FLAW DETECTION IN RAILROAD WHEELS USING RAYLEIGH-WAVE EMATS

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INTRODUCTION

Early work at the University of Houston [1] showed the efficacy of Rayleigh waves for detecting cracks in the tread of railroad wheels. Development work has been going on at the Fraunhofer Institute in Saarbrucken (IzfP) on an automated system using EMATs that could be installed in a railyard and used in a roll-by mode [2]. A prototype of their system is now operational in Luxembourg.

European railroad wheels are generally forged while U.S. wheels are cast. Also, the IzfP system characterizes flaws in locomotive wheels; our system inspects rolling stock (freight cars). Because the tread and track shapes differ between U.S. and European equipment, the U.S. Department of Transportation Federal Railroad Administration started a program to develop an on-line system for use on American equipment. Our previous work with EMATs has demonstrated their usefulness in generating long-wavelength SH waves to detect and size planar flaws in weldments [3,4].

EXPERIMENTAL

Our EMAT transducer was actually a separate transmitter and receiver for pitch-catch operation. As noted in Fig. 1, the transmitter meanderline was a printed circuit on polymer film. The conductor was 1-mm wide and the 6-mm period corresponds to the desired wavelength at 500 kHz. The choice of a five cycle length was based on the curvature of the wheel and the space required to mount the EMAT in the track. The geometry of the receiver coil was identical. This meanderline, however, was laid-up with wire on acetate-based adhesive tape. The enamel coated wire was 0.14 mm in diameter and series-wound through the pattern six times. This multiplicity added to the receiver sensitivity. Both coils were flexible to conform to the wheel shape and achieve the best electromagnetic coupling. We laid these two units atop one another and then shifted them along their length by a quarter period to keep the elements of one from shielding the other.

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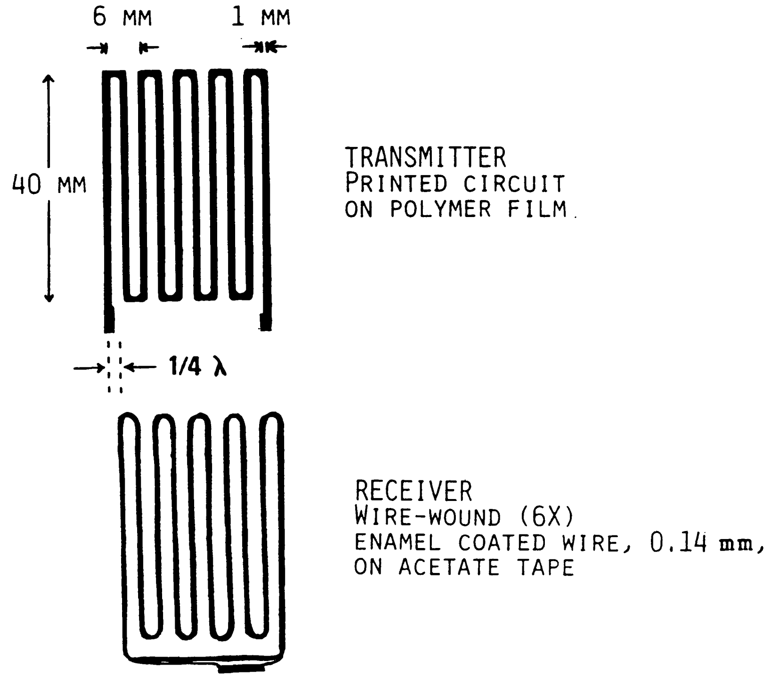

Fig. 1. Configuration of transmitter and receiver meanderlines on flexible substrates. They were placed on top of each other with a 1/4 wavelength lateral shift to prevent mutual shielding.

