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Phase Compensation Method for Active Phased Array Antennas in Operating Environment based on Electromechanical Coupling Model

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Abstract

Complex operating environmental loads lead to structure deformation of active phased array antennas (APAA), which could finally seriously degrade the electromagnetic performance of antennas. Based on the electromechanical coupling model of APAA, the phase compensation method is applied to recover the electromagnetic performance of the deformed antenna to the ideal performance as much as possible, where the excitation phase adjustment quantity of element is derived, and the application range of the method is discussed. Finally, the effectiveness of the method is verified by experiments on an APAA with 24×32 elements to compensate the effect of typical deformation in the operating environment. The work can provide theoretical basis to guarantee the electromagnetic performance of APAAs in real time.

1 Introduction

Active Phased Array Antennas have many advantages, including flexible beam, fast response, multi-function, strong anti-jamming, detection and tracking ability, and good stealth performance, which have been widely applied in the areas of ground defense, airborne fire control, missile-borne guidance and satellite communication [1-3]. With the development of science and technology, APAAs are required for more accurate target detection, tracking and recognition capabilities, and stronger detection and interference, which put forward more stringent requirements for the electromagnetic performance of APAAs [4-5]. However, APAAs work on various radar carrier platforms, where the complex environmental loads, including wind load, solar radiation, high thermal power consumption, random vibration and thermal environment, could cause structural deformation, which will seriously degrade the electromagnetic performance of APAAs [6-7], as shown in Figure 1. Moreover, array antennas tend to high performance, high frequency and high integration, the structural parameters and the electromagnetic performance are more closely coupled, which could seriously restrict the realization of high-performance APAAs.

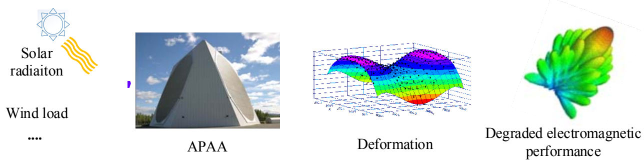


Figure 1. APAA with effect of operating environment

At present, two ways, structural compensation and electronic compensation, can be used for electromagnetic performance control. In terms of structural compensation, the actuator or adjustment mechanism is commonly used to control the structural flatness of the antenna array [8]. This method can actively compensate the influence of structural errors, but the precondition is that the antenna system can be able to install structural adjustment devices. In addition, by controlling the structure parameters of the active devices, the antenna performance can be controlled. Son changed the excitation phase by adjusting the length of cable of the phase shifter to eliminate the pointing error for a stair-planar phased array [9]. This method can be used to test and calibrate the antennas in the manufacturing stage, but not feasible in service stage. Besides, the application of new materials to automatic compensate the antenna performance. Song embedded shape memory alloy wires in the honeycomb structure to compensate for the effect of thermal deformation [10]. To sum up, structural compensation can control the antenna deformation actively, but the complexity of the antenna system will be increased. Therefore, how to compensate the electromagnetic performance without changing the structure is a key problem. Electronic compensation can be used by adjusting the excitation current of element to control the electromagnetic performance of array antennas. Schippers monitored phase differences between elements by installing an analog integrated circuit for each element, so as to adjust the radiation performance [11], but it can only compensate the internal phase difference of elements. An optimization of the phase through genetic algorithm to maximize the gain of the antenna had also been used [12], which requires much time to determine the phase because of optimization process. Takano used phase compensation to adjust the direction of the beam to be the target one for a multiple folding phased array [13] without structural distortion. It can been seen that there have works show that the phase adjustment is valid for the performance compensation [14], but it is still necessary to study how to quickly get the excitation phase adjustment quantity to compensate the performance of deformed antenna.

Therefore, based on electromechanical coupling model of APAA, the excitation phase adjustment is derived and the application range is discussed. Finally, the method is illustrated on an X-band APAA platform under the typical deformation in the service environment, which can provide theory basis to guarantee the performance of APAAs in service.

