Analytical Beam Forming for Circularly Symmetric Conformal Apertures

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***Abstract*—In this paper, we present an analytical beam-forming approach capable of synthesizing differently shaped beams for circularly symmetric conformal apertures with axisymmetrical excitations. Closed form formulas of far-field radiation are mathematically derived in order to obtain rotationally symmetric radiation patterns for typical conformal apertures frequently used in satellite and flight vehicle applications, such as the cone-surfaced, truncated cone-surfaced, hybrid disc-cone and sphere-cone apertures. Based on these formulas, various shaped beams, including pencil, flat-topped and bimodal beams can be rapidly achieved by adjusting either the geometric parameters or the excitation distributions of the conformal apertures. The deterministic approach proposed in this paper provides an efficient method to synthesize specified beam shapes for the aforementioned conformal apertures. Collaborating with conventional optimization based beam forming approaches, the proposed approach can effectively shorten the time-consuming optimization in the beam forming of circularly symmetric conformal arrays, especially large conformal arrays.**

***Index Terms*—Beam forming, circularly symmetric aperture, conformal arrays.**

I. Introduction

CONFORMAL array antennas have been studied for decades [1]. Owing to its advantage of being compatible with conformal surfaces of satellites and flight vehicles, conformal arrays are able to improve the aerodynamic characteristics, achieve large field of view (LFOV) and low observability, and effectively decrease extra volume occupation. In the past decades, conformal arrays have been widely used in various applications from aircraft antennas [2]–[4], radar array antennas[5] to wearable antennas[6]. From the volume saving point of view, conformal antennas are particularly suitable for satellite applications [7]–[9]. Compared with traditional satellite antennas, such as reflector antennas, cylindrical helix and horn arrays, conformal arrays can effectively reduce the profile of the antenna and accordingly leave precious inner space for satellite payloads. One typical example is the low-profile patch arrays used in Galileo navigation satellites [10], [11]. However, the beam forming of a conformal aperture is much difficult than that of a planar aperture due to the complex, three-dimensional geometry and the fact that the array periodicity would no longer simplify the analysis as in the case of planar aperture.

So far, various techniques have been proposed to synthesize the radiation pattern of a conformal array, such as the iterative least-squares method [12], [13], the projection method [14] and the adaptive algorithm for the synthesis of a spherical surface [15]. Recently, with the rapid development of computer and computation technologies, the most practical synthesis of conformal antenna arrays turns to the use of iterative, multidimensional optimization and evolutional approaches that rely mostly on large-capacity computations, which are normally very time-consuming for large arrays. Recent examples include some heuristic global algorithms, such as genetic algorithm [16], particle swarm algorithm [17], and differential evolution algorithm [18]. Nevertheless, all such optimization based beam forming algorithms are based on discrete conformal arrays, and therefore they are not adaptive for different circumstances. When the geometry or the aperture configuration of a conformal array is changed, the far-field radiation is also changed, and the optimization has to be repeated. Therefore, a deterministic beam forming approach based on a unified analysis capable of synthesizing conformal apertures with changeable degrees of freedom has a significant importance.

Up to now, deterministic beam forming algorithms mainly apply for planar apertures [19]–[21]. In our previous work, a deterministic beam forming approach that can be used to rapidly synthesize versatile, pre-specified beam shapes for planar apertures with concentric excitations satisfying multiple weighted sinc or Bessel function distribution was proposed [21]. Soon afterwards, this approach was extended to partially spherical-surfaced conformal apertures [22]. In this paper, we further propose a two-step beam forming approach for more complicated, circularly symmetric conformal apertures, including cone-surfaced aperture, truncated cone-surfaced aperture and some other compound curved circularly symmetric surfaces. Firstly, the closed form formulas of far-field radiation for given circularly symmetric conformal apertures are derived in detail, based on which the parameter sweeping or a local optimization algorithm can be

