Progress In Electromagnetics Research, PIER 46, 127–142, 2004

PHASE CENTRE OPTIMIZATION IN PROFILED CORRUGATED CIRCULAR HORNS WITH PARALLEL GENETIC ALGORITHMS

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Abstract—Achieving a high stability of the phase centre position in horn antennas with respect to frequency is a very desirable aim in reflector antenna design; a highly stable phase centre reduces efficiency dropping for defocusing at the frequency band extremes. By using an appropriate profile for the horn antenna it is possible to obtain horns both compact and with a stable phase centre. In this paper an automatic design procedure, based on Genetic Algorithms, to obtain such horns is described. The algorithm operates on many horn profile parameters, including corrugations, and is based on an accurate full-wave mode matching/combined field integral equation analysis code. To keep computing time down a full parallel algorithm over a 12 CPU parallel virtual machine is described.

1. INTRODUCTION

Profiled or dual profiled corrugated circular horns (PCCH or DPCCH) are among the best feeds used in modern antenna manufacture for their polarization purity and small size [1]. Furthermore, by appropriately designing the profile, very compact horns with very stable phase centre with respect to frequency, can be obtained. This is a highly desirable property since, especially in spaceborne applications, having compact horns with a phase centre which is stable over a broad frequency band can greatly simplify the cluster illuminating each single reflector [2, 3].

Horn characterization by using full-wave software simulators, based on mode matching and on combined field integral equation (CFIE) techniques, is accurate and can nowadays be performed on a conventional personal computer [4, 5]. Automatic design, on the other hand, requiring many different analyses, is much more time consuming. Although some interesting results were recently obtained for PCCH design by exploiting artificial neural networks (ANN) [6] this has the flaw that it cannot be easily generalized when design constraints change. An automatic optimization technique directly exploiting the full wave simulator is hence often preferable. Hence in this paper a different approach for optimizing the horn phase centre, size, pattern and return loss is presented, based on a Genetic Algorithm (GA) scheme. Other approaches to GA horn antennas optimization exist, but they concern planar [7] or disk structures [8], not PCCH or DPCCH, and are limited to simple objectives, not comprising a full set of electromagnetic characteristics. Furthermore, in this paper, a different kind of profiling, based on Non-Uniform Rational B-Splines (NURBS) [9] is presented. Profile optimization is indeed a topic of relevant practical interest, analysed in very recent papers [10–12], none of which dealing with the very versatile NURBS curves. This latter kind of horn will be addressed to as NPCCH (NURBS profiled corrugated circular horns).

The paper has the following organization: in Sections 2 and 3 the key points of optimization parameters and cost function are introduced; in Section 4 the parallel GA implementation and its characteristics are described; then in Section 5 some horn designs are presented. Finally Section 6 contains the conclusions.

2. DESIGN PARAMETERS

The key issues in any optimization procedure are: first the selection of the parameters of the optimization and of their allowable ranges; then the choice of an appropriate cost function. For what concerns PCCH many geometrical design parameters may be considered.

The horn profile r as a function of the axial co-ordinate z can obey to a square sine law next to the throat and to an exponential function at the aperture (DPCCH):

$$r(z)=\begin{cases} R_i+(R_s-R_i)\left[(1-A)\dfrac{z}{L_s}+A\sin^2\left(\dfrac{\pi z}{2L_s}\right)\right] & 0\le z\le L_s \\ R_s+e^{\alpha(z-L_s)} & L_s\le z\le L_s+L_e \end{cases} \tag{1}$$

Parameter $A \in [0,1]$ modulates the first region profile from linear to pure square sine, while the exponential profile is governed by $\alpha = [\ln(1+R_a-R_s)]/L_e$ [2,3] and the other terms are related to the horn geometry as shown in Fig. 1. Hence, for the square sine plus exponential profile, 5 design parameters can be recognized: L_s, R_s, L_e, R_a and A, being R_i fixed to the radius of the feeding circular waveguide.