2 Excitation Phase Compensation based on Electromechanical Coupling Model of APAA

As shown in Figure 2, an APAA arranged arbitrarily in the *oxy* plane with *N* elements. During the service process, the environmental loads could lead to the deformation of the array surface and make the position offset of element. Suppose that the position offset of element n relative to the element 0 is $\Delta \boldsymbol{r}_n(\boldsymbol{\delta}) = \Delta x_n \boldsymbol{i} + \Delta y_n \boldsymbol{j} + \Delta z_n \boldsymbol{k}$, and that the mutual coupling is ignored, the electromechanical coupling model of APAA is as below by analyzing the spatial phase distribution error of the interface field [15].

$$E_s(\theta,\phi) = \sum_{n=0}^{N-1} f_n(\theta,\phi) I_n \exp(j\varphi_n) \exp\left\{jk\left[\boldsymbol{r}_n + \Delta\boldsymbol{r}_n(\boldsymbol{\delta})\right]\cdot \boldsymbol{r}_0\right\} \quad (1)$$

where $f_n(\theta,\phi)$ is element pattern of element n ($n \le N$); $k = 2\pi/\lambda$ is the propagation constant, and λ is the wavelength; $\boldsymbol{r}_n = x_n\boldsymbol{i} + y_n\boldsymbol{j} + z_n\boldsymbol{k}$ is the initial position vector, where x_n, y_n and z_n are the position coordinates along *x, y* and *z* coordinate axes, respectively; $\boldsymbol{r}_0$ is the unit vector towards the direction of far observation point; I_n and φ_n are the initial excitation amplitude and phase, respectively; $\boldsymbol{\delta}$ is position error of element.

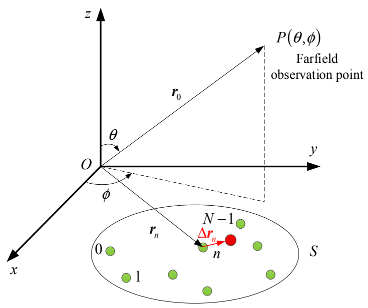


Figure 2. Array antenna elements in arbitrary distributed.

To compensate the performance of distorted APAA, the change of spatial phase distribution can be compensated by adjusting the excitation phase. Suppose the excitation phase is set as $\varphi_c = \varphi_n + \Delta\varphi_n$, where $\Delta\varphi_n$ is the phase adjustment. The compensated performance of APAA is

$$E_c(\theta,\phi) = \sum_{n=0}^{N-1} f_n(\theta,\phi) I_n \exp(j\varphi_n) \exp\{jk\boldsymbol{r}_n\cdot\boldsymbol{r}_0 + j\left[k\Delta\boldsymbol{r}_n(\boldsymbol{\delta})\cdot\boldsymbol{r}_0 + \Delta\varphi_n\right]\} \quad (2)$$

It is necessary to minimum the difference between the compensated and the ideal performance, that is

$$\min \left|E_c(\theta,\phi) - E_0(\theta,\phi)\right| \quad (3)$$

where $E_0(\theta,\phi) = \sum_{n=0}^{N-1} f_n(\theta,\phi) I_n \exp(j\varphi_n)\exp(jk\boldsymbol{r}_n\cdot\boldsymbol{r}_0)$ is the ideal electromagnetic performance.

The following equation can be derived from (3) as

$$\min \left|k\Delta\boldsymbol{r}_n(\boldsymbol{\delta})\cdot\boldsymbol{r}_0 + \Delta\varphi_n\right| \quad (4)$$

Since that the spatial phase error $k\Delta\boldsymbol{r}_n(\boldsymbol{\delta})\cdot\boldsymbol{r}_0$ is varying corresponding to the different beam directions, and that the needed phase adjustment should be the definite value, a beam direction should be specified, which is supposed as (θ_s,ϕ_s), the phase adjustment can be derived from (4) as below. In addition, for the accuracy of the main beam direction determines the accuracy of the target detection, (θ_s,ϕ_s) is usually selected as the main beam direction.

$$\Delta\varphi_n = -k\Delta\boldsymbol{r}_n(\boldsymbol{\delta})\cdot\boldsymbol{r}_{0s} \quad (5)$$

where $\boldsymbol{r}_{0s}=\sin\theta_s\cos\phi_s\boldsymbol{i} + \sin\theta_s\sin\phi_s\boldsymbol{j} + \cos\theta_s\boldsymbol{k}$ is the unit vector toward the specified direction (θ_s,ϕ_s).

