EMATS FOR ROLL-BY CRACK INSPECTION OF RAILROAD WHEELS*

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INTRODUCTION

Railroad safety depends on many factors. The integrity of the wheels on rolling stock is one that is subject to nondestructive evaluation. For some years, ultrasonic testing has been applied to the detection of cracks in wheel treads, with particular attention to automatic, in-rail, roll-by methods. We have begun constructing a system aimed at using relatively low frequency Rayleigh waves generated by electromagnetic-acoustic transducers (EMATs). The current design uses a permanent magnet to maintain a compact structure and minimize the size of the pocket machined into the rail. Measurements thus far indicate a responsiveness, even to small flaws. With the development of a signal processing and analysis system, field tests should soon be possible.

Cracks in railroad wheels may result from high stresses due to dynamic or static loads and residual stresses generated by such events as heating during braking. These flaws generally originate in the tread surface or flange and can lead to catastrophic wheel failure resulting in considerable equipment damage and possible derailment. This threat to personnel safety and the potential costs in time and money are inducements to search for an effective, automated method for nondestructive examination that will identify damaged wheels needing replacement.

The current method of examination is visual observation. In the early 1970's, an ultrasonic method was introduced [1-4]. This involves an in-rail system of piezoelectric transducers that generate Rayleigh waves, electronics for signal generation and processing, and a method for tagging suspect wheels. The goal is to examine each wheel of a train as it rolls by a checkpoint in a railyard. Two of these systems

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are currently in operation in this country. A companion portable hand­
held system subsequently verifies any flaw indications. The Fraunhofer
Institute (IzfP) in Saarbrucken, Federal Republic of Germany, has been
developing another ultrasonic system along this line [5], but using
electromagnetic-acoustic transducers (EMATs). IzfP has placed a
prototype into operation.

Our current research in this area [6-8] is the development of an
ultrasonic system using EMATs designed to work on American-style wheels
and rails. The objective is to check every wheel on a train, also in a
roll-by mode. Like the earlier systems, ours uses Rayleigh waves that
travel around the wheel tread. We are using EMATs for two main
reasons: 1. No ultrasonic path in the transducer itself and low
sensitivity to mode-converted signals mean a simplified, low-noise
signal that is relatively easy to interpret with high reliability, even
in an automated system; 2. Their noncontact nature eliminates the need
for ultrasonic couplants, i.e., no water sprays or liquid-filled boots.
Two extensive reviews of EMAT designs and applications have recently
been published [9, 10].

EQUIPMENT

In the electronic system, a function generator provides the rf
signal for a gated MOSFET power amplifier which drives the transmitter.
The toneburst consists of 5-10 cycles at 500 kHz with a pulse
repetition frequency (PRF) of 60 Hz. The receiver preamplifier is a
very low noise design. Electronic impedance matching is very important
for both transmitter and receiver to ensure maximum efficiency.

Our EMAT device (Fig. 1a) is meant for insertion into a recess cut
out of the rail. Therefore, one goal in the transducer design is to
keep the configuration as compact as possible to minimize both the

![Fig. 1. Rayleigh-wave EMAT construction.](image)

(a) Two meanderline coils, shifted to prevent shielding,
placed atop a magnet with field H. A foil eddy current
shield lays over the magnet and a thin, compliant foam
sheet is under the coils.

(b) Details of the wirewound meanderline.
amount of required machining in the rail and the loss of weight-bearing surface. Toward this end, we use a single permanent magnet (Nd-Fe-B for maximum field strength) 32 mm X 26 mm X 52 mm with the magnetization direction along the 32 mm direction and oriented normal to the tread. For pitch-catch operation, there are separate transmitter and receiver coils. These are meanderlines with a periodicity of 6 mm to generate a Rayleigh wave with this wavelength at 500 kHz (velocity = 3 km/s). This design generates and receives bidirectional Rayleigh waves traveling normal to the coil legs.

