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A New Speed Measurement Sensor Using Difference Structure

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Abstract: This paper proposes one new type of speed measurement sensor using difference structure to solve the problem of measurement errors resulted by the vibration of low-speed urban maglev train. By the design of the detection coils and the signal detection circuits, the sensor could fulfills the requirements of rapid and accurate detection. The experiment results show that the speed measurement sensor could effectively overcome the affect of the detection distance changes. The aim of reducing the locating errors caused by the vibration of the train body is achieved. At the same time, the measurement resolution is also increased.

Keywords: sensor, speed measurement, urban Maglev train, difference structure

1. INTRODUCTION

Maglev train is a new type of rail transport vehicle. The low-speed maglev technology has the potential to apply in urban transportation, especially for the short distance route with close stations on it. Depending on the interactions between the active control levitation electromagnet and the tracks, the urban maglev train can fulfill the requirements of sustentation and orientation. It is driven by the linear induction motors without any mechanical contact with the tracks. In comparison with the traditional transport systems, the urban maglev system has higher grade climbing ability, shorter turning radius, lower noises, lower vibration and lower energy consumption. Furthermore, the urban maglev is highly compatible with the environment, flexible in selecting lines, low expense in overall costs and it will promote the environment quality and improving the current urban traffic conditions. It is regarded as a green vehicle according with the development trend of the 21st century, and it has been drawn attention by the scholars all around the world [1-4].

Position and speed measurement system is an important unit in the operational control system for the maglev train. It not only provides the information, such as velocity, direction and location of train for operational control purposes, but also provides the information, such as the moving speed and travelling distance for the onboard traction system, such as brake system and track detection system. Because there is no any mechanical contact between the maglev train and the tracks, the method of measuring the rotate speed of the wheels in traditional wheel railway systems may not be used here.

At present, the main methods of speed measurement and relative positioning that are commonly used by urban maglev trains are the inductive loop-cable-based speed measurement and positioning method, Doppler speed radar method and the “sleeper induction” speed measurement and positioning method [5-8].This paper mainly makes research on one new diagram of speed and position measurement based on “sleeper induction” sensors.

A group of sensors are installed in a straight line on a bracket which is parallel to the tracks and is fixed on the bogie of the

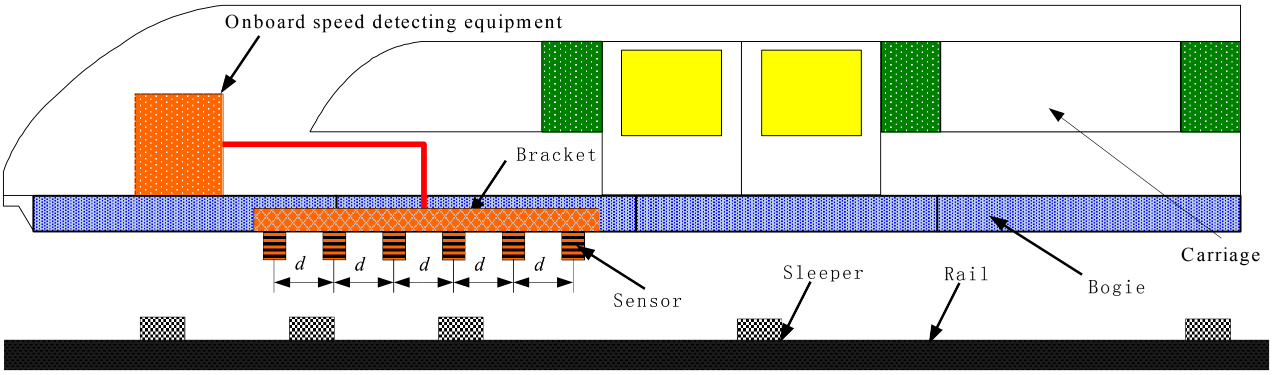

Fig.1. The diagram of speed and position measurement based on the “sleeper induction” sensors.

maglev train, as shown in Figure 1. As the train runs, the sensors sweep over the sleeper on the tracks, and produce the pulse signals. The onboard speed measurement equipment records the period t of the two adjacent sensors passing by the same sleeper, and calculates the train's speed V using the distance d between the two adjacent sensors. That is, $V = d / t$.