NURBS curves are alternative functions for the shaping of the profile: they are extremely versatile mathematical objects used mainly in computer graphics to model curves and surfaces. As conventional splines they are defined by an ordered set of points $\{\boldsymbol{P}_i\}$, $i=0,\dots,n$, or *control polygon*. But, differently than for splines, NURBS curves are vector valued piecewise rational polynomial functions of a parameter $u\in[0,1]$:

$$\boldsymbol{P}(u)=\frac{\displaystyle\sum_{i=1}^{n} w_i\boldsymbol{P}_i N_{i,p}(u)}{\displaystyle\sum_{i=1}^{n} w_i N_{i,p}(u)} \tag{2}$$

w_i is an assigned set of weights and $N_{i,p}(u)$ are the normalized B-Spline

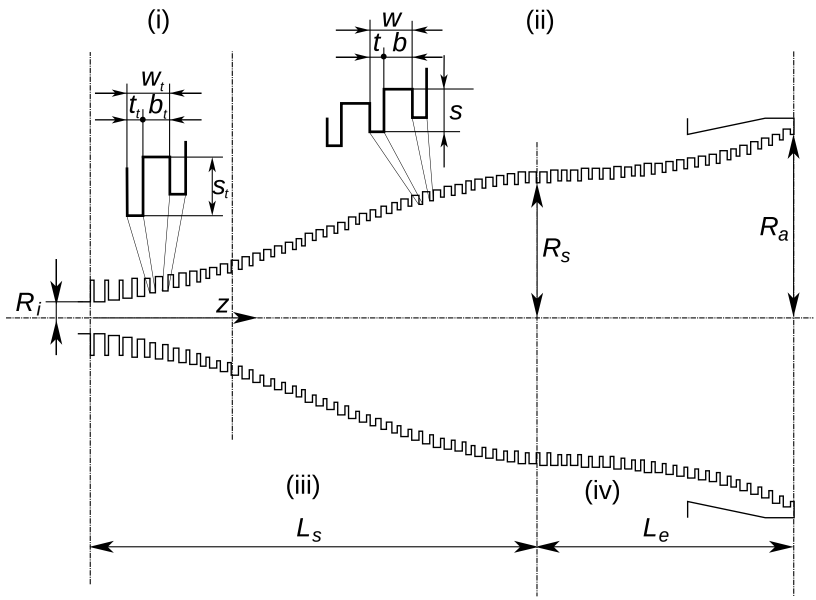

Figure 1. Dual profiled corrugated circular horn section with relevant geometrical parameters governing profile and corrugations. (i) zone of corrugations transition; (ii) zone of uniform corrugations; (iii) square sine region; (iv) exponential region.

basis functions of degree p:

$$N_{i,0}(u) = \begin{cases} 1 & \text{if } u_i \le u < u_{i+1} \\ 0 & \text{otherwise} \end{cases}$$
$$N_{i,p}(u) = \frac{u - u_i}{u_{i+p} - u_i} N_{i,p-1}(u) + \frac{u_{i+p+1} - u}{u_{i+p+1} - u_{i+1}} N_{1+1,p-1}(u) \tag{3}$$

being

$$\boldsymbol{U} = \{u_0, u_1, \ldots, u_m\}; \quad \text{with } u_0 \le u_1 \le \ldots \le u_m \tag{4}$$

the so-called knot vector and $m = n + p + 1$. To obtain a NURBS curve starting from point $\boldsymbol{P}_0$ and ending in point $\boldsymbol{P}_n$ the knot vector must have the first and last $p + 1$ elements coincident, that is $\boldsymbol{U} = \{0, \ldots 0, u_{p+1}, \ldots, u_{m-p-1}, 1, \ldots, 1\}$. The function $N_{i,p}(u)$ determines the influence of control point $\boldsymbol{P}_i$ on the position of the curve at u, whereas the presence of w_i, weighting each control point, gives additional degrees of freedom to the curve shape. When all the control

