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Research
Results

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On-line High-speed Rail Defect Detection

SUMMARY

The rail defect detection prototype, which is being developed by the University of California-San Diego (UCSD) under a Federal Railroad Administration (FRA) Office of Research and Development (R&D) grant, has produced encouraging results in recent field testing. The prototype was field tested at speeds of up to 10 mph in March 2008. The test track included three different sizes of internal head defects (3.5 percent, 35 percent, and 12 percent head area (HA)), two sizes of transverse surface head cuts (2 percent and 5 percent HA), and one size of oblique surface head cut (3.5% HA). The results of the tests revealed a high probability of detection for all defects present, ranging from a 75 to 100 percent success rate after 24 runs conducted in varying environmental conditions including wind and rain. The project goal is to develop a rail defect detection system that provides better defect detection reliability and higher inspection speed than is currently achievable. The primary target is the detection of transverse defects in the rail head. The method is based on ultrasonic guided waves, which can travel below surface discontinuities, hence minimizing the masking effect of transverse cracks by surface shelling. The inspection speed can be improved greatly also because guided waves run long distances before attenuating.

Recent work on the project was conducted on two fronts. First, a semi-analytical finite element (SAFE) method has been developed and applied to predicting unforced and forced guided waves propagating in rails. Second, a prototype based on noncontact excitation and detection of ultrasonic guided waves has been assembled and field tested in March 2008. The latest version of the prototype utilizes the results from the SAFE wave propagation models and features advanced statistical pattern recognition software to provide, in real time, the classification of (a) joints, (b) surface head shelling, and (c) internal head cracks. Further improvements are planned, including a faster laser to increase inspection speed up to 40 mph, better operational controls, repackaging for the harsh railroad environment, and installation on an FRA research vehicle for final field validation testing and technology demonstration.

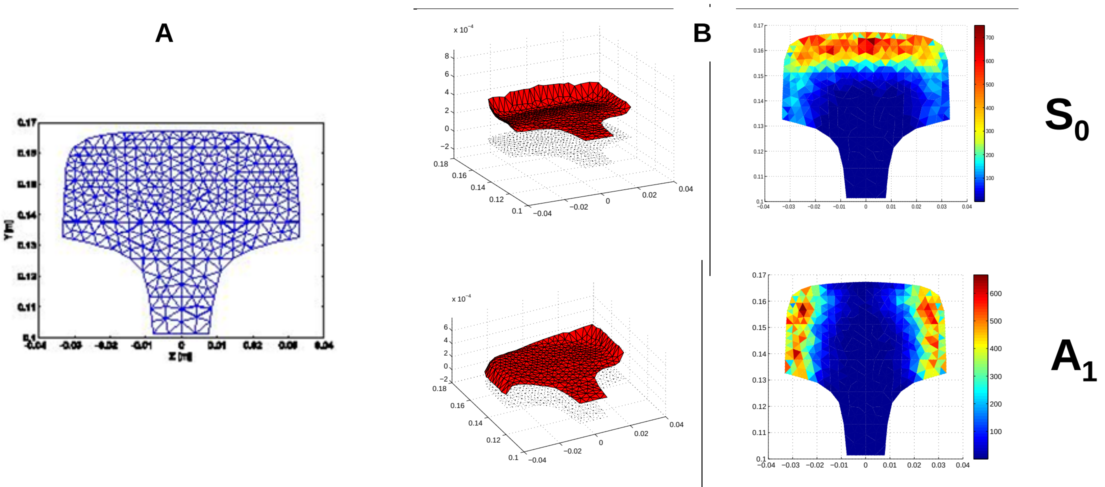


Figure 1. Waves in rails: mesh, mode shapes and strain energy for two wave modes at 200 kHz.

BACKGROUND

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 most serious drawback of this method is that shallow surface cracks (shelling) can mask the internal transverse defects. This limitation was the most likely cause of a train derailment in Superior, Wisconsin, in 1991, where an entire town had to be evacuated as a result of hazardous material spill. A second limitation is the low inspection speed, which results in limited range for conducting conventional rail inspection. The system under development, which is based on rigorous ultrasound propagation theory, noncontact ultrasound probing, and statistical pattern recognition, has shown promise for the classification of head cracks at speeds of up to 10 mph. The system was tested on transverse-type defects (TD), that during the decade 1992-2002 in the US were responsible for $162M in direct damage costs and 2,782 derailments according to FRA Safety Statistics Data. The system is in principle also sensitive to vertical split heads and compound fractures.

