UCSD/FRA Ultrasonic Guided-Wave System for Rail Inspection

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ABSTRACT

Recent train accidents, increasing tonnage and aging of the rail transportation infrastructure have reaffirmed the need to improve the current rail inspection technologies, consisting primarily of ultrasonic wheel testing. One of the recent developments in rail inspection is the use of ultrasonic guided waves in the 50 kHz-1 MHz range and non-contact probing techniques. This paper describes the latest version of the University of California-San Diego/Federal Railroad Administration (UCSD/FRA) rail defect detection prototype which is based on non-contact guided wave testing and real-time statistical pattern recognition for defect detection and classification. The system specifically targets transverse head cracks such as Transverse Fissures and Detail Fractures. It is also sensitive to longitudinal head cracks such as Vertical Split Heads and mixed-mode cracks such as Compound Fractures. The system was recently field tested in March and December 2008 at speeds of up to 10 mph with excellent results under changing
environmental conditions. Plans are in place for further improvements and a System Evaluation of the prototype to be performed at the Federal Railroad Administration's Transportation Technology Center (TTC), Pueblo, Colorado, in June 2009.

INTRODUCTION
Safety statistics data from the FRA [1] indicate that train accidents caused by track failures including rail, joint bars and anchoring resulted in 3,386 derailments and $685M in reportable direct costs during the decade 1998-2008. The leading cause of these accidents was the Transverse/Compound Fissure (reportedly responsible for $158M in direct damage cost and 808 derailments during 1998-2008), followed by the Detail Fracture (responsible for $136M in direct cost and 424 derailments during the same period). Transverse Fissures and Detail Fractures are cracks primarily growing in a plane perpendicular to the rail running direction (Transverse Defects – TDs). Conventional ultrasonic rail inspection uses piezoelectric transducers that are coupled to the top of the rail with ultrasonic wheels or sleds filled with water or other fluids. The transducers are typically operated at 2.25 MHz in a pulse-echo mode with two orientations, namely normal incidence for detecting horizontal cracks and 70° angle of incidence for detecting transverse cracks [2]. The most disconcerting drawback of ultrasonic wheels is the fact that horizontal shallow cracks (shelling) can mask the internal transverse defects. This limitation was the cause of the derailment of fourteen freight cars in Superior, WI in 1992, where hazardous material spillage caused the evacuation of more than 40,000 people. Following the Superior, WI accident, the National Transportation Safety Board issued a Safety Recommendation [3] to improve the detection of defects internal to the rail, particularly in the presence of shelling. Another undetected TD was responsible for the derailment in Hatfield, U.K. in 2000, which
caused four deaths and over thirty injuries. A second limitation of ultrasonic wheel inspection is its limited coverage, since the inspection is carried out at each cross-section of the rail at a time. A third problem with this technique is that the high frequencies used (typically 2.25 MHz) cannot penetrate alumino-thermic welds because of excessive attenuation when propagating through the weld’s coarse microstructure. In an effort to overcome some of the issues associated with ultrasonic wheel inspections, some research groups, including UCSD, are investigating ultrasonic guided waves for rail inspections [4-13]. There are several reasons for this. First, guided waves propagate along, rather than across the rail, and are thus ideal for detecting the critical TDs. Second, guided waves increase the inspection coverage (length of rail inspected at once) thereby relaxing limits on the achievable speed. Third, since guided waves penetrate a finite depth of the rail surface, they can travel underneath shelling and still interact with internal defects allowing for their detection. Fourth, since guided waves travel in the mid-frequency range, between 20 kHz and 1 MHz, they can penetrate alumino-thermic welds, hence potentially targeting weld cracks/discontinuities. The advantages of guided waves come with the difficulty in managing their complicated propagation behavior. The main issue is the guided wave multimode character (many modes can propagate simultaneously) and dispersive character (the propagation velocity depends on the frequency). Consequently, only when guided modes are properly “managed” can guided waves become an effective tool for rail defect detection. Hence, UCSD has utilized a Semi-Analytical Finite Element (SAFE) method that combines theoretical and numerical formulations to allow the study of high-frequency guided waves in rails in a computationally efficient manner. These studies have allowed an optimized design of the rail defect detection prototype. The UCSD/FRA prototype uses non-contact means of generating and detecting the guided waves in the rail. The solution of choice is a combination of laser and air-
coupled sensors, which were first proposed in 2000 for non-contact rail probing [14]. The prototype also uses a statistical pattern recognition algorithm for detecting and classifying defects. The uniqueness of this algorithm is that it does not require a “training” phase as in Neural Network-based classifiers, and it is hence very practical. This algorithm was successfully tested in the field with excellent results. This paper discusses the status of the UCSD/FRA rail defect detection prototype including the results of the last field tests performed in December 2008.