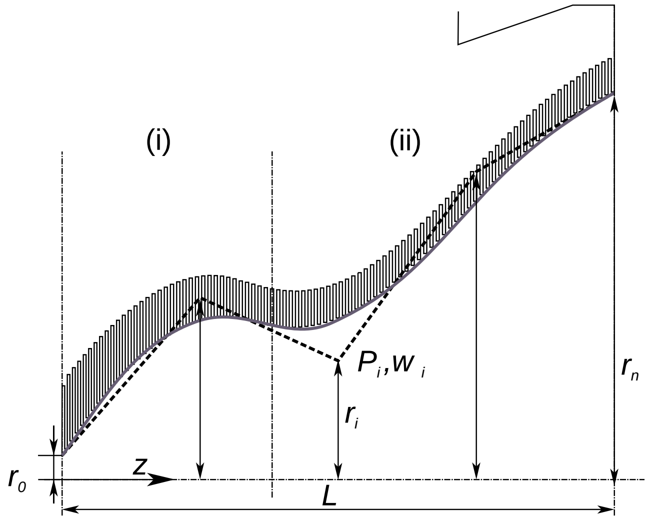

Figure 2. NURBS-profiled circular horn geometrical parameters; (i) transition region; (ii) uniform corrugations region.

points carry a weight of 1.0, the NURBS reverts to a conventional B-Spline, while, by adjusting the weights, one can precisely follow given geometries with very few control points. The set of n control points is chosen so that the first point defines the throat radius, while the last defines the radius of the aperture. The remaining control points are equally spaced along the axis (z direction) of the structure and positioned at a given distance, r_i, from it (Fig. 2). Hence the design parameters to define a NURBS profile are: the overall length of the structure, L, the number of control points n, their radial distance from the axis r_i and the relative weights, w_i.

As far as corrugations are concerned, for large horns it is often convenient to consider them uniform over a large part of the horn and characterized by a depth s and an overall width w, this latter split into a tooth width t and a slot width b. In the throat region there is a transition in which the corrugations start from a given geometry s_t, w_t, b_t and end to the desired s, w, b values. This transition can obey to a linear or polynomial law, or, as an alternative, each corrugation parameter can assume an arbitrary independent value. The transition of each parameter occurs over a given number of corrugations M, which may indeed be different for each parameter $\{M_s, M_b, M_w\}$ (Fig. 3). Hence the design parameters for corrugations may be as few as 9, $\{s_t, w_t, b_t, s, w, b, M_s, M_b, M_w\}$ for linear variation,

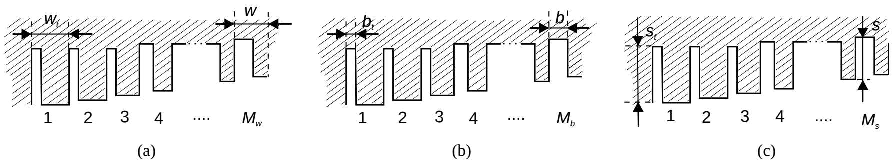

Figure 3. Transition corrugation regions and relative parameters: (a) w transition; (b) b transition; (c) s transition.

or as much as $(M_s + M_b + M_w)$ for independent variation. From these design parameters a subset is then selected and ordered into an optimization parameter vector $\boldsymbol{p}$ on which the optimization procedure will operate.

3. COST FUNCTION

For the key issue of the cost function for the optimization process several objectives are defined for the electromagnetic characteristics of the horn. The quantities relevant for a horn which is to be used as a feed for a reflector antenna are: the phase centre C location — in terms of its distance d from the horn aperture — the side lobe level SLL, the edge taper ET on the reflector equivalent edge, θ_{ET} from the horn broadside direction ($ET@\theta_{ET}$ for short), the cross-polar level XL and the return loss RL (see Fig. 4 for a graphical sketch of some of these parameters and [1] for a full definition of all).

In this paper, an optimization procedure based on a quasi-Newton method is exploited for the computation of the phase centre C.

