DETECTION OF TRANSVERSE DEFECTS UNDER SURFACE ANOMALIES

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ABSTRACT

Rail flaw detection has been an important maintenance-of-way tool in decreasing the number of in-service rail failures for the last 80 years. Ultrasonic inspection of rail steel has emerged as the predominate technique in non-destructive rail flaw inspection. One limitation of ultrasonic inspection of rail steel is surface anomalies which deflect the intended transmission path of the ultrasonic inspection beam. Rail surface anomalies most prominently include shells, engine burns, center rail spalling, slivers and head checking. These surface anomalies are known to initiate transverse defect development, which cause a high number of in-service rail failures. Another limitation of RSU based ultrasonic inspection is highly worn rail profile. The X-Fire™ product is targeted at reducing these limitations by means of transducers mounted in an RSU, with beam entry and angle optimized to allow the successful interrogation of the rail section beneath these abnormal rail surface conditions, and to reduce the effect of highly worn gage side rail profiles. To date we have demonstrated the X-Fire™ product to multiple Class 1 rail carriers with a high level of success. It is the intention of this paper to describe the X-Fire™ process, and show the results of the same. X-Fire™ truly possesses the ability to detect rail flaws in areas of the rail head that were previously hidden to standard rail flaw detection systems.
INTRODUCTION

The early detection of transverse defects in rail steel is an important tool in reducing service failures and resulting derailments in the rail industry. Transverse detail fractures, TDD’s, located off center of the rail head, are particularly difficult to detect using the industry standard ultrasonic transducer placement.

Detection of TDDs at the gage corners of the rail head is not easily accomplished due to the wear pattern which changes the geometry of the rail head. Other problems that affect the ability to find TDD’s are surface and subsurface anomalies that are produced during the normal service life of rail steel, and finally the orientation of the defect itself. Shelling, slivers, and head checking hinder the entry and exiting of ultrasonic energy at the gage side of the rail. This problem is most apparent when the ultrasonic beam is directly above the target of interest.

Transverse defect detection has long been on the Federal Railroad Administration list for research funding. A variety of techniques have been investigated ranging from low frequency eddy current, guided waves and laser induced ultrasonic’s. To date none of these techniques have been able to be used in routine flaw detection and survive the rigors of the railroad.

What is introduced here is the use of conventional ultrasonic transducers in an unconventional geometry. This is what Sperry Rail Service calls X-Fire™, pronounced cross fire.

IDENTIFICATION OF THE PROBLEM

The early detection of transverse defects in rail steel is of vital importance to the railway industry. Based upon FRA derailment data, over the past 9 years transverse defects have accounted for 43% of all derailments in the USA as shown in Figure 1. TDDs account for nearly half of these
derailments (18% of all derailments). The average cost of one derailment due to TDD’s is $730,000; however there is no upper bound on the liability of a single derailment.

![Graph showing % Derailments Due to TD’s](image)

**Figure 1 : TD Derailments in the USA vs. Year (FRA data)**

Therefore improvements in TDD detection were selected as a target for service failure reduction. It was felt that a supplementary transducer configuration was the best method of detecting more TDD’s. Typical service failures are shown in Figure 2.

![Typical Transverse Defect Service Failure](image)

**Figure 2 : Typical Transverse Defect Service Failure**
Detecting more TDDs meant dealing with multiple problems, specifically rail profile, surface and subsurface anomalies, and varying defect orientation.

**Rail Profile Problem**

Severe rail wear on the gage side of the rail changes the normal railhead profile. This change in profile alters the angle of the refracted beam as it enters the rail such that the ultrasonic beam is diverted from the intended path. This in turn affects the amount of signal that is returned from defects to the transducer, if at all. An extreme profile is shown in Figure 3 below. While Figure 4 shows that even with a more common profile that the 70 degree beam is deflected away from the transducer.

![Figure 3: Extreme Rail Profile](image)
Figure 4: Rail Profile with 70 Probe Reflected Sound Exit Point.

Sound is refracted in rail steel according to laws of physics (Snell’s Law). Following these laws, depending on the rail profile, all ultrasound energy that is introduced into the rail and reflected, does not follow the same path back to the origin. If the rail profile has even moderate levels of head wear there is a substantially reduced chance of detecting a TDD using the traditional transducer configuration.

