TITLE: Robust Laser Interferometer [RLI] Findings Relative Condiiton Monitoring and Diagnostics/Prognostics Engineering Management

ROBUST LASER INTERFEROMETER (RLI) FINDINGS RELATIVE CONDITION MONITORING AND DIAGNOSTICS/PROGNOSTICS ENGINEERING MANAGEMENT

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"Abstract" In recent years, a series of machinery condition and/or machinery health measurement projects have employed a Robust Laser Interferometer (RLI), a non-contact vibration measurement systen introduced for wideband vibration measurements. The specific implementation is described. Wideband (0-262.144 kHz), large dynamic range (up to 180 dB demonstrated in acceleration) measurement data is presented for differing machinery monitoring measurement projects. A discussion is presented regarding not only the availability of high frequency information, but also regarding its value for diagnostics and prognostics. Examples selected include direct spectrum/time series information, as well as envelope processed information.

System advantages are discussed in terms of dynamic effects, environmental effects, and ease of use. Specific examples and measurement history are provided to highlight individual parameters such as bandpass, sensitivity/signal-to-noise, dynamic range, amplitude frequency response, low frequency performance, high frequency performance, and user friendliness in the vibration measurement scenario.

Invited paradigm shifts are discussed, including the availability of improved "fault inception" tracking data and new measurement opportunities. Two implementation design approaches are discussed, point-and-shoot and fiber-optic routing. A summary is presented, including an assessment of growth potential.

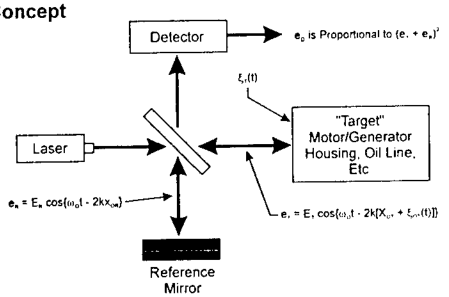
Key Words: Diagnostics; measurements; prognostics; vibration

1.0 Introduction

1.1 Concept: In recent years, a series of machinery condition or machinery health measurement projects have employed a Robust Laser Interferometer (RLI), a non-contact vibration measurement system developed by Epoch Engineering, Inc. (EEI). The concept of laser interferometry is illustrated on the left half of Figure 1.0. As noted in this figure, a laser interferometer is conceptually similar to a Doppler radar, comparing a reflected signal from the monitored point with the transmitted signal. The difference in the signals contains the desired information.

RLI - Robust Laser Interferometer

Concept



LI - Laser Interferometer:

Works much like Doppler Radar; it compares the reflected signal from the target (which has been modified by target motion) with the transmitted signal: the difference in signals (i.e., transmitted versus reflected) is a measure of target motion.

Implementation

- Wideband, Non-Contact Vibration Measurements (0.0 Hz to 524 kHz)
- Large Dynamic Range (up to 180 dB demonstrated in acceleration)
- Time Series Analysis
- Spectral Analysis
- Multiple Data Formats
  - Displacement
  - Velocity
  - Acceleration
- Other Post Processing Algoithms such as Envelope Detection

R - Robust:

EEI's LI has been designed robust so that it can measure small movements (i.e.< 10-11 meters) in the presence of large movements. (i.e.> 1 x 10-1 meters)

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Figure 1.0 System

1.2 Implementation: EEI's laser interferometer has been designed robust so that it can measure small movements (i.e., $<10^{-11}$ meters) in the presence of large movements (i.e., $>1\times10^{-1}$ meters). With the exception of the laser system, the RLI is self-contained in a rack-mounted Pentium II based PC. The master clock for data acquisition is a high resolution 10 MHz clock crystal. A Microsoft operating system is used. The laser system is an EEI-modified commercial system. The Laser Interferometer Head (LIH) for the system is connected to its pre-processing and support electronics module by a 20-foot cable, allowing great freedom in positioning the LIH. For test cell measurements, the monitor, keyboard and mouse to control the system were often located remotely, connected by up to 300 ft of CAT-5 cable. The RLI system design provides the following capabilities:

a. Wideband measurements (0.0 Hz to 524 kHz)
b. Large Dynamic Range (up to 180 dB previously demonstrated in acceleration)
c. Time Series Analyses
d. Spectral Analyses
e. Multiple Data Format - (1) Displacement, (2) Velocity, (3) Acceleration
f. Post Processing

