Robust, Accurate, and Non-Contacting Vibration Measurement Systems

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Supplemental Appendices Presenting 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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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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APPENDIX A

A-1. Muffin Fan (Ventilation Fan #1) Test

A-1.1 Muffin Fan Test

Arrangement: The first unit selected for comparison measurement testing was a three bladed ventilation fan removed from an electronics cabinet. The fan is similar in construction to fans used in kitchen exhaust ventilation systems. The fan is shown in Figure A-1 and A-2. The fan was tested in two configurations, running with the air passing freely, and running with air flow blocked. The WR-732 is mounted to measure the radial vibrations of the casing and the RLI is targeted at the casing of the WR-732. Since the fan is moving air perpendicular to the radial direction, the WR-731 is mounted on the fan's face to monitor transverse vibrations that may be seen by the WR-732 because of its transverse sensitivity. Baseline noise levels were measured for each sensor system with the fan turned off. These are shown in Figures A-3, A-4 and A-5.

A-1.2 Fan Running, Free Airflow:

In this test (#1226) the fan is running and moving air in a normal fashion. The RLI is targeted on the WR-732 accelerometer. Figures A-6 and A-7 illustrate the comparison measurements for this test set and indicate a good comparison. Table A-1 provides a quantified comparison of some of the more prominent lines.

A-1.3 Fan Running, Airflow

Blocked: In this test (#1227) the fan is running and airflow is blocked as much as possible. This represents an unloaded condition for the fan. Figures A-8 and A-9 illustrate the comparison measurements for this test and Table A-1 provides quantified data for some of the measurements.

Figure A-1 Muffin Fan (Front View)

Figure A-2 Muffin Fan (Side View)

Figure A-3 RLI Muffin Fan Baseline Noise Data (stopped)

Figure A-4 WR 731 Muffin Fan Baseline Noise Data (stopped)

Figure A-5 WR 732 Muffin Fan Baseline Noise Data (stopped)

Figure A-6 RLI Muffin Fan Data (Fan Running, Free Air Flow)

Figure A-7 WR 732 Muffin Fan Data (Fan Running, Free Air Flow)

Table A-1 Muffin Fan Test Series

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	-16.30%	
	716		-33.07	-41.81	-32.04	12.51%	
	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	-77.29%	
	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 A-8 RLI Muffin Fan Data (Fan Running, Flow Blocked)

Figure A-9 WR 732 Muffin Fan Data (Fan Running, Flow Blocked)

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APPENDIX B

B-1. Pump Test Results

B-1.1 Pump Test Configuration:

The second system tested was a small five-vane centrifugal pump driven by a 1/4 horsepower A.C. motor. The pump is arranged to take suction from and discharge to a tank. Figure B-1 illustrates the configuration of the pumping system and the tank.

B-1.2 Pump Baseline Test: Figure B-2 shows the location of accelerometers on the pump as tested. In the baseline test, #1228, there was no power supplied to the pump. Figures B-3, B-4 and B-5 indicate that the accelerometers and the RLI all see reasonably low noise floors and no power interference.

B-1.3 Pump Running, Pump Measurements, Inlet Comparisons:

For tests #1229, 1230 and 1231 the pump was running and the suction valve was fully open (#1229), half open (#1230) and closed (#1231.) The RLI was targeted at the casing of the WR-732 accelerometer which was mounted on the inlet connection of the pump. The WR-731 is mounted on the outlet connection. Figures B-6 through B-14 show good agreement between the RLI and the WR-732. Table B-1 quantifies some of the frequency readings that show excellent agreement for those readings that are uncontaminated.

B-1.4 Pump Running, Pump Measurements, Outlet Comparisons:

Tests #1232, 1233, and 1234 are repeats of 1229, 1230 and 1231 respectively except that the RLI is targeted on the casing of the WR-731 which is on the outlet connection of the pump. Figures B-15 through B-23 show the results and Table B-2 provides a quantification of some of the measured lines. Again, allowing for some contaminating factors, the agreement is very good.

B-1.5 Pump Running, Piping Measurements

B-1.5.1 For tests #1235, 1236 and 1237 measurements were made with the WR-732 accelerometer downstream of the valve installed in the suction piping. The valve was fully open (#1235), half open (#1236) and closed (#1237). The RLI was again targeted at the casing of the WR-732 accelerometer. As can be seen in Table B-3, agreement is excellent. Figure B-24 shows the location of the accelerometer and Figures B-25 and B-26 are examples of the comparison plots.

B-1.5.2 For tests #1239, 1240 and 1241 measurements were made with the WR-732 accelerometer upstream of the valve installed in the suction piping. The valve was fully open (#1239), half open (#1240) and fully closed (#1241). The RLI was targeted at the casing of the WR-732 accelerometer. As can be seen in Table B-4, agreement is excellent. Figure B-27 shows the location of the accelerometers and Figures B-28 and B-29 are examples of the comparison plots.

B-1.5.3 For tests #1242, 1243 and 1244 measurements were made with the WR-732 accelerometer much farther upstream of the valve installed in the suction piping. The valve was fully open (#1242), half open (#1243) and fully closed (#1244). The RLI was targeted at the casing of the WR-732 accelerometer. As can be seen in Table B-5, agreement is excellent. Figure B-30 shows the location of the accelerometers and Figures B-31 and B-32 are examples of the comparison plots.

Figure B-1 Pump Test Configuration

Figure B-2 Pump Test Series 1229, 1230, 1231, 1232, 1233, and 1234

Figure B-3 RLI Pump Test Data (stopped)

Figure B-4 WR 731 Pump Test Data (stopped)

Figure B-5 WR 732 Pump Test Data (stopped)

Figure B-6 RLI Pump Test Data (running, suction open)

Figure B-7 WR 731 Pump Test Data (running, suction open)

Acceleration plot of D41-1229

Figure B-8 WR 732 Pump Test Data (running, suction open)

Figure B-9 RLJ Pump Test Data (running suction half-open)

Figure B-10 WR 731 Pump Test Data (running suction half-open)

Figure B-11 WR 732 Pump Test Data (running suction half-open)

Figure B-12 RLI Pump Test Data (running, suction closed)

Figure B-13 WR 731 Pump Test Data (running, suction closed)

Figure B-14 WR 732 Pump Test Data (running, suction closed)

Table B-1 Pump Test Series 1229, 1230, and 1231

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	-11.68%	
	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	-10.40%	
	2025		-52.873	-51.022	-54.848	-20.34%	

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 B-15 RLI Pump Test Data (running, suction open)

Figure B-16 WR 731 Pump Test Data (running, suction open)

Figure B-17 WR 732 Pump Test Data (running, suction open)

Figure B-18 RLI Pump Test Data (running suction half open)

Figure B-19 WR 731 Pump Test Data (running suction half open)

Figure B-20 WR 732 Pump Test Data (running suction half open)

Figure B-21 RLI Pump Test Data (running, suction closed)

Figure B-22 WR 731 Pump Test Data (running, suction closed)

Figure B-23 WR 732 Pump Test Data (running, suction closed)