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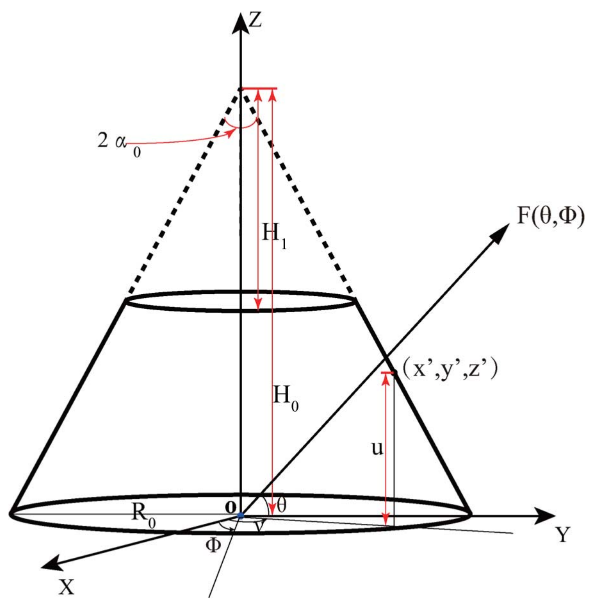

Fig. 1. Modeling of circularly symmetric cone-surfaced aperture.

used to rapidly obtain the continuous conformal aperture distribution for pre-specified rotationally symmetric beam shapes. Then, aperture discretization method discussed in [21] can be used to physically realize the conformal array. Owing to the fact that the projection of a circularly symmetric conformal aperture on its projective plane is a planar circular aperture, current distribution on the curved surface can be expanded into a Fourier series. Consequently, the corresponding far-field pattern can be further expressed in a compact closed integral form. The proposed deterministic beam forming approach based on theoretical far-field radiation formulas for conformal apertures can be used in a wide range of satellite and flight vehicle applications, helping to rapidly achieve the optimal performance.

This paper is organized as follows: In Section II, the modeling of circularly symmetric conformal apertures including four different kinds of conformal apertures is presented. Numerical results of two examples showing the effectiveness of the proposed approach are given in Section III. Finally, a conclusion is drawn in Section IV.

II. Formulation

A. Modeling of Cone-Surfaced Apertures

A circularly symmetric cone-surfaced aperture with a conical angle $2\alpha_0$, a height H_0 and a radius of bottom surface R_0 is depicted in Fig. 1 in Cartesian coordinate system. We establish parametric equations for point (x', y', z') located on the conical surface as:

$$\begin{aligned} x' &= \frac{H_0 - u}{H_0} R_0 \cos\nu \\ y' &= \frac{H_0 - u}{H_0} R_0 \sin\nu \\ z' &= u \end{aligned} \tag{1}$$

where $\nu \in [0, 2\pi]$ and u is an arbitrary real number.

For a continuous, linearly polarized current distribution denoted by $K(u,\nu)$ on the conical surface, the radiation far-field can be calculated by

$$F(\theta,\phi) = \int\limits_S K(u,\nu) e^{jk\Omega}\, dS, \tag{2}$$

where $k = 2\pi/\lambda$, λ is the free space wavelength, Ω is the scalar product of the position vector from origin to the source point (x', y', z') and the position vector from the origin toward the far-field observation point (x, y, z) [23]. Substituting $a_0 = R_0/H_0 = \tan\alpha_0$ and utilizing the spherical coordinate system sharing the same origin, $\Omega = a_0(H_0 - u)\sin\theta\cos(\phi - \nu) + u\cos\theta$ and $dS = a_0|H_0 - u|\sqrt{1 + a_0^2}du d\nu$. Therefore, $F(\theta,\phi)$ becomes

$$F(\theta,\phi) = \int\limits_S K(u,\nu) e^{jk[a_0(H_0-u)\sin\theta\cos(\phi-\nu)+u\cos\theta]} \cdot a_0|H_0 - u|\sqrt{1 + a_0^2}\, du\, d\nu. \tag{3}$$

