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Fault Analysis and Repair Strategies for Large Velocity Errors in Platform-Based Inertial Navigation Systems

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Abstract: To address a large velocity error fault that occurred in a certain type of platform-based inertial navigation system during ground calibration, fault tree analysis was adopted to carry out systematic troubleshooting. First, a fault tree with "large velocity error" as the top event was established, and the fault causes were sorted out according to the principle of "from the whole to the parts, decomposing level by level." On this basis, referring to the system schematic diagram, the signal flow in the system control loops was analyzed in depth to identify the key nodes affecting velocity accuracy. Subsequently, possible fault causes were checked one by one according to the fault tree. By means of parameter testing, signal measurement, and component swapping, and following the principle of "easy before difficult and eliminating items one by one," the fault scope was gradually narrowed. Finally, the fault was localized to the minimum replaceable unit, the fault point was confirmed and eliminated, and the system was restored to normal. This troubleshooting method is well-organized and highly targeted, greatly shortening the time for fault localization, and has certain reference value for the analysis and elimination of other similar faults in platform-based inertial navigation systems.

Keywords: Velocity Error; Fault Repair; Platform-Based Bnertial Navigation System; Gyroscope

1. Introduction

The platform-based inertial navigation system is the core navigation support equipment for ocean-going vessels. For this reason , its importance and echnical complexity is self-evident. This system can provide precise navigation information such as position, speed, attitude, and angular velocity in real time and continuously without any external information support. It not only provides solid basic information support for global navigation of ships, but also is the core premise for ensuring navigation safety, achieving precise positioning and maneuvering [1]. Due to the strong coupling between the inertial navigation system and the ship information system, when it fails, it not only affects the own functions of the ship's navigation navigation system but also greatly restricts the safety performance of the ship. However, precisely because of its highly integrated and complex coupling characteristics, once the inertial navigation system fails, its impact will far exceed the scope of a single navigation equipment. Its failure will not only directly lead to the failure of the ship's navigation function or a decrease in accuracy, but also may severely restrict the safety performance and overall navigation capability of the ship through information interaction [2]. For example, in dynamic positioning or complex sea conditions, even a small error of the navigation system can be amplified, leading to serious safety hazards such as "ship position drift". Therefore, accurately and efficiently diagnosing the faults of the platform-based inertial navigation system and identifying the causes of the faults, as well as deeply exploring the hidden factors behind the navigation safety risks, ensuring that the repaired ship has a good technical condition and meets the navigation technical indicators requirements, has become a key problem that urgently needs to be solved in the ship equipment support work.

Currently, the research on fault diagnosis and health management of inertial navigation systems is moving towards an intelligent and systematic direction. For instance, the case-based reasoning (CBR) method has been

introduced, which simplifies the process of knowledge acquisition by building a case library and retrieving historical similar fault cases, significantly enhancing the diagnostic efficiency [3,4]. With the rapid development of artificial intelligence technology, the fault prediction and health management (PHM) system has become a leading research direction. This system aims to monitor the equipment status in real time, utilize algorithms and models such as deep belief networks and SOM neural networks, to achieve early warning of faults, assessment of health status, and prediction of lifespan, promoting the maintenance mode from "post-event maintenance" and "regular inspection" to "predictive maintenance". These studies provide strong technical support for improving the reliability of inertial navigation systems and the efficiency of maintenance support, but their engineering application, especially in terms of real-time performance, accuracy, and robustness in complex marine environments, still faces many challenges. Traditional fault diagnosis methods mostly rely on rule-based expert systems or fault tree analysis (FTA) [5–7]. By establishing fault tree models, they conduct qualitative and quantitative analysis of potential system faults and can still effectively improve diagnostic accuracy and efficiency, warranting in-depth research.

2. Description of the Malfunction Symptoms

A certain type of platform-based inertial navigation system suddenly experienced a failure at sea while the vessel was underway. The system exhibited rapid divergence in accuracy and was unable to correct and converge; its eastward velocity (VE) continued to increase, eventually exceeding 200 knots. After the vessel returns to the dock and is in the mooring state, the alignment and startup are carried out. However, the speed error still cannot be eliminated. The emergency calibration "BO" stage of the eastward speed can increase to 210 knots. After the emergency calibration is completed, the drift value of the northward gyroscope calibration reaches 3.42°/h.

