Examination of Performance Capabilities and the Potential Role of the Robust Laser Interferometer (RLI) with Respect to Health Monitoring and Diagnostics of Railroad Transportation Infrastructure

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AREMA 2004
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ABSTRACT

Over the past decade, a Research and Development (R&D), Robust Laser Interferometer (RLI) has been employed in a variety of transportation component health measurement situations, and in a variety of functional measurement situations of potential significance for transportation infrastructure system health. Examples of RLI measurement data are taken from gearboxes and turbine jet engines in test cell measurements and from laboratory measurements that involve both controlled and empirical experiments. This data demonstrates the inherent ability of an RLI to obtain wideband (0 Hertz to over 500 kHz) and large dynamic range (up to 180 dB demonstrated in acceleration) measurement information.

Application of correct sensing provided by an RLI system gives the railroad community an available means to obtain information on the railroad transportation infrastructure [rail track, rail wheel (flats) and wheel bearing health] from RLI measurement data, including performance (health and stress) monitoring, diagnostics and prognostics.

While remaining work is required to mature the specific configuration, a recommended system design choice is selected and rationalized for introducing a new generation of “Advanced Health and Usage Monitoring Systems”.
INTRODUCTION

This paper examines the performance capabilities and a potential role for a system referred to as the Robust Laser Interferometer (RLI) with respect to health monitoring, diagnostics and prognostics for elements of the railroad infrastructure. The RLI, which has been demonstrated to provide wideband (0 Hertz to over 524,000 Hertz), large dynamic range (over 180 dB demonstrated in acceleration and displacement) measurement of displacement, velocity and/or acceleration of a surface, has been employed in a variety of transportation component health measurement situations, and in a variety of functional measurement situations of potential significance for transportation infrastructure system health. Examples are taken from measurements of gearboxes and turbine engines in test cells, field testing relative to bridge displacement and from IR&D (Independent Research and Development) laboratory measurements.

There is a long and notable history of technologies being shared among various elements of the transportation infrastructure, as noted in Figure 1.0. In times past, shared technologies ranged from the wheel through turbine prime movers. In current times, sophisticated materials, sensing/control technologies and modern computer and communications technologies are common to multiple elements of the transportation infrastructure. Looking to the future, it is suggested that additional shared technologies will be related to increased reliance on modern diagnostics and prognostics capabilities. The RLI measurement capability is one example of a significant enabling technology that could support this trend.

<table>
<thead>
<tr>
<th>Times Past -- wheel to turbine engine to…</th>
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<tr>
<td>Current Times -- examples from ‘times past’ plus materials, sensing/control technologies to…</td>
</tr>
<tr>
<td>Times Forward -- examples from ‘times past’ plus ‘current times’ plus increased reliance on modern diagnostics and prognostics to…</td>
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Figure 1.0  History of Shared Technologies in Transportation
**RLI SYSTEM DESCRIPTIVE SUMMARY**

Figure 2.0 provides summary system descriptive information for the RLI measurement system. A Laser Interferometer (LI) compares a reflected signal from a surface with the transmitted signal to, e.g., measure motion. The R for Robust in the Epoch Engineering IR&D developed LI was selected as the means to describe the design approach that enables measurement of small movements (i.e., $<10^{-11}$ meters) in the presence of large movements ($>1 \times 10^{1}$ meters). [The “high frequency” end of the displacement spectrum shown in the lower right corner of Figure 2.0 illustrates a displacement noisefloor approaching $10^{13}$ meters, i.e., less than one-millionth of one-millionth of a meter].

In addition to the wideband (0 Hertz to hundreds of kilohertz), larger dynamic range ($> 180$ dB demonstrated) measurement capability, the RLI system provides a variety of analysis/display options, including spectrums, time series and envelope detection. The RLI capability has been successfully demonstrated in “point-and-shoot” and “fiber-optic routed” configurations. Implementation of an RLI system involves use of a laser, optics and computer technology – all 21st century building blocks with substantial potential for additional performance gains and cost reduction. Reference 1 provides additional baseline information. Additional references and a bibliography are available.

