a solver for carrying out 3D analysis. This is efficient for extremely large structures. This is an extension of Physical Optics and uses Shooting Bouncing Ray (SBR) method. It is capable of tackling simulations with an electric size of many thousands of wavelengths.

Table 1. Electrical properties of radome material

Material	Epsilon (ε)	Tan δ
Core (Honeycomb)	1.07	0.005
GFRP	4.00	0.020

Radome geometry stored as CATIA model is imported into CST software and the material properties are assigned (see Table 1). Side looking radar antenna scans ±60° in azimuth and ±30° in elevation. It is modeled as a field source with 60° azimuth scanning, imported and positioned at the antenna location. The source is located 0.75 m from the leading edge irrespective of the length of the radome (Fig 3). The antenna pattern in the azimuth is shown in the inset. By default, the number of elements in the mesh is 27837. However, it is refined based on the size of the radome automatically.

The analysis is carried out to find out the change in antenna pattern over ±90° in azimuth (Phi) in steps of 1° and 180° (Theta) in elevation in steps of 1°. Three main characteristics to be observed are main lobe level, beam width (3dB) and side lobe level with and without radome. Since the changes in these parameters for boresight scanning are not very significant, the analysis is carried out with beam pointing at 60° azimuth. The antenna gain pattern with and without radome is overlaid and shown in Fig. 4.

It is observed that the change in main lobe level and the beam width is very less. However, the change in the side-lobe level is significant. In an initial design, this value is 2dB. The change in side-lobe levels is the design objective that will be minimised in order to get the antenna pattern with radome very close to that of the antenna without radome.

4. MULTI-DISCIPLINARY ANALYSIS AND OPTIMISATION

4.1 Problem Statement

The MDO problem with three disciplines and three design objectives can be stated as

Minimize $F(x) = (J_1(x), J_2(x), J_3(x))$ (5)

Subject to $Tsai - WuIndex < 1.0$ (6)

And $a \leq x \leq b$ (7)

where, $J_1(x)$ is drag, $J_2(x)$ is weight, $J_3(x)$ is EM signal loss and x is the design variable vector. a and b are the upper and lower limits for each design variable, also called the side constraints. The total number of design variables for this problem is 25. MDO is carried out for a chosen operational point of aircraft, i.e., for the aircraft flying at 0.4 Mach (137 m/s) airspeed and 2438 m (8000 ft) altitude. The radar operates at 9.5 GHz (‘X’ band).

4.2 Design Objectives

The first design objective radome drag ($J1(x)$) is evaluated using CFD analysis with ANSYS Fluent software. Two main components of drag are form or pressure drag and parasite drag.

