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Automatic test system of full electrical parameters for space traveling-wave tubes

Dapeng Gong, Tao Huang, Jianqing Li, Zhonghai Yang and Bin Li

School of Electronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu, People's Republic of China

E-mail: huangtao@uestc.edu.cn

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Abstract

In the development of space traveling wave tubes (TWTs), there have been many problems in testing their performance, such as too many test sections, complex operation processes, long test times and large amounts of test data. In this paper, an integrated test system for space TWTs is studied to achieve an accurate, fast and complete test of its full electrical parameters. The system can automatically switch the test instruments according to the tested contents, which eliminates the manual operation of setting the test bench and reduces personal error. Then, the one-button testing of full electrical parameters is realized by means of automatic test software of space TWTs, which greatly improves the test efficiency. Moreover, a standardized and scientific test data management system is established to ensure the integrity and objectivity of the test data. Finally, the testing accuracy and stability of the system are verified by data comparison.

Keywords: space traveling-wave tubes, electrical parameters, automatic test, data management

(Some figures may appear in colour only in the online journal)

1. Introduction

Space traveling-wave tubes (space TWTs) are one of electric vacuum devices. As a key component of satellite communication and space-borne transponder, the space TWT is the most important system unit in satellite system and is responsible for the amplification, forwarding and transmission of microwave signals. However, due to extremely stringent working environment [1, 2] and high-performance requirements [3, 4], space TWTs are the electric vacuum device with the highest performance requirement [5].

With the development of automatic testing technology and the improvement of microwave testing equipment function, the automatic testing system based on virtual instrument [6] has brought great efficiency improvement to various industries. However, the tests of the space TWTs are mostly completed manually or partially by independent automatic testing program at present, which results in the following four problems.

(1) The test process is greatly affected by artificial factors. The process of data recording is scattered and data arrangement is tedious, which cannot ensure the objectivity of the test data.
(2) The test data only record the final result data, lacking the process data, which may lead to some phenomena which cannot be observed in time and cannot ensure the integrity of the test data.
(3) A comprehensive test needs to cooperate with a variety of test equipment and devices, which puts forward higher requirements for testers. Besides, the construction time of the test system is long, and the test completion time may last several hours or even longer, which cannot achieve the desired high efficiency of the test.
(4) The existing automatic test programs can improve efficiency and avoid misoperation to a certain extent, but they mainly aim at specific test parameters of specific test objects and do not form a complete automatic test system for full electrical parameters, so the designs of

these systems are not universal enough. Due to the lack of database support, they cannot succeed at forming a complete product test data package quickly and automatically. Therefore, the existing testing process is not conducive to the traceability of aerospace products, nor can it store and manage a large number of test data, nor even can it provide a reference for improving product quality.

Relevant scholars have undertaken some corresponding research in related fields. Liu *et al* established an automatic hot test system for the gyrotron-traveling wave tubes in 2017, and obtained stable output power through beam adaptive PID feedback controlled by filament heating power and cathode anode beam voltage [7]. In 2018, Yan *et al* developed an automatic hot-test system for high average/CW power gyro-TWTs, and realized unattended hot-test for 100 h without interruption [8]. Huang *et al* briefly introduced the design and implementation of automatic test system for TWT electrical parameters on IVEC 2017 [9].

The authors refer to the previous work and design a complete automatic test system of full electrical parameters for space TWTs, including integrated test platform, automatic test software, data management system. First of all, the integrated testing platform can simplify the tedious manual operation of setting the test bench and reduce the human error and the mechanical failure of the device, which is of great significance to improve the test consistency and test accuracy. Secondly, the automatic test software not only realizes the basic measurement function; the emphasis is that the authors standardize the test flow, which greatly improves the test efficiency and test accuracy. Finally, the authors design a multi-level data management mechanism to ensure data security and improve data integrity, which can provide some reference for the design and optimization of space TWTs, and scientific data management also provides the possibility for subsequent big data analysis.

The structure of the article is as follows. Section 2 introduces the framework of automatic test system for space TWTs, including test platform, test server and data server. Section 3 focuses on some key functions of the automatic test software for full electrical parameters of space TWTs, and verifies the practicability of the system by comparing the data of manual testing with automatic testing. Section 4 introduces three kinds of test data management methods. Finally, section 5 is a brief summary.

2. Framework of space TWTs electrical parameter automatic test system

Figure 1 is a block diagram of automatic test system of space TWTs, including test platform, test server and data server. Among them, the test platform is the necessary hardware equipment to complete the test of electrical parameters, which consists of the tested TWT, matrix switch, test instrument and passive components and so on. The test server is the computer running the automatic test software of space TWTs, which is used to complete the specific test of electrical parameters. And the data server is used to store the test data from the test server. The test platform is in one-to-one correspondence with the test server, and both are directly connected through the data bus (LXI). Finally, the test data are saved to the data server to guarantee its integrity and uniformity.