C is placed on the horn axis for symmetry reasons and its position is hence determined by its distance d from the horn mouth O. The optimization technique minimizes the function

$$f(\tilde{d}) = \sum_i \sum_j w_{ij} \left| \phi_{\tilde{\boldsymbol{C}}}^{(\vartheta_i,\phi_i)}(\tilde{d}) - \phi_{\tilde{\boldsymbol{C}}}^{(0,0)}(\tilde{d}) \right| \qquad (5)$$

where $\tilde{\boldsymbol{C}}$ is a generic point at a distance $\tilde{d}$ from O and $\phi_{\tilde{\boldsymbol{C}}}^{(\vartheta,\phi)}$ is the phase of the far field in the direction (ϑ, ϕ) computed with $\tilde{\boldsymbol{C}}$ as reference point. Cost function (5) is computed over a discrete set of points (ϑ_i, ϕ_i) in the ranges $\vartheta_i \in [0, \vartheta_0]$ and $\phi_j \in [0, 2\pi]$ and exploiting a suitable set of weights w_{ij}.

This optimization is indeed very fast since, once the phases of the field $\phi_O^{(\vartheta,\phi)}$ are computed with respect to point O, the phases in the

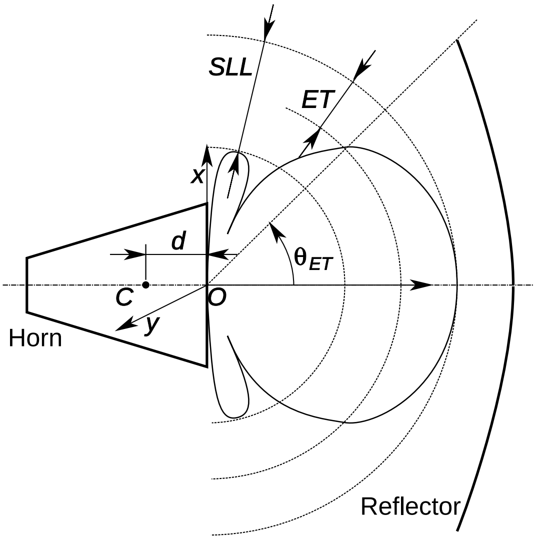

Figure 4. Some of the fundamental electromagnetic characteristics for a horn used as a reflector antenna feed.

generic point $\tilde{\boldsymbol{C}}$ are given by [13]

$$\phi_{\tilde{\boldsymbol{C}}}^{P(\vartheta,\phi)}(\tilde{d}) = \phi_{O}^{P(\vartheta,\phi)} - k\tilde{d}\cos\vartheta \tag{6}$$

where k is the wavenumber.

For the sake of simplicity the five electromagnetic characteristics mentioned above will be referred to as a single vector $\boldsymbol{c} = [d, SLL, ET@\theta_{ET}, XL, RL]$. Hence in the following c_1 will be the phase centre position, c_2 the side lobe level, etc.

For the desired characteristics both a nominal value ($\overline{\boldsymbol{c}}$) and two acceptable tolerance vectors ($\boldsymbol{\delta}^+$ and $\boldsymbol{\delta}^-$) are given as the design objective. The objective is reached if $\overline{c}_n - \delta_n^- \leq c_n \leq \overline{c}_n + \delta_n^+ \ \forall n$ over the specified set of frequencies and pattern cuts. Tolerances can be symmetric ($\delta^+ = \delta^-$) for characteristics which must be within an interval of the nominal value (like d and $ET@\theta_{ET}$) or an asymmetric threshold ($\delta^- = +\infty$, $\delta^+ = 0$) for characteristics which must stay below a nominal level (like SLL, XL and RL). The cost function is hence computed as a summation of the weighted distances $D(c_n(\boldsymbol{p}), \overline{c}_n, \delta_n^-, \delta_n^+)$ between each EM characteristic for the given parameters $c_n(\boldsymbol{p})$ and its nominal value and tolerance:

$$C(\boldsymbol{p}) = \sum_{n=1}^{5} w_n D(c_n(\boldsymbol{p}), \overline{c}_n, \delta_n^-, \delta_n^+) \tag{7}$$

being $\boldsymbol{w}$ the weights vector.

