Design and Implementation of Rail Flaw Detector Based on Eddy Current---A kind of accurate and efficient non-destructive flaw detection for rail transit

Zelin Yin*, Qinxu Yu

School of Electronic and Information Engineering Beijing Jiao tong University Beijing, China

*Corresponding author: 18721036@bjtu.edu.cn

Keywords: eddy current sensor; orbit; vehicle.

Abstract: The rapid development of rail transit puts forward higher requirements for rail inspection. In this paper, a kind of eddy current sensor is used to design a track flaw detector which can realize high-speed detection. The two eddy current sensors are placed one after the other at a fixed interval. When the train is running at a constant speed, the sensors perform detection in sequence. The two sensors measure the signal at a fixed point at a fixed time interval. When both sensors measure a crack signal at a certain point, the detector will give an alarm and determine its location to improve the reliability of detection.

1. Introduction

There are plenty of advantages of rail transit, especially in urban rail transit system which is characterized by fast speed and short driving intervals. Compared with the bus system, its transport capacity is far larger. A double-track rail transit line and a 16-lane highway have roughly the same transport capacity, which enables the priority of the road. Urban rail transit system includes tram, light rail and subway, etc. With electric energy as the main power and wheel-rail as the main mode of transportation, it is a transportation system in a higher speed capable of bearing a large number of public transportation tasks [1]. As for urban rail transit vehicles, they are less affected by the weather, traffic jams and road conditions with stable running time. Compared with buses, they have lower traffic accident rate and higher vehicle configuration. Therefore, it is convincing for urban rail vehicles to ensure safety and comfort [2]. The noise generated by rail transit is easy to control. For example, by using the extra-long seamless rail, the light-rail train is detected to reduce the operating noise to about 70 decibels [3]. Hence, urban rail transit has been vigorously developed. With the overall improvement of railway transport density and speed, higher and more stringent requirements have been put forward for rail flaw detection.

The fourth item in references introduces the locomotive specially designed for track flaw detection. The locomotive mentioned in the literature has quite complex designed functions, with a running speed of about 250 km/h and a maximum speed of 300 km/h. Since the usage of locomotives is complicated, the author optimizes the flaw detection vehicle through the optimization of the head shape and the design of the independent wheel set of the bogie, to reduce the air resistance of the track flaw detection vehicle and reduce its own mass. The rail flaw detection vehicle adopts laser cross-section scanning to realize the standardized detection of the rail contour, makes use of the force measuring wheel set device to detect the rail clearance and the turnout accuracy, and utilizes the ultrasonic rebound detector to detect the tunnel contour and the displacement of the lining platform. The eddy current sensor is mostly utilized to detect the scars or cracks inside the rail. Eddy current sensor is a typical non-contact sensor for metal interior detection, which has plenty of advantages such as high sensitivity, high efficiency, and resistance to various environmental interferences in application [5]. Therefore, in this paper a digital eddy current track flaw detection vehicle is designed and implemented to be applied to the rail flaw detector.

2. Principles of Flaw Detection And System Design

2.1 Principle of Eddy Current Flaw Detection

According to Faraday's law of electromagnetic induction, as shown in Figure 1, when the coil L_1 is added to the alternating current I1, the coil will generate sinusoidal alternating magnetic field H1 of corresponding frequency in the surrounding space. At this point, if the coil is close to the metal conductor, the magnetic force lines of the alternating magnetic field will penetrate the metal conductor. Thus, the alternating magnetic line of force will cause the conductor to generate the induced alternating current I2, and present a closed loop in the shape of water eddy current, which is eddy current I2. Similarly, alternating eddy currents I2 generate alternating magnetic fields H2 whose field lines also pass through the coil L1. Under electromagnetic induction, the coil generates an induced electromotive force which will block the change of I1. Therefore, the eddy current can be equivalent to a coil L2, and the two coils are equivalent to a transformer, as shown in Figure 2

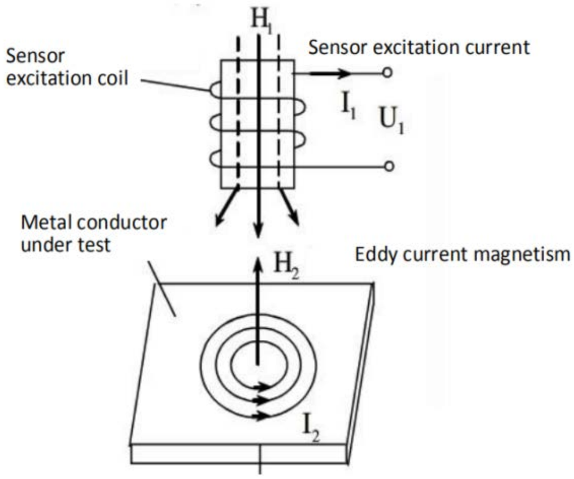

Figure 1. Schematic Diagram of Eddy Current Sensor.