Generally the tracks of the urban maglev train system use metal sleepers In consideration of the anti-interference performance, this speed measurement scheme should use inductive proximity switches as the speed measurement sensors. As the sensor passes a sleeper, it could be triggered to generate a pulse signal, in the condition of that the relative position between the sensor and the sleeper is close enough. This scheme is not affected by environmental changes and has good disturbance rejection performance and high reliability. The structure of the system is simple; meanwhile the production cost and maintenance workloads are all relatively low.

2. QUESTION RAISED

As mentioned above, the "sleeper induction" method selects eddy current sensors which are sensitive to metal, and, in the engineering practice, the inductive proximity switches (the sensor) are used to detect the metal sleepers. When the switch installed on the bogie of the train passes a sleeper, it generates a pulse signal.

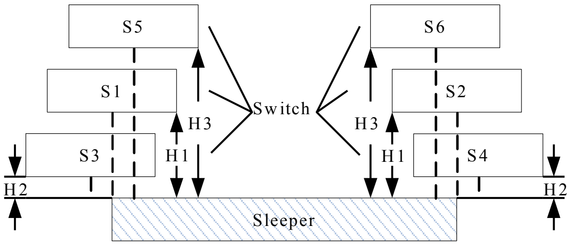

Fig. 2. The sectional view of relative position between the switch and the sleeper in the condition of three kinds of height.

In normal circumstances, shown in Figure 2, the distance between the sensor and the sleeper is H1. When the sensor passes the position S1 above the sleeper, the output signal jumps, and a rising edge is generated. When the sensor passes the position S2 above the sleeper, the output signal makes reverse, generating a falling edge, shown in Figure 3.

If the train body shakes, the distance between the sensor and the sleeper may change to H2 (H2<H1), as shown in Figure 2. Thus the rising edge position and falling edge position of the trigger pulse changes from S1&S2 to S3&S4. It would cause the pulse different from the normal situation. As a result, the duty ratio of the speed pulse becomes bigger, shown in Figure 3.

Similarly, as the distance between the sensor and the sleeper changes to H3 (H3>H2), the two position edges of the trigger pulse become S5 and S6 respectively, and the speed pulse duty ratio becomes smaller, shown in Figure 3.

As shown in Figure 3, when the train vibrates, the changes of the distance would cause the instability of the duty ratio. The uncertain changes may result in the error of speed measurement. The existing variable-area or variable-distance eddy current sensors could not completely solve this problem, so it is necessary to eliminate the limitation that the eddy current sensors are sensitive to the detection area and distance. Basis on the engineering application, and the paper designs a kind of inductive sensor which combines the advantages of variable-area and variable-distance eddy current sensors. It could detect the position of centre line of the sleeper accurately. In particular the scheme solves the problem that the detecting distance affects the detecting sensitivity, and the designed sensor eliminates the errors caused by the train's vibration effectively. At the same time, the special design of the coils could increase the resolution of the sensor.

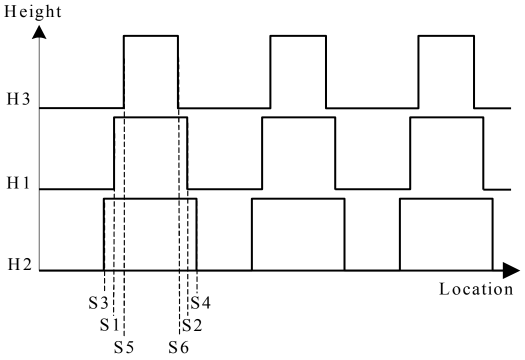

Fig.3. The duty ratio of the speed pulses as the height is reduced, normal and increased.

