Design and Implementation of a T/R Module Automatic Test System

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Abstract: Transmit/Receive (T/R) module is a key part of Active phased array radar (APAR). It is necessary to test (T/R) the module strictly before it is set up into the radar system, which is called Off-Line Test. An APAR system is generally composed of thousands of T/R modules, which results in the heavy test task. For the difficulties of heavy test task and complex operations, a T/R module automatic test system is introduced in this paper, including the design of the hardware platform and software system, especially the data processing and the timing control design. The system is applied successfully at present and shortens the test time to 0.5 hour from the traditional 20 hours for a Ku-band T/R module with 16 channels. It is characterized by high test efficiency, accurate measurement results and easy operation, hence solving the difficulties of T/R module test effectively.

Keywords: Active phased array radar (APAR); T/R module; Off-Line Test; Automatic test system

I. Introduction

Active phased array radar (APAR) is widely used in modern radar. Generally, an APAR encompasses a large number of Transmit/Receive (T/R) modules, antenna elements and passive feedback systems. Among these components, it is the T/R module who accomplishes the following works, e.g. amplifying the power of signals, providing special phases and amplitudes for beam forming and scanning signals. Therefore, the performance of T/R module is directly related to the whole radar system

In general, there are hundreds or even thousands of T/R modules in an entire radar system and each one has to be tested strictly before it is applied into the radar [1]. This kind of test is known as Off-Line Test. But the indices needed to be test in a T/R module varies from several to tens, which means that it is almost impossible to finish the huge test task by hand. Currently, several famous foreign centralized automatic T/R module test stations have been established [2], e.g. the Wiltron360B system [3]. In the United States, Agilent Instrument Company has successfully developed an analogous automatic test system, but its official price is about 20-50 million dollars. Besides, it belongs to confidential category abroad[4]. Therefore, developing an unique automatic T/R module test system is of greatly practical significance.

In terms of organization, Section Ⅱ analyzes the whole test scheme from three parts. Design details including hardware, software and the overall test process designs about the system are presented in Section Ⅲ while Section Ⅳ demonstrates some real test results for a Ku-band T/R module with 16 channels. Finally, Section V concludes this paper.

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II. Test Scheme Analysis

T/R module is an integrated component with multiple channels and working modes including receiving and transmitting. Furthermore, it contains not only analog microwave circuits to complete signal processing work, but also digital circuits to adjust the phase and amplitude of the signals. Thus, the T/R module test owns the following characteristics [5].

A. Large Number of Indices

Note that in Off-Line Test, T/R module does not work in real environment, simulative more practically. Thus, only indexes in its receiving mode are tested in this situation. Once the test results are obtained from our designed test system, comparing them with criterions expected to determine whether the T/R module is qualified or not. Meanwhile, the correctness of the automatic test system can be verified from the results. To be more explicitly for readers to understand, indexes are enumerated as follows: Voltage Standing Wave Radio (VSWR), Zero-Gain, Zero-Phase, Zero-Gain Consistency (ZGC), Zero-Phase Consistency (ZPC), Phase shift accuracy assessed in RMSE(PS-RMSE), Gain accuracy also assessed in RMSE(G-RMSE). The specific explanations about them will be presented in Section Ⅲ.

B. Long Test Time

T/R module usually plays a control role in the system with multiple channels and working modes. What is more, it is impossible to obtain PS-RMSE and G-RMSE straightforward. Firstly, every working mode has to be tested and the related data are recorded simultaneously. Secondly, compute the RMSE values according to the data recorded afore. There is no doubt that it takes a long time to accomplish the whole task by hand so it is necessary to exploit an automatic test system.

C. Intuitional Test Results

Given that there are many indices to be measured in T/R module test, it is in great demand for them to be classified and then stored to make the later dealing work conveniently [6]. Considering this term, the final results are automatically saved as an Excel report in this paper.

III. Design of Test System

A. Overall Test System Design

Firstly, it is noted that the whole test is divided into two parts including phase state and gain state test. Specifically, phase state means that only the phase value of T/R module is changed while the gain value stays invariably. On the contrary, the gain value of T/R module is changed while the phase value stays invariably when it is in gain state. Besides, S-parameter test scheme using continuous wave signals is used in this system.

Actually, it is worth nothing whether the input signal is discrete pulses or continuous waves, for the electrical characteristics of the T/R module are the same in both above situations. However, S-parameter test scheme using continuous wave signals is mature and easy to fulfill. Hence S-parameter test scheme with continuous wave signals is adopted to accomplish the T/R module test work [5].

