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STUDY ON RELIABILITY ANALYSIS OF SUSPENSION CONTROLLER OF THE MEDIUM AND LOW SPEED MAGLEV VEHICLE

Suspension controller is the core device of suspension system of the medium and low speed maglev vehicle, its reliability directly affects the stability, reliability and safety operation of the whole medium and low speed maglev train. Reliability analysis is of great theoretical and practical value for improving the performance of the suspension controller.

Taking Hunan Changsha maglev express as an application case, based on the mechanism and functional structure of the suspension controller, the reliability of the suspension controller is analyzed and studied. According to the Chinese standard GJB/Z 299C, the reliability prediction handbook for electronic equipment, the reliability of the suspension controller is calculated and analyzed by synthesizing the stress analysis method, the component counting method and the RBD reliability block diagram method. The reliability weak points of the suspension controller are analyzed, and the design optimization proposal is suggested to improve the suspension controller reliability.

Background: Medium and low speed maglev traffic has gained wide attention and engineering application in China. It is very necessary to study the reliability of the medium and low speed maglev train.

Purpose: The purpose of this paper is to carry out reliability research on the levitation control system of medium low speed maglev train.

Methods: The stress analysis method, component counting method and RBD reliability block diagram method are used to calculate and analyze the reliability of the suspension controller.

Results: The reliability quantitative analysis results of the suspension controller are analyzed, and the reliability weakness of the suspension controller is analyzed and studied. A design optimization proposal to improve the reliability of the suspension controller is proposed.

Conclusion: Through the reliability prediction analysis of the suspension controller, the reliability and weakness of the suspension controller can be determined, which provides theoretical guidance for the improvement of the design scheme and the performance optimization of the maglev train suspension controller.

Keywords: Medium and low speed maglev vehicle, Suspension Controller, Reliability Analysis, Reliability Prediction, Maglev Transportation

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1. INTRODUCTION

On Dec. 26th, 2015, China's first medium and low speed maglev railway, Changsha Maglev Airport Express line began trial operation, and officially began commercial trial operation one year later. Because of its obvious advantages, such as small turning radius, low noise, high comfort and so on, the medium and low speed maglev train has attracted wide attention of the rail transit field. Whether such a new rail transit mode is safe and reliable, especially whether the suspension system of maglev train which is quite different from the traditional wheel rail train can operate reliably, has become the key concern of maglev train operation. Therefore, the study of the reliability of the suspension controller has a very important practical value in engineering practice.

Reliability block diagram (RBD) uses the blocks and connections to draw the influence of each component on the functional characteristic of the system when failures occurred. In RBD, the blocks represent the different component units of the system, and the connections depict the interconnection of the components. The reliability block diagram shows the failure logic of the system by using interconnected blocks. It helps to evaluate the overall reliability of the system by analyzing the impact of the failure rate of each component in the system. Reliability prediction is the method of estimating products reliability under given working conditions. Based on the empirical data of some similar products or the reliability data of the units that make up the product, we can estimate the reliability parameters value of the product under given working or non-working conditions when there is no test data for the products. The commonly used methods include: component counting method, stress analysis method, mathematical model method, upper and lower limits method, Monte Caro method and so on.

When the internal structure of the suspension controller, detailed list of components, stress environment and other information are known, the failure rate of the product can be calculated accurately by using the stress analysis method. And then we can quantify the reliability of the product. For the components that cannot be determined temporarily, we can use the element counting method to estimate roughly.

In the case of reliability analysis, the reliability block diagram of the components inside the suspension controller should be analyzed first. Based on this, the mathematical model of system reliability prediction is obtained. The failure rate of each component module is calculated by component counting method or stress analysis method. By this method, the failure rate data of each module can be obtained, and the influence of internal structure on the reliability of the overall suspension controller can be taken into account.

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2. ANALYSIS OF THE FUNCTION STRUCTURE AND WORKING MECHANISM OF THE SUSPENSION CONTROLLER

The functional structure of suspension controller for the low-speed maglev trains is shown in Fig. 1.