SEMI-ANALYTICAL FINITE ELEMENT METHOD FOR MODELING HIGH-FREQUENCY WAVES IN RAILS

Semi-Analytical Finite Element (SAFE) methods have emerged for modeling high-frequency wave propagation in waveguides of arbitrary geometries, where theoretical solutions are non-existent or 3-D FEA becomes computationally too intensive [8, 12, 15]. The general SAFE approach for extracting the wave solutions (velocity, attenuation, mode shapes) uses an FE discretization of the cross-section of the waveguide alone. The displacements along the wave propagation direction are described theoretically as harmonic exponential functions. Thus only a 2-D FE cross-sectional discretization is needed, with considerable computational savings compared to a full 3-D FEA of the entire waveguide. In addition, since polynomial approximation of the displacement field along the waveguide is avoided, the method is applicable to predict waves with very short wavelengths, where a traditional 3-D approximation may fail. The application of the SAFE method results in solving the following first-order eigensystem [15]:

\[
A - \xi \mathbf{B} \begin{bmatrix} 2 \\ M \end{bmatrix} \mathbf{U} = 0
\]  

(1)
where $A$, $B$ and are related to the dynamic stiffness and mass matrices of the rail, and $U$ are its displacements. Solving eq. (1) at each frequency $\omega$, $2M$ eigenvalues $\xi_m$ and, consequently, $2M$ eigenvectors are obtained. The eigenvectors are the $M$ forward and the corresponding $M$ backward modes. In general the eigenvalues are pairs of complex conjugate numbers $(\pm \xi_{Re} \pm i\xi_{Im})$, representing propagating and evanescent waves along the $\pm x$-directions. The wave phase velocity can be evaluated by $c_p=\omega/\xi_{Re}$ and the attenuation, in Nepers per meter, by $\xi_{Im}$. Fig. 1 shows SAFE results obtained at a higher frequency of 200 kHz. Results are shown for the fundamental symmetric mode ($S_0$) and the 1-st order antisymmetric mode ($A_1$). The plots show the displacement mode shapes ($x$-component) and the cross-sectional strain energy associated with the two modes at 200 kHz. The symmetry of the mode is usually referred to the displacement $u_x$ relative to the vertical axis of symmetry ($z$) of the rail section. Accordingly, the mode shapes in Fig. 1 show a symmetric $u_x$ for $S_0$ and an antisymmetric $u_x$ for $A_1$. This behavior is therefore equivalent to an Axial-type motion for $S_0$ and a Horizontal Flexural-type motion for $A_1$. The strain energy plots indicate where the energy of the mode is focused across the rail section. It can be seen that while $S_0$ concentrates the energy at the center top of the rail head, $A_1$ primarily excites the flanges of the rail head. To some extent, this behavior can be generalized to all $S_i$ and $A_i$ modes. Therefore, in a defect detection context, symmetric-type modes are more effective to detect cracks located in the center of the rail head, whereas antisymmetric-type modes are more effective for targeting defects in the sides of the head. The consideration of a loading term in the SAFE definition of the problem, allows for the calculation of the forced response of the rail to a specific load [8, 12]. The forced response of the rail was studied for the case of a broadband excitation applied to the top of the rail head. The excitation simulated the laser pulse which is used in the defect detection prototype (see next section). Fig. 2 shows the
rail response to a symmetric (left) and to a nonsymmetric (right) laser excitation, at a distance of 4” (0.1 m) from the irradiation point. The response is shown in terms of strain energy for all excited guided wave modes. It is shown that while the symmetric excitation predominantly vibrates the center of the head, the nonsymmetric excitation favors one side of the rail head. Therefore, similarly to what is concluded for the unforced modes in the previous figure, a symmetric (or nonsymmetric) laser excitation should be used to focus the inspection to the center (or the gage-side) of the rail head.

