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Rail Track Field Testing Using Laser/Air Hybrid Ultrasonic Technique

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ABSTRACT

Nondestructive testing methods used for the testing of rail in tracks worldwide can be limited by discontinuity location or orientation within the rail. Vertical split head and rail base cracks are among those types of discontinuities that are difficult to detect, which in some cases may result in a rail failure in service. A noncontact and remote hybrid ultrasonic technique has been developed by combining laser generation with air coupled detection of ultrasonic signals in rails. The test apparatus mounts on a railroad pushcart and tests are performed in motion with all components kept above the running surface of the rail track. Tracks have been tested for vertical split head and rail base cracks with high success in detection.

Keywords: *ultrasound, laser ultrasound, air coupled ultrasound, vertical split head, rail base cracks.*

INTRODUCTION

Rail track field testing operations worldwide rely mainly on, but are not limited to, visual testing, magnetic induction and ultrasonic methods (Sperry Rail Service, 1999; Wickre, 1985). Visual testing is not effective in finding internal and tight fatigue cracks or in providing long distance coverage in a timely fashion. Magnetic induction and ultrasonic techniques have been available as early as 1928 and 1949, respectively. Although they are successful and reliable in finding many cracks in rails, a number of critical cracks remain undetected using these and other techniques that are currently available to the railroad industry. Detection of discontinuities may be affected by many factors, such as rail surface condition, rail geometry, discontinuity geometry and orientation and inadequate transducer to rail surface coupling (Garcia and Davis, 2002).

In general, current railroad testing technology requires constant or near contact conditions between the probe and rail tracks (Bray and Vezina, 1991). Federal Railroad Administration regulations mandate that any indication of a discontinuity from a test car must be immediately hand verified with a discontinuity detector. This leads to a start/stop test mode, which limits the speed of rail track test operations. Furthermore, obstacles along the test path of rail tracks impose an additional condition that limits test operations to be performed from the railhead with the detection apparatus kept above the running surface (which is the top surface) of the rail. This, in turn, makes current field testing techniques sensitive to certain types of discontinuities but incapable of detecting other types.

Some of these unfavorably positioned and orientated discontinuities include vertical split heads, rail base cracks and what are known in the railroad industry as "transverse defect detail" fractures. They are listed among critical cracks that can severely compromise the structural integrity of rail tracks (Clark et al., 2002; Garcia and Davis, 2002). For instance, vertical split head cracks have noncoplanar and nonlinear surfaces. When ultrasonic energy is directed towards a vertical split head, it reflects in different directions. In some cases, the reflection may be away from the source/receiver, making the detection process with the conventional rubber wheel a challenge (Clark et al., 2002). Detail fractures are transverse discontinuities propagating internally across the width of the railhead and may be associated with shelling on the top surface of the rail. Shelling is a horizontal separation, generally at the gage corner, extending longitudinally somewhat parallel to the running surface and gage side of the track. Although shelling does not usually compromise the structural integrity of rail tracks, it can prevent transverse cracks from being detected with the rubber wheels at the running surface of rails. Rail base cracks usually start at the outer edges of the rail base. They can grow very rapidly and cause failure without being detected. None of the test techniques available to the railroad industry today are capable of probing the outer edges of the rail base.

In an effort to improve railroad related test operations, noncontact and remote techniques are sought. In order to perform rail base tests without bringing the test apparatus below the running surface of the rail, the system must operate with a standoff distance of approximately 178 mm (7 in.) or greater. Laser, air coupled and water jet ultrasound transduction are the only methods that can meet such requirements. Water jet consumes large amounts of water and is more effective when test specimens are in an enclosure that collects and recycles water. Laser detection of ultrasound requires reflective, flat and smooth surfaces. The dark, curved and rough surfaces of rail tracks make optical detection of ultrasound very difficult or impractical for industrial applications (Kenderian et al., 2002b; Kenderian et al., 2003b; Cerniglia and Djordjevic, in press). Air coupled generation of ultrasound is not very effective when testing internal discontinuities in metals. Most of the energy of an acoustic wave, propagating from low density air to high density metals, reflects back to air while the remaining energy propagates mainly along the surface of the metal (Wooh, 2001). As a result, in the present investigation, laser generation is combined with air coupled detection to create a noncontact and remote hybrid ultrasonic technique that can operate under industrial conditions. Thin layers of oxides, water, grease and other contaminants usually enhance the laser generated signal as it provides for a constraining layer, which would recoil the force of ablation into the material (Scruby and Drain, 1990).

