Robust, Accurate, and Non-Contacting Vibration Measurement Systems

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Summary of Comparison Measurements of the Robust Laser Interferometer and Typical Accelerometer Systems

Prepared by
T. C. Goodenow, R. L. Shipman, H. M. Holland

Epoch Engineering, Inc.

Prepared for
U.S. Nuclear Regulatory Commission

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Robust, Accurate, and Non-Contacting Vibration Measurement Systems

Summary of Comparison Measurements of the Robust Laser Interferometer and Typical Accelerometer Systems

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Abstract: Epoch Engineering, Incorporated (EEI) has completed a series of vibration measurements comparing their newly-developed Robust Laser Interferometer (RLI) with accelerometer-based instrumentation systems. EEI has successfully demonstrated, on several pieces of commonplace machinery, that non-contact, line-of-sight measurements are practical and yield results equal to or, in some cases, better than customary field implementations of accelerometers. The demonstration included analysis and comparison of such phenomena as nonlinearity, transverse sensitivity, harmonics, and signal-to-noise ratio. Fast Fourier Transformations were performed on the accelerometer and the laser system outputs to provide a comparison basis. The RLI was demonstrated, within the limits of the task, to be a viable, line-of-sight, non-contact alternative to accelerometer systems.

Several different kinds of machinery were instrumented and compared, including a small pump, a gear-driven cement mixer, a rotor kit, and two small fans. Known machinery vibration sources were verified and RLI system output file formats were verified to be compatible with commercial computer programs used for vibration monitoring and trend analysis. The RLI was also observed to be less subject to electromagnetic interference (EMI) and more capable at very low frequencies.

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Executive Summary: In this report, Epoch Engineering, Incorporated (EEI) describes its successful phase I Small Business Innovation Research (SBIR) effort to measure machinery vibrations using its own, newly-developed, Robust Laser Interferometer and compares those measurements to accelerometer measurements taken simultaneously. In this effort, the Robust Laser Interferometer (RLI) demonstrated the ability to measure vibrations in a line-of-sight, non-contact fashion, to the same basic sensitivity as accelerometer measurements taken simultaneously. The company, a Maryland small business specializing in acoustics, vibrations and signal processing, has successfully demonstrated the non-contact vibration measurement capability on a series of small machines. It has also demonstrated some of the difficulties encountered with accelerometer measurements that its RLI system does not have.

In accomplishing its measurements for comparison, EEI selected several small machines: a small vane-type pump, a gear-driven cement mixer, and several fans. It also used, for calibration and comparison purposes, a Bently-Nevada rotor test kit, a customary demonstration device for the instrumentation industry. A lengthy calibration procedure was undertaken to assure a common baseline of measurements and is described in the report. A noise baseline of each machine was taken with the machine off. Accelerometers were used in complementary fashions in several instances in order to quantify such phenomena as transverse sensitivity.

Where possible, the small machines were run in different operating conditions in order to demonstrate the ability of the instrumentation systems to detect changes in the vibration patterns. Specifically, the flow to the pump was restricted, and the changing vibration pattern was recorded on all systems; the flow through one of the fans was blocked and the changed vibration pattern recorded; the cement mixer was run both loaded and unloaded and the different vibration patterns recorded on all systems.

The results of the data measurements are reported in tables in which the mechanical origin of the peaks is identified. The peak measurements are compared to show the vibration severity difference in percent, and for the more visible peaks the comparison is good, usually within 5 percent. For smaller, but still identifiable peaks, the percent

difference increases, occasionally to as high as 20 percent, but much of this is attributed to the smaller numbers involved in calculating the difference ratios. The absolute differences in the amplitudes of the smaller peaks are similar to the differences when the peaks are larger. In addition, plots of the data are presented and, when compared, show the comparability of the measurements and of the noise floors.

The report states that the RLI is able to make repeatable measurements of an accuracy similar to that of accelerometer systems. In many cases, the RLI measurements are more accurate than accelerometer measurements due to the absence of accelerometer limitations. The report discusses such accelerometer limitations as: nonlinearity, transverse sensitivity, signal-to-noise ratio, electromagnetic interference and intermodulation distortion. The differences between accelerometer and RLI measurements are highlighted. Some of the measurement differences are attributed to difficulties in measuring vibrations from the relatively small, lightweight machinery used in the experiment.

In the course of these measurements, two phenomena were observed that may prove to be important for future measurement systems. (1) As expected, the laser interferometer is not subject to electrical interference. Accelerometers located near the inexpensive motors or on electrically grounded mechanical parts were observed to have intermodulation distortion and other power and control circuit related problems. (2) The accelerometers were seen to have, as expected, a higher noise floor at low frequencies. It appears that the RLI is fundamentally better at measuring vibrations at frequencies below 1 or 2 Hertz.

In order to verify the RLI system output data format compatibility with commercially available trend analysis computer routines, EEI contacted a few of the providers of these routines and verified that the file formats and required inputs were compatible.

EEI finds that its RLI system does make readings of actual machinery vibrations that are comparable to, and, in some cases, better than accelerometer measurements. EEI concludes that a non-contact, line-of-sight vibration measurement system could be designed to be as good as or better than a typical industrial implementation of accelerometer-based technology for machinery monitoring and trend analysis.

Epoch Engineering recommends that further investigations include routing the laser signal to hard-to-reach places by fiber-optic cable, and splitting or multi-plexing the signal to route it to successive locations. These investigations would verify the concept that a distributed machinery monitoring system can be designed around one centrally located laser system and that vibration readings as good as those obtained using accelerometers, or better, can be obtained without the installation of an engineered device such as an accelerometer at each location. The verified insensitivity of the measurements to electrical interference makes the possibility of taking measurements in high electromagnetic fields, such as inside of operating motors and generators, worth investigating. Finally, the greater sensitivity at low frequencies may make it worthwhile to investigate seismic or structural applications where vibration frequencies are low.

Abbreviations

AS	Accelerometer Systems
dB	Decibel measurement
EEI	Epoch Engineering, Inc.
EMI	Electromagnetic Interference
FFT	Fast Fourier Transform
Hz	Frequency in Hertz
kHz	Frequency in Kilohertz
RLI	Robust Laser Interferometer
SBIR	Small Business Innovation Research
SNR	Signal-to-Noise Ratio
TS	Transverse Sensitivity
WR 731	Wilcoxon Research accelerometer model 731-201
WR 732	Wilcoxon Research accelerometer model 732A

1. Introduction

Epoch Engineering, Incorporated (EEI) has developed a laser based vibration measurement system called the Robust Laser Interferometer (RLI) that appears to have measurement advantages over accelerometer technology. The effort described in this report is a series of calibration steps and comparison measurements to quantify the anticipated superior capabilities of the Robust Laser Interferometer over accelerometer measurements, especially field implementations of accelerometer technology.

1.1 Comparison Description

1.1.1 The comparison of the RLI with accelerometer systems is performed in the frequency domain via Fast Fourier Transform (FFT) techniques, that is, a FFT is performed on the time series output data of both the RLI and the accelerometer systems.

1.1.2 While FFT techniques have the potential for good quantifiable data, there are also inherent limitations on their use and there are various areas where their use may (or will) generate errors.

1.1.3 Within this report the different accelerometer systems shall be designated as WR 731 (for the Wilcoxon Research Model 731-201), and WR 732 (for the Wilcoxon Research Model 732A).

1.1.4 Since there does not exist an absolute standard and because the RLI will be compared to all accelerometer systems, the RLI is chosen as the reference system. Therefore, the performance of WR 731 and WR 732 will be compared and referenced to the RLI.

1.2 Comparison Goals

1.2.1 The specifications for the accelerometers that are used are quantified and listed in Appendix E (appendices bound separately). The two that are important to our goals are: (i) amplitude specification and, (ii) frequency response. For the accelerometers to be used these requirements are given as:

WR 731: $\pm 5\%$ (amplitude) for frequencies from .6 - 650 Hz.

WR 732: $\pm 5\%$ (amplitude) for frequencies from 2.0 Hz - 15 kHz.

1.2.2 The comparison measurement goals have relative accuracies of $\pm 5\%$ in amplitude over the frequency range of each accelerometer.

1.2.3 To ensure the above goals, a calibration phase is required prior to measurements being made on individual pieces of equipment.

2. Calibration Efforts

2.1 System Descriptions and Configurations

2.1.1 Figures 2.1 and 2.2 are simple block diagrams of the systems used for the comparisons of the RLI and the accelerometer systems.

2.1.2 In particular it should be noted that each system has its own computer and, more importantly, each has its own individual clock. The clocks, of course, are not synchronous, which creates discrepancies in the resultant Fast Fourier Transfer (FFT) bins for both the RLI and the accelerometer system. For example, a measured value of acceleration will show up in a different FFT bin, RLI versus accelerometer. This anomaly is addressed in more detail in the calibration phase.

2.1.3 The clock provided for the accelerometer system is representative of what is normal for an accelerometer but is not of the accuracy provided for the RLI. •

2.1.4 The RLI sends a trigger signal to the accelerometer system such that both systems take data simultaneously (with a start difference of less than 10 milliseconds).

