Maintenance Optimization Model for One kind of Three-Dimensional Radar Antenna Array

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Abstract: For three-dimensional radar, maintenance cost is high and maintenance time is difficult to be determined. What's more, model simulation computing is significantly complex. The subject of this paper is a new generation of meter wave active, phased array 3D radar. We put forth a concept that maintenance should be done after dividing into several regions to the asymmetrical distribution planar array antenna. First, a failure model of array elements is built to analyze the influence from the element to antenna. Second, the maintenance optimization model is established. Finally, computer simulations are conducted to verify the feasibility and effectiveness of the proposed model.

Keywords: three dimensional radar; antenna array; maintenance optimization

1. Introduction
The three-dimensional radar(3D) has the feature of small bulk, light weight and simple structure. It plays an important role in the modern high tech war. It is of great significance to maintenance the 3D radar. As the main subsystem of the 3D radar, the optimization of array antenna’s maintenance gains more attention from military and scientific research units. Generally, the antenna has a large number of array elements, and is designed with a redundant structure, so it can be disposed as a \( K/n(G) \) system [1-2]. At present, there exists three main problems in the maintenance optimization of the antenna. The first one is the high maintenance costs and uncertain maintenance time; the second one is that the subject of this paper is a new generation of meter wave active, phased array 3D radar, which is referred to hereafter simply as 3D radar. Compared with conventional radar, it has the asymmetrical distribution of the antenna elements due to the use of amplitude weighting [3]; the last one is the difficult simulation and calculation of the optimal models because of the huge number of array elements. In recent years, there are few reports about how to solve these problems. In literature [4] a condition-based optimal maintenance model is proposed by taking the antenna as a uniform distribution array. This is why we take meter wave active, phased array 3D radar for example. This solves the first problem. However, the other two problems are not considered in literature [4]. To solve these problems, this paper proposes a maintenance optimization model. Firstly, the antenna will be divided into several regions according to the influence rule of the elements to the antenna performance, and then the proposed problems can be solved.

In order to study the relationship between elements’ failure and antenna performance, some experts introduce the idea of density weighting matrix, and a series of research results are achieved [5-7]. These references consider that the effect from element in different positions on the antenna performance is the same. So they mainly study the effect of failure rate on antenna performance. However, the influence of element in different positions on antenna performance is not investigated. In
fact, the influence of element in different position is different due to the amplitude weighting in array elements. Therefore, to divide the antenna, we should have to study the effect of different elements on antenna performance firstly, and then summarize the influence rule between array elements and antenna performance.

In this paper, the failure effect model of element in different locations is established, and the influence of array elements on antenna performance is studied with methods of theoretical derivation and simulation analysis. Then, maintenance optimization model is built. Finally, computer simulations and analysis are conducted to verify the feasibility and effectiveness of the proposed model.

2. Failure influence analysis of antenna element

2.1. Failure influence model of antenna element

Assuming that the planar antenna is composed of $M \times N$ array elements and the antenna element is isotropic. All the array elements are arranged in a rectangular grid way, and the element distance is $d_x = d_y = d$. The sketch of one planar antenna is shown in Fig.1. Let $B(m,n)$ denote the element in the $n$th columns and the $m$th rows, where $m=1,2,\cdots,M, \quad n=1,2,\cdots,N$.

![Figure 1. Sketch of planar antenna](image)

Set the element factor $S_A(\theta)=1$, since the isotropic of the antenna array element. Therefore, the antenna pattern in the direction of $\theta$ can be expressed as [8]

$$S(\theta) = \sum_{m=1}^{M} \sum_{n=1}^{N} I_{mn} \exp(jknd \sin \theta)$$  \hspace{1cm} (1)

where $k$ is the wave number, $k=2\pi/\lambda$. $\lambda$ is wavelength. $I_{mn}$ is the current amplitude value of $B(m,n)$. We uses the Taylor weighting in this paper.

