Study on Automatic Testing of Treads of Running Railroad Wheels

Hong FAN, Huiming JIA
Central Iron & Steel Research Institute
No.76, Xue Yuan Nan Lu, Hai Dian District, Beijing 100081, China
Tel: +86-10-62183118, Fax: +86-10-62182490
E-mail: fanhong@analysis.org.cn

Abstract

This paper provides a new electromagnetic acoustic technique for testing of in-service railroad wheels and discusses its technical features, advantages and future application versus conventional testing techniques.

Keywords: in-service railroad wheels, treads, electromagnetic acoustic testing, electromagnetic acoustic transducer (EMAT), nondestructive testing (NDT)

Nowadays, trains are an important means for traveling. The speed of trains has been increasing. For example, in Germany, a third generation high-speed train currently in service runs at 330km/h in normal operation. In China, with rapid economic growth in recent years, train speed is increasing time after time. For the Beijing-Shanghai high-speed railroad which is currently under construction, the design speed is up to 300km/h. As the train is going faster, more concern is given to the safe operation of trains and higher performance and quality are required for parts used in train.

1. Safe Operation of Trains and Defects on Wheel Tread

Wheels are key parts that enable the movement of train and bear loads. Good quality of wheels is critical to ensure safe operation of trains. Defects on wheels may cause a disaster. In June 1998, a German high-speed train, which is known for its safety and reliability, turned over. The terrible event shocked the world and resulted in large number of death and injury and huge loss of property. With careful investigation, it was found that the primary cause of this accident is the fatigue-induced cracks on the treads of railroad wheels[1]. In August the same year, in China, No.554-8081 cargo train ran off the rails. Likewise, fatigue-induced cracks on the wheel treads caused the accident. Therefore, the defects on wheels, especially the cracks on wheel treads, are potential to cause serious accidents. If these defects can not be early detected and properly repaired or corrected, with future increase of train speed, it is undoubted that similar accidents will take place more frequently due to heavier fatigue of wheels. We can not imagine the terrible results.

Primarily, two reasons account for the defects of wheels which may cause train accidents. Firstly, in the processes of steel smelting and wheel processing, stomata, sand holes, inclusion and scratches may be produced in the wheel. These defects may cause stress concentration in a running wheel. Secondly, during the high-speed running of a train, the friction between wheels and rails produces local high temperature on the wheel treads. This temperature becomes higher at the time of starting or braking. Frequent change of temperature can also lead to stress concentration on wheel surface.

At the area under stress concentration, the metal has less bearing capacity and is prone to cracking. Under continuous load, the crack develops. When it develops to the extent that the structure can not bear the load, the metal part will collapse resulting in a disaster.

In addition to the damage of wheel itself, the defects on wheel may impair the axle. If exfoliation or fall-blocks exist on a wheel (as shown in Figure 1), it may cause great vibration of train exerting heavier load on the axle. In extreme condition, the axle will break and the train will turn over. With the train speed goes on increasing, these accidents are expected to take place more frequently.

Fig. 1 Fall-block on Wheel Tread

Defects on wheels can not be completely avoided by using current metallurgical and manufacturing technology; and during the running of wheels, existing defects will develop and new cracks will form. Therefore, under the trend of increasing speed of trains, it is necessary to make frequent testing of in-service railroad wheels to monitor the health of wheels and ensure safe operation of trains. The importance of testing has been well recognized across the world.

2. Conventional Testing of Railroad Wheels

Generally, in-service railroad wheels are to be tested during major repair. Ultrasonic testing and magnetic powder testing techniques are widely used in testing of wheels.

Conventionally, piezoelectric ultrasonic longitudinal wave is used for testing of wheels, primarily the testing for internal defects [2]. The advantage of this technique is high sensitivity. However, the limitations are considerable. Firstly, it is less sensitive in testing for defects in wheel's radial direction which may cause exfoliation and even breakage; secondly, due to complicated operation, it is difficult to perform complete testing of wheels since most area of the wheel is hidden by other parts, especially when the wheel is not dismounted. Moreover, piezoelectric ultrasonic longitudinal wave is unable to detect treads and near treads of wheels. But, according to the theory of Fracture Mechanics, concentrated stress exists at the area about 6mm under treads where many fatigue-induced cracks may form.