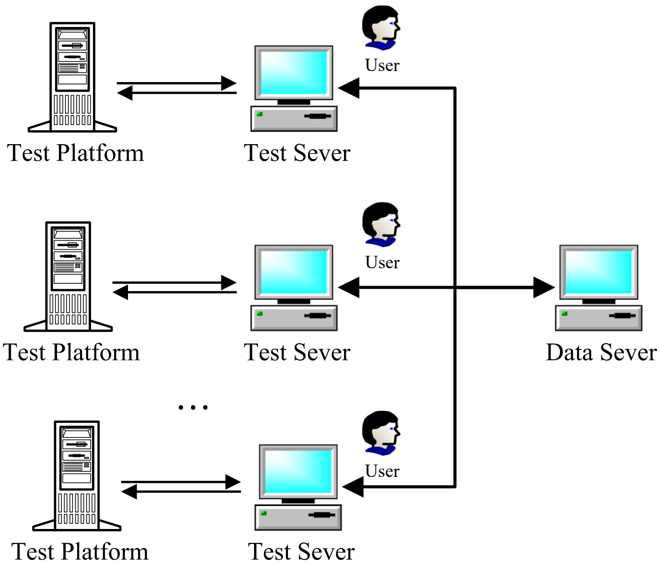


Figure 1. The block diagram of automatic test system of space traveling wave tubes.

2.1. Test platform

There are many electrical parameters of space TWT, and the test methods of each electrical parameter are different. Therefore, it is necessary to build the corresponding hardware system according to the test method before testing. However, the operation of setting the test bench will undoubtedly greatly increase the workload, which not only greatly reduces the test efficiency, but also may cause equipment damage and introduce system errors on account of repeatedly inserting and removing. Therefore, the authors have designed an integrated test platform for automatic test of electrical parameters of space TWTs, as shown in the figures 2 and 3.

The test platform is divided into two parts, namely high-power transmission loop and low-power testing loop. The former is, as shown in the blue box in the below figure, the power loop to guarantee the normal operation of the TWT under the testing, while the latter is coupled from the former to obtain the test signal and complete the test, as shown in the red box in the below figure. The two loops are connected into an entirety through the microwave matrix switch.

It is only necessary to replace the tested TWT in the platform before measurement. And the system will automatically switch the state of the matrix switch according to the tested characteristics to form the corresponding test system and complete the test. Table 1 details the connection of the matrix switch for different parameter test.

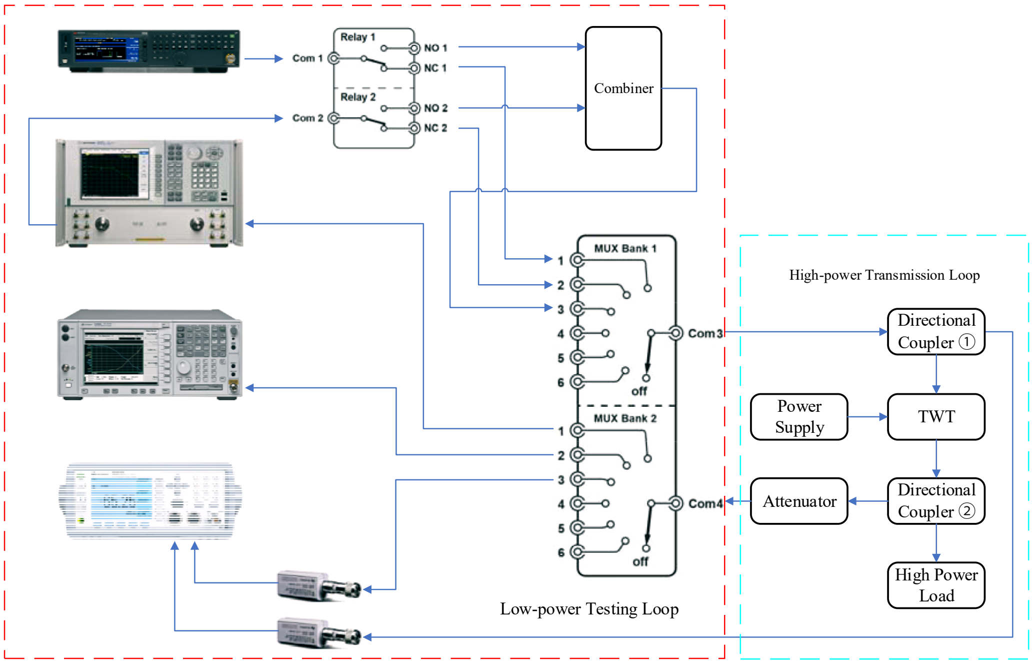


Figure 2. Block diagram of integrated test platform.

