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Discussion on Reliability Evaluation Method of Inertial Actuator

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Abstract

The inertial actuator provides the spacecraft with the control torque required for attitude stability or attitude maneuver, and its reliability directly affects the lifespan and accuracy of the spacecraft. In order to improve the lifetime and accuracy of inertial actuators, it is necessary to evaluate the reliability. The types of inertial actuators are introduced, mainly including reaction flywheel, momentum wheel, control torque gyro, etc. This article briefly outlines several different reliability modeling and analysis methods, including failure mode, impact and criticality analysis (FMMECA), fault tree analysis (FTA), Bayesian network model, GO method and Petri net model. The advantages and disadvantages of each analysis method are discussed. The reliability evaluation methods of different inertial actuators are analyzed, which provides a basis for the subsequent reliability analysis and research of inertial actuators.

Keywords

Inertial actuator; Reaction flywheel; Momentum wheel; Control torque gyro; Reliability assessment.

1. Introduction

With the rapid development of aerospace technology, spacecraft systems often fail due to their complex structure, harsh working environment, and high requirements for working accuracy, which increases the reliability requirements for spacecraft. To ensure the long life and high precision of the spacecraft, the technology and products of the actuator are important technical guarantees for the control system [1]. Generally speaking, inertial actuators include: control moment gyro, reaction flywheel, bias momentum wheel, frame momentum wheel and so on. The working principle of the inertial actuator is to realize the control torque output by adjusting and changing the magnitude or direction of the momentum moment of the actuator rotor. Inertial actuators have high torque output accuracy. With this feature, more than 90% of high-precision three-axis stabilized spacecraft attitude control systems use inertial actuators as the main actuators. The inertial actuator keeps the spacecraft's attitude stable or changes in accordance with a given law through momentum exchange with the spacecraft.

2. Reliability modeling and analysis methods

2.1 Failure Modes, Mechanisms, Effects, and Criticality Analysis (FMMECA)

The FMECA method is a qualitative reliability analysis method [2]. This method analyzes the possible failures of the product in the working process, classifies the failure modes according to the probability of these failures and the severity of the impact on the performance of the system, finds out the weak links of the reliability of the system and gives improvement measures. The advantage

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of this method is that it is easy to master and does not need to use complex mathematical methods to process data. It is very valuable in practical engineering applications, but the disadvantage is that it requires a lot of test data and it is difficult to quantify the reliability of each component of the system.

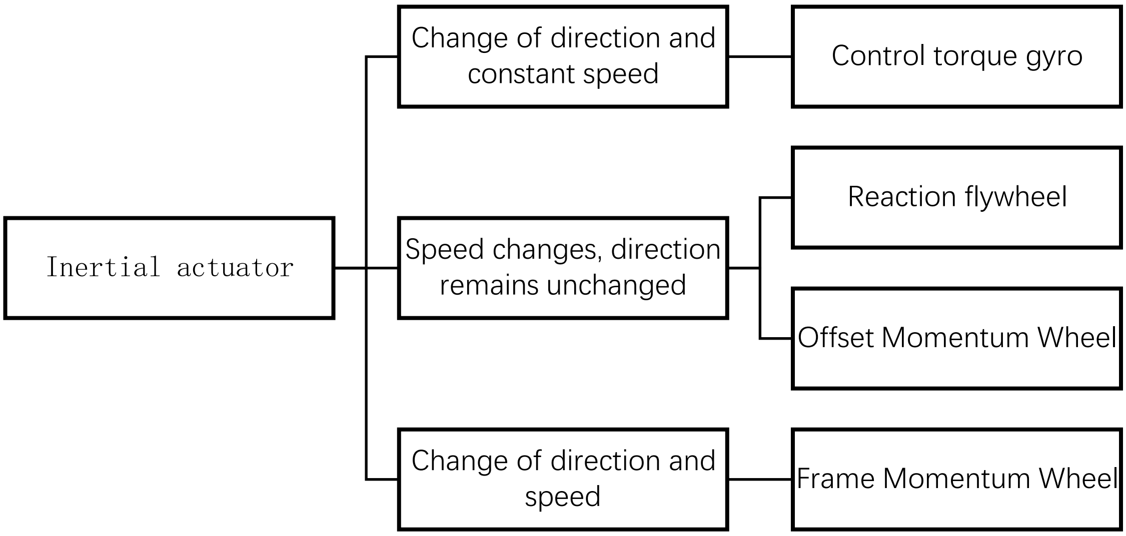

Figure 1. Inertial actuators are classified according to torque generation method