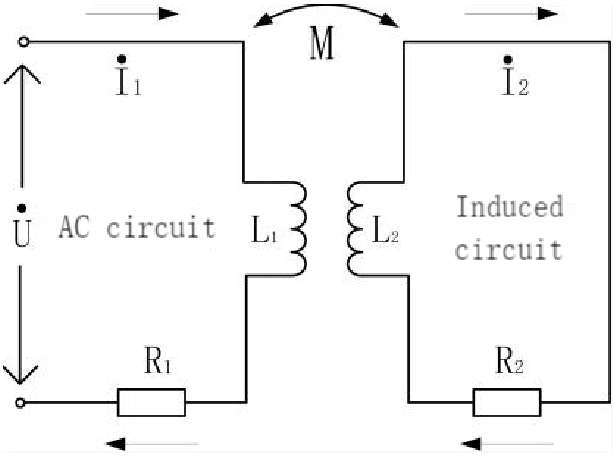

Figure 2. Eddy Current Equivalent Transformer Model.

According to Figure 2, the following equation can be obtained:

$$R_2 \dot{I}_2 + j\omega L_2 \dot{I}_2 - j\omega M \dot{I}_1 = 0 \tag{1}$$

$$R_1 \dot{I}_1 + j\omega L_1 \dot{I}_1 - j\omega LM \dot{I}_2 = \dot{U} \tag{2}$$

The expression can be obtained as follows:

$$\dot{I}_1 = \frac{\dot{U}}{R_1 + \frac{\omega^2 M^2}{R_2{}^2 + (\omega L_2)^2} R_2 + j\left[\omega L_1 - \frac{\omega^2 M^2}{R_2{}^2 + (\omega L_2)^2} \omega L_2\right]} \tag{3}$$

Further deduced from the above equations, the equivalent impedance of the sensor coil is:

$$Z=\dot{U}/\dot{I}=\left[R_1+\frac{\omega^2M^2}{R_2{}^2+(\omega L_2)^2}R_2\right]+j\left[\omega L_1-\frac{\omega^2M^2}{R_2{}^2+(\omega L_2)^2}\omega L_2\right] \tag{4}$$

Based on the circuit theory, it is known that the complex impedance of the L1 end of the primary coil is mainly related to the resistivity of the metal, the distance between the coil L1 and the metal conductor, the electromagnetic rate, the frequency of the excitation current, and the diameter of the eddy current. In practical application, the single value correspondence is chosen upon most occasions, such as the single value correspondence between impedance and metal resistivity for track flaw detection, and other quantities are constants. In this paper, the eddy current sensor has the characteristics of fixed metal distance, fixed excitation frequency and constant electromagnetic rate of rail. When there is a crack in the rail, the circuit resistance of the eddy current will suddenly increase, which was reflected from the complex impedance or the coil current I1, as shown in Figure 3.a that shows the signal when there is interference signal, and Figure 3.b shows the signal after filtering.

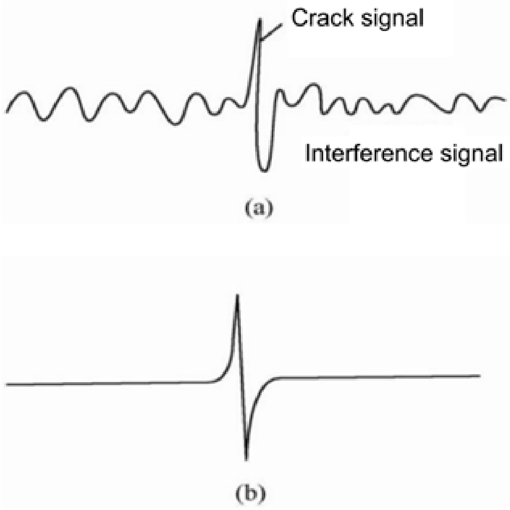

Figure 3. Cracks Encountered during Eddy Current testing.