3 Discussion on Application Range of Method

The range of antenna structural deformation that can be compensated is discussed. Take a linear APAA with N elements and interval of d as an example, the structural deformation is analyzed according to the uncompensated electromagnetic performance of the deformed antenna [7]. For the array form and feed distribution are related to array factor, when normal structure error δ_{zn} is caused by environment, the performance of the deformed antenna is

$$f_a(\theta,\phi) = \sum_{n=1}^{N} \mathbf{I}_n e^{jknd\sin\theta} e^{jk\delta_{zn}\cos\theta} \quad (6)$$

where $\mathbf{I}_n = I_n e^{j\varphi_n}$ is the initial excitation current vector.

Assuming that the performance in the beam direction θ_0 is compensated, the un-compensated performance is

$$f_{au}(\theta,\phi) = \sum_{n=1}^{N} \mathbf{I}_n e^{jknd\sin\theta} e^{jk\delta_{zn}(\cos\theta - \cos\theta_0)} \quad (7)$$

The above equation (7) can be approximately written as

$$f_{au}(\theta,\phi)=\sum_{n=1}^{N}\mathbf{I}_n e^{jknd\sin\theta}\left[1+jk\delta_{zn}\left(\cos\theta-\cos\theta_0\right)\right] \quad (8)$$

Assume position error of element is $\boldsymbol{\delta}=\left[\delta_{z1},\delta_{z2},\cdots,\delta_{zN}\right]^{\mathrm{T}}$, when electromagnetic performance error is specified as $E_{R_m}\le\zeta$, the antenna structural deformation that can be compensated can be derived as

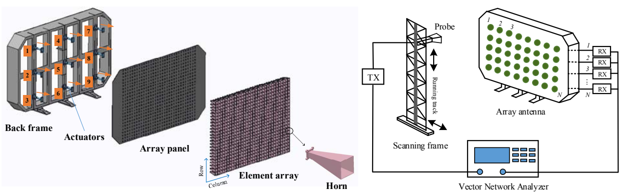
$$\boldsymbol{\delta}\le\left(\mathbf{E}_o^T\mathbf{E}_o\right)^{-1}\mathbf{E}_o^T\left[\frac{\zeta-f_a(\theta,\phi)}{jk\left(\cos\theta-\cos\theta_0\right)}\right] \quad (9)$$

where $\mathbf{E}_o=\left[\mathbf{I}_1 e^{jkd\sin\theta},\mathbf{I}_2 e^{jk2d\sin\theta},\cdots,\mathbf{I}_N e^{jkNd\sin\theta}\right]$ is the ideal far-field distribution for each antenna element.

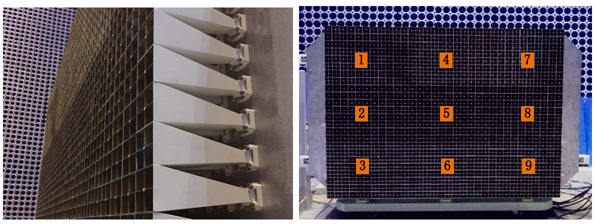
Take a linear array with 8 elements and interval of $\lambda/2$, and the initial excitation is in equal amplitude and phase, when the electromagnetic performance error is required to within 15%, the application range of phase compensation method is $\lambda/4$ for the typical cantilever deformation, and is $\lambda/2$ for the typical symmetrical deformation.

4 Experimental Verification

As shown in Figure 3, an X-band APAA with 24×32 elements is illustrated, which mainly includes the back frame, actuators, array panel and element array. Horn antenna is arranged in a square grid with interval 0.65λ. The array panel is connected with the back frame by nine actuators, which are controlled independently and used to simulate structural deformations in operating environment with maximum tensility of 32mm. The T/R modules are installed in the back frame and connected with the horn antennas to provide the excitation phase and amplitude for each element by phase shifter and attenuator, respectively. The initial excitation current provided is Taylor's weighted distribution in amplitude and equal in phase.



a. APAA composition b. Electrical performance test



c. Adjustment actuator d. APAA platform

Figure 3. Architecture of APAA platform.