2.2 Fault tree analysis (FTA)

The FTA method [3] is a process of modeling and qualitative or quantitative analysis of system reliability. By analyzing the fault state of the system layer by layer, the fault diagram expresses the internal connection between unit faults and system faults, and each The importance of each level of failure. The fault tree analysis method is suitable for practical engineering applications. At present, there are many mature analysis softwares. The disadvantage of this method is that it can only describe the interrelationships between faults with clear logical relationships, but cannot handle faults with unobvious logical relationships.

2.3 Bayesian network model

Bayesian network is a model based on probability theory and graph theory proposed by Pearl in 1986 to represent uncertain knowledge [4]. The method of using Bayesian network model to analyze reliability can comprehensively utilize various types of information sources, realize automatic modeling and update the model through learning, which can be of great help in analyzing reliability. However, when the established model is not accurate enough or the system is too complex, the calculation efficiency of the Bayesian network model is low, and the results cannot be applied to the actual system.

2.4 GO method

GO method [5] is an analysis technique that can deal with time-dependent characteristics. It is mainly used to solve the problem of complex timing relationships in the system or changes in state over time, and can fully express the relationship between components and systems. It is a graphical deduction method for system reliability analysis. The disadvantages of the GO method are that the symbols are cumbersome and complex, difficult to grasp, and the workload is large, and it is difficult to describe the influence of uncertainty causality.

2.5 Petri net model

Petri net is a general graphical and mathematical tool used to describe the relationship between states and events. It has been widely used in reliability engineering fields such as fault diagnosis and

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complex system reliability modeling and analysis. Reliability modeling and analysis based on Petri nets first needs to understand and analyze the system to establish a Petri net model, and then apply simulation technology to quantitatively analyze the Petri net model to obtain all the final states and the probability of each ignition path. The advantage of the Petri net model is its high flexibility, but it lacks in the qualitative analysis of reliability.

3. Reliability assessment of reaction flywheel

The principle of reaction flywheel control is to generate control torque through flywheel acceleration or deceleration, and the average angular momentum value is zero. The common method to improve the reliability of the flywheel is to predict the reliability of each component of the flywheel, combine the methods of fault tree and failure mode analysis to find out the links with poor reliability, and then give improvement measures, according to the overall system reliability index and reliability prediction As a result, the reliability distribution is carried out to improve the overall reliability [6,7]. The characteristic of the zero-momentum reaction flywheel three-axis attitude stabilization system is that the control system of the entire spacecraft is regarded as composed of three parts, which are three independent channel control systems for rolling, yaw and pitch, and three orthogonal zero-momentum reactions. The flywheel individually changes its own speed according to the error on the respective axis to achieve precise control of the attitude of each axis.

The method of reliability analysis abroad is mainly to carry out life experiment on flywheel electromechanical components to verify its reliability within a specified time. The domestic research on product failure analysis and reliability test evaluation technology is relatively late compared to the United States and Europe, and it does not have the test conditions to conduct large-scale, long-term reliability tests. It is difficult to conduct flywheel life tests and statistical failure rates. Get the desired result. In view of this situation, many experts' theoretical research on flywheel reliability is mainly focused on the reliability performance degradation theory, and the method of studying accelerated life test obtains the change curve of flywheel reliability in a relatively short time. Theoretically establish a curve of the reliability of the take-off wheel over time, which can be used to perform reliability analysis with less data.