Table B-2 Pump Test Series 1232, 1233, and 1234

Test Number	f (Hz)	ID	RLI (dB ref 1 g)	731 (dB ref 1 g)	Difference 731 ref RLI	732 (dB ref 1 g)	Comments
1232	29	rf	-42.463	-41.835	7.50%	-45.874	RLI is L and 731 is L
	37		-45.729	-45.198	6.30%	-49.386	
	46		-37.884	-37.406	5.66%	-40.786	
	59	pf	-38.863	-38.768	1.10%	-41.578	
	68		-41.765	-41.574	2.22%	-44.560	
	78		-40.347	-40.299	0.55%	-41.603	
	99		-39.498	-39.418	0.93%	-40.911	
	120	pf	-13.748	-14.268	-5.81%	-7.806	
	146	vf	-29.326	-29.880	-6.18%	-26.833	
	292	2(vf)	-47.554	-45.835	21.88%	-44.060	
	439	3(vf)	-41.463	-41.911	-5.03%	-49.394	
	480	pf	-40.524	-39.767	9.11%	-32.984	
	600	pf	-51.547	-52.783	-18.26%	-47.101	
1233	29	rf	-41.450	-40.677	9.31%	-44.517	RLI is L and 731 is L
	30	rf	-39.789	-39.475	3.68%	-43.542	
	59	pf	-41.030	-41.014	0.18%	-43.547	
	120	pf	-11.850	-11.881	-0.36%	-6.706	
	147	vf	-34.757	-36.151	-14.63%	-28.786	
	331		-50.799	-49.880	11.18%	-56.262	
	443	3(vf)	-45.437	-45.673	-2.68%	-51.210	
	480	pf	-39.396	-38.572	9.95%	-32.531	
	600	pf	-46.162	-47.033	-9.54%	-43.333	
1234	30	rf	-39.905	-39.644	3.05%	-43.487	RLI is L and 731 is L
	59	pf	-35.352	-35.314	0.44%	-37.837	
	120	pf	-11.954	-11.847	1.24%	-7.080	
	149	vf	-35.737	-35.876	-1.59%	-33.484	
	269		-38.432	-37.916	6.12%	-45.731	
	330		-52.248	-50.919	16.53%	-50.867	
	444	3(vf)	-46.345	-46.984	-7.09%	-46.674	
	480	pf	-38.543	-38.292	2.93%	-29.922	
	600	pf	-43.966	-44.833	-9.50%	-40.873	

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

Table B-3 Pump Test Series 1235, 1236, and 1237

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
1235	23		-42.589	-62.748	-42.756	-1.90%	SNR is very low
	29	rf	-59.507	-41.963	-58.539	11.79%	
	120	pf	-3.452	-9.311	-3.458	-0.07%	
	147	vf	-30.499	-30.634	-31.073	-6.39%	
	240	pf	-21.012	-35.650	-20.980	0.37%	
	360	pf	-31.727	-33.809	-31.903	-2.01%	
	389		-40.700	-46.168	-40.799	-1.13%	
	480	pf	-31.147	-36.919	-31.320	-1.97%	
	600	pf	-37.575	-47.642	-37.767	-2.19%	
	1291		-47.591	-34.286	-47.309	3.30%	
	1771		-44.753	-46.780	-45.496	-8.20%	Harmonic like (1771 Hz + 240 Hz)
	2011		-47.447	-48.627	-48.523	11.65%	
1236	23		-42.796	-65.437	-42.957	-1.84%	Harmonic like (1299 Hz + 480 Hz)
	30	rf	-51.647	-43.055	-51.713	-0.76%	
	42		-39.160	-34.919	-39.130	0.35%	
	59	pf & 2(rf)	-31.569	-37.650	-31.542	0.31%	
	120	pf	-3.197	-8.517	-3.240	-0.49%	
	148	vf	-22.879	-39.590	-23.104	-2.56%	
	240	pf	-17.545	-28.647	-17.591	-0.53%	
	360	pf	-29.281	-39.036	-29.371	-1.03%	
	390		-38.917	-50.244	-39.056	-1.59%	
	480	pf	-30.831	-39.432	-30.861	-0.34%	
	600	pf	-32.175	-45.007	-32.613	-4.92%	
	1299		-40.127	-29.726	-39.862	3.10%	
	1779		-46.684	-44.380	-43.787	39.58%	
1237	22		-47.266	-57.221	-47.469	-2.31%	
	30	rf	-57.285	-40.643	-56.835	5.32%	
	59	pf 2(rf)	-30.389	-35.695	-30.302	1.01%	
	90	3(rf)	-47.029	-46.641	-46.538	5.82%	
	120	pf	-2.382	-9.534	-2.526	-1.64%	
	148	vf	-22.252	-39.377	-22.436	-2.10%	
	240	pf	-17.662	-28.419	-17.708	-0.53%	
	269		-38.244	-38.280	-38.131	1.31%	
	297	2vf	-42.391	-48.206	-42.674	-3.21%	

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

Table B-3 Pump Test Series 1235, 1236, and 1237 (continued)

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
1237 (continued)	330		-52.017	-49.061	-51.921	1.11%	Harmonic
	360	pf	-34.414	-38.641	-32.409	25.97%	
	390		-38.189	-47.346	-38.408	-2.49%	
	420		-49.733	-52.861	-49.392	4.00%	
	450		-46.009	-49.028	-46.597	-6.55%	
	480	pf	-31.944	-42.490	-31.477	5.52%	RLI is L and 732 is L
	510		-50.190	-54.605	-51.255	-11.84%	
	600	pf	-30.005	-48.496	-30.114	-1.25%	
	1305		-35.446	-29.914	-35.560	-1.30%	Harmonic like (1305 Hz + 600 Hz)
	1905		-47.676	-41.823	-48.960	-13.74%	

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 B-24 Pump Test Series 1235, 1236, and 1237 Accelerometer Locations

Figure B-25 RLI Piping Vibration (pump running)

Figure B-26 WR 732 Piping Vibration (pump running)

Table B-4 Pump Test Series 1239, 1240, and 1241

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
1239	23		-41.828	-70.240	-41.891	-0.72%	Harmonic
	29	rf	-45.059	-41.626	-45.036	0.27%	
	60	pf	-44.201	-44.694	-44.070	1.52%	
	94		-45.191	-45.385	-45.043	1.72%	
	120	pf	-9.503	-8.274	-9.345	1.84%	
	147	vf	-23.578	-31.653	-23.418	1.86%	
	240	pf	-24.662	-34.757	-24.711	-0.56%	
	294	2(vf)	-53.636	-48.982	-52.252	17.27%	
	331		-40.519	-49.995	-40.218	3.53%	
	360	pf	-28.308	-33.586	-27.946	4.26%	
	389		-40.112	-45.831	-39.937	2.04%	
	451		-47.774	-65.000	-47.090	8.19%	
	480	pf	-31.028	-43.683	-30.386	7.67%	
	600	pf	-34.905	-52.739	-35.260	-4.00%	
	1292		-41.683	-33.523	-41.752	-0.79%	
	1773		-46.263	-46.891	-47.286	11.11%	
	1893		-54.114	-49.536	-55.094	10.67%	
	2013		-54.388	-47.773	-56.060	17.61%	
1240	23		-37.131	-68.602	-37.118	0.15%	Harmonic like (frequencies related by multiples of 120 Hz)
	30	rf	-51.486	-43.243	-52.371	-9.69%	
	61		-34.683	-43.200	-34.707	-0.28%	
	90		-46.227	-49.418	-45.909	3.73%	
	120	pf	-9.686	-9.121	-9.498	2.19%	
	148	vf	-23.863	-34.385	-23.761	1.18%	
	240	pf	-25.295	-29.683	-25.380	-0.97%	
	331		-42.407	-51.096	-41.850	6.62%	
	360	pf	-27.992	-41.228	-27.634	4.21%	
	390		-37.834	-45.385	-37.450	4.52%	
	420		-53.515	-57.668	-52.154	16.96%	
	450		-48.296	-53.973	-48.147	1.73%	
	480	pf	-32.806	-43.457	-32.067	8.88%	
	600	pf	-37.248	-46.438	-37.673	-4.78%	
	1299		-42.017	-31.260	-42.297	-3.17%	
	1780		-48.666	-45.915	-49.849	12.73%	
	1899		-52.113	-45.726	-53.938	18.55%	

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

Table B-4 Pump Test Series 1239, 1240, and 1241 (continued)

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
1241	22		-37.657	-55.264	-37.495	1.88%	
	30	rf	-45.989	-41.628	-46.394	-4.56%	
	59		-26.844	-31.174	-26.786	0.67%	
	89		-42.203	-46.790	-41.928	3.22%	
	120	pf	-10.277	-9.794	-10.037	2.80%	
	149		-33.302	-36.757	-33.669	-4.14%	
	240	pf	-21.955	-29.188	-21.962	-0.08%	
	330		-36.135	-46.853	-35.647	5.78%	
	360	pf	-28.640	-41.025	-28.334	3.59%	
	390		-38.350	-44.851	-37.958	4.62%	
	420		-47.603	-51.713	-47.247	4.18%	
	450		-49.575	-51.662	-48.988	6.99%	
	480	pf	-33.572	-44.750	-32.546	12.64%	Harmonic
	600	pf	-30.990	-44.725	-31.322	-3.75%	
	1305		-40.317	-30.283	-40.145	2.00%	
	1665		-48.522	-38.373	-50.219	-17.75%	Harmonic like (1305Hz + 360 Hz)
	1905		-49.984	-43.028	-51.466	-15.68%	Harmonic like (1665 Hz + 240 Hz)

