PVP-Vol. 484, Recent Advances in Nondestructive Evaluation
Techniques for Material Science and Industries
July 25-29, 2004, San Diego, California USA
PVP2004-2833

Locomotive Wheel Inspection with EMAT Technology

B.R. Tittmann and S. Jayaraman
Department of Engineering Science and Mechanics, Pennsylvania State University,
University Park, PA 16802

ABSTRACT

There is a need to analyze locomotive wheels for flank cracks in a non-destructive manner in order to prevent catastrophic failures. Flaw, shape, and size are desired parameters in establishing the quality of commercial tires. A variety of defects such as voids, inclusions, surface and internal cracks, or the like, must be discerned in order to prevent failure. This paper exhibits and compares the benefits of a number of different techniques used for flaw detection. Non-destructive evaluation (NDE) techniques used are magnetic particle inspection, dye penetrant, eddy current, electro-magnetic acoustic transducer (EMAT). The techniques vary in their ability to ascertain the flaw characteristics. Using a non-contact sensor such as the EMAT, to scan the wheels in an automated manner offers greater inspection speed at lower manpower. This paper reviews the basic concept of EMATs, introduces a recently developed technique for simulating EMAT performance by Finite Element calculation and features bench top results of waveform acquisition and signal-to-noise ratio dependence on lift-off. Next presented are calibration results for spark-eroded flaws in wheel sections for a variety of locations and sizes. Finally data are on flaw detection in a railroad service facility on several locomotives with wheels spinning at speeds up to 40 meters/minute. Results for both artificial and actual flaws are shown.

INTRODUCTION

Trains carry millions of tons of dangerous chemical and nuclear wastes every year. In the last year alone there were 1,757 derailments in the United States. Overall, the current methods for wheel crack detection are archaic, time consuming and require highly skilled operators to perform. None of the current methods can detect cracks beneath the surface. All methods require at least 20 hours of work per locomotive, as the wheels must be removed and carefully cleaned. Considering the critical role the integrity of the locomotive wheel plays in the safety of trains, it is vital that these methods be improved. The dirtiness of the surface of the wheel and the need to remove the wheel from the locomotive provide the biggest challenges for the new methods to detect defects in locomotive wheel sections.. We have examined locomotive wheel tire sections with various techniques for flaw detection, including magnetic particle, dye penetrant, eddy current and, electro-magnetic acoustic transducer (EMAT). It was determined the current methods worked with limited success. Eddy current method worked very well for surface flaws but however, due to skin depth constraint, did not detect sub-surface flaws. Surface acoustic wave (SAW) EMAT signals could determine the position of a defect at significant liftoff. Finite element simulations showed good convergence with experimental and theoretical results. A Prototype was used in an railroad service center and it detected manufactured as well as fatigue flaws in an actual locomotive wheel. A computer display system was also designed that would aid the operator in making decisions regarding the defects.

REVIEW OF LOCOMOTIVE WHEEL TESTING

Most locomotive wheels used for high-speed locomotives at Austrian OEBB are heat-treated; curved plate wheels made of a single block of metal, called mono-block wheels. A photograph of a locomotive axis is shown in figure 1. Many defects can occur in these wheels including: quarried out parts and cracks at rail contact surfaces, radial and tangential cracks, loose felly-to-tire shrinking, loose snap ring, and felly rotated against the tire, where signs do not overlap. The maximum size of the crack allowed depends on the type and position of the crack, as well as the individual requirements of the railroad company. For example, for tires to remain operable, OEBB has determined that detected crack size at inspection must not exceed a maximum length of 15 mm for tangential cracks, and 6 mm for radial cracks. In some areas, the radial crack must be smaller than 3 mm. There are currently three major methods of measuring cracks in locomotive wheels: Visual Inspection, Hammer Hit, and Magnetic Particle Evaluation. For all three methods, the wheel must be removed from the locomotive.