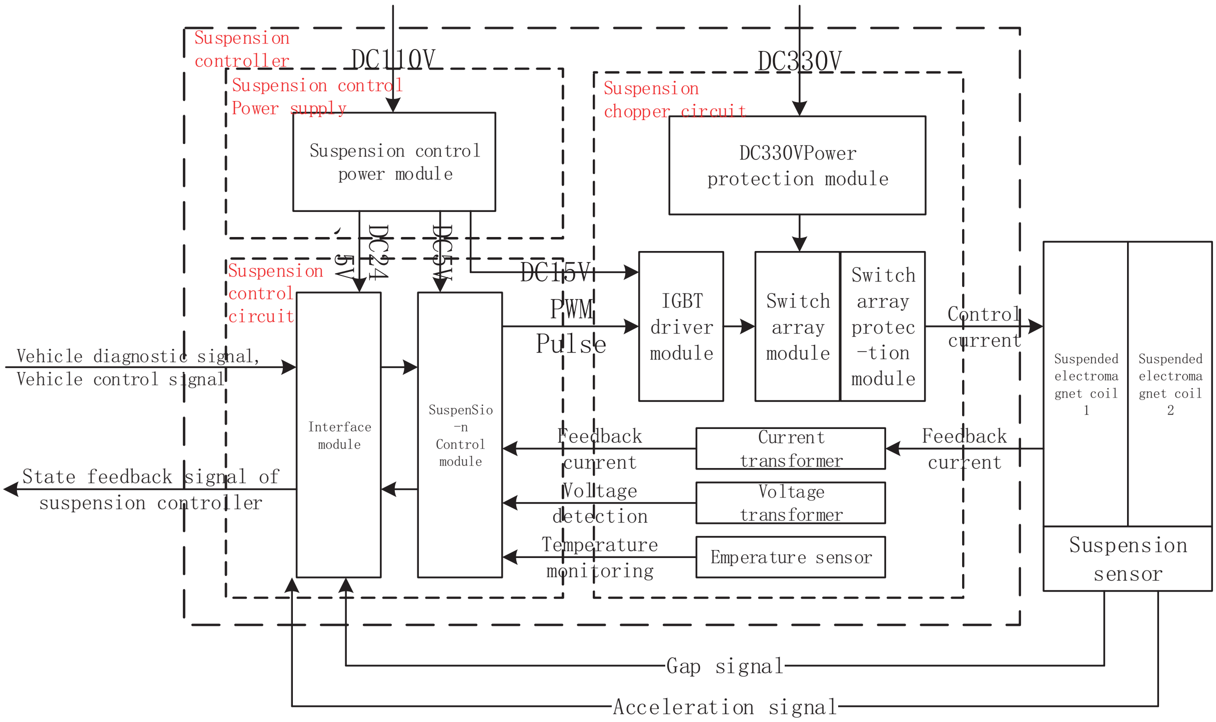

Fig. 1. Suspension controller structure diagram of the medium and low-speed maglev trains

The working principle of the suspension controller is a typical closed-loop control principle. The suspension sensor can measure the real time gap between the suspended electromagnet and the F rail and the vertical acceleration of the point. And the current sensor can measure the amount of current flowing through the electromagnet. The measured gap signal, acceleration signal and current signal are fed back to the suspension control module through the interface module of the suspension control circuit. Accordingly, the suspension control module is processed by the suspension algorithm, and the current needed by the electromagnet is calculated. The output PWM (Pulse Width Modulation) signal is sent to control the IGBT driving module. The IGBT driver module controls the turn-on and turn-off of the IGBT switches to output the main power supply. By turn-on and turn-off the DC/DC chopping principle of the DC330V module, the current required on the electromagnet is realized, thus the suspension gap is controllable. Furthermore, the suspension controller can also receive on-board control and diagnosis information via on-board network, and feedback the current state of the suspension control point

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to the superior train network. Thus the monitoring and control of the suspension system is realized via the vehicle network.

The interface module is an information exchange component to the suspension controller, which includes CAN interface unit, installation position interface unit, control network levitation control signal and state feedback signal interface unit, logic operation unit, the blank spring control unit, PWM pulse signal and drive board interface unit, reset signal circuit unit and 24V sensor power supply control unit, contactor control unit, power preprocessing unit and so on.

The suspension control module is the most important part of the suspension controller. The feedback signals and control signals are calculated and processed by the suspension control algorithm. In addition, the suspension control module can also implement the functional coordination of other modules of the suspension controller. It is mainly composed of signal filter unit, AD conversion unit, DSP processing unit, memory unit, arithmetic logic unit and power preprocessing unit.

3. RELIABILITY MODELING AND RELIABILITY PREDICTION ANALYSIS OF THE SUSPENSION CONTROLLER

3.1. Reliability modeling of the suspension controller

From the description of the functional structure of the suspension controller, we can see that any module failure will lead to the fail of whole controller, only when all these modules can work properly, can the suspension controller fulfill the requirements. The medium and low-speed maglev controller belongs to the RBD reliability model of pure series structure, as shown from Fig. 2 to Fig. 4.

