Accurate Calculation of Antenna Radiation of Elastic-borne Phased Array Radar based on Mutual Coupling

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Abstract. In order to solve the current difficulty of radiation calculation of current missile phased array radar arrays, the elemental radiation pattern of small arrays is used to calculate the unit radiation field in a similar environment in large arrays by the element active pattern equivalent method, and then the superposition theorem is used. Calculating the total radiation field of the large array avoids matrix operations in the calculation process and reduces the amount of calculation. And the linear array is extended to the missile-mounted phased array radar antenna array. The radiation pattern of a certain type of missile-loaded phased array radar antenna array considering mutual coupling is calculated. The obtained radiation pattern is in good agreement with the far field test results. The comparison with the far field experiment shows the effectiveness of the method.

Keywords: Missile phased array, Subarray, Mutual coupling, Active Element Pattern, Equivalent.

1. Introduction
The further development of precision guidance technology puts forward a series of requirements for the function of the seeker. The mechanical scanning antenna of the traditional radar can not meet these requirements, and the phased array seeker radar with many advantages becomes the precision guidance technology [1, 2]. Development direction, so how to improve the precision guidance performance of missiles by using phased array technology has become a topic of concern at home and abroad [3, 4]. Since mutual coupling has a great influence on the performance of the missile-loaded phased array antenna, it will reduce the missile guidance accuracy. Therefore, the mutual coupling effect must be considered when developing the missile-mounted phased array antenna.

The traditional direction pattern product method does not consider the mutual coupling when calculating the radiation pattern of the antenna [5], and the obtained pattern has a large difference with the true direction pattern [6].

In the case of considering mutual coupling, the integration of the radiation pattern of the missile-borne phased array radar antenna is an important issue and a major problem in the field of antennas. Usually, the moment method based on the integral equation method, the finite difference time domain method based on the differential equation method [7], and the finite element method are used. However,
the size of the missile-mounted phased array radar antenna array is too large, which is limited by the current computer memory resources. It takes a lot of time or even no calculation to use the above method. In recent years, subarray methods [8, 9] have been widely used in the analysis and synthesis of large arrays. This method can balance the calculation accuracy with the calculation speed. In this paper, based on the missile-loaded phased array radar antenna array, (active element pattern-AEP) equivalent method is proposed. The AEP of the corresponding array in a small array is used to equivalent the AEP of each unit in the large array. Finally, the superposition theorem is used to calculate its total radiation field. In this way, the complex operation of the matrix in the calculation process is avoided, and the line array method is extended to the area array. The calculation method of the radiation pattern of the missile phased array radar antenna is established. The simulation and far field experiments show that the calculation result of this method is good. The classical direction product method is consistent with the actual antenna array pattern, which shows the effectiveness of the method.

2. Classical Pattern Product Method

![Fig.1 Simple line array simple diagram](image)

Fig.1 is a schematic diagram of a linear array composed of \( N \) array elements, which are equally spaced along the \( X \) direction in the figure, with a cell spacing of \( d \), an excitation current of each antenna element being \( I_n \), and an electric field generated by the Nth unit in the far region is \( E_i \).

Array total field strength at the remote observation point:

\[
E = \sum_{n=0}^{N-1} E_n = \sum_{n=0}^{N-1} K_n I_n f_n(\theta, \varphi) e^{-\frac{2\pi r_n}{\lambda}}
\]

(1)

Further simplification

\[
E = E_e(\theta, \varphi) \sum_{n=0}^{N-1} I_n e^{\frac{2\pi d}{\lambda} \cos \theta \sin \varphi}
\]

(2)

\( E \) is the radiation field of a single antenna element in an isolated environment; \( I_n \) is the excitation current; \( d \) is the spacing of the elements.

3. AEP Equivalent Method

3.1. AEP line array equivalent

In order to fully consider the mutual coupling effect between cells, the array radiation field should be equal to the radiation field superposition of each cell in the array [10].
$$E(\theta, \varphi) = \sum_{n=0}^{N-1} I_n E_n(\theta, \varphi)$$

(3)

En is the AEP of the nth unit, that is, the array radiation field is fed only to the nth antenna unit with a unit amplitude source, and all other units are connected to the matched load.

Literature [8, 11] studies have shown that when the number of array elements is increased to a certain extent, the elements of the middle part of the array are approximately the same. Therefore, the cells in the array can be divided into a left unit, a right unit, and a central unit. The large line array can be equivalent to a small line array, and a large line array left and right can be used. The small line array left and right are equivalent, so that a small line array is equivalent to the array unit at the corresponding position of the large line array.

Assuming that the small line array unit is N in the figure 1 (N is an even number), and the large line array unit is M, and the N-element small array equivalent M-element array process is:

1. All intermediate units AEP of the M-ary large line array are equivalent to the intermediate unit AEP of the N-ary small line array, that is $E_{\text{central}}(\theta, \varphi)$.