In addition, the depth of the eddy current penetrating the metal is:

$$J_d=J_0e^{-d/h} \tag{5}$$

In this formula, h represents the axial penetration depth of the eddy current, and d represents the distance from a point in the metal conductor to the surface. The greater the resistivity of the measured body, the smaller the relative permeability. At the same time, the lower the excitation current frequency of the sensor coil, the greater the penetration depth h of the eddy current, which is specifically selected in practical applications.

2.2 Eddy Current Sensor Detection Circuit

There are many kinds of eddy current detection circuits, such as the bridge method measuring circuit. In the bridge method, the eddy current coil is used as an arm of the AC Bridge. Under normal conditions, the electric bridge is in a balanced state. When a crack is encountered, the complex impedance of the eddy current coil changes greatly, causing the unbalanced electric bridge. In this state, the unbalanced voltage output by the bridge is linearly amplified and detected to output a voltage signal proportional to the measured voltage. This kind of voltage signal circuit is simple, but the measuring accuracy is not high, which cannot meet the design requirements of high precision and large range in this design.

In this paper, a fixed frequency is utilized for amplitude modulation measuring circuit. The circuit forms an LC parallel resonance circuit with an eddy current sensor and a capacitor. The circuit block diagram is shown in Fig. 4 as the oscillation source of the detection circuit. In the block diagram, the crystal oscillator provides a high-frequency excitation voltage signal required by the detection circuit as a fixed frequency sinusoidal signal added to the parallel circuit of the eddy current coil and the capacitor. When the status of the detective conductor changes slightly, the frequency of the LC resonant circuit is in the same value as the frequency provided by the crystal oscillation. At this time, the circuit impedance and the output voltage drop reach the maximum value. When there are cracks in the conductor under test, the impedance of the coil changes, causing the output voltage of the detective circuit to decrease. During this process, the output voltage frequency does not change, and is called the fixed frequency amplitude modulation detection circuit.

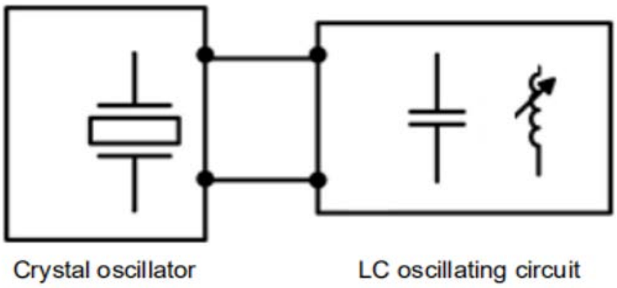

Figure 4. Amplitude Modulated Measuring Circuit.

Since the detection system is installed on a high-speed probe vehicle, assuming that the vehicle is running at a speed of 360km/h (the actual detection vehicle speed is 200km/h) which is 0.1mm/us. If the crack is less than 0.1mm level, the elapsed time of the train should be less than 0.1us. Therefore, this system chooses the crystal oscillation whose frequency is 20MHz. When the eddy current sensor passes through the track with cracks at high speed, it will generate a larger amplitude signal, as shown in Figure 3.b after filtering. Since the crack signal is narrow, a high-speed AD converter is usually used to collect the signal. There are various methods used to make judgments based on digital signals to obtain crack information. However, this method is more complicated in most instances. For this reason, a comparator is used to collect the amplitude signal, and the circuit is shown in Figure 5. In Figure 5, A1 amplifier outputs a comparison voltage, which is obtained by R1 and R2 partial voltages:

$$Vr=V_{CC}*\frac{R_1}{R_1+R_2} \tag{6}$$

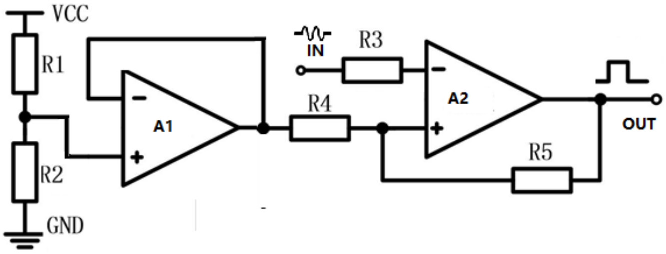

Figure 5. Amplitude Detection of Comparator.

A2 amplifier forms a hysteresis comparator, and the hysteresis difference is determined by the value of R4 and R5.

