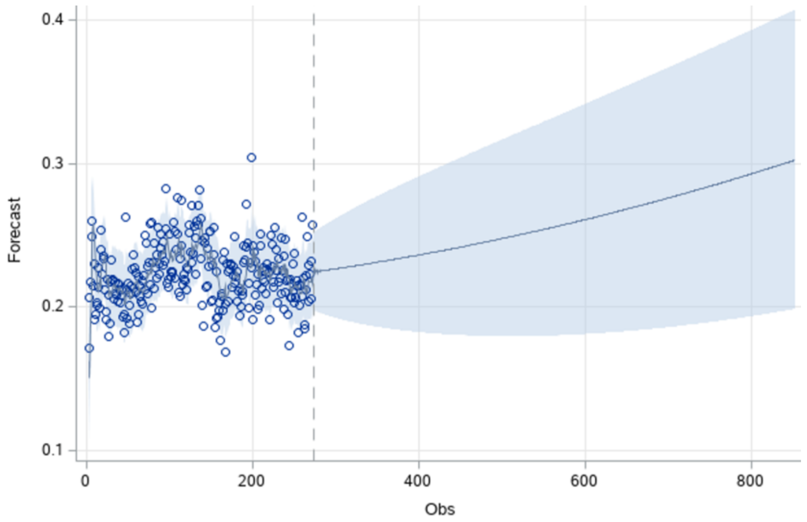
Machine Learning Applied in Rotating Machinery for Anomalies Detection and Remaining Useful Life (RUL) estimation - Case Study



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ML Applied in Rotating Machinery for Anomalies Detection and RUL estimation