In reference [5], S_{21} parameter is recommended to show the transmitting features of the two-port network. In detail, modulus of S_{21} is recognized to be the amplitude alteration of the two-port network, caused by the components inserted into the matching system. And the phase variation generated by the components to be tested is characterized by the phase of S_{21}, i.e. $\Phi_{21} = \arg S_{21}$. Indeed, once these definitions are clearly introduced, it is very easy to understand that the phase values we read from the VGN are the phase shifts caused by the T/R module. However, for APAR which usually contains numerous T/R modules, the phase and amplitude consistency owns more sense than the absolute phase and amplitude shift values. To be more specific, it requires each component in the APAR has the same amplitude and phase, in theory, while the control order indicates both of the two shift values are zeros. Only under this condition can we get the referencing phase and amplitude named as Zero-Phase and Zero-Gain as alluded to above in Section Ⅱ. In this paper, ZPC and ZGC (full-spelling are also in Section Ⅲ) are used to evaluate the consistency of T/R module in phase and gain, also see [5] for details.

Furthermore, precise timing control is necessary for the T/R module to work normally. And all of the timing control and other program blocks (e.g. data acquisition, processing, storage) are designed by means of functions in LabVIEW and SCPI (Standard Commands for Programmable Instruments) commands [7-8]. In simple terms, no extra hardware resources except for the voltage, current sources and additional process are in need. Moreover, a test system Graphical User Interface (simply written as GUI) is developed for operation simplicity. Thus, the complex test process becomes briefer and test efficiency is substantially enhanced.

B. Hardware Design

The hardware resources in the test system mainly include: VGN, a Master PC, T/R module, voltage source, current source, two isotropic microwave signal transmission lines, General-Purpose Interface Bus, simply written as GPIB, Line Print Terminal port, abbreviated as LPT, several electric wires, etc. In Fig.1, we display the connection sketch map between them. In particular, traditional two-port network test method is adopted to measure the gain and phase about the T/R module in its receiving mode while VNA acts as the main measure instrument, see [5] for details. Off-line Test utilizes one of the two ports in Vector Network Analyzer (VNA) to provide transmitted microwave signals for the T/R module and another to received microwave signals dealt by it. Obviously, some changes about the gain and phase of the signal will occur after it propagates through the T/R module. Actually, these changes in gain and phase are the original data we expect exactly. The VNA collects these information to fulfill data acquisition work.

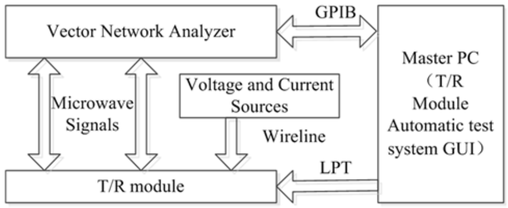

Fig.1. Hardware resources connection sketch map

C. Software Design

There are several functions which are mainly completed by the software system, including automatic calibration of VNA, parameters initialization, data acquisition, processing, and storage, etc. In Fig.2(a), software design flow chart is demonstrated exhaustively. Specially, calibration file is downloaded from the master computer to finish the calibration of VNA. Configure Measurement.vi and Configure Display Trace.vi (which are systematical inner functions in LabVIEW) are employed to create traces (see, e.g., [7] and the references therein) to show our test vividly. Since one T/R module contains multiple channels and working modes, it is very important to configure channel and mode numbers for the T/R module. What is more, timing control design is necessary for the T/R module to work normally. Once these are all done, the T/R module is well prepared which means that it is time to collect the original data. Generally, Read Data.vi is taken by the test system to read data from VNA and NI_Report Generation Toolkit is applied to complete data storage work. It is worthwhile to indicate that both Read Data.vi and NI_Report Generation Toolkit are functions in LabVIEW, see [7] for details.

Particularly speaking, all of the test system is developed in LabVIEW. Note that the three most important parts of the automatic test system are time-series design, data process and storage designs, specific design process about these three parts are described below in detail.

1) Timing Control Design

In Off-Line Test, timing control design is accomplished in advance according to the T/R module working references. Fig.2 (b) shows the several main timing control blocks in the system and the logical relationships about them. Fig.3 specifically demonstrates the waveforms of the sectional timing control such as trigger clock, data clock, transmitting and receiving control clock. Following the T/R module working references, the T/R module is required to be in standby mode at the beginning during which some control bits should be set as low level, voltage and current sources are modulated into a reasonable range. Once all these works are well prepared, the automatic test system will load relative timing control block through LPT from the master computer and run automatically to execute the whole measurement process. It is worthwhile to note that all the control work is incarnated by timing control. Once more for emphasis, all these timing control blocks are designed as function packages in LabVIEW afore. All the manipulator need to do is setting them appropriately on the automatic test GUI. More details will be introduced in later remark.

