Design and Implementation of Polarity Testing System of Contact-less Solenoid Valve Based on Wireless Sensor Networks

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Abstract. Solenoid valves are important control components in industrial production and are used in various aerospace vehicles. In view of the characteristics and requirements of the solenoid valve polarity test of the launch vehicle power system, combined with some current research on magnetic flux leakage detection, and considering the difficulty of operation, a design scheme of a contact-less solenoid valve polarity test system based on Wireless Sensor Networks (WSN) is proposed. The solenoid valve of the launch vehicle was tested and verified. The system organically combines wireless sensor network technology, leakage magnetic field measurement technology, and rapid monitoring and interpretation technology. It has the characteristics of miniaturization, portability and cable-free. The software interface of the test instrument is more concise and beautiful, and it is accurate to the solenoid valve polarity system. Degree, portability, test coverage and user experience have all been significantly improved, which has important reference significance for the application of subsequent wireless test technology in other space vehicle tests.

1. Introduction
With the rapid development of China’s aerospace industry and integrated control system, solenoid valve is a key component of system control and movement [1]. It can not only control the switch of a variety of liquids and gases compatible with the material of the solenoid valve, but also control the safety and protection interlocking system, and its application in the industrial field is becoming more and more extensive and flexible. Therefore, the detection of the solenoid valve action status has always been an important issue faced by various projects, and the accuracy of its detection is constantly improving.

With the increasing complexity of spacecraft, the number of solenoid valves has also increased significantly [2-3]. In the past, solenoid valve detection was done by connecting the sensor to the cable by the technical staff. However, due to the increase in the number of solenoid valves, the traditional method would consume a lot of manpower and time, the work efficiency was low, and the cable was not easy to move and save.

According to actual application needs, this paper designs a set of non-contact solenoid valve polarity test system based on Wireless Sensor Network technology [4]. The system is based on the design principles of intelligence, autonomy, small portability, and productization, and aims at high precision, rapid testing, and automatic interpretation. Combined with the research progress at home and abroad, combined with the actual use requirements of space vehicles, the test coverage and the degree of quantitative testing have been improved. At the same time, magnetic flux leakage detection method is
used in the test system, which has the advantages of non-destructive, non-contact, simple self-inspection process and high accuracy. While being easy to transport, it greatly reduces the complexity of sensor installation.

2. Basic principles and functions of the polarity test system

2.1. Wireless sensor network technology
According to the requirements of the spacecraft solenoid valve, this test system adopts the network structure of ZigBee protocol. While it has the advantages of low power consumption, low cost, short delay, high safety, etc., it can also meet the measurement distance with a transmission range of no more than 100m. Moreover, it is easy to add equipment such as repeaters in the ZigBee network structure, which can enhance the measurement signal and increase the test distance [5-6].

Due to the large size of aerospace vehicles, the distribution of solenoid valves is not concentrated on specific positions of the aircraft, so this test system adopts the wireless sensor network distribution mode of "one master and multiple slaves, master-slave separation". This network distribution mode has the advantages of high flexibility and convenient transportation, adapts to the complex environment in the space solenoid valve measurement test, and has little impact on other measurement equipment.

2.2. Magnetic flux leakage detection method and influencing factors
The measurement method using the principle of magnetic flux leakage captures the magnetic field change process of the solenoid valve at the moment of power-on and power-off. The change process of the magnetic field reflects the change process of the current, and then judges the movement state of the solenoid valve core [7]. Most of the solenoid valves used in the experiment are direct-acting solenoid valves. When the magnet coil is energized, the electromagnetic force will drive the valve core to move and close. The magnetic field in the valve wall is saturated in a very short time, and a large amount of magnetic lines of force leak out; similarly, the magnet coil is powered off later, it will also cause a large number of reverse magnetic lines of force to emanate. Therefore, the opposite characteristics of the magnetic field lines in these two states can reflect the on-off state of the magnet coil and the opening and closing process of the valve. Magnetic sensitive sensors can capture the signal generated in the change process, and convert them into usable output signals according to certain rules, and then process and integrate them in the core of the test instrument. In many magnetic sensors, most of them convert magnetic field information into electrical signals for measurement [8]. According to Faraday's law of electromagnetic induction, when the $N$-turn coil is moving in a constant magnetic field, and the magnetic flux passing through the coil is $\Phi$, then the induced potential $E$ in the coil has the following relationship with the change rate of magnetic flux $d\Phi/dt$:

$$E = -N\left(\frac{d\Phi}{dt}\right)$$

However, the electromagnetic environment of the test site is often harsh, and there is more periodic electromagnetic wave interference, which reduces the signal noise of the magnetic circuit signal.

2.3. Functions implemented by the system
The WSN-based non-contact solenoid valve polarity test system is mainly used in the final assembly test stage of launch vehicles and other aircraft, to test the polarity of solenoid valves contained in the aircraft system, and automatically compare and interpret the test results with the flight sequence. Thereby, the judgment result of whether the polarity of the solenoid valve is correct can be obtained.

