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Research on Key Technologies of a Temperature-Humidity-Vibration-Low Pressure Four-Pronged Test System

Yang Liu, Pei Liu, Zekai Li, Shuangshuang Li, Zhen Huang

Beijing Zhongguancun Shuimu Medical Technology Co., Ltd., Beijing 102600, China

Abstract: Objective To address the difficulty of traditional environmental test equipment in simulating the multi-stress coupling effects of equipment in service, this paper investigates a domestically produced temperature-humidity-vibration-low-pressure integrated test system. The aim is to analyze its system structure and key technical bottlenecks, propose innovative solutions, and promote the independent research and development of environmental test systems in my country. Methods Focusing on the structural configuration and functional indicators of the integrated test system, a technical analysis was conducted from the perspectives of sealing and vibration compatibility design, pressure balance and automatic centering control, lightweight box structure optimization, and temperature and humidity regulation technology under low pressure conditions. The system was specifically validated and evaluated for its two-stage rolling seal structure, pressure self-balancing centering mechanism, stress-equalizing rib design, and efficient heat and humidity control. Results The system operates stably under a thrust of 65 kN and a vacuum of ≤0.1 kPa. The leak rate of the sealing structure is less than $1\times10^{-2}Pa\cdot m^3/s$, the axial automatic centering accuracy of the vibration table reaches 0.05 mm, the box weight is reduced by over 30%, and the response speed and uniformity of temperature and humidity control are significantly improved. The system meets the complex service environment simulation requirements of high-end equipment such as inertial navigation components, optoelectronic systems, and missile control modules. Conclusion The domestically produced four-in-one test system has achieved technological breakthroughs in system coupling capability, key component integration and environmental simulation accuracy. It has good engineering application prospects and promotion value, and is of great significance to promoting the high-end and independent development of my country's environmental test equipment.

Keywords: Four-integrated Test System; Multi-stress Coupling; Key Technologies; Independent Research and Development.

1. Introduction

With the widespread application of modern high-end equipment in aviation, aerospace, weapons, nuclear energy and other fields, the working environment in which it is located has become increasingly complex and harsh. Electronic equipment, electromechanical systems and their components often need to operate stably for a long time under conditions such as low temperature, high humidity, severe vibration and low pressure[1,2].

The coupling effect of environmental stress not only accelerates material aging, but may also lead to various failure modes such as structural fatigue, loose connections, and electronic failures[3,4]. Therefore, studying how to effectively simulate and superimpose the above environmental stresses in the laboratory has become an important direction of equipment reliability engineering.

Traditional environmental tests often use single stress loading methods, such as constant temperature and humidity tests, high and low temperature alternating tests, vibration tests or low pressure tests, but these methods are difficult to truly reflect the multi-stress coupling effects of equipment in actual service. The proposal of the four-in-one test equipment is precisely to solve this bottleneck. By constructing a coupling test platform for four environmental factors of temperature, humidity, vibration and low pressure, it can more realistically simulate the environmental stress field of aircraft, missiles, satellites and other products when they are operating at high altitudes[5]. Currently, the key core components of the domestically produced four-component test system are primarily imported, and core technologies remain subject to foreign control. This article analyzes the key core components of the four-component test system, summarizing their technical difficulties and innovative breakthroughs. This analysis is of great significance to the independent research and development of environmental test systems in my country and the industrial development of the industry.

2. System Composition and Technical Indicators

2.1. System Composition and Functions

The four-in-one test system consists of four core modules [6], see Figure 1.