**COMPARISON WITH CONTACT ACCELEROMETERS AND ACOUSTIC EMISSION SYSTEMS**

Over the past decade, numerous side-by-side measurements have been made employing the RLI system and piezoelectric contact measurement systems. Figure 3.0 provides brief information regarding comparison of RLI measurements with those outlined from a quality accelerometer system. At low frequencies, RLI can provide measurement information not available from the contact accelerometer system. As an example, the data on the right side of Figure 3.0 illustrates that, in side-by-side measurements in a rotorcraft gearbox test cell, the accelerometer was incapable of identifying the first 10 (or so) harmonics of the main rotor rotational speed. (reference 2). At frequencies within the advertised accelerometer systems’ measurement bandwidth, the RLI system provides the desired information without concerns such as “mass loading”,...
**LI** - Laser Interferometer - compares a reflected signal from a surface with the transmitted signal to obtain information (e.g., measure motion)

**R** - Robust - EEI's LI has been designed robust so that it can measure small movement (i.e., $<10^{-11}$ meters) in the presence of large movements (i.e., $> 1 \times 10^{-7}$ meters)

**RLI provides:**
- wideband, non-contact measurement of displacement, velocity and acceleration (0.0 Hz to 524 kHz+)
- large dynamic range (up to 180 dB demonstrated)
- analysis capability (spectrums, time series, envelope detection,...)

RLI employs only a laser, optics and computer technology -- all 21st century building blocks because of their performance and reduced costs in quantity applications.

RLI is available in "point-and-shoot" and "fiber-optic routed" configurations. (Reference 3.0)

Additional References and Bibliography available

Figure 2.0 Robust Laser Interferometer (RLI) System Descriptive Summary
• At low frequencies, RLI can make measurements not available with contact accelerometer systems;

• At modest frequencies (advertised accelerometer system bandpass), RLI provides the desired measurement information without concerns such as “mass loading,” EMI, or the need for corrections as functions of frequency or temperature at the measurement point:

• At higher frequencies, RLI provides the information simply not available when employing contact accelerometer systems:

• No contact accelerometer system provides information over the RLI demonstrated bandwidth (0 Hertz to 524,000 Hertz+);

• RLI, with its large dynamic range, is more user friendly (i.e., no “a priori” range settings); and

• Contact accelerometer systems currently operate at or near their performance limits; RLI has substantial growth potential.

Figure 3.0 Brief Comparison with Contact Accelerometer Systems
EMI, or the need for corrections as a function of frequency or temperature at the measurement point. At higher frequencies, RLI provides the measurement information simply not available from employing piezoelectric accelerometer systems. No contact accelerometer system provides information over the RLI demonstrated bandwidth (0Hertz to hundreds of kilohertz). With its larger dynamic range and thoughtfully developed software, RLI is more user-friendly (i.e., no need for ‘a priori’ range settings; system autoscales;…). Accelerometer systems currently operate at or near their performance limits; in sharp contrast, RLI has substantial growth potential.

Figure 4.0 presents a brief summary regarding the RLI Acoustic Emission (AE) measurement capability versus that available from a contact piezoelectric AE system. In laboratory investigations, piezoelectric AE sensing was never singularly informative in spectrum output, while the RLI AE spectrum output always faithfully recorded the test scenario reality. [Details are provided in the reference items 1.0 and 6.0]. The ability of the RLI measurement system to provide faithful recording of reality provides unprecedented measurement potential for the mechanical aspects of systems. The data on the right of Figure 4.0, e.g., illustrates the substantial differences in the modulation of AE for a turbine engine under two different levels of engine stress. [The data is envelope processed. It is significant to recognize that the amplitude of the ordinate varies by over 100, providing a “strong observable”. Details are provided in reference 1.0].

EXAMPLES

Examples of RLI system strengths beyond the capability of legacy vibration and AE measurement systems are briefly noted in Figure 5.0. The first example provides insight into the RLI low frequency measurement capability. In particular, measurement ‘down to dc’, (i.e., “displacement”), was provided for the Rahall Transportation Institute (reference 4.0). The RLI system was under a CSX bridge in the Huntington, WV area, with the train traveling at approximately 23.4 miles per hour. An example of a large dynamic range in
In laboratory investigations, piezoelectric AE sensing was never singularly informative in spectrum output, while RLI AE sensing always faithfully recorded the (test scenario) reality. (Refs. 1 - 3)

Unprecedented measurement of Mechanical System Stress. (Ref 1)

References:

1 - 2004 IEEE Paper: “Performance Comparison of Robust Laser Interferometer (RLI) and Contact Accelerometer Technology in Aviation Health Monitoring”