The specific functions implemented by the system are as follows:

a) The use of Hall sensors and the principle of magnetic flux leakage to achieve non-contact measurement of the solenoid valve switching action of the aircraft system;

b) Use WSN to realize data communication between multiple test terminal nodes, and use AES-128 encryption algorithm to encrypt communication content;

c) The Beidou satellite navigation system/GPS is used to achieve high-precision timing and accurately record the action sequence of each solenoid valve;
d) The online configuration of the system is realized through software, which is flexible and widely applicable;
e) Using automatic data analysis and processing and intelligent comparison technology to realize automatic interpretation and accurate positioning of measured data.

3. Composition and design of solenoid valve polarity test system
The WSN-based non-contact solenoid valve polarity test system is composed of a wireless sensor terminal, a wireless signal repeater, a master node and a control terminal. The structure is shown in figure 1.

a) Wireless sensor terminal: It is composed of sensor probe, LED status indicator, signal cable and sensor terminal body; non-contact magnetic induction sensor is used to collect the changing magnetic field generated when the solenoid valve is opened and closed; the wireless sensor terminal collects the magnetic sensor. After data processing, the data is sent to the wireless signal repeater or directly to the master node through wireless transmission;

b) Wireless signal repeater: Receive the signal from the wireless sensor terminal and send it to the master node to increase and improve the wireless transmission distance and signal strength;

c) Master node: used for sensor signal acquisition, test data wireless communication, test data collection; receive data signals from wireless signal repeaters or directly receive signals from wireless sensor terminals, and send the data to the computer through the Ethernet interface.

d) Interpretation computer (control terminal): Responsible for controlling the operation of each module and interpreting data; before the start of the test, it can control the master node, wireless signal repeater and wireless sensor terminal for link self-checking and battery power self-checking. Functions such as inspection and time synchronization, and issue start/stop acquisition instructions; receive sensor data sent by the master node via Ethernet during the test, analyze and interpret the test data, and form a test report after the test.

3.1. Wireless sensor terminal design
According to the actual needs of the spacecraft during the measurement, due to the small intensity of the changing magnetic field generated when the solenoid valve acts, the Hall sensor is selected as the main signal acquisition element. The sensor has the characteristics of high sensitivity, small size and non-destructive measurement. However, due to the small size of the Hall sensor, a slight deviation of the relative position will cause a large gap in the measurement results. In order to improve the measurement accuracy and reduce the error in the process of pasting the sensor, three Hall elements are integrated in a magnetic induction probe, as shown in figure 2.
In order to improve the flexibility and portability of the test system, the induction probe and indicator light composed of Hall sensors are connected to the main body of the wireless sensor terminal through a one-to-two aerial plug cable, and the original integrated wireless sensor terminal is split. According to actual needs, the sensor probe cable can be replaced to meet the needs of different environments and different scenarios. The introduction of the status indicator light of the wireless sensor terminal makes it more convenient for the inspectors to observe the movement changes of the solenoid valve when the equipment is working.
3.2. Design of master node and wireless signal repeater
The master node and the wireless signal repeater have a similar structure, and are mainly composed of a main control unit, a power supply unit, a wireless communication module, a wired communication module, and a time synchronization module.

Since the battery is a consumable component, a replaceable battery compartment (X3) is added to the master node to improve the overall service life of the test system. The front and rear panels of the master node are arranged as shown in figure 4.

![Figure 4. The layout of the front and rear panels of the master node](image)

3.3. System software design
Solenoid valve polarity test system software includes embedded monitoring software and analytical interpretation software, both of which are installed in the main control board of the master node and the interpretation computer of the control end to complete the control of the system status data display, test and other processes. As well as the analysis and interpretation of test data and other functions, the specific software flow is shown in figure 5.
The embedded monitoring software is developed using the QuartusII integrated development environment. The system functions are realized by Verilog and C language. The software includes serial communication, timing module driver, wireless module driver, wired module driver, sensor data receiving and processing, status indication, command analysis, data packaging, main logic control and other parts. The software function module block diagram is shown as in figure 6.

The timing analysis and interpretation software run on the interpretation computer on the control end to view and process sensor data and generate timing test reports. The software uses Visual C++ 6.0, Measurement Studio 6.0 integrated development environment, and the operating system is Windows XP Chinese version. The software is mainly composed of three parts: Ethernet communication module, data processing and data display. The main interface of the operating software is clear, and all functions are tiled in the main interface in the form of buttons. The operation is simple and convenient for testing.
personnel. When data is collected, the received data is updated in real time in the table at the bottom left of the main interface, bottom right. There will be indicator icons updated with the data, which is convenient for inspectors to observe, find errors in time, and record in advance. The main interface of the software is shown in figure 7.