2.1.5 Prior to the calibration phase it was necessary to determine if there were/are "sneak paths" of vibration between the exciter and the RLI. A "sneak path" of large amplitude would contaminate the measurements of the RLI. To quantify the possible contamination a transfer function was measured between the exciter and the RLI. The transfer function is defined as:

$$XFR = \frac{\text{Measured Acceleration of RLI Laser Head}}{\text{Measured Acceleration of the Exciter}}$$

and,

$$XFR (dB) = 20 \log XFR$$

2.2 System Isolation Verification Measurements

2.2.1 The vibration of the RLI Laser Head is measured by an accelerometer and the vibration of the exciter is measured by the RLI. Figure 3 illustrates the configuration used in this set of measurements. The distance (R) between the exciter and the RLI is approximately 4 ft (121 cm). Table 1 lists the exciter frequency together with the amplitudes of acceleration measured by the RLI and the WR 731 accelerometer. The table indicates that any "sneak paths" to the RLI cause it to vibrate at least 72 dB less than that of the exciter (source). That is, the amplitude of vibration of the RLI Laser Head is less than 1/4000 of that of the exciter. As an example, from the table at an exciter vibration of 280 Hz, the RLI measures an exciter vibration of .102 g, which is shown as:

$$20 \log(.102) = -19.808 \text{ dB.}$$

The RLI Laser Head, by comparison, has an acceleration at that frequency of .000003362 g, which is shown as:

$$20 \log(.000003362) = -109.469 \text{ dB.}$$

2.2.2 The level of vibration in the RLI Laser Head is therefore considerably lower than the 72 dB difference thought necessary to effectively use the system. Based upon a review of the table, physical isolation appears more than adequate and "Sneak Paths" do not appear to be a problem for the calibration phase.

Note 1. The oven-controlled master clock is also called f_{cr} elsewhere in the report.

Figure 2.1 Block Diagram of Robust Laser Interferometer System

- Notes:
1. G=1 for the WR 732
G=2/7 for the WR 731
G=1/35 for the WR 768
 2. The master clock (crystal oscillator) is also labeled f_{cad} elsewhere in the report.
 3. DAQ 4.1 is an EEI Proprietary Software Program

Figure 2.2 Block Diagram of Accelerometer Systems

Figure 2.3 System Arrangement for Calibration

Table 2.1 Exciter Frequency Calibration Table

Test Number	fw (1 Hz Bins)	fm (1 Hz Bins)	Acceleration		Xfer (dB ref 1 g)	Comments
			RLI (dB ref 1 g)	731 (dB ref 1 g)		
1069	100	100	-19.690	-106.758	-87.068	
1070	120	120	-19.772	-97.255	-77.483	
1071	140	140	-19.875	-96.831	-76.956	
1072	180	180	-19.673	-122.563	-102.890	
1073	200	200	-19.595	-110.979	-91.384	
1074	220	220	-19.781	-115.198	-95.417	
1075	240	240	-19.739	-114.419	-94.680	
1076	280	280	-19.808	-109.469	-89.661	
1077	300	300	-19.822	-117.992	-98.170	
1078	320	320	-19.794	-130.000	-110.206	Measurement limited by noise floor
1079	340	340	-19.784	-130.000	-110.216	Measurement limited by noise floor
1080	380	380	-19.930	-130.000	-110.070	Measurement limited by noise floor
1081	400	400	-20.064	-130.000	-109.936	Measurement limited by noise floor
1082	420	420	-19.715	-130.000	-110.285	Measurement limited by noise floor
1083	440	440	-19.695	-130.000	-110.305	Measurement limited by noise floor
1084	480	480	-19.637	-130.000	-110.363	Measurement limited by noise floor
1085	500	500	-19.601	-130.000	-110.399	Measurement limited by noise floor
1086	600	600	-19.301	-112.816	-93.515	
1087	800	800	-19.900	-130.000	-110.100	Measurement limited by noise floor
1088	1000	1000	-20.252	-130.000	-109.748	Measurement limited by noise floor
1089	1200	1200	-20.419	-114.935	-94.516	
1090	1400	1400	-20.087	-104.394	-84.307	
1091	1600	1600	-19.728	-99.659	-79.931	
1092	1800	1800	-20.450	-97.670	-77.220	
1093	2000	2000	-20.165	-110.515	-90.350	
1094	4000	4000	-20.300	-103.676	-83.376	
1095	8000	8000	-21.266	-121.384	-100.118	

Notes:

- 1 - R = 121 cm (see figure 3)
- 2 - Exciter vibration as measured by RLI, noise floor = -85 dB ref 1g
- 3 - RLI laser head vibration as measured by accelerometer (731), noise floor = -130 dB ref 1g
- 4 - fw = the frequency of the signal generator
- 5 - fm = the frequency bin (for both RLI and AS) with the largest measured amplitude

2.3 System Frequency and Amplitude Comparison

2.3.1 Master Clock Arrangement:

Figure 2.4 illustrates the configuration for the various frequency and amplitude calibrations. It should be noted that there are three separate master clocks involved. The manner in which the clocks are involved is as follows:

2.3.1.1 The signal generator drives the exciter at a frequency f_w where f_w is generated from f_{cw} , the signal generator clock frequency. Therefore, the accuracy of f_w is only as good as the accuracy of f_{cw} .

2.3.1.2 The RLI measures the vibration of the accelerometer (which is mounted on the exciter) relative to its master clock f_{cr} . Therefore its measurement accuracy in frequency is dependent upon f_{cr} .

2.3.1.3 In turn, the accelerometer system provides a voltage signal that is sampled by an analog to digital (A→D) converter that is controlled by its master clock f_{cad} . The accuracy, in time, is controlled by the accuracy of f_{cad} .

2.3.2 Frequency Calibration: Tables 2.2 and 2.3 list the measured frequencies that were obtained from the frequency calibration phase.

2.3.2.1 Tables 2.2 and 2.3 show that there is a slight difference between RLI and signal generator (less than .128 Hz at 16 kHz) and a rather large difference between the accelerometer system and the signal generator. For example, with the signal generator set at 4800 Hz and a measurement duration of 1 second (which results in a 1 Hz wide bin width in the FFTs of the RLI and the accelerometer systems) the accelerometer system measures 4801 Hz and the RLI measures 4800 Hz.

2.3.2.2 This difference in frequency readings (between the RLI and the accelerometer system) is not critical on its own; however, it does significantly effect the amplitude comparison measurements of the RLI and the accelerometer system. This effect is discussed below.

2.3.3 Amplitude Calibration

2.3.3.1 Amplitude measurements made by the RLI and the accelerometer system are made by measuring the acceleration amplitude as a function of frequency as seen by an FFT; for example, the amplitude in an FFT bin is taken as the measured amplitude at the frequency of the FFT bin. However, the frequency that is being measured may not be at the frequency of the FFT bin. The amplitude response, as a function of frequency, for an FFT, resembles a wide picket fence to a certain degree. In this sense, the amplitude in the center of a bin is unity and for any other position within the bin the amplitude is less than unity. To further explain, for FFT bins separated by 1 Hz and centered at integer multiples of 1 Hz, the FFT would accurately measure a frequency of 77, 78, 79, etc. Hz. Signals at 77.5 or 78.5 Hz, for example, are reduced in amplitude by a factor of 0.8488 (or -1.424 dB), which is slightly less than 85% of the true value. (Our goal is to compare the RLI with the accelerometer system to better than +/-5%.)

2.3.3.2 To help quantify the above effect, consider the case of measuring an acceleration for one second at a frequency of 2400 Hz. The signal, 2400 Hz, falls in the center of the 2400 Hz frequency bin and therefore the RLI makes the correct measurement, however, the accelerometer system sees the frequency as 2400.5 Hz and therefore measures .8488 of the true amplitude in both bins 2400 Hz and 2401 Hz. Both bins record an erroneous signal, in error by more than 15%. This is the effect of non-tracking (RLI versus accelerometer system) in frequency and it must be accounted for in the amplitude calibration.

2.3.3.3 Table 2.4 lists the measurements used to amplitude calibrate the accelerometer system (with the WR 731 accelerometer) against the RLI. The WR 731 measures a lower value for acceleration than the RLI, taken to be -2.355 dB. To compensate for this offset a correction factor is inserted into the WR 731 software. The correction factor increases the processing gain of the WR 731 by 1.3114. With this correction factor the RLI and the WR 731 measure the same amplitude within +/-5%.

Notes: 1 - This Voltage Dividing Network provides a gain (G) set as a function of which accelerometer is used.

2 - DAQ 4.1 is an EEI Proprietary data analysis software program.

3 - The EEI Exciter System is a modified commercial speaker driven by a Signal Generator.

4 - F_{CW} , F_{CR} , and F_{CAD} are master clocks for each separate system.

