Research on the phase-frequency relationship of the field effect amplifier front-end of shipborne USB system

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Abstract. Normally, most researches on phase calibration of shipborne USB system focus on the means of phase calibration. This article starts with the research on the channel of the system. The composition of the channel is introduced, and the characteristics of the channel is analyzed. Taking the channel of the field effect amplifier front-end as the research object, a mathematical fitting algorithm is used to derive the functional relationship between the phase of the field effect amplifier front-end and the working frequency. The actual calibration data is used for simulation analysis to obtain the fitting order of the function. Combining the phase-frequency relationship of the field effect amplifier front-end and the microwave self-checking phase correction of the field effect amplifier back-end, a new phase calibration method is proposed.

Keywords: Dual-channel monopulse, Field effect amplifier, Phase-frequency relationship, Segmented phase calibration.

1 Introduction

The shipborne USB system uses a dual-channel monopulse program. There are many advantages in the tracking receiver of the system[1] ,such as relatively simple structure, high tracking accuracy, excellent angular error demodulation performance, and easy implementation. It is widely used in precise tracking and measuring radars, and it is a program used most in the tracking and controlling system currently.[2] The phase calibration module of the tracking receiver obtains the phase value and slope of both azimuth and pitch through angle calibration, which is used to demodulate the angle error during tracking[3] to realize tracking the target automatically.

At the dock, the shipborne USB system can obtain the accurate phase value through phase calibration facing tower. Since there is no fixed tower on the sea, the system cannot carry out phase calibration facing tower. At present, most researches on maritime phase calibration focus on the means of phase calibration, and there is little research on the signal transmission channel itself. This article starts with the channel, analyzes the characteristics

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of different channel parts, and studies the phase-frequency relationship of the channel, in order to provide a new idea for the phase calibration of the shipborne USB system.

2 Channel analysis

The signal transmission channel of a typical dual-channel monopulse tracking and controlling system is shown in Figure 1. After the target signal is received by the antenna feed, it enters the tracking coupler, and simultaneously excites the TE_{11} mode and TE_{21} mode to generate sum and difference signals. The sum and difference signals pass through the waveguide, field effect amplifier and switch, down-converter, slip ring, intermediate frequency level adjustment, switch matrix, until the tracking receiver performs angular error demodulation. Since it is impossible to achieve the same signal transmission delay characteristics of the sum and difference channels in engineering, the phase difference of the sum and difference channels will inevitably come into being. Normally, the phase difference of the sum and difference channels is calibrated by the method of facing tower. Ideally, the phase delay of a certain frequency signal transmitting through the two channels is fixed. However, when the external environmental conditions change drastically or the equipment performance of the channel changes, the transmission delay characteristics of the sum and difference signals will change. Therefore, it is necessary to check the phase difference frequently.

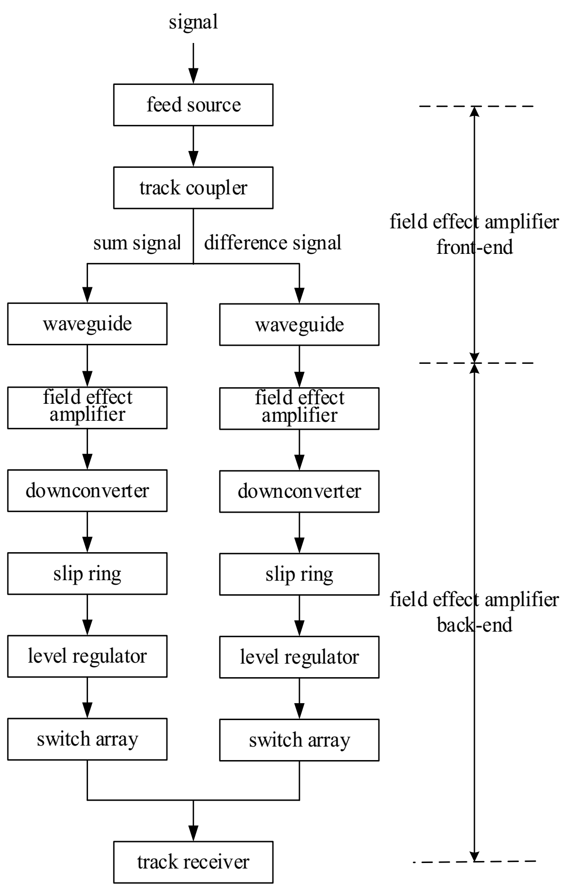

Fig. 1. Signal transmission channel.