Comprehensive considering the effect of environment load, a typical structural deformation as shown in Figure 4 is taken to verify the compensation method, where the adjustments of the nine actuators are 8mm, 8mm, 8mm, 3mm, 0mm, 3mm, 15.5mm, 16mm, 16mm, respectively.

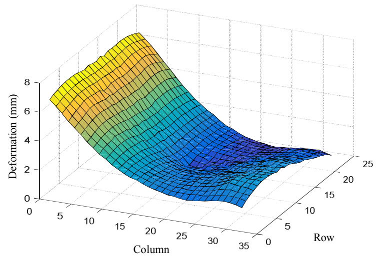


Figure 4. Deformation shape of the antenna.

First, the corresponding phase adjustment of antenna elements in (5) is calculated, as shown in Figure 5.

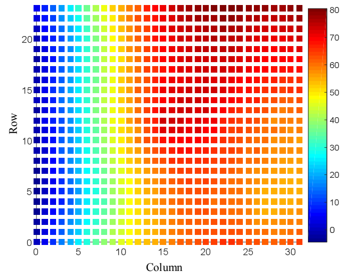
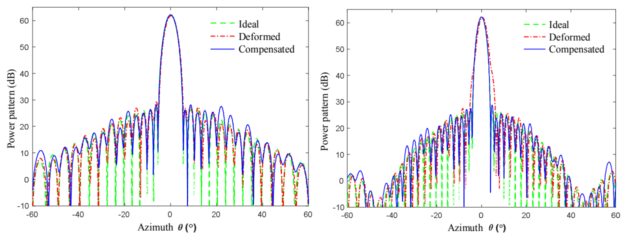


Figure 5. Excitation phase adjustment of elements.

The electromagnetic performance before and after compensation is tested respectively, as shown in Figure 6, and the corresponding parameters are shown in Table 1.



a. ϕ=0° plane b. ϕ=90° plane

Figure 6. Performance before and after compensation.

Table 1. Comparison of electronic parameters

Peformance	Gain loss/ dB	Maximum sidelobe level/dB		Boresight error/°		3dB beam width/°	
		ϕ=0° plane	ϕ=90° plane	ϕ=0° plane	ϕ=90° plane	ϕ=0° plane	ϕ=90° plane
Ideal	0	-35.37	-35.35	0	0	3.95	2.96
Deformed	0.37	-31.65	-32.03	0.11	0.21	3.98	3.12
Compensated	0	-33.64	-33.97	0	0	3.95	2.96

It can be seen from Figure 6 and Table 1 that under the structural deformation, the electromagnetic performance is degraded, that the gain decreases, the sidelobe level rises, the beam direction shifts, and the 3dB beam width expands. After compensation, the effect is as follows.

(1) For the main lobe region, the phase compensation can significantly compensation of the main lobe region.
(2) The phase compensation can reduce the rise of the maximum sidelobe level. But for the far sidelobe areas, the method has limited compensation ability.
(3) The boresight error and broaden of 3dB beam width in both planes can be effectively recovered as initial values.

In terms of the time, on the computer configured as core (TM) i7-6700 CPU 3.40GHz and 8G ram, the calculation time of the phase compensation method is 14ms, which can provide theoretical basics for real-time compensation.

5 Conclusion

Due to the fact that the electromagnetic performance of APAA could be seriously degraded by the operating environmental loads, the excitation phase compensation method is adopted based on electromechanical coupling and its application range is discussed. The compensation method is verified on an APAA with 24×32 elements for the effect of typical deformation in operating environment. The results show that the method can quickly calculate the phase adjustment quantity and effectively compensate the electromagnetic performance, especially for the gain-loss and boresight error. It could provide theoretical basis for the reliable service guarantee of APAAs under structural deformation. The compensation for the far side lobe area is a problem to be solved in the follow-up work.

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