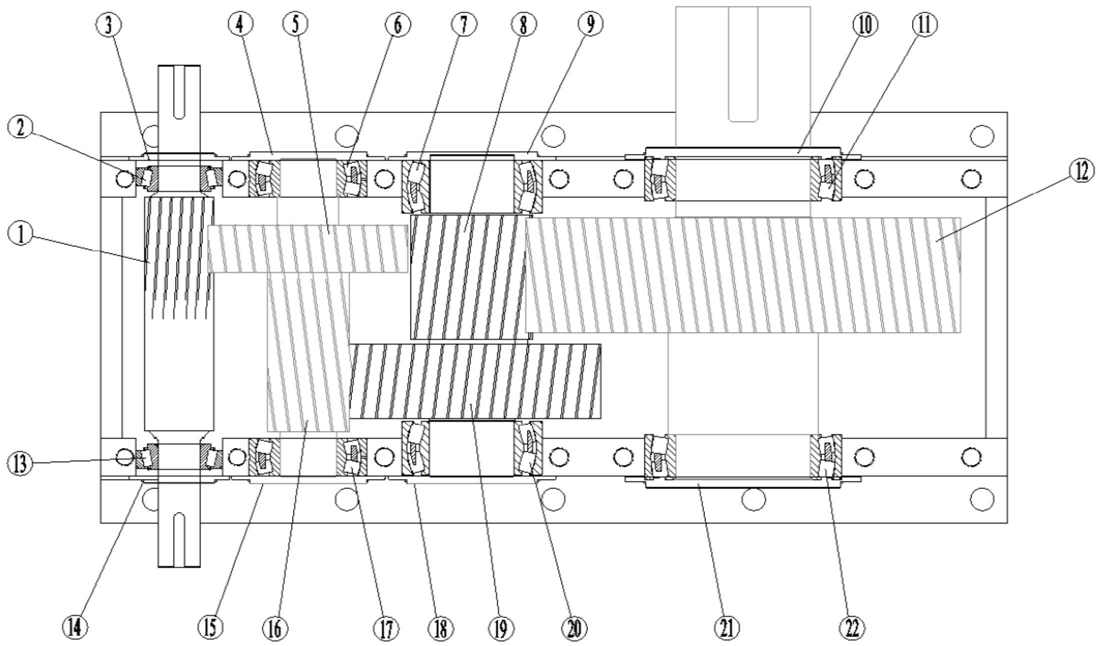
Ernesto Primera

Mechanical/Maintenance Engineer with 24 years of experience in Rotating Machinery, Condition Monitoring, Performance Analysis, and Reliability Evaluations. Experience in the Oil and Gas Industry, Power Plants and OEMs. A passionate about Data Analysis using technology platforms such as: R Studio, SAS, Minitab, SPSS Statistic & Modeler, Risk Simulator, @Risk, MS Power BI, and Tableau. Proven experience as employed for Chevron, Phillips-66, Williams, Flowserve and SKF. During the last 10 years Ernesto have worked in the Rotating Machinery Reliability Group at the Pascagoula Refinery in Mississippi (CHEVRON) and Lake Charles Refinery and Alliance Refinery in Louisiana (PHILLIPS-66). Global Instructor for the American Society of Mechanical Engineers (ASME), Industry Partner and Instructor for the Hydraulic Institute, certified Maintenance & Reliability Professional CMRP, Certified Vibration Analyst Category III by the Technical Associate of Charlotte. Bachelor’s Degree in Maintenance Engineering (University Complex AJS - Venezuela), Master’s degree in Predictive Maintenance & Diagnostics Technique (Sevilla University - Spain), Master’s degree in business Analytics (Grand Canyon University) and currently studying PhD in Applied Statistics in the University of Delaware. Ernesto is currently a SRE Lifetime National Member.

Content

ML Applied in Rotating Machinery for Anomalies Detection and RUL estimation

Technical Info



MODEL	647Z3-S
MO#	96-075332
RATIO	48.48
RATED HP	3300 HP
MOTOR HP	1650 HP
MOTOR RPM	900 RPM
UNIT WEIGHT DRY	53250 LBS
LS COUPLING	18F KOPFLEX
HS COUPLING	FALK 1140T10

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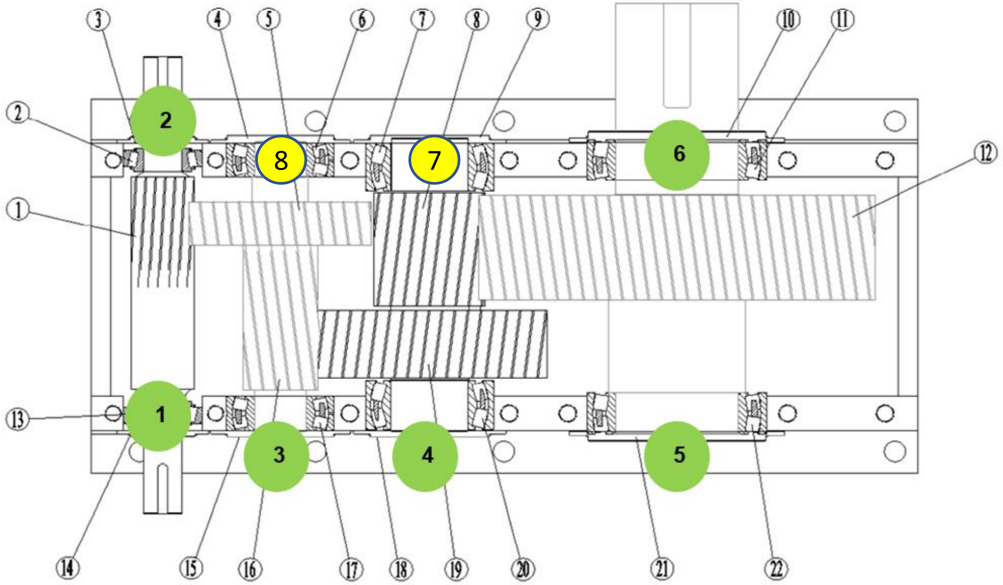
Sensors Hardware Setting



The green circles show the place (point) where the Triaxial wireless sensors are installed to measure vibrations and temperature.