2.0 Wideband, Large Dynamic Range Measurements

2.1 Bandwidth: RLI measurement projects have been conducted for the Nuclear Regulatory Commission (NRC), the US Army, the US Navy, and the US Air Force, inter alia. Examples included in the remainder of this paper were selected from the projects documented in the bibliography for this paper. Figure 2.0 illustrates wideband spectrum examples from a typical RLI rotorcraft gearbox measurement (left side) and a typical turbine engine measurement (right side). The gearbox spectrum, from measurements in a Sikorsky Aircraft test cell, is from 0 Hz to 262.144 kHz. Harmonics of an input gear mesh fundamental are readily visible in the spectrum to well over 200 kHz. Strong sidebands are also evident. The turbine engine spectrum, from Joint Strike Fighter seeded fault testing at Pratt and Whitney, FL. is also shown in Figure 2.0. The measurement point is at the end of an oil line, approximately 17 inches from the turbine engine bearing #1 being monitored. The RLI broadband measurements on this case were also from 0 Hz to 262.144 kHz. Substantial character can be noted in the spectrum, particularly below 50 kHz. In recent measurements associated with rotorcraft hanger bearing health monitoring, RLI broadband data from 0 Hz to 524 kHz was utilized (see reference [1]).

2.2 Dynamic Range: In the course of taking measurements on an S-61 rotorcraft gearbox in a test cell, the RLI has demonstrated the ability to measure a vibration in excess of 30 dB relative to one g, in the presence of an observed noise floor at a lower frequency of about -150 dB relative to one g, as illustrated in the lower right hand corner of Figure 2.0. Other large dynamic range examples have been observed in RLI measurement data [such as the measurement of a 2845.8 Hz main gear mesh vibration of 46.7 g's (33.2 dB rel 1g) and the measurement of the 5.96 Hz second harmonic of the main rotor rotational vibration of 0.000166 g's (-75.6 dB rel 1g) in an observed noise floor at low frequency (about 1 Hertz) of -115 dB rel 1g (0.0000018 g) for an H-53 rotorcraft gearbox test (see reference [2]). Clearly RLI can make the wide bandwidth, large dynamic range, non-contact, vibration measurement.

3.0 Higher Frequency Information

3.1 Direct Spectrum/Time Series: The upper left portion of Figure 3.0 presents a #1 bearing velocity spectrum for a turbine engine at idle, with a seeded fault (indents on the inner race). The measurements were taken at the end of an oil line and were from 0.0 Hz to 262.144 kHz. The frequency band from about 14 kHz to 20 kHz is interesting. The bottom left portion of Figure 3.0, which presents the velocity amplitudes in this frequency band, indicates the presence of impulsive events. Examination of these impulsive events (typically 10 microseconds or less) indicates that they occur in internals of time that are readily related to the seeded fault for the bearing (see reference [3]). It should also be noted that the measurement point was on a very hot operating turbine engine. Contact sensing does not provide correct information on hot surfaces at these frequencies.

3.2 Envelope Processing: The RLI provides envelope processing (see reference [4] - IEEE paper), which is particularly robust as a result of the correct higher frequency measurements made with the RLI. The right side of Figure 3.0 provides an example of RLI envelope processing of bearing measurement data from the oil line measurement point. In reality, there are pages of vibration excitation sources and frequencies in a

