HIGH-SPEED MONITORING OF SURFACE DEFECTS

IN RAIL TRACKS USING ULTRASONIC DOPPLER EFFECT

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INTRODUCTION

Railroads provide both efficiency and economy in passenger and freight transportation. Like other transportation modes, however, they are prone to various problems. Statistics show that over the course of this century, the average carload and trainload tonnage has increased significantly. There is also an increasing concentration of traffic on fewer main line tracks. The average length of haul has also risen [1,2]. Unfortunately, these trends have not been offset with a proportional increase in the amount of new rail laid. Consequently, the stress on rails and fatigue related failures may continue to increase. With the new demands, it is important to assess the rail integrity by detecting rail defects nondestructively and speedily.

Typical defects often found in railroad tracks include transverse and longitudinal defects in the rail head, web defects, base defects, surface defects as well as other miscellaneous damage such as head wear, corrosion, crushed head, burned rail, bolt hole cracks, head and web separation, etc [3]. In this work, we are interested in detecting surface defects, although the approach may be applicable for detecting the other flaw types.

Nondestructive evaluation (NDE) of rail tracks may be approached by “continuous monitoring” or “detailed inspection” [4]. In the context of rail assessment, monitoring results in global evaluation of the rail whereas inspection focuses on a particular area to locate and/or characterize a defect in detail.

In continuous monitoring, some techniques for inspection of rail flaws at an intermediate speed are currently available, but the technology lacks efficient monitoring techniques at a high speed comparable to the speed of a passenger car. One of the requirements for high-speed monitoring is the development of a detection system that does not require contact with the rail. Furthermore, existing detailed inspection techniques have limited capabilities, primarily due to poor sensor performances and the requirement of contact with the rail surface. It is necessary to develop a new sensor that can overcome these limitations.
Currently, surface defects are detected by means of a fairly old device called track circuit. This device uses the track as part of the electric circuit and uses the resistivity of the rail as an indication of surface discontinuities. Another approach is the use of ultrasonic probes in contact with the track surface by a rolling wheel. These techniques require contact with the sensor and the rail. Therefore, they are not quite suitable for high-speed monitoring. In this paper, we present the promising results of our feasibility tests. A laboratory scale experimental setup demonstrated that airborne ultrasound may be potentially used as a means of non-contact, high-speed rail condition monitoring.

HIGH-SPEED MONITORING USING DOPPLER EFFECT

Our unique approach to improved condition monitoring is to exploit the relative motion (created by the high-speed rail inspection car) between the propagating ultrasound and the rail defect. This results in a Doppler effect [5], which can be used to readily distinguish between acceptable and unacceptable rail.

Air-Coupled Transducers

A critical requirement of our high-speed monitoring scheme is that the transducer should not be placed on the rail in contact. Instead, the transducer should remotely sense the surface discontinuities through air. There are several NDE methods that operate in non-contact mode, including electromagnetic acoustic transducers (EMAT) [6] and laser-based ultrasound (LBU) [7].

Recently, air-coupled piezoelectric transducers were investigated and showed promising results in testing and characterizing some materials [8]. Air-coupled transducers are attractive since they allow ultrasound to propagate through gaseous media without requiring mechanical contact between the transducer and the target material. The major problem associated with such transducers is the difficulty in transmitting ultrasound into the material. For example, the acoustic impedance mismatch between the steel and air is so high so that most of the energy is reflected from the surface. Therefore, it is challenging to use air-coupled transducer for testing materials having buried defects.

However, this phenomenon suggests that we may use the method to our advantage, since our main interest is to detect surface flaws. The approach is to insonify the rail surface with ultrasound and analyze the signature of the signals reflected off of the surface. The amplitude of the return signal is expected to be high because of the high impedance mismatch. In the next section, we will describe how the air-coupled transducers can be effectively used for detecting surface flaws.

Experimental Setup for High-Speed Monitoring Simulation

A typical car speed for monitoring rail may reach above 60 mph. In fact, increased car speeds will lead to a more pronounced Doppler effect. Because it is impractical to test rail with cars over a suitable distance at 60 mph in a laboratory environment, a similar effect was simulated by using a motor to rotate a solid disk. In order to test the feasibility of enhanced monitoring with a Doppler effect, the experimental setup shown in Fig. 1 was developed at the MIT NDE lab.
In this experiment, the Doppler effect may be conceptualized as follows: consider two fixed (stationary) ultrasonic transducers, where one functions as a transmitting source (T) and the other as a receiver (R). If the ultrasonic beam is impinged upon a rotating interface, then a Doppler effect will be observed due to the relative velocity created between the transmitted ultrasound and any surface discontinuities. In the absence of a surface defect, a Doppler effect will not be detected since there is no relative motion involved.