Figure 2.4 Frequency and Amplitude Test Calibration

Table 2.2 WR 731 Frequency Calibration

Test Number	fw (Hz)	T (sec)	System	fm (Hz)	Acceleration			FT (Hz)
					fm-1 (dB)	fm (dB)	fm+1 (dB)	
1158	4.000	1	731	4.000	-38.501	-32.470	-38.476	4.001
			RLI	4.000	-41.498	-30.482	-32.623	
1159	10.000	1	731	10.000	-29.644	-23.597	-29.586	10.002
			RLI	10.000	-29.382	-21.538	-25.915	
1160	20.000	1	731	20.000	-28.271	-22.190	-28.147	20.004
			RLI	20.000	-26.966	-20.050	-25.215	
1169	40.000	1	731	40.000	-28.323	-22.199	-28.11	40.007
			RLI	40.000	-26.331	-19.879	-25.474	
1162	80.000	1	731	80.000	-28.423	-22.184	-27.981	80.014
			RLI	80.000	-26.212	-19.980	-25.768	
1163	160.000	1	731	160.063	-28.603	-22.137	-27.715	160.092
			RLI	160.000	-26.003	-19.883	-25.798	
1164	200.000	1	731	200.063	-28.774	-22.195	-27.663	200.099
			RLI	200.000	-25.848	-19.751	-25.689	
1165	300.000	1	731	300.063	-29.151	-22.285	-27.481	300.118
			RLI	300.000	-25.649	-19.581	-25.550	
1168	400.000	1	731	400.063	-29.352	-22.203	-27.135	400.136
			RLI	400.000	-25.621	-19.576	-25.566	
1167	500.000	1	731	500.125	-29.596	-22.157	-26.825	500.218
			RLI	500.000	-25.423	-19.395	-25.395	

- Notes:
1. fw = the frequency of the signal generator
 2. fm = the frequency bin (for both RLI and AS) with the largest measured amplitude
 3. FT = the "true frequency" for each system as interpolated from the two maximum amplitude frequency bins
 4. T = Time duration of each measurement

Table 2.3 WR 732 Frequency Calibration

Test Number	fw (Hz)	T (sec)	System	fm (Hz)	Acceleration			FT (Hz)
					fm-1 (dB)	fm (dB)	fm+1 (dB)	
1145	40.000	16	732	40.000	-26.786	-18.934	-23.242	40.007
			RLI	40.000	-25.362	-19.314	-25.339	
1146	100.000	16	732	100.000	-30.690	-19.710	-21.579	100.020
			RLI	100.000	-25.498	-19.547	-25.636	
1136	300.000	16	732	300.063	-25.243	-18.962	-24.726	300.064
			RLI	300.000	-25.192	-19.383	-25.617	
1137	600.000	16	732	600.125	-25.115	-18.581	-24.096	600.127
			RLI	600.000	-24.592	-19.009	-25.474	
1138	1200.000	8	732	1200.250	-25.362	-18.813	-24.313	1200.254
			RLI	1200.000	-24.726	-19.145	-25.593	
1139	2400.000	4	732	2400.500	-25.468	-18.917	-24.418	2400.508
			RLI	2400.000	-24.907	-19.359	-25.826	
1140	3400.000	4	732	3400.750	-22.970	-18.351	-25.851	3400.726
			RLI	3400.000	-24.115	-18.718	-25.378	
1141	3600.000	4	732	3600.750	-26.204	-19.402	-24.664	3600.763
			RLI	3600.000	-25.210	-19.822	-26.463	
1142	4800.000	2	732	4801.000	-24.949	-18.471	-24.041	4801.015
			RLI	4800.000	-24.280	-18.854	-25.384	
1147	6000.000	2	732	6001.500	-20.484	-19.946	-32.991	6001.276
			RLI	6000.000	-25.164	-19.483	-25.989	
1143	14000.000	1	732	14003.000	-23.654	-18.056	-24.505	14002.973
			RLI	14000.000	-27.117	-21.510	-28.034	
1144	16000.000	1	732	16003.000	-45.673	-33.757	-34.996	16003.383
			RLI	16000.000	-27.771	-23.573	-30.742	

- Notes:
1. fw = the frequency of the signal generator
 2. fm = the frequency bin (for both RLI and AS) with the largest measured amplitude
 3. FT = the "true frequency" for each system as interpolated from the two maximum amplitude frequency bins
 4. T = Time duration of each measurement

Table 2.4 WR 731 versus RLI Amplitude Calibration

Test Number	fw (Hz)	T (sec)	System	fm (Hz)	Acceleration			Delta RLI/Accel (db)
					fm-1 (dB)	fm (dB)	fm+1 (dB)	
1158	4.000	1	7	4.000	-38.501	-32.470	-38.476	-1.98800
			RLI	4.000	-41.498	-30.482	-32.623	
1159	10.000	1	731	10.000	-29.644	-23.597	-29.586	-2.05898
			RLI	10.000	-29.382	-21.538	-25.915	
1160	20.000	1	731	20.000	-28.271	-22.190	-28.147	-2.13992
			RLI	20.000	-26.966	-20.050	-25.215	
1169	40.000	1	731	40.000	-28.323	-22.199	-28.110	-2.31977
			RLI	40.000	-26.331	-19.879	-25.474	
1162	80.000	1	731	80.000	-28.423	-22.184	-27.981	-2.20302
			RLI	80.000	-26.212	-19.980	-25.768	
1163	160.000	1	731	160.063	-28.603	-22.137	-27.715	-2.25005
			RLI	160.000	-26.003	-19.883	-25.798	
1164	200.000	1	731	200.063	-28.774	-22.195	-27.663	-2.43776
			RLI	200.000	-25.848	-19.751	-25.689	
1165	300.000	1	731	300.063	-29.151	-22.285	-27.481	-2.68967
			RLI	300.000	-25.649	-19.581	-25.550	
1168	400.000	1	731	400.063	-29.352	-22.203	-27.135	-2.60127
			RLI	400.000	-25.621	-19.576	-25.566	
1167	500.000	1	731	500.125	-29.596	-22.157	-26.825	-2.72109
			RLI	500.000	-25.423	-19.395	-25.395	

- Notes:
1. fw = the frequency of the signal generator
 2. fm = the frequency bin (for both RLI and AS) with the largest measured amplitude
 3. T = Time duration of each measurement
 4. Delta RLI/Accel is the final difference in measurement (RLI versus 731) after FFT losses are accounted for

2.3.3.4 The above procedure is repeated for the WR 732. Table 2.5 lists the measurements. The factor inserted into the WR 732 is 0.95107 and corrects the WR 732 to measure amplitudes to within $\pm 5\%$ of the RLI.

2.3.3.5 For the measurements taken in this comparison effort, amplitudes will be taken from the 1 Hz bins. Narrower bins (requiring longer measurement time) may be utilized to help illustrate certain phenomena, but the system is well calibrated around 1 Hz bins and the commonplace items of machinery are expected to change speed slightly, causing their frequencies to wander. Narrower bins would be much harder to calibrate in amplitude in these conditions.

2.4 Results of Calibration Phase

During the calibration phase, the conditions within which the measurements have been made have been very well controlled. The vibration source is very steady and can be moved to convenient frequencies within the spectrum of interest. Nevertheless, at this point, the above calibrations establish that the RLI and the accelerometer systems are adequately physically isolated from one another and will make the same measurements of acceleration within the specification windows of the utilized accelerometers.

Table 2.5 WR 732 versus RLI Amplitude Calibration

Test Number	fw (Hz)	T (sec)	System	fm (Hz)	Acceleration			Delta RLI/Accel (db)
					fm-1 (dB)	fm (dB)	fm+1 (dB)	
1145	40.000	16	732	40.000	-26.786	-18.934	-23.242	0.44823
			RLI	40.000	-25.362	-19.314	-25.339	
1146	100.000	16	732	100.000	-30.690	-19.710	-21.579	0.34920
			RLI	100.000	-25.498	-19.547	-25.636	
1136	300.000	16	732	300.063	-25.243	-18.962	-24.726	0.42230
			RLI	300.000	-25.192	-19.383	-25.617	
1137	600.000	16	732	600.125	-25.115	-18.581	-24.096	0.43320
			RLI	600.000	-24.592	-19.009	-25.474	
1138	1200.000	8	732	1200.250	-25.362	-18.813	-24.313	0.33752
			RLI	1200.000	-24.726	-19.145	-25.593	
1139	2400.000	4	732	2400.500	-25.468	-18.917	-24.418	0.44750
			RLI	2400.000	-24.907	-19.359	-25.826	
1140	3400.000	4	732	3400.750	-22.970	-18.351	-25.851	0.41117
			RLI	3400.000	-24.115	-18.718	-25.378	
1141	3600.000	4	732	3600.750	-26.204	-19.402	-24.664	0.43204
			RLI	3600.000	-25.210	-19.822	-26.463	
1142	4800.000	2	732	4801.000	-24.949	-18.471	-24.041	0.38710
			RLI	4800.000	-24.280	-18.854	-25.384	
1147	6000.000	2	732	6001.500	-20.484	-19.946	-32.991	0.53402
			RLI	6000.000	-25.164	-19.483	-25.989	

- Notes:
1. fw = the frequency of the signal generator
 2. fm = the frequency bin (for both RLI and AS) with the largest measured amplitude
 3. T = Time duration of each measurement
 4. Delta RLI/Accel is the final difference in measurement (RLI verses 732) after FFT losses are accounted for

3. Comparison Measurement Preparations

After the conclusion of the calibration stage, and as we began the comparison measurement stage where we would attempt to measure the vibrations of "common-place rotating equipment," it became apparent that comparison measurement was not going to be a straightforward task. Although we anticipated a reasonable amount of problems in implementing and utilizing accelerometers, we had not allowed for the diversity and scope of all the problems that we actually encountered in providing for an indepth and meaningful set of comparison measurements. In performing comparison measurement, many complications exist, each of which could be analyzed and quantified in great detail. In keeping with the scope and object of this task, we limited our coverage of these complications.