The platform-based inertial navigation system is equipped with three gyroscopes: the azimuth gyroscope, the east-pointing gyroscope, and the north-pointing gyroscope. The latter two are generally referred to collectively as horizontal gyroscopes [8]. The gyroscope is the core component of the platform-type inertial navigation system. Thus, the accuracy of the scale of the gyroscope directly affects the determination of the gyroscope drift, and thereby affects the stability and accuracy of the inertial navigation output parameters [9]. If, based on ingrained habits of thinking and everyday repair experience, one observes the above fault—namely, excessive calibration drift in the north-facing gyroscope—one might blindly conclude that the north-facing gyroscope is faulty and proceed to replace it to resolve the issue. However, if the fault still cannot be eliminated after replacement, we will find ourselves at a loss, unable to pinpoint the exact source of the problem. Not only is this process time-consuming and labor-intensive, but it also wastes valuable inertial component resources and impedes the vessel's ability to fulfill its operational tasks.

3. Design of the Fault Analysis and Troubleshooting Process

The stabilization system is the core system that enables the stabilized platform of a platform-based inertial navigation system to track the navigation coordinate system. Its function is to control and maintain the stabilized platform so that it tracks the local geographic coordinate system in space, supports the accelerometers, and stabilizes them in inertial space, or causes them to track the geographic coordinate system according to commands from the navigation computer. Under the action of the stabilization system, the gimbals counteract the vessel's roll, pitch, and yaw motions, isolating the stabilized platform from the vessel's rotational motion and maintaining a static alignment with east, north, and sky in space, thereby providing a reference for measuring the vessel's attitude and heading. The stabilized platform consists of gimbals, gyroscopes, accelerometers, temperature control circuits, preamplifiers, and other components, allowing the inertial platform to move freely within a range of 360° in azimuth, 30° in pitch, and 45° in roll. The east-pointing gyroscope, north-pointing gyroscope, and azimuth gyroscope are mounted on the platform body. By applying torque to the three-axis platform, they keep the platform stable relative to the inertial platform. Each axis is controlled by a separate stabilization loop, which can counteract disturbances to the platform caused by the vessel's motion in the three axes.

3.1 Analysis and Troubleshooting of Major Eastward Velocity Faults

During emergency calibration at the dock, the platform-based inertial navigation system experienced an abnormal surge in eastward velocity, reaching over 200 knots. Taking single-axis stabilization control as an example, we analyze the control principle of its stabilization loop. When the platform base deviates from its initial equilibrium position at an angular velocity of ω, the single-degree-of-freedom gyroscope mounted on the platform sensitively rotates around its input axis, causing the angle sensor to output an error signal deviating from zero. After this error signal is amplified and rectified by the stabilization loop, it is converted into a DC current signal fed to the DC torque motor, generating a control torque that causes the gimbal to rotate in the direction opposite to the angular velocity, returning it to its initial position while simultaneously driving the gyroscope to precess back to its initial position. When ω = 0, the angle sensor's output signal is zero, and the stabilization loop is inactive. Thus, regardless of how the base rotates, the platform maintains its original equilibrium position relative to inertial space through the servo control loop.

The same principle applies to the control of a three-axis stabilized platform. The input axis of the azimuth gyroscope in the stabilization control system points toward the celestial axis. When there is angular motion of the heading around the celestial axis, the azimuth gyroscope's angle sensor outputs an error signal, which drives the torque motor on the heading axis via the heading servo control loop to maintain the stability of the heading axis. The input axes of the east-pointing gyroscope and the north-pointing gyroscope point toward the east and north, respectively. When angular motion occurs about the pitch and roll axes, error signals are output by the angle sensors of the east-pointing and north-pointing gyroscopes. These signals are fed to a coordinate transformer mounted on the yaw axis for decomposition. After decomposition, the signals are sent to the pitch and roll servo control loops to control the pitch and roll torque motors, thereby maintaining the stability of the platform in inertial space.