The solid disk used in this experiment was made out of aluminum, which was chosen primarily for availability and also because machining notches and other simulated defects can be done quickly. Since aluminum is lighter than steel, the load on the motor is significantly reduced, and the vibrations, which may distort the acquired waveforms, are much lower. Selecting the required radius, \( R \), for the disk is governed by the speed of the motor, \( \Omega \), and the equivalent linear velocity, \( v_s \):

\[
R = \frac{v_s}{\Omega}
\]  

For a motor speed of 1700 rpm and a linear velocity of 60 mph, \( R = 6 \) in. A notch having a depth and width of 0.125 in. was machined on the surface of the disk to simulate a surface defect. The notch was fully extended through the 0.5 in. thick disk.

A pair of Panametrics ultrasonic transducers (1.25 in. diameter, 100kHz center frequency) were configured in pitch-catch mode directly above the top of the disk. Both
transducers were positioned and aligned at 45° angles with respect to the top surface tangent for maximum reflection off of the circumference of the disk, as shown in Fig. 1. The transmitter input signal was a 100 kHz continuous sine wave which was created using an HP arbitrary function generator. The waveforms for this experiment were detected by a 500 MHz LeCroy digital oscilloscope. All waveforms were transferred through a GPIB connection to a PC for further analysis and processing.

Doppler Effect

Generally, a Doppler shift may be observed for sources emitting either continuous (CW Doppler), or pulsed (Pulsed Doppler) wave. It is sometimes advantageous to use pulsed Doppler, particularly when spatial information is required. However, if the repetition rate of the pulse is too low, then it may not be possible to observe a Doppler effect. In other words, the areas between the pulses cannot be detected by the transducer. For example, we were able to insonify only a 5° sector of the aluminum disk rotating at 1700 rpm, using a Panametrics pulser/receiver unit which has a maximum repetition rate of 2 kHz.

Moreover, pulsed signals are generally broadband and it requires more complicated signal processing techniques. On the other hand, CW waves are advantageous in our case since the rail surface is insonified continuously. With CW Doppler, the frequency shift effect will be immediately observable in both time and frequency domains, thereby eliminating the blind zone. Consequently, we used a single tone continuous wave of 100 kHz carrier frequency as the input source throughout the experiment.

Since the receiving transducer is not directly in front of the reflector (the notch), a “double” Doppler shift will occur. Taking this effect into account, the double Doppler shift can be expressed as

\[
\Delta f = \pm 2 f_s \left( \frac{v_s}{c} \right) \cos \psi \tag{2}
\]

where \( f_s \) is the frequency of the input signal, \( \Delta f \) is the difference between the input frequency and the Doppler shifted frequency, \( v_s \) is the linear speed of the reflector (notch), \( c \) is the wavespeed in the medium (air), and \( \psi \) is the angle between the direction of motion and the direction to the receiving transducer from the notch.

EXPERIMENTAL RESULTS

Figure 2 shows the entire signal obtained as the aluminum disk was in motion. The waveform appears as a black band of a single tone sine wave of 100 kHz carrier frequency. Due to the poor resolution of the printer used to prepare this manuscript, details of the sine waveform are not shown in this figure. The thin periodic peaks indicate reflections off of the notch (that is, one complete revolution of the disk).

Prediction of the Frequency Shift

The frequency of the signal reflected off of the surface would have the same frequency as the input signal and the one reflected from the notch has the frequency that is slightly Doppler shifted. Since these signals interfere with each other, the net result is that
Figure 2. As-obtained waveform reflected off of the circumference of the disk. The spikes above the black band show reflection off of the notch and indicate one complete revolution.

The received signal creates a wave packet. The interfered signals can be easily interpreted in the frequency domain using the Fourier Transform.

The predicted waveforms for the experiment are shown in Fig. 3. The velocity of ultrasound in air was taken as 340 m/s. With this data, the Doppler shift is expected to be approximately 11.5 kHz. Figure 3(a) shows the expected waveform captured off the surface of the disk with no defect present. Figure 3(b) shows the predicted waveform due to interference from the notch on the disk. The Fast Fourier Transform was used to represent the predicted signal in the frequency domain. Figure 3(c) gives the magnitude spectrum of the input signal. Since the transducer is driven at 100 kHz, the corresponding spectrum should take the form of delta function indicated by a vertical line at $f = 100$ kHz. Figure 3(d) shows the spectrum of the signal reflected off the notch. Note that there are two distinct frequencies observed in this case: one at 100 kHz and a second at 111.5 kHz. The second peak represents the Doppler shifted frequency from the surface notch.