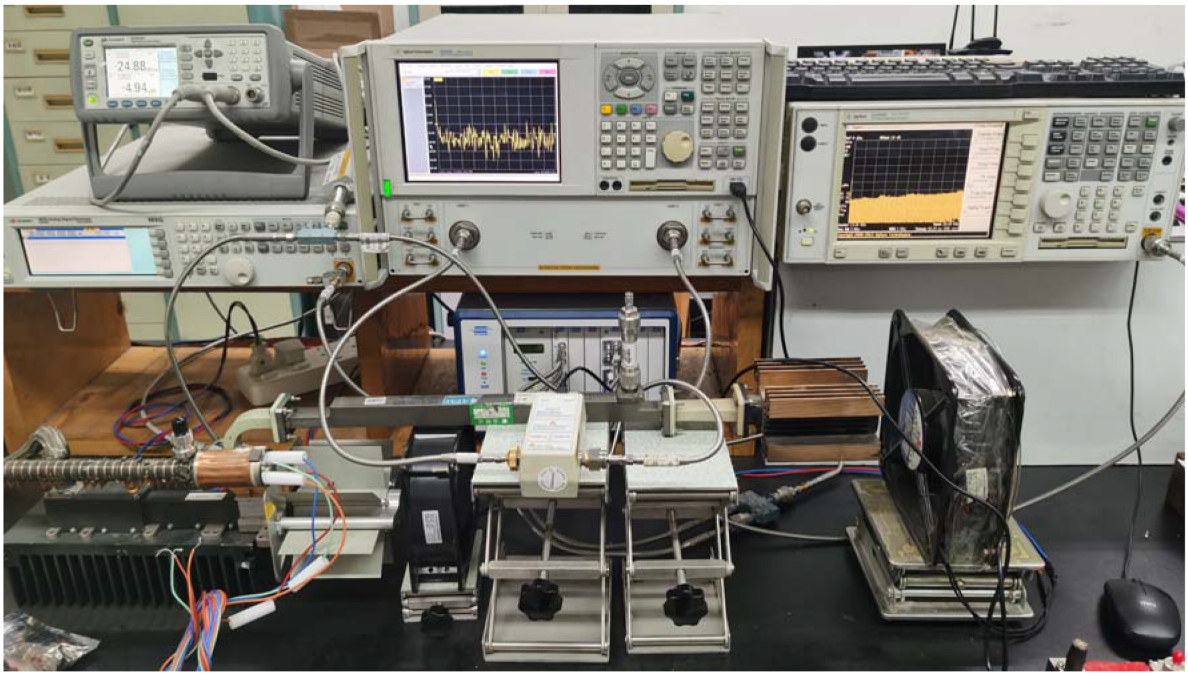


Figure 3. Image of the integrated test platform.

2.2. The test server

The automatic testing software for electrical parameters of space TWTs, the core of the test server, is developed based on NI Company's LabVIEW. LabVIEW is one of the important development environment of virtual instrument platform, which is widely used in data acquisition, data analysis and instrument control [10, 11]. The software framework is based on the producer/consumer structure, which is divided into two layers, test task and test method, as shown in figure 4. The test task is to realize the functions of parameter setting (sweeping parameters, testing parameters and test instruments, etc), starting and stopping of test process and data display. The test method is mainly the control of test process, including instrument parameter setting, acquiring of test data and process data analysis. The main purpose of this structure is to improve the uniformity of software. Different methods can be configured according to the specific test instruments. For example, harmonic output ratio characteristic, most spectrum analyzers already have the fast harmonic test module, which can

Table 1. The connection of the matrix switch for different parameter test.

Tested item	Instruments	Switch state	
1. Saturation characteristic 2. Input back-off characteristic	Signal source Power meter	Relay1: Com1 to NC1 Relay2: Com2 Negative	MUX Bank1: Com3 to 1 MUX Bank2: Com4 to 3
1. Harmonic characteristic 2. Clutter characteristic 3. Noise characteristic	Signal source Spectrum analyzer	Relay1: Com1to NC1 Relay2: Com2 Negative	MUX Bank1: Com3 to 1 MUX Bank2: Com4 to 2
1. Gain variation characteristic 2. Group delay characteristic 3. Nonlinear phase shift characteristic	Vector network analyzer	Relay1: Com1 Negative Relay2: Com2 to NC2	MUX Bank1: Com3 to 2 MUX Bank2: Com4 to 1
1. Third-order intermodulation characteristic	Signal source (Source #1) Vector network analyzer (Source #2) Spectrum analyzer	Relay1: Com1 to NO1 Relay2: Com2 to NO2	MUX Bank1: Com3 to 3 MUX Bank2: Com4 to 2

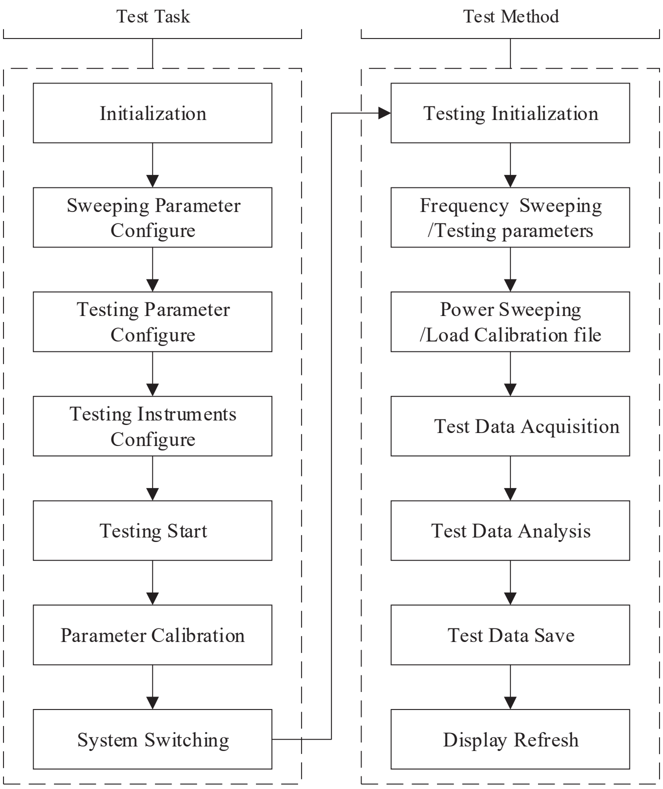


Figure 4. Unified software flow chart.