Owing to the circular symmetry of the conformal surface, the aperture distribution $K(u,\nu)$ can be expanded in Fourier series with coefficients $K_n(u)$, i.e. $K(u,\nu) = \sum_{n=-\infty}^{\infty} K_n(u) e^{jn\nu}$ [23]. Besides, according to Bessel expansion [24]

$$e^{jk[a_0(H_0-u)\sin\theta\cos(\phi-\nu)+u\cos\theta]} = \sum_{m=-\infty}^{\infty} (j)^m \cdot J_m\left(ka_0(H_0 - u)\sin\theta\right) e^{jm(\phi-\nu)} \tag{4}$$

where J_m is the mth-order Bessel function of the first kind. Substituting aperture distribution $K(u,\nu)$ and (4) into (3), and utilizing the orthogonality of the Bessel function, the far-field pattern can be further expressed as

$$F(\theta,\phi) = 2\pi a_0\sqrt{1 + a_0^2} \sum_{n=-\infty}^{\infty} j^n e^{jn\phi} \cdot \int_0^{H_0} K_n(u) J_n\left(ka_0(H_0 - u)\sin\theta\right) e^{jku\cos\theta} |H_0 - u|\, du. \tag{5}$$

According to (5), in order to obtain a rotationally symmetric radiation pattern, a ϕ-independent current distribution is required, meaning that n should be restricted to be zero. As a result, the circularly symmetrical distribution $K(u,\nu)$ on the conformal aperture is also ν-independent. In this case, aperture distribution $K(u,\nu)$ can be denoted as $K_0(u)$. Therefore, the final far-field radiation can be written as

$$F(\theta,\phi) = 2\pi a_0\sqrt{1 + a_0^2} \cdot \int_0^{H_0} K_0(u) J_0\left(ka_0(H_0 - u)\sin\theta\right) e^{jku\cos\theta} (H_0 - u)\, du. \tag{6}$$

If we remove the apical part of the cone denoted in the dotted line in Fig. 1, the curved surface turns to a truncated cone with a height ΔH, $\Delta H = (H_0 - H_1)$. According to (6), after replacing the integral region, we obtain the generalized expression of the far-field radiation pattern for both the cone-surfaced and the truncated cone-surfaced aperture, i.e.

$$F(\theta,\phi) = 2\pi a_0\sqrt{1+a_0^2} \cdot \int_0^{H'} K_0(u)J_0\left(ka_0(H_0-u)\sin\theta\right)e^{jku\cos\theta}(H_0-u)\,du. \quad (7)$$

where $H' = H_0$ or $H' = (H_0 - H_1)$ when the conformal aperture is cone-surfaced or truncated cone-surfaced. It is seen that when α_0 approaches 180 degrees or H' approaches 0, the conical surface turns to a planar circular aperture or a planar annulus aperture with a width of $R_0 - r_0$ [21]. This implies that the concentric circular apertures discussed in [21] can be considered as a special case of conical or truncated conical apertures.

For the conformal aperture based on conical surface, given the aperture distribution $K_0(u)$, the maximum directivity, denoted as D_0, can be expressed as [25], [26]

$$D_0 = \frac{4\pi}{\lambda^2}\cdot\left(\frac{\left|\int_S K_0(u)dS\right|^2}{\int_S |K_0(u)|^2\,dS}\right) = \frac{4\pi}{\lambda^2}\cdot\frac{\left|\int_0^{H'}\int_0^{2\pi} K_0(u)a_0\left|H_0-u\right|\sqrt{1+a_0^2}\,du\,d\nu\right|^2}{\int_0^{H'}\int_0^{2\pi}|K_0(u)|^2\,a_0|H_0-u|\sqrt{1+a_0^2}\,du\,d\nu}. \quad (8)$$