The components of the suspension controller are connected in series, so the mathematical model formula of the series system mentioned above is calculated by formula (1).

$$R_s(t) = \prod_{i=1}^{n} R_i(t) \tag{1}$$

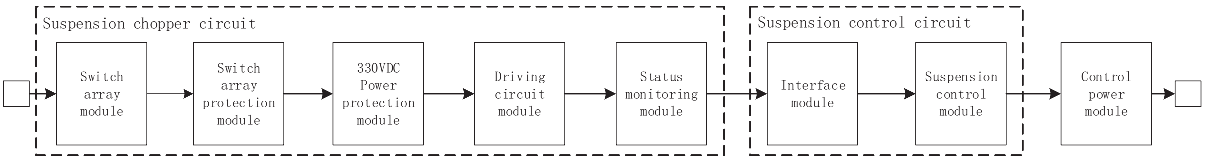

Fig. 2. RBD model of suspension controller

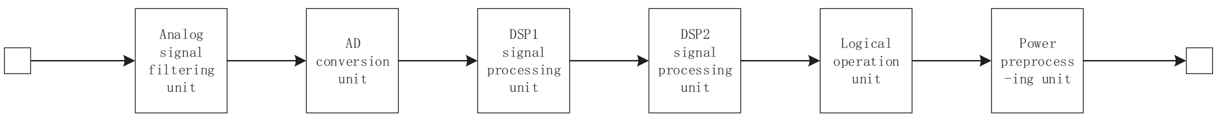

Fig. 3. RBD model of suspension control module

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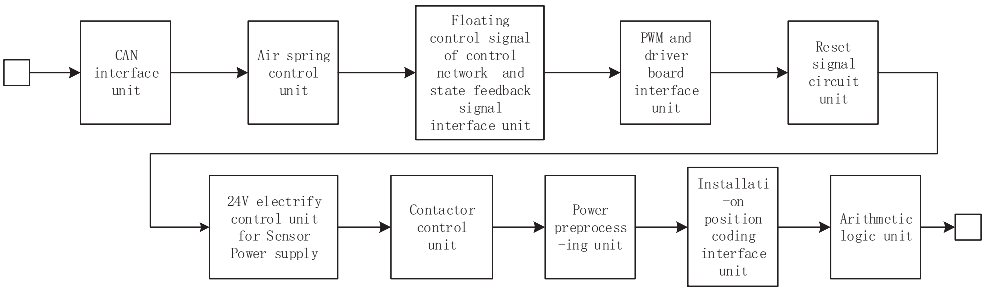

Fig. 4. RBD model of suspension controller interface module

The failure rate of most electronic products in accidental failure period follows exponential distribution. The formula of total failure rate of suspension controller is shown as formula (2).

$$\lambda_s = \prod_{i=1}^{n} \lambda_i \tag{2}$$

The average mean time to failure interval time (MTTF) of the suspension controller can be calculated by formula (3).

$$\text{MTTF} = \frac{1}{\lambda_s} \tag{3}$$

3.2. Reliability prediction of the suspension controller

After the establish of the reliability model of suspension controller for medium and low-speed maglev vehicle, the reliability analysis of suspension controller can be carried out as follows:

1) Determine the type and number of the components used in the unit.

According to the design data of the suspension controller circuit diagram , we can sort out the information of the components of each module unit, such as types, quantities, models and so on, which can facilitate the next work and finding the components data list for standby.

2) Determine the quality grade of components.

The quality grade of components is determined according to the selection, purchase, batch inspection and control of components. Due to the high quality requirements of the devices used in the levitation controller of low-speed maglev trains, the quality grades of the components are all in a higher grade.

3) Determine the ambient temperature.

Changsha Maglev Express Line located in Changsha City, Hunan Province in a subtropical monsoon climate. The annual average temperature in the urban area of Changsha is 17.2°C. In each county, the temperature is between 16.8–17.3 °C, so the ambient temperature of the suspension controller worked should be 17 °C.

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4) Identification of environmental categories.

In GJB/Z 299C, the application environment of electronic equipment is divided into more than ten categories. The vehicle body of medium and low-speed maglev trains is suspended on the track and has no obvious tremble. It can be regarded as steady ground movement and the environmental category is codenamed as G_{M1}.