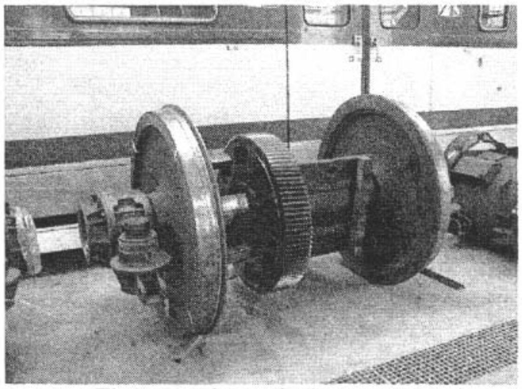


Figure 1: Photo of a locomotive axis

Visual Inspection

Visual inspection is the most common method used today to detect cracks in wheels. As the name implies, a mechanic carefully cleans the wheel and then visually inspects it. This method is extremely dependent on the skill of the operator, and is very time consuming. Also, visual inspection can not detect cracks beneath the surface.

Hammer Hit

Hammer hit can be explained as when a skilled worker hits the wheel with a hammer and listens to the sound. If the wheel has poor contact to the felly, the sound generated by the blow will differ from a properly attached wheel. This method is even more dependent on the skill of the operator than the visual inspection method. Not surprisingly, the hammer-hit method is often done in conjunction with the visual inspection method.

Magnetic Particle Evaluation

In magnetic particle evaluation, the wheel is cleaned, magnetized, and then magnetic particles are either dusted over the wheel, or suspended in a liquid (often kerosene), and poured over the wheel. A dye is added to the magnetic particles, which absorb ultraviolet light, and emit a yellow-green light. A surface defect forms a magnetic anomaly, which attracts and holds magnetic particles more than the other parts of the surface. Therefore, by shining ultraviolet light on a wheel treated with the magnetic particles, a yellow-green light is seen at the cracks.

This method is limited in that the wheel has to be made of a ferromagnetic material, which is not possible on most stainless steels. Also, magnetic particle evaluation is very dependent on the quality of the cleaning of the surface, and the skill of the operator. If a crack happens to appear along the grooves on the surface of a wheel, it is harder to detect it than if it lies perpendicular to the grooves. Finally, the wheel often has to be demagnetized after inspection, which can be time consuming and expensive.

Overall, the current methods for wheel crack detection are time consuming and require highly skilled operators to perform. Also, none of these methods can detect cracks beneath the surface. Moreover, all methods require the wheel to be removed from the locomotive and carefully cleaned and require, at least, 20 hours of work per locomotive. Considering what an important role the integrity of the locomotive wheel plays in the safety of trains, it is vital that these methods are improved.

OVERVIEW OF NON-CONTACT METHODS

Most non-destructive methods to measure anomalies require contact with a surface either directly or through a medium (often water). There are only a few viable methods that can be used without contact; we will focus on Eddy Currents and EMATs (Electromagnetic Acoustic Transmitters).

Eddy Current Method

Eddy currents are volumetric electrical currents in an electrically conducive material created by an exterior current. For example, when an alternating current flows through a coil close to a conducting surface, the magnetic field of the coil will induce circulating eddy currents in that surface (Fig. 2). The magnitude and phase of the eddy currents in the sample change the loading on the external coil, and its impedance. Therefore, a crack in the surface will affect the magnitude and phase of the eddy current thus changing the impedance of the external coil. It is therefore possible to detect changes in the integrity of a material by monitoring the voltage across the coil in such an arrangement.

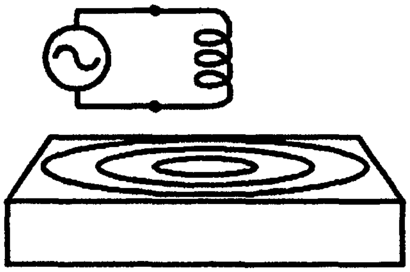
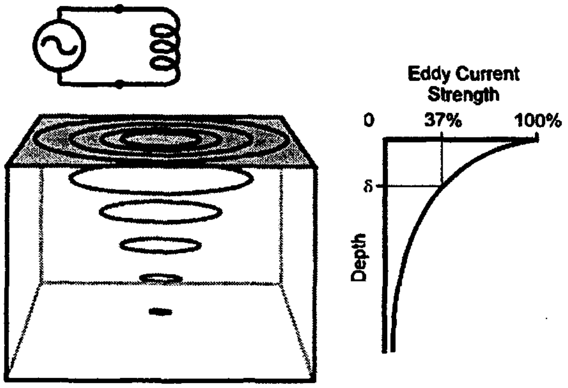