The resulting approach was not to ignore the complications (factors that affect comparison measurement), but rather to address and discuss, and to the extent possible to demonstrate, control and assess their individual impact on the comparison measurement process. A list of these factors (complications), not necessarily exhausting, is contained in the following sections.

3.1 Description of Intended Measurements

3.1.1 The measurement, for comparison purposes, of the vibration of commonplace items of rotating machinery is largely unrestricted. That is, compared to the signal generator that provided a constant amplitude signal at an ultra-narrow bandwidth (conservatively estimated at less than .01 Hz) commonplace rotating machinery will have very broadband vibrations. These should typically display themselves as numerous relatively narrowband (on the order of one or two Hz bandwidth) lines that exist over frequency ranges of hundreds or thousands of Hz. Additionally, these line components will be modulated in both amplitude and frequency over time.

3.1.2 The resultant FFT frequency spectrums are very complicated and when the non-tracking in

frequency factor (as discussed in the frequency calibration section) is added in, the resulting analysis, to establish and define comparison measurements, becomes difficult. As a starting point, we shall look at commonplace items and select multiple line components in their broadband frequency structures for comparison measurement.

3.2 Factors Affecting Comparison Measurements

Factors affecting comparison measurement are listed below together with a discussion of the potential impact and our attempt at resolution of each.

3.2.1 Difference in Master Clocks--RLI versus Accelerometer System (AS)

3.2.1.1 For the calibration phase where the single tone vibrations were "pure tones" (i.e., at constant frequency and constant amplitude), we were able to compensate and adjust for the differences in the comparison measurement caused by the differences in the master clock frequencies (RLI versus AS); however, in comparison measurement of commonplace rotating equipment this became a large problem. In commonplace rotating equipment, the frequency of rotation is never constant; it is always varying with time over some small variation of perhaps 1 to 2 Hz. In addition, the accompanying vibration amplitudes are not constant and vary to some degree with time. The result is that there are no pure tone frequencies in the spectrum signature of commonplace rotating equipment. As a result, the line components will appear and be measured differently by the Fast Fourier Transform (FFT) in the RLI versus the FFT in the AS. In addition, the windowing that is performed prior to the FFT exacerbates this problem. Because clocks with slightly different frequencies will record vibrations at slightly different frequencies, comparing frequency by frequency would be faulty because the same vibration would be recorded at slightly different frequencies in the two different systems. Simple calculations indicate that this problem/factor may contribute possible errors on the order of ± 25 percent; a value that is unacceptable in our comparison measurement task.

3.2.1.2 After ascertaining the above impact on comparison measurement, EEI revisited (with greater incentive) the difference in the master clocks problem. A technique was developed and employed in the RLI, where RLI effectively adjusted its clock to track that of the AS such that the difference between the two (RLI versus AS) was, for the purposes of comparison measurement, zero.

3.2.1.3 The impact of differences in master clock frequencies was eliminated.

3.2.2 Coincidence in the Start of comparison measurement (RLI versus AS)

3.2.2.1 Both the RLI and AS receive the command to take data at the same time. However, the "off the shelf" analog to digital converter (A→D) mounted in the computer appears to have a pipeline processing element that does not allow it to start taking data at the same time in a repeatable fashion. The result is the difference in start time between the RLI and the AS may vary from 0 to 10 milliseconds.

3.2.2.2 This problem was considered, and it was realized that data recording for comparison measurement is always for one second or longer; therefore, the impact of the slight time difference on comparison measurement will be on the order of 10 millisecond divided by 1 second or less (i.e. <1 percent). We did not attempt to change the system any further and consider that the data taken was, for all practical purposes, simultaneous.

3.2.3 Electrical Interference

3.2.3.1 The accelerometers (WR 731 and WR 732) both see varying degrees of electrical interference due to 60 Hz and its harmonics, which is obvious in the baseline noise measurements and which is less obvious and probably stronger in measurements with equipment running. Machinery running under load will cause higher currents to be drawn. This interference varies as a function of each particular test implementation and may be due to ground loops that excite the input of the amplifiers within each accelerometer; the WR 732 is affected more strongly, perhaps because it is more closely coupled to the A/D

converter than the WR 731. The accelerometer systems are particularly sensitive to this problem since the 60-Hz (and harmonics) power interference is coherent with the measured vibrations at 60 Hz (and harmonics), that is, they may either coherently add or interfere with the measurement of physical vibrations. Additionally, these interference effects create intermodulation distortion that further affects many of the comparison measurements.

3.2.3.2 Since our accelerometers are not provided with "ground isolation" (a feature provided by at least one manufacturer on a few of its accelerometers) we would expect that electrical interference of one kind or another is normally encountered in the application of accelerometers. In our comparison measurements we will note it in those cases where it is observed to contaminate comparison measurements.

3.2.4 Non-Linearity

3.2.4.1 All sensor systems are non-linear to some degree. The output of the sensor system is not perfectly proportional to the input and this lack of exact proportionality is the non-linearity. The effect of the non-linearity on the measurement of an oscillating object is to create apparent new oscillations. Typically, in the event the oscillation is at a single frequency, the non-linearity will create apparent frequencies at integer multiples of the true oscillation; in the event the oscillation contains more than a single frequency (e.g., $a_1 \sin(\omega_1 t) + a_2 \sin(\omega_2 t)$), where $[\omega_1 = 2\pi F_1]$, the non-linearity will create apparent frequencies at all integer multiples and combinations of the original frequencies. In the case where the input frequencies are F_1 and F_2 , there will be an infinite set of output frequencies at the frequencies of $\pm mF_1$ and $\pm nF_2$ (m and n are integers); however, in most cases for m and $n \gg 1$, the amplitudes of these frequencies components approach zero. In the case of multiple input frequencies, the apparent frequencies in the output are termed "intermodulation distortion."

3.2.4.2 It is difficult to build/obtain a nearly perfect linear system; therefore, it is difficult to measure the non-linearity of a sensor system. As a result, it is not easy to quantify the effects of non-linearity on comparison measurement; however, in some cases we may infer some of its (non-linearity) general characteristics. Some of the effects and general characteristics will be observed and noted in various measurements for comparison measurement.

3.2.4.3 The RLI was designed and built with the goal of maintaining good linearity. Previous measurements on a tuning fork designed to have a very pure tone, (a high "Q") indicate that its non-linearity is on the order of 0.1 percent or less.

3.2.4.4 The WR 732 and WR 731 accelerometers are both specified to have a non-linearity of 1.0 percent or less.

3.2.5 Transverse Sensitivity (Synonym - Cross Axis Sensitivity) is the parameter quantifying the unwanted output signal picked up by a motion transducer when subject to motion perpendicular to the normal axis of operation. The transverse sensitivity is usually given in terms of the maximum percent of the normal axis sensitivity.

3.2.5.1 Accelerometer Transverse Sensitivity - The WR 731 has a transverse sensitivity that is specified as one percent of axial. The WR 732 has a transverse sensitivity that is specified to be five percent of axial.

3.2.5.2 The RLI Transverse Sensitivity is given by:

$$TS_{RLI} = 100 \sin(v)\%$$

where v is the angle measured from the perpendicular to the surface being measured. For example, for the RLI to be 5 degrees off from the perpendicular to the surface, being measured, then transverse sensitivity (@ 5 degrees off) = 8.7 percent. However, for good to perfect alignment, transverse sensitivity approaches zero. Transverse sensitivity can be controlled for the RLI.

3.2.5.3 The specific problem with transverse sensitivity is that if the component of vibration that is required to be measured has a much stronger

component in the transverse direction than in the intended direction of measurement, the transverse sensitivity of the sensors will cause the intended measurement to be substantially effected by the vibrations in the transverse direction.

3.2.5.4 In order to detect where this is a problem in our measurements, an additional channel has been added to the accelerometer system, that is, two accelerometers are simultaneously making measurements with the RLI. One of the accelerometers is used as a monitor perpendicular to the principal accelerometer and the RLI in order to gage the effect that off-axis vibrations may have on the primary measuring accelerometer. In addition, special care is taken to ensure that the RLI is well aligned.

3.2.6 Harmonics

3.2.6.1 Closely related to the factors of nonlinearity and transverse sensitivity are harmonics. A periodic vibration at a relatively constant frequency probably does not vibrate in a pure sinusoidal fashion; therefore, a perfect measurement of its motion would reveal harmonics of the fundamental frequency. Since our sensor systems are not perfect, we expect them to insert additional false harmonics over those that are true. The false harmonics are a problem for comparison measurement.

3.2.6.2 To understand the false harmonic problem consider the two systems (A and B) measuring a tonal vibration where each system has a slightly different level of nonlinearity. Let the vibration motion be:

$$v(t) = V \sin(\omega t), \text{ where } (\omega = 2\pi f)$$

where f is the vibration frequency. System A has a nonlinearity of 1% and measures $v(t)$. It measures the n^{th} harmonic as:

$$v_{an}(t) = .01V \sin(\omega t)$$

System B has a nonlinearity of 0.5% and measures $v(t)$. It measures the n^{th} harmonic as:

$$v_{bn}(t) = .005V \sin(\omega t).$$

If we take a ratio:

$$R_{abn} = [v_{an}(t)] \div [v_{bn}(2)] = 2$$

that is, the two systems each created a false harmonic and, system-to-system, the "measurement" of that false harmonic differs by a factor of 2. Therefore, false harmonics have the potential for serious errors in comparing measurements of harmonics by different systems.