B. Modeling of Hybrid Disc-Cone Apertures

A conformal aperture composed of a truncated conical surface for the side and a planar circular surface at the top is shown in Fig. 2. The radius of the top disc area is $r_0 = (H_1/H_0)\cdot R_0$. Combining the analysis of the planar circular aperture in [21] and the far-field radiation (7) of the truncated cone-surfaced aperture, we obtain the far-field radiation of such a hybrid conformal aperture

$$F(\theta,\phi) = 2\pi e^{jk(H')\cos\theta}\cdot\int_0^{r_0} Kc_0(\rho)J_0(k\rho\sin\theta)\rho\,d\rho + 2\pi a_0\sqrt{1+a_0^2}\cdot\int_0^{H'} Kt_0(u)J_0\left(ka_0(H_0-u)\sin\theta\right) \times e^{jku\cos\theta}(H_0-u)\,du \quad (9)$$

where $H' = H_0 - H_1$, $Kc_0(\rho)$ and $Kt_0(u)$ are the current distributions on the top disc aperture and truncated cone-surfaced aperture, respectively. The first part in (9) represents the far-field of the top disc aperture, in which there is a spatial phase shift from the radiation expression in [21]. The second part is the radiation formula of the truncated cone-surfaced aperture. Similarly, when H' decreases to 0, the far-field radiation reduces to the radiation of a circular planar aperture.

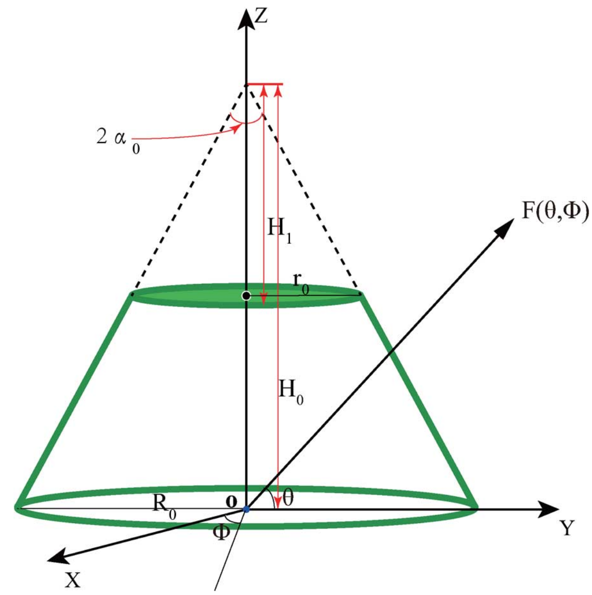

Fig. 2. Modeling of the hybrid disc-cone conformal aperture.

C. Modeling of Hybrid Sphere-Cone Conformal Apertures

A conformal aperture composed of truncated conical surface and a partial sphere-surfaced aperture is depicted in Fig. 3. The radius and the spherical angle of the top sphere-surfaced aperture are R_s and $2\alpha_s$, respectively. Considering the spatial phase shift along the z-axis of the top spherical surface and utilizing the far-field equation of partial spherical apertures derived in [22] and the truncated conical aperture derived above, the far-field radiation of such a hybrid conformal aperture can be expressed as

$$F(\theta,\phi) = 2\pi R_s^2 e^{-jk\Delta R\cos\theta} \cdot\int_0^{\alpha_s} Ks_0(\alpha)J_0(u'\rho)e^{j\nu'\cos\alpha}\sin\alpha\,d\alpha + 2\pi a_0\sqrt{1+a_0^2}\cdot\int_0^{H'} K_0(u)J_0\left(ka_0(H_0-u)\sin\theta\right) \times e^{jku\cos\theta}(H_0-u)\,du \quad (10)$$

where $\Delta R = R_s-(H_0-H_1)$, $r_0 = (H_1/H_0)\cdot R_0 = R_s\sin\alpha_s$, $\rho = R_s\sin\alpha/r_0$, $u' = kr_0\sin\theta$ and $\nu' = kR_s\cos\theta$. $Ks_0(\alpha)$ and $Kt_0(u)$ are the current distributions on the top spherical surface and the truncated conical surface, respectively. Again, when H' decreases to 0, (10) reduces to the radiation of a partial sphere-surfaced aperture discussed in [22].