Devices such as field effect amplifier and switch, down-converter, slip ring, intermediate frequency level adjustment and switch matrix are active, and their phase characteristics are susceptible to the changes of external environmental conditions. Microwave self-checking[4] is a commonly means for phase checking in tracking and controlling system. It mainly monitors the phase changes of the field effect amplifier back-end. The principle is that the signal is generated by the signal source, coupled from the front end of the field effect amplifier to the tracking channel, and the tracking receiver receives the signal to check the phase.

The feed source and waveguide in front of the field effect amplifier are passive devices, and their phase characteristics are relatively stable. This article mainly studies the phase characteristics of the field effect amplifier front-end.

3 Phase-frequency relationship of the field effect amplifier front-end

If a transmission system is composed of pure resistance, there will be no transmission delay. In the tracking channel, there are inert components such as inductors, capacitors, and transistors, and the output signal will always be later than the input signal for a period of time τ, which is the channel delay. Assuming that the transmission delay of a signal with a certain angular frequency ω_i is τ_0, the resulting phase shift generated is $\omega_i\tau_0$, if the signal delays of all frequencies are τ_0, then the resulting phase shift is

$$\varphi(\omega)=\omega\tau 0 \tag{1}$$

It can be seen that the phase shift varies with the angular frequency ω. The relationship curve between φ(ω) and ω is the phase-frequency relationship curve of the tracking channel. In theory, there is a linear relationship between φ(ω) and ω, [5] but it is not strictly linear in engineering practice. At this time, only a small section of the phase-frequency relationship curve is a approximately straight line in a small frequency range. The relative change relationship between the phase and the frequency in an infinitely small frequency band centered on the angular frequency ω is group delay characteristics[6]. Group delay describes the phase characteristics of the device and the time delay generated by signal passing through the device[7,8]. Its expression is

$$\tau(\omega)=\lim_{\Delta\omega\to 0}\frac{\Delta\varphi(\omega)}{\Delta\omega}=\frac{d\varphi(\omega)}{d\omega} \tag{2}$$

Group delay is one of the key parameters in digital communication systems.[9] It is the derivative of the phase-frequency characteristic of a linear system or a quasi-linear system with respect to the angular frequency. Ideally, when the group delay of the tracking channel is constant, the channel delay of each frequency of the signal is a constant value, that is, $\tau(\omega)=\tau_0$, $\varphi(\omega)=\omega\tau_0$, and the phase-frequency characteristic of the channel is a straight line . The phase-frequency characteristic of the actual channel is not a straight line, and the time delay varies with the angular frequency.

Considering that the devices in front of the field effect amplifier are passive, it can be ignored that the phase-frequency characteristics are affected by external environmental conditions such as temperature and humidity. The group delay characteristics of the field effect amplifier front-end can be realized by studying the functional relationship between the phase shift φ(ω) and the angular frequency ω. Since ω=2πf, that is to study the functional relationship between the phase shift φ(f) and the frequency f. Assuming that the functional relationship between φ(f) and the frequency f is

$$\varphi_1(f) = a_0 + a_1 f + a_2 f^2 + \cdots + a_k f^k \tag{3}$$

In the formula, a_i is the polynomial coefficient, and $i = 0,1,2,......k$ is the order of the polynomial.

In mathematical statistics, Gaussian estimation is the earliest form of least square estimation. It is an optimal linear unbiased estimation obtained under the condition that the random errors of several observation samples are equal variances and uncorrelated.[10] The coefficients of the functional expression between the phase of the field effect amplifier front-end and the working frequency is estimated by this method.