Figure 2 is an exploded sideview of the entire EMAT package. The two meanderlines were closest to the wheel (generally with a thin plastic sheet between for mechanical protection of the coils). Next was a thin (about 4 mm uncompressed) flexible polymer foam to allow good contact pressure against the curved tread. The compliance of this foam should also help with the problem of wheel profile changing with wear. The 1-mm thick aluminum sheet had several purposes. It was the pressure plate acting on the coils through the foam layer. The aluminum served as an eddy current shield to prevent any ultrasound generation in the magnet. This sheet was also part of a box which served as mechanical support for the overall system as well as container and handle for the magnet. The single Nd-Fe-B magnet was 52-mm long, 26-mm wide, and 31-mm high. Since the wheel is ferromagnetic, the magnet is strongly attracted and provides considerable pressure to hold the coils tightly against the tread. The field was normal to both the coils and the wheel rim. This transducer is bidirectional, generating or receiving Rayleigh waves traveling in both directions around the tread circumference.

The block diagram in Fig. 3 shows the relatively simple system used for these preliminary measurements. A function generator provides the rf signal for the gated MOSFET power amplifier which drove the transmitter. For these measurements, the input current to the transducer was ten cycles at 500 kHz and limited to 120 A peak-to-peak. (Present system maximum is 140 A.) Careful impedance matching of both coils on the wheel was necessary to ensure maximum efficiency. The preamplifier and amplifier were tuned devices with very low noise capable of maintaining a good signal-to-noise ratio. In the present system, only the function generator and the oscilloscope are commercial devices.

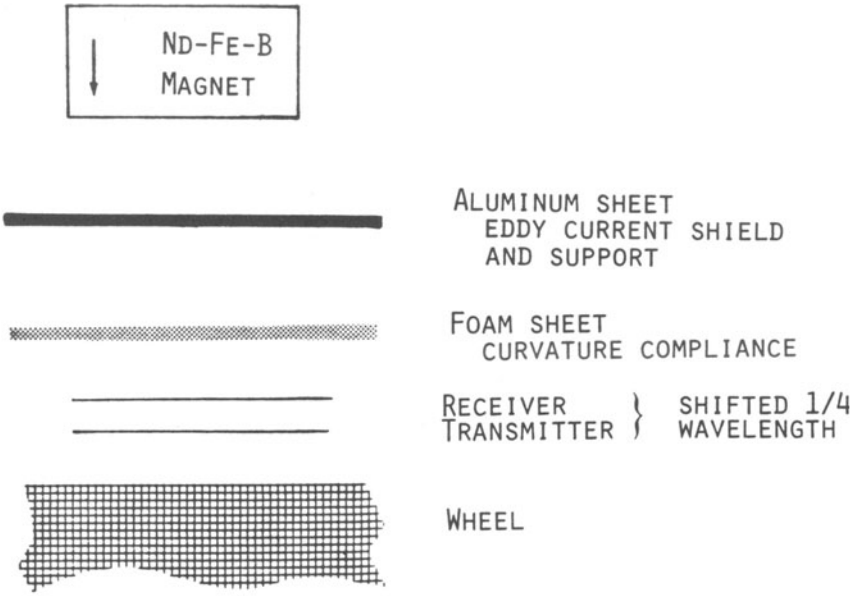

Fig. 2. Exploded sideview showing sequence of transducer parts.