3.2.7 Noise Floor and Signal-to-Noise Ratio (SNR)

3.2.7.1 The various signals to be measured for comparison measurement appear as "narrowband spikes" on top of a broadband background noise. For combinations of the factors mentioned earlier in this section (electrical interference, non-linearity and harmonics, principally), this background noise level is very complex, different from unit to unit and varies with operating conditions.

3.2.7.2 If a narrowband spike is 20 dB above the background noise, we say it has a signal-to-noise ratio of 20 dB (SNR = 20 dB). This implies that the signal in a frequency bin is approximately 10 times larger than the noise in that frequency bin. This says that the noise in the frequency bin is equal to 10 percent of the signal and that the noise has the potential to degrade the measurement of the signal in that frequency bin by up to approximately 10 percent. This effect will probably not be the same from system to system.

3.2.7.3 In resolving the impact of signal to noise ratio on the readings of the comparison measurements, two situations are encountered. In the first, the signal to noise ratio is similar in the measurements of both systems, so the machinery item itself is the source of the "noise floor." In the second case, there is a notable difference between measurement systems, so the situation is further investigated and attempts are made to understand what other measurement or interference phenomena may be contributing to a sensor "noise floor."

3.2.8 Minor Factors Impacting Measurements

3.2.8.1 Accelerometer Impact on Measurement -In some cases, either the mass or the dimensions of the measuring accelerometer may affect the vibration characteristics of the unit being measured. In these cases, and in other cases (for various reasons), the RLI will interrogate the casing of the accelerometer instead of what the accelerometer is mounted to. This ensures that the RLI is measuring what the accelerometer is measuring.

3.2.8.2 Ambient Noise - There is an air handling system (heating and cooling for building spaces) noise that varies over approximately 8 - 12 Hz.

3.3 Calibration Effort Summary

As a result of the calibration efforts it is recognized that the factors of electromagnetic interference, ground loops, harmonics, non-linearity, transverse sensitivity and signal-to-noise ratio all, to a degree that varies from test to test, make a contribution to the inaccuracy of accelerometer system readings. In light of this, and to simplify our efforts, we will consider agreement within ten percent (10 %), rather than the previously mentioned five percent (5%) to be good agreement.

3.4 Measurement and Data Formats

3.4.1 Time series measurements of acceleration are converted to spectrum levels that are in turn observed on a decibel (dB) basis relative to the acceleration due to gravity (1 g). The dB basis was chosen since it allows for simultaneous measurement over the entire dynamic range being measured.

3.4.2 The spectrums are limited to frequencies between 0 Hz and 2,048 Hz on a 1-Hz bin width. This is the region of more interest and seems to contain all of the available information for the units measured. In all cases, we scan the higher frequencies for possible high-frequency effects.

3.4.3 To resolve complicated frequency relationships, we sometimes employ high resolutions for better frequency measurements.

3.4.4 Amplitude measurements are always performed with 1-Hz bin widths, unless otherwise noted.

3.4.5 In most measurements, as previously mentioned, one of the accelerometers is employed as a monitor, normally perpendicular to the other in order to detect transverse sensitivity problems.

3.4.6 Those signals that are expected to be used for comparison measurement are read from the computer with a very high resolution and recorded in data tables.

4. Actual Comparison Measurements

4.1 Muffin Fan (Ventilation Fan #1) Measurement:

4.1.1 A ventilation fan removed from an electronics cabinet is our first item of commonplace machinery for demonstration. The fan, commonly, and hereafter, referred to as a muffin fan, is a three-bladed axial flow model that is similar to small fans often found in kitchen exhaust ventilation systems. The fan, which is driven by 60 Hz power is mounted as shown in Figure 4.1. The fan was tested under two conditions, loaded (moving air) or unloaded (flow blocked). The WR 732 accelerometer is mounted to measure the radial vibrations with the Robust Laser Interferometer (RLI) measuring the vibrations of the WR 732 casing. Since the fan is moving air perpendicular to the radial vibrations, the WR 731 accelerometer is mounted on the fan's face to monitor transverse vibrations, which may be seen by the WR 732 due to its transverse sensitivity.

4.1.2 Baseline measurements were taken with the fan off (test 1225) and measurements were taken with the fan running and free airflow (test 1226) and blocked airflow (test 1227). Table 4.1 shows the comparisons of the system outputs for the running tests and the plots of the WR 732 accelerometer and the RLI, taken simultaneously, are shown in Figures 4.2 and 4.3. Additional plots of other tested conditions are included in Volume 2, Appendix A.

4.1.3 A comparison of the plots shows good agreement, for the readings. Power frequencies, that is, multiples of 60 Hz, are typically seen to have a disparity. This is suspected to be due to the influence of the 60 Hz field and ground loops on the accelerometer system and is the subject of further investigation described later in the report.

Figure 4.1 Muffin Fan Configuration (Front View) for Test Series

Table 4.1 Muffin Fan Test Series 1226 and 1227

Test Number	f (1 Hz Bins)	ID	RLI (dB ref 1 g)	731 (dB ref 1 g)	732 (dB ref 1 g)	Difference 732 ref RLI	Comments
1226	27	rf	-28.26	-45.10	-27.56	8.39%	Harmonic RLI is L and 732 is L
	81	bf	-26.02	-36.87	-26.17	-1.76%	
	120	pf	-27.78	-20.46	-28.07	-3.32%	
	244	3(bf)	-37.97	-30.91	-38.52	-6.14%	
	480	pf	-34.61	-32.81	-36.16	-1.80%	
	716		-33.07	-41.81	-32.04	12.81%	
	1312	48(rf)	-28.85	-30.04	-29.23	-4.32%	
1227	27	rf	-37.52	-45.66	-36.79	8.83%	Probably Electrical Interference
	80	bf	-34.25	-51.09	-34.32	-0.83%	
	120	pf	-34.39	-28.81	-47.27	-12.46%	
	160		-32.93	-35.56	-33.19	-2.96%	
	240	pf & bf	-33.53	-28.95	-34.06	-5.95%	
	267		-38.13	-60.00	-38.50	-4.14%	
	641	24(rf)	-35.25	-58.81	-36.11	-9.48%	
	1295	48(rf)	-26.34	-29.08	-26.60	-2.86%	

NOTES:

- dB from 1 Hz bin width measurements

KEY:

SNR - Signal to local noise level

G - SNR > 20 dB

L - SNR < 20 dB

O - SNR < 0 dB

NOISE - Signal is "in the noise"

rf - Rotation Frequency

bf - Blade frequency

pf - Power frequencies (60 Hz and harmonics)

- Measurement probably contaminated by one or more factors

ID - Probable identification of the measured line

Figure 4.2 RLI Test Data, Muffin Fan

Figure 4.3 WR 732 Test Data, Muffin Fan

4.2 Pump System Measurement:

4.2.1 The second demonstration was made using a small five-vane centrifugal pump driven by a 1/4 horsepower A.C. motor. A system was arranged so that the pump took suction from and discharged to a small tank. Figure 4.4 illustrates the configuration.

4.2.2 The first group of test measurements consisted of measurements taken on the inlet and outlet connections of the pump. Figure 4.5 illustrates. Readings were taken with the pump off, to obtain a noise floor, and these results are included in Volume 2, Appendix B. The most illustrative measurements were taken with the pump running and the RLI targeted on the WR 732 accelerometer, which is mounted on the inlet connection of the pump. The WR 731 was mounted on the outlet connection of the pump during these tests. This was done in three configurations:

- Test 1229 - suction valve fully open
- Test 1230 - suction valve one-half open
- Test 1231 - suction valve closed

Table 4.2 shows the identifiable frequency lines from the measurements taken during these tests. Figures 4.6 and 4.7 are the plots of the data for test 1229, which show excellent agreement between the WR 732 accelerometer and the RLI. The plots of data for tests 1230 and 1231 are included in Volume 2, Appendix B.

4.2.3 Several additional configurations were tested, including targeting the RLI on the outlet connection of the pump and on the suction pipe upstream and downstream of the suction valve. Figures, tables and discussion of these results are included in Volume 2, Appendix B.