Points # 1 and 2 = 1st Shaft

Point # 3 = 2nd Shaft

Point # 4 = 3rd Shaft

Points # 5 and 6 = 4th Shaft

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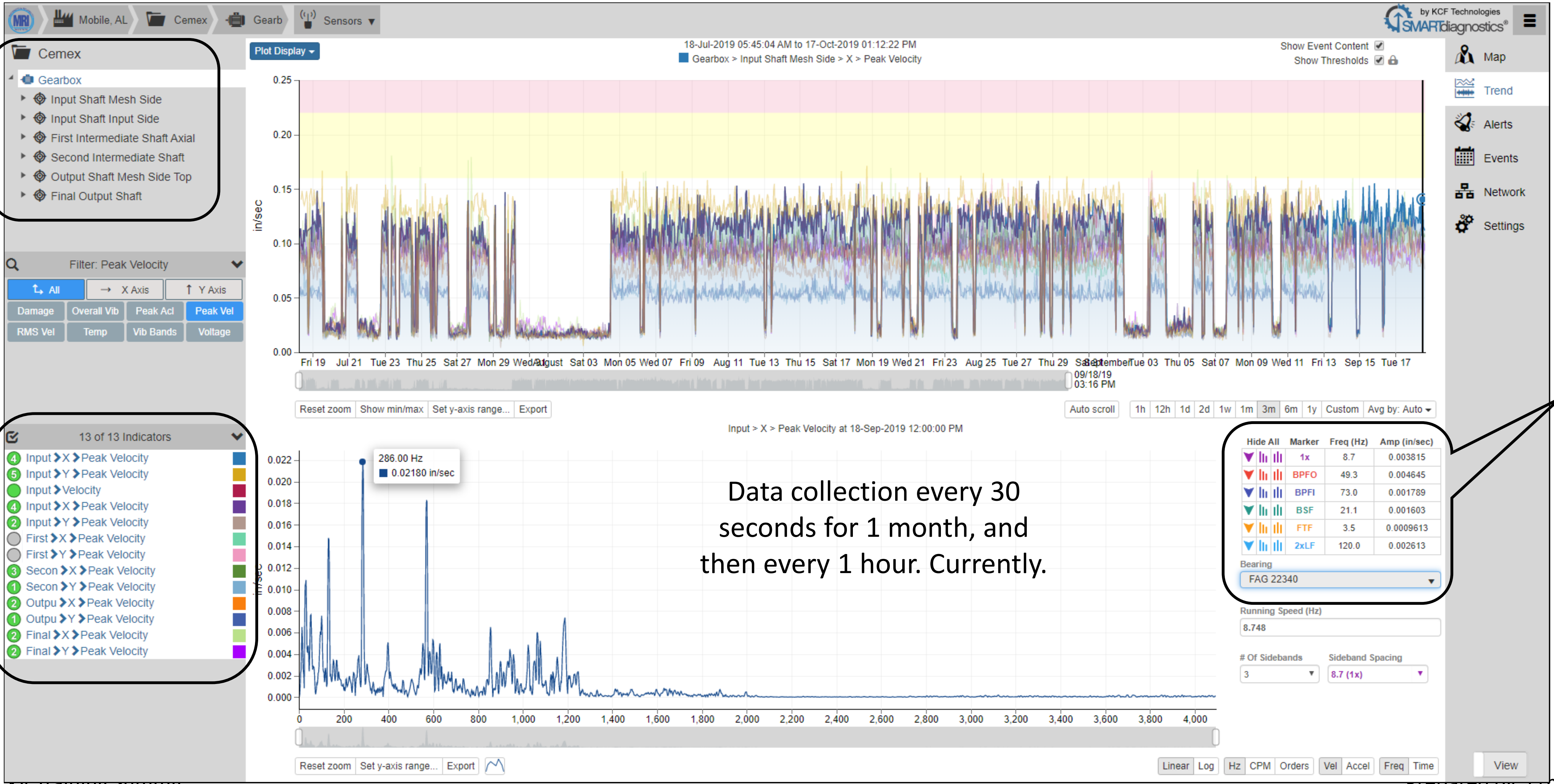
Vibration + Temp. Monitoring Software Setting

Data Points

Data Unit

Bearing Freq.