In the frequency range of 2200MHz～2300MHz, the frequencies separated by 5MHz are recorded as F_0 = [f_1, f_2, f_3 ... f_{21}], the phases by facing tower are recorded as T = [t_1, t_2, t_3 ... t_{21}], and the phases by microwave self-checking are recorded as W=[w_1, w_2, w_3 ... w_{21}], the front-end phase are recorded as G = [g_1, g_2 ,g_3 ... g_{21}] = T-W = [t_1-w_1, t_2-w_2, t_3-w_3 ... t_{21}-w_{21}]. The following relations can be obtained.

$$\begin{cases} g_1 = a_0 + f_1 a_1 + f_1^2 a_2 + \cdots f_1^k a_k + \eta_1 \\ g_2 = a_0 + f_2 a_1 + f_2^{\,2} a_2 + \cdots f_2^{\,k} a_k + \eta_2 \\ \cdots\cdots \\ g_{21} = a_0 + f_{21} a_1 + f_{21}^{\,2} a_2 + \cdots f_{21}^{\,k} a_k + \eta_{21} \end{cases} \tag{4}$$

{ η_i } is the random error of the front-end phase, which satisfies

$$E(\eta_i) = 0 \quad i = 1,2,\cdots,21$$

$$E(\eta_i \eta_j) = \begin{cases} \sigma^2 & i = j \\ 0 & i \neq j \end{cases}$$

Order $G = \begin{bmatrix} g_1 \\ g_2 \\ \cdots \\ g_{21} \end{bmatrix}$, $F = \begin{bmatrix} 1 & f_1 & \cdots & f_1^k \\ 1 & f_2 & \cdots & f_2^{\,k} \\ \cdots & \cdots & \cdots & \cdots \\ 1 & f_{21} & \cdots & f_{21}^{\,k} \end{bmatrix}$, $A = \begin{bmatrix} a_0 \\ a_1 \\ \cdots \\ a_k \end{bmatrix}$, $\eta = \begin{bmatrix} \eta_1 \\ \eta_2 \\ \cdots \\ \eta_{21} \end{bmatrix}$, $\hat{A} = \begin{bmatrix} \hat{a}_0 \\ \hat{a}_1 \\ \cdots \\ \hat{a}_k \end{bmatrix}$.

Then, the matrix form of equation (4) is

$$G = FA + \eta \tag{5}$$

In the formula, $rankA = k$, $E(\eta) = 0$ and $E(\eta\eta^T) = \sigma^2 I$.

When $k < 21$, that is, when the number of samples is more than the fitting order, take the residual square sum of equation (4)

$$Q = (G - F\hat{A})^T (G - F\hat{A}) \tag{6}$$

Reach the smallest $\hat{A}$ as an estimate of A . It can be obtained by the principle of extreme value

$$\hat{A} = (F^T F)^{-1} F^T G \tag{7}$$

And the error covariance of the parameter estimator $\hat{A}$ is

$$P_{\hat{A}} = (F^T F)^{-1} \sigma^2 \tag{8}$$

Formula (7) and (8) are the Gaussian estimation of the unknown parameter vector A and the error covariance matrix. $\hat{A}$ is called the least square estimation of the unknown parameter vector A under the condition of equal variance and uncorrelated. Substituting $\hat{A}$ into equation (3), the relationship between the front-end phase and the working frequency is obtained as:

$$\varphi(f) = \hat{a}_0 + \hat{a}_1 f + \hat{a}_2 f^2 + \cdots + \hat{a}_k f^k \tag{9}$$

4 Simulation analysis and application

Take a certain mode baseband calibration data as an example to analyze. The data is shown in Table 1.

Table 1. Baseband calibration data.