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 B-27 Pump Test Series 1239, 1240, and 1241 Accelerometer Locations

Figure B-28 RLI Piping Vibration (pump running)

Figure B-29 WR 732 Piping Vibration (pump running)

Table B-5 Pump Test Series 1242, 1243, and 1245

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
1242	22		-51.847	-68.894	-52.288	-4.95%	Harmonic Harmonic like (1414 Hz + 360 Hz)
	29	rf	-46.175	-38.427	-45.763	4.86%	
	59	pf	-38.304	-48.371	-38.222	0.95%	
	88		-33.253	-49.922	-33.341	-1.01%	
	120	pf	-6.834	-10.819	-6.794	0.46%	
	147	vf	-22.159	-32.785	-23.181	-11.10%	
	240	pf	-23.196	-32.056	-23.529	-3.76%	
	294		-36.648	-46.584	-37.444	-8.76%	
	360	pf	-29.492	-32.328	-29.949	-5.13%	
	389		-36.369	-48.307	-37.201	-9.13%	
	441	3(vf)	-42.204	-42.961	-40.146	28.74%	
	480	pf	-25.621	-37.870	-24.855	9.22%	
	600	pf	-37.825	-49.145	-37.734	1.05%	
	1414		-47.030	-39.092	-46.756	3.20%	
	1774		-49.796	-45.285	-48.034	22.49%	
	2014		-56.285	-45.736	-56.025	3.04%	
1243	23		-47.608	-60.029	-47.568	0.46%	Harmonic Harmonics
	30	rf	-47.654	-39.870	-48.047	-4.42%	
	64		-39.092	-48.870	-39.179	-1.00%	
	92		-37.482	-48.607	-37.683	-2.29%	
	120	pf	-5.975	-10.001	-6.307	-3.75%	
	148	vf	-25.403	-40.982	-26.902	-15.85%	
	240	pf	-20.435	-29.498	-21.193	-8.36%	
	295	2(vf)	-36.956	-57.235	-39.226	-23.00%	
	360	pf	-25.528	-41.934	-27.055	-16.12%	
	390	17(23)	-37.084	-45.895	-38.055	-10.58%	
	480	pf	-26.943	-40.196	-24.876	28.87%	
	600	pf	-38.215	-46.818	-36.838	17.15%	
1245	23		-48.975	-62.259	-49.246	-3.07%	
	30	rf	-45.225	-38.488	-45.251	-0.30%	
	60	pf	-33.558	-36.158	-33.435	1.43%	
	89		-36.915	-49.214	-37.266	-3.96%	
	120	pf	-5.550	-8.535	-5.585	-0.40%	

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

Table B-5 Pump Test Series 1242, 1243, and 1245 (continued)

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
1245 (continued)	148	vf	-27.013	-38.560	-27.074	-0.70%	Harmonic
	240	pf	-19.346	-29.550	-20.069	-7.99%	
	268		-41.658	-42.574	-42.372	-7.89%	
	330		-36.587	-47.690	-36.445	1.65%	
	360	pf	-24.882	-35.375	-26.072	-12.80%	
	480	pf	-24.655	-40.565	-24.577	0.90%	
	600	pf	-32.344	-45.923	-31.607	8.86%	
	1306		-52.091	-31.776	-54.345	-22.86%	
	1666		-60.986	-38.179	-56.055	-76.42%	
	1906		-56.612	-40.523	-54.239	-31.42%	
							Intermodulation distortion Harmonic like (1306 Hz + 360 Hz) Harmonic like (1666 Hz + 240 Hz)

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 B-30 Pump Test Series 1242, 1243, and 1245 Accelerometer Locations

Figure B-31 RLI Piping Vibration (pump running)

Figure B-32 WR 732 Piping Vibration (pump running)

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APPENDIX C

C-1. Arrangement of the Rotor Test Kit

C-1.1 Arrangement of the Rotor Test Kit:

The third item tested is the Bently-Nevada rotor test kit. Many tests were conducted on this unit and it provides many good examples of the pitfalls and opportunities that exist in comparison measurements for the Robust Laser Interferometer (RLI) and the accelerometers.

C-1.1.1 Figure C-1 shows the rotor test kit in reasonable detail. The kit consists of a variable speed D.C. motor coupled, via a rubber coupling, to a long shaft. The shaft is suspended at both ends by bearings within 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 unit provides a variable D.C. voltage to control the speed of the D.C. motor.

C-1.2 Unique Features of the Rotor Test Kit:

The following elements and their characteristics are important in understanding or interpreting the various vibration signatures that occur during the comparison measurements of the rotor test kit.

C-1.2.1 Motor Speed Control: The motor speed control unit rectifies 60 Hz A.C. power into a D.C. voltage, which is available to the D.C. motor. Since the power supplies are not perfect, artifacts of the 60 Hz power modulate the D.C. power to the motor and impact its operation.

C-1.2.2 Motor Speed Control Probe: The shaft has a wheel attached to it with twelve notches evenly spaced around its circumference. The motor speed control probe senses the passing of these notches and adjusts the D.C. voltage to the motor accordingly. Feedback control is provided twelve times for each shaft rotation.

C-1.2.3 As shown in Figure C-1, the D.C. speed control cabling is wired and attached directly to the motor housing and support hardware. All exposed metal parts (chassis, bearing housings, etc.) are connected to ground. The accelerometers were attached directly to the inboard bearing housing as shown in Figure C-2. It appears that the wiring configuration contributes to the 60 Hz interference problems. This is evident in the baseline noise graphs and can be inferred from some of the measured values in the tables.

C-1.2.4 Figure C-2 shows the location of the accelerometers. They are mounted diametrically opposing on the inboard bearing housing; and the RLI is targeted closely adjacent to the WR-731. In this configuration both accelerometers are compared to the RLI.

C-2 Measurement of the Rotor Test Kit

C-2.1 Non-Rotating Tests: Test #1250 is a baseline set of measurements and is illustrated in Figures C-3, C-4 and C-5. It is apparent from these figures that:

- The RLI does not see any 60 Hz (and harmonics) lines. It has a relatively smooth noise floor.
- The WR-731 has, in general, a very low noise floor with line components extending well above the floor.
- The WR-732 is very noisy, in particular with strong 60 Hz (and harmonics) lines.

Figure C-1 Bently Nevada Rotor Kit

Figure C-2 Rotor Kit Accelerometer Locations

Figure C-3 RLI Rotor Kit Data (baseline, stopped)

Figure C-4 WR 731 Rotor Kit Data (baseline, stopped)

Figure C-5 WR 732 Rotor Kit Data (baseline, stopped)

C-2.2 Very Slow Rotation: Tests #1251 and 1252 are very slow rotational speed tests, the quietest operating condition. Amplitude measurements are made in Figures C-6, C-7 and C-8 for test #1251. Test #1252 is a repeat of the same test with higher resolution processing. The higher resolution aids in identifying individual frequency components. Figures C-9, C-10 and C-11 show the frequencies up to 256 Hz. Table C-1 provides a sample of the measured values from tests #1251 and 1252 and indicates that in this quiet mode many of the observed individual frequencies are related to the motor drive and are probably contaminated by power interference.

C-2.2.1 A comparison of RLI measurements in Figures C-3 and C-6 shows that Figure C-6 is dominated by measured vibrations. A similar comparison for the WR-731, Figures C-4 and C-7 shows that Figure C-7 is also dominated by measured vibration, and Figures C-5 and C-8 show that the WR-732 is dominated by baseline noise in the lower frequencies (0 - 100 Hz) while the rest of the spectrum shows measured vibrations. Figures C-9, C-10, and C-11 help to decipher the low frequency portion of the measurements.

C-2.3 Very Fast Rotation: Tests #1254 and 1255 are very fast rotational speed tests, approximately 6800 RPM. This high speed causes relatively strong vibrations at the bearing housing. At this vibration level the WR-731 is close to being out of its specified range of operation. Table C-2 lists some measured values for these tests. For various reasons only one measured vibration frequency in the spectrum signatures appears valid for comparison: the rotational frequency at 113 Hz. In general, however, there appears to be good and consistent agreement between the RLI and the WR-732. Figures C-12 through C-17 illustrate the vibration patterns for these tests.

