COMPUTER-AIDED DESIGN OF MULTIMODE HORNS WITH CHANGED FLARE ANGLES

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1. INTRODUCTION

As is well known that the multimode horns, as high performance feeds, are widely used for reflector antennas due to their rotationally symmetric pattern, extremely low cross-polarization, and low sidelobe level. Although the design works in this area have been reported from time to time [1-3], its electromagnetic behavior, however, is remarkably complicated and for this reason a great deal of work has been based upon design curves, experiment and experience.

In this paper, a computer-aided analysis and design of multimode horn with changed flare angles on optimization technique are presented. When considering not only the coincidence of phase centers in principle planes but also the axial symmetric pattern with some illumination level, we could regard multimode horn as series two-port network and its optimum dimensions can be obtained by solving nonlinear nonconvex multi-objective programming.

2. MODELLING AND OPTIMIZING

2.1 Optimum Aperture mode Ratio

The multimode horn being used as feed, the TM_{11} and TE_{12} modes are predominant components among all higher order modes(TM_{1n} , TE_{1n}), and the others have much small amplitudes, so are not considered in calculating radiation pattern. Therefore, the field pattern functions of circular aperture with TE_{11} , TM_{11} and TE_{12} modes in principal planes can be determined[4]

In the E-plane

$$F_E(u)=(1+\cos\theta)\left\{(2-0.411M_{H12})\frac{J_1(u)}{u}-\frac{J_1'(\nu_{11})}{J_1(\mu_{11})/\mu_{11}}\cdot\frac{2J_1(u)}{(\nu_{11}/u)^2-1}M_{E11}\right\} \tag{1}$$

In the H-plane

$$F_H(u)=(1+\cos\theta)\left\{\frac{2J_1'(u)}{1-(u/\mu_{11})^2}-0.411\frac{J_1'(u)}{1-(u/\mu_{12})^2}M_{H12}\right\} \tag{2}$$

where J_1 , J_1' are Bessel function of the first kind and order one, and its derivative with respect to argument u, M_{E11} , M_{H12} denote complex mode ratios of TM_{11} , and TE_{12} to TE_{11} at aperture, respectively, $u=ka\sin\theta$, $k=2\pi/\lambda$ is free-space wave number, θ is angle from line perpendicular to the horn aperture(see Fig.1), a is radius of the feed aperture, $\mu_{11}=1.841$, $\mu_{12}=5.332$, and $\nu_{11}=3.832$.

Both $F_E(\theta)$ and $F_H(\theta)$ are maximum for $\theta=0°$, and have the same value of $F_m=(1-0.2055)M_{H12}$. The normalized pattern functions are then $f_E(u)=|F_E(u)/F_m|$ and $f_H(u)=|F_H(u)/F_m|$.

On the other hand, the phase performance of radiated field is also directly dependent on the aperture field distribution related to mode ratio. In the region of smaller θ , relative location of phase centres in H- and E-plane(on Z-axis and from the horn aperture) can be determined as follows[5]

$$E_x(\rho,\varphi)=(1+M_{H12})\sum_{i=0}^{5}(U_i+V_i\sin^2\varphi)\rho^i+M_{E11}\sum_{i=0}^{5}(U_i+V_i\cos^2\varphi)\rho^i \tag{3}$$

$$\frac{d_{H(E)}}{\lambda} = -2\pi\left(\frac{a}{\lambda}\right)^2 I_m\left\{\frac{\int_0^{2\pi}\int_0^1 E_x(\rho,\varphi)\cos^2(\phi-\varphi)\rho^3 e^{-j\psi\rho^2}d\rho\, d\varphi}{\int_0^{2\pi}\int_0^1 E_x(\rho,\varphi)\rho\, e^{-j\psi\rho^2}d\rho\, d\varphi}\right\} \tag{4}$$

where $E_x(\rho,\varphi)$ is one of aperture field components and the other, $E_y(\rho,\varphi)$, will not be taken into account because of not making contribution to radiation field in principal planes. U_i and V_i are fitting coefficients, and have been found by Gauss' method of least squares[5]. d_E and d_H are relative location of phase centres and corresponding with $\phi=0°$ and $90°$ respectively.

