Design of Portable Reflectivity Test Probe

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Abstract. This paper introduced the design of a portable probe which can measure the reflectivity of the surface radar stealth coating. By using swallowing pulse in the design of variable frequency division phase-locked frequency synthesis technology to microwave circuit, automatic control circuit and the H horn probe integration, solve the rigid connection deformations of RF cable and adapter vulnerability caused by the phase and impact the measuring accuracy of standing wave change. With the special design of the new probe, it has the characteristics of high stability, good repeatability, small effect of environmental temperature, excellent reliability and automation.

1. Introduction
The radar stealth coating applied to the metal surface of the weapon equipment is used to reduce the reflection of the radar electromagnetic wave by the weapon equipment. The basic parameter that characterizes the stealth property of radar stealth coating is its reflectivity to electromagnetic wave [1]. Due to the differences in spray uniformity, consistency, and the operational characteristics of weapon equipment of radar stealth coatings, their absorbing properties decrease to different degree with the use time or the movement characteristic of weapon equipment. When to repair and replace the radar stealth coating in which area of the equipment surface, it needs to be checked on the spot, maintained and repaired in time to meet the effectiveness of equipment stealth property.

The traditional probe is connected to the host of the test equipment through a micro-wavelength cable. During the use, due to the frequent need to move the probe's position, the twists and deformation of the microwave cable will lead to changes in the phase and the standing wave of the microwave transmission path affecting calibration accuracy, resulting in measurement error[2]. On the other hand, different frequency bands require different probes. Replacing the probe frequently will lead to wear and poor contact of microwave cables and adapters, resulting in the drift of the test curve and poor repeatability of the measurement results[3]. In this paper, a new automatic reflectance testing probe designed for rapid and accurate measurement of radar stealth coating on the surface of weapon is introduced. The probe is different from the traditional simple probe [4](standard/ non-standard horn probe, standard/ non-standard waveguide probe), which integrates the microwave circuit and automatic control circuit, and has an adaptive optimization design on the probe structure. It satisfies the high repeatability and stability requirements of on-site measurement of radar stealth coating reflectivity.

2. The probe design

2.1. Microwave structure
The test probe microwave structure is shown in the dotted line of Figure 1. It consists of time base, broadband phase-locked source, a timing controller, an amplifier, a ring coupler, a mixer, and digital demodulation processing.

Figure 1. the microwave structure of probe.

In the design, the constant temperature crystal is used as the reference time base [5] to provide the frequency reference for the whole system, and the frequency output accuracy is stable and not affected by the environment temperature. Using the constant temperature crystal as the reference source, it is controlled by a closed-loop which consist of the VCO, loop filter, frequency divider, phase detector and controller. The frequency output accuracy is equivalent to the reference source ensuring measurement repeatability and dynamic range[6]. The timing control double-locked phase source simultaneously transforms the output frequency, and the two are separated by a fixed frequency to form a fixed intermediate frequency super-heterodyne structure [7]. The phase-locked source and the microwave devices such as the amplifier, the circulator and the waveguide probe are all solidified on the generalized probe. The microwave structure of the special structure eliminates the rigid connection line of the microwave RF signal, and removes the influence of the RF connection contact not tight or attenuation easily change with the cable deformation.

2.2. Band design

The probe adopts a sub-band design, and the design idea of each band is generally consistent. Taking the 8GHz~12GHz band as an example, the design scheme is as described. The VCO uses the HMC588, which has an output frequency range of 8 GHz to 12.5 GHz, an output power of +5 dBm, and a low phase noise of -95 dBc/Hz@100 KHz. It is powered by a single power supply +5V. The other part adopts HMC702, which integrates phase detector, reference frequency division, dual mode frequency division and dual-modulus prescaler [8] on a single chip. Has the following features:

1) The cycle-skipping prevention function helps the phase-locked loop to quickly stabilize the phase lock;
2) Ultra-low phase noise: output 12GHz, using 50M reference, -103dBc/Hz@20KHz;
3) VCO input frequency up to 14GHz, fully adapted to the frequency synthesis requirements of 8-12GHz;
4) Fixed front divider frequency division;
5) 16-bit loop integer divider, 24-bit loop fractional divider, if 50M reference is used, the frequency resolution can reach 6Hz;
6) Reference input frequency is up to 200MHz;
7) A crystal oscillator which is suitable for CMOS/sine wave output.

In summary, the HMC702's highly integrated features provide a reliable, high-performance frequency synthesis source [9]. The connection block diagram is shown in Figure 2.
2.3. Probe structure
The probe structure adopts an H-horn structure. Using the 3D full-wave electromagnetic simulation software CST, after repeated simulation, the optimal expansion angle and length of the expansion section are selected. The probe structure is shown in Figure 3, and the unit is mm. ① is the measuring port of the probe. It needs to be closely attached to the radar stealth coating during the measurement. The port length is 32mm (X-band) and the height is 10.16mm (X-band). ② is the expansion section with special expansion angle and expansion length. The expansion angle is about 13.2°, the length of the expansion section along the axis is 39.5mm (X-band); ③ is the traditional waveguide, the section size is 22.86mm × 10.16mm (X-band); ④ is the standard waveguide flange (X-Band).

