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Whole-machine calibration approach for phased array radar with self-test

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Abstract. The performance of the missile-borne phased array radar is greatly influenced by the inter-channel amplitude and phase inconsistencies. In order to ensure its performance, the amplitude and the phase characteristics of radar should be calibrated. Commonly used methods mainly focus on antenna calibration, such as FFT, REV, etc. However, the radar channel also contains T/R components, channels, ADC and messenger. In order to achieve on-based phased array radar amplitude information for rapid machine calibration and compensation, we adopt a high-precision plane scanning test platform for phase amplitude test. A calibration approach for the whole channel system based on the radar frequency source test is proposed. Finally, the advantages and the application prospect of this approach are analysed.

1. Introduction
The increasing complex battlefield environment poses a higher and higher demand for missile-borne radar. Since Phased array radars can flexibly change its beam shapes and orientations and form various types of antenna pattern characteristics, which has been rapid developed in the field of missile-based radar.

Phased array radar consists of multi-channel antenna. The internal RF channel and the information channel contain a wealth of microwave components, as well as kinds of cables. Due to manufacturing tolerances, assembly errors, there is a certain degree of amplitude and phase error among the channels, which makes that the antenna gain is reduced and the sidelobe is increased. Therefore, the radar should be calibrated. The various channels should be compensated in order to meet the standard. Some of the commonly used calibration methods such as near-field scanning [7], commutation measurement methods [8], fast Fourier transform (FFT) [2], mutual coupling positive method, curve fitting method, rotation vector method (REV)45, which only concern the radar antenna calibration, and do not consider the calibration of the upper channel, ADC and other radar calibration machine. In this paper, a spring-loaded phased array radar calibration system is introduced, which is measured by a high-precision near-field scanning platform. The calibration system is used to calibrate the channel characteristics. The RF signal comes from the frequency source of the radar itself, which can effectively maintain the consistency of the transceiver signal. At the same time, the whole channel calibration not only includes the radar antenna calibration, but also the radar machine calibration. This has more practical engineering significance and improves the radar antenna pattern compensation accuracy and efficiency.

2. System composition and principle
Phased array radar is composed of many antenna elements, relying on the control of each unit phase to change the direction of the synthetic beam and to achieve beam scanning. And this beam is the array.
of all antenna elements radiated electromagnetic wave vector synthesis. The initial phase error, element failure and mutual error of each element have important influence on the beamforming of the antenna. These effects can cause the beam to deviate from the theoretical value, appear sidelobe elevation, gain reduction phenomenon. And through the near field calibration can minimize the amplitude and phase error between the channels.

2.1 System Components

The current calibration of phased array radars requires not only phase-phase calibration of phased-array antennas, but also the calibration of the corresponding channels (including antennas, TR components, channels and stations) \[3\]. The purpose of it is that the array radar is calibrated integrally. The phased array radar machine channel composition diagram is shown in Figure 1.

As can be seen from Figure 1. The radar is dual polarized phased array radars, which are the M-element H-polarized channel and the N-element V-polarized channel. By using the radar’s own frequency source and receiving allegations of computer control, the calibration system is built from the probe to the M \( \times \) N receive channel link. Completing a unit channel calibration usually requires the following five steps:

1. a clock signal is sent to the DDS from frequency source, issued by the DDS IF signal;
2. Through the frequency conversion, Intermediate frequency (IF) signal achieves the antenna side. One of the RF signal is sent to one end of the probe through the test channel;
3. The probe sends the signal to the unit under test, and the unit start receiving the signal;
4. For wave-controlled sampling, RF signal is changed to the ADC by the down-conversion, and which is sent for DDC analysis. The results is recorded in a digital memory through the fiber;
5. Each unit is tested in turn. After the end of the test, the phase compensation value of the cell is calculated by the stored data.

![Figure 1. Phased array radar channel composition](image)

2.2 Platform composition

Because the test system scans the unit by the probe, the accuracy of the amplitude and phase calibration depends on the building test platform certainly. The precision requirement of three axes is 0.01mm. The structure diagram of the precision measurement platform is shown in Figure 2. The phased array radar is fixed on the central base. The high-precision gantry is equipped with a probe, which have a fixed distance from every antenna unit for the corresponding radar front. We calibrate all
units in a certain order. The work processes of the test platform is: 1) we pull out the tray and fix the erected radar in the installation with a fixed base of the tray; 2) we start loading the lift frame into the test cabin; 3) the radar unit is tested by driven test probe of XY precision platforms; 4) when scanning finished, we pull out the target in reverse order. Then, the test is completed.

2.3 Calibration principle
In this paper, the missile array is composed of 1000 unit antennas. According to the design requirements, the entire front divides into a number of sub-arrays. Each sub-array consists of 50 to 100 units. Each module is roughly 2 × 4 units. As the phased array radar design modules are controly by the same switch transceiver, the calibration is completed by module. In accordance with the above discussion, we choose front scanning, which is a usual plane scanning method. However, the interference is eliminated by Phase-Toggle elimination method for each module. This is the integrated equipment test approach.