Remark: The automatic test GUI also belongs to software category. However, the objective of the paper is not so much to present the GUI design (see, [7] and the references therein) but to introduce the whole test system. So we omit the corresponding details about the GUI design for brevity. Fig.4 demonstrates the test GUI.

2) Data Processing

According to definitions of the indices and the working references of VNA, some (e.g. phase, gain) can be directly obtained from the S_{21} parameter while others are computed from the S_{21} parameter. See below for details. For easy understanding, some necessary notations about the meaning of these indices are given as follows.

Indices can be obtained directly from the parameters including VSWR, Zero-Phase and Zero-Gain.

VSWR: Voltage Standing Wave Radio;

Zero-Phase: The phase of T/R module while it is in gain state in which the phase shift value is defaulted as zero or in phase state in which the order implies that the phase shift value is zero;

Zero-Gain: The gain of T/R module while it is in phase test state in which the gain alteration is defaulted as zero or in gain state in which the order implies that the gain alteration is zero.

Indices that are calculated from S_{21} are similarly listed for reading convenience.

Let $\Delta\phi_{R_{0\max}}$ and $\Delta\phi_{R_{0\min}}$ separately denotes the maximum and minimum value of Zero-Phase in the same frequency. Similarly, G_{omax} and G_{omin} independently represents the maximum and minimum value of Zero-Gain in the same frequency. Then, Zero-Phase Consistency (abbreviated as ZPC) $\Delta\phi_{R_0}$ and Zero-Gain Consistency (simply written as ZGC) ΔG_{o} are

$$\Delta\phi_{R_0} = \pm(\Delta\phi_{R_{0\max}} - \Delta\phi_{R_{0\min}})/2 \quad (1)$$

$$\Delta G_{\text{o}} = \pm(G_{\text{omax}} - G_{\text{omin}})/2 \quad (2)$$

The specific sense of Phase shift accuracy assessed in RMSE(abbreviated as PS-RMSE) and Gain accuracy also evaluated in RMSE(simply written as G-RMSE) are given by

$$\text{PS-RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\phi_i - \phi_{i0})^2} \quad (3)$$

$$\text{G-RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\text{A}_i - A_{i0})^2} \quad (4)$$

where ϕ_i and ϕ_{i0} respectively denotes the actual measurement and theoretical value of phase in our test frequency. Analogically, A_i and A_{i0} separately manifests the actual measurement and theoretical value of gain in our test frequency, n denotes the number of total test states. Considering the T/R module used contains 6 control bits, n can be computed by $n = 2^6 = 64$.

3) Data Storage

Given that it is very complicated to manage the large amount of data produced in the T/R module test, LabVIEW Report Generation Toolkit is taken to store the final test as an Excel report. So that it is convenient to carry out later process about it such as data comparison, analysis, printing, saving and so on [9-11].

D. Overall Test Process

The whole Off-Line Test is carried out by the following steps:

Preparation before Formal Test

a) Connect every part of the automatic test system according to Fig. 1.

b) Pre-heat and calibrate the vector network analyzer. Specially to say, before the test begins, turn on the vector network analyzer until it is stable. Then, the Master PC sends relative orders to VNA via GPIB to perform calibration work automatically, see [12] for details.

c) Set voltage and current sources under the instructions of T/R module working references. Evidently, reasonable settings about every part of the test system are indispensible and prior conditions for the whole system to work normally.

Formal Test

Firstly, turn on the T/R module automatic test software on the Master PC. Secondly, the test software sends relative orders (see, e.g., timing control) through LPT to T/R module to make it work in our expected receiving mode. Thirdly, the VNA accepts orders coming from Master PC through GPIB so that it can provide input signals for T/R module. Besides, the VNA completes data acquisition synchronously. Finally, the system automatically calculates the ultimate test results according to the data collected and stores them as an Excel report. It should be noted that the four steps mentioned above are not as separately as they are expressed here. For the test system working as a whole, only if every part of the system runs harmoniously can we get the true expected test results.

IV. Test Results

The automatic test system has been applied successfully at present in the test of T/R module (with 16 channels, see Fig.5) which belongs to a Ku-band APAR. For comparison, we do some statistical work about the performance between the traditional test method and our automatic test system and the conclusions are as follows. In general, it approximately takes about 20 hours to fulfill all of the test work of one T/R module with 2 or 3 people working together in traditional method. Besides, some unpredictable errors will be brought in because of our handmade operation. However, 0.5 hour is enough for our proposed automatic test system to finish the identical test work with just one operator. In addition, errors caused by our unstable handmade operation are eliminated naturally for the reason that the whole test process is completed automatically thoroughly. Our proposed automatic test system greatly improves the efficiency of the T/R module test. For easy reference, the test results about one T/R module (the reader is reminded that it contains 16 channels) of a Ku-band APAR are summarized in Table 1 and Table 2.