The propagation mode, frequency and wave front of the laser generated acoustic signal can be controlled to best fit the need of test operations (Kenderian et al., 2003a). Unlike optical detection, air coupled detection is insensitive to surface color and much less affected by surface roughness or curvature. It detects larger areas than the point sensing of optical techniques. In addition, it tolerates a few degrees of angular misalignments (Kenderian et al., 2001). As a result, the laser/air hybrid ultrasonic technique is found to be very flexible and successful in detecting a variety of cracks in the lab, including vertical split heads, transverse discontinuity detail fractures and rail base cracks. This paper presents proof of concept

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field test results of vertical split head and rail base crack detection performed at the Rail Defect Test Facility at the Federal Railroad Administration's Transportation Technology Center located in Pueblo, Colorado.

EXPERIMENT

For the generation of ultrasound, an infrared Nd:YAG pulse laser is used operating with a 4 to 7 ns pulse width and a maximum energy of 800 mJ per pulse. The laser beam is delivered through a set of beam steering mirror assemblies and shaped through a set of lenses before illuminating the surface of the rail. The laser source is focused to a point or a line, depending on the type of discontinuity testing to be performed. The testing of internal cracks, such as vertical split head cracks, requires bulk waves, where a point source is more effective (Kenderian et al., 2002a). For the testing of surface cracks, such as rail base cracks, a line source is used for better directivity of the acoustic wave (Aindow et al., 1982) and sensitivity to surface discontinuities (Kenderian et al., 2001; Kenderian et al., 2003c). The laser source operates in the ablative regime with water being added to rail surface as a constraining layer to increase the amplitude of the acoustic signal. To examine the damage caused by ablation, three rail specimens marked with the letters *A*, *B* and *C* are ablated with 1, 10 and 100 pulses each. The nine ablated regions, in addition to those outside ablation, are labeled alphanumerically, indicating the rail specimen and the number of laser pulses, as shown in Table 1. The laser operates with a 10 Hz repetition rate, while the beam is focused to a 1 mm (0.04 in.) point and optimized for a maximum energy output of 800 mJ per pulse.

Table 1 Tested region nomenclature for rail specimens A, B and C

Laser Pulses	Specimen A	Specimen B	Specimen C
0	A0	B0	C0
1	A1	B1	C1
10	A10	B10	C10
100	A100	B100	C100

Optical micrographs of the nine ablated areas, compared with those outside the ablated region, show no trace of phase transformation, brittle microstructure, thermal microcracking or any apparent metallurgical change caused by ablation. Observations are made with 50×, 100× and 500× magnification power. Figure 1 shows digital images of the microstructure of regions A0, A1, A10 and A100 with a magnification power of 100×.

Table 2 shows average microhardness test results performed on rail specimens A and B, using the Vickers scale under 0.5 kg (1.1 lb) of force. The hardness of the regions of specimens A and B that endured 1, 10 and 100 ablative laser pulses does not differ significantly from the hardness of the regions outside ablation, A0 and B0. This is true for measurements at the surface and subsurface, 6.5 mm (0.25 in.) deep. However, the hardness at the surface is lower than that below the surface due to decarburization at the surface. If brittle microstructure is produced, such as bainite and martensite, as a direct result of the heat introduced by the ablative laser pulse, the hardness at the ablated regions is expected to be much higher. The hardness of bainite in rail steel is typically higher than 400 and that of untempered martensite can approach 800 on the Vickers scale.

