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Coupled structural-electromagnetic modeling and analysis of hexagonal active phased array antennas with random errors

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ABSTRACT

The structural and electromagnetic performances of planar hexagonal active phased array antenna (APAA) are degraded because of the position errors of radiating elements caused by manufacturing processing, assembly and environment loads. It seriously restricts the realization of high performances of phased array antenna. By considering the changeable mutual coupling parameters and introducing the structural distortion factor into the antenna pattern function, the coupled structural-electromagnetic model of planar hexagonal array antennas was developed. The quantitative relationship between the structural error and the electromagnetic performances of antenna was discussed with consideration of the mutual coupling. The influence of the plane assembling accuracy and flatness on antenna performance was analyzed with the change in the number of array elements. The presented valuable simulation results could be used in antenna engineering to provide guidance for the antenna designers to set the optimal performance-driven tolerance in manufacturing antenna.

1. Introduction

Active phased array antenna (APAA) with multi-function, high reliability, good stealth performance, high detection and tracking capability, has been widely applied in various radar systems [1–4]. Because the different radar systems have different carrier and operating environment, the corresponding phased array antennas have many kinds of the aperture shape. For example, the planar hexagonal APAA is widely used in shipborne surveillance radar. With the development of world military technology, the requirements for tactical and technical indexes of phased array radar system are increasingly strict. The antenna gain, sidelobe level, beam pointing accuracy, etc. are closely linked with radar performance parameters. To an extent, these antenna performances determine the phased array radar ability. In addition, the random error generated in manufacturing and assembly can make the position displacement of radiating elements and degrade the antenna performances, such as the gain loss, sidelobe level upgrade, inaccurate beam pointing, etc. [5–8]. Moreover, the structural error can lead to the change in mutual coupling effects, and then disturb the desired implementation of high antenna performances [9]. The structural errors also seriously restrict the realization of high performances of phased array antenna, for example the high gain, ultra-low sidelobe and so on. Meanwhile, the influence becomes more serious at higher operation frequency. Therefore, it is necessary to explore deeply the coupling relationship between the phased array antenna structure and electromagnetic factors [10–13].

There are many references available which focus on the effects of structural errors [14–19] on the antenna performance (see Table 1). (1) In random error analysis, errors on the amplitude and phase values of the excitations have been taken into account by means of probability statistical techniques [14,15]. It was assumed that the random error was subject to the standard normal distribution, and the approximate relationship between the variance of random error and single electrical parameters such as gain [15], sidelobe level [14,15] was deduced by using the probability statistical method. However, the derivation of the formula is often very complex, and unable to consider the mutual coupling. Besides, for the structural design of PAA, probability statistical methods did not subdivide array elements' random position errors into installation accuracy and flatness to carry on comparative analysis. In contrast to previous work, an electromechanical coupling method which established a direct relationship between structural error and electromagnetic performance of planar hexagonal array antennas had been proposed [16]. The random errors are subdivided into the array flatness and the installation accuracy, and investigated

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Table 1
Advantages of electromechanical coupling method in comparison with the previous works.

	Probability statistical method	Electromechanical coupling method
Random errors	(1) Deduce approximate formula of single electrical parameters with random errors (2) Deducing process complex (3) Random errors equivalent to amplitude and phase errors of the excitations	(1) Establish direct relationship between structural errors and antenna performances (2) Deducing process relatively simple (3) Random errors subdivide into installation accuracy and flatness
Classical Ref.	[14,15]	[16]
Distortion	(1) The structural distortion is regarded as a fixed one (2) Unable to analyze the practical distortion which made by structural finite element analysis	(1) Can analyze the fixed structural distortion (2) Can also analyze the practical distortion which made by structural finite element analysis
Classical Ref.	[17]	[18]
Random errors and distortion	Unanalyzable	Analyzable
Mutual coupling	Unanalyzable	Analyzable

their impact on the electromagnetic performance of APAA. Some significance results with good application value for antennas in practice were achieved. But it did not consider the effect of random errors on antenna with different array plane size and radiated element number. (2) In structural distortion analysis, it is generally regarded array plane distortion as a fixed or initial one. Ref. [17] discussed the effect of four array plane deformations including the sag, potato chip, sinusoidal and Bessel character on the performances of large S-Band PAA based on the probability statistical method. Actually this method cannot analysis the practical distortion which made by the structural finite element analysis. Conversely, the electromechanical coupling method establish direct relationship of electrical performances and structural errors, it can analysis both the fixed distortion and practical distortion. Ref. [18] studied the effect of the bend shape distortion and bowl shape distortion on the performance of PAA by using electromechanical coupling method. Besides, when antenna has varied plane size and different radiated elements, the specific influence of structural errors on antenna performances has been not presented in Ref. [14–18]. (3) Researchers have studied the effect of mutual coupling on ideal APAA [19], but when the radiating elements of APAA exist position errors, the electromagnetic performance analysis generally ignore mutual coupling effect or take the mutual coupling values of ideal radiating elements position instead. Hence, the impact analysis of structural error on antenna performance is inaccurate.