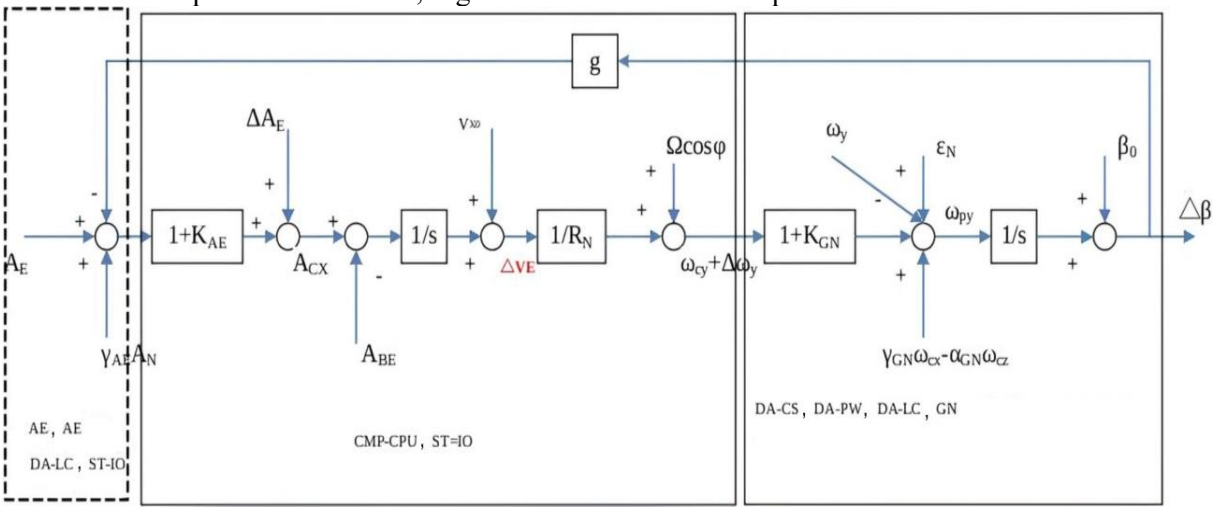


Figure 1. Flowchart of the AE-GN Horizontal Correction Loop

As shown in Figure 1, the workflow of the AE-GN horizontal correction loop reveals that every stage depicted in the flowchart has the potential to cause an increase in eastward velocity. It is also evident from Figure 1 that the hardware through which the loop passes includes the eastward accelerometer (AE), the eastward accelerometer (AE) circuit, the pulse-coding circuit, the subsystem interface board (ST-IO), the computer motherboard (CMP-CPU), the coarse/fine conversion current source board (DA-CS), the coarse/fine conversion polarity switch board (DA-PW), the digital-to-analog conversion logic board (DA-LC), the north-pointing gyroscope (GN), the coordinate transformer, the stabilization loop circuit, the torque motor, and related wiring. Based on the AE-GN horizontal correction loop flowchart, a fault tree analysis diagram for the VE velocity fault was constructed, as shown in Figure 2 [10]. The potential factors listed in Figure 2 were investigated one by one; the specific investigation process is shown in Figure 3.