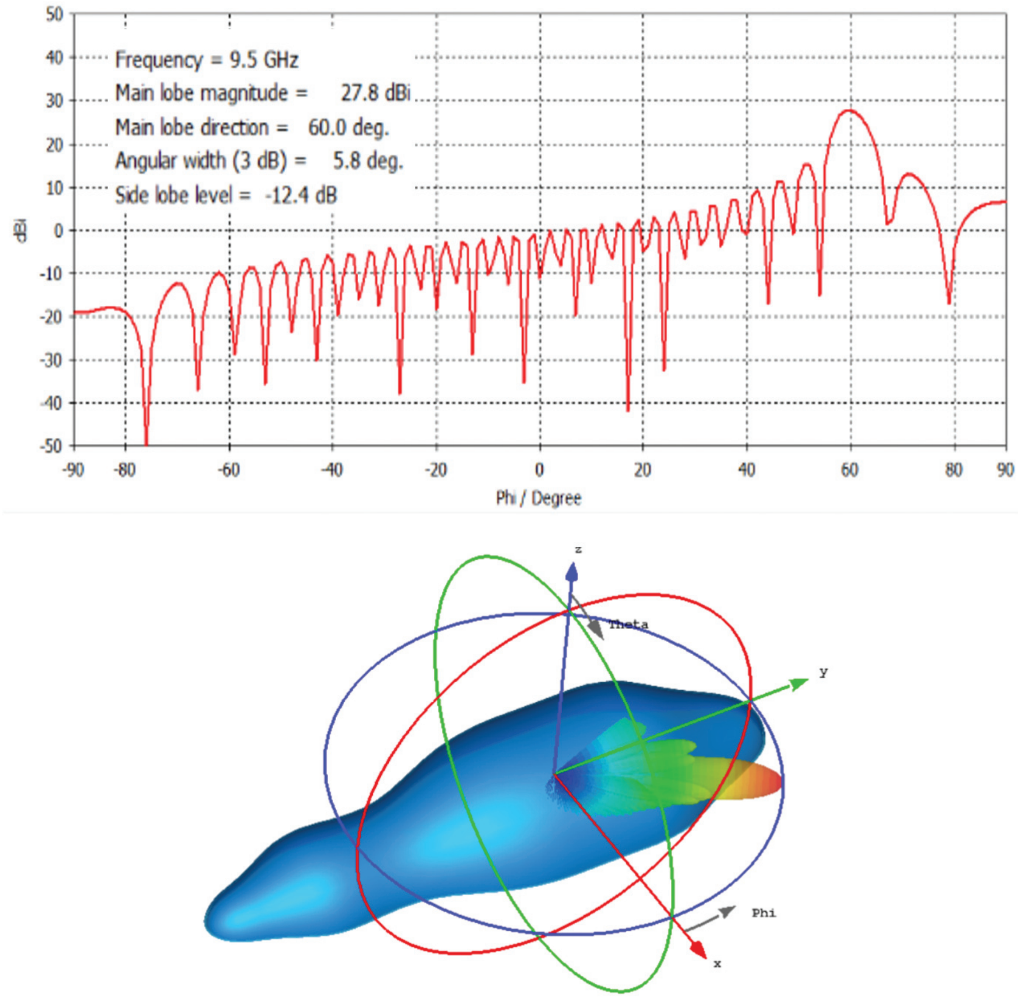


Figure 3. Radome with X band source, antenna pattern in azimuth (inset).

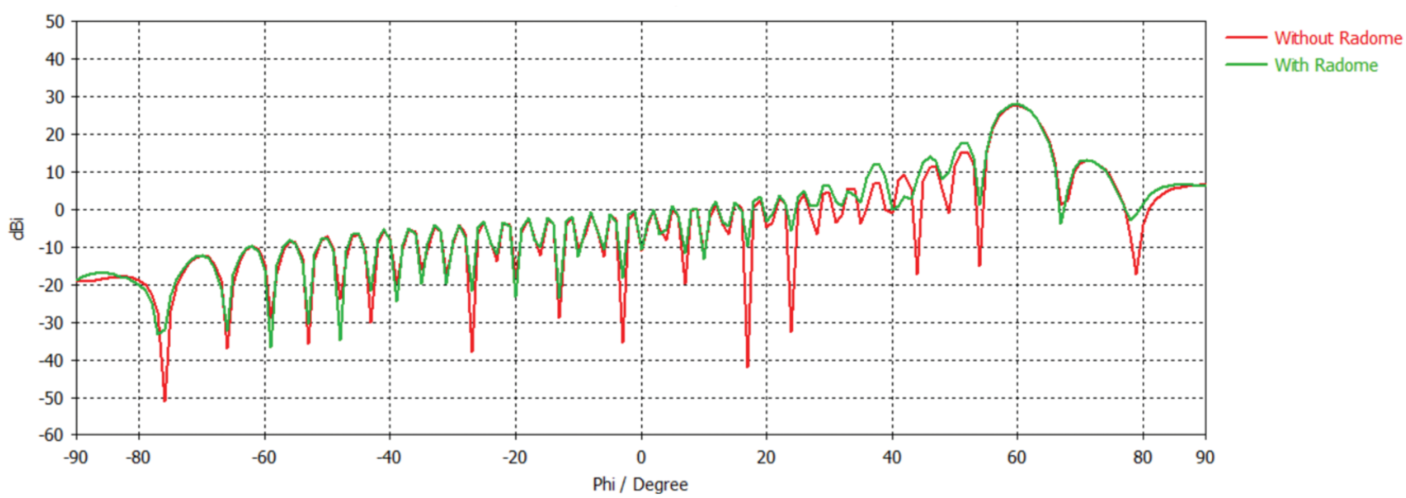


Figure 4. Comparison of antenna gain.