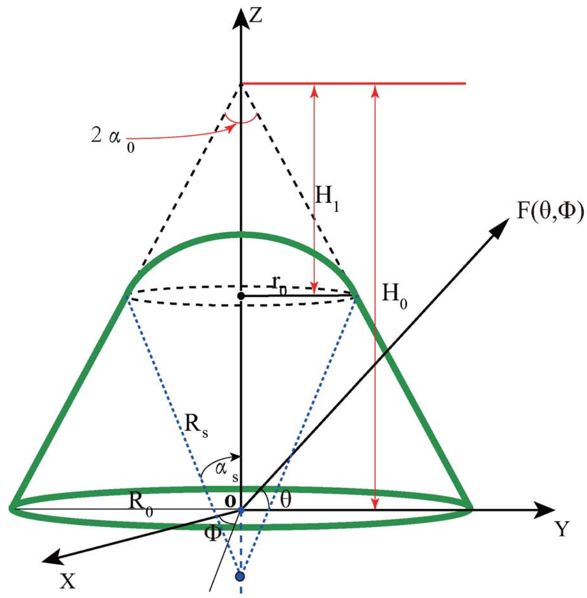

Fig. 3. Modeling of the hybrid sphere-cone conformal aperture.

Therefore, for both hybrid disc-cone and hybrid sphere-cone conformal apertures, given the aperture distribution, the maximum directivity D_0 can be written as

$$D_0 = \frac{4\pi}{\lambda^2} \cdot \frac{\left| \int_{S_1} K_{S_1}\, dS_1 + \int_{S_2} K_{S_2}\, dS_2 \right|^2}{\int\limits_{S_1} |K_{S_1}|^2\, dS_1 + \int_{S_2} |K_{S_2}|^2\, dS_2} \tag{11}$$

where S_1 is the truncated cone-surfaced aperture with an aperture distribution $K_{S_1} = Kt_0(u)$. If the conformal aperture is hybrid disc-cone or sphere-cone, S_2 is disc-surfaced aperture or sphere-surfaced aperture, $K_{S_2} = Kc_0(\rho)$ or $K_{S_2} = Ks_0(\alpha)$, respectively.

Based on the above theoretical analysis of circularly symmetric conformal apertures and the far-field radiations depicted by (7), (9) and (10), we can find that the synthesis of a rotationally symmetric beam is reduced to finding an axisymmetrical current distribution $(Kt_0(u), Kc_0(\rho), Ks_0(\alpha))$, no matter whether it comes from numerical optimizations or given quadrature functions, such as weighted sinc or Bessel functions used in [21] and [22].

III. Numerical Experiments and Results

From the far-field radiation (7), (9) and (10), we see that different from planar apertures whose radiation patterns are fully determined by the aperture distribution, the radiation patterns of the discussed conformal apertures also depend on geometric parameters. This provides additional degrees of freedom for conformal beam forming. Since the sinc or Bessel function based parameter sweeping method for achieving versatile beam shapes has been extensively discussed in [21] and [22], in this paper, we mainly focus on the effects of tuning the geometric parameters to the far-field radiation. In order to reduce the spatial phase shift on the conformal aperture and keep the aperture's low profile, in the following examples, all the cone-surfaced apertures are described by $2\alpha_0 = 150$ degrees. Given parameters α_0, R_0, H_1, α_s, other parameters, $H_0 = R_0/\tan\alpha_0$, $r_0 = (H_1/H_0)\cdot R_0$, $R_s = r_0/\sin\alpha_s$, can be easily obtained by mathematical transformation.