directly get the results of harmonic output ratio. However, the old model of spectrum analyzer can only obtain the amplitude of fundamental wave and each harmonic component through its basic spectrum analysis function, and then get the final test results by software calculation.

One of the core contents of automatic test software is remote communication with test instruments via data buses and operational commands. For standard instruments such as signal sources, power meters, spectrum analyzers, and vector network analyzers, VISA and SCPI are introduced to realize the above functions. Among them, VISA is the abbreviation of virtual instrument software structure and is the general name of I/O interface software standards and specifications formulated by VXI plug & play alliance [12]. Programmable instrument standard command, SCPI for short, is a standard programming language based on the existing standards IEEE 488.1 and IEEE 488.2 [13], and it follows a variety of standards, which simplifies remote instrument programming and improves interoperability of test instruments by standardizing command message and advanced utility functions [14]. For customized equipment, such as power supply of TWTs, manufacturers usually achieve device control by common data buses (such as LAN, RS232, etc) and custom communication protocol.

2.3. Data server

The core of the data server is the database. Considering the amount of data in this system, the open source and relational database MySQL developed by MySQL AB of Sweden is selected.

With the help of the database, all the test data are no longer independent but related to each other, achieving centralized storage and scientific management of test data, which is conducive to the implementation of subsequent data analysis functions.

3. Automatic test software for electrical parameters of space TWTs

An automatic test system is designed to realize automatic switching of sweeping parameters, automatic setting of test equipment, automatic acquiring, analyzing and recording of test data. At present, the system has realized the test function of all electrical parameters in table 1, including nine major items and 15 minor items. In order to improve the versatility and maintainability of the software, the process of all test characteristics is unified in the software system, as shown in figure 4.

3.1. System calibration

The purpose of system calibration is to reduce system errors and obtain more accurate test data. There are two situations in this system. One is absolute error calibration. It mainly refers to the insertion loss and coupling degree in the system, including coaxial cables, converters and directional couplers, etc. Users are required to obtain the power-frequency data (offset data) of the power loop that needs to be calibrated by other means, and then add the data to the calibration files of the system. The system will automatically load the corresponding offset data to calibrate the test data according to the test frequency in the test process. The other is relative error calibration which refers to the port calibration of the vector network analyzer [15]. Firstly, users are required to perform single-port calibration, dual-port calibration or pass-through calibration according to the tested characteristics, and save the calibrated state as a *.csa file to the local of vector network analyzer after the calibration is completed. Then, the user needs to add the *.csa file saved in the vector network analyzer to the software system. During testing, the system will automatically load the calibration file and select the corresponding test channel and trace to complete the parameter test. In addition, when the user selects the calibrated test trace, the system will automatically obtain the parameters of instrument corresponding to the test trace as optimization parameters, including scanning range, scanning points, scanning time, IF bandwidth, average parameters, smoothing parameters and so on. These parameters can be modified before or during the test to help the user obtain the optimal sweeping data. After the test is completed, these parameters will be saved and correspond to the sweep data one by one, which can guarantee the integrity of the test data. However, since some parameters are related to the calibration state, in order to achieve the most accurate calibration, it is not recommended to make great changes in the parameters such as the number of sweep points and IF bandwidth after the calibration is completed.

3.2. Test mode

In order to meet the different test requirements of users, this system sets two test modes. The first one is independent test which means the user tests an electrical parameter individually. The other is to realize one-button test by means of the integrated test platform, that is, users only need to set the test parameters and test sequence, and the system will automatically switch the test system according to the test items and complete parameters test and data storage. Therefore, the test process can perform without manual participation, and the test efficiency can be greatly improved, which is also one of the highlights of the system.

Because most of the electrical parameter tests are based on saturated driving power, such as gain variation in saturation state and group delay in saturation state, so it is necessary to obtain saturated driving power before testing some electrical parameters. For the independent tests, one method is that the user can firstly perform a saturation test to obtain the saturated driving power. The other method is to automatically perform the test of input-output power scanning (b2,1) using vector network analyzer according to user-set parameters (test frequency, power sweep range, sweep points, etc.). The system calibration cannot be achieved by the second method. However, the port calibration has been carried out prior to the test of electrical parameters, such as full dual port calibration before the group delay characteristic test. Therefore, the saturated driving power obtained by the second method must be added to insertion loss of the input loop to be the exact saturated driving power.