RAIL DEFECT DETECTION PROTOTYPE
The UCSD/FRA rail defect detection prototype is based on ultrasonic guided waves and non-contact probing. Certain wave frequencies are chosen, which penetrate the entire rail head, and can hence interact with surface or internal head cracks, located either at the center or at the gage-side of the head. While guided waves are preferentially sensitive to transverse-type cracks, the used wave paths are also sensitive to longitudinal cracks and mixed-mode cracks such as Vertical Split Heads and Compound Fractures, respectively. The current system targets exclusively the rail head, hence no coverage is provided for the web and base. The guided waves are excited and detected in a non-contact manner. An Nd:YAG pulsed laser is used for wave generation while an array of air-coupled sensors is used for wave detection. The sensors stay 2” (50.8 mm) above the rail head. The ultrasonic excitation, detection and processing are performed in light of the SAFE model predictions to maximize the sensitivity to (i) the presence of head cracks and (ii) the type of head cracks (surface vs. internal). A statistical pattern recognition algorithm, proprietarily developed by UCSD, has been added to provide real-time indication of defects in a statistically robust manner. The algorithm does not require any learning cycle on known defects, which
would be impractical to obtain given the large variety of defect cases possible. A plot of a Damage Index is shown in Fig. 3. This result is from a run conducted at 10 mph at the Gettysburg, PA test site (see next section). The largest peaks are joints, and the smaller peaks are defects. Notice that the Signal-to-Noise Ratio (SNR) of the data is extremely high. The discontinuity-free portions of the rail show an almost identically zero Damage Index. This level of SNR could not be achieved with deterministic information such as the typical threshold-crossing of a single ultrasonic measurement.

FIELD TEST RESULTS
The most recent field test of the prototype was conducted in Gettysburg, PA in December 2008. ENSCO, Inc. provided technical support throughout the field tests, including the installation of the prototype on a servo-assisted arm on the back of the FRA hy-railer. The prototype on the servo-arm is shown in Fig. 4, along with the layout of the Gettysburg test site. The inspected track consisted of a segment of railway siding, 160 ft (49 m) in length, containing known defects. Several joints were present along the test section. Three, 1.8 m (6 ft) long, 139-lb A.R.E.M.A. sections with known internal defects in the head were inserted, and secured with joint bars, in the test section. From ultrasonic hand mapping, three internal defects were located and sized, with 3.5% head area (HA), 35% HA, and 12% HA, respectively. The hand mapping also indicated that all internal defects were primarily transverse, with two located in the gage side and one located in the head-center. In addition, two surface cuts were machined perpendicularly to the rail running direction, with sizes of 5% and 2% HA, respectively. Two oblique surface cuts (45 degree inclination from the running direction) were also added at the top of the head, both about 3.5% HA. Various runs were made during four days of testing. The runs were used to collect
Damage Index data for estimating the Probability of Detection (POD) for the present defects. To assess the robustness of the system, the tests were performed under various conditions including calm vs. windy, dry vs. wet rail, 5 mph vs. 10 mph, and using two different powers of laser excitation. The performance of the prototype, evaluated in terms of POD, is summarized in Table 1. The results are shown separately for the 5 mph and the 10 mph testing speeds. The “cumulative” POD, obtained by considering all tests regardless of testing speed, is also shown. The POD was calculated as the ratio between the number of runs where a given defect was detected, over the total number of usable runs. A defect was considered detected when at least one of the statistical Damage Indices was activated. A statistical Damage Index was called “activated” when the corresponding value was above a fixed threshold level. Table 1 shows an excellent performance in detecting all present defects. Particularly noteworthy is the high POD obtained for the three Internal Defects. The reliability of detection for the surface and the oblique cuts was also high. It can also be noticed that, except for one of the oblique cuts, the performance did not degrade with switching from the 5 mph speed to the 10 mph speed. The low False Positive indications (last column of Table 1) are also reassuring since false positives would require an inspector to manually verify the indication in the “stop and confirm” mode. The False Positives were calculated as the percentage ratio between the sum of false positive detections over all the runs and the total number of the readings, excluding the ones related to the discontinuities (joints and defects). Finally, it should be noted that the POD was maintained high within the large range of environmental conditions encountered, including rain and wind.

