APPLICATION OF GENETIC ALGORITHMS TO THE OPTIMISATION OF ADAPTIVE ANTENNA ARRAYS AND RADAR ABSORBERS

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INTRODUCTION

Genetic algorithms (GAs) have emerged as effective adaptive search techniques based on the concept of natural selection. The power of GAs in optimisation has become apparent from the wide range of applications identified in the areas of automatic and adaptive control [1],[2], but only a few authors have reported on their application to the optimisation of electromagnetic structures [3] - [7]. In this contribution, we review our continuing work on the application of genetic algorithms to the optimised design of multi-element adaptive antenna arrays and both passive and active wideband radar absorbers, e.g. [8] - [16]. In particular, we present new results for the case of an end-fire array antenna with both adaptive nulling and radiation pattern envelope limitations applied and for the case of wideband, high performance cylindrical radar absorbers.

ADAPTIVE ANTENNA ARRAYS

Suppression of interference by null steering in phased and complex arrays may be achieved by controlling some array parameters such as the complex element weights, element phases, amplitudes or element positions. Several analytic solutions have been utilised to determine the required changes in these parameters in order to steer the nulls to the required interference directions. Null steering by complex weight control requires the adjustment of both amplitudes and phases of the array elements. Having greater numbers of degrees of freedom results in better control of the null sterring. On the other hand, it increases the array design complexity and can be comparatively slow due to the large number of variables that have to be determined. Array pattern nulling can also be achieved by phase only or element position variations. The solutions in these cases are based on assumptions of relatively small variations. These latter solutions are most effective when the nulls are situated in the side lobe region, but often result in reduced accuracy of the imposed null locations and null depths. An alternative to analytic based methods is adaptation by a GA. To implement a GA in this application, the array variables, such as element spacing or phase, are represented as genes and a complete set of all the variables, i.e. the array, becomes a chromosome.The optimisation of adaptive antenna arrays has been implemented in the MATLAB programming environment using the GA Toolbox written by the Department of Automatic Control and Systems Engineering at the University of Sheffield. In our case, the GA operates on real, rather than encoded, variables so as to increase the computational efficiency and precision of the algorithm. The mutation rate is 0.7, much higher than for binary representations, as this is found to search the problem space more effectively. The usual population size of antenna designs is 30 and selection for breeding is carried out using the "roulette wheel" selection method. Each new population is made up of the best 30% of the "parent" generation and 70% of the "offspring" generation. Table 1 shows the functions which have been used in the antenna optimisations; they are the array factors for N-element broadside and end-fire arrays. The functions vary slightly according to the type of adaption used. F_θ and F_ϕ are the values of the array factor in the directions θ and ϕ where θ is measured from the normal to the array axis and ϕ is measured from the axis, as shown in Figure 1. In each case, x_n is the genotypic variable, d is the uniform spacing between the elements, and k is the wave number ($k = 2\pi/\lambda$, where λ is the incident or radiated wavelength). No interactive effects between elements have been considered.

At each specified null angle the objective function calculates the array factor and subtracts the required null depth value. The fitness of an individual array is the greatest positive difference between the required and actual values. A further constraint may be added by creating a pattern envelope and calculating the objective values at all angles. The algorithm is successful only when all array factor values are less than the corresponding pattern envelope values. Depending on the number of elements in the array, the adaptation type, and the number of points at which the objective function is evaluated, each iteration may take between 5 seconds and 2 minutes to complete using a 33 MHz 486DX computer. A successful result sometimes occurs as early as 4 or 5 generations (though around 50 is more usual).With the pattern

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envelope constraint, several hundred generations are sometimes necessary. Typical radiation patterns for 12 element broadside and end-fire adaptive arrays are shown in Figures 2 - 7.