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Vibration Trend Analysis

Severity Criteria		
	Green	= Good / Acceptable
	Yellow	= Alert / In observation
	Red	= Warning / Need Attention

Observations:

The trend chart shows vibration in Velocity values, which are keeping within the alert limits, however there are 6 events in which the global value touches the first alert limit.

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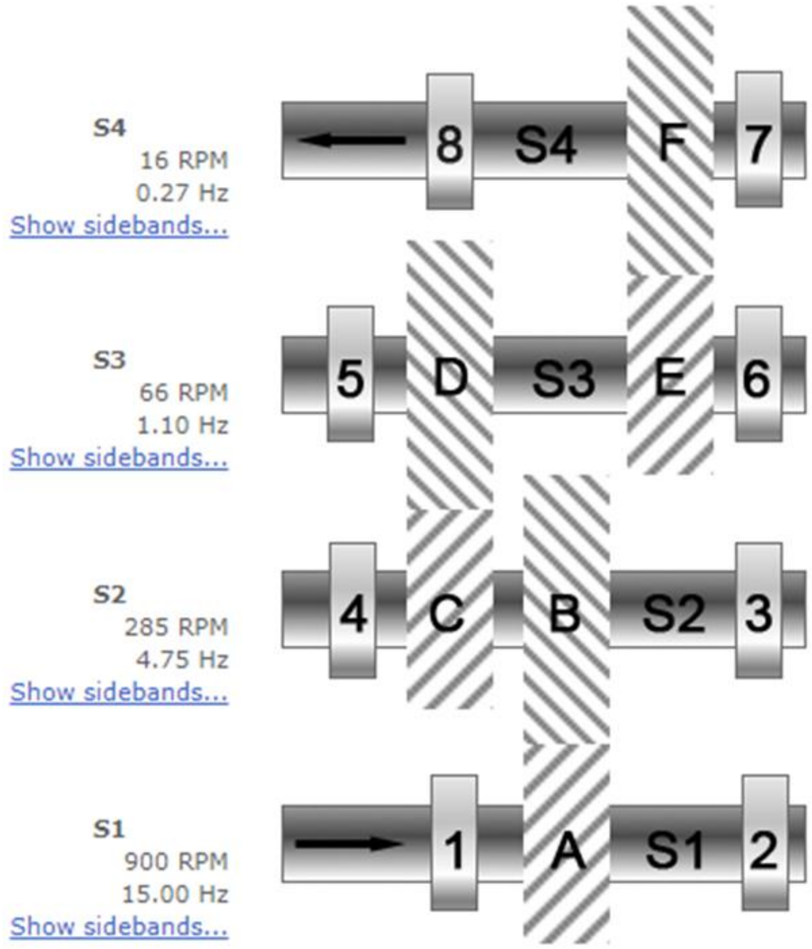
Failure Diagnostic

Gears Frequencies Analysis



S4 E & F		
	CPM	Hz
-2	899	14.98
-1	915	15.25
0	931	15.52
1	947	15.78
2	963	16.05

A complete simulation of the Gearbox train was performed, to identify the specific failure frequencies for each shaft and each gear.

Shaft	Speed	Gear Teeth		GMF		GMF Orders				MA Ratio	
S1	900 RPM					S1	S2	S3	S4	S1	1.000
	15.00 Hz	A	19	A & B	17100 CPM	19.0	60.0	257.1	1083.7		
S2	285 RPM	B	60		285.00 Hz					S2	0.317
	4.75 Hz	C	14	C & D	3990 CPM	4.4	14.0	60.0	252.9		
S3	66 RPM	D	60		66.50 Hz					S3	0.074
	1.10 Hz	E	14	E & F	931 CPM	1.0	3.3	14.0	59.0		
S4	16 RPM	F	59		15.52 Hz					S4	0.018
	0.27 Hz										

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Failure Diagnostic

Bearings Frequencies Analysis

Bearing Frequencies Calculator

This calculator is used to calculate the different bearing defect frequencies of bearing applications. One can search for an existing SKF bearing or input the different bearing parameters manually. The bearing defect frequencies can be displayed in Hertz, CPM or in orders of the rotational speed.