CONCLUSIONS

This paper has presented the status of the rail defect detection prototype being developed at
UCSD under FRA sponsorship. The prototype uses ultrasonic guided waves, rather than bulk waves used by conventional ultrasonic wheel inspections. Guided waves, propagating along the rail running direction, offer several advantages compared to wheel-based inspections. These include, a preferential sensitivity to transverse-type defects, a better ability to overcome the problem of “defect masking” in the presence of surface shelling, and a larger inspection range which can in turn increase inspection speed. However, guided waves in rails are complicated because of their multimode and dispersive character. The first part of the paper therefore presents a Semi-Analytical Finite Element (SAFE) method to model guided waves in rails at frequencies as high as 1 MHz, which would be impossible to model with conventional Finite Element Analysis using off-the-shelf computing resources. The SAFE analysis was used to predict wave velocity and attenuation curves, as well as wave patterns in the rail due to different excitations. These models allowed for the selection of the appropriate mode/frequency combinations in the prototype under development, for the detection and classification of head defects. Although the prototype was initially designed to target Transverse Defects, wave paths are used which can also detect Vertical Split Heads and Compound Fractures. The prototype excites and detects guided waves in the rail in a non-contact manner, using a combination of laser and air-coupled sensors. The software analyzes the sensor indications in real time using a statistical pattern recognition algorithm which greatly increases defect detectability compared to deterministic analysis. The prototype was field tested in December 2008 at speeds of up to 10 mph. The test track included three different sizes of Internal Head Defects (3.5%, 35% and 12% H.A.), two sizes of transverse Surface Head Cuts (2% and 5% H.A.), and one size of oblique Surface Head Cut (3.5% H.A.). The results of the tests indicated a high Probability of Detection for all defects present, ranging from 75% to 100% success rate over twenty-four runs conducted with varying
environmental conditions including wind and rain. Further improvements are planned, including a new higher frequency laser to increase inspection speed up, better operational controls, and repackaging for the harsh railroad environment. The system will be evaluated at the Federal Railroad Administration's Transportation Technology Center (TTC), Pueblo, Colorado, in June 2009.

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REFERENCES


TABLE 1. Defect Detection Reliability During March 2008 Field Test At Gettysburg, PA.

<table>
<thead>
<tr>
<th>POSITION FROM START</th>
<th>Surface cut (5% H.A)</th>
<th>Surface cut (2% H.A)</th>
<th>Internal defect (gage side, 3.6% H.A.)</th>
<th>Internal defect (gage side, 35% H.A.)</th>
<th>Oblique cut (3.5% H.A.)</th>
<th>Internal defect (center head, 12% H.A.)</th>
<th>Oblique cut (3.5% H.A.)</th>
<th>False positive %</th>
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<tr>
<td>POD (5 MPH)</td>
<td>100.0</td>
<td>97.7</td>
<td>100.0</td>
<td>100.0</td>
<td>81.8</td>
<td>95.5</td>
<td>84.1</td>
<td>100.0</td>
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<tr>
<td>POD (10 MPH)</td>
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<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>75.0</td>
<td>87.5</td>
<td>100.0</td>
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<tr>
<td>POD (Cumulative)</td>
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<td>98.1</td>
<td>100.0</td>
<td>84.6</td>
<td>92.3</td>
<td>84.6</td>
<td>100.0</td>
<td>1.1</td>
</tr>
</tbody>
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FIGURE 1: SAFE Results For Guided Waves In A 115-lb A.R.E.M.A. Rail At High Frequency: Mesh, Displacement Mode Shapes And Strain Energies For Two Wave Modes At 200 kHz.
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