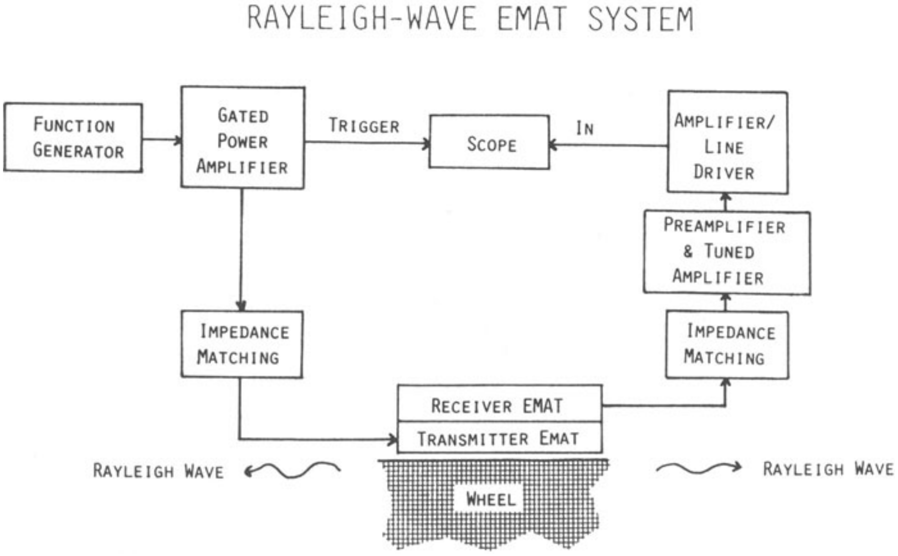

Fig. 3. Block diagram of laboratory system.

RESULTS

To characterize the ultrasonic beam from our EMAT, we cut a shallow circular slot into a flat carbon-steel plate and made several measurements of the signal reflected from this flaw. These involved both translating the EMAT parallel to the slot at 16- and 32-cm separations and also rotating it at the 32-cm location. The results indicated that the beam is about 9 degrees wide (6-dB down points). On repeating the rotational sequence with the transducer turned end-for-end, the results were virtually identical and showed the truly bidirectional nature of this device.

With the EMAT on an unflawed railroad wheel, the signal traveled unimpeded around the rim. It was possible to observe at least 14 round trips before the signal decayed into the noise level. With a wheel circumference of about 2.6 m, this meant we could watch the signal travel more than 36 m.

With a small slot in the rim only 1-mm deep, it was possible to see a distinct reflection. However, the critical cracks for U.S. wheels are about 6-mm deep. Therefore, we are interested in distinguishing between cracks of greater depth (no longer safe) and those of lesser depth (satisfactory for continued use). Accordingly, we sawcut an initial circular flaw into the center of the tread along a wheel radius with a maximum depth of 5.6 mm and a surface length of 38 mm.

While EMATs are non-contact devices, the signal strength does decrease rapidly with any increase in separation from the specimen. Since an inspection system in a railyard would have to cope with a wide range of conditions during actual use, we examined the decrease in the signal-to-noise ratio (S/N) with increasing liftoff (Fig. 4). The signal reflected from the 5.6-mm deep slot does drop dramatically but is still useful even at the 1.5-mm liftoff; probably, 1 mm or less should be possible in practice.

A typical oscilloscope trace taken from the sawcut wheel is in Fig. 5. The first signal, A, is a reflection of the Rayleigh wave which has traveled about 30% of the circumference to the slot and back. Signals B and D have traveled once and twice, respectively, around the entire rim. Signal C is a reflection of the beam which has traveled 70% of the circumference to the slot and back. Since the tread was fairly rusty from exposure while in storage, the transducer coupling varied slightly with location. (Note: after sanding to clean the rust from a small section of tread there was virtually no change in the data.) In railyard usage the tread will likely be bright metal from rolling wear, but other factors such as dirt may cause variations in liftoff. As a consequence, the round-trip signal, B, was used as a normalizing factor, i.e., the measurement parameter was the ratio of the amplitude of flaw signals and first round-trip signal (A/B and C/B).

With a slot depth of 5.6 mm and length of 38 mm, we measured the amplitudes of signals A, B, and C as a function of position on the wheel, moving the transducer in 5-cm steps from one side of the flaw all the way around to the other. The arrival time of signals B and D remained constant; as the distance from the slot increased, signals A and C moved closer to B until they coincided with it at the half-way point. On advancing the EMAT, the signals crossed in arrival time and then receded from B. Obviously, the signal timing indicates the flaw position relative to the probe.