The reliability prediction stress analysis method has many parameters and large data volume. For each component, after finding the basic data of each component, the failure rate of each component can be calculated according to the reliability model.

3.3. Reliability prediction results of the suspension controller

With the help of professional reliability analysis software Isograph RWB11.0, each component parameter can be input, and the failure rate of each component can be obtained by consulting the built-in reliability prediction manual standard. The predicted results of the components in the suspension controller are as follows:

1) Suspension chopper circuit

From the data of reliability prediction, it can be seen that the failure rate of other parts in the suspension chopper circuit is higher than 700 FITS except for the switch IGBT driving module. The electrolytic capacitance of switch array protection circuit, (587.00 FITSs) and IGBT (215.82 FITS) have a high failure rate.

2) Interface module

The parts of high failure rate in the interface module are 24V sensor power supply unit and power preprocessing unit. Among them, the fuses (760 FITS), TPS75733 voltage regulation chip (186,26 FITS) contribute more failure rates.

Table 1. Reliability Prediction Results of Suspension Chopper Circuit

Number	Description	Failure rate (Fits)	Quantity (/N)	N x Failure rate(Fits)	MTTF (h)
1	Suspension chopper circuit	4446.92	1	4446.92	2.25E+05
1.1	Switch array module	722.04	1	722.04	1.39E+06
1.2	Switch array protection module	1196.64	1	1196.64	8.36E+05
1.3	330VDC Power protection module	930.58	1	930.58	1.08E+06
1.4	IGBT Driver module	39.10	1	39.10	2.56E+07
1.5	Status monitoring module	1558.56	1	1558.56	6.42E+05

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Table 2. Reliability Prediction results of Interface Module

Number	Description	Failure rate (Fits)	Quantity (/N)	N x Failure rate(Fits)	MTTF (h)
2.1	interface board	4933.27	1	4933.27	2.03E+05
2.1.1	CAN interface unit	409.21	1	409.21	2.44E+06
2.1.2	Air spring control unit	96.81	1	96.81	1.03E+07
2.1.3	Feedback signal unit	190.08	1	190.08	5.26E+06
Number	**Description**	**Failure rate (Fits)**	**Quantity (/N)**	**N x Failure rate(Fits)**	**MTTF (h)**
2.1.4	PWM and driver board interface unit	6.02	1	6.02	1.66E+08
2.1.5	Reset signal circuit unit	3.25	1	3.25	3.08E+08
2.1.6	24V Sensor power unit	1702.77	1	1702.77	5.87E+05
2.1.7	Contactor control unit	381.00	1	381.00	2.63E+06
2.1.8	Power preprocessing unit	1578.34	1	1578.34	6.34E+05
2.1.9	Installation position coding interface unit	36.88	1	36.88	2.71E+07

3) Suspension control module

Table 3. Reliability Prediction Results of Suspension Control Module

Number	Description	Failure rate (Fits)	Quantity (/N)	N x Failure rate(Fits)	MTTF (h)
2.2	Suspension control module	6570.66	1	6570.66	1.52E+05
2.2.1	Input analog signal filtering unit	417.07	1	417.07	2.40E+06
2.2.2	DSP1 signal processing unit	1059.20	1	1059.20	9.44E+05
2.2.3	Arithmetic Logic Unit	1168.60	1	1168.60	8.56E+05
2.2.4	Power preprocessing unit	1516.32	1	1516.32	6.60E+05
2.2.5	DSP2 signal processing unit	867.55	1	867.55	1.15E+06
2.2.6	AD Conversion unit	1541.93	1	1541.93	6.49E+05

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Except for the input signal filter unit in the suspension control module, the failure rates of other parts are all high, and most of the components in each unit are integrated chips. For example, the CPLD chip (1168.60 FITS) and the AD converter chip (739.08 FITS), IS61Lv6416 asynchronous static random access memory(514,35 FITS), EEPROM memory chip (372,96 FITS) and so on.

The overall reliability of the suspension controller is expected to be shown in Table 4.