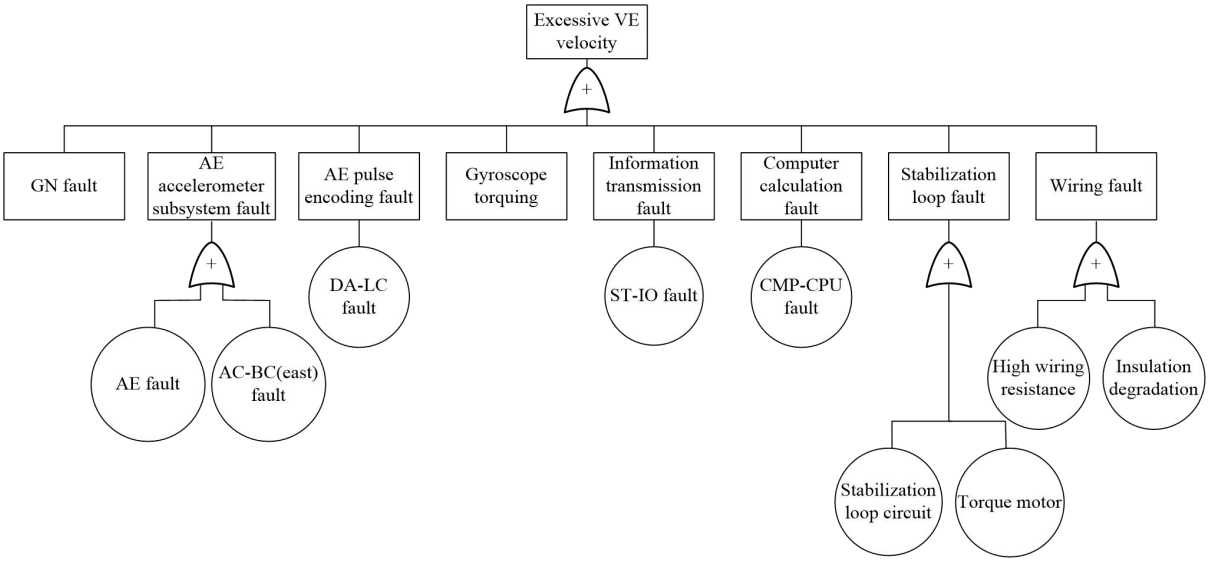


Figure 2. Fault Tree Analysis of Major Eastward Velocity Faults

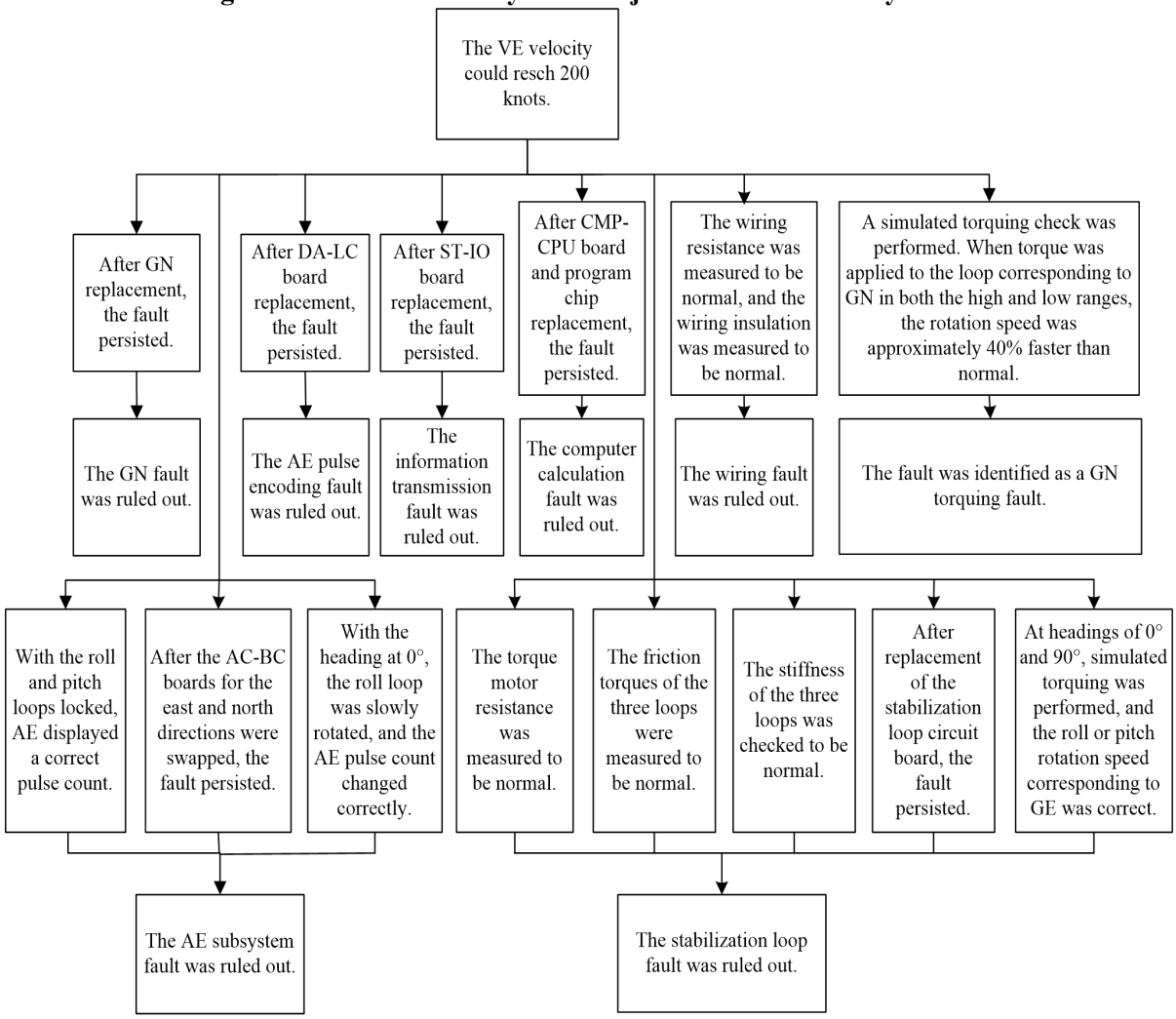


Figure 3. Flowchart of the Comprehensive Inspection for Eastward Velocity Faults

3.2 Failure Analysis and Troubleshooting of North-pointing Gyroscope Torque Application