From high efficiency standpoint, now the problem is how to determin mode ratios M_{E11} and M_{H12} to obtain the "best fit" phase centres and the best coincidence of pattern functions $f_E(u)$ and $f_H(u)$ over the interval $0\le u\le u_m$ ($0\le\theta\le\theta_m$). If let X_1 denote a column vector of two mode ratios and $F_1(X_1)$ a objective function depending on X_1, a nonliner programming problem of the following form can be established

$$\text{minimize } F_1(X_1)=\left\{\sqrt{\sum_{i=1}^{N}\left[f_H(u_i)-f_E(u_i)\right]^2/N} + W\cdot\left|\ln(d_H/d_E)\right|\right\} \tag{5}$$

subject to $0<H_m<1,\ 0\le H_p\le 2\pi;\ 0<E_m<1,\ 0\le E_p\le 2\pi$

where $E_m=|M_{E11}|$, $E_p=\arg(M_{E11})$; $H_m=|M_{H12}|$, $H_p=\arg(M_{H12})$; $X_1=(H_m, H_p, E_m, E_p)^T$
w is a weighting factor for the phase term, usually w=1.

The optimal solution $X_1^*=(H_m^*, H_p^*, E_m^*, E_p^*)^T$ could first be solved by Monte Carlo method[6], and in order to save CPU time and increse precision DFP(Davidon-Fletcher-Powell method) could then be employed for local optimization used Monte Carlo's solution $X_{10}=(H_{m0}, H_{p0}, E_{m0}, E_{p0})^T$ as initial values.

2.2 Optimum Demensions of Multimode Horn

The following step is how to control demensions of horn to realize required mode ratios M_{E11}^* and M_{H12}^* obtained above. When a fundamental mode TE_{11} is incident into conical junction from left waveguide port, there are only higher modes TE_{1n} and TM_{1n} ($n\in N=1,2,3...$) because of its symmetrical construction.

In practice, the flare angles in these horns are usually rather small, so reflection can be negligible and only TE_{11}, TM_{11}, and TE_{12} are taken into consideration. Viewing these taper sections as several series mode-transducers, we can easily establish amplitude-phase relationship for each mode through the cross-sectional plane p=1,2,3.
for TE_{11} mode

$$TE_{11}^{1R}=TE_{11}^{1L}K_{H11}^{1}=TE_{11}K_{H11}^{1} \tag{6a}$$

$$TE_{11}^{qL}=TE_{11}^{pR}\exp(-j\phi_{H11}^{p-q}) \qquad p=1,2,3;\ q=p+1 \tag{6b}$$

$$TE_{11}^{qR}=TE_{11}^{qL}K_{H11}^{q} \qquad q=2,3,4 \tag{6c}$$

where superscripts p(q)R and p(q)L in expressions denote the Right and Left side of section p(or q). $K_{H11}^{p}=TE_{11}^{pR}/TE_{11}^{pL}$ is mode conversion coefficient of TE_{11}^{pR} to TE_{11}^{pL}, and they have been tabulated in[7]. ϕ_{H11}^{p-q} is phase shift for TE_{11} mode when propagating from the right side of section p to the left side of section q=p+1, it can easily obtain by

$$\phi_{H11}^{p-q}=2\pi\frac{l}{a_2}\sqrt{\left(\frac{a_2}{\lambda}\right)^2-C_1^2} \qquad \text{type (a), (b); } p=2,\ q=3 \tag{7a}$$

or else

$$\phi_{H11}^{p-q}=2\pi\cot\alpha_p\left\{\left[\sqrt{(\frac{a_q}{\lambda})^2-c_1^2}-\sqrt{(\frac{a_p}{\lambda})^2-c_1^2}\right]-c_1\left[\cos^{-1}(c_1\frac{\lambda}{a_q})-\cos^{-1}(c_1\frac{\lambda}{a_p})\right]\right\} \qquad p=1,2,3\;;\; q=p+1 \tag{7b}$$

