Phased-array Surface Monitoring Method Based on Compensation Correction Technique

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Abstract. Phased-array radar has a huge array of microwave feeding network and antenna lobe performance depends on the array amplitude and phase errors. Therefore, it is necessary to monitor the array surface to ensure the performance of the array. In the traditional test method, there is a bad test precision and slow speed. In this paper, a monitoring method based on compensation correction technique is proposed. The inside and outside of the measurement method, two kinds of tests complement each other, can cover the unit level, ensure the favorable array amplitude and phase characteristics, to provide important support for high precision tracking.

1. Introduction
For active phased array, a large number of microwave feeder networks are needed to ensure the operating range, which results in large aperture of radar array and a large number of channels. The lobe performance of array antenna is the key to realize the power and accuracy of radar. The lobe performance of array antenna depends on the array amplitude and phase error [1]. It is necessary to design a perfect active array monitoring system to calibrate and calibrate the array accurately.

In order to achieve high-precision amplitude and phase calibration of sea-based phased array radar array and ensure high-precision measurement of radar system, a computer-aided measurement and compensation correction technique in array is proposed. The error correction method combining darkroom test and field front monitoring is used to separate the amplitude and phase of main feeder and monitoring feeder, and the combination of internal and external monitoring ensures the antenna array characteristics. The coverage depth of both internal and external monitoring reaches the unit level, which can realize fault location and amplitude and phase compensation at the unit level.

2. Traditional Measurement Methods
Advanced phased array radar has a huge microwave feed network. In order to ensure the performance of each link, necessary monitoring is needed. The traditional internal monitoring principle is shown in Figure 1. The monitoring network and switch coupler are connected with the feeder network, and the T/R channel of the feeder network is unified by switch control, so that the working condition of the feeder network on the front can be monitored. The more network ports and states are, the larger the measurement amount is. In order to improve the efficiency, it is necessary to measure quickly and automatically. In addition, for phase-temperature sensitive devices such as T/R amplifier and annulus, in order to measure the phase and amplitude distribution in the working state, fast measurement must be carried out to reduce the influence of temperature change on the measurement of array system.

Fig.1, the switching test port of the switch can quickly monitor the amplitude and phase transmission of the feeder network, but the accuracy of this method is not high. First, the monitoring network is adjusted to the full equal-amplitude and equal-phase distribution, then the monitoring and
feeder network measurement data can be considered as the amplitude and phase distribution data of the feeder network. However, the monitoring network cannot achieve the full-band ideal state, so the monitoring network errors. The difference becomes the test error, and the error has a great influence. The test result is that the amplitude and phase data of feeder network measured in advance under constant temperature condition are different from the joint measurement. Although the scheme has large error and can not accurately understand the amplitude and phase distribution changes of the array feed, it can act on fault location.

Figure 1. Microwave test of feed network of phased array radar

3. Array Monitoring Method
The composition of the array monitoring system is shown in figure 2.

Figure 2. Composition diagram of array monitoring system
3.1. External Monitoring

In the case of external monitoring, the receiver and frequency source are connected to the external monitoring horn branch, and the external monitoring horn transmits a reference signal to the array surface or receives the signal transmitted by the array surface [3].

When monitoring the receiving channel, under the control of the monitoring control computer, the frequency source generates a single point frequency signal, which is converted into optical signal by the photoelectric converter, and then transmitted to the external monitoring horn by the optical fiber, and converted into electrical signal by the photoelectric converter on it, and then radiated to the array surface after amplification by the power amplifier. Open the receiving branch of the T/R component under test, and the non-tested channel will receive the load of the branch channel. The receiving network will send the amplified signal of the T/R component under test to the receiver, process the original data and form the amplitude and phase distribution of T/R channel on the array surface. The amplitude and phase errors between each unit and the central unit are recorded by the monitoring control computer, and the fault unit is judged according to the criterion.

In the test of the transmitting branch, the rf test signal generated by the frequency source is amplified through the pre-transmission stage to promote the T/R component on the whole array. For the T/R channel under test, the channel is in the transmitting working state to amplify the test signal, which is radiated out by the corresponding antenna unit, but the channel under test is not connected to the load, so the signal is not amplified. The monitoring horn receives the test signal, then amplifies the signal and converts it into optical signal, which is sent to the monitoring receiving channel 2 by optical fiber, and the monitoring receiver measures the channel amplitude and phase of the signal. The amplitude and phase errors of each unit and the central unit are recorded by the monitoring control computer, and compared with the amplitude and phase values of the central unit, the amplitude and phase errors of the T/R channel are obtained, and the fault unit is judged according to the criteria.

During external monitoring, the amplitude and phase of the measured T/R component channel are determined by the rotation vector method to avoid the influence of leakage signals from other non-measured channels on the measurement results.

3.2. Internal Monitoring

When internal monitoring is adopted, the monitoring receiver and the monitoring front stage are connected to the internal monitoring network, and the reference signal (receiving monitoring) is injected into each T/R component on the front through the internal monitoring network, or the output signal (transmitting monitoring) of each T/R component is received. The signal coupler of the key components is shown in Fig3.