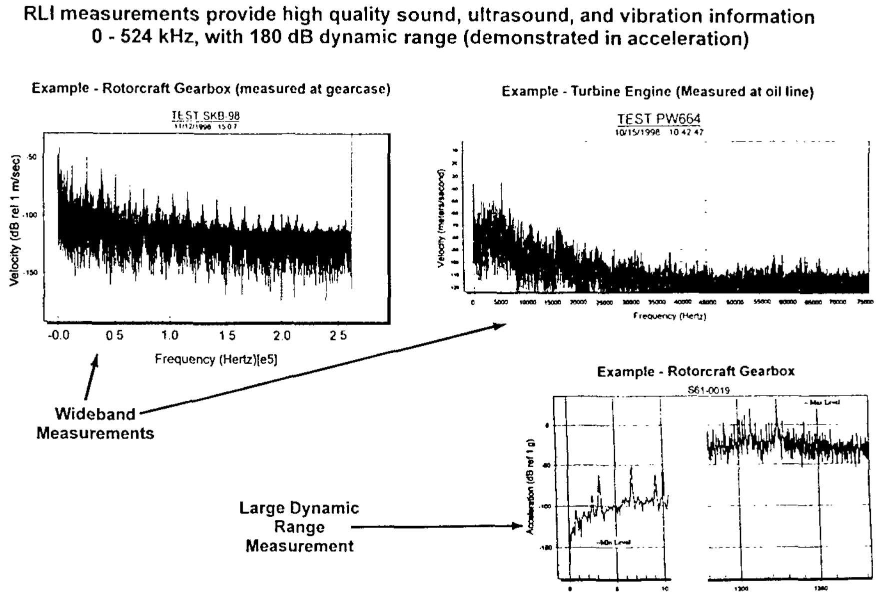


Figure 2.0 Measurements

turbine engine. One example is the first fan rotor, identified as "fs1". The top and bottom portions of the right side of Figure 3.0 illustrates the results of applying the RLI envelope processing for the case where the bearing is under stress. For the top portion, the envelope processing is applied for the frequency range of 26 kHz to 100 kHz; for the bottom portion, the envelope processing is applied for the frequency range of 100 kHz to 200 kHz. Clearly, there is information of value in the higher frequencies measured by the RLI.

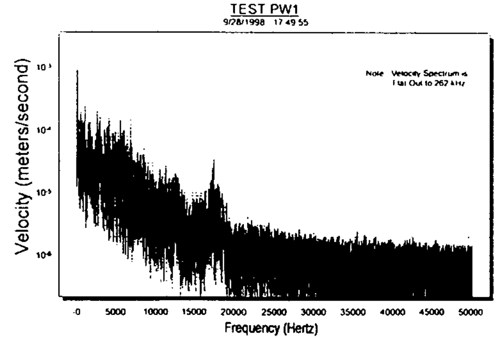
4.0 System Advantages

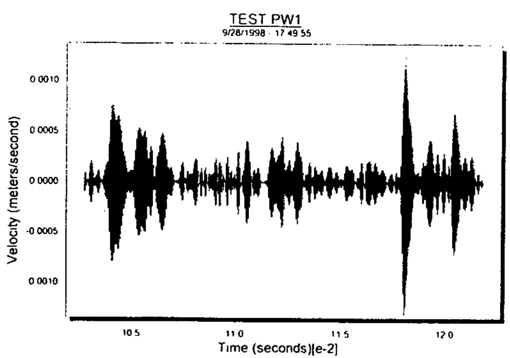
4.1 Overview: The left side of Figure 4.0 presents a comparison of RLI and contact sensing system considerations. The "concerns" identified as "dynamic" and "environmental" are from the reference [5] article in Sensors Magazine, March 1999. Similarly, the quantitative values for contact sensing for these two categories were also gleaned from the same reference. The right side of Figure 4.0 provides minor elaboration of a few of these comparisons to illustrate typical, practical advantages of RLI for the user ----- beyond the fact that RLI provides correct measurement of amplitude and frequency over a wide bandwidth, with a large dynamic range.

4.2 Examples: The dashed lines on the graph to the right of the arrow marked i) depict the typical frequency response (from specification sheets) for typical contact sensors.