where $C_1=1.841/(2\pi)$

For convenience, symbol EH is used to denote TM_{11} or TE_{12}, then

$$EH^{qL}=EH^{pR}\exp(-j\phi_{EH}^{p-q}) \qquad p=1,2,3\;;\; q=p+1 \tag{8a}$$

$$EH^{qR}=EH^{qL}K_{EH}^{q}+TE_{11}^{qR}K_{EH}^{q} \qquad q=2,3,4 \tag{8b}$$

where

$$\phi_{EH}^{p-q}=\begin{cases}2\pi\cot\alpha_1\left\{\left[\sqrt{(\frac{a_2}{\lambda})^2-C_{EH}^2}-C_{EH}\cos^{-1}(C_{EH}\frac{\lambda}{a_2})\right]-j\left[C_{EH}\ln(\frac{C_{EH}+\sqrt{C_{EH}^2-(\frac{a_1}{\lambda})^2}}{a_1/\lambda})-\sqrt{C_{EH}^2-(\frac{a_1}{\lambda})^2}\right]\right\} & (9a)\\ \qquad \text{type (a),(b),(c)}\;;\; p=1,\; q=2 & \\ 2\pi\cot\alpha_p\left\{\left[\sqrt{(\frac{a_q}{\lambda})^2-C_{EH}^2}-\sqrt{(\frac{a_p}{\lambda})^2-C_{EH}^2}\right]-C_{EH}\left[\cos^{-1}(C_{EH}\frac{\lambda}{a_q})-\cos^{-1}(C_{EH}\frac{\lambda}{a_p})\right]\right\} & (9b)\\ \qquad \text{type (c)} \quad p=2,3\;;\; q=p+1 & \\ 2\pi\frac{l}{a_2}\sqrt{(\frac{a_2}{\lambda})^2-C_{EH}^2} \qquad \text{type (a),(b)}\;;\; p=2,\; q=3 & (9c)\end{cases}$$

where $C_{EH}=3.832/(2\pi)$(for TM_{11}) or $5.332/(2\pi)$(for TE_{12})

Finally ratios M'_{E11} and M'_{H12} at the aperture are easily written as:

$$M'_{E1}=TM_{11}^{4R}/TE_{11}^{4R}=E'_m\exp(jE'_p) \tag{10a}$$

$$M'_{H12}=TE_{12}^{4R}/TE_{11}^{4R}=H'_m\exp(jH'_p) \tag{10b}$$

When M'_{H12} and M'_{E11}, which are under the control of the diameter, flare angle and length of tapered waveguide sections, are equal(or approximate) to M^*_{H12}, M^*_{E11} obtained above, we would have optimum solution.

3. PRACTICE

The computer programs have been run to design (a)-(c) of multimode horns in X band and measured field patterns(amplitude and phase) and a photo of the type (a) are shown in Fig.3 and 4.

It is seen that a high degree of rotationally symmetrical pattern and extremely low sidelobe level(less than -25 dB) are obtained. Furthermore, the phase deviation in H- and E-plane is less than 6°over the angle range $\theta=0°$ to 30°.

4. REFERENCES

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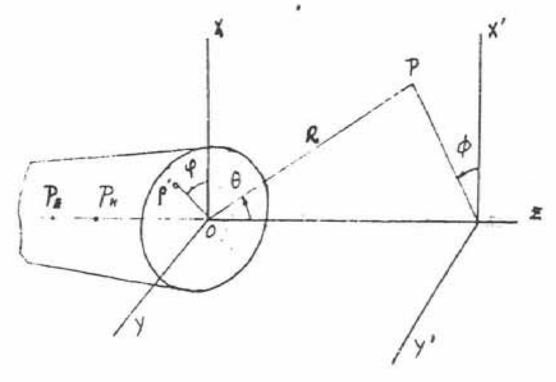