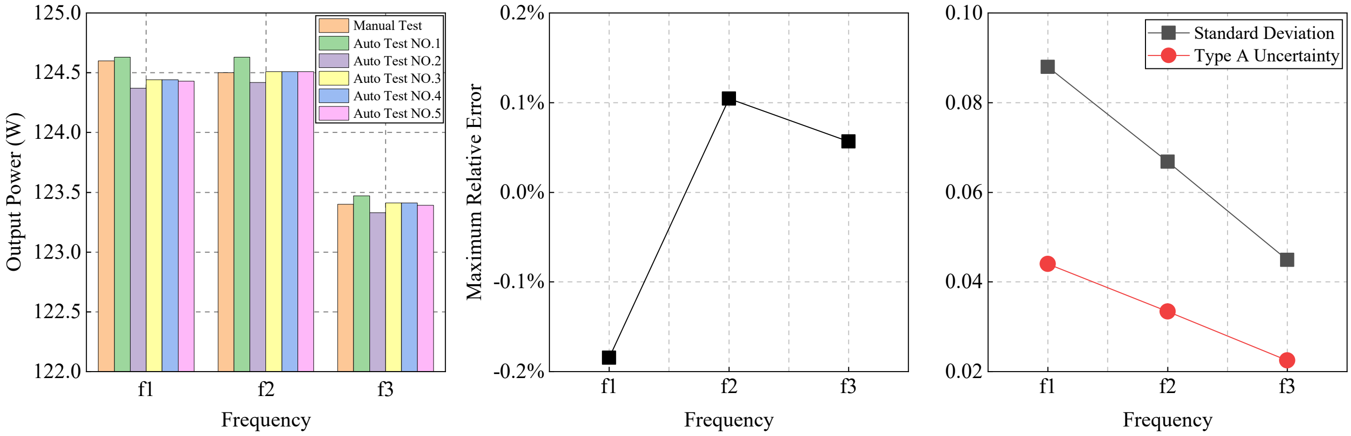
Moreover, in order to ensure the continuity of the test process and the consistency of saturated driving power, the system adopts another idea for one-button test, that is, the saturated characteristic test is the highest priority option. And the subsequent test characteristics automatically obtain the corresponding saturated driving power from the test project file of saturated characteristic.

3.3. Test data

L-band space TWT is taken as the test object. Due to space limitation, four representative electrical parameters are selected here to compare the results of manual test and five automatic tests. First of all, all the instruments in the integrated test platform are used in the four electrical parameter test methods. Secondly, the group delay and nonlinear phase-shift characteristics correspond to the two modes of sweep frequency and sweep power of vector network analyser. The maximum relative error between automatic test and manual test is used to measure whether the system can replace manual test, and the stability of the system is measured by the standard deviation and type A uncertainty of five automatic test data.

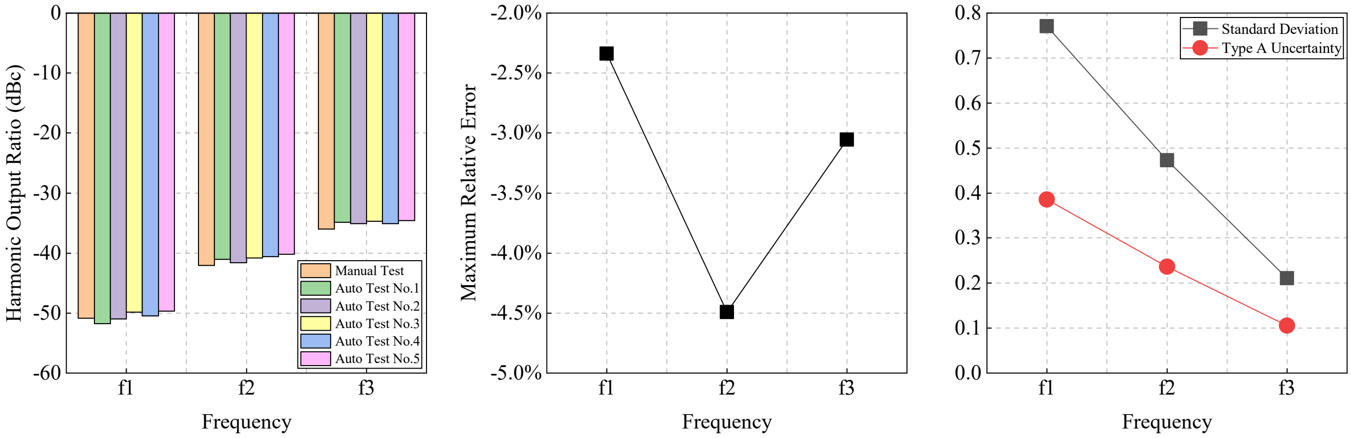
First of all, although the absolute error is relatively small, the maximum relative error of automatic test is close to 30% compared with manual test, as shown in figure 9, and the relative error of automatic test is larger with the increase of back-off power. The main reason is that the measurement value becomes smaller and smaller with the back-off power, even if the absolute error is unchanged, its relative error will become larger and larger. In addition, as shown in the above figure (figures 5–9), the standard deviation and type A uncertainty of the five automatic test data are kept in a relatively small range. In other words, the difference of data generated by any independent measurement is relatively small, which proves that the software system has good stability.