**Surface and Subsurface Anomaly Problem**

Surface and subsurface anomalies such as shells, head checking, gage cornering cracking (GCC) and grease can mask TDDs from detection, particularly on the gage corner of the rail head.
Shell Problem

“Shelling is a progressive horizontals separation which may crack out at any level on the gage side, generally at the upper gage corner. It extends longitudinally, not as a true horizontal or vertical crack, but at an angle related to the amount of rail wear. Growth depends on the loading. The separation progresses in the path of least resistance. Shelling may turn down to form a transverse separation, in which case the defect would be classified as a detail fracture from shelling.” Figure 5 is a typical TDD under a shell.

![Figure 5: Typical Shell with TDD](image)

The location and geometry of shelling act as masking agents for ultrasonic beam introduced by the standard 70 degree transducer configuration. A TDD lying under a shell is often shielded from the ultrasonic beam by the horizontal separation of the shell and associated surface condition. The only chance the traditional 70 degree transducer has of detecting the TDD is if it is located at the extreme
end of the shell, and lies in an orientation that reflects energy back to the transducer. An example of this problem is shown in Figure 6.

**Head Check Problem**

Head check is a type of rolling contact fatigue. “Rolling contact fatigue (RCF) is a family of damage phenomena that appear on and in rails due to overstressing of the rail material. Head checks are fine surface cracks resulting from cold working of the metal under contact stress.” TDDs originating from head checking have had high profile derailments associated with them in recent
years. This can be traced back to the increase in both train traffic densities, and increased speed of the same.

![Figure 7: Typical Head Checking](image)

**Grease and Other Surface Irregularity Problem**

There are other factors which play a part in masking the detection of TDDs. Grease and rail grinding predominate on the gauge corner of the rail. The natural wear pattern of the rail tends to keep the center of the rail clear of these masking agents. This is a design factor in the development of the X-Fire™ transducer configuration.

**Defect Orientation Problem**

All TDDs do not lie in the rail head at the same plane. Early investigation and transducer development determined the best angle to find the majority of TDs was at 70 degrees. To reduce the noise from gauge related anomalies such as head checking and slivers, transducers were positioned to direct the beam along the length of the rail. By doing so, transducers orientated in this
way are limited to finding TDDs within a reduced angular deviation. The result is a subset of all TDDs evades detection using the standard array of three 70 transducers deployed 90 degrees to the length of the rail.

**Current methods of TDD detection.**

Generally three seventy degree transducers are used to segregate the head into three zones, the gauge, center and field. This standard orientation has been optimal for detecting defects oriented transverse to the rail; however it is affected by changes in rail profile and surface anomalies which interfere with the transmission of sound entering the rail. As discussed earlier transverse defect orientation also is a factor which determines the successful detection of the same.

**SOLUTION TO THE PROBLEM**

The solution to finding more TDDs, particularly under surface anomalies and curve worn rail was a combination of revisiting history, and taking a fresh look at an old problem. The work has culminated in a new transducer design, system modifications, and operator training.

**History**

Sperry Rail Service embarked on a 20 year engineering effort to find hard to detect TDD type defects. Initial transducer design and RSU wheel mounting were also developed during this period. Trials were conducted at its facility in Danbury CT and continued in the field. The original design was deemed to be too sensitive to gauge corner surface conditions. The present three transducer array at 90 degrees to the length of the rail is a result of this original work.

The Chinese Ministry of Rail has used skewed transducers in walking stick units to detect small detail fractures. In an effect to develop an automated method of detection we received five rails from the China Academy of Rail Science with TDDs that were particularly difficult to detect using conventionally accepted techniques. Using these rails as a basis we were able to study the best approaches to automating the process of detection.
One of the major problems of making a predictable test in rail steel is the rail head geometry always changing as a result of wear. As the rail head shape changes so does the sound beam as it enters the rail and is refracted according to laws of physics. All sound that is injected into the rail does not follow the same path back to the origin. This is the challenge when trying to optimize the detection of small TDDs. The center of the head usually has the most consistent geometry and generally does not have shells or head checking which interfere with introducing sound into the rail.