The distance is itself defined as a weighted summation over the selected characteristic obtained via the full wave simulation [5] over a suitable set of discrete frequency values $f_i,\ i = 1, \ldots, N_f$ and over a discrete set of ϕ cuts $\phi_j,\ j = 1, \ldots, N_\phi$.

$$D(c_n(\boldsymbol{p}), \overline{c}_n, \delta_n^-, \delta_n^+) = \sum_{i=1}^{N_f} \sum_{j=1}^{N_\phi} u(\{c_n(\boldsymbol{p})\}_{ij}, \overline{c}_n, \delta_n^-, \delta_n^+) |c_n(\boldsymbol{p})\}_{ij} - \overline{c}_n| \tag{8}$$

having indicated with $\{c_n(\boldsymbol{p})\}_{ij}$ the value of the n-th characteristic at frequency f_i and on cut ϕ_j. It is worth noticing that for $n = 3$, that is the edge taper, specifications are usually given only for the centre-band frequency, hence no summation over i is necessary, while for $n = 5$, that is the return loss, the identification of a ϕ cut loses significance, hence no summation over j is performed.

The weight $u(\{c_n(\boldsymbol{p})\}_{ij}, \overline{c}_n, \delta_n^-, \delta_n^+)$ is a non-linear function which assures that the value of the cost function does not vary if a characteristic is already within the acceptable tolerance from the nominal value and that characteristics very distant from the nominal value have a higher penalty. Its analytical expression is:

$$u(\{c_n(\boldsymbol{p})\}_{ij}, \overline{c}_n, \delta_n^-, \delta_n^+) = \begin{cases} 0 & \text{if } \{c_n(\boldsymbol{p})\}_{ij} - \overline{c}_n \in [-\delta_n^-, \delta_n^+] \\ 1 & \text{if } \{c_n(\boldsymbol{p})\}_{ij} - \overline{c}_n \in [-\Delta_n^-, -\delta_n^-] \bigcup (\delta_n^+, \Delta_n^+] \\ 100 & \text{if } \{c_n(\boldsymbol{p})\}_{ij} - \overline{c}_n \in (-\infty, -\Delta_n^-] \bigcup (\Delta_n^+, +\infty) \end{cases} \tag{9}$$

where Δ_n is an additional set of tolerance levels introduced to speed up convergence. Its value is to be tuned on the problem at hand, but experience has showed that $\Delta_n^\pm = 3\delta_n^\pm$ leads to good results.

4. PARALLEL GA

Any automatic optimization procedure relies on some appropriate deterministic or stochastic algorithm for the minimization of the problem cost function. It is well known that deterministic algorithms are accurate but may get trapped in local minima, whereas stochastic algorithms, although more CPU intensive, perform a global search, hence avoiding that shortcoming. Among the stochastic techniques genetic algorithms (GA) are very interesting [14].

The hybrid MM/CFIE full wave package described in [5] and used both in [6] for neural network learning and in [2, 3] for human-driven design is very accurate but somewhat CPU intensive, requiring few minutes for each frequency point on fast modern PC (Pentium III, 733 MHz clock). The GA operates over a population of some tens of possible designs, for hundreds of generations. For each design at each generation one simulation over the desired frequency points is necessary; it is easy to understand how the number of analyses required can grow up to several thousands.

Among the characteristics of the GA is that the analyses relative to different members of the population at a given generation are independent and can hence be computed in parallel. The GA has then been implemented over a 6-node Beowulf cluster [15], by exploiting the PVM libraries [16], each comprising a dual Pentium III system. The optimization procedure has been built in a master/slave paradigm; the GA master process, residing on a node, sends parameter vectors $\boldsymbol{p}$ to a set of slave processes scattered all over the cluster, which perform the full wave analysis and return the cost function value. This is highly efficient inasmuch the bottleneck of a Beowulf cluster consists in the relative slowness of the network interconnection between the nodes. In the proposed master/slave architecture only the extremely concise information contained in the vector parameters and the value of the cost function are actually passed among processes.

5. OPTIMIZATION RESULTS

Two horn designs are shown here.