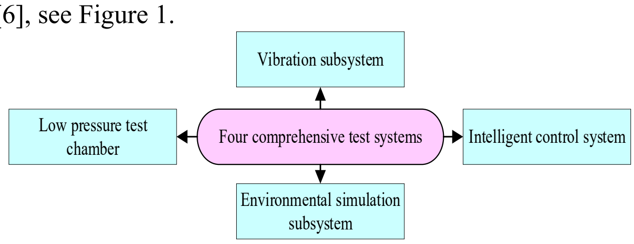

Figure 1. Components of the Four-Pronged Test System

2.1.1. Vibration Subsystem

Water-cooled electromagnetic vibration table, rated sinusoidal thrust of 65 kN, frequency range of 5~3000 Hz;

2.1.2. Low-pressure Test Chamber

Volume of 1000 L, operating pressure of 0.1 kPa~101 kPa (corresponding to altitudes≥30,000 meters);

2.1.3. Environmental Simulation Subsystem

Temperature range of ~70°C to +150°C, humidity range of 20% RH to 98% RH;

2.1.4. Intelligent Control System

Multi-sensor closed-loop feedback, supporting single-factor and multi-factor combination programming tests.

The system can simulate complex scenarios such as spacecraft in orbit, aircraft climb/cruise, and equipment operation at high altitudes. By integrating comprehensive environmental stresses to stimulate potential failures, it quantitatively assesses the environmental adaptability limits of products.

2.2. Analysis of Key Technical Bottlenecks

The core contradiction of the four-in-one test system lies in the system compatibility under multi-physical field coupling, which is specifically manifested as follows:

2.2.1. Conflict between Sealing and Vibration

The interface between the vibration table and the low-pressure box needs to maintain high vacuum sealing (≤0.1kPa) under dynamic displacement [7];

2.2.2. Inhibition of Heat and Moisture Transfer in Low-Pressure Environments

The thin air causes a sharp drop in convective heat transfer efficiency, and conventional temperature and humidity control methods fail [8];

2.2.3. Lightweight Structure and Pressure Safety

The large-volume box needs to withstand the internal and external pressure difference while meeting the vibration transmission stiffness requirements [9].

In order to solve the above problems, interdisciplinary collaborative technology research is needed, see Table 1.

Table 1. List of key technologies for the four-in-one test system

Serial number	Technical direction	Core challenge
1	Vibration table and low-pressure box interface	Dynamic seal failure and vibration transmission distortion
2	Box structure	Conflict between lightweighting and high pressure bearing capacity
3	Low-pressure and temperature and humidity control	Weakened convection leads to uneven temperature distribution and difficulty in humidification

3. Analysis of Key Technical Difficulties

3.1. Sealing Technology for the Connection between the Vibration Table and the Low-Pressure Chamber

In a low-pressure environment, a significant pressure difference forms within the system, placing extremely high demands on the sealing performance of the connection between the vibration table and the test chamber. Traditional fixed connection methods are difficult to cope with the structural stress and trace leakage caused by the pressure difference, and there is a certain risk of leakage, which in turn affects the stable operation of the system under extreme working conditions [10,11]. Therefore, in order to solve the vacuum leakage problem caused by vibration displacement, the system proposes a two-stage rolling sealing technology path: First, an elastomeric rolling seal ring with independent intellectual property rights is used as the first-level sealing component, and its elastic deformation ability is used to compensate for the transient gap formed during the vibration process. The measured leakage rate is controlled below 1×10^{-2}Pa·m³/s; second, an innovatively designed auxiliary airtight cavity is used as the second-level sealing unit, and inert gas is injected to form a stable air pressure barrier, structurally cutting off potential leakage channels and effectively improving the safety redundancy of the system sealing. Under 65kN thrust loading conditions, the sealing structure can maintain the internal pressure fluctuation of the test chamber within ±5% in the frequency range of 10Hz~2000Hz, fully verifying its reliability and practicality under the working conditions of high-intensity vibration and low air pressure coupling.

3.2. Vibration Table Automatic Centering and Air Pressure Balancing Technology

In test environments with severe air pressure fluctuations, the vibration system itself is susceptible to axial deviation due to pressure differentials. This can cause the excitation force to deviate from the designed centerline, resulting in reduced excitation efficiency, shifted system resonant frequencies, and even serious structural damage. To effectively address this issue, this paper proposes an automatic centering control scheme based on an air pressure self-balancing mechanism. By integrating a pressure feedback channel with a floating vibration isolation structure, it achieves real-time dynamic control of the vibration platform's axial position. The system utilizes a symmetrically arranged dual-chamber balancing structure with independent pressure chambers on either side of the dynamic coil. A high-response servo valve precisely adjusts the air pressure differential between the chambers, providing active leveling capabilities. Simultaneously, displacement sensors provide high-precision monitoring of the vibration table's axial offset. Combined with a closed-loop control algorithm, the support air pressure is dynamically adjusted to ensure that the dynamic coil always maintains the set axial position. The automatic centering accuracy is better than 0.05mm. This design not only significantly improves the vibration system's axial stability and excitation linearity under low-pressure coupling conditions, but also effectively ensures consistent system response and structural reliability during long-term, high-intensity vibration testing.