Bearing Data

SKF bearing designation*	22340 CC/W33 [Search]	
Measurement system	○ Metric ◉ Imperial	
Bearing type*	SRB	
Pitch diameter*	12.33	in
Rolling element diameter*	2.205	in
Number of rolling elements (per row)*	15	
Contact angle*	12.75	degrees
Rotational speed*	285	rpm
Rotating ring*	◉ inner ○ outer	

Output

◉ Hertz ○ CPM ○ Orders

Shaft speed frequency	4.750 Hz
Inner race defect frequency (BPFI)	41.839 Hz
Outer race defect frequency (BPFO)	29.411 Hz
Cage defect frequency (FTF)	1.961 Hz
Ball spin frequency (BSF)	12.877 Hz
Rolling element defect frequency	25.753 Hz

Source: **SKF.**

Bearing Frequencies Calculator

This calculator is used to calculate the different bearing defect frequencies of bearing applications. One can search for an existing SKF bearing or input the different bearing parameters manually. The bearing defect frequencies can be displayed in Hertz, CPM or in orders of the rotational speed.

Bearing Data

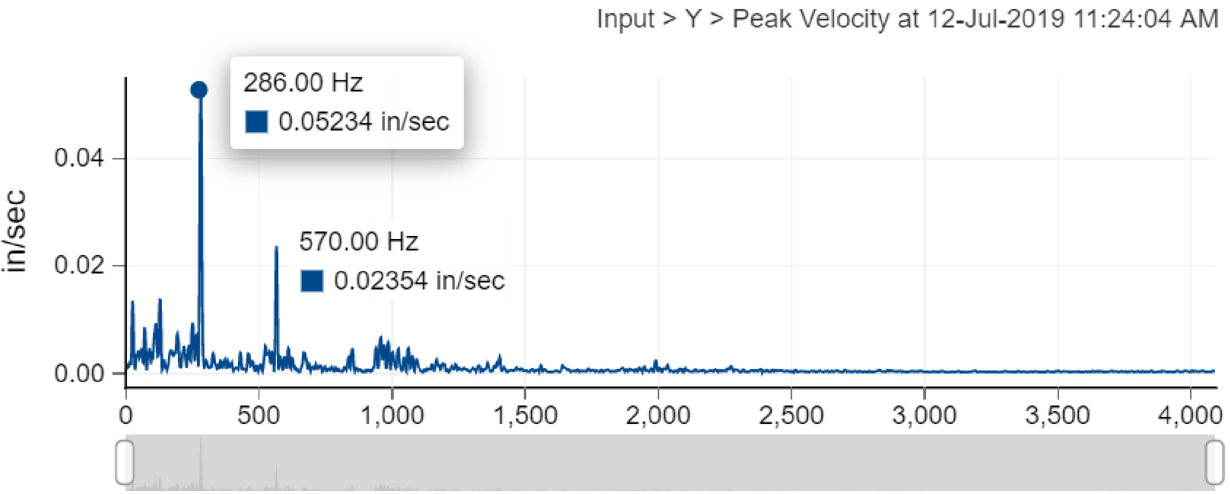
SKF bearing designation*	24160 CC/W33 [Search]	
Measurement system	○ Metric ◉ Imperial	
Bearing type*	SRB	
Pitch diameter*	15.84	in
Rolling element diameter*	1.969	in
Number of rolling elements (per row)*	22	
Contact angle*	14.75	degrees
Rotational speed*	66.58	rpm
Rotating ring*	◉ inner ○ outer	