C-2.4 Moderately Fast Rotation:

For tests #1256 and 1257, the kit was rotated at 4140 RPM (69 Hz). This test begins to show the presence of intermodulation distortion that will exist for non-linear sensors. At this vibration level the WR-731 should be operating within its specification range. Table C-3 shows some of the specific frequency readings and provides results similar to Table C-2. It

is still apparent that the WR-731 performance is still erratic, just as it was in the previous tests (#1254 and 1255). Figures C-18 through C-23 illustrate.

C-2.4.1 Intermodulation distortion is evident for the WR-731 from the measured vibration frequencies at 9, 18 and 27 Hz, which are manifestations of the first second and third modulations of the difference between 69 Hz (rotational speed) and 60 Hz (line frequency.) These signals are not evident in the WR-732 measurements or the RLI, which are operating in a more linear fashion and do not show the false vibration signals at 9, 18, and 27 Hz. See Figures C-19 and C-22.

C-2.5 Moderately Slow Rotation:

For tests #1258 and 1259 the speed is approximately 3180 RPM (53 Hz) and the vibration levels are lower than the previous tests. This is evident from the better, more consistent performance of the WR-731, which is shown in Table C-4. A small amount of intermodulation distortion for the WR-731 is shown at 7 Hz (60 Hz minus 53 Hz) and 14 Hz. The only good measured vibration frequency for CM is the rotational frequency at 53 Hz, the others are all impacted by such things as motor control and line frequency interference. Figures C-24 through C-29 illustrate.

C-2.6 Very Fast Rotation: For tests #1262 and 1263, the rotational speed was approximately 7620 RPM (127 Hz). The vibration levels are very high and intermodulation distortion is evident in the signatures of both the WR-731 and WR-732, principally in the lower frequency portions of the signatures that are filled with what appear to be broadband noise and some signals. Figures C-30 through C-35 illustrate. This situation is clearly shown by a comparison of the RLI in Figure C-33 with the two accelerometers in Figures C-34 and C-35.

C-2.7 Intermodulation Distortion

Demonstration: To intentionally show how severe intermodulation distortion can become, the test kit was run at a rotational speed of 3708 RPM (61.813 Hz). The vibration levels at this speed are small, well within the range of the WR-731. Figure C-36 (RLI) shows no evidence of intermodulation distortion except one line at 58.188 Hz, which is probably a real physical vibration caused by the very close power frequency and rotational frequency. The WR-731, in Figure C-37, shows a substantially different noise floor in the lower frequency ranges, principally from intermodulation distortion. The WR-732, in Figure C-38, shows much less severe intermodulation distortion. Figures C-39, C-40, and C-41 are higher resolution plots for the lower frequencies of the same operating condition.

Figure C-6 RLI Rotor Kit Data (very slow rotation)

Figure C-7 WR 731 Rotor Kit Data (very slow rotation)

Figure C-8 WR 732 Rotor Kit Data (very slow rotation)

Figure C-9 RLI Rotor Kit Data (very slow rotation) (low frequency)

Figure C-10 WR 731 Rotor Kit Data (very slow rotation) (low frequency)

Figure C-11 WR 732 Rotor Kit Data (very slow rotation) (low frequency)

Table C-1 Rotor Kit Series 1251 and 1252

Test Number	ID	f (1 Hz Bins)	f (1/8 Hz Bins)	RLI (dB ref 1 g)	731 (dB ref 1 g)	Difference 731 ref RLI	732A (dB ref 1 g)	Difference 732 ref RLI	Comments
1251-1 Hz Bins 1252-1/8 Hz Bins	rf	7	7.125	-81.798	-82.204	-4.57%	NOISE		The 731 is G and the 732 is O Harmonic
	14rf	97	99.375	-73.608	-73.649	-0.47%		-28.68%	
	12rf	83	84.875	-66.366	-67.572	-12.96%	-78.439	-76.09%	<div style="text-align: center;"> Frequencies are related to motor control and power </div>
	12rf+60	143	144.875	-59.733	-61.364	-17.12%	-61.142	-14.97%	
	12rf+120	203	204.875	-48.888	-51.185	-23.24%	-50.783	-19.60%	
	12rf+3(60)	263	264.875	-58.064	-59.779	-17.92%	-59.391	-14.17%	
	12rf+2(120)	323	324.875	-52.063	-54.157	-21.42%	-53.315	-13.42%	
	12rf+5(60)	383	384.875	-54.702	-56.497	-18.67%	-55.671	-10.66%	
	12rf+3(120)	443	444.875	-55.452	-56.978	-16.11%	-56.292	-9.22%	
	12rf-60	23	24.875	-79.217	-78.968	2.91%	-78.439	9.37%	
									The 731 is L and the 732 is L Power frequency Power frequency
		107	109.750	-76.870	-77.427	-6.21%	-76.933	-0.72%	
	pf	60	60.000	-68.534	-69.246	-7.87%	-59.489	-13.30%	
	pf	120	120.000	-51.850	-53.262	-15.00%	-51.635	-2.51%	

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

pf - Power frequencies (60 Hz and harmonics)

 - Measurement probably contaminated by one or more factors

ID - Probable identification of the measured line

Table C-2 Rotor Kit Series 1254 and 1255

Test Number	ID	f (1 Hz Bins)	f (1/8 Hz Bins)	RLI (dB ref 1 g)	731 (dB ref 1 g)	Difference 731 ref RLI	732 (dB ref 1 g)	Difference 732 ref RLI	Comments
1254-1 Hz Bins 1255-1/8 Hz Bins	rf	113	113.250	-17.319	-17.735	-4.676%	-17.408	-1.02%	The 731 is G and the 732 is O
	2rf	226	226.375	-42.067	-43.907	-19.090%	-43.776	-17.96%	
	3rf	339	339.625	-38.257	-41.391	-30.289%	-39.719	-15.49%	
	4rf	453	452.875	-56.178	NOISE		-56.857	-7.62%	
	5rf	566	566.250	-57.269	-52.409	-74.986%	-60.226	-28.85%	
	6rf	769	679.250	-47.950	-50.599	-28.288%	-49.017	-11.56%	
	7rf	792		-29.029	-31.706	-26.623%	-30.181	-12.42%	
	8rf	905	905.750	-37.873	-39.655	-18.548%	-38.870	-10.84%	
									Harmonics
	12rf	1358	1358.500	-16.534	-18.843	-23.343%	-17.796	-15.52%	Frequencies are related to motor control and power
	2(12rf)	2715	2717.125	-33.938	-25.577	-181.848%	-35.820	-19.48%	
	12rf-60	1298	1298.500	-17.838	-20.373	-26.312%	-19.003	-12.55%	
	12rf-120	1238	1238.500	-14.159	-15.456	-13.871%	-15.420	-13.51%	
	12rf-3(60)	1178	1178.500	-31.636	-41.581	-89.176%	-32.970	-14.24%	
	12rf-2(120)	1118	1118.500	-33.281	-39.056	-49.666%	-34.661	-14.89%	
	12rf-5(60)	1058	1058.500	-33.940	-38.712	-42.270%	-35.473	-18.16%	
	12rf-3(120)	998	998.500	-44.737	-45.152	-4.888%	-46.113	-14.68%	
	12rf-7(60)	938	938.375	-34.796	-335.000	-100.000%	-36.000	-12.64%	
	12rf-4(120)	878	878.375	-38.678	-44.287	-47.574%	-39.868	-12.80%	
	12rf-9(60)	818	818.375	-33.298	-36.016	-27.373%	-34.410	-12.62%	
	12rf-5(120)	758	758.375	-42.793	-42.295	-5.901%	-43.974	-12.71%	
	12rf-11(60)	698	698.375	-54.193	-53.225	-11.789%	-55.318	-12.16%	
	12rf+60	1418	1418.625	-22.804	-26.380	-33.75%	-24.105	-13.81%	
	12rf+120	1478	1478.625	-20.730	-22.861	-21.76%	-21.970	-13.30%	
	12rf+3(60)	1538	1538.625	-22.969	-24.408	-18.27%	-24.181	-13.02%	
	12rf+2(120)	1598	1598.625	-26.695	-27.243	-6.11%	-27.928	-13.23%	
	12rf+5(60)	1658	1658.625	-38.787	-38.291	-5.88%	-40.104	-14.07%	
	12rf+3(120)	1718	1718.625	-29.085	-28.069	-12.41%	-30.638	-18.37%	
	12rf+7(60)	1778	1778.625	-31.086	-31.530	-4.88%	-32.583	-15.83%	
	12rf+4(120)	1838	1838.750	-27.094	-26.501	-7.07%	-28.622	-18.13%	
	12rf+9(60)	1898	1898.750	-28.031	-27.194	-10.12%	-29.550	-18.04%	
	12rf+5(120)	1958	1958.750	-34.173	-35.406	-13.23%	-35.734	-18.45%	
	12rf+11(60)	2018	2018.750	-36.145	-35.247	-10.89%	-37.731	-18.69%	
									Power frequency Power frequency
	pf	60	60.000	-59.899	-43.070	-694.14%	-57.680	-29.11%	
	pf	120	120.000	-47.093	-41.245	-96.06%	-47.820	-8.03%	