BROADBAND RADAR ABSORBERS

One generic class of broadband radar absorbers is based on a stack of spaced resistive sheets (the Jaumann configuration) and its theoretical background has strong similarities to that of the antenna arrays discussed above. Referring again to Figure 1, for the absorber case the array elemental sources are replaced by e.m. waves reflected from the impedance discontinuities at the resistive sheets. Further more, unlike the array case, multiple interactions between the absorber elements are also taken into account. In general, multi-layer absorbers have been optimised using GA's to achieve maximum bandwidth at a given level of reflectivity (i.e. $10 \log_{10} (\rho^2)$, where ρ is the reflection coefficient). Because of the large number of variables in some of the configurations considered and the time taken to compute absorber bandwidths, a "purpose-built" GA algorithm was used, rather than the MATLAB GA Toolbox. This used floating-point variables, a typical population size of 60, breeding from the top 20% of each generation using multi-point crossover and an elitist strategy. Mutation was also used to ensure escape from local optima. Most of the results discussed below were obtained using a P5/90 computer. For the smaller problems, convergence was obtained in less than one hundred generations, but especially for problems involving cylindrical geometries or large numbers of variables, several thousand generations / several hours of computer time might be required.

A typical result for a 5 layer, normal incidence Jaumann absorber with maximum -20dB bandwidth is shown in Figure 8. Often, absorbers need to be effective against e.m. waves incident at some angle θ from the normal (e.g. in jet engine intake ducts) and in these cases the absorber performance is dependent not only on θ, but also the incident wave polarisation. The GA software has been used to produce absorber designs which have similar reflectivity-bandwidth performance for both polarisations even at incidence angles as large as 60°. For these designs, the GA was required to optimise a function of the form

$$F = \frac{BW_{\parallel} BW_{\perp}}{\left(\left|BW_{\parallel} - BW_{\perp}\right| + 1\right)}$$

where $BW_{\parallel}$ and $BW_{\perp}$ are the normalised absorber bandwidths for parallel and perpendicular polarised incident waves. A typical result is shown in Figure 9 and compared to the performance of the same absorber at normal incidence. In practice, absorbers need to be protected from environmental and mechanical damage using a skin constructed typically from fibre-reinforced plastic. This also acts as an additional reflecting layer whose characteristics can be utilised to improve the absorber performance, as shown in Figure 10. Absorbers are not only used in planar form but, for example, can be wrapped around curved surfaces such as a submarine periscope or antenna mast. Figure 11 compares the performance of a GA optimised planar Jaumann absorber, its degraded performance when wrapped around a conducting cylinder and the GA optimised cylindrical absorber. Useful designs may be realised for even small cylinder radii.The discussion so far has considered only "passive" radar absorbers, i.e. those whose performance is fixed by the nature of the materials used at the time of manufacture. Recent advances in conducting polymers, however, have pointed to the possibility of "active" absorbers, i.e. those whose performance can be changed dynamically via external control [16]. Control of such e.m. structures is thus very similar to that required for the adaptive antenna arrays discussed in the previous section. Figure 12 shows the performance of an adaptive radar absorber, where GA optimisation has been used to adjust the sheet resistances of a 5 layer Jaumann configuration so as to produce superior performance (i.e. deeper nulls) at particular frequencies. In a second example, shown in Figure 13, an absorber configuration containing a high-permittivity skin and a layer incorporating controllable sheet resistance and capacitance is configured by the GA so as to provide either moderate wideband or excellent narrow band performance.

CONCLUSIONS

We have shown that GAs are robust, and for our applications, out-perform other optimisation techniques such as down-hill simplex and simulated-annealing. GAs have been shown to facilitate the optimisation of a wide range of complex e.m. structures, for many of which analytic solutions for optimum designs are either not available or are only approximate.