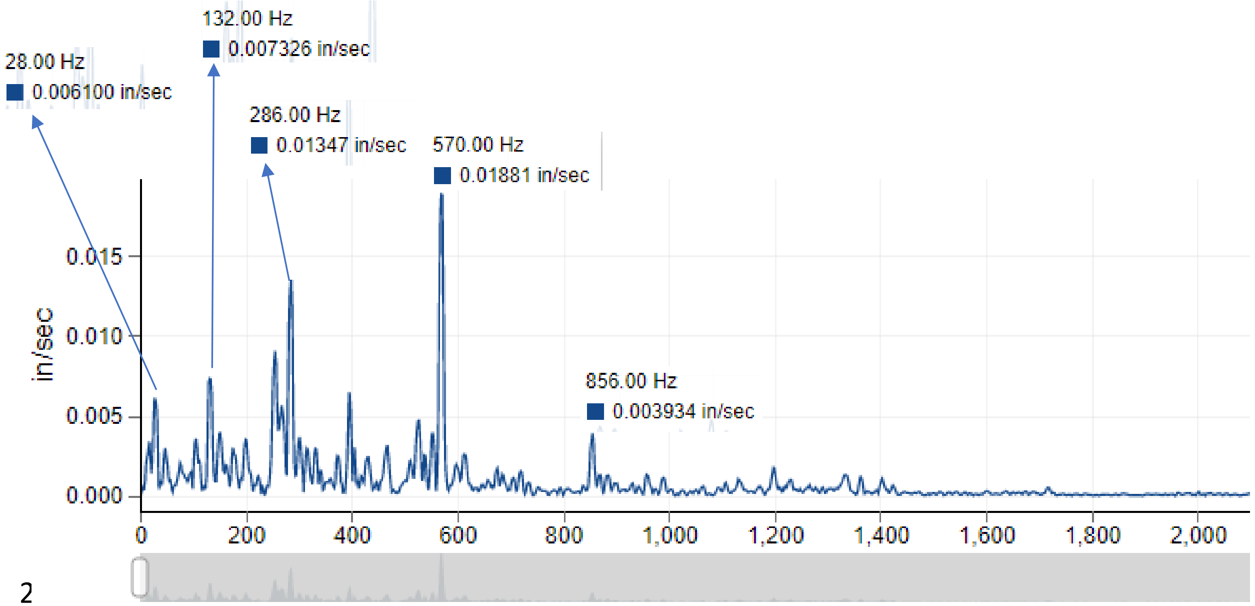
Output

◉ Hertz ○ CPM ○ Orders

Shaft speed frequency	1.110 Hz
Inner race defect frequency (BPFI)	13.674 Hz
Outer race defect frequency (BPFO)	10.739 Hz
Cage defect frequency (FTF)	0.488 Hz
Ball spin frequency (BSF)	4.399 Hz
Rolling element defect frequency	8.798 Hz

Failure Diagnostic





Spectrum Analysis Shaft N°1

The shaft 1 clearly shows the failure frequencies of gear teeth that are highlighted in the simulation, these correspond to 1x and 2x of the frequency of failure of the gears of shaft 2, which are transmitted to shaft 1.

With a frequency amplification, we can also observe the coupling failure frequency (28 Hz), as well as the appearance of the 3x (856 Hz) of the gear teeth failure of shaft 2.