The first example concerns a horn that works at 100 GHz, with a 20% band, with a complete set of design specifications. The horn has a square sine plus exponential profile. The total length of the horn was fixed to 61.5 mm, which corresponds to 20.5λ. The set of optimization parameters comprises M_s, s_t, s, b_t, and b, defining the throat corrugation geometry, L_s, A, R_s, and R_a, which define the dual profile. Parameters M_b, M_w, w_t and w were fixed to have full control on the overall length of the structure. The overall width of corrugations, w, varies following a linear law from w_t to w. All useful data relevant to each parameter are shown in Tab. 1. Optimization goals were represented by the three vectors $\boldsymbol{c} = [-2.5\,\text{mm}, -35\,\text{dB}, -25\,\text{dB@}20°, -30, 30]$, $\boldsymbol{\delta}^+ = [6\,\text{mm}, 0, 0, 0, \infty]$, $\boldsymbol{\delta}^- = [6\,\text{mm}, \infty, 0, \infty, 0]$. The two auxiliary tolerances were $\boldsymbol{\Delta}^+ = [18\,\text{mm}, 0, 0, 0, \infty]$, $\boldsymbol{\Delta}^- = [18\,\text{mm}, \infty, 0, \infty, 0]$.

The constraints were sampled and added to the total cost at 90 GHz, 100 GHz and 110 GHz ($N_f = 3$), and all constraints were checked and considered in the cost on the horn pattern main cuts (E-plane, H-plane and the $\phi = 45°$ in between, $N_\phi = 3$). From the GA point of view, a simple GA [14] was run over 15 generations with populations of 55 specimens. The crossover probability was 0.8, the

Table 1. First design example: design parameter values.

DESIGN PARAMETER			Variation range		Optimized GA value	A priori fixed value
			Min	*Max*		
CORRUGATIONS	s	s_t [λ]	0,39	0,518	0,495	-
		s [λ]	0,18	0,308	0,234	-
		M_s	14	30	27	-
	w	w_t [λ]	-	-	-	0,4
		w [λ]	-	-	-	0,3
		M_w	-	-	-	20
	b	b_t [λ]	0,02	0,276	0,092	-
		b [λ]	0,15	0,278	0,238	-
		M_b	-	-	-	20
PROFILE	L_s [λ]		8,8	18,4	11,8	-
	A		0,338	0,9	0,647	-
	R_s [λ]		0,445	2,493	1,987	-
	R_a [λ]		1,976	3	2,72	-

mutation probability was 0.1, and the running time 5 hours. Fig. 5 and Fig. 6 show the results obtained. It is important to notice the excellent stability achieved for the phase centre in the given band.

The second example concerns a NPCCH that works at 100 GHz but with a 30% band. The overall length was fixed to 57 mm which corresponds to 19.05λ. The length of the horn was fixed. This was obtained by fixing the total number of corrugations and, in the transition region, by fixing parameters w_t, w, M_w and M_b. So for what concerns the corrugations geometry, 5 optimization parameters have been used: M_s, s_t, s, b_t, b. For the NURBS profile shaping a control polygon with 5 control points, $P_i\,(i = 0, \ldots, n;\ n = 4)$, has been defined. The points are equally spaced along the axis of the horn. Then, the five weights, w_i, as well as the five radial coordinates, r_i, were the profile optimization parameters. As in the first example all useful data relevant to design parameters are shown in Tab. 2. Optimization goals were represented by the three vectors $\boldsymbol{c} = [-3.6\,\text{mm}, -35\,\text{dB}, -22\,\text{dB@}19^\circ, -30.30]$, $\boldsymbol{\delta}^+ =$

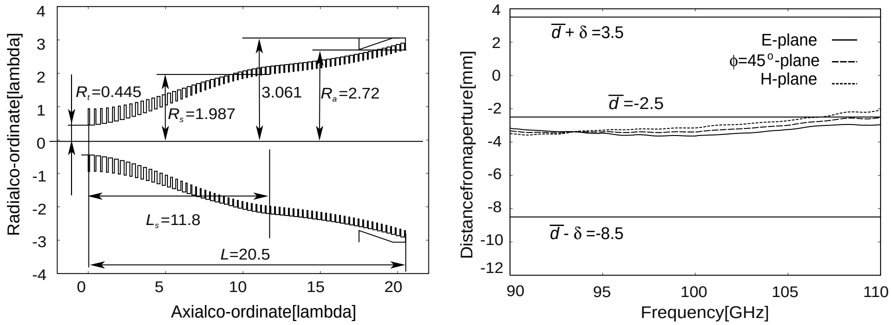

Figure 5. First design: synthesized geometry and phase centre position vs frequency on the three pattern main cuts.