2. The left AEP and right AEP field contributions of the M-shaped large linear array are equivalent to the field strengths $E_{\text{left}}(\theta, \varphi), E_{\text{right}}(\theta, \varphi)$ of the corresponding positions of the N-ary small linear array, respectively.

3. After obtaining each unit AEP of the M-element array, the total radiation field can be expressed as a superposition of each unit.

The flow diagram is shown in Figure 2:

Fig. 2 N-element small line array equivalent M-element large line array chart

Then the total radiation field of the small line array can be derived as:
The total radiation field of a large linear array is derived from (4):

\[
E_M(\theta, \varphi) = \sum_{n=0}^{N-1} E_{M,n}(\theta, \varphi) = E_{\text{left}}(\theta, \varphi) + E_{\text{central}}(\theta, \varphi) + E_{\text{right}}(\theta, \varphi) \quad (4)
\]

\[
\sum_{n=0}^{N-2} E_{N,n}(\theta, \varphi) + E_{M,\frac{N}{2}}(\theta, \varphi) + \sum_{n=\frac{N}{2}+1}^{N-1} E_{N,n}(\theta, \varphi)
\]

The total radiation field of a large linear array is derived from (4):

\[
E_M(\theta, \varphi) = \sum_{n=0}^{N-1} E_{M,n}(\theta, \varphi) = E_{\text{left}}(\theta, \varphi) + E_{\text{central}}(\theta, \varphi) \sum_{n=1}^{M-N+1} e^{j \frac{2\pi}{\lambda} (\frac{M-N}{2} + 1)(n-1) \cos \theta \sin \varphi} + E_{\text{right}}(\theta, \varphi) e^{j \frac{2\pi}{\lambda} (M-N) \cos \theta \sin \varphi} \quad (5)
\]

3.2. AEP equivalent method of missile-borne radar array

A type of missile-mounted phased array antenna is shown in Figure 3. It is octagonal and has 480 antenna elements.

![Fig.3 Schematic diagram of the missile phased array](image)

The study found that the increase in the number of rows or columns only increases the main lobe gain of the planar array and does not significantly change or the shape of the radiation pattern in the plane. Therefore, it is proposed to use the N-element small linear array AEP to D equivalent K×L rectangular planar phased array AEP, so as to obtain the missile-loaded phased array radiation pattern considering mutual coupling.

A type of missile-mounted phased array antenna is an octagonal shape, which can be regarded as a rectangular planar array, and defines a unit position matrix \( P_{k \times L}(k, l) \). If the unit exists, it is 1, otherwise 0.

Let the abscissa X be the row, the ordinate Y be the column, the number of cells in each row and each column is greater than N, the coordinate system definition is the same as in Fig. 1, and the specific steps of the line array extended to the missile phased array antenna array are as follows:
(1) N-ary linear array equivalents are respectively equivalent to the $K_{\text{max}}$ line (the line with the largest number of units in all rows) $l_{\text{max}} (l_{\text{max}} > N)$ units and $L_{\text{max}}$ columns (one column with the largest number of units in all columns) $k_{\text{max}} (k_{\text{max}} > N)$ units.

(2) Calculate the $\varphi = 0^\circ$ plane radiation field: radiate the field with the $L_{\text{max}}$ column unit equivalent to the radiation field of all the other units of the same row position.

(3) Calculate the $\varphi = 90^\circ$ plane radiation field: use the unit $K_{\text{max}}$ line unit radiation field to equate the radiation field of the unit with the same column position of all the remaining lines.

(4) Using the superposition theorem, the far-field radiation field is calculated from equation (6).

$$E(\theta, \varphi) = \sum_{k=1}^{K} \sum_{l=1}^{L} P_{k\times L}(k,l) I_{kl} E_{kl}(\theta, \varphi)$$

(6)

$E_{kl}(\theta, \varphi)$ is the array far-field radiation field when the $(k,l)$ unit is excited by the unit amplitude source and the other cells are connected to the load; the excitation current of the unit is $I_{kl}$.

4. Experimental Verification

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4.1. Application verification on AEP equivalent method online array

Firstly, the array of phase-loaded phased array antenna elements is selected to test the application of the AEP equivalent method on the line array. The missile-loaded phased array antenna unit is a microstrip patch antenna. The structure is shown in Figure 4. The metal patch has a size: $L = 9.5mm$, $W = 9.0mm$. The dielectric substrate has a thickness 1.2mm, and the relative dielectric constant is 2.73. The antenna performance is good.

![Fig.4 Antenna unit structure](image_url)

According to the literature [12], the 7-element array is selected as the small linear array, and the 20th row of the missile-loaded phased array has the largest number of units, with 34 intervals and a spacing of $0.35\lambda$, $\varphi = 90^\circ$. The red line in Fig. 5 is the calculation result of the AEP equivalent method, the blue line is the result of the direction product multiplication method, and the black line is the HFSS simulation result as a reference value.
It can be seen from Fig. 5 that the antenna pattern obtained by the direction product method is approximately consistent with the main lobe and HFSS simulation results, but the field strength is reduced by about 1 dB. After the first side lobe region, as the angle deviates from the main lobe direction, the error is getting larger and larger, and the waveform and zero depth have large errors. The AEP equivalent method is basically consistent with the HFSS simulation results in the whole angle range, which indicates that the AEP equivalent method can calculate the antenna pattern more accurately than the traditional method.