3. DESIGN OF THE SPEED MEASUREMENT SENSOR USING DIFFERENCE STRUCTURE

The urban maglev train speed measurement sensor with difference structure is based on the eddy current effects. The interaction between the eddy current sensor and the metal to be detected is equivalent to the circuit shown in Figure 4 [9]. In the circuit, the left side is the equivalent circuit of the coils where R0 is the equivalent resistance between the processing circuit and the detecting coils, C is the resonant capacitance using parallel connection with the detecting coils, R1 is the equivalent resistance of the detecting coils and L1 is the inductance of the detecting coils. The right part is the equivalent circuit of the metal to be detected, where R2 is the equivalent resistance of the metal, L2 is the inductance of the metal and M is the mutual inductance between the detection coils and the metal.

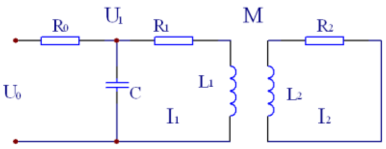

Fig.4. The equivalent circuit of the detecting coils and the metal.

The equivalent impedance Z of the eddy current sensor coils is related to the factors of the electric conductivity and the magnetic conductivity of the metal conductor to be detected, the frequency of the excitation signal, the distance between the coils and the metal conductor, the relative covering area and the size factors of the coils (including the structure and the shape) [10]. As the other factors are fixed, the equivalent impedance of the coils could be equivalent to the univalent function of one certain factor. For variable-area eddy current sensors, if other factors are constant, the relative area of the metal conductor and the coils will be the only one that is related to the equivalent impedance of the coils. Based on the analysis of the equivalent circuit, the equivalent impedance of the coils is:

$$Z = \left(R_1 + R_2 \frac{\omega^2 M^2}{R_2^2 + \omega^2 L_2^2} \right) + j\omega \left(L_1 - L_2 \frac{\omega^2 M^2}{R_2^2 + \omega^2 L_2^2} \right) \quad (1)$$

When there is not any metal conductor, the impedance of detection coils is: $Z_0 = R_1 + j\omega L_1$. When some metal conductor approaches, the equivalent resistance R and the equivalent inductance L are changed:

$$R = R_1 + R_2 \frac{\omega^2 M^2}{R^2 + (\omega L_2)^2} \quad (2)$$

$$L = L_1 - L_2 \frac{\omega^2 M^2}{R_2{}^2 + (\omega L_2)^2} \quad (3)$$

The mutual inductance M is reduced when the detecting distance increases [11]. From the equivalent impedance equations (2) and (3), it could be seen that as the coils approach the metal conductor, the equivalent inductance L decreases, and the equivalent resistance R increases. Thus, the change of the relative horizontal positions of the detecting coils and the metal conductor is converted into the change of the equivalent impedance of detecting coils which may be indirectly detected as $U1$ by the signal processing circuit.

It is assumed the detection distance is fixed when a single unit of coils moves relative to a sleeper along the rail direction, the inductance L of the coils is varied relative to the horizontal position between the coil and the sleeper, as shown in Figure 5, in which the width of the sleeper is 200mm, the scale '0' presents the centre line of the sleeper and the shape of the coils is rectangular (200mm long and 100mm wide). The Figure 5 shows that, when the coils come into the position where the sleeper exists below, the inductance decreases because of the influence of the eddy current effects; when the centre line of the coils covers the centre line of the sleeper, the influence of the eddy current effect is the largest, and the inductance is the lowest; when the coils go away from the sleeper centre line, the inductance increases gradually. As the coils don't cover the sleeper completely, the inductance is the biggest because of the lack of eddy current.

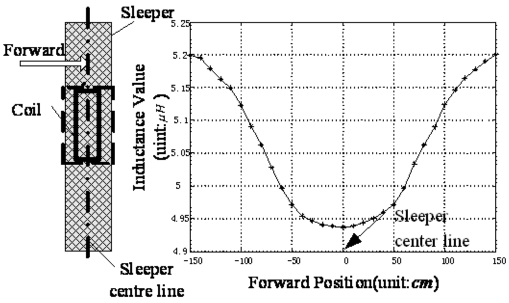

Fig.5. Simulation curve for inductance change of single unit coils.