The former is due to the blockage any shape offers to flow and the latter is dependent on the surface area wetted by the airflow. Streamlined shapes offer less form drag and more parasite drag due to large wetted areas. On the other hand, bluff bodies have a lower surface area and hence have lower parasite drag but due to higher blockage, they offer higher form drag. The drag hence is a compromise in terms of length and bluffness of the shape.

Radome weight ($J_2(x)$) is the second design objective. Radome weight depends on the surface area, number of laminae in the inner and outer skins, the thickness of the laminae (a constant here) and the thickness of the core. The weight of radome is calculated with Eqn. 8.

$$J_2(x) = SA_R * [(N_L * T_L * \rho_L) + (T_c * \rho_c)] \tag{8}$$

where, SA_R is radome surface area, N_L is the number of laminae in the inner and outer skin, T is the thickness, ρ is the density, subscript 'L' denotes Lamina and subscript 'c' denotes Core. ANSYS ACP is used for structural analysis.

Due to different media (like GFRP and honeycomb) in the radome, EM ray is refracted when traveling from one medium to another. It also undergoes internal reflections. The antenna pattern undergoes variation due to radome. The difference in antenna sidelobe level (in dB), without and with radome, is taken as the design objective) for EM discipline and is minimised.

4.3 Design Constraints

The first design constraint, Tsai-Wu Index of the radome structure calculated using Eqn. 9.

$$F_1\sigma_1 + F_2\sigma_2 + 2F_{12}\sigma_1\sigma_2 + F_{11}\sigma^2{}_1 + F_{22}\sigma^2{}_2 + F_6\tau_{12} + F_{66}\sigma^2{}_6 < 1.0 \quad (9)$$

where, F_{ij} are constants calculated from material properties. The radome has to accommodate a planar antenna of size 0.5 m x 0.25 m. Dimensional constraints are imposed such that the radome height is above 0.25 m, where antenna is located.

$$\text{Subject to } 0.25 - y \leq 0 \forall 0.5 \leq x \leq 1.0 \quad (10)$$

Side constraints (see paragraph 4.1) are in addition to the above design constraints.

4.4 Multi-Disciplinary Analysis (MDA) process

The analysis blocks of aerodynamics (flow), structures and electromagnetics are integrated on a multi-physics analysis framework Modefrontier. The software has built-in functions to invoke and execute various analysis routines in batch-mode. Wrappers are available to read in/write out and to parse output files to fetch necessary data. Design variables, constraints and objectives can be defined and monitored during program execution. A process is set up for carrying out analysis in sequence feeding inputs/outputs intra-analysis blocks. MDA process is shown in Fig. 5. The process follows Multidiscipline Feasible (MDF) architecture. For each complete iteration, one feasible solution will be available, subject to fulfilling the constraints. MDO of the radome with aerodynamic and structural disciplines was studied previously[2]. Electromagnetic discipline is added in this study. The optimiser starts with a set of ten designs (called a generation/population) initiated using DOE. Successive populations (offsprings) are generated by mating chosen parents using genetic operators (cross-over and mutation). Parents are selected for mating based on their fitness (objective values) based on probabilistic functions. The optimisation process is stopped either when a certain number of generations are evaluated or when there is no improvement in the objective over a few generations.

4.5 Pareto Optimality

Multi-Objective Optimisation (MOO) problems do not have a single optimum design since the objectives often conflict with each other. Number of optimal designs is found in a situation called Pareto optimality. For the twin objective (drag and weight) problem the Pareto front is a 2D curve, in which the designs are non-dominated i.e., there is no design in this front, which is superior to all other designs in all objectives.

The previous study[2] explored the Pareto optimality for structural and aerodynamic disciplines using MOGA II and PilOPT algorithms and established the Pareto fronts. It was shown that the optimised drag and weight values are within 15 % variation for both algorithms. With three objectives under study, the Pareto front will be a 3D plane involving three axes.