Furthermore, table 2 shows the time comparison between manual test and automatic test, wherein the automatic test time is the average time of five tests. It should be noted that the aforementioned test data for comparison are only the data of the non-linear phase-shift characteristics at central frequency, while the time comparison is the test time of performing three test frequencies. In addition, the time comparison in table 2 starts from the static state of the tested TWT, including the process of test instrument parameter setting and data recording, but excluding the time consumed by system calibration and software parameter setting. Automated testing can save at least 80% of the test time compared with manual test, so testing is more efficient. In the case of ensuring that the test



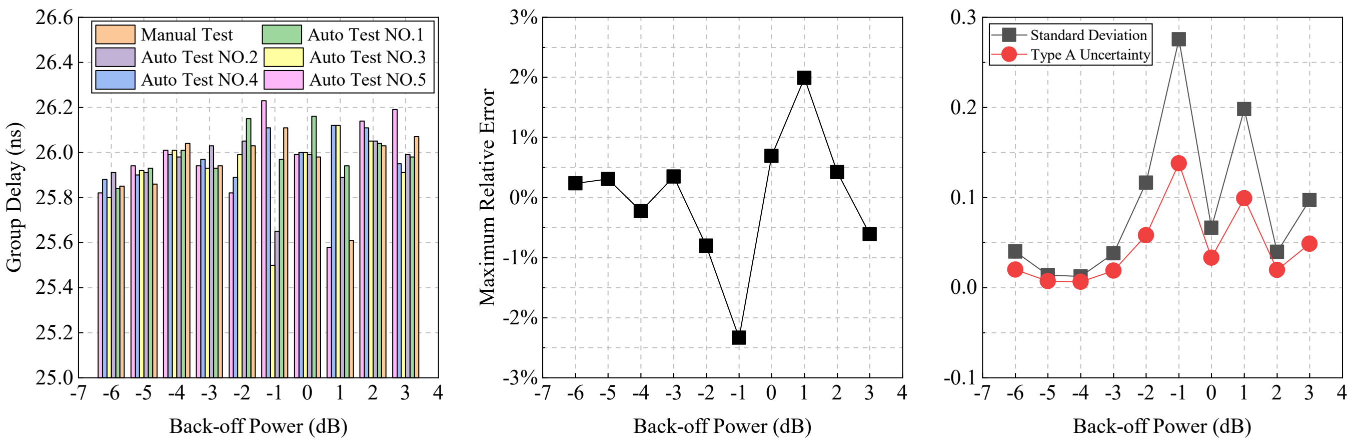
(a) Test data for manual and automatic testing (b) The maximum relative error between automatic test and manual test (c) Standard deviation and class A uncertainty of five automatic tests

Figure 5. The comparison of the saturated output power of the space TWT at three frequencies tested manually and five times automatically.



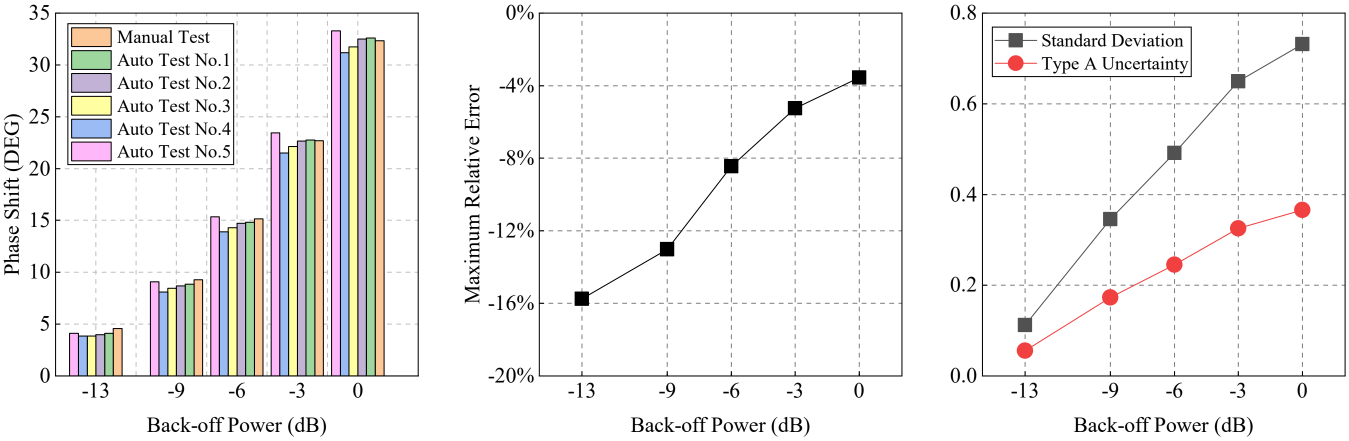
(a) Test data for manual and automatic testing (b) The maximum relative error between automatic test and manual test (c) Standard deviation and class A uncertainty of five automatic tests

Figure 6. The comparison of the second harmonic output ratio between manual test and five automatic tests.