Therefore, a fault tree analysis diagram for the north-pointing gyroscope torque application failure can be drawn, as shown in Figure 4. The possible factors listed in Figure 4 were investigated one by one; the specific investigation process is shown in Figure 5.

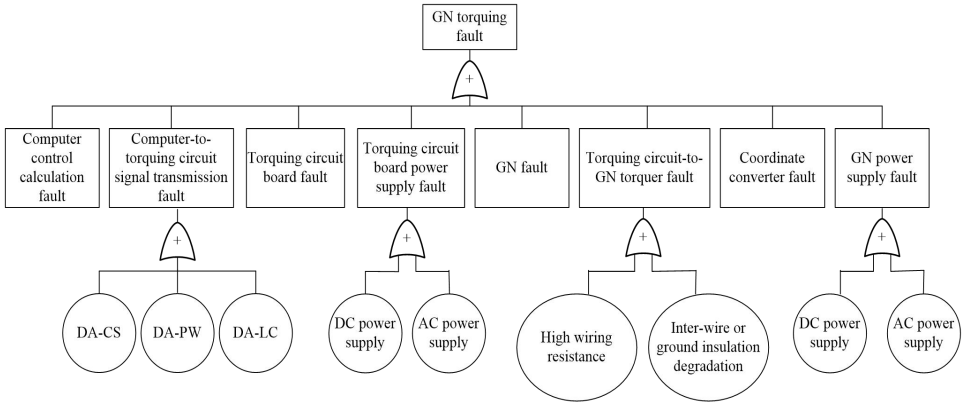


Figure 4. Fault Tree Analysis of North-pointing Gyroscope Torque Application Failure