For detection, single or multiple capacitive air coupled transducers are used. These detectors operate with a broadband frequency spanning between 50 kHz and 2.25 MHz. A multichannel 250 kHz

Table 2 Microhardness test results in Vickers scale at the surface and subsurface, 6.5 mm (0.25 in.) deep

Specimen	Surface	Subsurface
A0	228	309
A1	244	318
A10	228	311
A100	235	312
B0	247	299
B1	229	284
B10	250	308
B100	258	308

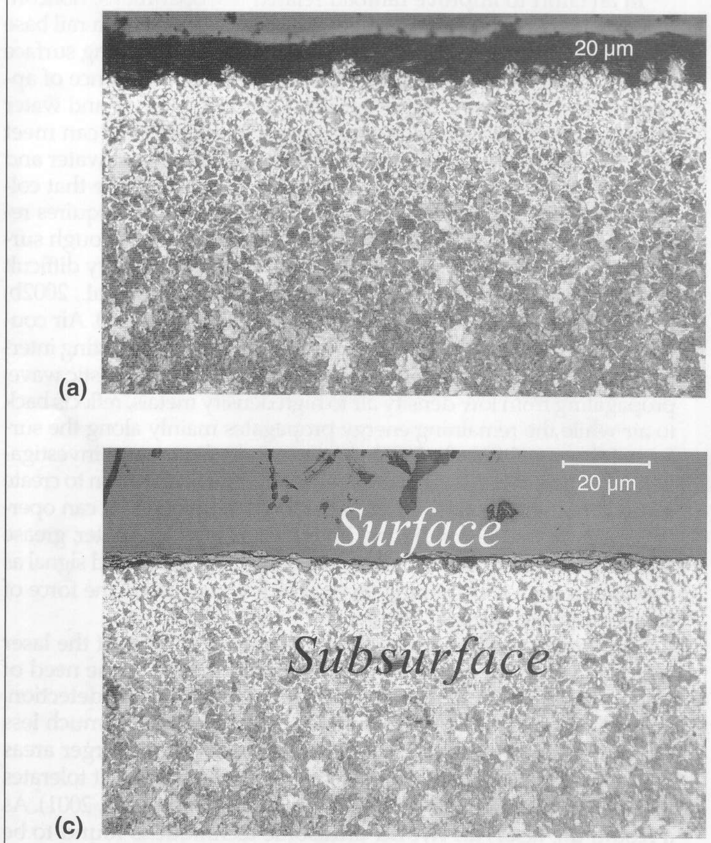

Figure 1 — Optical micrograph images of rail specimen A with regions enduring ablative laser pulses, showing lack of damage due to ablation: (a) with no pulses; (b) after one pulse; (c) after 10 pulses; (d) after 100 pulses.

high pass filter is used to filter out the lower frequency components to eliminate mechanical noise. Detected signals are received and stored in a multichannel digital oscilloscope. The complete laser/air hybrid ultrasonic technique and supporting assembly is mounted on a rail pushcart (Figure 2). Dynamic measurements are taken by pushing the assembly along the rail track at walking speeds. In the present experiment, the limiting factor to the test speed is the storing capability of the oscilloscope at hand. However, the technique itself is capable of operating at speeds exceeding 161 km/h (100 mi/h).

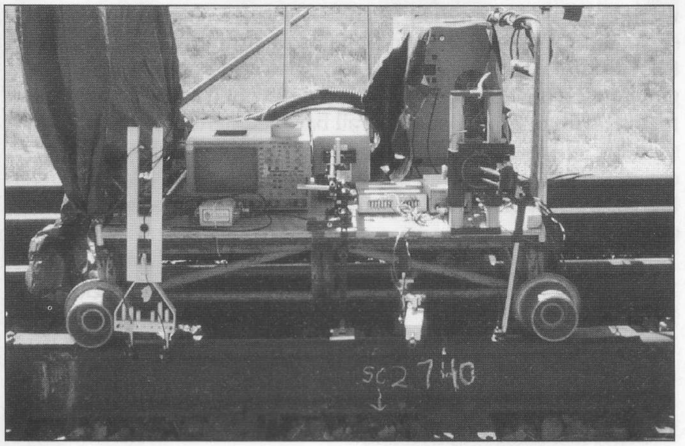

Figure 2 — The complete laser/air hybrid ultrasonic technique system on a pushcart.