Figure 2: AC current in coil creating Eddy Currents in Sample



Note that cracks must interfere with the surface eddy current flow to be detected. Cracks lying parallel to the current path will not cause significant interruption and are harder, if not impossible, to detect. The eddy current and the impact of a defect decrease when moving into the sample (Fig. 3). As a result, this method is only effective for surface cracks.

Figure 3: Decrease in eddy current strength vs. depth

EMAT Technique

EMATs are ultrasonic transmitters that do not need to have contact with the material to create strong acoustic waves. First, a permanent magnet is placed near the surface of the sample, creating a magnetic field within the sample. A wire with an AC current is then placed near the surface of the sample, creating an alternating field within the sample, which creates eddy currents. These eddy currents interact with the permanent magnetic field and create deformations in the material. Finally, the deformations create acoustic waves (Fig. 4). The type of acoustic wave created in the sample depends on the shape of the external coils and permanent magnet above the sample. Currently, there are three major types of EMAT systems used: Meander Coil (Fig. 5), Pancake Coil, and Racetrack Coil.

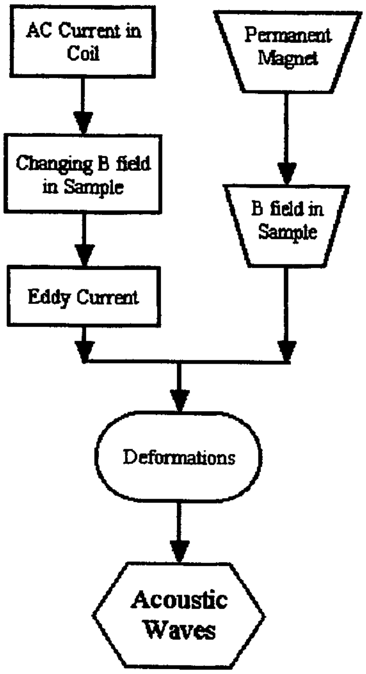


Figure 4: EMAT method to create acoustic waves

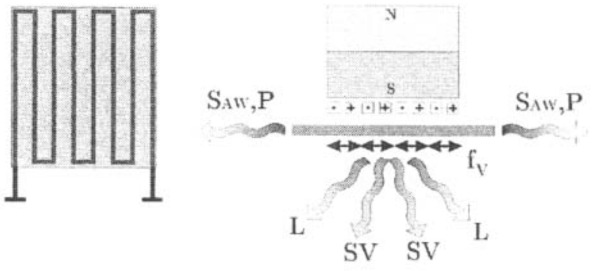


Figure 5: Meander Coil - Excites surface, longitudinal and vertical polarized shear waves.

FINITE ELEMENT SIMULATIONS

Numerical simulations and especially finite element method are widely used tools that can facilitate and speed up the design process of new acoustic transducers by reducing the number of prototypes. A modeling scheme was developed using the CAPA finite element software for the 2-D simulation of the wave generation and reception process with the electromagnetic acoustic transmitters based on the Lorentz force mechanism. Simulation and experiments were carried out for a 0.24-mm thick Aluminum plate (figure 5) with through-transmission setup of the EMATs to qualitatively compare waveforms from the simulation with those obtained with real EMATs (figure 6).