Figure 4.4 Pump Test Configuration

Figure 4.5 Pump Test Accelerometer Arrangement

Table 4.2 Pump Test Series

Test Number	f (Hz)	ID	RLI (dB ref 1 g)	731 (dB ref 1 g)	732 (dB ref 1 g)	Difference 732 ref RLI	Comments
1229	29	rf	-43.897	-39.432	-43.707	2.21%	Harmonic like - frequencies are related by multiples of 120 Hz
	30	rf	-44.752	-40.903	-45.132	-4.28%	
	120	pf	-6.818	-11.766	-6.876	-0.67%	
	147	vf	-27.015	-30.126	-27.079	-0.73%	
	240	pf	-27.845	-30.678	-28.111	-3.02%	
	294	2(vf)	-40.028	-48.192	-40.456	-4.81%	
	441	3(vf)	-45.411	-43.922	-45.928	-5.78%	
	1173		-51.045	-45.602	-50.740	3.57%	
	1293		-39.980	-33.651	-40.110	-1.49%	
	1773		-40.547	-44.832	-41.309	-8.40%	
	1893		-46.657	-48.850	-47.114	-5.13%	
	2013		-44.214	-48.166	-45.057	-9.25%	
1230	29	rf	-44.826	-40.490	-44.434	4.62%	Harmonic like - frequencies are related by multiples of 120 Hz
	30	rf	-43.915	-40.247	-44.096	-2.06%	
	120	pf	-6.804	-11.275	-6.864	-0.69%	
	148	vf	-28.073	-35.335	-28.273	-2.28%	
	296	2(vf)	-44.102	-56.753	-44.582	-5.38%	
	443	3(vf)	-53.834	-45.650	-53.319	6.11%	
	1180		-48.604	-45.280	-48.760	-1.78%	
	1300		-36.150	-30.125	-36.364	-2.43%	
	1780		-45.986	-44.541	-47.056	-11.33%	
	1900		-45.003	-43.741	-46.401	-14.87%	
	2020		-49.330	-54.850	-49.538	-2.37%	
1231	29	rf	-44.373	-39.815	-43.931	5.22%	Harmonic like - frequencies are related by multiples of 120 Hz
	30	rf	-43.019	-39.217	-43.193	-1.98%	
	120	pf	-6.996	-12.318	-7.048	-0.60%	
	148	vf	-35.289	-43.191	-34.806	5.72%	
	296	2(vf)	-46.083	-52.742	-46.274	-2.17%	
	445	3(vf)	-46.376	-47.615	-46.321	0.64%	
	1185		-47.835	-45.657	-48.190	-4.00%	
	1305		-35.712	-29.257	-35.856	-1.64%	
	1785		-51.024	-52.998	-51.943	-10.04%	
	1905		-42.820	-40.863	-43.774	-10.02%	
	2025		-52.873	-51.022	-54.848	-20.24%	

NOTES:

- dB from 1 Hz bin width measurements

KEY:

SNR - Signal to local noise level

G - SNR > 20 dB

L - SNR < 20 dB

O - SNR < 0 dB

NOISE - Signal is "in the noise"

rf - Rotation Frequency

vf - Vane rotation frequency

pf - Power frequencies (60 Hz and harmonics)

- Measurement probably contaminated by one or more factors

ID - Probable identification of the measured line

Figure 4.6 RLI Pump Test Data

Figure 4.7 WR 732 Pump Test Data

4.3 Rotor Kit Measurement

4.3.1 The third demonstration was made using a Bently-Nevada rotor test kit, a commonly used demonstration device in the instrumentation industry. The rotor kit, and the accelerometer mounting locations are shown in Figures 4.8 and 4.9. The rotor kit consists of a variable speed D.C. motor coupled (via a rubber coupling) to a long shaft that is suspended at both ends by bearings contained in bearing housings. Mounted on the shaft, between the bearings, is a mass that can be adjusted in and out of balance. The motor speed control provides a variable D.C. voltage to control the speed of the D.C. motor.

4.3.2 There are several electrical compromises in the construction of the rotor kit, such as having all stationary metal parts grounded, causing ground loop problems, and having 60 Hz modulations appear on the rectified D.C. power. In addition to this, speed is controlled by an induction circuit that senses the passing of twelve evenly spaced notches on the rotating system. A speed control function is then taken twelve times each rotation. These compromises and peculiarities make the measurement task of the accelerometers particularly difficult.

4.3.3 Two tests, 1256 and 1257 were selected from the others to illustrate the impact of these problems. For these tests the unit was running at 4,140 RPM (69 Hz). Table 4.3 shows the results of the tests. The WR 731 accelerometer, despite being within its linear range, was having measurement problems. WR 731 is considerably influenced by the power (60 and 120 Hz) modulations on the speed correction signal (12 times 69 Hz or 828 Hz). The readings on the lower modulations, such as 347.5 Hz (12 times 69 Hz minus 4 times 120 Hz) are off by almost 100%. The upper modulations around 828 Hz are not nearly so erratic. In addition, there is considerable presence of 9 Hz (69 Hz minus 60 Hz) and 18 Hz (two times 69 Hz minus 120 Hz) in the readings of both the WR 731 and WR 732 accelerometers. These and other lower frequency modulations contribute to the flat noise floor across the lower frequencies. The RLI readings have a greatly reduced presence of these power and control frequency signals and have a much lower noise floor in the lower frequencies. Figures 4.10 through 4.15 illustrate.

4.3.4 Several additional tests are included in Volume 2, Appendix C. In one of these, test #1265, a severe intermodulation distortion is demonstrated. In this situation, the RLI is shown to have a linearity that is on the order of .0001%, or approximately four orders of magnitude better than the WR 731 accelerometer.

Figure 4.8 Bently-Nevada Rotor Kit

Figure 4.9 Rotor Kit Accelerometer Locations

Table 4.3 Rotor Kit Test Results

Test Number	ID	f (1 Hz Bins)	f (1/8 Hz Bins)	RLI (dB ref 1 g)	731 (dB ref 1 g)	Difference 731ref RLI	732 (dB ref 1 g)	Difference 732 ref RLI	Comments
1256-1 Hz Bins 1257-1/8 Hz Bins	rf	69	69.000	-22.099	-22.826	-8.03%	-22.309	-2.39%	The 731 is G and the 732 is O ↑ Harmonics ↓
	2rf	138	138.000	-49.592	-52.695	-30.04%	-49.711	-1.36%	
	3rf	208	207.000	-57.615	NOISE		-60.476	-28.06%	
	4rf	277	276.000	-49.430	-51.829	-24.13%	-51.938	-25.08%	
	5rf	346	345.000	-57.310	-60.599	-31.62%	-58.414	-11.94%	
	6rf	415	414.000	-60.758	-63.797	-29.62%	-61.805	-11.36%	
	7rf	485	483.000	-57.181	-58.841	-17.40%	-57.493	-3.53%	
	8rf	554	552.000	-48.180	-49.279	-11.88%	-49.080	-9.64%	
									↑ Frequencies are related to motor control and power ↓
	12rf	831	828.000	-15.023	-16.388	-14.64%	-16.192	-12.59%	
	2(12rf)	1662	1655.875	-47.452	-47.224	2.66%	-46.810	7.67%	
	12rf-60	771	767.875	-18.359	-19.926	-16.61%	-19.578	-13.09%	
	12rf-120	711	707.875	-27.053	-29.169	-21.62%	-28.352	-13.89%	
	12rf-3(60)	651	647.875	-34.180	-36.327	-21.90%	-35.568	-14.77%	
	12rf-2(120)	591	587.875	-42.298	-42.701	-4.63%	-43.916	-17.00%	
	12rf-5(60)	531	527.875	-50.076	-46.634	48.83%	-51.092	-11.04%	
	12rf-3(120)	471	467.875	-54.808	-49.608	81.97%	-55.900	-11.81%	
	12rf-7(60)	411	407.875	-78.799	-59.738	197.63%	-78.000	9.64%	
	12rf-4(120)	351	347.750	-62.286	-56.536	93.87%	-65.550	-21.32%	
	12rf-9(60)	291	287.750	-69.409	-53.329	636.83%	-70.430	-11.03%	
	12rf-5(120)	231	227.750	-71.757	-51.534	926.01%	-74.187	-24.40%	
	12rf-11(60)	171	167.750	-89.000	-52.564	8634.37%	NOISE		
	12rf+60	891	888.000	-23.484	-25.020	-16.21%	-24.650	-12.66%	
	12rf+120	951	948.000	-29.465	-30.655	-12.80%	-30.557	-11.61%	
	12rf+3(60)	1011	1008.000	-33.538	-34.092	-5.16%	-34.914	-14.85%	
	12rf+2(120)	1071	1068.000	-27.667	-28.298	-7.01%	-29.097	-16.16%	
	12rf+5(60)	1131	1128.000	-38.225	-38.939	-7.89%	-39.639	-16.02%	
	12rf+3(120)	1191	1188.125	-39.219	-40.289	-11.58%	-40.555	-14.28%	
	12rf+7(60)	1251	1248.125	-34.765	-34.714	0.05%	-36.061	-13.86%	
	12rf+4(120)	1311	1308.125	-41.290	-42.487	-12.67%	-42.504	-13.04%	
	12rf+9(60)	1371	1368.125	-37.258	-37.906	-7.18%	-38.550	-13.82%	
	12rf+5(120)	1431	1428.125	-40.489	-40.471	0.21%	-41.711	-13.12%	
	12rf+11(60)	1491	1488.125	-45.131	-45.403	-3.08%	-46.647	-16.02%	

NOTES:

- dB from 1 Hz bin width measurements
- 1/8 Hz measurements are used to facilitate ID

KEY:

SNR - Signal to local noise level
G - SNR > 20 dB
L - SNR < 20 dB
O - SNR < 0 dB
NOISE - Signal is "in the noise"

rf - Rotation Frequency
vf - Vane rotation frequency
pf - Power frequencies (60 Hz and harmonics)
- Measurement probably contaminated by one or more factors
ID - Probable identification of the measured line