RESULTS

Vertical Split Head

The vertical split head is a progressive longitudinal fracture in the head of the rail, where separation along a seam spreads vertically through the head at or near the middle of the head (Sperry Rail Service, 1999). The crack originates internally, progresses longitudinally and vertically for some distance and then gradually turns out to the gage or field side of the head. Growth is usually rapid and the crack is not visible on the surface until it has grown longitudinally to over a meter. In its advanced stages, the crack breaks the surface and a gap can be visibly seen on the running surface of the rail. Yet, even in their most advanced stages, these cracks are often missed by test techniques currently available to the railroad industry. Figure 3 shows a rail specimen which contains a vertical split head crack.

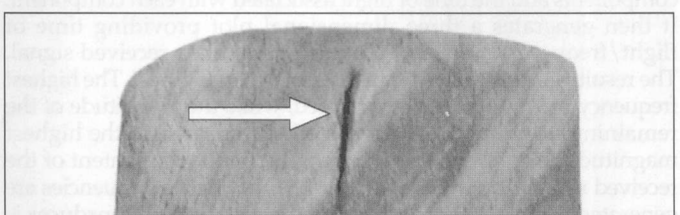

Figure 3 — Rail track sample containing a vertical split head.

With the laser/air hybrid ultrasonic technique, tests are performed in the track with the air coupled transducer, which is the closest component to the rail (though it maintains a separation distance of approximately 50 mm [2 in.] above the running surface, as shown in Figure 4). The laser source is focused to a point illuminating the field side of the railhead. In the absence of a crack, longitudinal and shear bulk waves propagate through the railhead, while a rayleigh wave propagates along the running surface, as shown in Figure 5. In the presence of a nonsurface breaking vertical split head

Figure 4 — Air coupled transducer configuration for vertical split head testing.

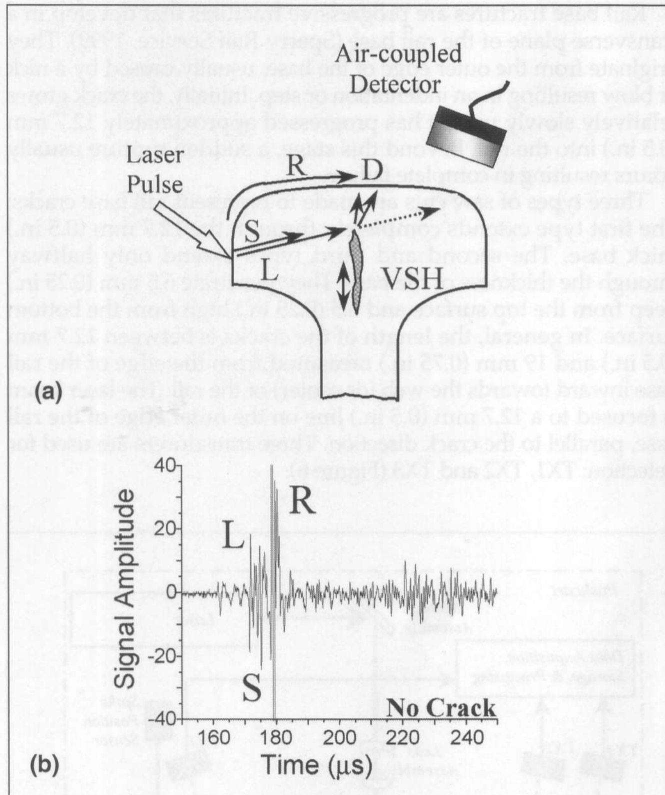

Figure 5 — The effects of vertical split head cracks on surface and bulk waves: (a) test configuration; (b) signal amplitude as a function of time in a situation with no crack; (c) signal amplitude as a function of time in a situation with a crack. Throughout, L = longitudinal, S = shear and R = rayleigh waves.

crack, the surface wave is unaffected, while the bulk waves interact with the crack. They reflect and mode convert from, transmit through, diffract around and resonate between the boundaries of the crack. As a result, the direct bulk waves, which arrive before the surface wave in the absence of the crack, attenuate due to transmission through the crack when present.