2 - “Acoustic Fault Detection for Rotorcraft Transmissions and Engines”

3 - IR&D Unpublished Test Data

Figure 4.0 Brief Comparison with Contact Acoustic Emissions (AE) Sensing
Figure 5.0 Examples of Strengths Beyond Legacy Vibration/AE Measurement Capabilities

A single measurement is provided for a rotorcraft gearbox (references 2.0 and 7.0). The particular measurement includes an acceleration component at +30g in the presence of acceleration @ −150g at a low frequency. High frequency measurements with RLI have included vibration measurement information related to both high frequency ‘harmonics’ of the ‘equipment design signature characteristics’ and AE. The AE/high frequency example included in Figure 5.0 illustrates RLI measurement of AE for NASA, where it was demonstrated that RLI measured AE provides pre-fire alertment (i.e., substantial AE before the outbreak of fire). Reference 8.0 applies.

STATUS

RLI status is summarized in Figure 6.0. There is one IR&D RLI unit. It has been employed for a large variety of empirical and controlled ‘knowledge development’ investigations, with many identified as
references in this paper. RLI development is continuing, and it is suggested that potential applications include those related to health monitoring, diagnostics and prognostics efforts associated with railroad infrastructure protection. Also, in addition to providing higher quality information in situations where the RLI measurement capability might replace legacy vibration and AE accelerometer systems, it is suggested that entirely new roles should be pursued. These are of both a ‘niche’ and ‘integrated’ nature. Niche capabilities could include monitoring crack nucleation and growth, monitoring the health of electrical system wiring, or providing a pre-fire alertment. An ‘integrated’ capability could include providing a variety of capabilities all with one “engineered product”. References 9.0 and 10.0 apply. The data on the right side of Figure 6.0 provides an indication of the “RLI measurement playing field”. [The nomograph used is common to sensing products, and is often used in sales literature. When velocity is plotted against frequency, the slopes provide displacement and acceleration]. The dark portion illustrates ‘normal vibration’ measurements, as identified from the text noted on the figure. The “Xs” identify the positions on the expanded nomograph (Figure 6.0 right side) where RLI measurements have been made.

TYPICAL FUNCTIONAL (RAILROAD) INFRASTRUCTURE AREAS FOR POTENTIAL RLI APPLICATIONS

Figure 7.0 lists typical candidate (railroad) functional infrastructure areas for potential RLI applications.

Rail health is fundamental. An obvious measure of rail health is AE, as AE is generated by crack nucleation, microcrack growth and macrocrack growth. With RLI providing an unprecedented AE measurement capability, employment of RLI for rail health monitoring provides one valuable candidate for consideration. RLI bearing health monitoring is the “natural” from more than one perspective. For example, there is a history demonstrating the ability of the RLI measurement capability providing notable bearing health information for “deep seated bearings” (references 1.0 and 6.0). Also, RLI has a bandwidth that enables direct observation of indicators of bearing health that fall outside of the bandwidth of, e.g., accelerometer systems. RLI monitoring of wheel health offers choices, and much depends upon the interest of the information user. For example, the broad RLI bandwidth enables choices from simple “audio” (akin to a microphone or accelerometer system) through AE approaches aimed at assessing damage. Structural health is ordinarily monitored with a variety of technologies, including AE.
History of empirical and controlled measurements

One “aging” Research & Development unit

Development continuing

Assessed to be capable of supporting both “Niche” and “Integrated Monitoring” needs (references 9.0 and 10.0)

Niche Examples

- Crack monitoring
- Electrical wiring health
- Pre-fire alertment

Integrated Examples

Using one RLI for crack monitoring, electrical wiring health, pre-fire alertment, ...