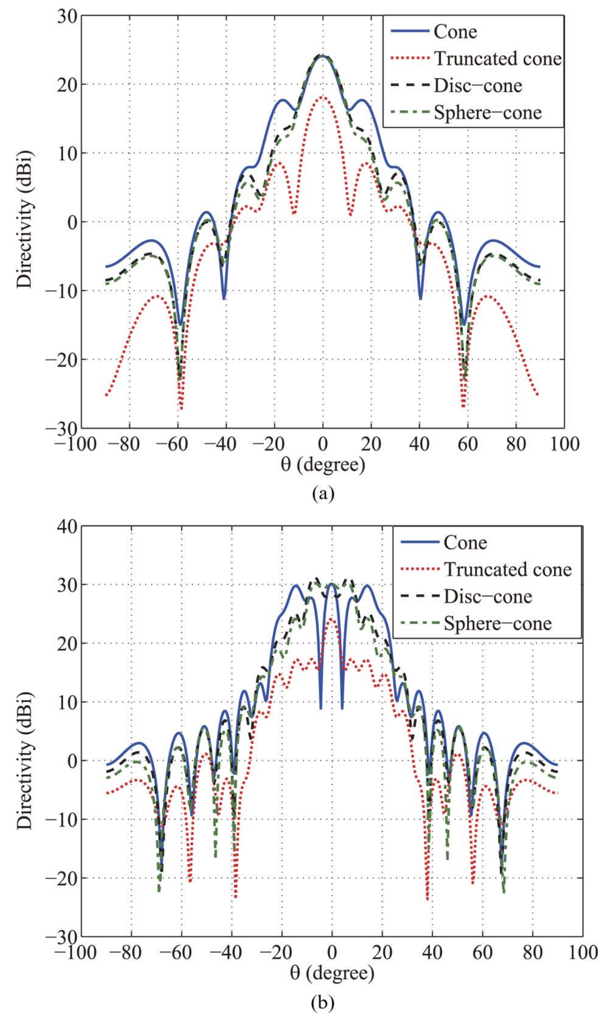

Fig. 4. Far-field pattern of the various circularly symmetric conformal apertures with uniform distribution (a) $R_0 = 2.5\lambda$. (b) $R_0 = 5\lambda$.

In the first illustration, the truncated height is assumed to be $H_1 = 0.5H_0$, the spherical angle is $\alpha_s = 5$ degrees. When the current distribution is uniform ($Kt_0(u) \equiv 1$, $Kc_0(\rho) \equiv 1$, $Ks_0(\alpha) \equiv 1$), the far-field pattern of the discussed circularly symmetric conformal apertures with different radius R_0 for the bottom circle can be directly calculated by (7), (9) and (10), as shown in Fig. 4. We see that, when $R_0 = 2.5\lambda$ (Fig. 4(a)), all the conformal apertures can generate pencil beams; however, the side lobe of the pattern generated by cone-surfaced aperture (blue curve) is much higher than other conformal apertures. This result indicates that the larger the spatial phase shift on the conformal aperture, the higher the side lobe will be. Besides, the directivity of the truncated conical aperture is the lowest since the size of the projected aperture on the bottom is the smallest than the others. When the conformal apertures are larger and $R_0 = 5\lambda$ (Fig. 4(b)), grating lobes in the pattern of the cone-surfaced aperture (blue curve) appear. After truncating the top of

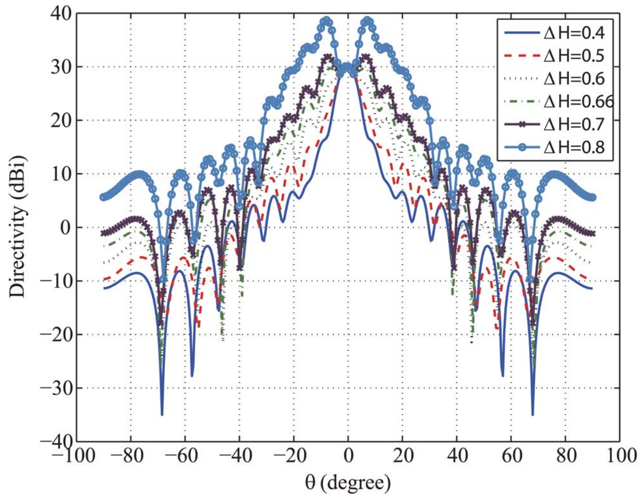

Fig. 5. Far-field pattern of various sphere-cone apertures with uniform distribution when $\alpha_s = 5$.