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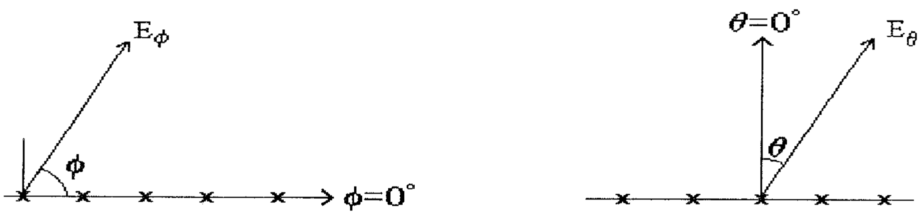
	Broadside	End-Fire
Uniform array factor	$F_\theta = \sum_{n=(1-N)/2}^{(N-1)/2} e^{jkdn\sin\theta}$	$F_\phi = \sum_{n=0}^{N-1} e^{jkdn(\cos\phi-1)}$
Amplitude adaptation	$F_\theta = \sum_{n=(1-N)/2}^{(N-1)/2} x_n e^{jkdn\sin\theta}$	$F_\phi = \sum_{n=0}^{N-1} x_n e^{jkdn(\cos\phi-1)}$

Phase adaptation	$F_\theta = \sum_{n=(1-N)/2}^{(N-1)/2} e^{jkdn(\sin\theta + x_n)}$	$F_\phi = \sum_{n=0}^{N-1} e^{jkdn(\cos\phi - 1 + x_n)}$
Position perturbation along the array axis	$F_\theta = \sum_{n=(1-N)/2}^{(N-1)/2} e^{jk(dn + x_n)\sin\theta}$	$F_\phi = \sum_{n=0}^{N-1} e^{jk(dn + x_n)(\cos\phi - 1)}$
Position perturbation normal to the array axis	$F_\theta = \sum_{n=(1-N)/2}^{(N-1)/2} e^{jk(dn\sin\theta + x_n\cos\theta)}$	$F_\phi = \sum_{n=0}^{N-1} e^{jk(dn(\cos\phi - 1) + x_n\sin\phi)}$

Table 1: Array factors used for adaptive array optimisation



5-element End-Fire Array

5-element Broadside Array

Figure 1 Array antenna configurations

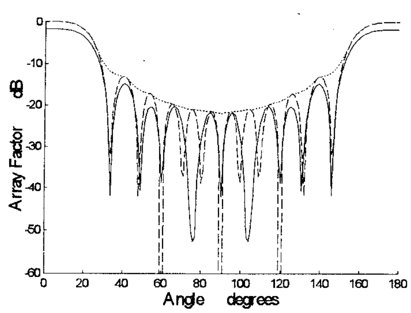


Figure 2: End-fire null steering by amplitude adaptation.
Each element has an amplitude between 0.7 and 1.0.
The requirement of -50 dB at 75° and 105° with no pattern envelope constraint was achieved after 37 generations.

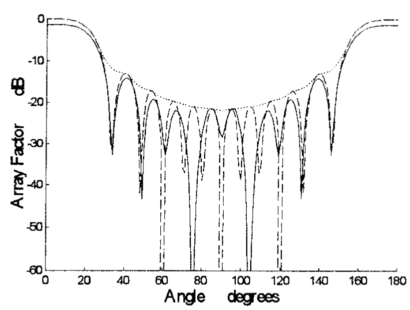


Figure 3: End-fire null steering by amplitude adaptation.
Each element has an amplitude between 0.7 and 1.0.
The requirement of -50 dB at 75° and 105° with a pattern envelope constraint was achieved after 52 generations.

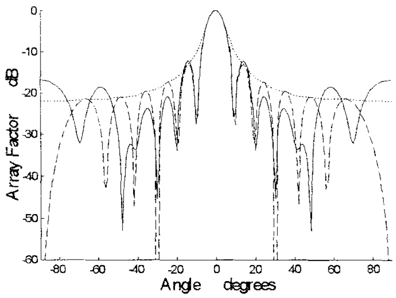


Figure 4: Broadside null steering by position perturbation along the array axis without pattern envelope constraint. Each element is perturbed by up to ±4 cm (1/10 wavelength). The requirement of -50dB at ±48° was achieved after 5 generations.