Figure 6.0 Status

Addressing the potential of RLI in detail in this one area could require “volumes” of data: at a minimum, it should be noted that RLI is assessed to have substantial potential in this area, and further that such potential could be of value for the railroad infrastructure for monitoring and protecting high value assets beyond rails. Systems associated with handling hazardous materials come to mind. RLI could likewise have a role in abuse protection, providing critical measurement information ranging from weighing mobile cars (reference 4.0) through providing protection information as part of a security system. Processing and management software could be added to an RLI computer to augment the basic RLI technical capability. This could enable matching RLI test capability with selected asset maintenance levels (e.g., truck assemblies). A research and test capability is available with the RLI.
### Functional Area | Potential Application Consideration
--- | ---
**Rail Health** | Mobile configuration for Acoustic Emissions (AE) monitoring of crack nucleation and crack growth.
**Bearing Health** | Wideband (0 Hertz to hundreds of kilohertz), non-contact monitoring of bearings operational condition.
**Wheel Health** | Selected bandwidth(s), (audio through Acoustic Emission frequencies), monitoring of wheel geometries and health.
**Structural Health** | Monitoring relative to the health of high value/critical assets such as those associated with hazardous material.
**Abuse Protection** | ‘RLI based scale’, Component of security systems;…
**Selected Maintenance Levels Unit Health** | Monitoring health of units at interchangeable maintenance unit level, (e.g., truck assembly).
**Research and Test** | “Hip-pack”, handheld, lightweight, field portable RLI capability; Support for investigations related to seismic concerns, track geometry or any other situation where precise displacement, velocity or acceleration information is sought.

Figure 7.0 Typical Functional Areas for Potential RLI Application

Repackaged, RLI could be provided as a “hip-pack” handheld, field portable measurement instrument. RLI research and test configurations could be employed for a variety of technical investigations that are dependent upon correct measurement of displacement, velocity and/or acceleration. Track geometry, lubrication measurement issues and seismic concerns come to mind as areas of potential interest.

**RECOMMENDED SYSTEM DESIGN**

If RLI is to provide a meaningful candidate for railroad adaptation of non-railroad developed technology, focus on a single application is recommended. A recommended starting point would involve investigation of an RLI dedicated rail health monitoring system, as noted in Figure 8.0. This concept would involve deployment from a moving platform, either a special test vehicle or a ‘platform of opportunity’ adaptation of the technology. Rail health focus would be developed around the utility of AE information for detecting crack nucleation, as well as monitoring microcrack and macrocrack development. Schijve’s scale of crack...
nucleation, on the bottom of Figure 8.0, was initially developed for non-railroad purposes (primarily aviation structural health concerns). However, it illustrates the point that AE is considered useful over the entire range of initial crack detection through failure. While complex and possibly difficult at first, it is suggested that such a recommended ‘niche’ RLI system design, once successfully developed, could provide a meaningful capability. The statement from reference 11.0 leading Figure 9.0, namely that “Internal defects actually experience a growth in size, although the type of growth cannot be classified, nor the defect size measured (except by hand test) until the rail is broken to show the face of the defect. Furthermore, this classification and measurement is only possible for those defects which are transverse.” underwrites the potential value of such a measurement system for rail health monitoring, diagnostics and eventually prognostics. With correct exploitation of AE, it is not necessary to wait until “the rail is broken”. The concept is further illustrated on the lower left hand portion of Figure 9.0. Success would depend on establishing a capability that would take advantage of a ‘sound short’ through the rail, wheel, bearing and structure to the measurement point on the structure. The experiences from a parallel monitoring test where AE was tracked over time, noted on the lower right of Figure 9.0, (reference 12.0) argue well that this suggested approach, carefully implemented, could provide an initial new capability based upon non-railroad developed RLI technology.

REFERENCES

1. “Performance Comparison of Robust Laser Interferometer (RLI) and Contact Accelerometer Technology in Aviation Health Monitoring”, IEEE 2004 Paper.

- Dedicated Rail Health Monitoring System
- Deployed on Mobile Platform(s)
  - Special Purpose
  - “Platforms of Opportunity”
- Focus on ‘Acoustic Emissions’ (AE)
  - Crack Nucleation
  - Microcrack Growth
  - Macrocrack Growth
- Complex, but meaningful, “Niche” application

Schijve's Scale of Crack Dimension

Figure 8.0 Recommended System Design


“Internal defects actually experience a growth in size, although the type of growth cannot be classified, nor the defect size measured (except by hand test) until the rail is broken to show the face of the defect. Furthermore, this classification and measurement is only possible for those defects which are transverse.”

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<thead>
<tr>
<th>Concept</th>
<th>“Parallel” from RLI Measurement History</th>
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<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
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Sound Path - Detect AE through rail to wheel through bearing to measurement point on a structure.

Sound Path - AE through bearing outer race (and housing) through or along the oil pipe to measurement point on the outer surface of the engine.

Figure 9.0  Today

5. IR&D Laboratory Data