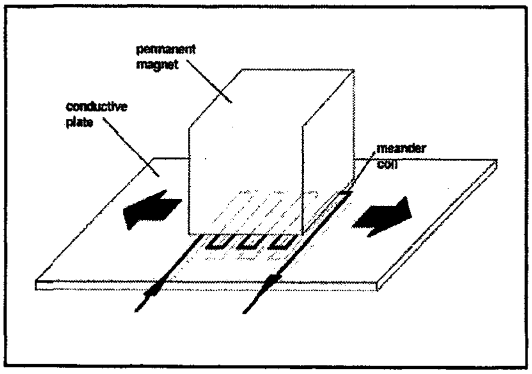


Figure 5: Setup of a Plate Wave EMAT.

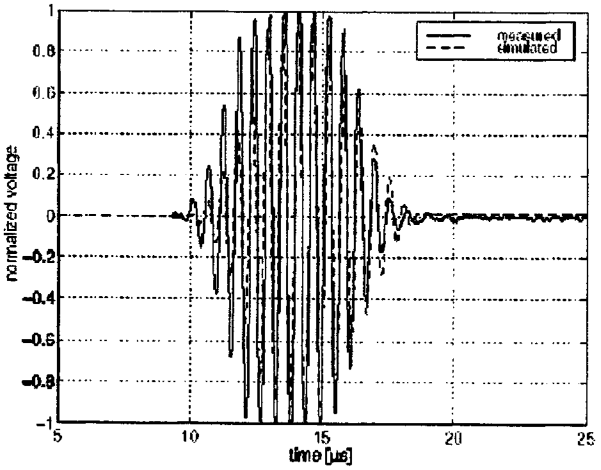


Figure 6. Comparison of Signals from Simulation and Experiments

The group velocity dispersion curves (Fig. 7) calculated using CAPA agree well with the theoretical and experimental results.

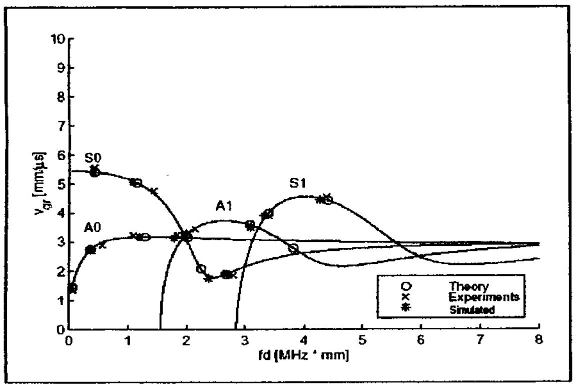


Figure 7. Measured, Theoretical and Simulated Group Velocity Dispersion Curves

LIFTOFF DEPENDENCE IN SAW EMATS

The EMAT system was modified to have adjustable cylindrical roller bearings to create various air gaps between the EMAT coil and the sample surface and to allow the EMAT system to move smoothly (Fig. 8). To accurately measure the liftoff, a feeler gauge was employed. A RITEC (RAM-1000) Pulser system was used with a Gated RF Signal output at 10 µs delay. The breakthrough pulse at the beginning was gated out. A signal with a frequency of 1.01 MHz and amplitude of 1.2 V was used as input to the EMAT system. Figure 9 shows the driving signal where the intensity was damped by – 40 dB (or 10^{-4} less intensity) so that the signal could be recorded without overloading the oscilloscope.