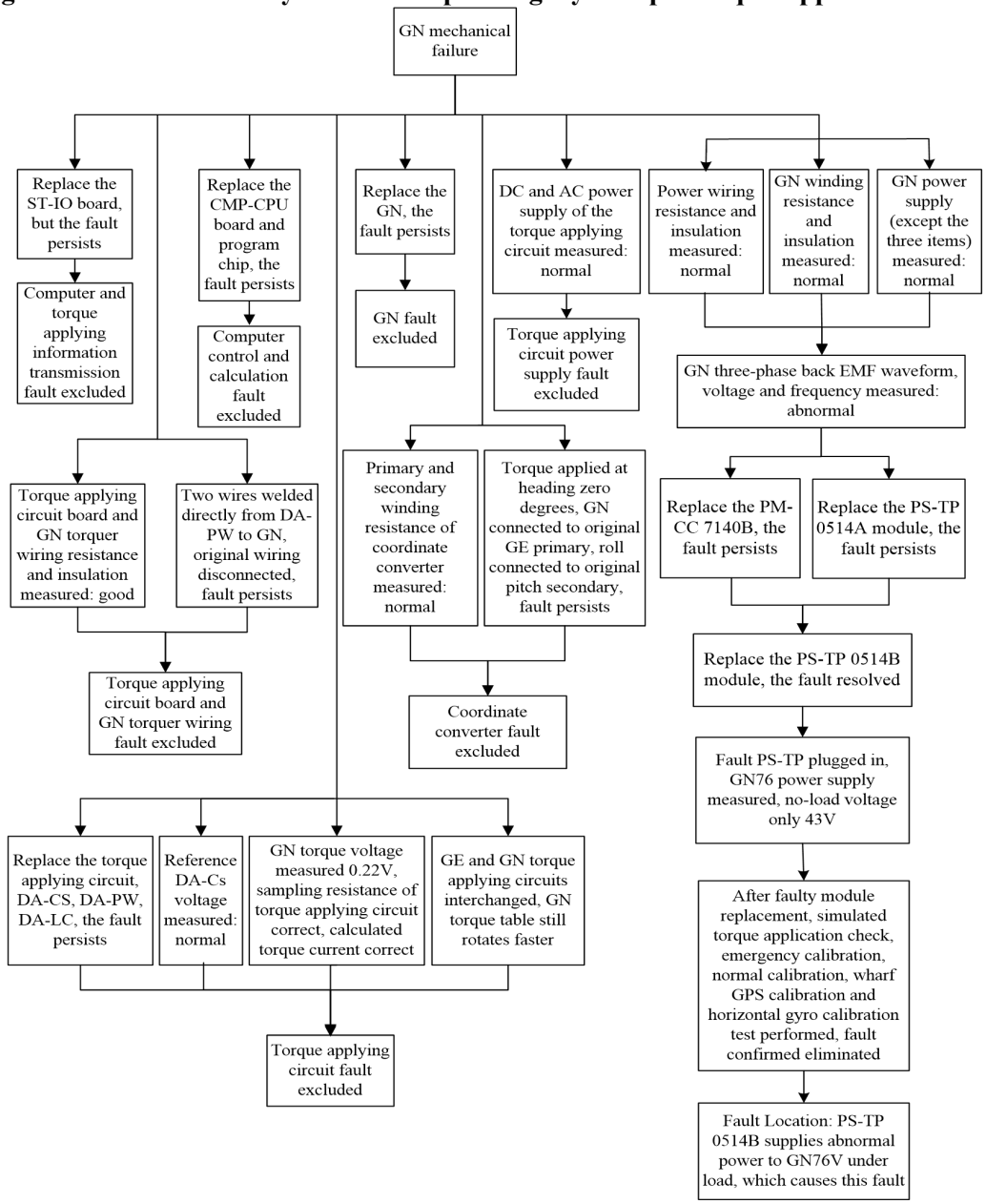


Figure 5. Troubleshooting Flowchart for North-pointing Gyroscope Torque Application Failure

The encoding and conversion logic circuit consists of the coarse/fine conversion current source board (DA-CS), the coarse/fine conversion polarity switch board (DA-PW), and the digital-to-analog conversion logic board (DA-LC). This system facilitates information

exchange between the computer and the inertial platform, converting the velocity increments output by the accelerometer into binary codes that the computer can receive, and then converting the digital information representing gyroscope precession—calculated by the computer—into torque application signals for the gyro torque actuator, thereby ensuring that the inertial platform accurately tracks the geographic coordinate system. According to the gyroscope torque signal flowchart principle, the hardware components through which the gyroscope torque signal passes includes the computer motherboard (CMP-CPU), the subsystem interface board (ST-IO), the coarse/fine conversion current source board (DA-CS), the coarse/fine conversion polarity switch board (DA-PW), the digital-to-analog conversion logic board (DA-LC), the north-pointing gyroscope, the coordinate transformer, the stabilization feedback circuit, and the torque motor. Additionally, there are power supplies for the north-pointing gyroscope and circuit boards, as well as related wiring [11,12].