2.3 Detection System Design

The system block diagram is shown in Figure 6. The STM32F373 MCU is the core of the instrument because the STM32F373 is powerful and the system clock can reach up to 72MHz. This system adopts a working mode which has 32MHz crystal oscillator frequency, 32k bytes of SRAM, 84-wire I/O port. The system monitors the rising edge of the sensor clock through an external interruption. Once it detects a signal input, it enters the interrupt subroutine for judgment. In order to improve the anti-interference ability, this system designs two eddy current sensors which are placed at a distance of 1m between the front and rear. If there is a crack in the rail, the two sensors will detect it in turn, otherwise it will be considered as an interference signal. The time interval between the front and rear sensor signals are calculated based on the detected vehicle speed. Assuming that the vehicle is running at a speed of 360km/h that is equivalent to 0.1m/ms, the running time of 1m interval is 10ms. In this system, ports connect keyboard and LCD display, and RS485 communicates between the instrument and the system, which uploads the detected results to the system.

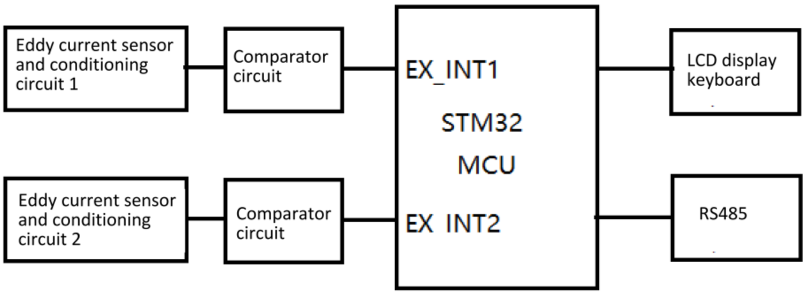

Figure 6. System Block Diagram.

2.4 Software Processing

The process of judging whether there is a crack in the track is completed in the interrupt program. When the rising edge of EX_INT1 enters the interrupt subroutine of EX_INT1, the time counting starts, which means that the first sensor detects the crack information. In order to increase reliability, the system uses two sensors placed one after the other. According to the above vehicle speed, the signal from the second sensor is about 1ms later. Therefore, the interrupt flow chart of EX_INT2 is shown in Figure 7. When the signal is timed from 0.9ms to 1.1ms after EX_INT1 (the two parameters can be set according to the actual vehicle speed and judgment regulations), it can be considered that both sensors have detected cracks information. At this time, the system will read the GPS position information and locate the cracks in the track, which is convenient for maintenance personnel to check the positioning and perform maintenance after further confirmation.

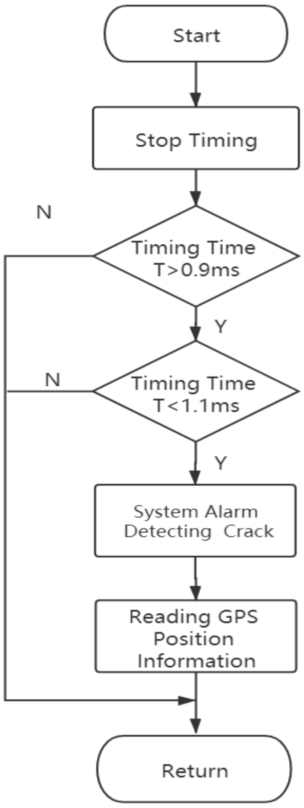

Figure 7. EX_INT2 Interrupt Flow Chart.

3. Conclusion

According to the demand, this paper designs a track crack detection and alarm system. Since the eddy current sensor is susceptible to interference, two eddy current sensors are used for detection in turn. When the crack information is detected by two eddy current sensors at the same time, it is considered as a crack signal, which improves the anti-interference performance of the system. The system on the one hand is used for track detection to detect tracks, and on the other hand, it can be installed on ordinary trains to patrol and detect pipelines to improve train safety.

References

[1] Lin Hao. Suggestions based on enrollment strategies for urban rail transit vehicle technology majors [J]. Forum on Industry and Technology, 2019, 018(001):228-230.

[2] Gong Tongwei. Research on time-space agglomeration of urban rail transit stations based on Baidu thermal map [J]. Statistics and Policy, 2019(24):59-63.

[3] Chen Yunsha, Xia Lisha, Huang Rui, et al. Evaluation and analysis of platform noise in urban rail transit stations [J]. Science and Technology Innovation and Application, 2015, 000(031): 12-13.

[4] Yang Qiang, Li Taotao, Sheng Junjie, et al. Structural design of high-speed rail flaw detection vehicle [J]. Mechanical Engineer, 2020, 000(004): 25-27.

[5] Hou Xiaoyun. Research on the design of STM32 eddy current ranging sensor [J]. Light Textile Industry and Technology, 2019, 048(012):23-24.