In early experiments, conventional piezoelectric ultrasonic Rayleigh wave was used for testing of wheel treads. But it failed because of need of liquid couplant, weak transmission of wave and low testing efficiency. Necessity of liquid couplant is a significant limitation for dynamic testing.

Magnetic powder testing is a non-destructive technique for testing of defects on surface of work pieces. It is characterized with high sensitivity and easy operation. However, it can only detect very thin layer at the surface of wheels and the result is determined at individual discretion. So, this technique is merely useful for static manual testing. Just as the piezoelectric ultrasonic testing, complete testing of wheel treads is impossible by using magnetic powder testing since the wheel is hidden by other parts and rails if the wheel is not dismounted. Magnetic powder technique is suitable to test separate wheels in factories or major repair plants primarily for defects on surface of rims and spokes.

3. Electromagnetic Acoustic Testing of Wheel Treads

With the progress of NDT technology, in recent years, some developed countries start researching the EMA Rayleigh wave technique – a non-contact testing technology without need of liquid couplant[3]. This technique enables complete testing of treads of wheels to counteract the weaknesses of conventional techniques. Furthermore, the devices can be installed on the rails to allow for dynamic real-time testing of running railroad wheels. Because the EMA technique has many advantages in testing of wheel treads (e.g. no couplant, non-contact, quickness, sensitivity etc.), it is expected to be soon used in the in-service trains.

3.1 Generation of EMA Rayleigh Wave

EMA Rayleigh wave is generated in wheels by a transducer. The principle of the transducer is shown in Figure 2. An EMAT (Electromagnetic Acoustic Transducer) consists of magnets and coils carrying high-frequency current. Coils are directed in a tortuous way in the magnetic field (as shown in Figure 2).

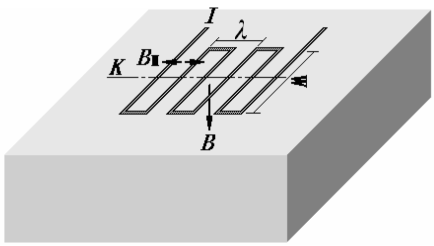

Fig. 2 Principle of EMAT

Generally, EMA wave is generated primarily by two effects: Lorentz force and magnetostriction force, which can interact with the surface of work piece to generate ultrasound. The principle of Lorentz force effect is: when high-frequency current flows through the tortuous coils, eddy current with corresponding frequency is induced on metal surface; under an external magnetic field *B*, the eddy current produces a force, i.e. Lorentz force; the transmission of Lorentz force in the work piece results in ultrasonic wave. The principle of magnetostriction effect is: when high-frequency current flows through the tortuous coils, under the high-frequency current excited magnetic field and external magnetic field *B*, the magnetic domain in ferromagnetic metal will move and rotate resulting in macroscopic deformation, i.e. magnetostriction; the transmission of magnetostriction in work piece generates ultrasonic wave.

Because the railroad wheels are made of ferromagnetic metal, the EMAT generates Rayleigh wave in the wheels primarily based on magnetostriction effect. As shown in Figure 2, a constant magnetic field *B* is provided in wheel's radial direction; an alternating magnetic field B_M is generated in circumferential direction by high-frequency coils. Because coils are regularly arranged along the circumferential direction, the Rayleigh wave generated by magnetostriction will transmit circumferentially. The magnetostriction is related to the external magnetic field as shown in Figure 3. The amplitude of magnetostriction is not simply linearly related to the magnetic filed. There are two peaks. At a certain level of the field strength, the amplitude of magnetostriction reaches its peak value, reflecting the corresponding peak value of Rayleigh wave, i.e. the maximum testing sensitivity.

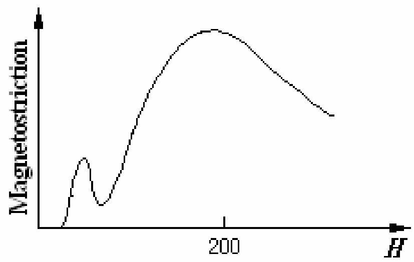

Fig. 3 Relation between
Magnetostriction and Field Strength

According to above discussed principle of EMA Rayleigh wave, the wheel itself is a necessary part of the transducer and the ultrasonic wave is directly generated in the wheel. Therefore, there is no need of couplant.