4. Troubleshooting and Fault Diagnosis

Following the troubleshooting flowchart for this platform-based inertial navigation system as described in the above analysis, while measuring the startup power supply for the horizontal gyroscope of the three-phase power supply module (0514B), it was found that the voltage for the north-pointing gyroscope was normal when the gyroscope was not yet activated; the normal supply voltage is 76 V. However, after the gyroscope was started and operated under load with 76 V AC, a power supply failure occurred; the actual measured supply voltage for the north-pointing gyroscope was only 43 V, resulting in abnormal back-EMF waveforms, voltage, and frequency for the north-pointing gyroscope. The drop in supply voltage to the north-pointing gyroscope's three-phase gyro motor caused the motor speed to decrease. This reduction in motor speed increased the command scale factor, which in turn resulted in an eastward acceleration of over 200 knots during emergency calibration, as well as other malfunctions such as a significantly increased horizontal gyro calibration scale and the north-pointing gyroscope's simulated torque platform rotating approximately 40% faster than normal. After replacing the three-phase power module (0514B), working modes such as simulation torque application, emergency calibration, and normal calibration were carried out. It was measured that the actual supply voltage of the north-facing gyroscope was normal after startup, and the system was working properly. Thus, it was confirmed that the fault had been eliminated.

5. Conclusions and Prospects

Proposed in this paper, the fault repair strategy for the platform-based inertial navigation system completely breaks away from the traditional, habitual mindset of relying solely on the personal experience of maintenance personnel to troubleshoot problems. It realizes the transformation from "experience-based maintenance" to "scientific maintenance". During the troubleshooting process, the first step is to conduct a detailed on-site inspection and testing of the malfunctioning equipment to fully understand the fault symptoms and the technical condition of the equipment. Next, precise measurements of the technical condition data of key components are taken to provide firsthand evidence for subsequent fault analysis. Building on this foundation, this paper conducts an in-depth study of the operating principles of the stabilization loop in a platform-based inertial navigation system. It also systematically outlines the entire process of signal generation, transmission, amplification, and feedback in each control loop. The influence mechanism of each link's signal flow on the final output result of the system is analyzed, and the key nodes that may cause faults are clearly identified. At the same time, by combining the fault tree analysis method, the fault symptoms are systematically broken down into several intermediate and root events. Thereby, a logically rigorous and clearly structured troubleshooting path were established. This strategy follows the principle of “starting with the easy and moving on to the difficult, and ruling out possibilities one by one.” It involves measuring and verifying each suspicious area individually to accurately identify the root causes hidden behind surface-level fault symptoms, eliminate superficial interference, and thereby achieve precise localization of the fault point. The entire troubleshooting process is not only a beneficial exploration of equipment maintenance methods, but also deepens the learning, understanding and practical application of the working principle of the platform-based

inertial navigation system. Thus, the process achieves the organic combination of theory and practice. This "exploratory" point-by-point inspection method is guided by a solid theoretical foundation in conducting maintenance work. By conducting a thorough and meticulous analysis through science, a detailed troubleshooting plan can be formulated. It enables rapid fault resolution, limits the scope of the fault to the minimum, and accurately pinpoints the fault location in the end. In this way, the maintenance cycle has been significantly shortened and the equipment maintenance support capability has been greatly enhanced. Ultimately, it can provide important references and lessons for the analysis, troubleshooting, and repair of platform inertial navigation systems and other similar equipment failures.

To further improve the scientific nature and work efficiency of fault diagnosis for platform-based inertial navigation systems, the next step is to continue research in the following three directions. First, promote the intelligent development of fault diagnosis. Integrate the fault tree analysis method with artificial intelligence technology. Firstly, collect and organize typical failure cases, and establish a failure case database and an expert knowledge base. Secondly, research the model based on machine learning which focusing on the fault diagnosis. Then it can gradually achieve intelligent analysis and automatic location of faults. Ultimately reduce the reliance of maintenance work on human experience. Second, carry out applied research on prognostics and health management technology. By installing data acquisition equipment, the key signals of the system can be monitored and recorded in real time. And then analyze the changing trends of performance parameters and explore the degradation patterns of key components. Promote the transformation of the maintenance model from "reactive maintenance" to "predictive maintenance", and identify potential failure risks in advance. Third, improve the troubleshooting method system. Standardize and normalize the existing "exploration-style" investigation methods. Compile typical fault troubleshooting manuals and maintenance procedures, and form standardized maintenance processes that can be replicated and promoted. And by relying on training methods, we aim to enhance the theoretical knowledge and practical skills of maintenance personnel. Thereby it can overall improve the effectiveness of equipment maintenance and support.

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