The plot of normalized signal versus EMAT position in Fig. 6a has three very distinct regions. The first section shows a very large negative slope up to about 70 cm. With the beam divergence of 9 degrees noted above, the ultrasonic energy has not spread out to the full tread width of 10 cm until it has traveled 70-80 cm. Therefore, inside this distance the flaw intercepts a very large fraction of this concentrated energy and generates a

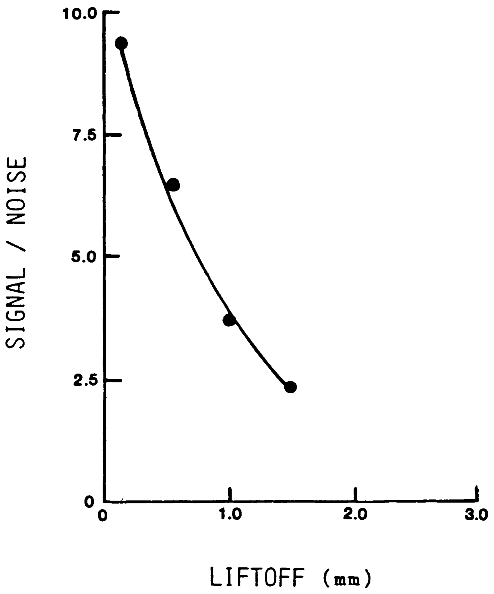

Fig. 4. Signal-to-noise ratio as a function of separation between EMAT and wheel.

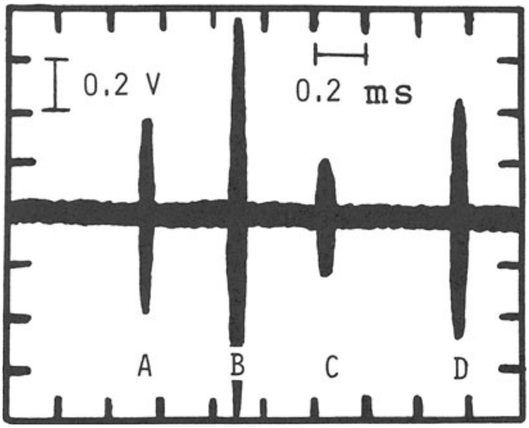

Fig. 5. Typical oscilloscope pattern on wheel. A and C are slot echos. B and D are round trip signals.