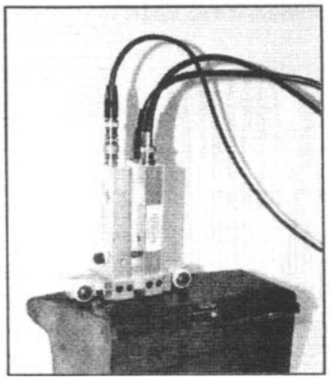


Figure 8: Positioning SAW EMATs for liftoff dependence

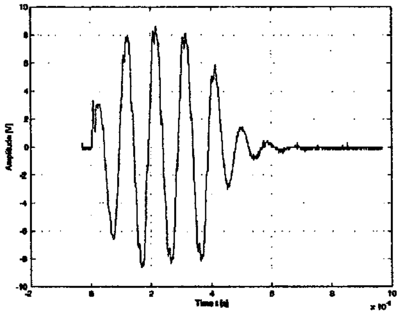


Figure 9. Input signal

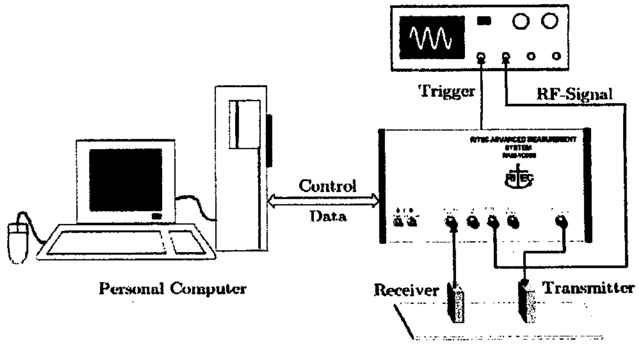


Figure 10. Outline of the Measurement System

The signal was then recorded at a distance of about 32-mm with several different liftoff positions. For low liftoff, the signal was clearly visible without much signal processing. However, for high liftoff, the signal was much clearer for more signal summation averages. Therefore, for a low liftoff of 0.53 mm the signal was only summed over 7 signals (Fig. 11), while for a liftoff of 1.2 mm the signal was summed for 100 signals (Fig. 12). Note that there is a factor of 10 in the amplitude of the reflection from the crack between figures 12 and 13 caused by the different liftoff. Also, in figure 13 the amplitude of the echo signal is only 2.2 times larger than noise. Higher liftoff values than 1.2 mm did not provide distinct peaks even with summations of signals.

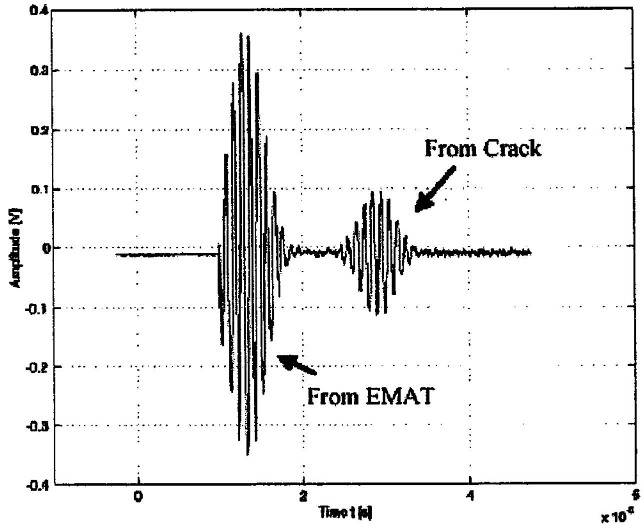


Figure 11. Signal at 0.53-mm Lift-off

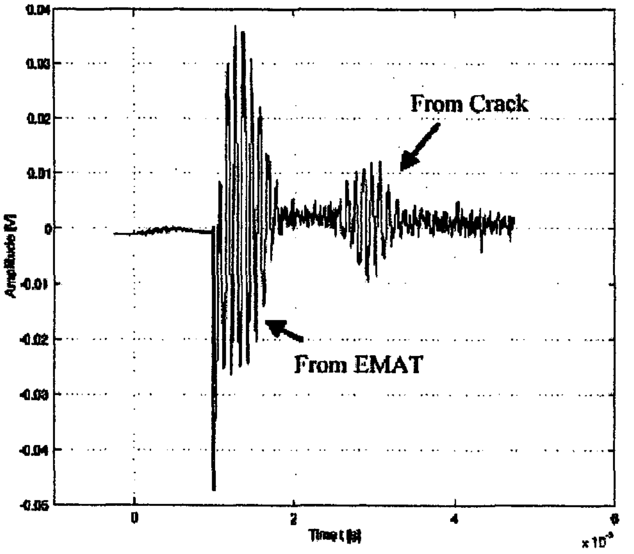


Figure 12. Signal at 1.2-mm Lift-off

A signal processing technique using auto-correlation was used to determine the amplitude of both the reflection from the crack and the direct signal from the driving EMAT as a function of liftoff (Fig. 13).