Rather than stacking the transmitter and receiver coils directly atop one another, we shifted them by a quarter period so they do not shield each other. To prevent signal complications from ultrasound production in the magnet, we cover it with a thin foil of copper or aluminum to minimize eddy current generation in the Nd-Fe-B. Between this shield and the coils are a few millimeters of compliant material (currently, polymer foam); this layer compresses under the wheel's weight and their flexible substrate allows the meanderlines to conform to the curvature and taper of the wheel tread. This minimizes liftoff for maximum efficiency and signal/noise.

The present coil design contains eight cycles or loops in the meanderline. The receiver coil is AWG 36 enamel-coated wire that has been wound through the pattern six times on acetate-based adhesive tape (Fig. 1b). This multiplicity adds to the sensitivity since the repetitions are series-connected. The flexible tape allows the coil to conform to the wheel's curvature.

We've constructed the transmitter coil in two forms. The first is a printed circuit on polymer film. The conductor is about 1 mm wide and 0.025 mm thick. In this form, the impedance is very low (about 1.3 Ω including a current limiting resistor). Our power amplifier can deliver about 140 A of rf current into this coil. The second form is identical to the wire-wound receiver, and the much higher impedance limits the drive current to about 30 A.

The greater the current flow through the transmitter, the greater is the eddy current induced in the specimen. While the printed circuit coil permits the maximum current, the wirewound coil passes the current through the EMAT aperture multiple times and the current density (A/mm²) induced in the specimen is roughly the same, i.e., the size of our ultrasonic signal is nearly identical with either form of transmitter. Using the lower current coil will increase the longevity of the power amplifier, and will allow an increase in the pulse repetition frequency (PRF) to as much as 250 Hz, should this prove desirable later. At present, the limit on the PRF is due to two factors in the power amplifier: ohmic heating of the MOSFET output drivers and the time required to recharge the power supply filtering capacitors.

EXPERIMENTAL RESULTS

We have recently constructed a short (4 m) section of track in which we mounted the transducer (Fig. 2). Rolling an actual wheel set (two wheels mounted on an axle) over the device much more closely simulates field conditions than our initial static measurements [7]. The goal is to debug several parts of the system: mechanical mounting, compliant coil backings, geometric variations in the size and position
of magnet and coils, triggering (if necessary), and signal collection and storage. Since the wheels have a few centimeters of side-to-side play in normal operation, this rolling test will also show us the importance of the wheel's transverse position with respect to the transducer.

For these initial measurements, we had two wheel sets, well used but nominally uncracked. The wheels were rolled onto the transducer and held stationary or rolled over the EMAT site at a few kilometers per hour. In both wheels of one set, this arrangement produces a signal which was still detectable after 16 round trips or about 42 m of travel. In both wheels of the other set, the signal traveled around the tread only six times before being attenuated into the noise level. Metallurgical variables due to such factors as manufacture, wear, etc., have a very large influence on the wheel's acoustic response. Any signal analysis will have to account for this effect.

The critical flaw depth is about 6 mm, so our interest is in distinguishing between cracks of greater depth (no longer safe) and those more shallow (safe for continued use). Initially, however, we saw-cut a very shallow circular flaw into the center of the tread along a wheel radius. This flaw depth into the wheel was almost 2 mm at the maximum; the length was oriented along the tread width and 12 mm long at the surface.

To determine how far a wheel can move across the transducers and still return a useful signal, we rolled the wheel in small steps across the EMATs and measured the signal strength as the initial contact point moved across the coils. This indicated that the effective EMAT aperture within which the wheel must be located to both transmit and receive our test signal is about 5-8 cm long. This aperture is actually slightly longer than the coils because the wheel radius is relatively so much larger, and the flexible coils conform to the tread curvature. While it would be desirable to introduce multiple pulses into the wheel in order to improve statistics for a higher signal-to-noise ratio, this may not be feasible since the Rayleigh wave travels several times around the circumference. To avoid processing confusion, it will be necessary to delay any new pulse until the prior one has sufficiently decayed. Since each round trip takes nearly one full millisecond, this means a delay interval of about 10-16 ms. To get even two test pulses into the wheel (one at the beginning and end of a 5 cm window) means the train cannot travel faster than 5 cm/10 ms or about 18 km/h. This would likely be unacceptably slow for a field system, so we shall probably have to settle for a single transmitter pulse. A likely scenario is to use a trigger device to start the pulse as the wheel enters the window. Recording just the data arriving before the return of second round trip signal (see below) takes nearly 2 ms, so the maximum train speed could be about 5 cm/2 ms, or 90 km/h. There are other factors (signal processing time, timing accuracy of pulse trigger, etc.) that will likely limit the allowable speed to somewhere under this value.