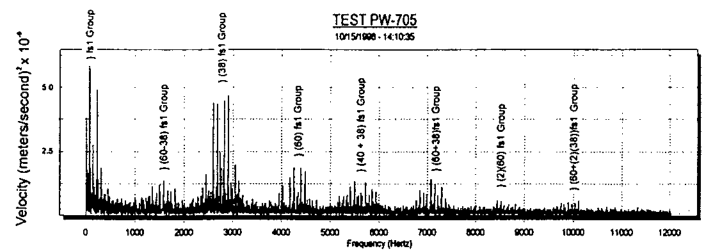
There is information of value in the higher frequencies measured by the RLI

Quality Direct Spectrum and TimeSeries Analysis [Example - JSF Bearing #1 Seeded Fault]





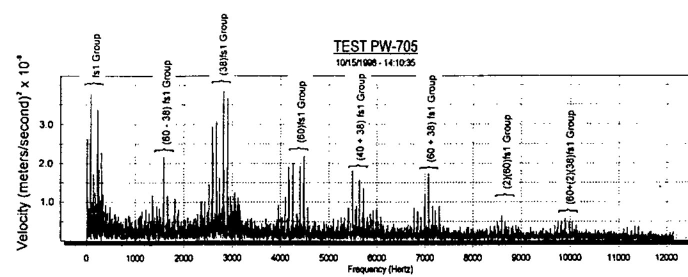
Quality Envelope Processing [Example - Broadband Indicated Stress]



a.) Envelope frequency band is 26 kHz to 100 kHz

20 kHz - 100 kHz

Note: A frequency group consists of a principal excitation force together with its sidebands which are comprised of ± n fs1 and ± j fs2 where 0 ≤ n ≤ N and 0 ≤ j ≤ J. N and J in turn may range from 0 to near 10.



b.) Envelope frequency band is 100 kHz to 200 kHz.

100 kHz - 200 kHz

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Figure 3.0 Information

The solid straight line depicts the flat RLI frequency response, alleviating the user of frequency dependent uncertainties and compensation concerns.

The curved lines to the right of the arrow marked ii) depict typical monitoring problems with contact sensing as a function of frequency. Sophisticated and expensive mounting techniques can enable some marginal improvements in performance with increasing frequency, but only non-contact sensing such as that provided by the RLI can alleviate this concern totally.

The dashed lines on the graph to the right of the arrow marked iii) depicts the typical temperature response at the measurement point (from specification sheets) for typical contact sensors. The solid straight line depicts the flat RLI response, alleviating the user of temperature dependent uncertainties and comparison concerns.

For contact sensing at higher frequencies (at frequencies where accelerometer measurements are not even attempted), Acoustic Emission (AE) sensors are sometimes employed. The graph to the right of the arrow marked iv) depicts AE sensor spectrum output when subjected to an input consisting of two frequencies. The RLI, pointed at the AE sensor case, reported only the two input frequencies present in the particular laboratory comparison. Even with a single frequency input, the AE sensors routinely reported a complex spectrum at the output (see reference [6]).

For contact sensing at lower frequencies and approaching 0 Hz, accelerometer systems' performance becomes unreliable. For more complex signals, substantial artifact issues can arise (see reference [2]). The graph to the right of the arrow marked v) indicates the level of difference in reporting low frequency information observed between a quality accelerometer system (the top spectrum) and the RLI (the bottom spectrum. In a number of "simultaneous measurement" situations, RLI was able to report the measurement of the frequency and amplitude of low frequency excitations (such as the main rotor rotational frequency for a rotorcraft -- known to be present from design characteristics). Accelerometer system measurements' noise floor often "masked" such opportunities for accelerometer systems.

Non-contact sensing by the RLI has provided the opportunity to obtain quality vibration information in situations where contact sensors are not practical. The situations to the right of the arrow marked vi) identifies a few where RLI has proved itself to be practical. Clearly RLI has substantial advantages over contact sensing.

5.0 Invited Paradigm Shifts

5.1 Flexibility: The two graphs providing data marked "test 213" on the left side of Figure 5.0 provide a straightforward, simple, example of the value of RLI bandwidth. Both are from the 0-262.144 kHz wide measurement of the turbine engine bearing seeded fault discussed in Section 3.1. The upper one is the time series for the bandwidth of 9 kHz to 15 kHz; the lower one is the time series for the bandwidth of 36 kHz to 56 kHz.