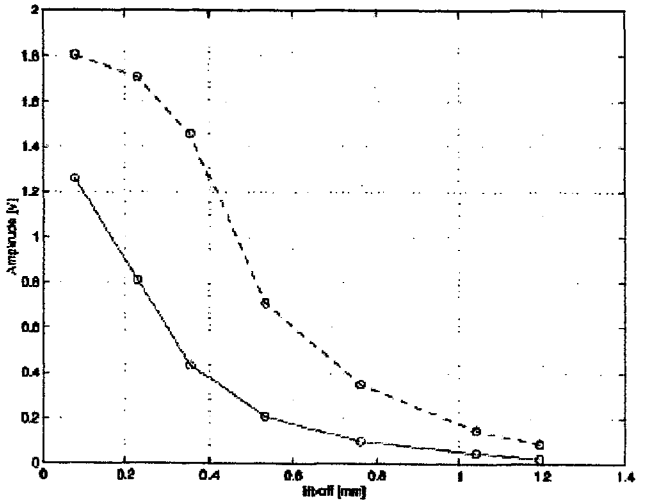


Figure 13. Amplitude of direct echo (dashed) and crack echo (solid) versus liftoff.

EXPERIMENTS AT AUSTRIAN OEBB

Experiments were conducted on locomotive wheels at the Austrian OEBB. A jack was used to raise the locomotive wheel (Fig. 14) and an EMAT array was mounted on the wheel. Tests were performed to detect any flaws including fatigue cracks. Tests were conducted with some manufactured flaws (3-mm and 1.5-mm boreholes and simulated notches) to investigate the effectiveness of the EMAT system, as well (Fig. 15). The EMAT system indicated the presence of the manufactured flaws as well as the fatigue crack (Fig. 16) in the locomotive wheel, very well.