3.2 Profile of EMA Field on Wheel Treads

The profile of strength of EMA Rayleigh wave in wheel treads is important in the testing. Defects on wheel treads are detectable only when they are within an effective sound field with sufficient strength.

With EMAT placed at the center of the wheel tread, the profile of Rayleigh wave along the circumferential direction is measured as shown in Figure 4. Figure 4 presents the field strength of Rayleigh wave versus the half-angle of spread. Measured values at one side of the symmetric field are given in the figure. The width of transmitting coil used in the experiment is 30mm.

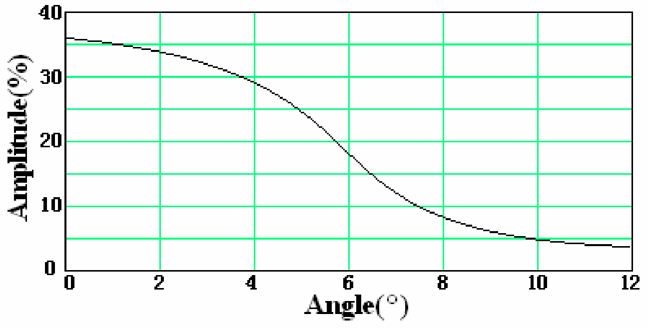

Fig. 4 Sound Field Strength versus Half-Angle of Spread

As shown in the chart, the profile of EMA Rayleigh wave presents the following features: 1. the half-angle of spread is about 8º, 2. the strength declines slowly as the angle increases; but the field strength reduces by more than a half at 6 º, which reflects low sensitivity in testing.

The profile of EMA field in wheel treads helps us understand the findings in testing of wheels. For example, when the transducer is approaching the defect near flange of wheel, generally, the first echo wave occurs later than the halfway between the initial wave and transmitted wave. In other words, a certain distance between the transducer and the defect near flange is necessary to ensure proper testing. Too short distance may lead to omission of defects. The dead zone due to the radiating angle accounts for this finding.

On the wheel treads, sound field strength declines linearly as the beam path distance increases. So, for proper testing, it is necessary to maximize the power of the electromagnetic acoustic wave.

3.3 Method of Avoiding Dead Zone in Testing of Wheel Treads

In the testing of railroad wheels by using EMA Rayleigh wave, there are two dead zones namely “beam index” and “transmitted beam index”. The reason for “beam index” dead zone

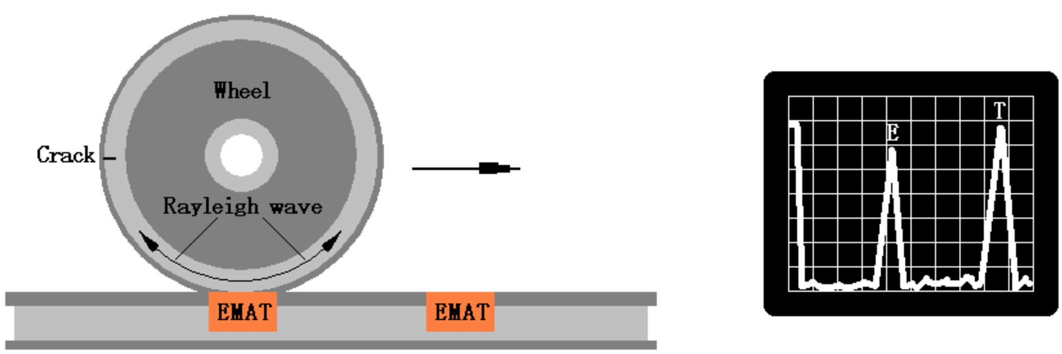

Fig. 5 Transmission of Rayleigh Wave in Wheel Treads and Display

is that the initial pulse (transmitting pulse) starts at the same time as the wheel contacts with the EMAT. The reason for "transmitted beam index" dead zone is that the echo wave from the defect at wheel top travels same distance as the transmission of initial wave for a full circle around the wheel; in case of a defect at wheel top, the echo wave will be overridden by the transmitted wave. See Figure 5.

For complete testing of wheel treads, it is necessary to avoid the dead zones. The solution is to repeat a testing at the point 1/4 wheel perimeter from the previous point. In this way, the dead zones in first testing are detectable in the second testing. For testing of running wheels, two EMATs can be installed on the rail at an interval of 1/4 wheel perimeter. The two transducers are complementary each other to avoid dead zones.