The detecting principles of the eddy current sensor indicate that it's necessary to enhance the sensitivity of the sensor, so that the position of the sleeper centre line could be detected accurately. Figure 5 shows that when the coils are near the center line of the sleeper, the change rate of the inductance is not very large. The largest inductance change rate occurs where a portion of the coils enter the area of the sleeper or they are about to leave. However, it is necessary to point out that, if the distance between the coils and the sleeper varies during the movement, what the curve in Figure 5 shows may not be accurate. In fact, the variety of the distance between the coils and the sleeper is unavoidable as the maglev train runs. So we need to design a type of eddy current sensor with differential structure.

The arrangement of the detecting coils in the sensor with difference structure is shown in Figure 6. The detecting coils in the speed detecting sensor are installed along the moving direction of the train. D denotes the maximum space between the two adjacent sleepers. The width of the coils is d which denotes the position resolution. Meanwhile, in order to ensure the continuity of the speed signals, at least one group of coils should be above the sleeper. Also the group number N of the coils should satisfy $N > D/d$. In this paper, according to the requirements of detecting accuracy for the maglev train and the actual condition of the sleepers laid on the 1.5km trial line, the number of the coils is set as $N = 15$, and the width of the coils is set as $d = 10cm$.

On the condition of that the detecting accuracy is unchanged, in order to establish the relation between the position with maximum change rate of the inductance and the position of the sleeper center, a method of second order difference for the inductance values of three adjacent detecting coils is proposed in the paper. In addition, the method increases the ability of the disturbance rejection for the sensor. Take the coils C1, C2 and C3 in Figure 6 for example. The inductance L2 of C2 is subtracted from the inductance L1 of C1, and the difference inductance L12 between the two groups of coils C1 and C2 is obtained. Similarly, the difference inductance L23 between the two groups of coils C2 and C3 is obtained too. Then the second difference is to subtract L23 from L12, and the difference inductance L123 of the three adjacent coils could be obtained. The simulation curve of the difference inductance is shown in Figure 7. The curves of upper half presents the change of the equivalent inductances of the three detecting coils C1, C2 and C3 when they are moving, and the lower half presents the change of the inductance after second order differences.

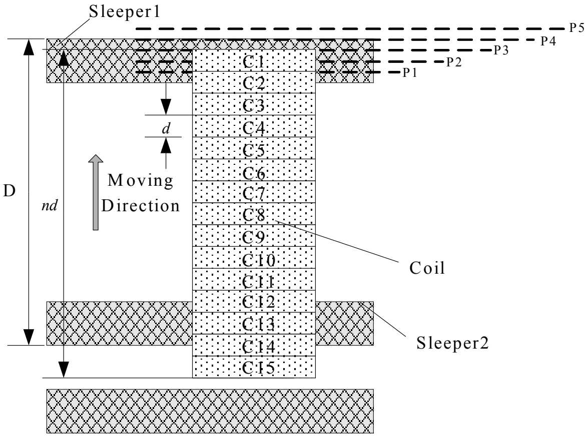

Fig.6. The assignment of the fifteen detecting coils.

From the curves in Figure 7, the L123 is zero at the following four positions: where C1, C2 and C3 don't enter the area of the sleeper, where the centre line of C1 nearly covers the position 2, where the centre line of C3 nearly covers the position 2 and where C1, C2 and C3 all completely leave the area of the sleeper. In case of mistaking the position signal, The paper regards the second 'zero' as the position signal, that is, when the center line of the detecting coils C1 is at the center line of the sleeper. The following three conditions could be applied to judge the relative position between the coils and the sleeper:

$$L_{123} = \left|L_{12} - L_{23}\right| = \left|L_1 + L_3 - 2L_2\right| < \sigma \qquad (4)$$

$$-L_{12} > \eta_1 > 0 \qquad (5)$$

$$-L_{23} > \eta_2 > 0 \qquad (6)$$

First, by controlling the value of σ (where σ approximates to zero) in equation (4), the zero crossing point of L123 could be determined. Then by calibrating the value η_1 and η_2 in equations (5) and (6), the pattern of the second order difference inductance is presented from the center line of the sleeper to the outside. By the three conditions above, whether the detecting coils is at the center line of the sleeper could be determined accurately. Similarly, each group of detecting coils is at the center line of the sleeper or not is determined too. As the width of the detecting coils d is known, the speed of the maglev train $V = d / \Delta t$ is calculated after measuring the time interval Δt between the two adjacent coils passing the center line of the same sleeper.