Comparison

Concern	Typical Contact Transducer System	RLI
Dynamic[1] Sensitivity/Signal to Noise	Higher sensitivity leads to larger units	High sensitivity across bandwidth
Dynamic Range	~ 80 dB	180 dB (demonstrated in acceleration)
Amplitude Frequency Response	± 5% to approximately 20% of resonance frequency	Flat
Phase Frequency Response	Time delay[f (frequency)]	Near instantaneous; can be < 1 microsecond
Amplitude Nonlinearity	Approximately 1%; generates artifacts in data	< 0.01%
Transverse Sensitivity	1 - 5% at low frequencies	0% of axial for flat surface
Mass and Size	Attachment, resonance and mass loading issues	N/A for RLI @ measurement point
Environmental[1] Temperature	Non-linear as f (temperature)	Flat with temperature
Thermal Transient Sensitivity	Multiple concerns	N/A for RLI
Base Strain Sensitivity	Mounting issue	N/A for RLI
Electromagnetic Sensitivity	Serious concern; often leads to shielding	N/A for RLI @ measurement point
Acoustic Sensitivity	Problem when SPL > 100 dB	N/A for RLI @ measurement point
Radioactive Environments	Materials/life issues	N/A for RLI @ measurement point
Humidity	Leakage paths	N/A for RLI @ measurement point
Grounding/Electrical Isolation	System noise concern	N/A for RLI @ measurement point
Placebo/Noise Monitor Channel	Added complication	N/A for RLI
Other Bandpass	Typically 0-20 kHz; more costly units to 40-50 kHz	0-524 kHz
High Frequency Performance	Limited to approximately 40-50 kHz	Linear to 524 kHz+
Low Frequency Performance	Artifacts related to non-linearity	linear to "near dc"
Type Measurement	Contact	Non-contact
Installation Mounting	Degradation as f (frequency)	N/A for RLI
Re-calibration	Required at regular intervals	N/A for RLI
Information Robustness	Artifacts in data at all frequencies; pronounced at low and high frequencies	Extremely robust; correct measurement of both amplitude and frequency

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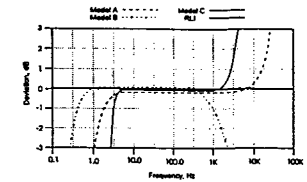
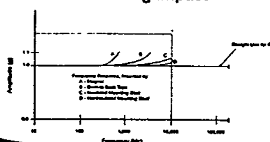
[1] Dynamic and Environmental Effects on Performance Parameters from article by Jon Wilson, *Sensor* Magazine, March 1999

The RLI non-contact measurements are preferable to contact system measurements [such as accelerometer systems and/or acoustic emission sensor system measurements.]

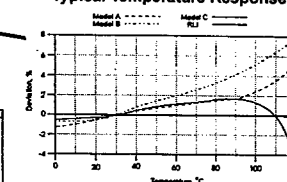
i) Typical Frequency Response



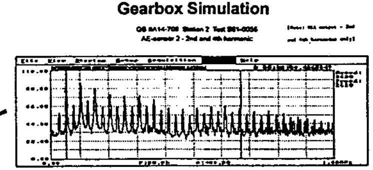
ii) Mounting Impact



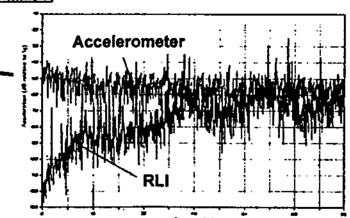
iii) Typical Temperature Response



iv) Gearbox Simulation



v)



vi) Hostile Surface Measurements

- "Hot" Jet Engines
- "High Voltage" or Nuclear Powered Submarine
- "Inaccessable" Hanger Bearings

Figure 4.0 System Advantages

While both contain the same "time series periodicity information", the visibility of the periodicity via the shock pulses at the higher bandwidth is clear. The flexibility of the RLI enables intelligent use of a priori design and related physics considerations to enable proper selection of where to seek information of interest.

5.2 Improved Tracking Data: The two "middle sheet" amplitude tracking graphs on Figure 5.0 represents time series for comparable bandwidth measurements of the same "fault" under two different conditions, two days apart.

The upper one indicates a "nominal "maximum velocity of 0.0002 m/sec; the lower one indicates a "nominal" maximum velocity an order of magnitude higher, namely approximately 0.002 m/sec. With its correct measurement of both amplitude and frequency, the RLI enables precise monitoring of events of interest, such as those associated with fault growth. The upper right side figure is from the Joint Strike Fighter Seeded Fault testing where a particular seeded fault decreased with bearing operating time. From all of the sensors used for the particular seeded fault test series, only the RLI provided information which indicated that the "sharply defined" defect was polished away. This was confirmed by physical inspection (see reference [1]).