3.3. Lightweight Low-Pressure Chamber Structure Design

To enhance the structural adaptability and system integration efficiency of the four-comprehensive test system in low-pressure environments, this study abandoned the traditional thick-walled carbon steel welded construction of the test chamber and instead selected 4mm thick 304 stainless steel as the primary material for the chamber. Its excellent mechanical properties (yield strength ≥ 205 MPa) significantly reduced the weight while maintaining structural strength, resulting in a weight reduction of over 40% compared to the traditional 8mm carbon steel structure. A multi-dimensional ribbed plate layout was employed within the chamber. Finite element simulation analysis was used to characterize the stress distribution. Radial ribs were precisely positioned at key locations based on the stress contours, raising the critical buckling pressure to 0.05 kPa and achieving a safety factor exceeding 2.5, significantly enhancing its compressive stability. To balance structural strength and manufacturing efficiency, the weld process was optimized through simulation to ensure consistent stress transfer and ease of processing. While ensuring structural reliability, a hydraulic lift mechanism and universal traversing mechanism were incorporated into the system, enabling convenient mobility and addressing the bulk and transportation difficulties associated with traditional equipment. Through the dual optimization of lightweight structure and movable design, the total mass of the box is reduced by more than 30% compared with the prototype structure. While meeting the requirements of vibration, air pressure, temperature and humidity multi-coupling tests, the integration flexibility and on-site deployment efficiency of the equipment are significantly improved.

3.4. Temperature and Humidity Control Technology under Low Pressure Environment

Under low pressure conditions, the air density decreases and the heat exchange efficiency of the traditional evaporator decreases, making it difficult to achieve the expected temperature and humidity control. This system uses heat sink-assisted heat exchange technology to integrate refrigeration and heating circuits in the box body to achieve rapid temperature change control. In terms of humidity control, a high-efficiency pressurized humidifier is used, supplemented by condensation pipe dehumidification and dry air replacement method to improve the humidity response speed and accuracy[12]. A special water storage tank and condensation drainage device are set up to ensure drainage reliability under stable system operation.

4. Technical Comparison of Similar Products Internationally and Internationally

4.1. Current Status of International Mainstream Four-Component Test Systems

In the field of environmental stress test equipment, developed countries in Europe and the United States developed early, particularly after World War II. Driven by research into the reliability of weapons and equipment, environmental simulation technology systems were gradually refined. Countries like the United States, Germany, and Japan have established numerous national environmental testing stations and developed a number of companies specializing in the manufacture of comprehensive stress test equipment for temperature, humidity, vibration, and air pressure, such as ACS in the United States and ESPEC in Italy. These companies possess strong system integration and independent development capabilities. The “Combined Effects Chamber” of NASA Glenn Research Center in the United States and the "4-Component Test Facility" of IABG in Germany represent leading international standards, but these devices are subject to an import embargo in my country. Internationally advanced four-component test systems generally possess the following characteristics:

4.1.1. Mature System Configuration

Utilizing a modular approach, each stress unit can operate independently or be controlled collaboratively;

4.1.2. Highly Intelligent Control Systems

Equipped with multi-channel closed-loop control, multi-mode test programming, and user-friendly human-computer interaction;

4.1.3. Sophisticated Sealing Design

The sealing solution for pressure differential stress utilizes composite materials and multi-channel isolation to ensure long-term stable operation;

4.1.4. Highly Integrated

The equipment footprint is well-controlled, compactly arranged, and easy to transport and install;

4.1.5. An Environmental Assessment Database

Test parameters can be correlated with measured data to enable replication of standard scenarios.