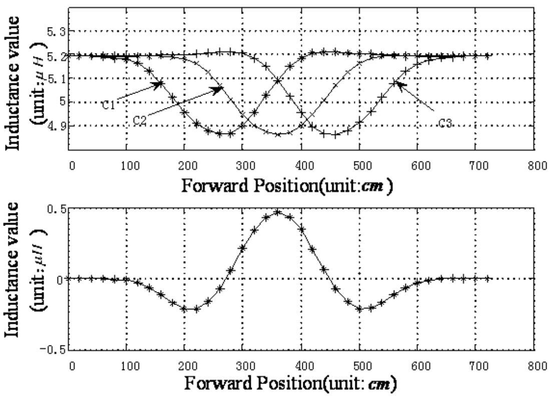

Fig.7. The inductance change of the three adjacent coils and the results of their second order difference.

From what could be seen in the star-like curve in the lower half of Figure 7, the change rate of the inductance is obviously increased after the second order differences. This effectively avoids the misjudgements caused by the poor change of the inductance. Otherwise, the sensitivity of the sensor is increased and the ability of disturbance rejection of the sensor is enhanced. The curve in Figure 8 shows that when the detecting distance is changed, the position where the value of second order differences is zero does not change almost. It means that by using the method of second order differences, the detecting errors caused by the change of detecting distance could be eliminated.

4. THE REALIZATION AND EXPERIMENT

The circuit of the speed measurement sensor with difference structure mainly consists of the detecting coils, the exciting circuits, the analogy signal processing circuits, the synchronous demodulation circuits and the digital signal processing circuits, etc.

Each detecting coils has a corresponding synchronous demodulation circuit. The demodulated signal is sent to the digital signal processing circuit. By using the reference signals with different frequencies for the adjacent coils and the synchronous demodulation method, the disturbance between the adjacent detecting coils could be avoided effectively[12].

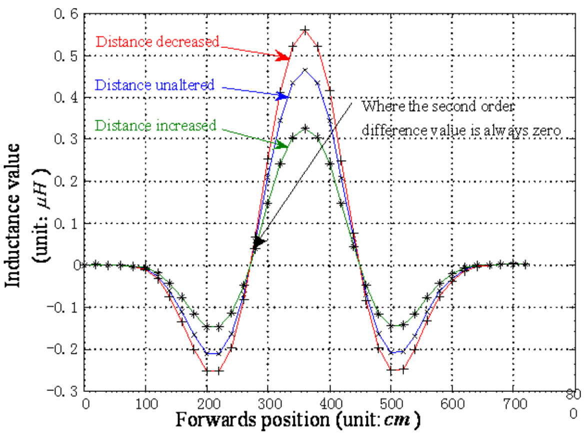

Fig.8. The second order difference curves of three adjacent coils with the changing of detecting distance

The demodulated signal is sent into the digital signal processing circuit for the second order difference, and the signal P_i that stands for the relative position between the detecting coils and the sleeper could be calculated. Finally P_i is sent to the speed measurement equipment. Subsequently the speed of the maglev train is achieved. The processing flow is shown in Figure 9.