Table 4.3a Rotor Kit Test Results (continued)

Test Number	ID	f (1 Hz Bins)	f (1/8 Hz Bins)	RLI (dB ref 1 g)	731 (dB ref 1 g)	Difference 731ref RLI	732 (dB ref 1 g)	Difference 732 ref RLI	Comments
1256-1 Hz Bins 1257-1/8 Hz Bins (continued)	rf-60	9	9.250	NS	-52.251	NA	NOISE	NA	Intermodulation distortion
	2(rf-60)	18	18.000	NS	-58.323	NA	NOISE	NA	
	3(rf-60)	28	26.875	NS	-65.453	NA	NOISE	NA	Power frequency Power frequency
	60	60	60.000	-62.109	-50.882	-11.227	-56.290	-6.408	
	120	120	120.000	-47.862	-49.905	-2.043	-47.858	0.005	

NOTES:

- dB from 1 Hz bin width measurements
- 1/8 Hz measurements are used to facilitate ID

KEY:

- SNR - Signal to local noise level
- G - SNR > 20 dB
- L - SNR < 20 dB
- O - SNR < 0 dB
- NOISE - Signal is "in the noise"
- NS - No signal (The signals seen by the accelerometers are artifacts created by the intermodulation distortion; therefore, there is no true vibration (signal) for the RLI to measure.)

- rf - Rotation Frequency
- vf - Vane rotation frequency
- pf - Power frequencies (60 Hz and harmonics)
- Measurement probably contaminated by one or more factors
- ID - Probable identification of the measured line
- NA - Not Applicable

Figure 4.10 RLI Rotor Kit Test Data

Figure 4.11 WR 731 Rotor Kit Test Data

Figure 4.12 WR 732 Rotor Kit Test Data

Figure 4.13 RLI Rotor Kit Test Data (Low Frequency)

Figure 4.14 WR 731 Rotor Kit Test Data (Low Frequency)

Figure 4.15 WR 732 Rotor Kit Test Data (Low Frequency)

4.4 Cement Mixer Measurement

4.4.1 The fourth test item was a small cement mixer driven by a 1/2 horsepower A.C. motor. The motor drives a belt that provides a speed reduction of approximately 3.5:1 to a gearbox where a worm gear turns a larger gear directly coupled to the drum of the mixer. The total reduction from the 3600 RPM motor to the drum rotation rate of approximately 26 RPM is approximately 130:1. The drum is suspended from the gearbox and has two internal paddles, which mix the contents. Figures 4.16 and 4.17 illustrate.

4.4.2 The mixer was tested in the unloaded and loaded (120 pounds of sand, 2 gallons of water) condition. The WR 732 accelerometer was installed on the gearbox near the worm gear bearing, and the WR 731 was installed perpendicular to it nearby. Vibration levels were very strong, and the WR 731 (rated only to .5 g) was overdriven substantially during much of the testing. For this reason, the RLI was targeted at the WR 732, principally. Tests 1272 and 1273, with the cement mixer unloaded, are shown in Table 4.4, which illustrates the good comparison between the WR 732 and RLI readings. The plots of test 1273, included as Figures 4.18 and 4.19 show the very good comparison except at the lowest frequencies. Figure 4.20, a low frequency expansion of Figure 4.18, clearly shows the drum rotational frequency at .438 Hz and the two times drum rotational frequency (which corresponds to the paddle frequency) at approximately .885 Hz. By referring back to Figure 4.19, the much higher noise floor of the WR 732 accelerometer makes the identification of these lines impossible in the accelerometer output.

4.4.3 The loaded test of the mixer, tests 1274 and 1276 is also included here. Here the WR 732 and RLI agree well, but the WR 731 is still overdriven and its response is erratic. Table 4.5 shows that there is considerable harmonic activity in the lower frequencies, from .438 Hz to 6 Hz, but a comparison of the lower frequency plots from test 1276, Figures 4.21 and 4.22 show a substantial difference in measurement capability in the low frequency ranges. Figure 4.23 is a low frequency expansion of Figure 4.21 and shows the benefit of the lower noise floor of the RLI at these frequencies.

Figure 4.16 Cement Mixer Front View

Figure 4.17 Cement Mixer Rear View

Table 4.4 Cement Mixer Test Series Results (Unloaded)

Test Number	ID	f (1 Hz Bins)	f (1/16 Hz Bins)	RLI (dB ref 1 g)	731 (dB ref 1 g)	732 (dB ref 1 g)	Difference 732 ref RLI	Comments
1272-1 Hz Bins	drf		0.438					
	2(drf)		0.875					
	17(drf)	7	7.125	-60.191	NOISE	-61.522	-14.21%	Harmonic
1273-1/16 Hz Bins			12.688					
			15.938					
			16.375					
	gbisrf	17	16.813	-49.770	NOISE	-51.341	-16.55%	Contains harmonics of drf
			17.188					
			18.063					
		25	25.375	-62.563	NOISE	-62.309	2.97%	
			29.438					
			32.750					
			33.125					
	2(gbisrf)	33	33.563	-58.945	NOISE	-51.417	137.90%	Harmonic
			34.000					
			34.375					
		38	38.063	-42.363	NOISE	-42.138	2.62%	
	3(gbisrf)	51	50.688	-59.204	NOISE	-56.706	33.32%	Harmonic
			56.188					
			58.938					
	mrf	60	59.813					
	pf	60	60.000	-14.832	-17.387	-14.391	5.21%	
			60.625					
		63	63.375	-39.927	-46.579	-39.468	5.43%	
			67.125					
			67.500					
			71.938					
			72.500					
			76.063					
			80.188					
			83.938					
			88.750					
		89	89.125	-40.623	-38.362	-40.542	0.94%	
		102	101.375	-47.045	-39.532	-46.693	4.14%	
			105.500					
		114	114.063	-46.975	-35.163	-46.578	4.68%	
			117.500					
	2(mrf)		119.693					

NOTES:

- dB from 1 Hz bin width measurements
- 1/16 Hz measurements are used to facilitate ID

KEY:

- drf - Drum Rotation Frequency
- mrf - Motor Rotation Frequency
- pf - Power Frequencies (60 Hz and harmonics)
- gbisrf - Gear Box Input Shaft Frequency

Alphanumeric - 731 is operating well out of its specified +J78 range

NOISE - Signal is "in the noise"

ID - Probable identification of the measured line

Alphanumeric - Measurement probably contaminated by one or more factors

Table 4.4a Cement Mixer Test Series Results (Unloaded) (continued)

Test Number	ID	f (1 Hz Bins)	f (1/16 Hz Bins)	RLI (dB ref 1 g)	731 (dB ref 1 g)	732 (dB ref 1 g)	Difference 732 ref RLI	Comments
1272-1 Hz Bins 1273-1/16 Hz Bins (continued)	pf	120	120.000	-34.124	-26.034	-33.804	3.75%	
			120.438					
			120.875					
			126.750					
			130.875					
			134.207					
			139.000					
		140	139.438	-22.070	-22.145	-21.972	1.13%	
			139.875					
			151.688					
		152	152.125	-28.074	-18.526	-27.790	3.32%	
			152.500					
			184.188					
		185	184.625	-32.738	-22.696	-32.458	3.28%	
			185.063					
			190.125					
		202	202.375					
			202.813	-29.065	-26.263	-28.796	3.15%	
			203.250					
		203	203.625					
			418.125					
			419.875					
		420	420.250					
			420.688					

NOTES:

- dB from 1 Hz bin width measurements
- 1/16 Hz measurements are used to facilitate ID

KEY:

- drf - Drum Rotation Frequency
- mrf - Motor Rotation Frequency
- pf - Power Frequencies
(60 Hz and harmonics)
- gbisrf - Gear Box Input Shaft Frequency

- Alphanumeric - 731 is operating well out of its specified range
- NOISE - Signal is "in the noise"
- ID - Probable identification of the measured line
- Alphanumeric - Measurement probably contaminated by one or more factors

Table 4.5 Cement Mixer Test Series Results (Loaded)

Test Number	ID	f (1 Hz Bins)	f (1/16 Hz Bins)	RLI (dB ref 1 g)	731 (dB ref 1 g)	732 (dB ref 1 g)	Difference 732 ref RLI	Comments
1274-1 Hz Bins 1276-1/16 Hz Bins	drf		0.438					Harmonic Contains harmonics of drf
			0.813					
			1.188					
			1.625					
			2.000					
			2.375					
			2.813					
			3.188					
		6	6.063	-32.477	-33.272	-34.281	-18.75%	
		13	NOISE	-44.456	-42.697	-44.744	-3.26%	
		36	36.313	-45.200	-48.191	-44.748	5.34%	
	mrf	59	59.000	-21.516	-38.254	-20.483	12.63%	
			60.500					
		85	84.750	-43.962	-36.718	-43.444	6.15%	
		112	111.688	-44.980	NOISE	-44.654	3.82%	
		120	120.063	-35.672	-41.609	-35.525	1.71%	
		145	144.875	-44.707	NOISE	-44.122	6.97%	
		160	159.688	-43.757	-42.979	-43.72	0.43%	
		176	175.688	-36.722	-39.413	-36.528	2.26%	
		193	193.250	-31.828	NOISE	-31.558	3.16%	
		597	NOISE	-24.804	NOISE	-24.769	0.40%	