Fig.1 Geometry of multimode horn

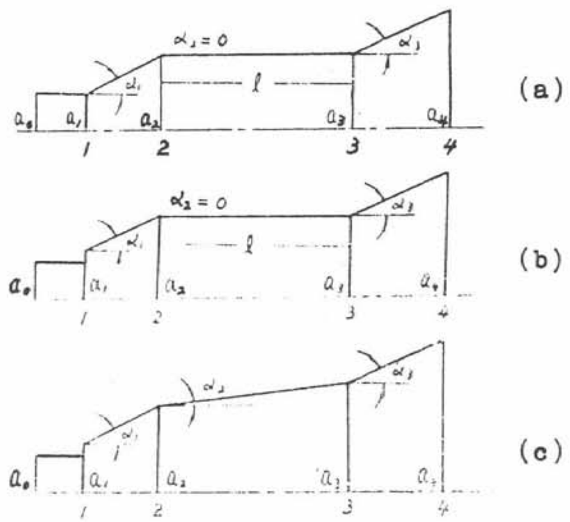

Fig.2 Three basic types of conical multimode horns

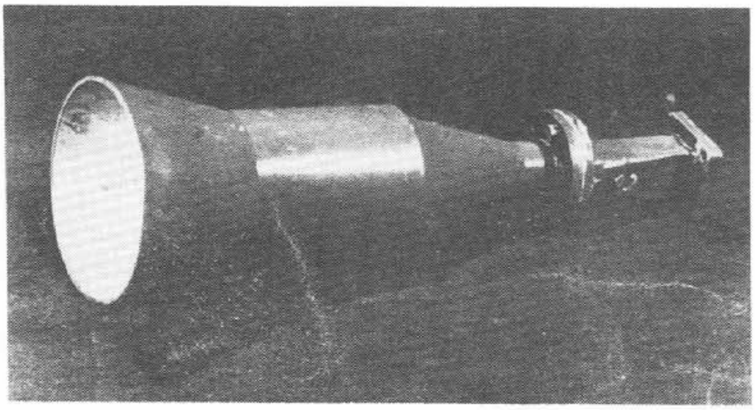

Fig.3 photo of type (a) multimode horn used as feed for Cassegrain reflector antenna

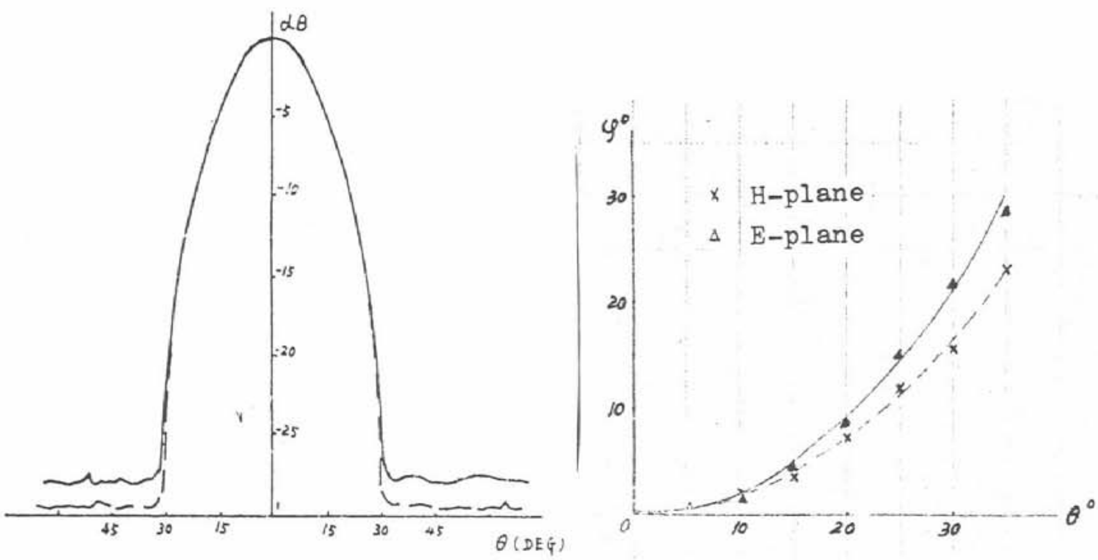

Fig.4 Measured field patterns(amplitude and phase) at 11.7GHz