4. Reliability assessment of momentum wheel

The control principle of the bias momentum wheel is to generate control torque through the acceleration or deceleration of the flywheel, and there is bias momentum [8]. The characteristic of the three-axis attitude stabilization system of the offset momentum wheel is that it relies on the fixed axis of the flywheel offset momentum. To control the entire spacecraft, only the roll and pitch attitude information is needed, and a flywheel is installed on the pitch axis without the need for three-axis attitude measurement. The control principle of the frame momentum wheel is to generate control torque by adjusting the direction and size of the rotor momentum moment. The torque generated by changing the rotational speed of the momentum wheel is used to overcome the environmental disturbance momentum and stabilize the satellite [9-12]. Studies have shown that, in most cases, the bearing and lubrication system determine the reliability of the momentum wheel [13]. The reason for the failure of the momentum wheel is that a lubricating film cannot be formed due to long-term volatilization and creep. These two processes run through the life cycle of the momentum wheel [14]. Therefore, the research on the reliability of the momentum wheel can be considered mainly from the bearing and the lubrication system, and establish a complete and complete standard from bearing pretreatment to cleaning, assembly and testing. At the same time, it is necessary to design the structure and select high-quality materials and temperature. Consider the control design [15,16]. When modeling the degradation process of the momentum wheel in China, the degradation model is usually used, and the method of extrapolation is used to carry out the reliability assessment of the momentum wheel [17]. From the perspective of failure physics analysis, a failure physics-based evaluation framework for the momentum wheel is proposed. Combined with the failure analysis, the momentum wheel discrete Bayesian network model is established from the ground test data of the momentum

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wheel. The ground test of the momentum wheel conducts reliability analysis. Perform statistical analysis on the performance data of the momentum wheel in the ground test, establish a momentum wheel hybrid Bayesian network model based on the performance data, and use the previously built model to analyze the on-orbit reliability of the momentum wheel. Combining the previous hybrid model and the model of momentum wheel performance over time, a dynamic Bayesian network is established, and the dynamic Bayesian network is used to carry out life budget and reliability evaluation of the momentum wheel [18]. Lubrication degradation models involving dynamic environmental factors should be useful for reliability assessment, continuous monitoring and system management of spacecraft momentum wheels operating in harsh space environments [15].

5. Reliability assessment of control torque gyro

The control principle of the control moment gyro is to generate the control moment by changing the direction of the moment of momentum, that is, the frame rotation. The characteristic of the three-axis attitude stabilization system of the control moment gyro is that according to the gyro effect of the gyro rotor, the torque output is realized by controlling the angular rate of the frame rotation to change the direction of the rotor angular momentum. When the power is low, a larger linear torque is generated and can be used more Small mass, power consumption and small size can obtain large control torque. The control moment gyro is an ideal actuator for long-life, heavy-duty spacecraft [19]. To analyze the reliability of the control moment gyroscope structure, the limit state function of the structure must first be established. The limit state function generally includes response quantities such as stress, strain, displacement and frequency. For complex mechanical structures, the response amount cannot generally be obtained by analytical methods, but can only be obtained by numerical calculation methods, such as finite element method, so it is not easy to obtain the explicit function expression of the limit state function [20]. According to the analysis of the structural composition and main failure modes of the control moment gyroscope, its reliability assessment adopts a system synthesis method. Based on the reliability assessment of high-speed components and low-speed components, the reliability of the control moment gyro is estimated by the series model [21]. Use the PDS module of ANSYS to analyze the reliability of the natural frequency of the control moment gyroscope structure, obtain the reliability at the required frequency, and point out the main factors affecting the natural frequency. Use it to perform reliability analysis on the strength and stiffness of shell components, and use strength and stiffness failure as a series model for reliability analysis, which can provide references for reliability analysis of more failure modes [22].

6. Conclusion

As the requirements for precision, lifetime and reliability of spacecraft become higher and higher, actuators must satisfy. more requirements. For high-reliability and long-life products, they often face the problem of small samples. The traditional reliability analysis method based on a large number of life data is no longer applicable, so the reliability evaluation method based on performance degradation is often used. . The method based on performance degradation requires small sample size and can solve the problem of no failure. At present, when studying the reliability analysis of inertial actuators, several methods are sometimes used to merge with each other to ensure that the analysis results are more accurate.

References

[1] S.Z. Liu. Development and Prospect of My Country's Space Inertial Execution Agency (1), Sea, Land, Air, and Sky Inertial World, vol. 9 (2013), p. 151-152. (In Chinese).

[2] B.H. Jin: System Reliability Engineering (National Defense Industry Press, China 2004). (In Chinese).

[3] Q.Z. Mei,J.S. Liao,X.Z. Sun: Basis of System Reliability Engineering (Science Press, China 1987). (In Chinese).