NOTES:

- dB from 1 Hz bin width measurements
- 1/16 Hz measurements are used to facilitate ID

KEY:

- drf - Drum Rotation Frequency
- mrf - Motor Rotation Frequency
- pf - Power Frequencies (60 Hz and harmonics)
- gbisrf - Gear Box Input Shaft Frequency

- Alphanumeric** - 731 is operating well out of its specified range
- NOISE** - Signal is "in the noise"
- ID** - Probable identification of the measured line
- Alphanumeric** - Measurement probably contaminated by one or more factors

Figure 4.18 RLI Cement Mixer Test Data (Unloaded)

Figure 4.19 WR 732 Cement Mixer Test Data (Unloaded)

Figure 4.20 RLI Cement Mixer Test Data (Unloaded) (Low Frequency Expansion)

Figure 4.21 RLI Cement Mixer Data (Loaded)

Figure 4.22 WR 732 Cement Mixer Data (Loaded)

Figure 4.23 RLI Cement Mixer Data (Loaded) (Low Frequency Expansion)

4.5 Twin Fan (Ventilation Fan #2) Measurements

4.5.1 Twin Fan Arrangement: The fifth demonstration unit selected was a used window fan which contains two identical fans in a flexible housing. This fan is shown in Figures 4.24 and 4.25. The fans were near the end of their useful life. One of the fans, called the "good fan" runs reasonably well and turns reasonably freely. The other fan, called the "bad fan" needs to be pushed to get started. The shaft of the "bad fan" is very loose and an intermittent rub can be felt when it is turned by hand. Numerous problems were encountered in attempting to test this set of fans and these are discussed in Appendix E. One worthwhile demonstration was produced by this test article.

4.5.2 Good Fan Blocked, Bad Fan

Running: Tests #1294 and #1295 were done with the bad fan running and the good fan blocked. Figures 4.26, 4.27 and 4.28 illustrate a strong harmonic content in their measurement and Table 4.6 identifies these frequencies. This is a classical signature for a "loose shaft" or a "rotor rub" and illustrates the good comparison between the WR 732 and the RLI after making allowance for the interference factors.

Figure 4.24 Twin Fan Configuration (Top View)

Figure 4.25 Twin Fan Configuration (Side View)

Figure 4.26 RLI Twin Fan Test Data

Figure 4.27 WR 732 Twin Fan Test Data

Table 4.6 Twin Fan Test Results

Test Number	f (1 Hz Bins)	f (1/16 Hz Bins)	ID	RLI (dB ref 1 g)	731 (dB ref 1 g)	732 (dB ref 1 g)	Difference 732 ref RLI	Comments
1292 1293	21	20.813		-53.006	-45.126	-53.680	-7.47%	RLI is L and 732 is L Harmonic Harmonic Harmonic RLI is L and 732 is L RLI is L and 732 is L
	28	27.250	rf	-30.687	NOISE	-31.919	-13.22%	
	30	30.313		-31.902	-22.236	-32.554	-7.23%	
	39	39.125		-55.260	-42.810	-55.225	0.40%	
	55	54.938	2(rf)	-62.314	NOISE	-66.310	-38.68%	
	60	60.000	pf	-40.858	-27.762	-42.984	-21.71%	
	81	80.875	3(rf)	-48.308	-42.070	-49.949	-17.22%	
	90	89.688		-38.536	-22.885	-38.145	4.60%	
	111	110.688	bf	-35.286	-22.779	-36.885	-18.81%	
	120	120.000	pf	-22.265	-7.372	-23.751	-15.72%	
	150	150.375		-31.772	-25.011	-30.493	15.86%	
	210	209.688		-29.635	-25.160	-28.850	9.46%	
	231	230.750		-33.960	-39.857	-33.498	5.46%	
	261	251.063		-31.243	-29.903	-30.858	4.53%	
	471	471.063		-29.113	-30.254	-30.402	-13.79%	
	498	498.063		-34.774	-44.179	-35.967	-12.83%	
1294 1295	14	13.625	5(rf)	-84.677	-45.628	-80.580	60.27%	With the exception of 60 Hz and 120 Hz, all other frequencies are multiples of 0.5(rf)
	27	26.688	rf	-34.463	-31.390	-35.427	-10.50%	
	40	39.625	1.5(rf)	-54.217	-47.587	-55.227	-10.98%	
	53	53.313	2(rf)	-51.555	-38.158	-52.475	-10.05%	
	60	60.000	pf	NOISE	NOISE	-69.609		
	67	66.563	2.5(rf)	-43.478	-31.216	-44.459	-10.63%	
	80	80.125	3(rf)	-47.320	-41.523	-48.690	-14.58%	
	93	93.438	3.5(rf)	-51.574	-25.412	-50.155	17.75%	
	107	107.188	bf	-42.742	-35.621	-44.309	-16.51%	
	120	120.063	pf	-16.997	-6.463	-18.002	-10.93%	
	213	213.438	2(bf)	-17.724	-25.703	-17.826	-1.17%	
	267	266.750	10(rf)	-15.396	-14.410	-15.479	-0.95%	
	454	454.563	17(rf)	-22.321	-20.573	-22.489	-1.92%	
1296 1297	26	20.813	rf					Contains Harmonics SNR is L SNR is L Intermodulation Distortion
	34	25.813	rf	-31.960	-29.676	-33.037	-11.66%	
	46	34.625		-56.228	-57.206	-56.458	-2.61%	
	60	46.625		-48.791	NOISE	-48.899	-1.24%	
	69	60.000	pf	-45.062	-35.275	-47.064	-20.59%	
	97	69.125		-48.782	-39.456	-51.559	-27.36%	
	120	97.438		-39.837	-29.375	-40.641	-8.84%	
	143	120.000	pf	-17.658	-9.288	-17.468	2.21%	
	217	140.827		-29.965	-21.808	-28.370	20.16%	
	286	217.375		-25.435	-23.260	-25.138	3.48%	
	389	285.563		-22.424	-28.144	-22.678	-2.88%	
	509	389.000		-28.329	-33.990	-28.206	1.43%	
		509.250		-25.883	-34.108	-26.533	-7.21%	

NOTES:

- dB from 1 Hz bin width measurements
- 1/16 Hz measurements are used to facilitate ID
- SNR - Signal to local noise level

KEY:

- rf - Rotation frequency
- bf - Blade frequency
- pf - Power Frequencies (60 Hz and harmonics)
- L - SNR < 20 dB

- Alphanumeric - 731 is operating well out of its specified range
- NOISE - Signal is "in the noise"
- ID - Probable identification of the measured line
- Alphanumeric - Measurement probably contaminated by one or more factors

5. Findings, Conclusions, and Recommendations

5.1 Findings

The RLI makes readings that are comparable to, and often better than, accelerometer systems. When accelerometer application problems are obvious, such as ground loops, electrical interference, or non-linearity, RLI provides readings that are without the interferences and are judged to be better than accelerometer measurements.

5.2 Conclusions

The RLI, because it is able to measure as well as accelerometer systems in situations where accelerometer systems are working well, and because it is able to measure with similar accuracy in situations where accelerometer systems are encountering electrical interference and other difficulties, is a potentially beneficial technology for condition based assessment using vibration monitoring. Because of its demonstrated non-contact, line-of-sight capability, it is potentially beneficial for vibration measurement in hard-to-reach locations or where personnel access is difficult.

5.3 Recommendations

The RLI should be more deeply investigated as a vibration sensing system for condition based assessment of machinery in service. Because it is able to measure vibrations as accurately, and often more accurately, than accelerometer systems; and because of its ability to measure in a line-of-sight, non-contacting fashion, it offers obvious advantages. The ability to send the laser signal, and return the vibration signature, through a fiberoptic cable should be investigated to see if a central monitoring system using a single, centrally located laser is practical. Due to the widespread, reasonably effective use of accelerometers throughout industry, the RLI should be investigated for major replacement programs or new design installations.

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Results of Phase I Small Business Innovation Research Contract Efforts

11. ABSTRACT (200 words or less)

Epoch Engineering, Incorporated (EEI) has completed a series of vibration measurements comparing their newly-developed Robust Laser Interferometer (RLI) with accelerometer instrumentation systems. EEI has successfully demonstrated, on several pieces of commonplace machinery, that non-contact, line-of-sight measurements are practical and yield results equal to or, in some cases, better than customary field implementations of accelerometers. The demonstration included analysis and comparison of such phenomena as nonlinearity, transverse sensitivity, harmonics, and signal-to-noise ratio. Fast Fourier Transformations were performed on the accelerometer and the laser system outputs to provide a comparison basis. The RLI was demonstrated, within the limits of the task, to be a viable, line-of-sight, non-contract alternative to accelerometer systems. Several different kinds of machinery were instrumented and compared, including a small pump, a gear-driven cement mixer, a rotor kit, and two small fans. Known machinery vibration sources were verified and RLI system output file formats were verified to be compatible with commercial computer programs used for vibration monitoring and trend analysis. The RLI was also observed to be less subject to electromagnetic interference (EMI) and more capable at very low frequencies.

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