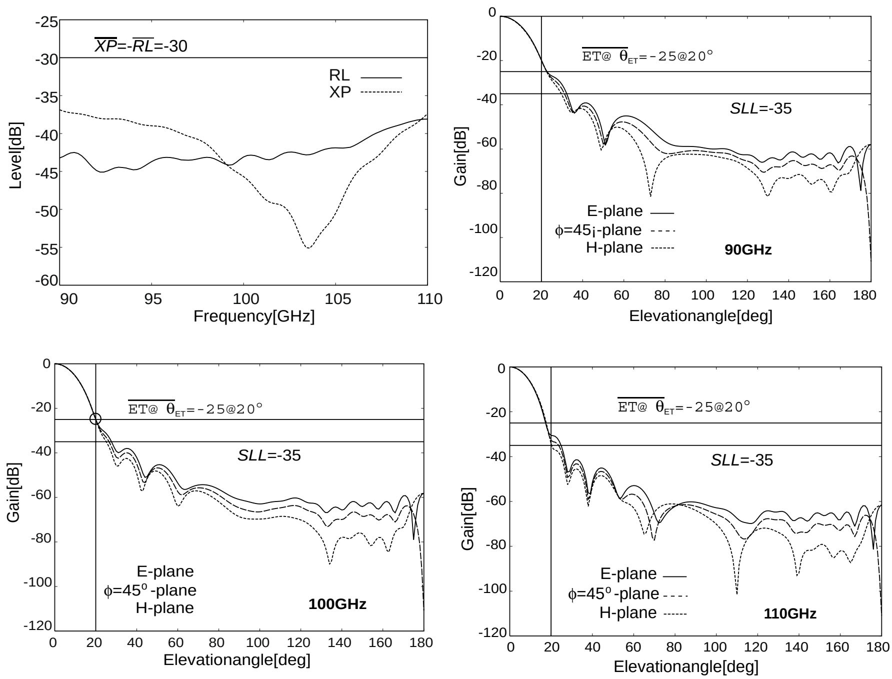

Figure 6. First design: maximum cross-polar level and reflection coefficient (top-left) and co-polar pattern at centerband and band limits.

Table 2. Second design example: design parameter values.

DESIGN PARAMETER			Variation range Min	Variation range Max	Optimized GA value	A priori fixed value
CORRUGATIONS	s	s_t [λ]	0,39	0,518	0,393	-
		s [λ]	0,18	0,308	0,248	-
		M_s	14	30	18	-
	w	w_t [λ]	-	-	-	0,4
		w [λ]	-	-	-	0,3
		M_w	-	-	-	33
	b	b_t [λ]	0,02	0,276	0,071	-
		b [λ]	0,15	0,278	0,261	-
		M_b	-	-	-	33
PROFILE	L [λ]		-	-	-	19,05
	n		-	-	-	5
	P_0	z_0 [λ]	-	-	-	0
		r_0 [λ]	0,445	0,573	0,466	-
		w_0	0,5	1,5	0,8125	-
	P_1	z_1 [λ]	-	-	-	4,7625
		r_1 [λ]	0,97	1,089	1,066	-
		w_1	0,5	1,5	0,75	-
	P_2	z_2 [λ]	-	-	-	9,525
		r_2 [λ]	1,494	1,75	1,721	-
		w_2	0,5	1,5	0,5625	-
	P_3	z_3 [λ]	-	-	-	14,2875
		r_3 [λ]	2,083	2,339	2,107	-
		w_3	0,5	1,5	0,6875	-
	P_4	z_4 [λ]	-	-	-	19,05
		r_4 [λ]	2,544	3,056	2,626	-
		w_4	0,5	1,5	0,8125	-