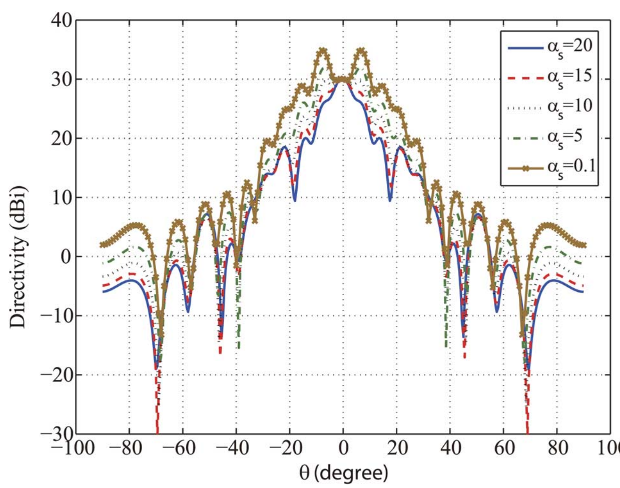

Fig. 6. Far-field pattern of various sphere-cone apertures with uniform distribution when $\Delta H = 0.7\lambda$.

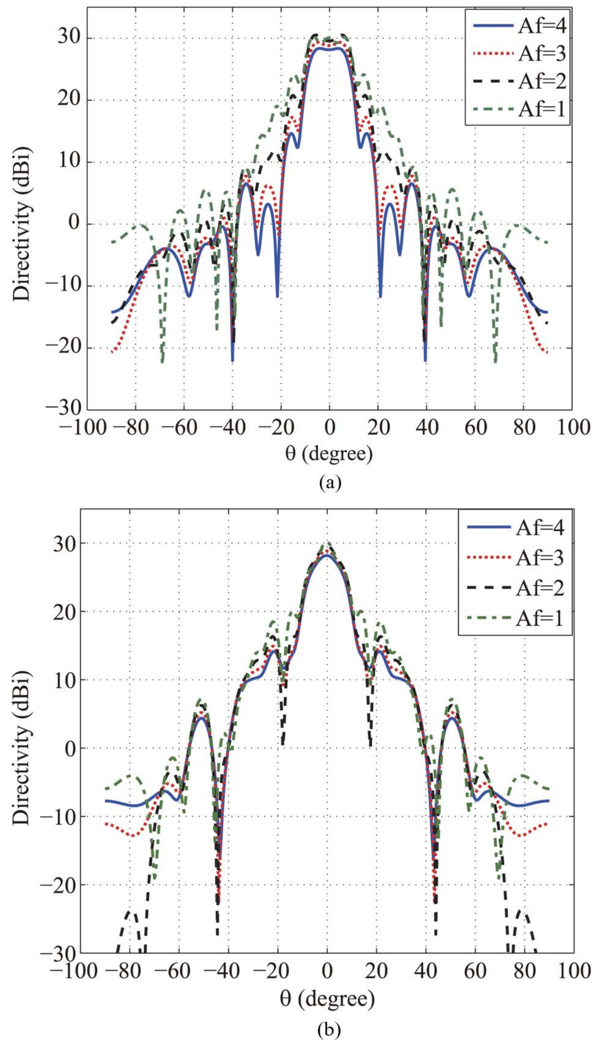

Fig. 7. Far-field pattern of the sphere-cone aperture for aperture distributions with different Af when (a) $\alpha_s = 5$. (b) $\alpha_s = 20$.

the cone, we observe that the beams generated by other conformal apertures do not have notable grating lobes, and the patterns shaped by both the disc-cone aperture and the sphere-cone aperture (dashed black and green curves) look like flat-topped beams, although with some deformations. The biggest difference between Fig. 4(a) and Fig. 4(b) is the spatial phase shift distributed on the conformal aperture. Although the temporal excitations on the conformal surfaces are uniform, when R_0 is increased, the spatial phase shift on the conformal aperture becomes larger, resulting in the discrepancy between the patterns generated by various R_0 values.

In practical applications, the size of the bottom circle of the discussed conformal apertures is normally fixed. In the following, we discuss the beam forming of circularly symmetric conformal apertures with a specific bottom circle. In all examples, the radius of the bottom circle is assumed to be $R_0 = 5\lambda$. The aperture distributions are again assumed to be uniform. Under the above assumption, we observe the radiation patterns while tuning the geometric parameters of the conformal apertures in the original model of sphere-cone conformal aperture.