The solution to this problem is to position and orientate the entry point of the sound beam to maximize the amount of energy entering the rail regardless of the rail surface condition. The angle, position, and orientation of the sound beam of the X-Fire™ have been configured in just such a way as to maximize the clearest pathway to the target defects.

**X-Fire™ Transducer Design**

The X-Fire™ transducer design has taken into account all of the problem areas mentioned above, Rail profile, surface anomalies, and defect orientation. The new design has defined an optimized rail entry point, transducer angle, and skew.

**Entry point**

The entry point of the X-Fire™ transducer beam has been moved away from the rail outer edges toward the middle of the rail to eliminate surface anomalies and rail wear conditions which would otherwise block entry into the rail.

**Optimal angle**

The angle of the X-Fire™ transducers has been optimized to find the target TDs. The ability to find defects under shells requires the use of the second leg and therefore the transducer has been optimized to maximize from the second leg, while still having the ability to use the first.
**Skew**

The skew angle of the transducer has been optimized to find defects that the standard DF transducer would normally not “see”. This fills the gap that the original historical X-Fire™ design attempted and failed. The new X-Fire™ design is an optimization of the ultrasonic entry point, angle and skew to avoid surface anomalies but also allows the detection of oddly oriented transverse defects.

The X-Fire™ transducer orientation is shown in Figure 8. The transducers incorporated into a production ultrasonic wheel are shown in Figure 9.
System Changes

The X-Fire™ product consists of transducer design and changes to the detection system to accommodate the same. These system changes include data display, and detection algorithms.

Display of data

Integral to the success of the X-Fire™ project was the ability to display the resulting data in a form to which the operator could readily relate. The new X-Fire™ data has been geometrically corrected and displayed in a bright new color scheme in the same data set as the other ultrasonic information. This allows the operator to see other ultrasonic and induction channel data in the same collaborative display. The nature of the TDD formation and often its close proximity to surface anomalies make this collaborative channel display helpful in many cases. In other cases the X-Fire™ is the only
channel that gets a return from the TDD. This is not surprising due to the defect orientation in the rail and rail profile at the point of the defect. The BSCAN images are shown in Figure 10. One shows the original 70 BScan presentation, the second the new color and shape of the X-Fire BScan presentation.

Figure 10: Current 70 BSCAN vs. X-Fire™ BScan Indications

Figure 11 shows a full BScan image showing typical responses to rail reflectors, such as bolt holes, and rail head reflectors.
Defect algorithm.

Since the test system already utilizes 70 degree transducers and complimentary induction channels the defect detection algorithms can use the combination of all of these channels to make defect decisions. This has been done and benefits derived.

**X-Fire™ Specific Training**

When a new piece of equipment has been entered into service there is a level of training and support that goes with it. In the case of the X-Fire™ project the method of hand testing has been adjusted to make the operator aware of the peculiarities of the defects now being detected. The adjustments include the skew of the hand held transducer and the depth that the defect was
detected at. Since many of the defects are being detected much deeper (second leg) the hand test procedure has been adjusted to repeat this.

**Hand Test**

Verification of TDDs under surface anomalies offers its own challenge as anyone in the industry can attest to. The hand test for suspected defects under shell and head checking are no exception. The following hand test techniques are helpful when making the final determination if a defect resides under a surface anomaly.

**Across head**

Some TDD defects can be verified during the hand test by use of a 45 degree probe across the width of the rail head. This technique has been added to the set of tools used during verification of X-Fire™ defects.

**Position of Entry into rail and Skew.**

The operator is briefed on the entry point and the skew of the X-Fire™ ultrasonic beam. This is helpful during hand test to keep him away from surface anomalies which would block his hand test and introduce surface signals that could result in misleading back reflections.

**Dampening surface waves.**

In areas where defects are to be found under shells and other surface anomalies, the technique of dampening surface waves that might be produced during the hand test is a point of emphasis. In this way potentially misleading signals from these artifacts can be identified.

**VALIDATION OF RESULTS**

The results of the X-Fire™ RSU have been monitored over 78,000 miles of Class 1 railroad main line and secondary track (Data up to January 2009). Over twenty vehicles and 5 railroads
contributed to the data set. The results have been surprising not just in the initial increase in TDD detection rate but in the continuation of TDD detection.