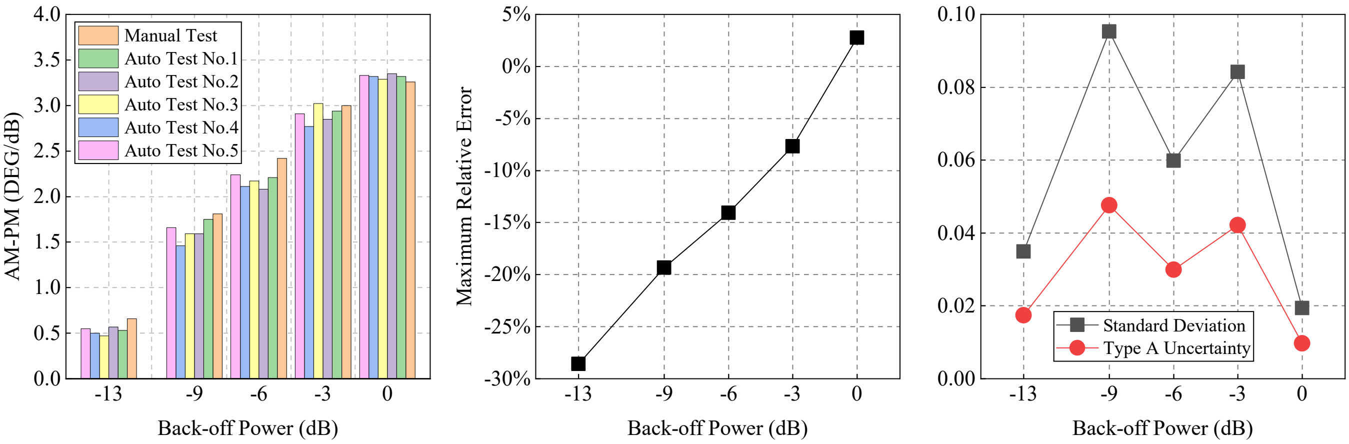
(a) Test data for manual and automatic testing (b) The maximum relative error between automatic test and manual test (c) Standard deviation and class A uncertainty of five automatic tests

Figure 7. The comparison of the group delay between manual test and five automatic tests.



(a) Test data for manual and automatic testing (b) The maximum relative error between automatic test and manual test (c) Standard deviation and class A uncertainty of five automatic tests

Figure 8. The comparison of phase shift at center frequency between manual test and five automatic tests.



(a) Test data for manual and automatic testing (b) The maximum relative error between automatic test and manual test (c) Standard deviation and class A uncertainty of five automatic tests

Figure 9. The comparison of AM/PM at center frequency between manual test and five automatic tests.

accuracy is basically consistent with the manual test, it is of great significance to use the automatic test system instead of the manual test to improve the production efficiency of space TWTs.

4. Test data management of electrical parameters of space traveling-wave tubes

There are three management forms for test data of electrical parameter of space TWTs, namely test project files, general data files and databases. The test project files contain all the parameters related to the test process, which is the key to the whole data management. As an important supplement to test project documents, general data files provide a more general form of data management to meet users' multi-level requirements. The database is the core of the database server, for it provides more scientific and standardized data management functions.

4.1. Test project files

The test project file is a very important form of data management. For one thing, it is the project document of automatic test software which saves all system information, setting parameters, test data, even screen captures, with multiple data types and a complex structure. For another thing, it is also a medium for data transfer between the test server and the data server. Therefore, the system chooses extensible markup language (XML), which has the advantages of self-description, extensibility and openness [16], as the concrete form of test project files.

As multiple electrical parameters are involved, and the setting parameters of each characteristic are different, the data structure of each project file is quite different. In order to reduce the difficulty of data analysis on the data server and make the data storage more standardized, the data structure in the test project file has been unified and standardized to some extent, as shown in the figure 10. The project files for any test

Table 2. Time comparison between manual test and automatic test.

Tested items	Time(s) Manual test	Time(s) Automatic test	Comparison (%)
Saturation characteristic	543	72	−86.74
Harmonic characteristic	191	35	−81.68
Group delay characteristic	450	70	−84.44
Nonlinear phase shift characteristic	675	77	−88.59