Experimental Verification of the Shifted Frequency

Figures 4(a) and 4(b) are the detailed views of the acquired waveform shown in Fig. 2. The waveform shown in Figure 4(a) indicates reflection off of the surface of the disk. This will correspond to the 100 kHz sine wave transmitter input. In the vicinity of the notch (Figure 4(b)), wave packets are clearly observable. These wave packets, which are the results of the Doppler shift of the impinged ultrasound, indicate a discontinuity on the surface. Figures 4(c) and (d) show the corresponding frequency spectra. Note the excellent agreement between Fig. 3(d) and Fig. 4(d).
Figure 3. Predicted waveforms: (a) Continuous wave input signal, (b) Doppler-shifted signal, (c) Magnitude spectrum of input signal, and (d) Magnitude spectrum of Doppler-shifted signal.

MONITORING SCHEME

As addressed before, rail condition should be monitored in a non-stop mode and the monitoring system should issue an alarm signal in the presence of suspicious flaws. If an alarm is issued, then a complementary detailed inspection scheme should be used to verify the alarm signal. It was shown in this paper that Doppler effect using airborne ultrasonic transducers can be used as a criterion for the alarm.

The signal can be processed in the time-domain. Since the Doppler effect results in wave packets, it may be possible to find an algorithm that can detect such patterns. However, amplitude information is very much dependent on the surface condition and is sensitive to environmental noise. As a result, it may be difficult to analyze the data in the time domain.

On the other hand, it can be shown that the frequency domain analysis is a more stable criterion. As shown previously, the Doppler shift appears as a peak in the spectrum
whose location in the frequency can be accurately estimated by knowing the speed of the train, input carrier frequency, and the wavespeed in air.

If the peak of the carrier frequency and the shifted frequency is clearly separable (which is true in our case for the train speed of 60 mph), it is possible to monitor the peak amplitude within a gate set in the frequency axis. Since the speed of the rail car is measurable, the location and width of the gate can be accurately estimated to cover the shifted signal only. For example, the opening gate can be set at 105 kHz and the closing gate can be set at 115 kHz for our given condition. For a lower car speed, the distance between the peaks gets closer or the Doppler effect is less pronounced. In other words, the faster the speed of the train, the more pronounced the Doppler effect is. This effect has an added benefit because our objective is to increase the monitoring speed as high as possible.

A criterion to set a threshold magnitude should be established. Once the threshold is determined, the system can be designed to issue an alarm when the peak amplitude in the gate exceeds the threshold value. This condition may indicate any surface anomalies and thus can be used as a criterion for the alarm. The more systematic and efficient signal processing technique such as Short-Time Fourier Transform was developed and efficiently

Figure 4. Detailed views of the as-obtained wave shown in Fig. 2: (a) Input signal, (b) Doppler-shifted signal off of notch, (c) Magnitude spectrum of input signal, and (d) Magnitude spectrum of reflection off of notch.
used to extract a better information. But it is beyond the scope of this paper and will be discussed elsewhere.

SUMMARY AND CONCLUSIONS

A novel concept based on the Doppler effect was introduced for continuous monitoring of rail defects at high speed. This approach exploits the relative motion between the propagating ultrasound and the rail defect. It was shown from the feasibility tests that low frequency air-coupled transducers can be effectively used for detecting rail surface defects, thereby eliminating contact between the transducers and rail surface.

The feasibility of this technique was experimentally studied and verified in a laboratory setting. In a test conducted using a rotating aluminum disk with a notch on the periphery, the Doppler effect was clearly observed. The frequency of the continuous-wave ultrasonic signals reflected from the notch were Doppler-shifted, resulting in wave packets in the as-obtained waveform. Due to the narrow bandwidth of the signal, the magnitude of the shifted frequency was clearly pronounced in the frequency spectrum. The shift was experimentally measured in the frequency domain and agreed well with the prediction.

It is believed from this feasibility test that CW Doppler can be used as an effective means of high-speed rail monitoring, particularly for detecting surface defects and broken rails. However, further investigation is necessary for it to be used for monitoring internal defects which may also seriously affect the rail integrity.

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REFERENCES