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

pf - Power frequencies (60 Hz and harmonics)

- Measurement probably contaminated by one or more factors

ID - Probable identification of the measured line

Figure C-12 RLI Rotor Kit Data (very fast rotation)

Figure C-13 WR 731 Rotor Kit Data (very fast rotation)

Figure C-14 WR 732 Rotor Kit Data (very fast rotation)

Figure C-15 RLI Rotor Kit Data (very fast rotation) (low frequency)

Figure C-16 WR 731 Rotor Kit Data (very fast rotation) (low frequency)

Figure C-17 WR 732 Rotor Kit Data (very fast rotation) (low frequency)

Table C-3 Rotor Kit Series 1256 and 1257

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	-28.08%	
	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	-3.63%	
	8rf	554	552.000	-48.180	-49.279	-11.88%	-49.080	-8.84%	
									↑ Frequencies are related to motor control and power ↓
	12rf	831	828.000	-15.023	-16.388	-14.54%	-16.192	-12.69%	
	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	-4.43%	-43.916	-17.00%	
	12rf-5(60)	531	527.875	-50.076	-46.634	48.63%	-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	797.63%	-78.000	9.64%	
	12rf-4(120)	351	347.750	-62.286	-56.536	93.87%	-65.550	-31.32%	
	12rf-9(60)	291	287.750	-69.409	-53.329	536.80%	-70.430	-11.09%	
	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	6834.37%	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	-11.81%	
	12rf+3(60)	1011	1008.000	-33.538	-34.092	-6.18%	-34.914	-14.65%	
	12rf+2(120)	1071	1068.000	-27.667	-28.298	-7.01%	-29.097	-16.18%	
	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	-11.59%	-40.555	-14.26%	
	12rf+7(60)	1251	1248.125	-34.765	-34.714	0.59%	-36.061	-13.86%	
	12rf+4(120)	1311	1308.125	-41.290	-42.487	-12.87%	-42.504	-13.04%	
	12rf+9(60)	1371	1368.125	-37.258	-37.906	-7.19%	-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 C-3 Rotor Kit Series 1256 and 1257 (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	Power frequency Power frequency
	3(rf-60)	28	26.875	NS	-65.453	NA	NOISE	NA	
	60	60	60.000	-62.109	-50.882	264.21%	-56.290	95.41%	
	120	120	120.000	-47.862	-49.905	20.96%	-47.868	0.05%	

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 C-18 RLI Rotor Kit Data (moderately fast rotation)

Figure C-19 WR 731 Rotor Kit Data (moderately fast rotation)

Figure C-20 WR 732 Rotor Kit Data (moderately fast rotation)

Figure C-21 RLI Rotor Kit Data (moderately fast rotation) (low frequency)

Figure C-22 WR 731 Rotor Kit Data (moderately fast rotation) (low frequency)

Figure C-23 WR 732 Rotor Kit Data (moderately fast rotation) (low frequency)

Figure C-24 RLI Rotor Kit Data (moderately slow rotation)

Figure C-25 WR 731 Rotor Kit Data (moderately slow rotation)

Figure C-26 WR 732 Rotor Kit Data (moderately slow rotation)

Figure C-27 RLI Rotor Kit Data (moderately slow rotation) (low frequency)

Figure C-28 WR 731 Rotor Kit Data (moderately slow rotation) (low frequency)

Figure C-29 WR 732 Rotor Kit Data (moderately slow rotation) (low frequency)

Table C-4 Rotor Kit Series 1258 and 1259

Test Number	ID	f (1 Hz Bins)	f (1/8 Hz Bins)	RLI (dB ref 1 g)	731 (dB ref 1 g)	Difference 731 ref RLI	732 (dB ref 1 g)	Difference 732 ref RLI	Comments
1258-1 Hz Bins	rf	53	53.500	-28.237	-28.828	-6.58%	-28.710	-5.30%	The 731 is G and the 732 is O
1259-1/8 Hz Bins	2rf	107	107.000	-34.710	-34.713	-0.03%	-35.825	-12.05%	Harmonics
	3rf	160	160.500	-54.104	-52.515	20.07%	-52.587	19.08%	
	4rf	214	214.000	-37.230	-40.450	-30.98%	-39.666	-24.46%	
	5rf	267	267.500	-41.341	-43.581	-22.73%	-43.113	-19.46%	
	6rf	321	320.875	-28.871	-31.178	-23.33%	-30.429	-16.42%	
	7rf	374	374.375	-39.522	-41.798	-23.05%	-40.985	-16.50%	
	8rf	428	427.875	-53.711	-56.793	-29.87%	-54.897	-12.76%	
	12rf	641	641.875	-31.038	-32.798	-18.34%	-32.418	-14.69%	Frequencies are related to motor control and power
	2(12rf)	1283	1283.750	-33.819	-33.632	2.18%	-35.011	-12.82%	
	12rf-60	581	581.875	-36.690	-38.786	-21.44%	-38.388	-17.76%	
	12rf-120	521	521.875	-36.296	-37.255	-10.45%	-37.045	-8.28%	
	12rf-3(60)	461	461.750	-39.027	-40.213	-12.76%	-40.019	-10.79%	
	12rf-2(120)	401	401.750	-45.137	-45.798	-7.33%	-46.191	-11.43%	
	12rf-5(60)	341	341.750	-49.718	-50.713	-10.82%	-50.998	-13.70%	
	12rf-3(120)	281	281.750	-56.316	-57.505	-12.79%	-57.982	-17.46%	
	12rf-4(120)	160	160.500	-54.104	-52.515	20.07%	-52.567	19.08%	
	12rf+60	701	701.875	-27.392	-28.955	-16.47%	-28.680	-13.78%	
	12rf+120	761	761.875	-22.031	-23.359	-14.18%	-23.252	-13.11%	
	12rf+3(60)	821	821.875	-19.191	-20.265	-11.63%	-20.350	-12.49%	
	12rf+2(120)	881	882.000	-33.966	-34.594	-6.97%	-34.933	-10.54%	
	12rf+5(60)	941	942.000	-31.363	-32.388	-11.13%	-32.694	-14.21%	
	12rf+3(120)	1001	1002.000	-42.287	-43.170	-9.67%	-43.753	-16.53%	
	12rf+7(60)	1061	1062.000	-42.607	-43.676	-11.58%	-44.139	-16.17%	
	12rf+4(120)	1121	1122.000	-52.282	-54.059	-18.60%	-53.844	-16.46%	
	12rf+9(60)	1181	1182.000	-54.046	-54.492	-6.01%	-55.391	-14.36%	
	12rf+5(120)	1241	1242.125	-35.175	-35.036	1.61%	-36.357	-12.72%	
	12rf+11(60)	1301	1302.125	-44.173	-44.847	-7.47%	-45.446	-13.93%	
									Intermodulation distortion Intermodulation distortion
	60-rf	6	6.5	NS	-76.069	NA	NOISE	NA	
	2(60-rf)	13	13.125	NS	-80.368	NA	NOISE	NA	Power frequency Power frequency
	pf	60	60	-62.788	-62.378	4.83%	-61.281	18.95%	
	pf	120	120	-48.199	-50.488	-23.17%	-48.582	-4.31%	