Define the indicative functions $X(m)$ and $Y(n)$, where $m=1,2,\cdots,M, \quad n=1,2,\cdots,N$. Set $X(m)=1$ and $Y(n)=1$ when element in $B(m,n)$ works. Set $X(m)=0$ and $Y(n)=0$ when element in $B(m,n)$ fails. Thus, the indicative matrix $H_{m\times n}$ reflecting the working state of the $M\times N$ elements is obtained.

$$H(m,n) = X(m) \cdot Y(n)$$  \hspace{1cm} (2)

Further more, the failure influence model of element could be established as

$$S(\theta) = \sum_{m=1}^{M} \sum_{n=1}^{N} H(m,n) I_{mn} \exp(jknd \sin \theta)$$  \hspace{1cm} (3)

Considering the importance of the antenna gain and sidelobe level, influence of element in different locations on these two parameters is studied as follows.

2.2. Failure influence of element on antenna gain

The power of a single array is proportional to the square of the amplitude of the array element. Set $Q$ be the proportional coefficient, then the power $P_e$ of the element $B(m,n)$ is

$$P_e(m,n) = Q |H(m,n)I_{mn}|^2$$  \hspace{1cm} (4)

Hence, the power $P$ of the whole planar antenna is [9]
\[ P = \sum_{m=1}^{M} \sum_{n=1}^{N} P_e(m, n) \]  

(5)

The gain of the element failure in the direction \( \theta_0 \) at the maximum lobe is

\[ G(\theta_0) = \frac{4\pi}{Q} \sum_{m=1}^{M} \sum_{n=1}^{N} |H(m, n)I_{mn}|^2 \]  

(6)

When all the elements are in good condition, set \( H(m, n) = 1 \). It follows that the maximum antenna gain \( G_0(\theta) \) is

\[ G_0(\theta) = \frac{4\pi}{Q} \sum_{m=1}^{M} \sum_{n=1}^{N} |I_{mn}|^2 \]  

(7)

The decrease rate \( \alpha \) of antenna gain is defined as

\[ \alpha = \frac{G_0(\theta_0) - G(\theta_0)}{G_0(\theta_0)} = 1 - \left( \frac{\sum_{m=1}^{M} \sum_{n=1}^{N} |H(m, n)I_{mn}|^2}{\sum_{m=1}^{M} \sum_{n=1}^{N} |I_{mn}|^2} \right) \cdot \frac{\sum_{m=1}^{M} \sum_{n=1}^{N} |I_{mn}|^2}{\sum_{m=1}^{M} \sum_{n=1}^{N} |H(m, n)I_{mn}|^2} \]  

(8)

Assuming that the antenna array consists of \( M \times N = 100 \times 100 = 10000 \) array elements, the influence of element failure on antenna gain is shown in Fig.2. The results indicate that the decrease rate of antenna gain is less than 0.2\% when element in different locations fails. So the effect of a single element on antenna gain is little and can be ignored. When different numbers of array element break down, the decrease rate increases, which means that the antenna gain changes dramatically. When all the elements are invalid, the antenna gain becomes 0.

![Figure 2. Influence of failure element on antenna gain](image)

2.3. Failure influence of element on sidelobe level

According to the failure influence model, the failure effect of element on sidelobe level can be studied by means of simulation. Assuming that there are \( M \times N = 100 \times 100 = 10000 \) elements in the planar antenna, and the desired sidelobe level is -35dB, the element is subject to Taylor distribution. The relationship between element in different locations and peak values of the sidelobe is shown in Fig.3. It is shown that the failure influences of elements in symmetrical locations on sidelobe are almost the same. And in a certain range, the failure influences of different elements are also equal. Considering the large numbers of the array elements, the effect of single element on the side lobe level is little. But due to the high requirement of sidelobe, it is necessary to study the effects of element in different locations on sidelobe level.
3. Maintenance Optimization model

Through the above analysis, we can know that the effect on antenna performance varies with the elements' position and number. But there exists a certain failure range of different elements (denoted as area $R_i$), where the failure effect of element in different locations on antenna performance is basically the same. The influence rule can be extended to more antenna arrays with any array elements. Therefore, the antenna array can be divided into different $R_i$ as shown in Fig.4.