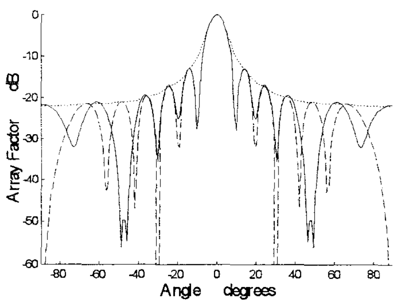


Figure 5: Broadside null steering by position perturbation along the array axis with a pattern envelope constraint. Each element is perturbed by up to ±4 cm (1/10 wavelength). The requirement of -50dB at ±48° was achieved after 240 generations.

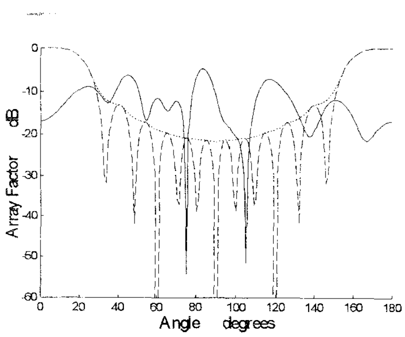


Figure 6: End-fire null steering by phase adaptation without pattern envelope constraint. Each element has a phase change of between $+\pi/8$ and $-\pi/8$. The requirement of -50dB at 75° and 105° was achieved after 40 generations.

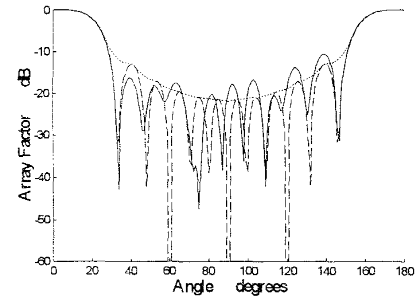


Figure 7: End-fire null steering by position perturbation normal to the array axis with a pattern envelope constraint. Each element was perturbed by ±4cm (1/10 wavelength). The requirement was -50dB at 66°. This is the result after 500 generations (success not yet achieved).

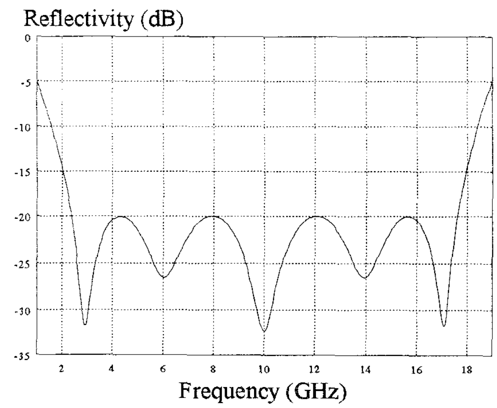
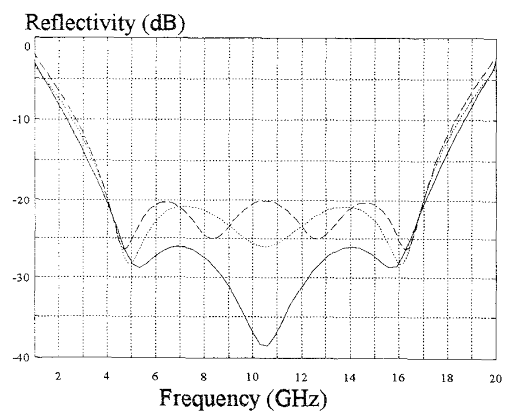


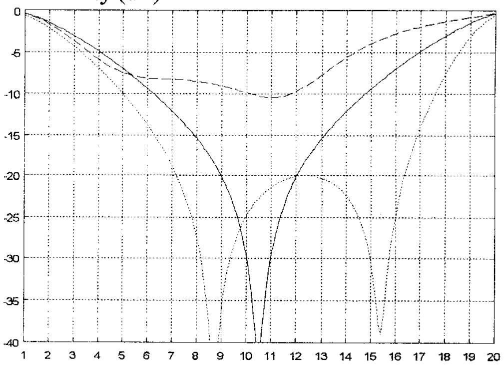
Figure 8 G.A. optimised 5 layer -20dB Jaumann radar absorber



Key: ________ $\theta = 0^o$
.... $\theta = 60^o$ perpendicular poln.
__ __ __ $\theta = 60^o$ parallel poln.