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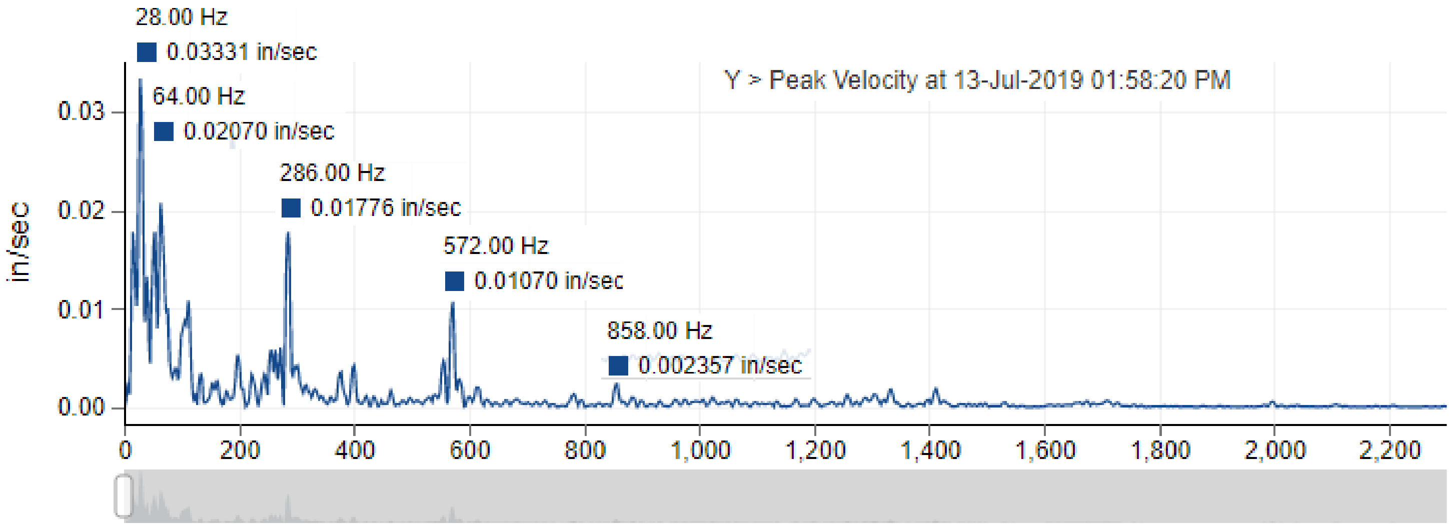
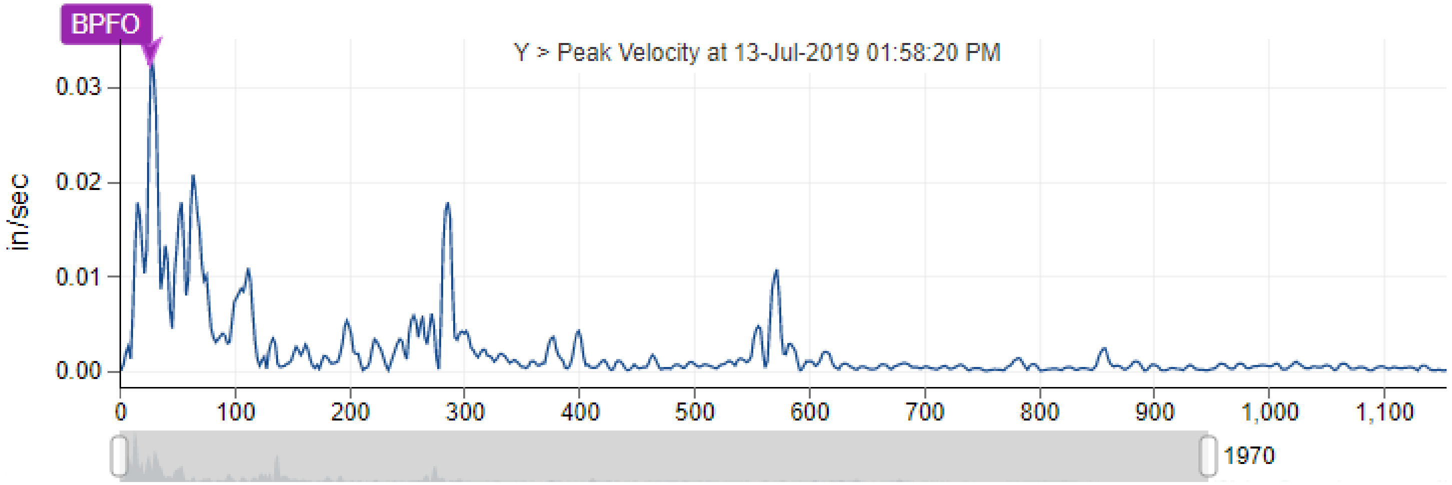
Failure Diagnostic