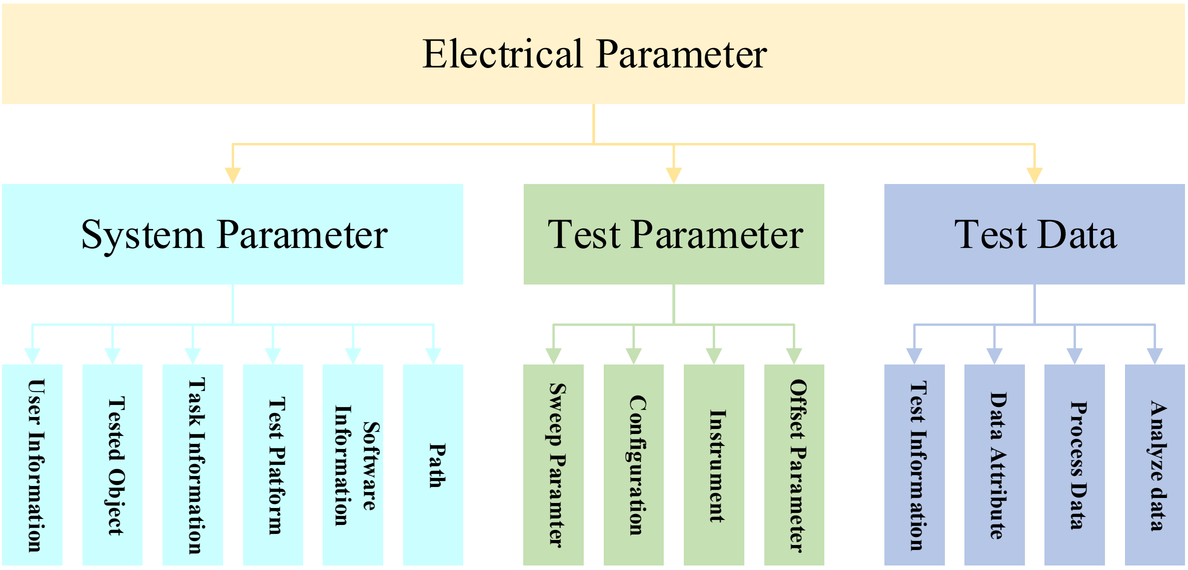


Figure 10. The data structure in test project file.

characteristics are regularly divided into three layers as shown in the figure. Among them, the difference of each file is mainly reflected in the specific content of the third layer. In addition to the parameter setting and original data related to the test, there are also a large number of flag information in the project files. First of all, the flag information is the only basis to distinguish from other project files. Then, the flag information is also the key to the subsequent implementation of structured data storage.

4.2. General data files

In order to ensure data safety, the data in the test project files will not exist in the form of plaintext, so it only can be recognized by the automatic test software. Hence, two kinds of general data files are added to the system to meet the multi-level needs of users, including system-defined data files and user-defined data reports. Among them, the former is that the system exports the test data in a fixed format, usually presented in Excel files, which is convenient for users to perform an in-depth analysis or other forms of management on the data. The latter has highly customized attributes, and the system will generate data files in the format required by the user, usually presented in Word files. It can be archived as test process data or as a product data sheet, eliminating the process of data organization by the user.

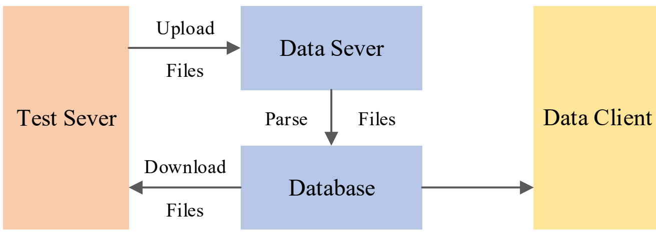


Figure 11. Data transfer process between the test server and the data server.

4.3. Database

The data files that are generated by the two methods mentioned in sections 4.1 and 4.2 need to be saved on the computer of the test service by the user, which will emerge the following disadvantages. First of all, the original data in the files are easy to be modified and the data structure is easy to be destroyed. Then, with the accumulation of tests, more and more data files will be generated, which is easy to cause data confusion.

To achieve scientific management of test data, the system will conduct structured storage of test data that are uploaded by users to the data server, which is the core of the whole data management, and its data storage process is shown in the figure 11.

On the one hand, the test project files from the test server will be stored in the database as a whole. On the other hand, the data in the files will be stored in the database structurally after being parsed by the data server. The information data in the project files will be stored as the relational flag of the database, and the original test data will be subdivided and stored independently according to the physical meaning. Thus, even if all data is divided and stored independently, they are also guaranteed to be interrelated and unique. The user can check the data by downloading the saved test project files to the test server and even complete the parameter test again with the setting parameters in the files. Alternatively, the user can remotely view test data in the database through the data client.

Since the test project files store semi-structured data, while the MySQL relational database stores structured data, so this paper adopts the storage method of XML documents based on XML Schema in the relational database, and realizes the conversion of XML documents to the relational database [17]. Because of space limitations, it is not explained in detail here.

5. Conclusion

This paper introduces an automatic test system for testing the electrical parameters of space TWTs in detail. In terms of hardware, the integrated test platform in the system eliminates the tedious operation of setting the test bench. In terms of software, automatic test software can help users quickly complete automatic testing of the electrical parameters of space TWTs. The combination of hardware and software greatly improves the test efficiency. In addition, multi-level data management modes meet the different storage requirements of users. Moreover, the test data are managed uniformly with the help of a database, which also provides the possibility for the subsequent analysis of big data.

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ORCID iDs

Dapeng Gong https://orcid.org/0000-0003-0198-7276
Tao Huang https://orcid.org/0000-0003-0351-1976
Jianqing Li https://orcid.org/0000-0003-0858-9334
Zhonghai Yang https://orcid.org/0000-0002-8021-8872
Bin Li https://orcid.org/0000-0003-4397-1651

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