5.3 New Opportunities: The bottom of Figure 5.0 provides a time zoom on typical acoustic emissions observed by RLI from the JSF seeded fault testing. [The "wideband" down the middle illustrates the approximate background noise over the measurement bandwidth]. Not only do the individual pulse like events have amplitude up to and greater than 5 times the noise baseline, but they also exhibit a great variation in the characteristics of the individual AE events. The variations extend from a variation in pulse length and shape to variation in the individual frequency content. The availability of this type of RLI data could be expected to provide various "knowledge gains"/opportunities. Clearly, RLI measurements can both enable and seduce increased reliance upon trending and health monitoring diagnostics and "prognostics".

6.0 Future

6.1 Proven Performance - Point and Shoot: The table on the left side of Figure 6.0 illustrates both the application demonstrations and functional demonstrations provided to date with the RLI non-contact "point and shoot" information. Many additional opportunities still exist for validating RLI value added, particularly in niche areas related to gears, bearings, electrical systems, structures, and other physical phenomonologies that exhibit either wideband spectrums or spectrums with large amounts of information concentrated at higher frequencies.

6.2 RLI Fiber Optic System: RLI fiberoptic system routed measurements have also been demonstrated (See reference). Comparison measurements between the baseline "point and shoot" RLI and RLI "fiberoptic routed" measurements have been made for various scenarios, including background noise comparisons, comparative measurements of small vibrations in the presence of large vibrations, comparative measurements of

The RLI measurements are of such quality and robustness that they will both enable and seduce increased reliance upon trending and health monitoring diagnostics and "prognostics"