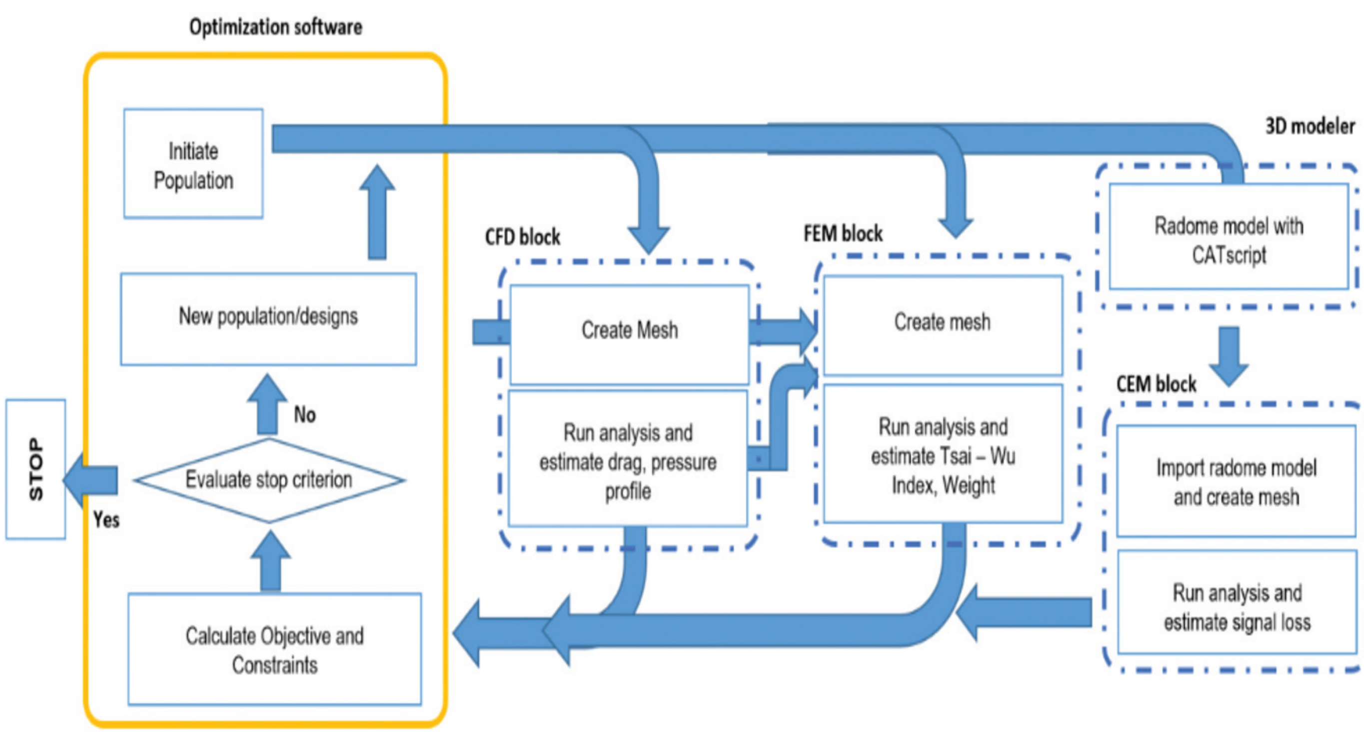


Figure 5. MDA Process flow.