The spherical front of a point source laser generated acoustic signal provides the condition that results in a wide range of angular scattering upon reflection from an irregular surface, such as that of a vertical split head crack. The same condition promotes diffraction around the crack tip. Mode converted and resonating waves radiate from the crack tip toward the surface of the railhead. Collectively, a substantial amount of a delayed signal (arriving after the surface wave) is received by the detector, thus indicating the presence of an internal crack such as a vertical split head. The time of flight of the rayleigh wave serves as a guideline for the no crack condition, where bulk modes arrive before the rayleigh wave and the crack condition, where the delayed modes arrive after. Using this technique, 89 measurements are collected, with a 100% success rate of finding a vertical split head crack.

Rail Base Fracture

Rail base fractures are progressive fractures that develop in a transverse plane of the rail base (Sperry Rail Service, 1999). They originate from the outer edge of the base, usually caused by a nick or blow resulting in an indentation or step. Initially, the crack grows relatively slowly until it has progressed approximately 12.7 mm (0.5 in.) into the rail. Beyond this stage, a sudden rupture usually occurs resulting in complete failure.

Three types of saw cuts are made to represent rail base cracks. The first type extends completely through the 12.7 mm (0.5 in.) thick base. The second and third types extend only halfway through the thickness of the base. They penetrate 6.5 mm (0.25 in.) deep from the top surface and 6.5 (0.25 in.) high from the bottom surface. In general, the length of the cracks is between 12.7 mm (0.5 in.) and 19 mm (0.75 in.) measured from the edge of the rail base inward towards the web (or center) of the rail. The laser beam is focused to a 12.7 mm (0.5 in.) line on the outer edge of the rail base, parallel to the crack direction. Three transducers are used for detection: TX1, TX2 and TX3 (Figure 6).

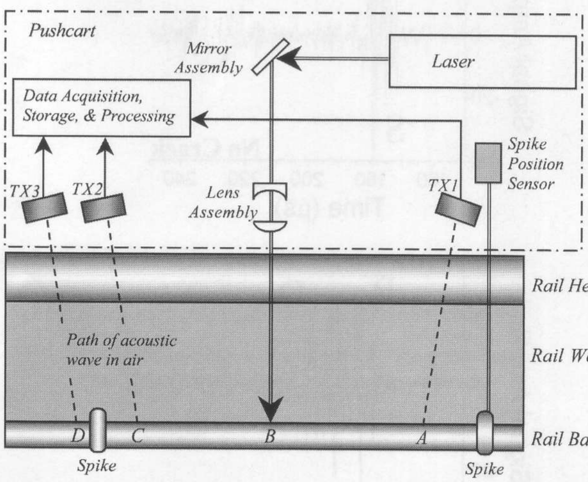

Figure 6 — Test configuration for rail base testing showing all components contained in a pushcart and above the running surface of the rail.

The acoustic wave propagates a distance of *BA*, *BC* and *BD* in steel for the three transducers, respectively, then 175 mm (6.9 in.) in air. The first two detectors, TX1 and TX2, are equidistant from the generation point *B*, where *BA* = *BC* = 250 mm (9.8 in.). The third detector is placed such that *BD* = 340 mm (13.4 in.). In the likelihood that TX2 may be positioned over a clip, which would partially obscure a surface wave from the transducer, the acoustic wave would be detected by TX3 instead. Each transducer is inclined 6.5 degrees from the normal to the surface and optimized to detect a surface wave propagating along the rail base in the direction facing the transducer in accordance with the Snell's law calculations. The position and orientation of the three transducers are configured in a way that would cover rail segments spanning between two consecutive spikes (or clips) with slight overlap. If a crack is present, the three transducers are expected to detect direct, reflected and transmitted waves, as shown in Table 3. A position sensor is installed to sense the spikes and trigger the laser accordingly. The laser beam then illuminates a point on the base, halfway between spikes, and generates acoustic waves propagating away from the illuminated region. With one laser pulse, a rail base segment between two consecutive spikes is tested. Other configurations can be designed to cover a distance of several spikes between the three transducers. In the present experiment, the setup is limited to the space available on the pushcart.