After divided into several regions, the failure effect of element in different $R_i$ on sidelobe level is different. Yet, in the same region, the failure effect is regarded as the same. As the antenna is always regarded as a $K/N$ system, the system can be decomposed into $r$ different regions by determining the different $R_i$ ($i=1,2,\cdots,r$), and array elements is regarded as the same in the same area. This lays a foundation for solving the maintenance optimization problem of asymmetrical antenna. Then, the key problem is how to carry out the regional division work.

### 3.1. Regional division criteria

The regional division criterion is on the base of the variation of the sidelobe level when one array element is invalid. The criteria has two purposes. One is that it can solve the maintenance optimization problem of the asymmetrical antenna. The other is that it can reduce the amount of model calculation. Combined with the front simulation and analysis, the quantitative criterion can be established as follows.

1. In the same region $R_i$, the variation range of the sidelobe level is not more than $\Delta B$ dB when one array element in different location is invalid.
2. There is no intersection between $R_i$ and $R_j$, and the total number of elements in all the region equals the number of elements in the antenna.
3. The numbers of array elements in divided region $R_i$ can be controlled, and the calculation is in the operational range of person computer.

### 3.2. Model steps

According to the established regional division criterion, and combining with the failure influence rule of the different elements on sidelobe level, the maintenance optimization for the planar antenna
should be conducted. The detailed steps are given as follows:

**Step1** Set the number of rows $M$ and the columns $N$.

**Step2** Set regional level denotes the region number. Due to the large number of array elements, it is very difficult for a common computer to conduct the simulations and calculations, so it brings the problem of engineering application. To solve this problem, we can set the number of elements in each region to enhance the model’s performance of engineering appliance. The method to confirm the regional division levels is given in Fig.5.

**Figure 5.** Method to confirm parameter level

**Step3** According to the failure influence model, the peak value of sidelobe level $PSLL(m,n)$ can be calculated when the element $B(m,n)$ in different location is invalid.

**Step4** Construct the peak value database $PSLL$ of sidelobe level, which contains a number of $M \times N$ items.

**Step5** Calculate the maximum and minimum value of the peak value side lobe level, these values can be denoted as $Max=max\ \{PSLL\}$ and $Min=min\ \{PSLL\}$, respectively.

**Step6** According to user needs, calculate the variation value $\Delta B$ of peak sidelobe level, where $\Delta B=(Max-Min)/level$.

**Step7** Achieve the final regional results $R$. Traversing the database of $PSLL$, searching and confirming the element $B(m,n)$ in the range of variation $\Delta B$. Finally, determining which region $R$ the element $B(m,n)$ belongs to.

4. Simulations and analysis

As an example, we have known that an antenna array composed of $M \times N=100 \times 100=10000$ elements, the desired sidelobe level is $-35\text{dB}$, and the feed amplitudes of the array elements follow a Taylor distribution. Set the parameter of $maxk=2000$ and $mink=100$. According to the proposed model, we can achieve the results easily by a simulation tool, such as MATLAB. Simulation results are shown in Fig.6. As a result, the planar antenna is divided into 9 regions, and there is no intersection between different regions.
The detailed element number in each region is listed in Tab.1. From the table, we can see that the number of the array element is controllable, and the sum number of array elements in each region equals the total number of array elements.

### Table 1. Numbers of array elements in each region

| Region  | Number |
|---------|--------|
| Region1 | 142    |
| Region2 | 710    |
| Region3 | 900    |
| Region4 | 1210   |
| Region5 | 1994   |
| Region6 | 1776   |
| Region7 | 1298   |
| Region8 | 1074   |
| Region9 | 896    |
| Total   | 10000  |

Hence, when the large antenna is divided into several small regions, we can carry out the maintenance optimization research easily on this basis. Therefore, this paper has offered a scientific and reasonable theoretical basis for conducting the optimal maintenance work of the large planar antenna.

### 5. Conclusions

To solve the existing maintenance problems, at first, the failure influence model is established, and the influence rules are summarized. Then the maintenance optimization model is built. Finally, simulations and analysis are conducted to verify the presented model. Results show that the large planar can be divided into several small regions by using the proposed method.

However, there still exist some problems to be solved. The main question is that the classification standard $\Delta B$ in regional division criterion is constant. To make the results more reasonable, we will design the parameter $\Delta B$ in the future research.

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