The sensor could increase the speed measurement resolution, eliminates the impact on measurement accuracy caused by the

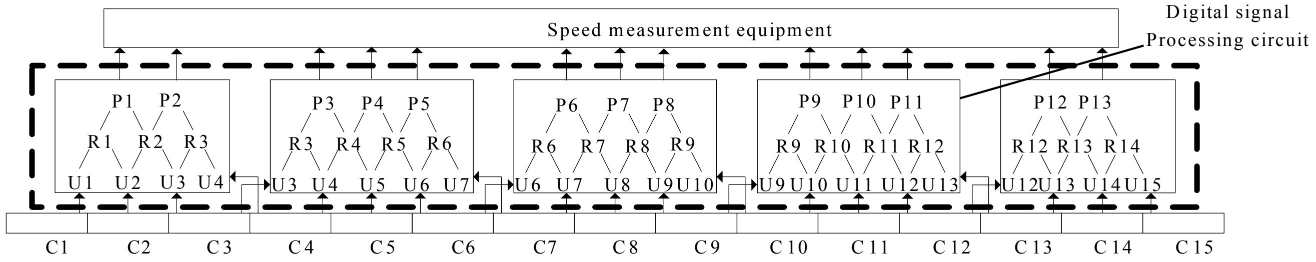

Figure.9.Diagram of the processing flow for the speed measurement equipment.

variation of the detecting distance in the “sleeper induction” method. Therefore, in order to evaluate the performance of the sensor, calibration platform is used to change the detecting distance to simulate the situations as if the train is vibrating.

On the calibration platform, when the sensor is moving, the sensor stably sweeps over the sleeper with a detecting distance of 50mm. From the position where the detecting coils enter the area of the sleeper to the position where the detecting coils leave the area, the amplitude of the demodulated signal would be recorded every 20mm. Three-dimensional curve is drawn after recording. Then it is tested that the sensor sweeps over the sleeper at the height of 53mm and 47mm. The results after the second order difference are shown in Figure 10. X-axis denotes the position of the sensor along its moving direction, Y-axis denotes the detecting distance of the sensor and Z-axis denotes the amplitude of the signal after the second order difference.

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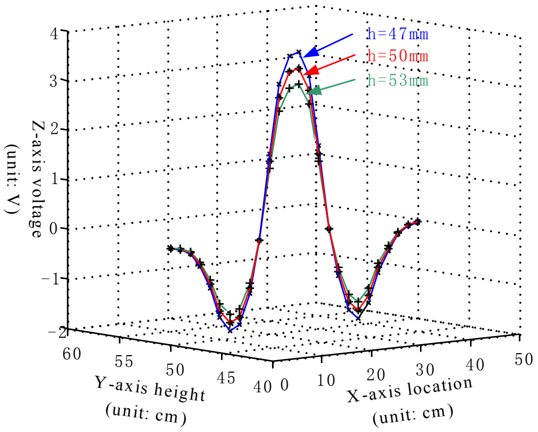

Fig.10. Three-dimensional curves for the comparison of the amplitude of the signal after the second order difference when the detecting distance is changed.

Figure 10 indicates that although the detecting distance of the sensor is changed, the position where the value of the second order difference is zero would not change.

Then take the detecting coils C1, C2 and C3 as the research objects to simulate the situations that the train body vibrates by plus-minus 3mm vertically as the train is running. From the position where the detecting coils enter the area of the sleeper to the position where the detecting coils leave the area, adjust the height of the calibration platform by 3mm every 20m, and record the amplitude of the signal after the second order difference. It is shown in Figure 11. In order to see more clearly whether the sleeper position obtained after the second order difference would change as the detecting distance changes, project the three-dimensional curve in Figure 11 on the Z-X plane and the two-dimensional curve is obtained. It is shown in Figure 12.

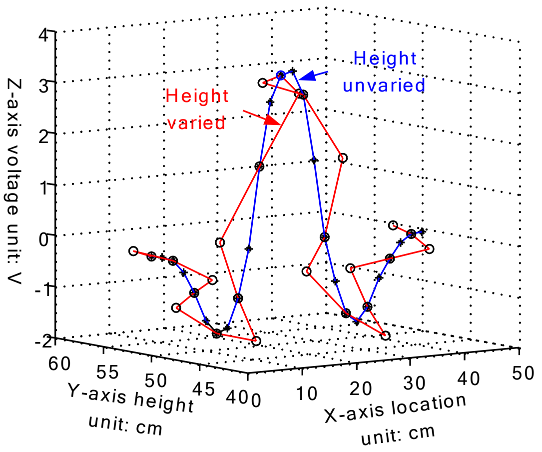

Fig.11. Three-dimensional comparison curves of the signals after the second order difference as the height is unchanged and changed by 3mm.