The near field scanning technique for the scanning measurement of the probe is based on the electromagnetic theory. The probe samples the electric field around the closed surface of the array. The distance field pattern and the array phase distribution are obtained by numerical calculations. In the calibration process, the independent role of each element is only considered and the antenna channel is calibrated by antenna near field measurement equipment in turn. the signal of the m-th row, the n-column unit transmits is given as the complex form

\[ X_{mn}(t) = a_{mn}(1 + \delta_{mn}) \exp[j(2\pi f_s t + \phi_{mn} + \sigma_{mn})] \]  

(1)

In the formula, \( a_{mn} \) and \( \phi_{mn} \), are the amplitudes of the unit phase. \( \delta_{mn} \) and \( \sigma_{mn} \), are the amplitude phase errors; \( f_s \) is the signal calibrating frequency. The reference unit \((c, d)\) is selected. The plural form is expressed as:

\[ X_{cd}(t) = a_{cd}(1 + \delta_{cd}) \exp[j(2\pi f_s t + \phi_{cd} + \sigma_{cd})] \]  

(2)

The transmit signal \( X_{cd}(t) \) of the other channels is sequentially compared with \( X_{mn}(t) \). the available calibration factor \( M \) is obtained by

\[ M(m, n) = \frac{X_{mn}}{X_{cd}} = \frac{1 + \delta_{mn}}{1 + \delta_{cd}} \exp[j(\sigma_{mn} - \sigma_{cd})] \]  

(3)

In the module, all antenna units share a same channel, which is shown in Figure 3. Active phased array radar can be independent of the unit transceiver control. It can be applied in reversing elimination method (Phase-Toggle). That is, when the probe measures the m unit the N module, the other m-1 unit also can be controlled. the channel reception value is:
According to (1), the formula can be expressed as
\[ X_{m1}(t_i) = a_{m1}(1 + \delta_{m1}) \exp[j(2\pi f_d t + \phi_{m1} + \sigma_{m1})] \]  

(5)

Invert to change the test of the unit \( m1 \), and the other units remain the maximum attenuation phase, then we have
\[ X_{m1}(t_2) = a_{m1}(1 + \delta_{m1}) \exp[j(2\pi f_d t - \phi_{m1} + \sigma_{m1})] \]  

(6)

The reverse channel value is received as
\[ X_N(t_2) = X_{m1}(t_2) + \sum_{i=2}^{\infty} X_{mi} \]  

(7)

(4) and (7) can be subtracted from the other units of interference
\[ X_N(t) = X_N(t_i) - X_N(t_2) = X_{m1}(t_i) - X_{m1}(t_2) = X_{m1}(t) \]

Then, we can get that
\[ X_{m1}(t) = a_{m1}(1 + \delta_{m1}) \exp[j(2\pi f_d t + \sigma_{m1})] \expj\phi_{m1} - \expj(-\phi_{m1}) \]

The relative phase value of unit under the test can be measured by the above calculation. This constitutes a phased array radar calibration system. For the exits modules, each module contains a unit of phased array radar. Its test flow is shown in Figure 4.

\[ X_{m1}(t_i) = X_{m1}(t_2) + \sum_{i=2}^{\infty} X_{mi} \]  

(4)
Enter the calibration mode, test the system self-test

Open the module to receive the N channel, turn off all other channels

Move the scanning frame, scan the antenna unit using the near-field scanning method, and point the probe to the m unit

When aligning the m unit, the other module channels of the module are controlled at maximum attenuation, the phase is fixed at 0°, and the phase value of m units is adjusted according to the test angle

The effect of the other units is checked by the inverse method and the result of the N module is recorded

Data calibration processing

Data record

**Figure 4.** The test flow chart

3. **Validation analysis**

According to the above method, the missile-borne phased array radar is calibrated. The antenna unit is calibrated by the previous calibration method. The calibration coefficient is obtained. The radar antenna pattern is calculated.

The antenna pattern of beam in the U-V coordinate is as follows:

**Figure 5.1** Phase error for the sum beam three-dimensional space and azimuth antenna pattern

The antenna pattern of azimuth difference beam in the U-V coordinate system is as follows:
Figure 5.2 Phase error for the Az difference beam three-dimensional space and azimuth antenna pattern

Elevation difference beam in the U-V coordinate system under the antenna pattern:

Figure 5.3 Phase error for the El difference beam of three-dimensional space and azimuth antenna pattern

It can be seen from Figure 5.3 that the amplitude and phase error of each channel and the mutual coupling between the elements are less affected by the beam pointing and beam width. The influence on the array sidelobe level is more serious. The low sidelobe antenna is calibrated only, which does not consider the phase difference between the elements and the channels. The calibrated minor lobe of the antenna is still high which need a calibration once again. However, the calibration approach of the integrated equipment can solve the above problems better. The sidelobe level of pattern and the lobe width become better. The calibration results are shown in the following figure:

Sum beam in the U-V coordinate system under the antenna pattern:

Figure 6.1 Phase error for the sum beam three-dimensional space and azimuth antenna pattern (After using this calibration method)

Azimuth difference beam in the U-V coordinate system under the antenna pattern:

Figure 6.2 Phase error for the Az difference beam three-dimensional space and azimuth antenna pattern (After using this calibration method)

Elevation difference beam in the U-V coordinate system under the antenna pattern:
Figure 6.3 Phase error for the El difference beam three-dimensional space and azimuth antenna pattern (After using this calibration method)

It can be seen from the comparison that the accuracy of the whole calibration method is better, since it considers a higher full channel effect. The efficiency is improved in the actual calibration. However, this method requires a higher test environment, which needs a high-precision test equipment to ensure the accuracy of the calibration coefficient.

4. Summary and Prospect
In this paper, the structural characteristics of the missile-loaded phased array radar are considered. The high-precision near-field scanning test platform is constructed. The self-test method and inverse elimination method are used to scan from the whole to the local combination. The whole machine is constructed. Simulation shows that the system not only calibrates the phase characteristics but also reduces the error caused by the coupling. The most important thing is that this improves the efficiency of the radar test calibration as a whole calibration. This method is consistent with the actual engineering application. A large number of actual test for the test platform would be carried out in the next step. Some optimization will be done in the future.

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