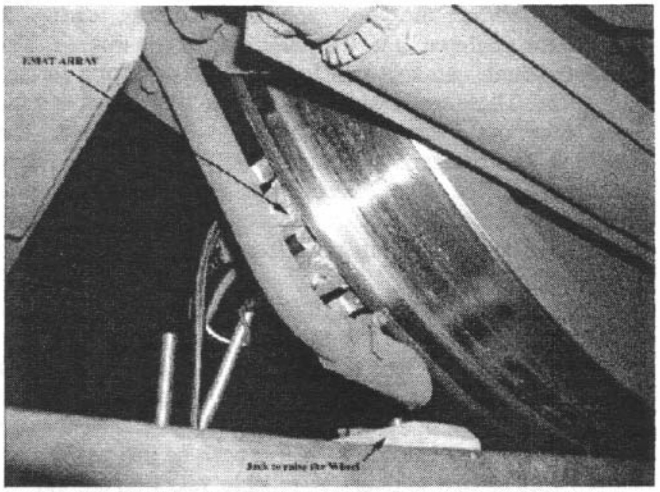


Figure 14. EMAT Array on the Wheel and the Jack to Raise the Wheel

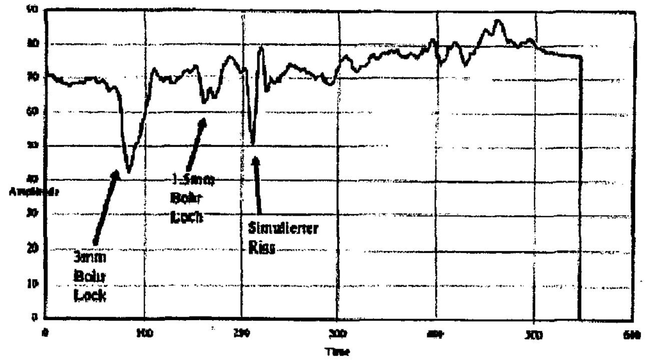


Figure 15. Manufactured Flaws Detected by the EMAT Array

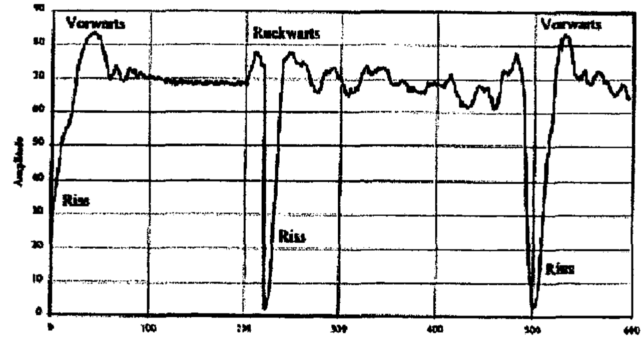


Figure 16. Fatigue Crack Detected by the EMAT Array

COMPUTER DISPLAY SYSTEM

A computer display system was developed at Sonic Sensors, CA that utilizes the information obtained from the sensors while scanning the locomotive wheels to provide a guideline to the operator to detect defects. The computer displays the RF signal amplitude and the result of a numerical algorithm. The adjustable algorithm interprets the RF amplitude for the detection of cracks. The algorithm has two purposes: to detect a crack and to remove or minimize any anomalous indications. The inspection is based on the adequate amplitude of an ultrasonic wave traveling over a given path. When the wave confronts a crack, energy is reflected or scattered, and the amplitude is diminished. The signal amplitude can also change from alignment or a surface irregularity. These small variations need to be ignored and the signal drop out from a crack needs to be enhanced. The algorithm was designed to ignore small effects and be very sensitive to crack type effects. The algorithm converts a "good" signal into a small number and a "crack" indication into a large value. The algorithm result is compared to two thresholds, a "yellow Caution" and a "Red Rejection" threshold. These adjustable thresholds provide a simple accept/reject criterion for the engineer to set for the operator. A Green – Yellow – Red display (Fig. 17) provides a clear visual indicator of the condition of the wheel. Including all this information on one display provides the operator a sense of understanding of the quality of the scan he just performed, and provides an easy to interpret, reliable, rejection criteria.

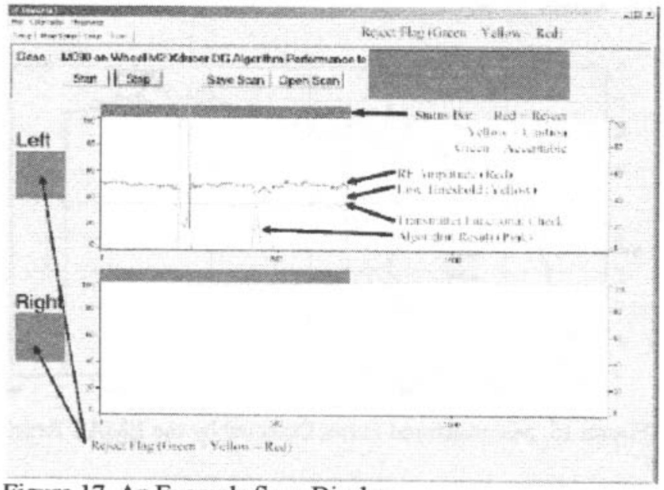


Figure 17. An Example Scan Display

CONCLUSIONS

Several relevant experiments have been conducted. We have shown that the SAW EMAT signals can determine the position of a defect at significant liftoff. The Finite element modeling using CAPA proved that simulation results compare very well with theory and experiment which helped in reducing the number of prototypes. The EMAT array system worked well when tested on the actual locomotive wheel with both manufactured as well as fatigue defects. Finally, A computer display system has been developed that can aid the operator in making decisions on the health of the locomotive wheel.

References

[1] Bray, D.E. & Stanley, R.K. 1997. *Nondestructive Evaluation: A Tool in Design, Manufacturing, and Service*, CRC Press, pp. 98-99.

[2] Thompson, D. O. & Chimenti, D.E. 1998. High-Speed Monitoring of Surface Defects In Rail Tracks Using Ultrasonic Doppler Effect, *Review of Progress in Qualitative Nondestructive Evaluation,* **Vol 17** pp.