![Figure 3. The monitor coupler distribution and configuration](image_url)

When monitoring the receiving channel of T/R module level, the RF signal generated by the frequency source is amplified by the monitoring front stage, then sent to the unit level monitoring network by circulator. The monitoring signal is distributed to the circular polarizer in front of each T/R module by the unit level monitoring network (including the monitoring network in the unit combination and the monitoring wave-guide network in the unit level), and fed to the T/R module by
the circular polarizer. Receive the port, open the receiving branch of the tested T/R module, and receive the load of the non-tested channel. The receiving network transmits the amplified signal of the tested T/R module to the wide-band receiver on the array, and measures the amplitude and phase information of the signal through the receiver. The amplitude and phase errors between each element and the central element are calculated, and the fault element is judged according to the criterion.

When testing T/R module-level transmitter branch, the RF test signal generated by frequency source is amplified by transmitting preamble, which promotes the T/R module on the whole array. For the T/R channel under test, the channel is in the transmitting working state. The test signal is amplified and fed back to the unit-level monitoring network by the directional coupler on the circular polarizer, instead of receiving the load, the measured channel does not amplify the signal. The unit level monitoring network sends the signal to the monitoring receiving channel 1, and the amplitude and phase of the signal are measured by the monitoring receiving channel 1. The amplitude and phase errors of the T/R channel are obtained by calculating the amplitude and phase information of each element and comparing with the amplitude and phase values of the central element, and the fault element is judged according to the criterion.

Before using the internal monitoring method to correct the antenna's amplitude and phase, it is necessary to determine the reference amplitude and phase of the T/R module. That is, the antenna array is initially calibrated by the microwave anechoic chamber near-field test method, so that the antenna array equipment can meet the amplitude and phase distribution of the index. Based on this condition, the amplitude and phase distributions of T/R modules are tested by internal monitoring method, and the test results are saved. The antenna array needs to be monitored again and the standard timing. The internal monitoring method is used to re-measure the amplitude and phase information of the T/R module. The difference between the amplitude and phase of the T/R module and the reference state is used as the compensation data for the calibration of the antenna array.

4. Compensation Amendment

4.1. Field Focus Monitoring Method

As shown in Fig. 4, when the observation point is located at infinite distance from the antenna array, the pattern formed by N antenna elements at an angle of $\theta_0$ with the normal direction of the array can be written as follows:

$$f_a(\theta_0) = \sum_N a_n \exp(j\phi_n)\exp(-j\frac{2\pi}{\lambda}nd\sin\theta_0)$$

In the formula, $a_n, \phi_n$ the amplitude and phase of the nth antenna element and the spacing of antenna elements are d.

$$\phi = \frac{2\pi}{\lambda} dsin\theta$$

![Figure 4. Formation schematic diagram of far-field array antenna pattern](attachment:figure4.png)
As shown in Fig. 5, when the observation point is located at a finite distance $r$ from the antenna array, the pattern formed at an angle of $\theta_0$, which is smaller than the normal direction of the array, can be approximately written as follows:

$$ f_\theta(\theta_0) = \sum_{n} a_n \exp(j \phi_n) \exp(-\frac{2\pi}{\lambda} \sqrt{(nd)^2 + r^2 - 2nd \cdot r \sin \theta_0}) $$

$$ \approx \sum_{n} a_n \exp(j \phi_n) \exp(-\frac{2\pi}{\lambda} nd \sin \theta_n - \frac{2\pi}{\lambda} r_n) $$

$$ r_n = \sqrt{(nd)^2 + r^2} \quad (2) $$

Figure 5. Principle of directional pattern formation of near-field array antenna

Comparing the two formulas mentioned above, it can be seen that the difference between mid-field and far-field measurements is only more in the phase of each antenna element. If the phase difference is compensated by the phase shifter of the T/R module, the pattern formed by the focusing method in the mid-field region is consistent with the far-field pattern of the antenna position. It can calibrate the amplitude and phase of the mid-field array and test the pattern.

4.2. Method of Compensation Amendment

Front calibration is based on the combination of darkroom test and field front monitoring. The specific steps are as follows:

- By using the near-field test in the microwave anechoic chamber, the initial amplitude-phase curves $A_{mi}(f)$, $m_i(f)$ ($i=1,2,...,n$);
- External monitoring: using the out-of-plane monitoring system to collect the amplitude and phase data of each unit, and combining with the initial amplitude and phase curve $A_{Ri}(f)$, $R_i(f)$ ($i = 1, 2,...,N$), forming the compensation data of each unit’s amplitude and phase errors:

$$ A_{Fi}(f) = A_{Ri}(f) - A_{mi}(f) $$

$$ F_i(f) = R_i(f) - m_i(f) $$

- Internal monitoring: Based on the antenna performance requirements, the array amplitude and phase data are measured by the internal monitoring method, and the amplitude change values $A_{Ti}(f)$, $T_i(f)$ ($i = 1,2,...$ are extracted. (n) Amplitude and phase compensation of internal monitoring method:

$$ A_{Fi}(f) = A_{Ti}(f) - A_{mi}(f) $$

$$ F_i(f) = T_i(f) - m_i(f) $$

- After updating the amplitude and phase compensation data, the performance of the antenna is tested and validated by the mid-field focusing method. If the antenna does not meet the requirements of the index, the antenna is monitored and compensated again.