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
- 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 C-30 RLI Rotor Kit Data (very fast rotation)

Figure C-31 WR 731 Rotor Kit Data (very fast rotation)

Figure C-32 WR 732 Rotor Kit Data (very fast rotation)

Figure C-33 RLI Rotor Kit Data (very fast rotation) (low frequency)

Figure C-34 WR 731 Rotor Kit Data (very fast rotation) (low frequency)

Figure C-35 WR 732 Rotor Kit Data (very fast rotation) (low frequency)

Figure C-36 RLI Rotor Kit Data (inter-modulation distortion)

Figure C-37 WR 731 Rotor Kit Data (inter-modulation distortion)

Figure C-38 WR 732 Rotor Kit Data (inter-modulation distortion)

Figure C-39 RLI Rotor Kit Data (inter-modulation distortion) (low frequency)

Figure C-40 WR 731 Rotor Kit Data (inter-modulation distortion) (low frequency)

Figure C-41 WR 732 Rotor Kit Data (inter-modulation distortion) (low frequency)

APPENDIX D

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APPENDIX D

D-4. Cement Mixer Test Results

D-4.1 Cement Mixer Test

Configuration: The fourth item of machinery tested was a portable cement mixer driven by a 1/2 horsepower A.C. electric motor. Figures D-1, D-2 and D-3 illustrate the arrangements of the various components of the mixer. The belt drive provides approximately a 3.5:1 reduction in electric motor output speed to the input of the 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.

D-4.1.1 Baseline tests were conducted with the accelerometers installed as shown on Figure D-3. The RLI was alternately targeted on both accelerometers with the untargeted accelerometer being used as a monitor, principally to detect high levels of transverse motion which would cause the transverse sensitivity of the accelerometers to have an impact on the readings. Baseline noise graphs with the mixer off are shown in Figures D-4, D-5 and D-6.

D-4.1.2 Initial accelerometer readings with the mixer running revealed that the WR-731 accelerometer was subject to vibrations of greater acceleration levels than its specified range. This caused the internal amplifier to be overdriven during some portion of the measurement cycle, resulting in measurement error. For this reason, the WR-731 accelerometer readings are very unreliable for this test.

D-4.2 Unloaded Cement Mixer Test:

The mixer was tested in the unloaded 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. The RLI was targeted at the WR 732. Tests

1272 and 1273 are shown in Table D-1, which illustrates the good comparison between the WR 732 and RLI readings. The plots of test 1273, included as Figures D-7 through D-12 show the very good comparison except at the lowest frequencies. Figure D-13, a low frequency expansion of Figure D-10, 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 D-11, the much higher noise floor of the WR-732 accelerometer makes the identification of these lines impossible in the accelerometer output. Figures D-9 and D-12 show that the WR-731 accelerometer is not giving valid readings because of the previously mentioned problem with high acceleration levels.

D-4.3 Loaded Cement Mixer Test:

The loaded test of the mixer, tests 1274 and 1276, is also included here. The mixer was loaded with approximately 120 pounds of sand and two gallons of water. Here the WR 732 and RLI agree well, but the WR 731 is still overdriven and its response is erratic. Table D-2 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 D-14, D-15 and D-16 show a substantial difference in measurement capability in the low frequency ranges. Figures D-17, D-18 and D-19 are lower frequency, higher resolution plots of the same test condition. Finally, Figure D-20 is a low frequency expansion of Figure D-17 and shows the benefit of the lower noise floor of the RLI at these frequencies. The obvious pattern of the peaks from 0.4 Hz to 6 Hz is very likely to reveal some diagnostic intelligence.

D-4.4 Additional Tests: These tests were repeated with the RLI targeting the overdriven WR-731 accelerometer. The results of these tests routinely and expectedly show a substantial disparity between the overdriven accelerometer and the RLI. No figure or tables of these test results are included.

Figure D-1 Cement Mixer Front View

Figure D-2 Cement Mixer Rear View

Figure D-3 Accelerometer Locations on Cement Mixer Gearbox

Figure D-4 RLI Cement Mixer Baseline Data (mixer off)

Figure D-5 WR-731 Cement Mixer Baseline Data (mixer off)

Figure D-6 WR-732 Cement Baseline Data (mixer off)

Table D-1 Mixer Test Series 1272 and 1273

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	drf		0.438					
	2(drf)		0.875					
	17(drf)	7	7.125	-60.191	NOISE	-61.522	-14.21%	Harmonic
			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 range
- NOISE - Signal is "in the noise"
- ID - Probable identification of the measured line
- Alphanumeric** - Measurement probably contaminated by one or more factors

Table D-1 Mixer Test Series 1272 and 1273 (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					
			202.375					
	203		202.813	-29.065	-26.263	-28.796	3.15%	
			203.250					
			203.625					
			418.125					
			419.875					
			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

Figure D-7 RLI Cement Mixer Running Data (mixer unloaded)

Figure D-8 WR 732 Cement Mixer Running Data (mixer unloaded)

Figure D-9 WR 731 Cement Mixer Running Data (mixer unloaded)

Figure D-10 RLI Cement Mixer Running Data (mixer unloaded) (low frequency)

Figure D-11 WR 732 Cement Mixer Running Data (mixer unloaded) (low frequency)

Figure D-12 WR 731 Cement Mixer Running Data (mixer unloaded) (low frequency)

Figure D-13 RLI Cement Mixer Running Data (mixer unloaded) (special low-frequency expansion)

Table D-2 Mixer Test Series 1274 and 1276

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 D-14 RLI Cement Mixer Running Data (mixer loaded)

Figure D-15 WR-732 Cement Mixer Running Data (mixer loaded)

Figure D-16 WR-731 Cement Mixer Running Data (mixer loaded)

Figure D-17 RLI Cement Mixer Running Data (mixer loaded) (low frequency)

Figure D-18 WR-732 Cement Mixer Running Data (mixer loaded) (low frequency)

Figure D-19 WR-731 Cement Mixer Running Data (mixer loaded) (low frequency)

Figure D-20 RLI Cement Mixer Running Data (mixer loaded) (special low-frequency expansion)

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APPENDIX E

E-1. Twin Fan (Ventilation Fan #2) Test

E-1.1 Twin Fan Test Arrangement:

The fifth item tested was a used window fan that contains two identical fans in a flexible housing. The fans selected 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 "bad fan" makes a great deal of audible noise when it is running and runs in a very erratic fashion. Both fans are supposed to run together when the unit is turned on. Figures E-1 and E-2 illustrate the twin fan unit. Part of the unit's outer housing has been removed to mount the accelerometers.

E-1.1.1 The original idea was to test a piece of equipment with one unit running well and the other unit having an obvious problem. This did not work so well for several reasons.

E-1.1.1.1 The shaft of the good fan is slightly loose but the fan seems to turn well. The shaft of the bad fan is very loose and an intermittent rub can be felt as it is turned by hand.

E-1.1.1.2 When the bad fan is running its rotational frequency varies as a random variable, that is, it will cycle from some low to higher speed, and vice versa, in a random fashion over a period of time. These time periods vary from less than one second to greater than sixteen seconds. Only a small amount of this behavior is visible in the test of the good fan.

E-1.1.1.3 Vibration levels are very high with the bad fan running. These levels are higher than those specified for the WR-731. As a result the WR-731 provides inaccurate measurements for the bad fan running test portions. With only the good fan running, the WR-731 is just within its specified operating range.

E-1.1.2 In summary, both fans are operating in a speed varying fashion over time with the bad fan far more erratic than the good fan. With the fans varying in speed as the accelerometers and RLI attempt to take a "picture", the captured data is not so amenable to analysis. An FFT works best when the signal to be measured is relatively stable in time or is somewhat repetitious from one period of measurement to the next. This condition does not exist for the twin fans. Also, the test procedure calls for taking a 1.0 second measurement, which yields amplitude levels in 1.0 Hz bins. This test is shortly followed by a measurement of 8.0 seconds or 16.0 seconds, principally to aid in identifying various measured lines and to determine their probable relationship to other measured lines. Since there was very little stability from test to test, it was difficult to analyze and interpret the results of tests on the twin fans.