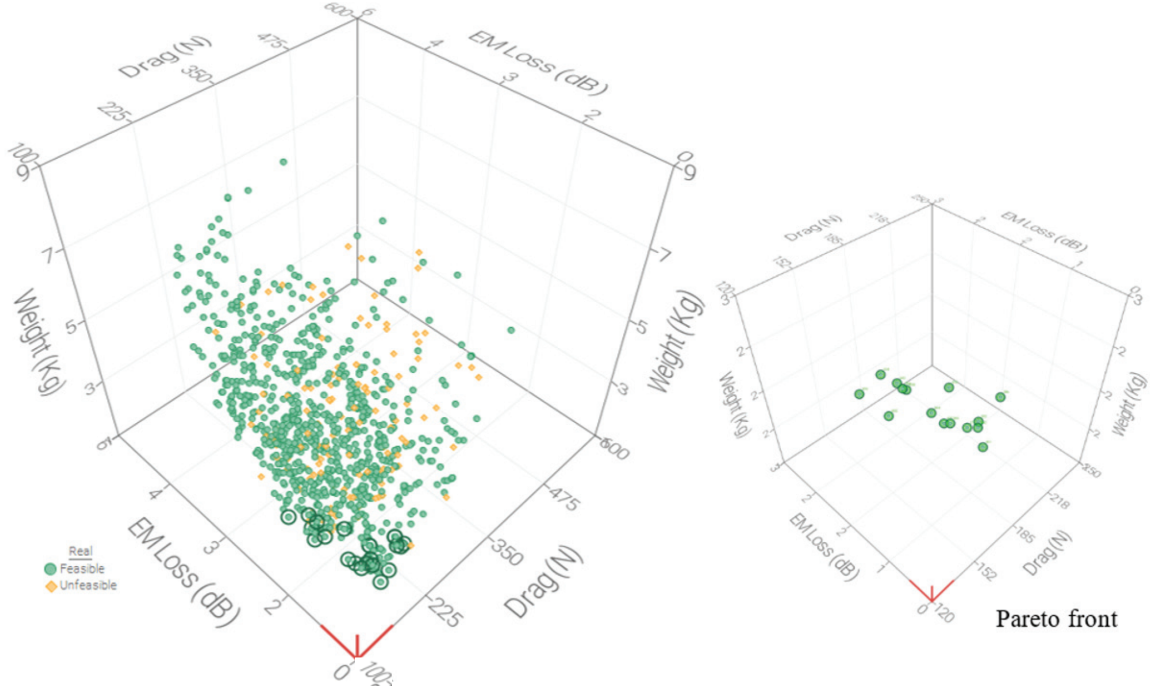
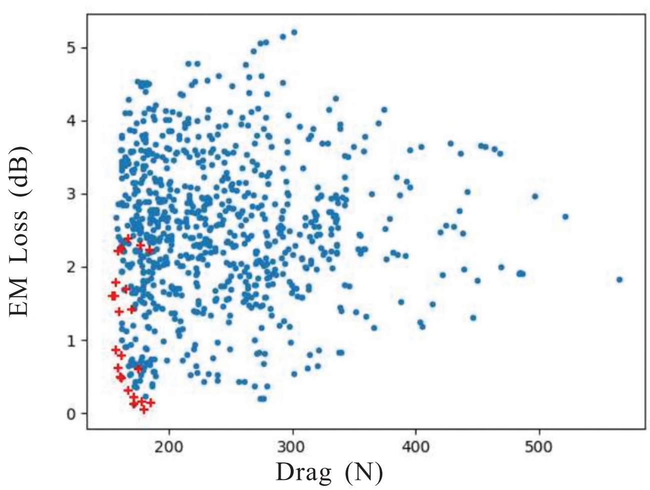
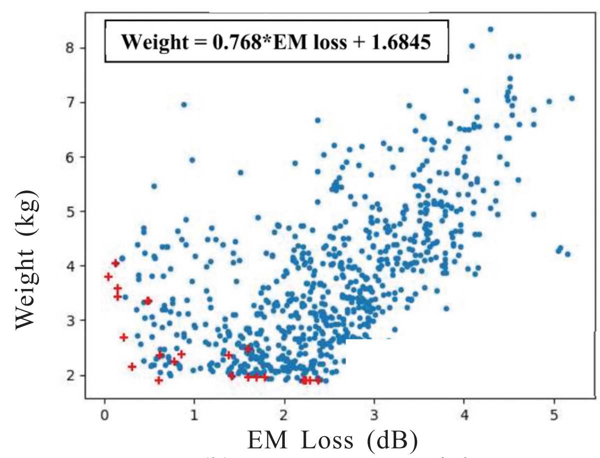