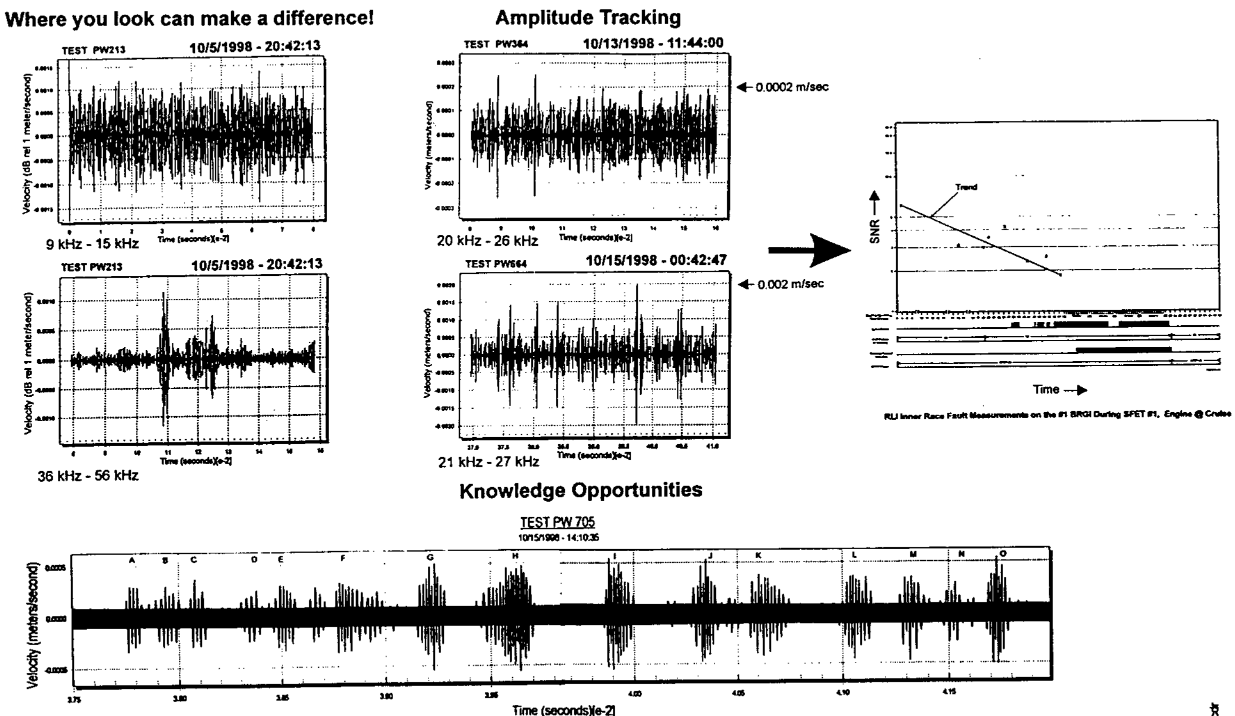


Figure 5.0 Invited Paradigm Shifts

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large amplitude complex vibrations, and high frequency measurement comparisons. The data on the right side of Figure 6.0 illustrates one set of data, that being the high frequency (260 kHz to 262 kHz) background noise for the baseline (point and shoot) RLI and a fiber-optic routed RLI measurement. [Demonstration measurements were made through 20 meters of fiber-optic cable]. Clearly RLI can spawn a new generation of sound, ultrasound and vibration measurement systems.

7.0 Summary

Figure 7.0 summarizes RLI findings. RLI also has substantial growth potential. The RLI system is based upon employment of an inexpensive laser, optics, and computer technology --- all technologies with histories of performance growth and cost reduction. [For example, RLI has been in development for about a decade. According to the reference [7] article in the March 2000 Scientific American, "... the average price per megabyte for hard-disk drives plunged from $11.54 in 1988 to $0.04 in 1998, and the estimate for last year is $0.02]." RLI provides a flexible, meaningful capability. As paradigm shifts evolve in health monitoring, diagnostics and prognostics of rotating machinery and other infrastructure components, RLI is positioned to provide multiple stand-alone and/or integrated configurations.

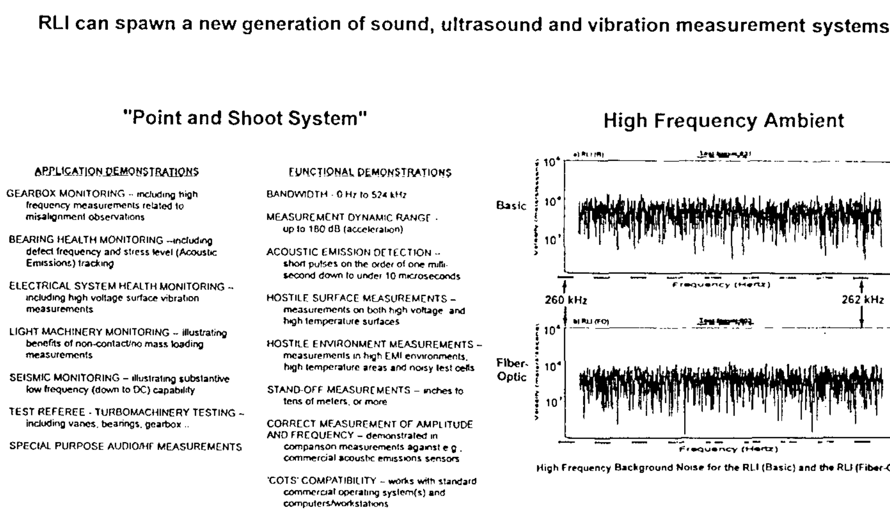

Figure 6.0 Future

Summary

Findings

- RLI measurements provide high quality vibration information 0 - 524 kHz with 180 dB dynamic range (demonstrated in acceleration).
- There is information of value in the higher frequencies measured by RLI.
- PRI measurements are preferable to contact system measurements [such as accelerometer or Acoustic Emission (AE) sensor measurements].
- RLI measurements are of such quality and robustness that they will both enable and seduce increased reliance on trending and health monitoring diagnostics and prognostics.
- RLI can spawn a new generation of sound, ultrasound and vibration measurement devices.

Growth Potential

- System based upon lasers, optics, computational power and memory - all technologies with histories of performance growth and cost reduction.
- Flexible, meaningful capability - paradigm shifts should be anticipated.
- Multiple stand-alone and/or integeated configurations feasible.

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Figure 7.0

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