Therefore, according to the structural characteristics of the planar hexagonal APAA, the coupling problem between structural error and electromagnetic performance is studied. By introducing the mutual coupling parameter, a novel coupled structural-electromagnetic model was developed taking into account the change of mutual coupling effect. With the application of the developed coupling model, the influence of structural error on the antenna performance considering the mutual coupling effect were analyzed, and the specific formula between random error and gain loss was given. In addition, the effect of flatness and installation accuracy were discussed on performance of antenna with the uniformly distributed excitation current and low sidelobe level weighted excitation respectively. The simulated results and

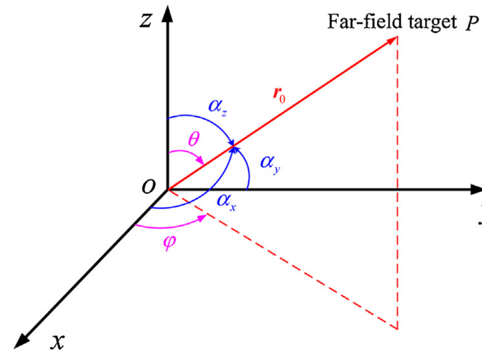

Fig. 1. Space geometrical relationship of far-field target.

research method could provide corresponding theoretical guidance for the structural design and the reasonable tolerance allocation of APAA.

2. Coupled structural-electromagnetic modeling

It is assumed that the direction of the far-field target relative to the coordinate system $O-xyz$ is (θ, φ), whose direction cosine is $(\cos\alpha_x, \cos\alpha_y, \cos\alpha_z)$. According to the space geometry relationship illustrated in Fig. 1, the calculation formula for the angle of the far-field target relative to the coordinate axis and the direction cosine is given as follows.

$$\begin{cases} \cos\alpha_x = \sin\theta\cos\varphi \\ \cos\alpha_y = \sin\theta\sin\varphi \\ \cos\alpha_z = \cos\theta \end{cases} \tag{1}$$

It is known that the small structural distortion error of array antennas only influences the phase of the electrical field of radiated element without the change of the amplitude. Therefore, the position deviation of array radiated elements can be introduced to the antenna pattern function as the additional phase factor.

It is supposed that a planar hexagonal APAA locates in the $O-xy$ plane plotted in Fig. 2. The symmetrical dipole antenna is adopted as the radiated element and the hexagonal array has M oblique columns and N rows. In Fig. 2, the horizontal interval of the array radiated element is d_x; the longitudinal interval of the radiated element is d_y; the base angle is β. The coordinate system and element serial number are also shown in Fig. 2. Where $m = 0, \pm 1, \pm 2,$

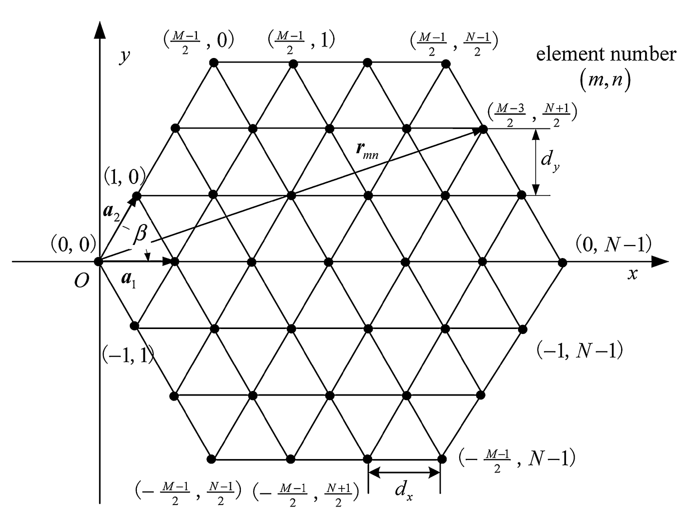

Fig. 2. The element configuration of planar hexagonal APAA.