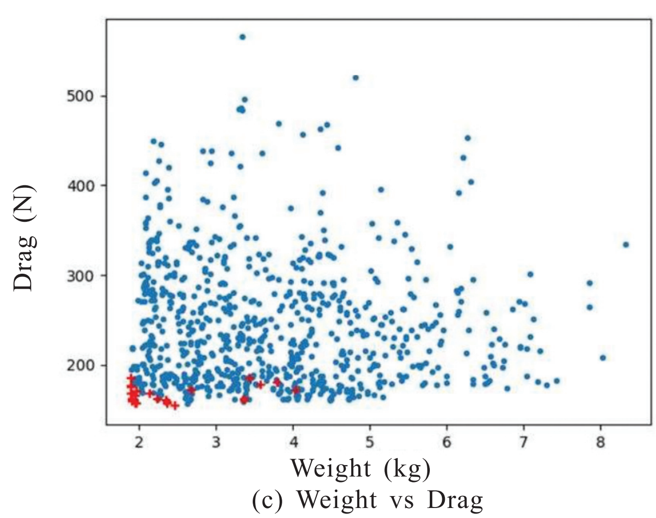
Figure 6. Designs with NSGA II algorithm (Pareto front is inset).



(a) Drag vs EM Loss



(b) EM Loss vs Weight



(c) Weight vs Drag

Figure 7. Comparison of two objectives.

5.1 NSGA II Algorithm

To start the optimisation, ten designs are generated using Latin-Hypercube sampling as the first generation of designs. Using the NSGA II algorithm, 100 generations (every ten designs) were created and analysed. All the designs are plotted in Fig. 6. Fifty four designs are unfeasible due to violation of geometry constraint (Eqn. 10). The Pareto front has twenty-seven radome designs, shown by circles. A closer view of the Pareto front is in the inset picture.

The designs are plotted against two objectives at a time in Fig. 7 with designs in the Pareto front highlighted with circles. From Fig. 7(a), it can be seen that there is a large variation in EM loss for a smaller range of drag. As the EM loss depends to large extent on the thicknesses (of layers and core) and to some extent on the shape undulations. Drag depends on the shape and length as seen in the previous study1. Weight and EM loss vary proportionately as both of them depend on thickness and length. Surface area (indirectly the undulations) is another factor for weight and EM loss.

This phenomenon is shown by Fig. 7(b). Weight and Drag vary independently and this is captured in designs as shown in Fig. 7(c). The Pareto front is clearly seen with the help of Fig. 7. The weight and drag behave in a contradictory manner. However, EM loss and weight move in unison as explained. Contradictions are seen in EM Loss and drag to a small extent only.

Table 2. Best designs – NSGA II

Design ID	EM loss (dB)	Drag (N)	Weight (kg)	Pareto front
Best designs in EM loss				
439	**0.044**	180.00	3.790	yes
149	**0.131**	172.05	4.041	yes
350	**0.131**	172.00	4.040	yes
Best designs in Drag				
924	1.600	**154.00**	2.470	yes
895	1.610	**157.00**	1.960	yes
956	1.790	**158.00**	1.960	no
Best designs in Weight				
959	2.220	159.05	**1.900**	yes
899	2.400	218.00	**1.910**	no
902	2.420	218.00	**1.910**	no

Table 2 shows the three best feasible designs in each of the design objectives. All the individual best designs are not lying in the Pareto front. The utopia point, which is a theoretical minimum of all objectives is (154 N, 1.9 kg, 0.044 dB). Although this design cannot be achieved, it shows the minimum values that can be achieved if only one disciplinary objective is looked at in isolation. The decision maker can get better designs, in terms of other objectives, if a slight compromise can be made in the desired discipline. Best radomes in terms of weight (#959), EM loss (#439) ad drag (#924) are depicted in Fig. 8 (designs are scaled).

The least weight design (1.9 kg) has the lowest length of all and 2 layers in the inner and outer layers. Its length is 1.5 m and its height is 308mm. The core thickness is 6.75 mm. Radome with the least EM loss design (0.044 dB) is 1.7 m long and 307 mm tall. It has 2 layers in inner & outer layers and 4.25 mm core. The radome which offers the least drag (154 N) is having a length of 1.9 m long and a height of 304 mm.