Frequency	Phase	
	□Facing tower	Microwave self-checking
2200	89.45	167.34
2205	92.81	159.26
2210	96.68	161.37
2215	110.74	164.53
2220	112.5	159.96
2225	117.45	159.26
2230	123.05	156.28
2235	120.59	153.28
2240	123.75	152.58
2245	128.32	151.88
2250	132.54	144.84
2255	131.48	149.06
2260	139.57	153.28
2265	141.33	145.9
2270	145.36	145.52
2275	147.3	145.69
2280	148.36	149.06
2285	153.63	146.25
2290	152.93	151.88
2295	158.2	155.04
2300	159.26	152.58

According to Table 1, the phases of the field effect amplifier front-end can be obtained from the difference between Phases by facing tower and phases by microwave self-checking. Then they are fitted and the results under different fitting orders are recorded. The fitting results from first-order to fourth-order and the original phases of the field effect amplifier front-end are graphically compared and displayed, as shown in Figure 2.

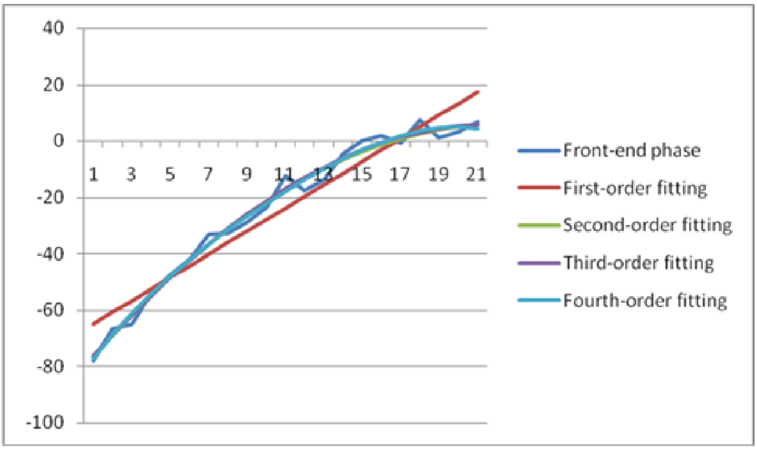

Fig. 2. Phase fitting results of the of the field effect amplifier front-end.

It is not difficult to see that the difference between the first-order fitting results and the actual data is large, and the fitting results above the second-order are basically coincident, and the difference with the actual data is small. It can be seen that the phase-frequency characteristic of the field effect amplifier front-end is indeed not a straight line, and the phase changes with frequency, which is a quadratic curve approximately. In the actual mathematical fitting, the second-order fitting can be applied.

$$\varphi(f) = \hat{a}_0 + \hat{a}_1 f + \hat{a}_2 f^2 \tag{10}$$

After obtaining the phase-frequency relationship of the field effect amplifier front-end, the phase of the field effect amplifier front-end at any frequency can be obtained. The phase of the field effect amplifier back-end can be obtained by the microwave self-checking phase calibration. Based on this, the entire tracking channel can be divided into two sections: the first section is from the antenna feed source to the front of the field effect amplifier, and the second section is from the field effect amplifier to the tracking receiver. Then the phase of the entire tracking channel is the sum of the phase of the field effect amplifier front-end and back-end.[11]

Assuming that the phase of the field effect amplifier front-end at a certain frequency is φ1, and the phase of the field effect amplifier back-end is φ2, the phase φ of the entire tracking link is

$$\varphi = \varphi 1 + \varphi 2 \tag{11}$$

This is a phase calibration method based on channel segmentation. It utilizes the high stability of the field effect amplifier front-end and the comprehensive coverage of the microwave self-checking on the field effect amplifier back-end to achieve efficient and accurate phase calibration.

5 Conclusion

This paper analyzes the channel characteristics of the shipborne USB system and studies the phase-frequency relationship of the field effect amplifier front-end. According to the phase-frequency relationship, the phase of the field effect amplifier front-end can be obtained at any frequency. Combining that the phase of the field effect amplifier back-end can be obtained by the microwave self-checking phase calibration, a segmented phase calibration method is proposed. This method is a new idea based on the study of channel phase-frequency characteristics, which can effectively solve the problem of no-tower calibration of the shipborne USB system at sea.

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