Table 4. Reliability Prediction Results of Each Module of Suspension Controller

Number	Description	Failure rate (Fits)	Quantity (/N)	N x Failure rate(Fits)	MTTF (h)
1	Suspension chopper circuit	2888.36	1	2888.36	3.46E+05
2	Suspension control circuit	11503.93	1	11503.93	8.69E+04
3	Suspension control power	5582.78	1	5582.78	1.79E+05

According to the reliability block diagram of the suspension controller shown in Fig. 2. the working failure rate of the whole suspension controller can be calculated, and the result is 21533,63 FITS.

$$\lambda = 21533.63 \times 10^{-9} / h \tag{4}$$

Therefore, the average failure interval of the suspension controller is:

$$\text{MTTF} = \frac{1}{21533,63 \times 10^{-9}} = 4.644 \times 10^{4} h \tag{5}$$

According to the reliability prediction results, the least replaceable units, components or components of the suspension controller for the medium and low-speed maglev trains can be sorted in accordance with the contribution of failure rate, and the main components that affect the reliability of the suspension controller can be found out.

Table 5. Sorting of Components with High Failure Rate in Suspension Controller

Component name	Type of components	Failure rate of single component /FIT
CPLD	XC95144XLTQ100	1168.6
Fuse	RUE185, BS88	760.00
AD Conversion chip	AD7864	739.08
Electrolytic capacitor	epcosB43310	587.00
Asynchronous static random access memory	IS61Lv6416	514.35

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It can be seen from Table 5 that the programmable logic device CPLD chip has a great influence on the reliability of the suspension controller in the medium and low-speed maglev trains. According to the device analysis, the methods and measures to improve the reliability of the suspension controller can be put forward as follows:

• Device screening:

The inherent reliability of electronic components depends on the reliability design of the products, The average life of components with early failure is much shorter than that of normal products. The reliability of electronic devices is based on the reliability of electronic components. If the components of early failure are installed with equipment, the failure rate of early failure of equipment will be greatly increased, its reliability can't meet the requirements, but also pay a great deal of cost to repair. Therefore, the components with early failure should be excluded as much as possible before the electronic components are installed with equipment. For this reason, the components should be screened. Based on the experience of screening at home and abroad, the total failure rate of components can be reduced by 1 ~ 2 orders of magnitude through effective screening, so the screening of components is an important means to ensure reliability.

• Derating design:

The so-called derating design of equipment is that make the working stress of components or equipment properly lower than the rating specified of components or equipment, so as to reduce the basic failure rate and improve the reliability. Among them, the reliability of electronic products is sensitive to its electric stress and temperature stress. The commonly used derating parameters are voltage, frequency, input current, power consumption and junction temperature. For all kinds of electronic components, there is an optimal reduction range, in which the variation of working stress has a significant impact on the failure rate of components, and is also relatively easy to achieve in design, and will not be realized in the volume of the equipment. The derating criteria and application guidelines for all types of components are in accordance with the national military standard GJB/Z35 "Derating criteria for electrical, electronic and electromechanical parts".

• Structural optimization:

The starting point of improving reliability from the structure level is to increase the redundancy of the integrated circuit appropriately, so that we can avoid the negative impact of failure rate accumulation on the reliability of the suspension controller. The key modules of the circuit can be designed redundant within the limits of space and cost.. Take the control card as an example, suppose that the design of the suspension control card has a backup redundancy module, its failure

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rate can be reduced from 6904 Fits to 47 Fits and the reliability of 1000 hours was increased from 0.99312 to 0.99995 (calculated on the basis of the reliability of 1000 h). It can be seen that the reliability of the levitation controller of the low-speed maglev trains can be greatly improved by increasing the redundancy of the easy failure module structure.

• On-line diagnosis and status detection:

Improving the reliability of suspension controller from the system level depends on the further development of on-line testing and fault diagnosis technology. We can set test points at key nodes of important devices, such as the key output pin of the chip, voltage output of the control power circuit, and set up a digital code for each test point. By extracting and analyzing the circuit eigenvalues under the working state of each test point, judging whether the circuit is invalid or not on line. According to the feedback code of the online fault diagnosis system, the "focus" of the fault can be accurately tested. Even further, we can introduce the technology of fault prediction and health management (PHM). And by analyzing the difference or similarity between the circuit to be tested and the standard fault-free circuit, we can judge the health state of the circuit under test and predict the potential failure form. The reliability of the suspension controller is raised to a new level from a preventive point of view.

4. CONCLUSION

Based on the engineering application of the first medium and low-speed maglev railway in China, this paper analyzes the reliability of suspension controller for Changsha Maglev Express Line synthetically by using the component counting method and the stress analysis method. By analyzing the reliability prediction of levitation controller, the weak points of reliability of suspension controller can be determined. And it provides theoretical guidance for the design improvement and performance optimization of maglev train suspension controller.

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