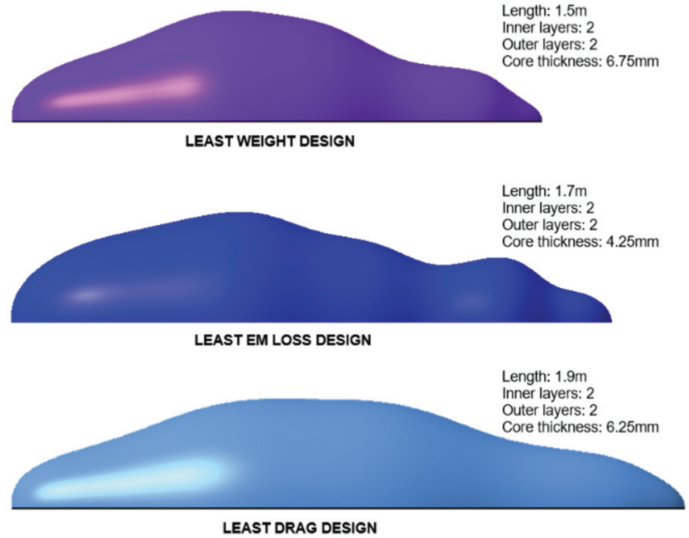


Figure 8. Best radome designs.

Table 3 gives details of designs, which are least optimum in terms of each objective, lying on the Pareto front. On a Pareto front, designs are such that if there is degradation in one objective, there is betterment in others.

Table 3. Least optimum designs in Pareto front

Design ID	EM loss (dB)	Drag (N)	Weight (kg)
Least optimum EM loss			
525	**5.200**	301	7.08
546	**5.150**	292	4.22
667	**5.070**	274	4.34
Least optimum drag			
553	1.830	**565**	3.34
519	2.680	**521**	4.81
634	2.970	**496**	3.36
Least optimum weight			
517	4.300	335	**8.83**
566	4.080	208	**8.03**
539	4.605	265	**7.85**

6. CONCLUSIONS

In this study, one parameter of EM loss is taken as a parameter for optimisation to demonstrate the inclusion of EM discipline in overall MDO. The choice of the parameter can be fine-tuned for better EM designs. Also, the best EM designs of radomes offer a starting point for the decision maker or designer to fine-tune the design by considering real-life aspects like losses due to paints and coatings, water ingressions, and manufacturing issues. The difference between first- and second-best designs in EM loss is 0.087 dB (increase). Disciplinary analysis corroborated the results; however, the designs have to be revisited. However, a side-lobe difference of up to 0.5 dB with and without radome is generally acceptable.

Multi-objective optimisation of the radome was performed using NSGA II and the results are presented. The Pareto front is clearly captured with this direct search algorithm. Optimisation with MOGA II algorithm is presently progressing and needs to be compared with the NSGA II as to how well this algorithm can capture the Pareto front and the designs in the Pareto front compare. Plotting two disciplinary objectives at a time, the Pareto front is better understood. The relation between the disciplinary objectives is clearly brought out. Requirements of structure and aerodynamics contradict each other and hence the designs with the least drag tend to have higher weight and vice versa. Structure and EM disciplinary objectives seem to change in the same directions and it is seen that heavier radomes tend to have higher EM loss due to higher thicknesses. Since drag depends on the surface area and undulations and EM depends on the cross-section thicknesses, we find designs with a range of EM losses for a small range of drag values.

One hundred generations of radome designs (about 1000 designs) are evaluated for finding the Pareto front. The designer or the decision maker is presented with twenty-seven designs of radome in the Pareto front which are better than the design solutions in the interiors (dominated designs). Comparison of best designs in each discipline shows the variation in objective values is very small except for EM as pointed out earlier. Hence best designs in terms of each objective can be compromised for getting better designs in other disciplines involved.