4.2. AEP equivalent method of missile-loaded phased array array verification
Firstly, the far-field radiation test of the missile-borne phased array radar is carried out to obtain the far-field radiation pattern. The far-field test system is shown in Fig. 6. According to the above-mentioned application of the area array method, the far-field radiation of the missile-borne phased array radar is calculated.

The experimental results are shown in Fig. 7 (\(\phi = 0^\circ\)) and Fig. 8 (\(\phi = 90^\circ\)). * is the far field test result of the missile phased array, the blue line is the far field test fitting result, and the red line is the AEP equivalent fitting result.
Through the comparison in Fig. 7, the results obtained by the AEP equivalent method and the measured data are basically consistent with the area after the main lobe and the first side lobe, and the results obtained by the direction product method at the main lobe are basically consistent, but the first side lobes and subsequent errors are large. And it can be seen that the maximum value of the main lobe is increased by about 2 dB due to the mutual coupling of the cells.

Through the comparison in Fig. 8, the results obtained by the AEP equivalent method and the measured data are basically consistent with the area after the main lobe and the first side lobe, and the results obtained by the direction product method and the measured data are slightly deviated from the main lobe. At time $\theta > 0$, the amplitude of the result obtained by the direction product method and the measured data is substantially the same in the first side lobes and later. However, at time $\theta < 0$, the magnitude of the result obtained by the direction product method and the measured data produced a large deviation after the first side lobes and thereafter. It can also be seen that the maximum value of the main lobe is reduced by about 3 dB due to the mutual coupling of the cells.
5. Conclusion

(1) Analyzed the insufficiency of the classical direction product method. Based on the AEP equivalent method, the calculation formula of the small linear array equivalent large linear array was deduced and compared by simulation experiments, indicating that the AEP equivalent method can be considered compared with the traditional method. Mutual coupling to the array elements to calculate the antenna pattern more accurately.

(2) The AEP equivalent model of a certain type of missile-borne phased array radar antenna is established. The far field experiment is carried out to verify the effectiveness of the AEP method to the area array.

(3) Considering the problem of mutual coupling, the problem of accurate calculation of the phase diagram of the missile phased array radar is solved. Using this method can reduce the number of far field experiments in the development of the missile phased array radar, saving a lot of money, and at the same time the foundation of mutual coupling compensation in the calibration of the missile-borne radar has laid a foundation.

References

[1] Barton D K. Modern radar system analysis [M]. Artech House, 1988.
[2] Fan Jinrong. Prediction of the Development of Precision Guidance Technology in the First 20 Years of the 21st Century[J].Modern Defence Technology,
[3] Brookner E.Recent developments and future trends in phased arrays [C]// IEEE International Symposium on Phased Array Systems and Technology. IEEE, 2013:43-53.
[4] Gao Fei. Basic Features and Key Technologies of Phased Array Seekers [J]. Guidance and Fuze, 2005, 26(4): 1-5.
[5] Shu Xianrong, He Bingfa and Gao Tie.phased array radar antenna [M]. Beijing: National Defense Industry Press, 2007
[6] B. Lu, S.-X. Gong, S. Zhang, Y Guan, and J. Ling. Optimum spatial arrangement of array elements for suppression of grating-lobes of radar cross section.IEEE Antennas and Wireless Propagation Letters. 2010, 9: 114-117.
[7] Jiang Yongjin, PanYichun, Fu Wenbin, et al.Analysis of MP-STD-FDTD hybrid algorithm for irregular patch microstrip antenna [J].Acta Electronica Sinica, 2009, 37 (6): 1367- 1372.
[8] D. F. Kelly, W. L. Stutzman. Array antenna pattern modeling methods that include mutual coupling effects. IEEE Trans. Antennas Propagat. 1993, 41(12): 1625- 1632.
[9] D. M. Pozar. The active element pattern. IEEE Trans. Antennas Propagat. 1994, 42 (8): 1176-1178.
[10] Zhang Shuai, Gong Shuxi, Jiang Wen. A New Method for Calculating the Radiation and Scattering Field of Large Array Antennas Considering Mutual Coupling [J]. Acta Electronica Sinica, 2011, 39 (09): 2142-2147.
[11] Zhang Shuai, Gong Shuxi, Guan Ying, et al..The Small Matrix Extrapolation Calculation and Synthesis Method for Radiation Pattern of Large Planar Array Antenna [J].Chinese Journal of Computation! Physics, 2011, 28 (04): 554-560.
[12] Zhang Shuai. Research on Radiation and Scattering Analysis and Control Method of Array Antenna [D]. Xi'an University of Electronic Science and Technology, 2012.