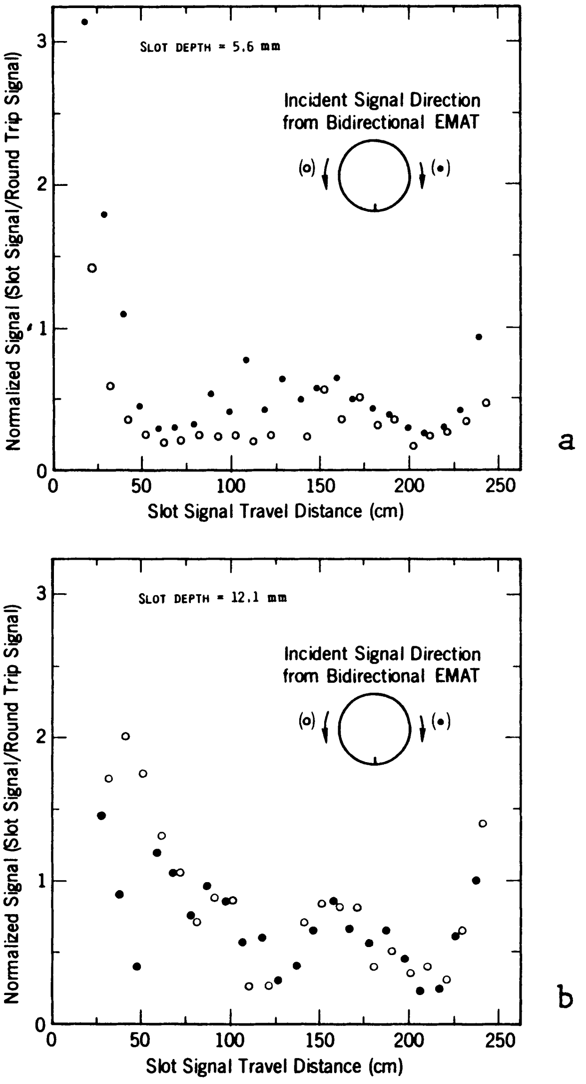

Fig. 6. Signal amplitude as a function of transducer position around the wheel circumference. The slot was located at 0 cm (262 cm).
a) Slot depth = 5.6 mm.
b) Slot depth = 12.1 mm.

very large reflection. Once the beam has spread out to full width, the flaw and round-trip signals remain fairly constant until about 225 cm. At this point the flaw again intercepts a large fraction of the ultrasonic beam. The flaw consequently decreases the size of the round-trip signal and causes an increase in the signal ratio.

The signals traveling in the opposite directions should generate the same data. While this trend appears, there does seem to be a slight systematic shift. Possibly there is a slight difference in the smoothness of the two sides of the sawcut slot.

As a next step, we used the same saw blade to enlarge the slot to a depth of 12.1 mm and a surface length of 53 mm. The repeat measurements are plotted in Fig. 6b and the data follow the same basic pattern as in Fig 6a. For the deeper flaw, the initial high-slope section extends to approximately 100 cm. While there seems to be some increase in scatter, the signal level is somewhat higher than for the shallower flaw; i.e., size discrimination does seem possible. In both Figs. 6a and b, there seems to be a local maximum occuring at about 150 cm; we are currently seeking an explanation for it.

To explore the feasibility of mounting a transducer of this general design in a rail, the magnet was placed in a brass box and inserted into a machined recess in a short section of track. With the foam and coils taped onto the box, the track assembly was placed in a position relative to the wheel approximating that expected in service. Even with this crude form of the transducer, the ultrasonic signals approached those seen with the aluminum box mount and without the surrounding ferritic iron. The steel rail does not seem to cause any deterioration in performance due to distortion of the magnetic field. Furthermore, the liftoff between the tread and the track-mounted EMAT does not seem to degrade the signal appreciably.

DISCUSSION

While these results are preliminary, they have been achieved in only a few months. They do indicate that the electronics and this transducer design will generate a strong Rayleigh wave in a cast iron railroad wheel. On the basis of two artificial flaws it appears likely that depth discrimination is possible with a rather simple approach.

Two locations on the circumference, each about 10-cm long, cannot be inspected with the current design. One location is centered right at the transducer and is the result of dead time due to the recovery of the receiver amplifier following the transmitter pulse. Another is exactly half way around the circumference where any flaw signal will coincide with the round-trip signal.

In addition to the signal amplitude, it will be necessary to determine the signal time in order to locate the fault (if desired) and determine which portion of the sizing curve to use. Another possible flaw sizing parameter is the decay rate of the round-trip signals: the deeper the flaw the more rapid the decay.

Some steps remaining to produce a useful system are:

1. Measure additional artificial flaw sizes at various locations across the tread.
2. Inspect real cracks.
3. Determine size discrimination capability.
4. Develop a sizing algorithm for automatic operation.

5. Develop a reliable in-rail transducer mounting system.
6. Determine variability due to wheel position and liftoff.
7. Perform a field test.

ACKNOWLEDGEMENTS

This work was sponsored by the U.S. Department of Transportation Federal Railroad Administration, Washington, D.C. Conversations with H. J. Salzburger of IzfP were an invaluable guide in this work. We also wish to thank the Transportation Test Center, American Association of Railroads, Pueblo, Colo., and, in particular Britto Rajkumar, for advice and also providing test wheels.

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