Table 3 Crack position and type of signals detected by each transducer

Crack Position	TX1	TX2	TX3
Between A and B	transmitted	direct and reflected	direct and reflected
Between B and C	direct and reflected	transmitted	transmitted
Between C and D	direct and reflected	direct	transmitted

Figure 7 shows waveforms captured by the three detectors with the pushcart in motion. A 6.5 mm (0.25 in.) crack is located between points *A* and *B*, breaking the bottom surface of the rail base. As charted in Table 3, the first detector receives a transmitted wave, which is severely attenuated by the crack. The remaining detectors, TX2 and TX3, each receive a direct and a reflected wave. Therefore, with one laser pulse, all three detectors indicate that a crack is present within the rail base segment under test. Surface breaking cracks on the opposite side of a plate, relative to the ultrasonic source and receiver, are not always easily detected; such is the case in this part of the experiment. Signal processing using wavelet transform can provide complementary information on the nature of these waves and the manner in which they interact with the crack (Cerniglia and Djordjevic, 2002).

The wavelet transform breaks down the signal into its frequency components and the time of flight associated with each component. It then generates a three dimensional plot providing time of flight/frequency/magnitude information of the received signal. The resulting plots are shown in the bottom of Figure 7. The highest frequency magnitude is plotted in red, while the magnitude of the remaining frequencies is normalized with respect to the highest magnitude and plotted accordingly. The frequency content of the received signals in general is below 1 MHz. Higher frequencies are generated with the laser source and the air coupled transducer is capable of detecting up to 2.25 MHz frequency signals. However, attenuation increases with frequency and is more severe in low density materials such as air. As a result, with a 175 mm (6.9 in.) propagation path in air, only frequencies below 1 MHz are available to the detector.

The velocity of longitudinal, shear and rayleigh waves in steel is 5.9, 3.2 and 3 mm/µs (0.23, 0.13 and 0.12 in./µs), respectively. At frequencies less than 1 MHz, the wavelength of these waves is less than 5.9, 3.2 and 3 mm (0.23, 0.13 and 0.12 in.), respectively. Therefore, the detected acoustic signal is a complex mix of rayleigh and lamb waves (surface and plate mode waves) and their interaction with the crack.

Similar analysis applies to the testing of the remaining two types of cracks, through cracks and top surface cracks, though they are generally easier to detect. Acoustic signals are found to propagate along the rail base unaffected by clips, spikes, anchors and other