REPRESENTATIVE RESULTS

Models of Ultrasonic Guided Wave Propagation in Rails

Conventional finite element analysis (FEA) is not feasible to model ultrasonic wave propagation in rails because the short wavelengths involved would imply a prohibitively large number of degrees-of-freedom for the mesh (rule of thumb dictates at least ten elements per wavelength). An alternative method, called SAFE method, was used here to allow modeling high-frequency ultrasonic waves in rails in a computationally efficient manner. The SAFE method uses a finite element discretization of the cross-section of the rail alone, and imposes theoretical harmonic solutions along the rail running direction. Hence SAFE reduces a three-dimensional discretization problem to a two-dimensional one. SAFE wave solutions, in terms of wavenumber $k=2\pi/\lambda$ (λ = wavelength) and frequency ω, are found from the following eigenvalue problem:

$$(\mathbf{A}-k\mathbf{B})\mathbf{U}=\mathbf{p}$$

where the matrices A and B are related to the dynamic stiffness and mass matrices of the system, the vector U contains the nodal displacements and the vector p contains the nodal forces.

The rail response at a generic location $x=x_U$ to an external harmonic force applied at $x=x_F$, can be obtained in terms of displacements U as a linear combination of the eigensolutions (k_m-Q_m) for the mth mode:

$$\mathbf{U}=\sum_{m=1}^{M}\left(-\frac{\mathbf{Q}_m^L\mathbf{p}}{B_m}\right)\mathbf{Q}_m^{Rup}\exp\left[ik_m\left(x_U-x_F\right)\right]$$

where $B_m=Q_m^L B Q_m^R$, Q_m^L and Q_m^R represent the left and right eigenvectors, Q_m^{Rup} represents the upper part of the right eigenvector and i is the imaginary unit. The response to a generic force can be then obtained by combining the different harmonic responses in the spatial frequency domain (Fourier Transform).

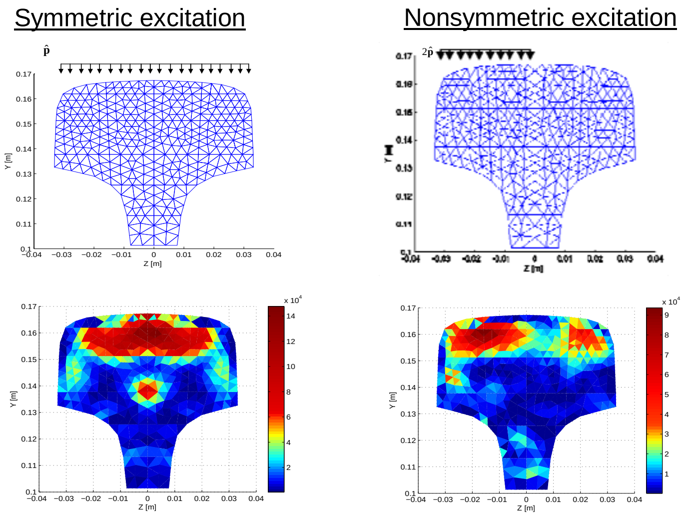

Symmetric excitation
Nonsymmetric excitation

Figure 2. Dynamic rail response to different patterns of broadband (laser) excitation.

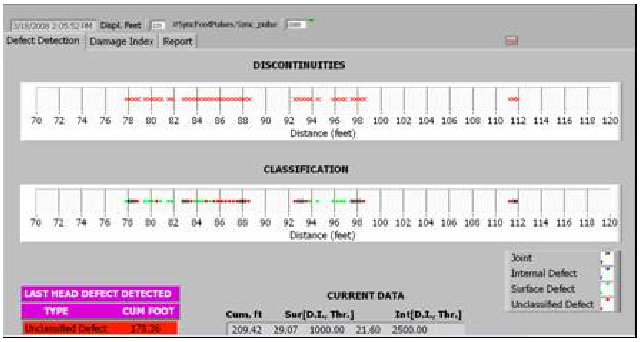
The SAFE method was applied to model ultrasonic waves propagating in 115 lb, American Railroad Engineering Maintenance-of-Way Association-approved rails. Figure 1 shows the mesh used for the rail, along with (a) mode shapes and (b) strain energy of a symmetric mode (S_0) and an antisymmetric mode (A_1) at a frequency of 200 kHz. The color plots indicate that these modes would be selectively sensitive to different head cracks. S_0 would be best suited for detecting center head cracks, whereas A_1 would be highly sensitive to gage- or field-side cracks in the head flanges.