To the radar stealth coating (reflectance is about -5dB to -7dB and thickness is 0.4mm), the test results of the H-horn structure can be very well matched (offset value is less than or equal to 0.2dB) under the far field conditions. The test results of the standard waveguide [11] deviate from the curve under far field conditions by 0.6dB to 1.6dB. As shown in Figure 4.
The same conclusion can be drawn by testing more radar stealth coatings, that is, comparing with the standard waveguide structure, using the H-horn structure to test the radar stealth coating, the obtained curve can better approach the test result under the far field conditions.

3. key technologies

3.1. Broadband RF signal generation technology

The phase-locked frequency synthesis scheme using the swallow pulse variable frequency divider uses a radio frequency integrated circuit to have a faster phase-locked stabilization time [12] during the frequency-by-frequency scanning process. The composition of the swallow pulse divider is shown in Figure 5.

![Figure 5. The block diagram of the swallow pulse divider](image)

The swallow pulse divider includes a dual-modulus prescaler, a main counter, an auxiliary counter, and a mode control circuit. Dual-modulus divider has \( \frac{P}{\text{P}} \) and \( \frac{P+1}{\text{P}} \) Two crossover modes. In Figure 5, when the mode control circuit is in high level, the division ratio of the dual-modulus divider is \( \frac{P}{\text{P}} \). When the mode control circuit is in low level, the division ratio of the dual-modulus divider is \( \frac{P+1}{\text{P}} \).

In Figure 5, when the mode control circuit is in high level, the division ratio of the dual-modulus divider is \( \frac{P}{\text{P}} \). When the mode control circuit is in low level, the division ratio of the dual-modulus divider is \( \frac{P+1}{\text{P}} \). After that, the input pulse continues, and the dual-modulus divider continues to work with the main counter until the main counter is full. \( N \), the mode control circuit resumes high level, dual-modulus divider recovery the frequency division ratio at \( \frac{P}{\text{P}} \), each component enters the second counting cycle. As mentioned above, in a counting cycle, the total pulse amount is:

\[
N = (P+1)A + P(N-A) = PN + A \tag{1}
\]

The swallow pulse division ratio is:

\[
\frac{f'_0}{f_0} = \frac{1}{PN + A} \tag{2}
\]

In the formula, \( f'_0 \) represents the repetition rate of divider output, \( N, A \) are all integers. The above formula shows when a frequency synthesizer is constructed by a swallow pulse divider, the lowest frequency interval can be equal to \( f'_0 \), and the output frequency is:

\[
f_0 = (PN + A)f'_0 \tag{3}
\]

According to the frequency division principle, the principle of the swallow pulse phase-locked frequency synthesizer is constructed and shown in Figure 6.
Figure 6 shows the two counters \( N \), \( A \). Their actual count values can be predetermined by the channel selection switch through the logic storage circuit to achieve high frequency, small interval and preset purpose [13]. Here, the preset memory unit can be realized by a single chip microcomputer (SCM), an EPROM or other storage unit.

3.2. Frequency Control SCM Requirements Design

A single-chip microcomputer is needed on the probe to change the output frequency of the two phase-locked loops, and control the acquisition card for data acquisition. At the same time, at least one serial port must interact with the computer [14]. The design requirements are as follows:

3.2.1. Number of IO ports

The SCM should have enough IO ports to complete the control function, using HMC phase-locked loop chip, two phase-locked loops SEN, SCK, SDI and SDO (total 8); 2 trigger signals; 2 serial ports. A maximum of 12 pieces are required. At least 16 single-chip microcomputers meet this requirement.

3.2.2. In-chip storage space

The storage resources in the SCM can store the register code words required for the two phase-locked loops. The longest sweep band is 6GHz bandwidth, 1200 points at 5MHz, total 2400 points for two phase-locked loops, 2 bytes per register, a total of 4800 bytes, about 4.8KByte. The program code includes serial ports communication, control phase-locked loop write and other functions, and the occupied code amount will not exceed 1Kbyte. So 8Kbyte of in-chip space is sufficient, and the 16Kbyte single-chip memory can be selected.

3.2.3. Execution efficiency

The speed of the SCM is required to be as fast as possible. Both the C8051 and the AVR are SCM with a reduced instruction set structure, and the instruction cycle is equal to the machine cycle. Compared with the 89c51 and PIC SCMs, the external 12MHz crystal oscillator, the instruction cycle of C8051 and AVR is also 12MHz, while he instruction cycle of 89c51 is 1MHz, PIC is 3MHz. So we only consider the models in the C8051 and AVR. However, the IO port of such a SCM follows the ‘read-write-read’ operation step, and it takes 2 instruction cycles to change the IO level.