In the specific operation process, step 1 is the near-field test of the inner darkroom, which is used to collect the amplitude and phase reference data, step 2 is the out-of-plane monitoring, which is mainly
used to test and compensate the front amplitude and phase when the active components are replaced on a large scale or the front is maintained monthly/quarterly; step 3 is the in-plane monitoring, which is used to monitor the front state and compensate the amplitude and phase before the daily mission; step 4 is the mid-field focusing day. Linear performance test is used to test and verify the array performance after external monitoring and internal monitoring amplitude and phase compensation.

5. Error Analysis

The measurement error of array amplitude and phase includes two aspects: equipment and method. Errors on the equipment refer to the errors brought by the measuring equipment itself, such as the mutual position between the phased array antenna and the measuring horn, multi-path, channel isolation and system mismatch during external monitoring. The method error refers to the error caused by the measurement model and data processing [5].

5.1. Measurement Equipment Error

The relative measurement error expression of the transmission coefficient between the phased array antenna and the monitoring horn is as follows:

\[ \delta = \sqrt{\delta_t^2 + \delta_o^2 + \delta_a^2 + \delta_r^2 + \delta_d^2} \]  

(3)

\( \delta_t \) is temperature difference for temperature instability of microwave system. Because of the method of comparing with the reference amplitude, the difference between the measured and the reference length in temperature change \( \Delta L \) and coefficient of temperature change \( \Delta L \) is as follows:

\[ \delta_t = \frac{a \times \Delta T \times \Delta L}{\lambda} \]  

(4)

For external monitoring, this error can be neglected due to the short measuring time.

\( \delta_o \) is errors caused by phase-locked instability of microwave signal source:

\[ \delta_o = \frac{\Delta F \times \Delta L}{F \times \lambda} \]  

(5)

The error can be neglected when using a signal source with frequency stability than \( 10^{-6} \).

\( \delta_a \) is errors caused by amplitude and phase testing equipment. For external monitoring, it often works on the dynamic edge, with an estimated value of 0.3 dB and 3 degrees. For internal monitoring, the measurement dynamic is about 20 dB, and the estimated value is 0.2 dB and 2 degree.

\( \delta_r \) is error caused by system mismatch is usually 0.038.

\( \delta_d \) is error caused by data acquisition and transmission is estimated to be 0.06 dB under uniform distribution.

According to the above errors, the accuracy of amplitude and phase is about 0.34 dB and 3.6 degree respectively in external monitoring and 0.18 dB and 2.3 degree respectively in internal monitoring.

5.2. Errors Caused by Mutual Position Between Phased Array Antenna and Measuring Horn

It is divided into vertical and horizontal errors. Vertical errors will cause square-rate phase errors of array aperture.

\[ \delta_r (r) \approx \frac{k \times \Delta R \times \left( \frac{r}{R} \right)^2}{2} \]  

(6)
This kind of square error will lead to phase weighting and change the lobe width. Generally, it is required that the phase error of the aperture edge be normalized to a center of less than $\frac{\lambda}{100}$, about 0.4mm. Horizontal errors can lead to linear phase errors of array aperture:

$$\delta_p(r) \approx \frac{k \times \Delta r \times r}{R}$$

(7)

This kind of linear phase error will lead to the pattern offset, which is generally required to be about 0.4mm and $\frac{\lambda}{100}$.

5.3. Channel Leakage Error
Because the monitoring system detects cell level, the influence of leakage on cell level network and sub-array level network must be paid much attention. Error statistics show that the amplitude and phase errors are distributed in a basin shape along the irradiation center, edge and periodicity, which brings considerable systematic errors to the measurement of side-lobe level and pointing accuracy. In internal monitoring, the rotating vector method is used to determine the amplitude and phase of the T/R module channel under test, so as to avoid the influence of leakage signals from other non-measured channels on the measurement results.

6. Acknowledgments
Aiming at the disadvantage of traditional testing for huge T/R components, a computer aided measurement and compensation correction technique in array is proposed based on practical engineering experience. Through the construction of test system and the use of internal and external joint test methods, the two methods complement each other and work together to effectively improve the test efficiency. In the test of an experimental radar, the amplitude and phase of the array are tested repeatedly with the detection system. The results are as follows: the phase error is < 3 and the amplitude error is < 0.8dB. Practical application shows that this method can not only accurately judge the faults of T/R components, but also provide accurate compensation data, ensure the amplitude and phase characteristics of the array, and make an important contribution to high-precision tracking.

7. References
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