However, these systems also have limitations, such as large overall system size, long customization cycles, and high prices. Furthermore, key core algorithms and hardware interface control protocols are often closed-source, making deep localization and customization difficult.

4.2. Development Level of Typical Four-Component Test Systems in China

In recent years, with the advancement of my country's strategy for independent control of high-end equipment, domestic companies have gradually achieved breakthroughs in multiple core technologies and made significant progress in the field of integrated environmental test systems. Representative companies such as Sushi Testing Group, Chongqing Yinhe Company, and Dongling Company have already developed the R&D and production capabilities for three- or even four-integrated test systems.

Looking at mainstream products in the market:

Sushi's first-generation product utilizes a fixed low-pressure chamber combined with a non-mobile vibration table, suitable for static environmental testing. However, its bulky structure makes it difficult to maintain.

Sushi's second-generation product incorporates a liftable and movable low-pressure chamber, significantly improving equipment integration and operational flexibility.

Sushi's third-generation product achieves cost control while maintaining a compact layout, making it suitable for mass-produced applications.

Chongqing Yinhe's system retains a traditional suspended structure design, offering strong adaptability but slightly limited stability.

Some emerging companies still lack engineering experience in low-pressure sealing, vibration control, and thermal-humidity coupling.

Overall, domestic equipment is gradually approaching international advanced levels in terms of appearance, craftsmanship, and functional layout. However, there are still gaps in control system coordination, stress superposition accuracy, intelligent data analysis, and long-term operational stability. Through a horizontal comparison of typical four-in-one equipment at home and abroad, it can be seen that foreign products have certain advantages in control system refinement, long-term operation reliability and environmental database construction, while domestic systems are more competitive in system customization, cost control and delivery cycle.

5. Application Cases and System Promotion Prospects

5.1. Verification of Inertial Navigation System Environmental Adaptability

As core sensors in aerospace equipment, inertial navigation systems must maintain high-precision operation in extreme environments such as high altitude, strong vibration, and drastic temperature fluctuations. A comprehensive temperature-humidity-vibration-low-pressure system has been widely used in practical applications to test the environmental adaptability of certain high-precision inertial navigation components.

The test includes a combination of temperature, humidity, and pressure curve loading for a typical flight profile and complex random vibration excitation. By setting different duty cycles and dynamic transition states, the environmental variations throughout the flight mission are simulated. The system records the inertial navigation sensor output in real time and analyzes multiple indicators, including drift rate, signal noise, and error accumulation. The test results verify the stability of the inertial navigation component under conditions of -50°C to +70°C, 20% to 95% relative humidity, 15kPa air pressure, and 6g RMS vibration, providing environmental reliability support for its deployment.

5.2. Electro-Optical System Performance Verification in Plateau Environments

The temperature, humidity, vibration, and low-pressure integrated equipment was successfully used to simulate plateau environmental testing for a certain type of airborne electro-optical system. This system is sensitive to atmospheric pressure fluctuations and often experiences image jitter and focus drift in the complex plateau climate. By utilizing a combined low-pressure, temperature, and vibration test mode, the system effectively recreates typical plateau takeoff and landing and flight conditions.

During the test, a high-definition image acquisition device and feedback control unit were placed within the low-pressure chamber. The optical lens assembly remained operational during dynamic pressure fluctuations, and the system monitored its stability, thermal drift, and structural coupling response. This ultimately resulted in a correction algorithm and structural compensation recommendations, directly improving the device's stable imaging capabilities in plateau environments.

5.3. Missile Electronic Control Module Screening and Failure Analysis

Researchers used this system to conduct fault reproduction and screening experiments for an unplanned failure of a missile control module during launch. The test employed a coupled stress cycle of high temperature and humidity, random vibration, and rapid decompression, while also monitoring the power supply, chip solder joints, and signal chain. During the third round of testing, voltage fluctuations were detected on some control boards during periods of sudden humidity surges. X-ray and thermal imaging analysis confirmed localized conductive corrosion on the PCB. The system's robust induction capabilities not only helped locate the root cause of the failure but also established process screening criteria to guide subsequent process optimization and product selection improvements.