REFERENCES

1. Shankar, M.; Niranjanappa, A. & Dattaguru, B. Aerodynamic optimisation of airborne radome for maritime patrol radar. *Int. J. Eng. Adv. Technol.*, 2020, **9**(3), 956-962. doi:10.35940/ijeat.B3422.029320
2. Shankar, M.; Niranjanappa, A. & Dattaguru, B. Aerodynamic and structural optimisation of maritime patrol radar system radome using evolutionary algorithms. *Def. Sci. J.*, 2021, **71**(4), 421-428. doi:10.14429/dsj.71.16249
3. Deb, K.; Pratap, A.; Agarwal, S.; & Meyarivan, T. A fast and elitist multiobjective genetic algorithm NSGA-II. *IEEE Trans. Evol. Comput.*, 2002, **6**(2), 2182-2197. doi:10.1109/4235.996017
4. Pulvirenti, G.; Tromboni, D.; Marchetti, M.; Delogu, A.; Maccapani, A.; & Aricò, R. Surveillance system airborne composite radome design. *In* Proceedings of International Conference on Fracture, 2005
5. Lee, K.W.; Chung, Y.; Hong, I. & Yook, J. An effective design procedure for A-Sandwich radome, *In* IEEE Antennas and Propagation Society International Symposium, 2010, 1-4. doi: 10.1109/APS.2010.5561702
6. Nair, R. & Jha, R. Electromagnetic design and performance analysis of airborne radomes: trends and perspectives [antenna applications corner]. *In* IEEE Antennas Propag Mag., 2014, **56**(4). doi**:** 10.1109/MAP.2014.6931715
7. Vandenbosch, G.A.E. & Vasylchenko A. A practical guide to 3D Electromagnetic Software Tools, *In* Microstrip Antennas, edited by N. Nasimuddin, IntechOpen, 2011, 507-520. doi:10.5772/14756
8. Poian, M.; Poles, S.; Bernasconi, F.; Leroux, E.; Steffe W. & Zolesi, M. Multi-objective optimisation for antenna design, *In* IEEE International Conference on Microwaves, Communications, Antennas and Electronic Systems, 2008. 1-9. doi: 10.1109/COMCAS.2008.4562817.
9. Sheret, T.; Clive, P. & Allen, B. Efficient design of a radome for minimised transmission loss. *IET Microw. Antennas Propag.*, 2016, **10**(15), 1662-1666. doi:10.1049/iet-map.2016.0041
10. Meng, H. & Dou, W. Multi-objective optimisation of radome performance with the structure of local uniform thickness, IEICE Electronic Express, 2008, **5**(20), 882-887. doi:10.1587/elex.5.882
11. Deng, J.; Zhou. G. & Qiao. Y. Multidisciplinary design optimisation of sandwich-structured radomes, *Proc. Inst. Mech. Eng. C. J. Mech. Eng. Sci.*, 2019, **233**(1), 179-189. doi:10.1177/0954406218757268.

ACKNOWLEDGEMENT

Authors express sincere thanks for the computation facilities provided by CABS. The work is part of the studies for doctoral research of the first author for which he is thankful to Director, CABS.

CONTRIBUTORS

Dr M.R. Shankar is Scientist G & Head, Aircraft Division in DRDO-Centre for Airborne Systems, Bengaluru, India. His areas of interest include: Aircraft structural modification & integration, new product development, structural design and optimisation.
He carried out EM and other modelling and integration, carried out the analysis and compiled results.

Dr A.C. Niranjanappa, retired as Outstanding Scientist from DRDO-Centre for Air Borne Systems, Bengaluru, India. He is an expert in the field of Advanced Polymer Composites and specialised in the design and development of sandwich radomes for airborne applications.
He guided principal author as internal guide in checking the disciplinary modelling, interpretation of analysis of results.

Prof B. Dattaguru retired as Chairman of Department of Aerospace Engineering, Indian Institute of Science, Bangalore and currently working as Professor at Jain-Ddeemed-to-be University. His areas of interest are: Aerospace structures and materials, fracture and computational mechanics.
He guided principal author in validating the MDO frame work, interpretation of MDO results and presentation