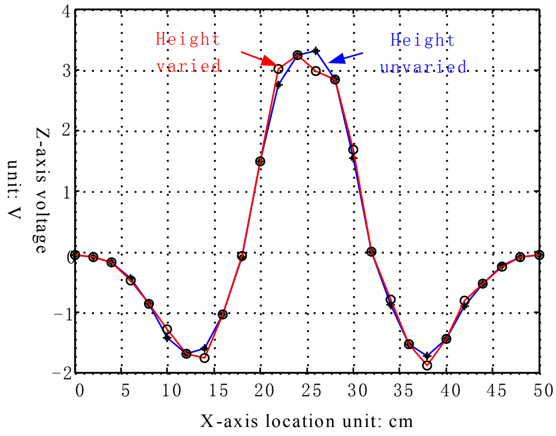

Fig.12. Two-dimensional comparison curves of the signals after the second order difference as the height is unchanged and changed by 3mm.

5. CONCLUSIONS

This type of sensor has been applied on the “sleeper induction” method speed measurement system on the 1.5km long low-speed urban maglev trial line in Tangshan, China. The test results show that the eddy current speed measurement sensor with difference structure overcomes the influence of the variation of detecting distance. The purpose of eliminating the detecting errors caused by the vibration of the train body has been achieved.

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REFERENCES

Samavedam, G., Raposa, F., Feder, R. (2003). Applicability of CHSST Maglev Technology for U.S. Urban Transportation. *U.S. Department of Transportation Federal Transit Administration Office of Technology*.

Yasuda, Y., Fujino, M., Tanaka, M. (2004). The first HSST maglev commercial train in Japan. *Proceedings of the Maglev'2004*, 76-85.

Wu, X.M. (2003). *Maglev Train*, pp. 1808-1811. Shanghai Science and Technology Press, Shanghai, China.

Lee, H., Kim, K., Lee, J. (2006). Review of Maglev Train Technologies. *IEEE Transactions on Magnetics*, 42, 1917-1925.

Dai, C.H., Song, X.L., Dou, F.S., Long, Z.Q. (2011). Study on the Speed and Location System for Low Speed Maglev Vehicle. *Proceeding of the IEEE International Conference on Automation and Logistics*, China, 220-224.

Long, Z.Q., Li, X.L., Zhou, W.W., Liu, S.S. (2003). Study on the Techniques of the Location and Speed-measuring of the Aerotrain. *Journal of National University of Defense Technology*, 21, 82-88.

Dai, C.H., Dou, F.S., Song, X.L., Long, Z.Q. (2011). Analysis and Design for Speed and Position System of Maglev Vehicle. *Sensors*, 11, 8526-8543.

Heide, P., Magori, V., Schwarte, R. (1995). Coded 24GHz Doppler radar sensors：A new approach to high precision vehicle position and ground speed sensing in railway and automobile applications. *IEEE NTC' 95. Microwave Systems Conference*, Orlando, USA, 101-104.

Bernieri, A., Betta, G., Rubinacci, G., Villone, F. (2000). A measurement system based on magnetic sensors for nondestructive testing. *IEEE Transactions on instrumentation and measurement*, 49, 455-499.

Cheng, D. (1965). The reflected impedance of circular coil in proximity of semi-infinite medium. *IEEE Transactions on Instrumentation and Measurement*, 3, 107-116.

Weiping Z., Liting S., Xusen Z. (1998). The principle and design for long distance electric eddy current sensor with double coils. *ACTA Electronica Sinica*, 12, 61-65.

Feng G.P. (2008). *Resonant sensing theory and devices*, pp. 112-113. Tsinghua University Press, Beijing, China.