There are possibilities for triggering mechanisms to signal the proper moment during a wheel's transit to pulse the EMAT. For these initial tests, we placed a simple membrane switch between the coils and the magnet. The compliant foam transmitted the wheel pressure and switch closure triggered both the high current pulser and a digital oscilloscope to capture the transient ultrasonic signal from the single pulse. At the low speeds possible on our short test track, this system has been both reliable and consistent with our current spatial window.
The transducers are bidirectional and generate Rayleigh waves traveling clockwise and counterclockwise around the railroad wheel tread. Figure 3 indicates schematically the signal paths to a flaw and the resulting scope trace. Signals A and C are echoes that have traveled about 22% and 78% of the way around the wheel circumference to the 2 mm deep flaw and then back. Signals B and D are first and second round trip signals. Signal A' is the short path echo after the initial pulse has already traveled once around the entire circumference. Frequently some splitting occurs in these signals and this likely has at least two sources. Each round trip signal is a combination of counter-rotating signals. The path length is quite long (about 2.6 m) and some phase incoherence between these two becomes likely over this distance before they again combine on arriving back at the transducer. Also, the Rayleigh wave has some tendency to spread out to the wheel flange where it has a somewhat longer path than along the tread. The amount of ultrasonic energy in a wheel depends on the closeness of EMAT coupling and the wheel condition, e.g., grain size and residual stress state. Consequently, we are presently using the amplitude of the first round trip signal as a normalizing factor; the amplitude ratios A/B and C/B are our current flaw depth indicators.

The arrival time of signal B remains constant, of course, while A and C move closer to B as the EMAT-flaw distance increases until they all coincide when the flaw is exactly opposite the transducer. Thus, there are two zones on the circumference where meaningful measurements are not possible. Both of these are about 24 cm long; one is centered at the transducer and the other is exactly opposite. The first is due to recovery of the receiver amplifier following the transmitter pulse; the second is due to the merging of the round-trip and flaw signals when their acoustic path lengths become identical. As a result, approximately 80% of the tread can be inspected with each pass. A second pair of EMATs located 0.5-1 m down track would assure 100% inspection.

FUTURE WORK

The electronics for this system fall in two basic categories: 1. transducer (high current pulser for the transmitter and amplifier for the receiver) and 2. signal processing (digitizing and logic). The designs for the first category are working very well, and we are packaging them in a form suitable for routine use. Work on the second instrumentation system has now begun.

While our present EMAT design is producing excellent signals, there are several possible improvements we will be investigating. Among these are the use of a physically smaller magnet to reduce the size of the pocket machined into the rail, alternate materials for the compliant layer under the coils, and variations in the design and physical structure of the coils. Other wheel-detection mechanisms to trigger the current pulse are possible.

Further investigation into the size discrimination capabilities of this system is also necessary. This will entail a series of measurements on artificial flaws, initially, and then actual cracks.

Our goal is to deliver a working system to the Transportation Test Center in Pueblo, Colorado, and conduct full-scale field tests.
Fig. 2. Current test configuration.

(a) Standard wheel set rolled along a short length of track.

(b) EMATs mounted in rail. A protective film covers the coils and they are represented schematically in this photo.

Fig. 3. Flaw echoes.

(a) Typical oscilloscope signal for 2 mm deep cut. A and C are short and long path flaw echoes. B and D are first and second round trip signals. A' is the short path echo after a complete round trip (A + B).

(b) Schematic of bidirectional Rayleigh-wave travel to a flaw. A is the short path and C is the long path.
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