Fig. 5 shows the various patterns generated by sphere-cone surfaced aperture with different heights of the truncated cone ΔH, when the spherical angle of the partial spherical surface is $\alpha_s = 5$ degrees. We see that when ΔH is increased from 0.4λ to 0.8λ, various shaped beams like pencil, flat-topped and bimodal beams can be formed. When $\Delta H = 0.7\lambda$ and the sphere-cone aperture is excited with a uniform distribution, the far-field patterns with different α_s are shown in Fig. 6. It is seen that when α_s is swept from 0.1 to 20, we can also obtain differently shaped beams. Note that when α_s approaches zero, the aperture turns into a disc-cone aperture.

To demonstrate the degree of freedom of tuning the excitation, we further tune the radiation patterns by slightly adjusting the aperture distribution with different $Af(Af = Ks_0/Kt_0)$ ratios. Fig. 7(a) and (b) plot the patterns generated by different aperture distributions when Af varies with $\alpha_s = 5$ and $\alpha_s = 20$, respectively. It is seen that when Af is swept from 1 to 4, the shaped beams can be further optimized, such as the directivity, beam width, side lobe and the depth of the notch in the bimodal beams.

The above demonstrations show that the mathematically derived, deterministic equations can be effectively used in rapid beam forming for multiple conformal apertures. The different shaped beams can be easily optimized by either adjusting the geometric parameters of the surfaces or jointly tuning the aperture distribution. Compared with conventional optimization-based approaches that mainly focus on the optimization of aperture distribution, which are very time-consuming for large conformal arrays, our approach can be very fast, and can provide more degrees of freedom for the conformal aperture synthesis. With the derived closed form equations, iterative parameter sweeps can be simply used to quickly determine the geometry and the current distribution of a continuous circularly symmetric conformal aperture for a given beam shape. The computing time is independent of the aperture size, and the parameter sweeping can be normally finished in a few seconds.

As indicated in [21], our method can also be cooperatively used with optimization-based approach, providing initial values close to the final result and significantly decreasing the computation time. After continuous distribution is obtained, standard discretization approach can be used in the physical implementation of the real conformal array antennas with properly designed unit radiators. Detailed information and examples of such discretisation approaches can be found in [21] and [27].

IV. Conclusion

In conclusion, we presented in this paper an analytical beam-forming approach capable of synthesizing differently shaped beams for circularly symmetric conformal apertures with axisymmetrical excitations. Closed form formulas of far-field radiation are mathematically derived in order to obtain rotationally symmetric radiation patterns for typical conformal apertures, such as the cone-surfaced, truncated cone-surfaced, hybrid disc-cone and sphere-cone apertures. Based on these formulas, various shaped beams, including pencil, flat-topped and bimodal beams can be easily achieved by adjusting either the geometric parameters or the excitation distributions. The deterministic approach proposed in this paper provides an efficient method to rapidly synthesize specified beam shapes for the aforementioned conformal apertures. Collaborating with conventional optimization based beam forming approaches, the proposed approach can effectively shorten the time-consuming optimization in the beam forming of circularly symmetric conformal arrays, especially large conformal arrays. Our approach can be used in a wide range of applications in synthesizing conformal apertures in satellite and flight vehicle applications.

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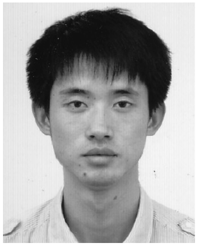

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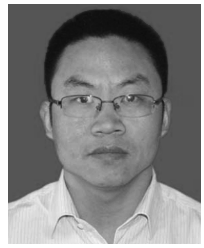

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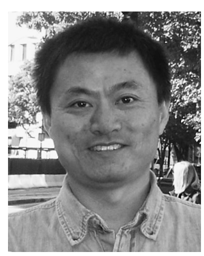

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