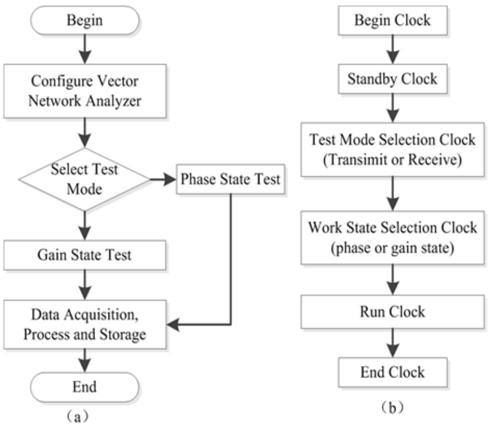

Fig.2. Design flow chart of the test system software
(a) Software. (b) Clock Blocks.

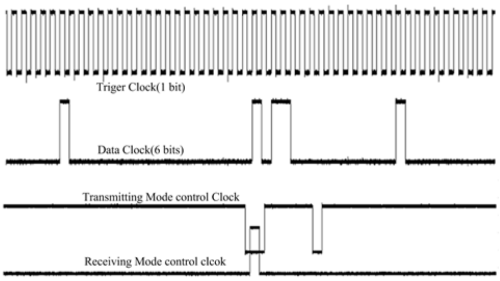

Fig.3. Timing Control

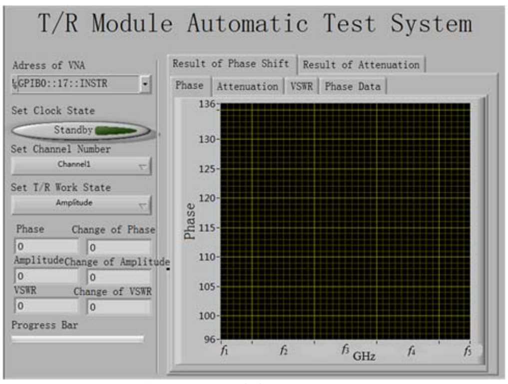

Fig.4. GUI of the test system

V. CONCLUSIONS

In this paper, an automatic test system is developed aiming at testing the digital receiving indices of the T/R module, which solves the difficulties of the T/R module test. In order to improve the testing efficiency and intuitively display the test results, the timing control, data analysis, data storage as well as a GUI blocks are all integrated in the automatic test system. The system has the advantages of convenient operation, accurate and reliable test results, which is a good solution to the problem of T/R module test.

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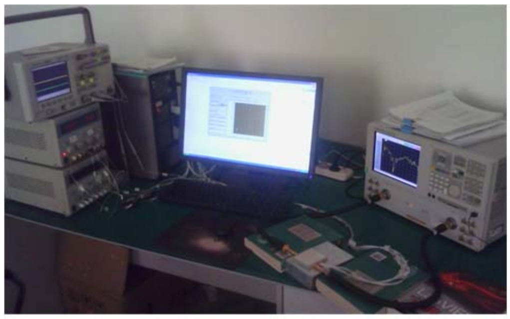

Fig.5. Real measurement platform of the system

TABLE I. Test results of one channel in phase state

Frequency(Hz)	Criterion	f_1	f_2	f_3	f_4	f_5
PS-RMSE(degree)	≤5	2.642	2.684	2.698	2.683	2.699
Zero-Phase(degree)	$\propto f$	124.032	114.4694	104.6514	95.017	85.767
VSWR	≤1.8	1.445	1.4499	1.4498	1.450	1.453
Zero-Gain(dB)	≥14	14.85	14.745	14.734	14.70	14.69
ZGC(degree)	≤1	0.582	0.568	0.558	0.571	0.574

TABLE II. Test results of one channel in gain state

Frequency(Hz)	Criterion	f_1	f_2	f_3	f_4	f_5
G-RMSE(dB)	≤1	0.455	0.456	0.463	0.462	0.468
Zero-Phase(degree)	$\propto f$	130.802	121.262	111.770	102.064	92.886
VSWR	≤1.8	1.415	1.419	1.420	1.422	1.424
Zero-Gain(dB)	≥14	15.299	15.219	15.245	15.186	15.166
ZPC(degree)	≤5	2.732	2.861	3.135	3.208	3.535

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