WHAT LONG TERM RESULTS HAS THE SOLUTION HAD?

Over 78,000 miles and nearly 2000 X-Fire™ TDD detected resulting in an over 30% increase in TDD detection compared to the same equipment without X-Fire™. The data contained in Table 1 documents the performance of the X-Fire™ equipment.

Table 1 : Test Vehicle Performance with X-Fire™

<table>
<thead>
<tr>
<th>Car</th>
<th>Miles</th>
<th>Total Defects</th>
<th>Total DF’s</th>
<th>X-Fire™ DF’s</th>
<th>Defect per Mile DF’s per Mile X-Fire™ DF’s % X-Fire™ to DF’s</th>
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<tbody>
<tr>
<td>SRS_1</td>
<td>9,276.19</td>
<td>1534</td>
<td>569</td>
<td>172</td>
<td>0.165 0.061 0.019 30%</td>
</tr>
<tr>
<td>SRS_2</td>
<td>9,025.54</td>
<td>910</td>
<td>538</td>
<td>143</td>
<td>0.101 0.060 0.016 27%</td>
</tr>
<tr>
<td>SRS_3</td>
<td>7,421.46</td>
<td>1169</td>
<td>358</td>
<td>135</td>
<td>0.158 0.048 0.018 38%</td>
</tr>
<tr>
<td>SRS_4</td>
<td>3,524.53</td>
<td>621</td>
<td>391</td>
<td>138</td>
<td>0.176 0.111 0.039 35%</td>
</tr>
<tr>
<td>SRS_5</td>
<td>714.88</td>
<td>128</td>
<td>56</td>
<td>29</td>
<td>0.179 0.078 0.041 52%</td>
</tr>
<tr>
<td>SRS_6</td>
<td>3,049.88</td>
<td>741</td>
<td>203</td>
<td>77</td>
<td>0.243 0.067 0.025 38%</td>
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<td>SRS_7</td>
<td>4,835.27</td>
<td>1579</td>
<td>805</td>
<td>282</td>
<td>0.327 0.166 0.058 35%</td>
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<tr>
<td>SRS_8</td>
<td>2,427.54</td>
<td>395</td>
<td>141</td>
<td>13</td>
<td>0.163 0.058 0.005 9%</td>
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<tr>
<td>SRS_9</td>
<td>2,521.11</td>
<td>538</td>
<td>229</td>
<td>41</td>
<td>0.213 0.091 0.016 18%</td>
</tr>
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<td>SRS_10</td>
<td>4,144.01</td>
<td>670</td>
<td>187</td>
<td>58</td>
<td>0.162 0.045 0.014 31%</td>
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<tr>
<td>SRS_11</td>
<td>3,730.14</td>
<td>594</td>
<td>215</td>
<td>54</td>
<td>0.159 0.058 0.014 25%</td>
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<tr>
<td>SRS_12</td>
<td>3,271.51</td>
<td>395</td>
<td>209</td>
<td>30</td>
<td>0.121 0.064 0.009 14%</td>
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<tr>
<td>SRS_13</td>
<td>4,510.11</td>
<td>550</td>
<td>238</td>
<td>58</td>
<td>0.122 0.053 0.013 24%</td>
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<tr>
<td>SRS_14</td>
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<td>353</td>
<td>221</td>
<td>76</td>
<td>0.171 0.107 0.037 34%</td>
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<tr>
<td>SRS_15</td>
<td>1,701.84</td>
<td>242</td>
<td>72</td>
<td>24</td>
<td>0.142 0.042 0.014 33%</td>
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<tr>
<td>SRS_16</td>
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<td>374</td>
<td>187</td>
<td>96</td>
<td>0.299 0.150 0.077 51%</td>
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<tr>
<td>SRS_17</td>
<td>795.96</td>
<td>313</td>
<td>52</td>
<td>7</td>
<td>0.393 0.065 0.009 13%</td>
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<tr>
<td>SRS_18</td>
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<td>692</td>
<td>349</td>
<td>118</td>
<td>0.405 0.204 0.069 34%</td>
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<tr>
<td>SRS_19</td>
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<td>672</td>
<td>276</td>
<td>77</td>
<td>0.394 0.162 0.045 28%</td>
</tr>
<tr>
<td>SRS_20</td>
<td>4,282.17</td>
<td>1314</td>
<td>485</td>
<td>80</td>
<td>0.307 0.113 0.019 16%</td>
</tr>
<tr>
<td>SRS_21</td>
<td>2,989.96</td>
<td>137</td>
<td>33</td>
<td>10</td>
<td>0.046 0.011 0.003 30%</td>
</tr>
<tr>
<td>SRS_22</td>
<td>3,812.27</td>
<td>511</td>
<td>347</td>
<td>195</td>
<td>0.134 0.091 0.051 56%</td>
</tr>
<tr>
<td>Totals</td>
<td>78,758.19</td>
<td>14,432.00</td>
<td>6,161.00</td>
<td>1,913.00</td>
<td>0.183 0.078 0.024 31%</td>
</tr>
</tbody>
</table>