E-1.2 Twin Fan Tests

E-1.2.1 Non-Running Tests: For test #1284, both fans are blocked to keep them from rotating and the fan is turned on. Figures E-3, E-4 and E-5 show the baseline noise levels for the first group of tests. These figures indicate that as a result of the 60 Hz power to the twin fans there are both real vibrations (the RLI is unaffected by electrical interference) and electrical interference at the power frequencies (60 Hz and its harmonics). The RLI is targeted at the WR-731, which is mounted on the face of the fan.

E-1.2.2 Good Fan Running, Bad Fan

Blocked: For tests #1285 and #1286, the good fan is running and the bad fan is blocked to keep it from rotating. The RLI is targeted on the WR-731, which is mounted on the face of the fan. Figures E-6 through E-11 show the results where, except for a signal at 37 Hz and known contaminating factors of electrical origin, agreement is quite good.

Figure E-1 Twin Fan Configuration (Top View)

Figure E-2 Twin Fan Configuration (Side View)

Figure E-3 RLI Twin Fan Baseline Data (power on, fans blocked)

Figure E-4 WR-731 Twin Fan Baseline Data (power on, fans blocked)

Figure E-5 WR-732 Twin Fan Baseline Data (power on, fans blocked)

Figure E-6 RLI Twin Fan Data (good fan running, bad fan blocked)

Figure E-7 WR-731 Twin Fan Data (good fan running, bad fan blocked)

Figure E-8 WR-732 Twin Fan Data (good fan running, bad fan blocked)

Figure E-9 RLI Twin Fan Data (good fan running, bad fan blocked) (low frequency)

Figure E-10 WR-731 Twin Fan Data (good fan running, bad fan blocked)
(low frequency)

Figure E-11 WR-732 Twin Fan Data (good fan running, bad fan blocked)
(low frequency)

E-1.2.3 Bad Fan Running, Good Fan

Blocked: For tests #1287 and #1288 the bad fan is running and the good fan is blocked. For tests #1289 and #1290, both fans are running. The RLI is targeted at the WR-731 accelerometer, which is being driven so hard by the vibration levels that its output preamplifier is "clipping" and not correctly reporting vibration amplitudes. The results for these tests are summarized in Table E-1. Figures E-12 through E-17 illustrate. The very low noise floor of the RLI at low frequency is again demonstrated.

E-1.3 Radial Vibration Measurements

E-1.3.1 Baseline for Radial Vibration

Measurements: In order to use the WR-732, which is within its normal range of vibration measurement, another baseline set of readings (test #1291) was taken with both fans turned on but blocked from rotating. The WR-732 is mounted to read radial vibrations and the RLI is targeted on it. The WR-731 is mounted on the face of the fan to measure axial vibrations and is still being overdriven by the vibration amplitudes. The results are displayed in Figures E-18, E-19 and E-20.

E-1.3.2 Good Fan Running, Bad Fan

Blocked: Tests #1292 and #1293 were taken with the good fan running and the bad fan blocked from rotating. The RLI is targeted at the WR-732, which is measuring radial vibration. The WR-731 is mounted on the face of the fan and is measuring axial vibration and remains overdriven due to the vibration amplitudes. The speed of the fan is changing from 26.625 Hz to 27.25 Hz during the two sets of readings. Figures E-21 through E-26 illustrate the results and Table E-2 provides the readings for comparison measurement. With the exception of one measured frequency, 150 Hz, the agreement between the WR-732 and the RLI is very good.

E-1.3.3 Good Fan Blocked, Bad Fan

Running: Tests #1294 and #1295 were done with the bad fan running and the good fan blocked. Figures E-27, E-28, and E-29 illustrate a strong harmonic content in their measurement and Table E-2 identifies these frequencies. This is a classical signature for a "loose shaft" or a "rotor rub" and illustrates to some extent the problems in performing comparison measurements on the twin fans. Table E-2 shows good agreement between the RLI and the WR-732 after making allowance for the interference factors.

E-1.3.4 Both Fans Running: Tests #1296 and #1297 are done with both fans running and the RLI targeted on the WR-732, which is installed to monitor radial vibration. Figures E-30 through E-32 illustrate the results of this test. Table E-2 provides a quantitative comparison of the comparison measurements. Again, after allowances for interference, the agreement between the WR-732 and the RLI are very good.

Table E-1 Twin Fan Test Series 1272 and 1273

Test Number	f (1 Hz Blns)	f (1/16 Hz Blns)	ID	RLI (dB ref 1 g)	731 (dB ref 1 g)	732 (dB ref 1 g)	Difference 731 ref RLI	Comments
1285 1286	27	26.625	rf	-26.160	-27.962	-32.588	-16.74%	Contains Harmonics Intermodulation Distortion Intermodulation Distortion Intermodulation Distortion Harmonics Harmonics Harmonics
	30	30.000		-26.543	-27.707	-33.965	-12.64%	
	37	37.500		-34.809	-36.121	-51.001	-14.02%	
	54	53.250	2(rf)	-42.455	-43.034	-63.647	-6.45%	
	60	60.000	pf	-29.383	-30.458	-48.948	-11.64%	
	81	81.125	3(rf)	-43.930	-44.647	-54.458	-7.92%	
	90	90.000		-25.719	-28.212	-41.937	-24.85%	
	107	106.625	bf	-26.508	-27.984	-44.251	-15.63%	
	120	120.000	pf	-6.576	-8.187	-22.862	-16.93%	
	150	150.000		-26.896	-27.063	-37.698	-1.90%	
	187	186.313	7(rf)	-31.423	-30.738	-41.905	8.21%	
	213	213.973	8(rf)	-32.010	-31.932	-30.615	0.90%	
	427	426.625	16(rf)	-36.544	-44.391	-39.381	-59.48%	
	440	439.875	16.5(rf)	-39.647	-40.976	-49.821	-14.19%	
	454	453.563	17(rf)	-35.523	-34.787	-35.731	8.84%	
1287 1288	25	24.438		-28.028	-33.320	-49.027	NA	
	52	NOISE		-42.409	-40.014	-60.926	NA	
	60	NOISE		-47.435	NOISE	-64.222	NA	
	99	95.688		-28.990	-35.556	-42.045	NA	
	107	104.125		-20.984	-30.000	-35.684	NA	
	120	120.000		-5.310	-9.287	-22.328	NA	
	131	128.563		-17.199	-23.251	NOISE	NA	
	145	144.438		-14.146	-18.604	-28.782	NA	
	227	227.938		-18.679	-26.934	-28.640	NA	
	418	414.438		-12.474	-16.453	-17.876	NA	
	538	534.438		-24.947	-32.806	-31.814	NA	
1289 1290	24	24.000		-27.583	-35.935	NOISE	NA	
	27	25.313		-27.828	-36.848	-30.983	NA	
	60	NOISE		-37.676	-41.422	-55.898	NA	
	99	NOISE		-29.765	-44.431	-43.757	NA	
	102	101.813		-25.120	-40.931	-47.473	NA	
	120	120.063		2.420	-5.256	-12.126	NA	
	144	143.563		-21.808	-31.913	-31.010	NA	
	168	168.873		-25.097	-39.460	-30.192	NA	
	216	216.063		-17.959	-31.501	-24.780	NA	
	289	NOISE		-20.246	-33.634	-25.357	NA	
	409	410.563		-18.886	31.599	-21.894	NA	
	528	NOISE		-28.725	-34.643	-25.725	NA	

NOTES:

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

KEY:

- rf - Rotation frequency
- bf - Blade frequency
- pf - Power Frequencies (60 Hz and harmonics)

- 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
- NA - Not Applicable

Figure E-12 RLI Twin Fan Data (bad fan running, good fan blocked)

Figure E-13 WR-731 Twin Fan Data (bad fan running, good fan blocked)

Figure E-14 WR-732 Twin Fan Data (bad fan running, good fan blocked)

Figure E-15 RLI Twin Fan Data (bad fan running, good fan blocked) (low frequency)

Figure E-16 WR-731 Twin Fan Data (bad fan running, good fan blocked) (low frequency)

Figure E-17 WR-732 Twin Fan Data (bad fan running, good fan blocked) (low frequency)