5.4. Analysis of System Technology Promotion and Application Potential

The domestically produced high-end four-in-one test system has demonstrated superior versatility and customizability in practical applications, offering broad prospects for technology promotion:

5.4.1. Comprehensive Promotion in Military Equipment Development

In the development of high-end weapon systems such as aviation, aerospace, shipborne, and missile systems, environmental adaptability verification is an essential step in final testing and quality assessment. The system is widely applicable to multi-level testing at the system, component, and module levels.

5.4.2. Construction of an Electronic Component Reliability Screening Platform

It can serve as a reliability test bench for basic component suppliers, particularly suitable for environmental screening and failure prediction of high-risk components such as microelectronics, high-precision sensors, and connectors.

5.4.3. Research Tool for Environmental Stress Coupling Mechanisms in Research Institutions

With its flexible programmability, it can serve as an important platform for universities and research institutes to conduct research on multi-stress mechanisms and lifespan prediction, providing experimental data support for the development of reliability theoretical models.

5.4.4. Extension to Higher-Integration Systems

In the future, based on the existing four-integrated test system, it can be expanded to a six-integrated system (including environments such as light radiation and electromagnetic interference), creating a multi-physics field high-simulation test system to meet the system-level verification needs of more complex equipment.

5.5. Challenges in Promotion and Application

Although the domestically produced four-integrated test system has strong competitiveness in terms of structural design and technical indicators, it still faces the following challenges in its promotion:

5.5.1. Differences in Customer Customization Requirements

Different industries have significantly different requirements for environmental stress combination models, requiring enhanced modular configuration capabilities.

5.5.2. Personnel Training and User Entry

The system parameters are complex, requiring a strong environmental engineering background in test design, and supporting the development of standardized user manuals and training systems.

5.5.3. Market Awareness and Trust Building

Some users are still accustomed to using imported equipment, requiring more practical application cases and comparative data to enhance market acceptance. Overall, the domestically produced four-in-one test system has not only been implemented in numerous key scientific research and model projects, but also serves as a model for promoting the high-end and localized development of my country's environmental testing systems. Through collaborative development across multiple fields, the system is expected to become a key pillar of future "intelligent, multi-stress, and high-reliability" environmental verification platforms.

6. Conclusion

This paper systematically investigates the key technologies of a domestically produced integrated temperature-humidity-vibration-low-pressure test system. Addressing the difficulty of traditional environmental test equipment in simulating the effects of multiple stress coupling, innovative solutions were proposed, including a dual-stage rolling seal, pressure self-balancing and automatic centering, a lightweight ribbed plate structure, and efficient heat and humidity control under low-pressure conditions. These solutions significantly improve the system's environmental simulation accuracy and reliability. Results demonstrate that the system operates stably under a thrust of 65 kN and a vacuum of ≤0.1 kPa, with a seal leakage rate below $1 \times 10^{-2} Pa \cdot m^3/s$, a vibration centering accuracy of 0.05 mm, a box weight reduction of over 30%, and significantly improved temperature and humidity control response and uniformity. This system meets the complex service environment simulation requirements of inertial navigation systems, optoelectronic systems, missile control modules, and other applications. Compared to similar foreign equipment, the domestically produced system offers advantages in compactness, customized design, and cost control. While some gaps remain in long-term operational stability and intelligent control sophistication, it demonstrates independent control of key technologies. The future development direction should focus on the construction of a higher-dimensional integrated simulation platform for multiple physical fields, and evolve towards the “six comprehensives" and even "intelligent integrated test system”, and realize full-factor coupling testing by introducing stress sources such as electromagnetic interference and light radiation; at the same time, the application of artificial intelligence and big data in test control and result analysis should be strengthened, and intelligent decision-making and failure prediction models should be constructed to promote the development of environmental test equipment towards digitalization, intelligence and standardization, so as to fully support the reliability verification and independent innovation system construction of my country's high-end equipment.

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