![Solenoid Valve Polarity Test Software](image)

**Figure 7. The main interface of time analysis and interpretation software**

4. **System completion and test verification**

After completing the hardware and software development and debugging of the non-contact solenoid valve polarity test system, a real-time test of the polarity of the power system solenoid valve of a certain type of rocket was carried out during the final assembly stage.

Take the ground test results of a certain type of aircraft project as an example, the project needs to complete the action of 12 solenoid valves at the same time. Before the test system performs polarity detection, it is necessary to install the sensor probes of 12 wireless sensor terminals. Place the sensor probes as close as possible to the upper edge of the solenoid valve without affecting the function of the aircraft, and then perform the wireless sensor terminal on the control end. Rename it so that the wireless sensor terminal corresponds to the number of the solenoid valve under test, and then perform the system self-test.

The self-checking test has three main functions: communication link self-checking, battery power self-checking, and memory full state checking, as shown in figure 8.

a) Communication link self-check: the computer directly sends the command to the master node, waiting to receive the master node, wireless repeater, wireless sensor terminal (only command receiving response), the waiting time is 2s, if no response is received, it is considered that the communication link between the computer and the master node is disconnected. If a response from the master node is received but no response from a certain terminal is received, it is considered that the wireless communication link between the terminal and the master node is disconnected.

b) Battery power self-check: After the command is issued, it waits to receive the response of each device (including the master node, wireless repeater, and wireless sensor terminal), and the waiting time is 2s. Jump out of the self-check result window and display the battery power status of each device (including the master node and the terminal) (including full power and low power). If the battery power response of a certain device is not received, the battery power status of the device is displayed. Obtain.

c) Memory full status check: You can choose single or all devices, after the command is issued, wait for the return data, jump out of the memory full status check result window, determine the memory full status of the selected device based on the returned data, and display the check of each device. The results include the display of “full capacity” and “full capacity”.
After the self-test is completed, the acquisition process can be started, and the collected signal collection records can be formed into a table and displayed on the main interface of the interpretation software, which is convenient for testers to monitor the solenoid valve in real time. After the test is completed, the operation stops the data collection process, and then you can choose to perform the data interpretation operation and automatically export the interpretation file to facilitate comparison and save the test results.

| Solenoid valve name | Device ID | Action state | Relative Time | Absolute time |
|---------------------|-----------|--------------|---------------|---------------|
| Extension 7         | 7         | Close        | 0             | 17:01:56'0    |
| Extension 3         | 3         | Close        | 15            | 17:02:11'0    |
| Extension 3         | 3         | Open         | 29.2          | 17:02:25'2    |
| Extension 7         | 7         | Open         | 33.4          | 17:02:29'4    |
| Extension 5         | 5         | Close        | 42.8          | 17:02:38'8    |
| Extension 1         | 1         | Close        | 56.8          | 17:02:52'8    |
| Extension 1         | 1         | Open         | 69.6          | 17:03:05'6    |
| Extension 5         | 5         | Open         | 73.6          | 17:03:09'6    |
| Extension 6         | 6         | Close        | 82.8          | 17:03:18'8    |
| Extension 2         | 2         | Close        | 96.6          | 17:03:32'6    |
| Extension 2         | 2         | Open         | 109.4         | 17:03:45'4    |
| Extension 6         | 6         | Open         | 113.4         | 17:03:49'4    |
| Extension 8         | 8         | Close        | 123.2         | 17:03:59'2    |
| Extension 4         | 4         | Close        | 136.8         | 17:04:12'8    |
| Extension 4         | 4         | Open         | 148           | 17:04:24'0    |
| Extension 8         | 8         | Open         | 152.2         | 17:04:28'2    |
| Extension 10        | 10        | Close        | 161.4         | 17:04:37'4    |
| Extension 12        | 12        | Close        | 161.8         | 17:04:37'8    |
| Extension 12        | 12        | Open         | 162.8         | 17:04:38'8    |
| Extension 10        | 10        | Open         | 175           | 17:04:51'0    |
| Extension 11        | 11        | Close        | 184.8         | 17:05:00'8    |
| Extension 9         | 9         | Close        | 184.8         | 17:05:00'8    |
| Extension 11        | 11        | Open         | 196.4         | 17:05:12'4    |
| Extension 9         | 9         | Open         | 196.4         | 17:05:12'4    |

From the comparison of Table 1 and internal test timing documents, it can be seen that the test results of the test system are accurate, consistent with the action timing of the solenoid valves of the aircraft, and the test is true and credible.
5. Conclusion
This paper designs and implements a set of non-contact solenoid valve polarity test system, which combines wireless sensor network technology, magnetic flux leakage detection technology, and document interpretation technology. The introduction of wireless signal repeaters not only greatly increases the distance of signal collection, but also replaces the traditional heavy and cumbersome transmission cables, which significantly improves the portability of equipment transportation and the flexibility of sensor measurement. While ensuring the quality of the test, it improves the test efficiency and optimizes the operating experience, which has strong engineering practicability and promotion value.

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