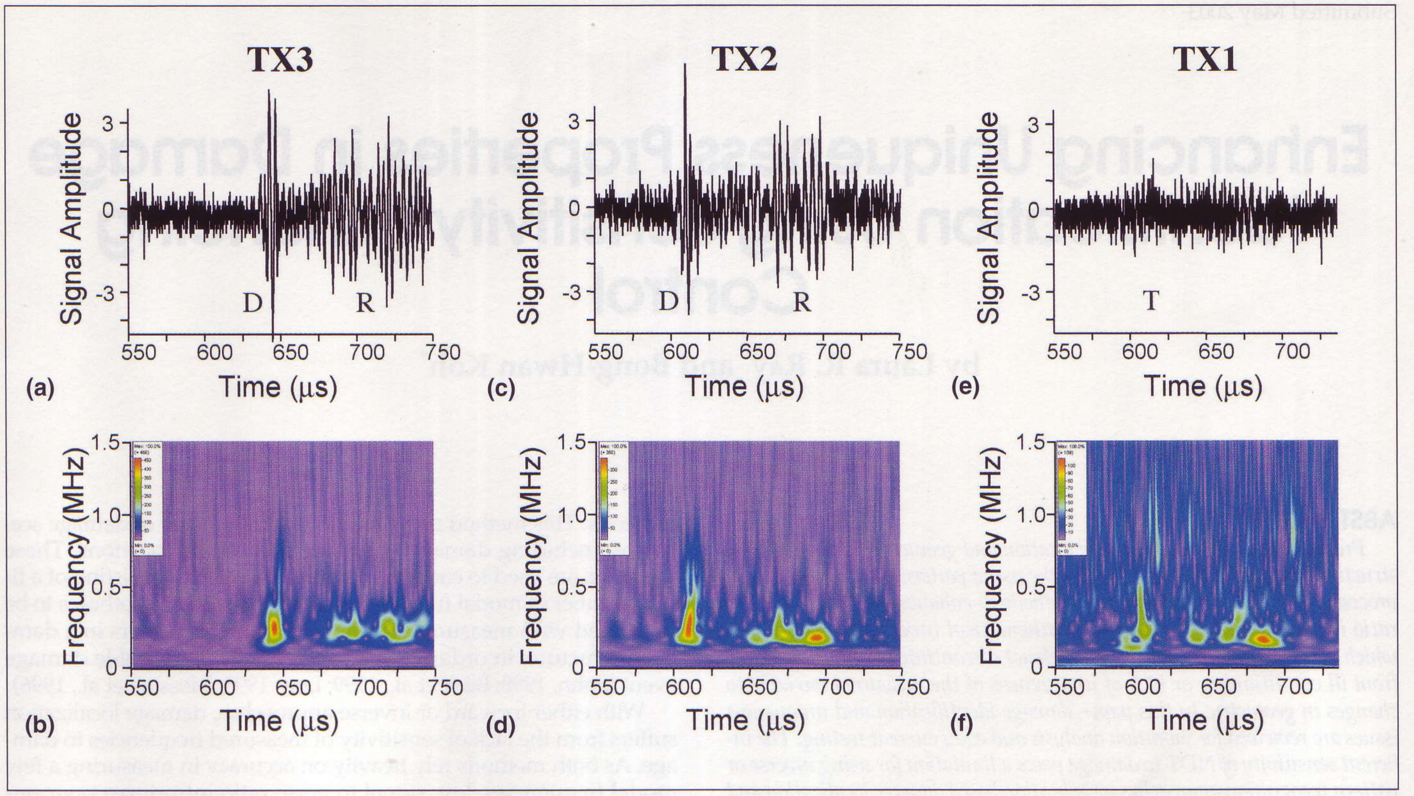

Figure 7 — Acoustic signal waveforms and wavelet transform plots showing direct, reflected and transmitted waves detecting a bottom surface crack on a rail base: (a) waveform for transducer TX3; (b) plot for TX3; (c) waveform for transducer TX2; (d) plot for TX2; (e) waveform for transducer TX1; (f) plot for TX1. Throughout, D = *direct,* R = *reflected and* T = *transmitted waves.*

regularly spaced parts that are found in the tracks. Overall, a total of 100 measurements are taken. Although it is not possible to distinguish between the three types of cracks, the determination of crack and no crack zones are made with a 90% success rate.

CONCLUSION

The laser/air hybrid ultrasonic technique has been tested at the Rail Defect Test Facility at Transportation Technology Center to detect vertical split head and rail base cracks. These cracks can compromise the structural integrity of rail tracks and sometimes pass testing with techniques currently available to the railroad industry. The noncontact and remote nature of the laser/air hybrid ultrasonic technique provides it with the flexibility to perform high speed tests of cracks that are in unfavorable positions and orientations for current NDT techniques under industrial conditions. The setup is mounted on a railroad pushcart with its lowest component being higher than the running surface of the rail. Tests are performed with the pushcart in motion at walking speed. Overall, 89 measurements are collected for the vertical split head with a 100% success rate of crack/no crack indication. For the rail base, 100 measurements have been collected with a success rate of 90%. Digital data collection makes it possible for dedicated data acquisition and processing systems to automate signal interpretation in real time to make rail testing operations faster and more reliable.

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