ISSN: 2414-1895 DOI: 10.6919/ICJE.202009_6(9).0032

[4] J. Pearl. Fusion, Propagation, and Structuring in Belief Networks, Artificial Intelligence, Vol. 29 (1986) No. 3, p. 241-288.

[5] B. Guo, X.Y. Wu, X.B. Zhang, et al: System Reliability Analysis (National University of Defense Technology Press, China 2002). (In Chinese).

[6] H. Bao: Reliability Analysis and Fault-tolerant Design of Reaction Flywheels (Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, China 2014). (In Chinese).

[7] H. Bao, J.F. Wu, Y.H. Wu. Reliability Research of Reaction Flywheel, Micromotor,Vol. 047 (2014) No. 012, p. 6-11. (In Chinese).

[8] R. Niu, W.S. Zhu, L.L. Li, et al. Design of Gaofen-5 Satellite Attitude and Orbit Control Subsystem, Shanghai Aerospace,vol. S2 (2019), p. 61-66. (In Chinese).

[9] Z. Ismail, R. Varatharajoo. A study of Reaction Wheel Configurations for A 3-axis Satellite Attitude Control, Advances in Space Research, Vol. 45 (2010) No. 6, p. 750-759.

[10] K.D. Kumar, M.J. Tahk, H.C. Bang. Satellite Attitude Stabilization Using Solar Radiation Pressure and Magnetotorquer, Control Engineering Practice, Vol. 17 (2009) No. 2, p. 267-279.

[11] A.M.S. Mohammed, M. Benyettou, Y. Bentoutou, et al. Three-axis Active Control System for Gravity Gradient Stabilised Microsatellite, Acta Astronautica, Vol. 64 (2009) No. 7-8, p. 796-809.

[12] S. Taniwaki, Y. Ohkami. Experimental and Numerical Analysis of Reaction Wheel Disturbances, Jsme International Journal, Vol. 46 (2003) No. 2, p. 519-526.

[13] M. Tafazoli. A Study of On-orbit Spacecraft Failures, Acta Astronautica, Vol. 64 (2009) No. 2-3, p. 195-205.

[14] G. Jin, L. Qiang, J. Zhou, et al. RePofe: Reliability Physics of Failure Estimation Based on Stochastic Performance Degradation for the Momentum Wheel, Engineering Failure Analysis, vol. 22 (2012), p. 50-63.

[15] G. Jin, D. Matthews, Y. Fan, et al. Physics of Failure-based Degradation Modeling and Lifetime Prediction of the Momentum Wheel in a Dynamic Covariate Environment, Engineering Failure Analysis, Vol. 28 (2013) No. 3, p. 222-240.

[16] Q. Liu, J.L. Zhou, G. Jin, et al. Momentum Wheel Reliability Evaluation Based on Random Threshold Gauss-Brown Failure Physical Model, Astronautics Journal, vol. 05 (2009), p. 371-377. (In Chinese).

[17] K. Yu: Momentum Wheel Reliability Evaluation Based on Information Fusion (University of Electronic Science and Technology, China 2019). (In Chinese).

[18] H.T. Li: Momentum Wheel Reliability Modeling and Analysis Based on Bayesian Network (Graduate School of National University of Defense Technology, China 2007). (In Chinese).

[19] S.Z. Liu. Development and Prospect of My Country's Space Inertial Execution Agency, Sea, Land, Air, and Sky Inertial World, vol. 10 (2013), p. 159-160. (In Chinese).

[20] J.Q. Tang, S.P. Zhao, K Wang. Reliability Design and Optimization of Magnetic Levitation Control Torque Gyro Locking Mechanism, Optical Precision Engineering, Vol. 026 (2018) No. 003, p. 597-605. (In Chinese).

[21] J.H. Luan, Y.D. Dai, X.G. Zhu, et al. Research on the Life and Reliability Evaluation Method of A Certain Control Torque Gyro, Aerospace Manufacturing Technology, vol. 5 (2019), p. 6-9. (In Chinese).

[22] S.R. Shu: Reliability Analysis of Small Control Torque Gyro Using Finite Element Method (Harbin Institute of Technology, China 2009). (In Chinese).