SAFE was also used to study the waves excited in the rail by a broadband (i.e. laser) excitation having different patterns. Figure 2 shows the wave response to a symmetric (left) and to a nonsymmetric (right) laser excitation, at a distance of 4 in from the irradiation, in terms of wave strain energy. These results indicate that a symmetric excitation would be most sensitive to center head cracks, whereas a nonsymmetric excitation would be more sensitive to gage-side cracks.

Noncontact Guided-wave Rail Inspection Prototype

A prototype based on noncontact ultrasonic probing of the rail and advanced signal processing algorithms for real-time defect detection and classification was assembled and field-tested in 2007 and 2008 in Gettysburg, Pennsylvania. The ultrasonic excitation, detection, and processing are performed according to the SAFE model predictions to maximize the sensitivity of the prototype to (1) the presence of head cracks and (2) the type of head cracks (surface vs. internal). The field tests were carried out primarily on transverse-type defects, which were successfully detected at speeds about 10 mph. Figure 3 shows a picture of the prototype at the Gettysburg site. The prototype's software features an advanced statistical pattern recognition algorithm, which is based on two levels of defect classification. The first classification level identifies discontinuities in the track, while the second level flags each discontinuity as joint, surface defect, internal defect, or unclassified defect. The classification was implemented to minimize the chances of missing a defect (i.e., minimizing false negatives) and to provide the defect classification whenever possible. Figure 4 is a snapshot of the software's user interface showing the "defect detection" window during one of the test runs at the Gettysburg site.

Figure 3. Prototype hardware (left), with UCSD, ENSCO, and FRA personnel (right) at the Gettysburg site.



LAST HEAD DEFECT DETECTED
TYPE CUM FOOT
Unclassified Defect 178.36

CURRENT DATA
Cum. ft Sur[D.I., Thr.] Int[D.I., Thr.]
209.42 29.07 1000.00 21.60 2500.00

Figure 4. The defect detection window of the user's interface showing and joint classification

Table 1. Defect detection reliability during third field test (Gettysburg, March 2008).

Defect	Surface cut (5% H.A)	Surface cut (2% H.A)	Internal defect (gage side, 3.6% H.A.)	Internal defect (gage side, 35% H.A.)	Oblique cut (3.5% H.A.)	Internal defect (center head, 12% H.A.)	Oblique cut (3.5% H.A.)	
POSITION FROM START	81'_7"	82'_7.5"	86'_4"	91'_3.5"	95'_1"	96'_4"	97'_8"	**False positive %**
POD (5 MPH)	**100.0**	**97.7**	**100.0**	**81.8**	**95.5**	**84.1**	**100.0**	0.8
POD (10 MPH)	**100.0**	**100.0**	**100.0**	**100.0**	**75.0**	**87.5**	**100.0**	2.9
POD (Cumulative)	**100.0**	**98.1**	**100.0**	**84.6**	**92.3**	**84.6**	**100.0**	1.1

A summary of defect detection reliability determined from the March 2008 Gettysburg tests is given in Table 1. Clearly, the system showed good promise for the detection of surface and internal head cracks at speeds of up to 10 mph.

CONCLUSIONS

A rail inspection system based on ultrasonic guided waves and advanced signal processing algorithms is being developed at UCSD under FRA funding. The system is designed to probe the rail with ultrasonic modes particularly sensitive to certain types of head cracks as determined by rigorous numerical models of wave propagation in rails. The prototype was field-tested at speeds up to 10 mph in March 2008, on a track with known defects with promising results. Plans are in place for further enhancements, including increased speed up to 40 mph, final testing, and technology demonstration in the fall 2008.

ACKNOWLEDGMENTS

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