After simulation, a complete write operation is performed on the two phase-locked loops by using a single-chip microcomputer. A total of 10 32-bit registers had been written, and the instruction had been executed 4,064 times. Under the 8 MHz crystal oscillator, it takes 508 mS [15]. If using the 24MHz clock source, the time can be shortened to 170uS. Consider the longest time, that is, the sweep bandwidth of 6 GHz, one point every 5 MHz, to complete a sweep measurement requires the SCM to complete 1201 times operations on the two phase-locked loops. A total of 205mS is required. Changing the frequency one time at the actual operation doesn’t require rewriting the 5 registers of each phase-locked loop, so the time will be shorter. If we only need to write one register for changing a frequency point, then it is only 42mS [16] to control the two phase-locked loops to complete one sweep.
The probe uses a 24MHz clock, so we can use a reduced instruction set SCM that can be operated at this clock.

3.2.4. Power dissipation
Because it uses battery power, it consumes less power.

3.3. Calibration Technology
The test probe is a single-port component, and this design uses a single-port calibration technique. The model is shown in Figure 7:

![Figure 7. the model of the single-port technique](image)

Each probe requires three calibration kits of known load (short-circuit load, short-circuit delay load, matched load) to solve for three independent error quantities \(a\), \(b\), \(c\):

\[
\Gamma_{d1} a + b - \Gamma_{d1} \Gamma_{m1} c = \Gamma_{m1} \quad (4)
\]

\[
\Gamma_{d2} a + b - \Gamma_{d2} \Gamma_{m2} c = \Gamma_{m2} \quad (5)
\]

\[
\Gamma_{d3} a + b - \Gamma_{d3} \Gamma_{m3} c = \Gamma_{m3} \quad (6)
\]

In order to achieve a perfect calibration results, each set of probes needs to provide an additional set of high-precision calibration kits, which is costly and has a complicated calibration algorithm. It is generally only used on high-precision instruments, such as microwave vector network analyzers (VNA). On the other hand, calibration techniques have certain limitations in eliminating system internal errors [17]. If the internal impedance mismatch of the system and the standing wave on the probe face are too large, the calibration can only partially improve the measurement results. Therefore, the probe structure also needs to be carefully designed to reduce the undesired conditions such as impedance mismatch and surface standing wave [18]. Therefore, the combination of calibration technology and probe structure design can ensure the accuracy of system measurement to the utmost.

The test probe is calibrated with a single port at design time and does not require calibration when used in the field. Due to the use of all radio frequency integrated circuits, as well as the structure of the integrated structure of the RF circuit and the probe, the temperature uniformity of the microwave system circuit and the consistency of long-term use are greatly guaranteed. Therefore, the way of one-time calibration and periodic calibration checks before leaving the factory can solve the calibration problem in daily use once and for all. Of course, the user can also directly measure the smooth aluminum metal plate with the probe before each test, and the curve should be a straight line of 0 dB with a deviation of 1 dB or less to confirm that the calibration state of the probe is normal. If the calibration status is not normal, it is very possibly that the state of the probe (loose structure, device failure, contamination by oil, etc.) has changed significantly and needs to be repaired.

4. verification test
Two samples of radar absorbing coating material were fabricated, and the standard reflectance data of the two samples were obtained by using the laboratory vertical reflectivity arch method. Then use the portable absorbing coating reflectance test system to measure the reflectivity of the same two samples.
of the material from 1 to 18 GHz, and find out the difference between the segmentation measurement data and the key point reflectance value of the standard data as shown in Table 1.

Table 1. Reflectance test data comparison difference.

| Frequency (GHz) | 1.5  | 3.0  | 6.0  | 10.0 | 15.0 |
|----------------|------|------|------|------|------|
| 1#sample difference (dB) | 0.36 | 0.21 | 0.73 | -0.34 | 0.06 |
| 2#sample difference (dB) | 0.28 | 0.49 | -0.11 | -0.58 | 0.53 |

According to statistics, the maximum difference of the reflectance of the portable absorbing coating reflectance test and the vertical reflectance by arch method test is <1 dB in the range of 1 to 18 GHz.

In order to verify the repeatability of the system, for the same absorbing coating sample, the vertical reflectance by arch method test system was used to perform one measurement and the standard data was recorded. Then use the portable absorbing coating reflectance test system for 10 measurements. Record and statistics as shown in Table 2 at intervals of 2 hours each time:

Table 2. Maximum difference statistics between 10 measurement data and standard date.

| Frequency | 1st  | 2nd  | 3rd  | 4th  | 5th  | 6th  | 7th  | 8th  | 9th  | 10th |
|-----------|------|------|------|------|------|------|------|------|------|------|
| Maximum difference | 0.73 | 0.56 | 0.60 | 0.54 | 0.43 | 0.67 | 0.55 | 0.42 | 0.65 | 0.53 |

The tests have shown that the absolute repeat error of portable absorbing coating reflectance measurements is <1 dB.

5. Conclusion

In this design, the microwave circuit is integrated on the probe, and the microwave circuit and the front-end signal feeding part are completely connected by the solidified circuit, which removes the RF cable connection between the host and the probe in the conventional manner. The microwave signal is generated and transmitted in the probe, and the echo signal is received at the same time. The data are processed to improve the degree of automation. The specially designed new portable probe has been tested by the laboratory and has the characteristics of high measurement stability, good repeatability, small influence on the ambient temperature, excellent vector cancellation effect, high reliability and high degree of automation.

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