Figure 9 4 layer -20 dB Jaumann absorber G.A. optimised for best oblique incidence performance for both incident polarisations simultaneously

Reflectivity (dB)

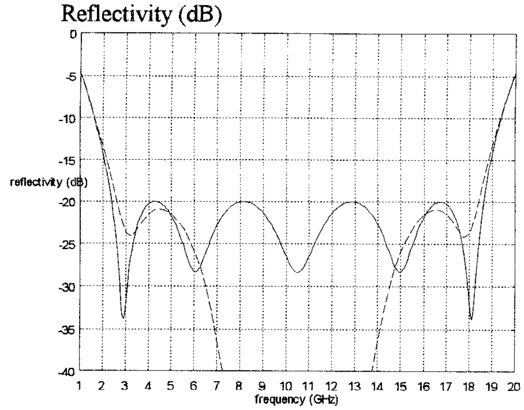


Frequency (GHz)

Key: ____ Original
__ __ Skin degraded
.... Re-optimised

Figure 10 Skinned Salisbury screen. Original, skin-degraded and re-optimised reflectivity performance, skin parameters: d = 1mm, $\varepsilon_r = 4.0$

Reflectivity (dB)

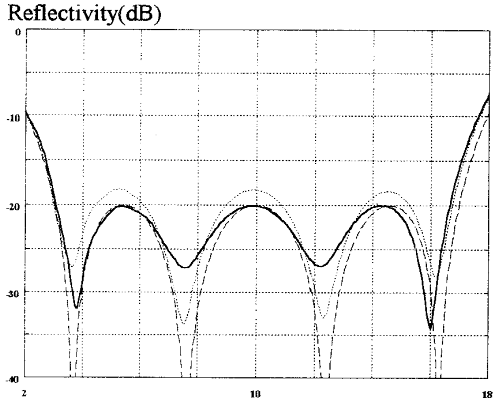


Frequency (GHz)

Key: _____ Original frequency response,
__ __ Modified frequency response

Figure 12 Adaptive 5 layer Jaumann absorber using sheet resistance control

Reflectivity(dB)

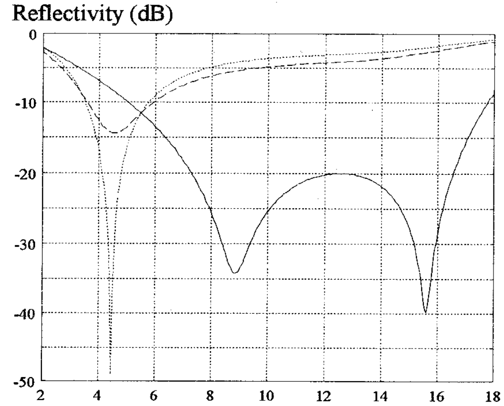


Frequency (GHz)

Key: _______ Optimum -20 dB planar absorber
.... Optimum planar absorber wrapped around p.e.c. cylinder,
__ __ __ GA optimised cylindrical absorber

Figure 11 4 layer cylindrical -20 dB Jaumann absorber, TM case, p.e.c. cylinder radius = 30 mm

Reflectivity (dB)



Frequency (GHz)

Key: ________ Original frequency response,
_ _ _ _ _ _ Control using C only,
.................Control using R and C

Figure 13 Adaptive Salisbury screen absorber with skin. Active layer contains both sheet resistance and capacitance.