Figure E-18 RLI Twin Fan Baseline Data (both fans blocked)

Figure E-19 WR-732 Twin Fan Baseline Data (both fans blocked)

Figure E-20 WR-731 Twin Fan Baseline Data (both fans blocked)

Table E-2 Twin Fan Test Series (Radial Measurements)

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	-39.88%	
	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	-22.685	-38.145	4.60%	
	111	110.688	bf	-35.286	-22.779	-36.885	-16.81%	
	120	120.000	pf	-22.265	-7.372	-23.751	-15.72%	
	150	150.375		-31.772	-25.011	-30.493	-15.66%	
	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	-10.68%	
	80	80.125	3(rf)	-47.320	-41.523	-48.690	-14.55%	
	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		20.813	rf					Contains Harmonics SNR is L SNR is L Intermodulation Distortion
	26	25.813	rf	-31.960	-29.676	-33.037	-11.66%	
	34	34.625		-56.228	-57.206	-56.458	-2.61%	
	46	46.625		-48.791	NOISE	-48.899	-1.24%	
	60	60.000	pf	-45.062	-35.275	-47.064	-20.69%	
	69	69.125		-48.782	-39.456	-51.559	-27.36%	
	97	97.438		-39.837	-29.375	-40.641	-8.64%	
	120	120.000	pf	-17.658	-9.288	-17.488	2.21%	
	143	140.827		-29.965	-21.808	-28.370	-20.16%	
	217	217.375		-25.435	-23.260	-25.138	3.48%	
	286	285.563		-22.424	-28.144	-22.678	-2.88%	
	389	389.000		-28.329	-33.990	-28.206	1.43%	
	509	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

Figure E-21 RLI Twin Fan Data (good fan running, bad fan blocked)

Figure E-22 WR-732 Twin Fan Data (good fan running, bad fan blocked)

Figure E-23 WR-731 Twin Fan Data (good fan running, bad fan blocked)

Figure E-24 RLI Twin Fan Data (good fan running, bad fan blocked) (low frequency)

Figure E-25 WR-732 Twin Fan Data (good fan running, bad fan blocked) (low frequency)

Figure E-26 WR-731 Twin Fan Data (good fan running, bad fan blocked) (low frequency)

Figure E-27 RLI Twin Fan Data (bad fan running, good fan blocked)

Figure E-28 WR-732 Twin Fan Data (bad fan running, good fan blocked)

Figure E-29 WR-731 Twin Fan Data (bad fan running, good fan blocked)

Figure E-30 RLI Twin Fan Test (both fans running)

Figure E-31 WR-732 Twin Fan Test (both fans running)

Figure E-32 WR-731 Twin Fan Test (both fans running)

APPENDIX F

Appendix F - List of Figures

Figure	Page
F-1 WR-731-201 Specification Sheet	F-1
F-2 WR-732A Specification Sheet	F-2

FEATURES:

- Compact construction to fit in tight spaces
- Ultra-high sensitivity
- Ultra low-noise electronics for clear signals at very low vibration levels
- Miswiring protection

Model 731-201 Ultra Low Frequency Seismic Accelerometer

SPECIFICATIONS**DYNAMIC**

Sensitivity, $\pm 10\%$, 25°C	10 V/g
Acceleration Range	0.5 g peak
Amplitude Nonlinearity	1%
Frequency Response:	
$\pm 5\%$	0.6 - 650 Hz
$\pm 10\%$	0.5 - 850 Hz
$\pm 3\text{ dB}$	0.2 - 1,300 Hz
Resonance Frequency, mounted, nominal	2.4 kHz
Transverse Sensitivity, max.	1% of axial
Temperature Response	see graph

ELECTRICAL

Power Requirement:	
voltage source	18 - 30 VDC
current regulating diode	2 - 10 mA
Electrical Noise, equiv. g, nominal:	
Broadband 2.5 Hz to 25 kHz	2 μg
Spectral 2 Hz	0.12 $\mu\text{g}/\text{Hz}$
10 Hz	0.06 $\mu\text{g}/\text{Hz}$
100 Hz	0.03 $\mu\text{g}/\text{Hz}$
Output Impedance, max.	500 Ω
Bias Output Voltage, nominal	10 VDC
Grounding	case grounded

ENVIRONMENTAL

Temperature Range	0 to 80°C
Vibration Limit	50 g peak
Shock Limit	250 g peak
Electromagnetic Sensitivity, equiv. g.	20 $\mu\text{g}/\text{gauss}$
Base Strain Sensitivity	0.0005 g/ μstrain

PHYSICAL

Weight	30.5 grams
Case Material	nickel plated aluminum
Mounting	adhesive
Connections	microdot

OPTIONS: Customer specified sensitivity, filtering, connectors.

ACCESSORIES AVAILABLE: Cementing studs, power supplies, amplifiers, signal conditioners, cable assemblies.

Due to continued research and product development, Wilcoxon Research reserves the right to amend this specification without notice.

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Figure F-1 WR-731-201 Specification Sheet

FEATURES:

- Wide dynamic range
- High sensitivity
- Compact construction to fit in tight spaces
- Wide frequency range
- Standardized sensitivity
- Hermetically sealed

Model 732A

Model 732AT

Model 732A/732AT High Frequency Accelerometer

SPECIFICATIONS

DYNAMIC

Sensitivity, $\pm 5\%$, 25°C	10 mV/g
Acceleration Range ¹	500 g peak
Amplitude Nonlinearity	1%
Frequency Response	
$\pm 5\%$	2.0 - 15,000 Hz
± 3 dB	0.5 - 25,000 Hz
Resonance Frequency, mounted, nominal	60 kHz
Transverse Sensitivity, max.	5% of axial
Temperature Response	see graph

ELECTRICAL

Power requirement:	
voltage source	18 - 30 VDC
current regulating diode ^{1,2}	2 - 10 mA
Electrical Noise, equiv. g:	
Broadband 2.5 Hz to 25 kHz, nominal	200 μ g
Spectral	
10 Hz	20 μ g/√Hz
100 Hz	3 μ g/√Hz
1,000 Hz	2 μ g/√Hz
10,000 Hz	2 μ g/√Hz
Output Impedance, max.	100 Ω
Bias Output Voltage	10 VDC
Grounding	case grounded

ENVIRONMENTAL

Temperature Range	-50 to 120°C
Vibration Limit	500 g peak
Shock Limit	5000 g peak
Electromagnetic Sensitivity, equiv. g	100 μ g/gauss
Base Strain Sensitivity	0.005 g/ μ strain

PHYSICAL

Weight	13 grams
Material	316L stainless steel
Mounting	10-32 tapped hole
Output Connector	10-32 coaxial
Cabling: Mating Connector	Wilcoxon R1 (10-32 coaxial)
Cable	J93, coaxial, Teflon jacket, 30 pF/ft

NOTES: ¹ To minimize the possibility of signal distortion when driving long cables with high vibration signals, 24 to 30 VDC powering is recommended. The higher level constant current source should be used when driving long cables (please consult Wilcoxon Customer Service).

² A maximum current of 6 mA is recommended for operating temperatures in excess of 100 °C.

OPTIONS: Stainless steel outer braid; customer specified sensitivity; filtering; top connector (BNC); PVC jacketed cable.

ACCESSORIES SUPPLIED: SF1 mounting stud, R12-J93-10 cable assembly, calibration card, CCD card

ACCESSORIES AVAILABLE: Power supplies, amplifiers, signal conditioners, SF5 cementing studs, magnetic mounting bases, SF4 isolating studs.

Due to continued research and product development, Wilcoxon Research reserves the right to amend this specification without notice.

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Figure F-2 WR-732A Specification Sheet

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER
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Epoch Engineering, Incorporated
806 West Diamond Avenue, Suite 200
Gaithersburg, Md. 20878

9. SPONSORING ORGANIZATION - NAME AND ADDRESS (If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission,

Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555 - 0001

10. SUPPLEMENTARY NOTES

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-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.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

Laser Vibration Measurement, Condition-based maintenance, Predictive maintenance Nuclear Power Plant Aging and Residual Lifetime Evaluation, Improved methods for inservice inspection of nuclear power plant components, Instrumentation error.

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