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A sustained increase of 30% TDD detection rate has been attributed directly to the addition of X-Fire™ equipment to the Ultrasonic transducer configuration. The continuation of this 30% detection increase is interesting and points to the origin of the TDD, which is from rail wear components (example: shells and head checking) rather than inherent manufacturing process defects.

**Monitoring Field Results**

Field TDD detection rate data has been accumulated and made available for customer review since the inception of the X-Fire™ project. A product manager was assigned to the task to oversee not just the installation but the overall performance review and data integrity. We feel confident on the success story told by the data we have compiled and maintained over the last two years.

*Data Gathering and analysis*

X-Fire™ TDD data was analyzed on an individual defect basis, with cooperation of field operatives and the Sperry Rail Service information services department. Quarterly review meetings with customers were conducted to detail the progress and keep everyone abreast of the status of the X-Fire™ project.

**Rail Breaking**

At the beginning of the X-Fire™ project and continuing on into project time line as new systems were deployed, rail breakings were conducted at Sperry Rail Service facilities and customer sites.

The rail breakings were used both to validate the authenticity of defects and to train operators in the TDD formation and location relative to abnormal surface conditions. Examples from these rail breakings are in Figures 12 and 13.
Figure 12: Reverse Detail Fracture (TDD)

Figure 13: Detail Fracture (TDD) Under a Shell
PLANNED REFINEMENTS FOR THE FUTURE

The X-Fire™ project has been a very successful one, resulting in better TDD detection and a decrease in rail service failure rates. The project continues in the laboratory where refinements in mechanical packaging and other aspects are being looked at.

The angle of the X-Fire™ has been optimized for detection of TDD’s but not without some compromises in the potential for unwanted response from surface irregularities. Work continues to characterize and fully understand this component of the X-Fire™ Ultrasonic beam profile.

Sperry is focused on enhancing the existing capabilities of the X-Fire™ RSU both for the North American and World markets. There are also plans to extend the technology into other areas of business operations, for example Sperry has developed a special walking stick version of the existing X-Fire™ to supplement its manual rail inspection service. This technology will also be used to help with the detection of transverse defects that propagate from gauge corner cracking (GCC) or rail contact fatigue (RCF) on European railroads.

CONCLUSIONS

This technology is providing a new means of detecting defects that were previously were not possible. Clear evidence of this capability has been demonstrated by breaking rails of marked defects for several railroads. Not only has it shown that defects under shells, engine burns, spalling, and head checking can be found but substantially smaller defects can be detected.

This technology is less affected by the rail profile than conventional 70 degree probe detection techniques as evidenced by verified X-Fire™ only indications.
Introduction of the new technology initially resulted in about a 50% increase in TDD detection. After removal of these previously undetected defects the number of detections remains about 30% higher than with conventional technology.

In conclusion, the new X-Fire™ technology has proven itself in real world rail testing conditions providing the ability to detect defects under shells, engine burns, spalling and head checking. The technology continues to impress with its increase in TDD detection.
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References

1 Data provided by US Dept. of Transportation, through 2008.
3 Excerpt from : “Development of Rolling Contact Fatigue (RCF) and its Prevention”, a paper presented by Vinod Bhangale, Sr. DEN/N/Nagpur, C. Railway Ashok Kumar, DEN/Track, Delhi, N. Railway, Shiv Om Dwivedi, XEN/Const., N.Railway