4. Automatic Testing of Treads of Running Railroad Wheels

Automatic testing of treads of running wheels by using EMATs installed on rails is a brand new concept. Central Iron & Steel Research Institute began researching this technique since early 2000's. We install EMATs on rails. At the exact moment when the wheel runs over the transducer, the Rayleigh wave is generated and begins transmitting along the perimeter of the tread to test surface defects and inner defects beneath the surface in the wheel.

The Rayleigh wave transmits at 2,900m/s in steel. On the basis of the perimeter of a railroad wheel of about 3m, it will take about 1ms for the Rayleigh wave to travel for a full circle along the perimeter of the wheel. To ensure reliable testing for defects in wheel treads, the wave needs to travel at least two circles. So, the contact between EMAT and wheel should last no less than 2ms. Based on the length of our transducer, the allowable train speed is about 30km/h. It is recommended to perform the testing when the train runs into the garage at low speed.

For the automatic testing, a groove should be cut on the outer side of the rail to allow the transducer to be installed as shown in Figure 6. Since the groove is very small, it does not impair the bearing capacity of the rail.

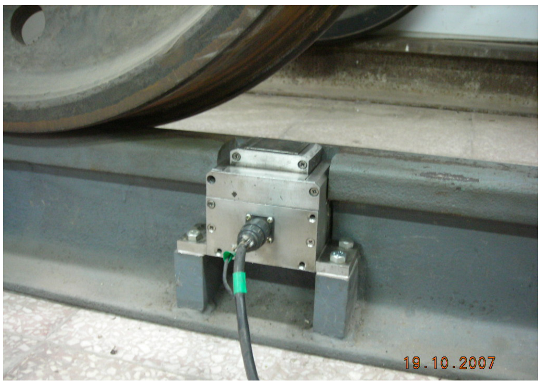

Fig. 6 EMAT is installed on rail

By using this technique, we can reliably detect the artificial notch of 1mm depth and 20mm length on the wheel tread. It is effective to detect common defects on treads on in-service wheel, such as fatigue-induced cracks, exfoliation and fall-blocks etc. Figure 7 shows an example of display of signals in testing of the treads of running wheels. In the display, A reflects a 1×20mm notch; B reflects a fall-block; C reflects a transmitted wave.

Although the EMA testing is a non-contact testing, it has stringent requirement on the lift-off. According to EMA theory, the sensitivity will decline by 96dB corresponding to every 1mm increment of the gap between the transducer and work piece. For testing of railroad wheels, the gap between the transducer and wheel tread should be within 0.5mm. However, the weight of a train is huge. When a train is running over a rail, each

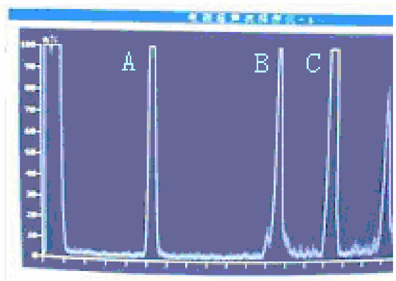

Fig. 7 Display of Testing Signals

wheel exerts several tens of tons of pressure on the rail, together with lateral force and intense vibration. So, in order for successful testing, it is critical to minimize the gap between the transducer and wheel as well as protect the transducer from damage. Moreover, EMATs are installed on rails where is subject to severe environments, such as electromagnetic interference, vibration and weathering etc. These may result in noise in the testing. To avoid noise and ensure the reliability of testing, shield, enclosure and noise-control instrument etc. are needed.

Automatic testing of running railroad wheels is a real-time dynamic process. It is required to record and store the testing results at the same time of testing process (transmission, reception, processing, display, identification of multi-channel ultrasound). In this field, we have done a lot of useful studies.

5. Conclusion

As the train speed increases, better safety of train is required. Frequent monitoring of in-service railroad wheels is very important to avoid potential accidents. It is said that there are several tens of train repair plants and several hundreds of depots in China. To use automatic EMA technique for testing of in-service wheel treads, especially for automatic testing as the train runs into the garage, will greatly help to early identify and correct wheels of poor quality and avoid potential accidents.

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