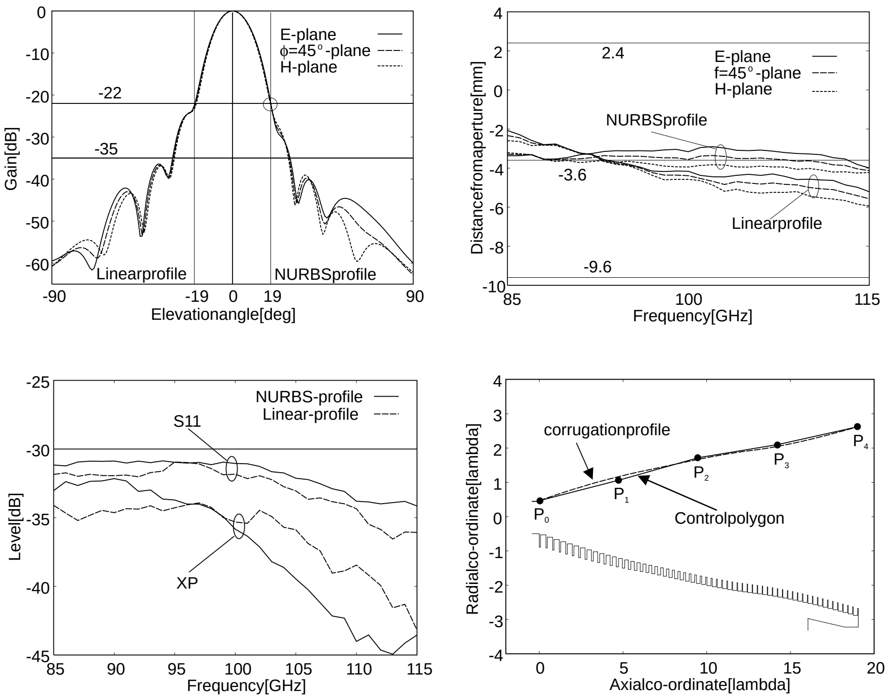

Figure 7. Second design: comparison between the optimized NPCCH and the nearest linear horn patterns at 100 GHz (top-left) and phase centre positions (top-right) on the $\phi = 0$, $\phi = 45°$ and $\phi = 90°$ planes; comparison between cross-polar and return loss levels (bottom-left); NPCCH profile and control polygon (bottom-right).

$[6\,\text{mm}, 0, 0, 0, \infty]$, $\boldsymbol{\delta}^- = [6\,\text{mm}, \infty, 0, \infty, 0]$. The two auxiliary tolerances were $\boldsymbol{\Delta}^+ = [18\,\text{mm}, 0, 0, 0, \infty]$, $\boldsymbol{\Delta}^- = [18\,\text{mm}, \infty, 0, \infty, 0]$. From the GA point of view the population encompassed 90 specimens over 40 generations with a crossover probability equal to 0.8 and a mutation probability equal to 0.1. Elitism was also exploited. The running time was about 21 hours. Fig. 7 shows the obtained results: the electromagnetic characteristics are compared with those obtained by a linear horn of comparable dimensions. In Fig. 7 is also shown the obtained NPCCH profile.

6. CONCLUSIONS

In this paper a GA approach to the design of DPCCH and NPCCH has been presented. Two relevant cases of design attained with the method were shown. In both cases the horn length was fixed *a priori*, as it is often the case in satellite applications, and the design main goal was to attain the highest phase centre stability over the prescribed band, together with the other standard electromagnetic requirements. In the second example a rather complex optimization problem has been presented: the horn was requested to work in a 30% band and the design was performed exploiting NPCCH. A comparison between the optimized NPCCH and the nearest linear horn has been shown as well.

ACKNOWLEDGMENT

This work was partially supported by the Italian National Research Council (CNR) under contract CNR/ASI.ARS 1/R/27/00 and by the Italian Space Agency (ASI) under contract ASI 1/R/62/00.

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