Spectrum Analysis Shaft N°2

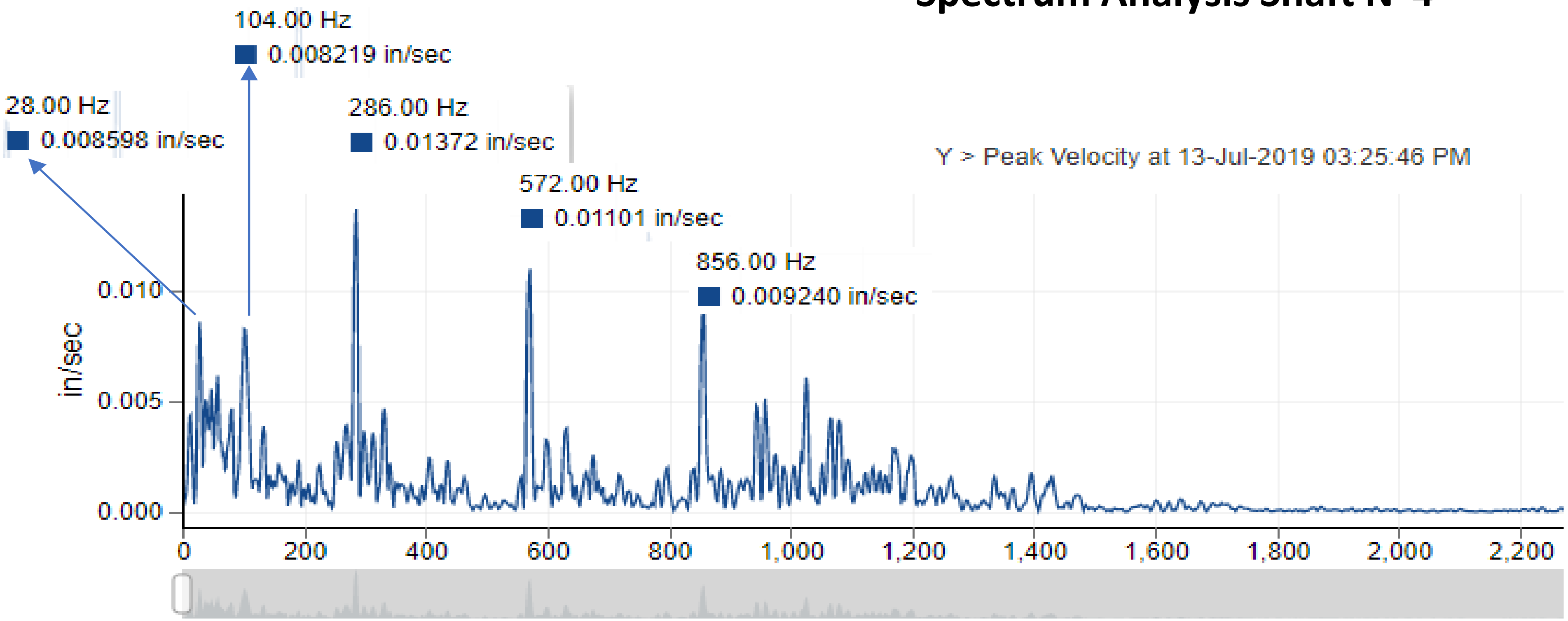
The shaft 2 clearly shows the frequencies 1x, 2x and 3x of the gear tooth failure frequency, as well as a high amplitude in the coupling failure frequency (28 Hz) that is amplified with the BPFO frequency (Ball Pass Frequency Outer) corresponding to the shaft 2 bearing.

Failure Diagnostic

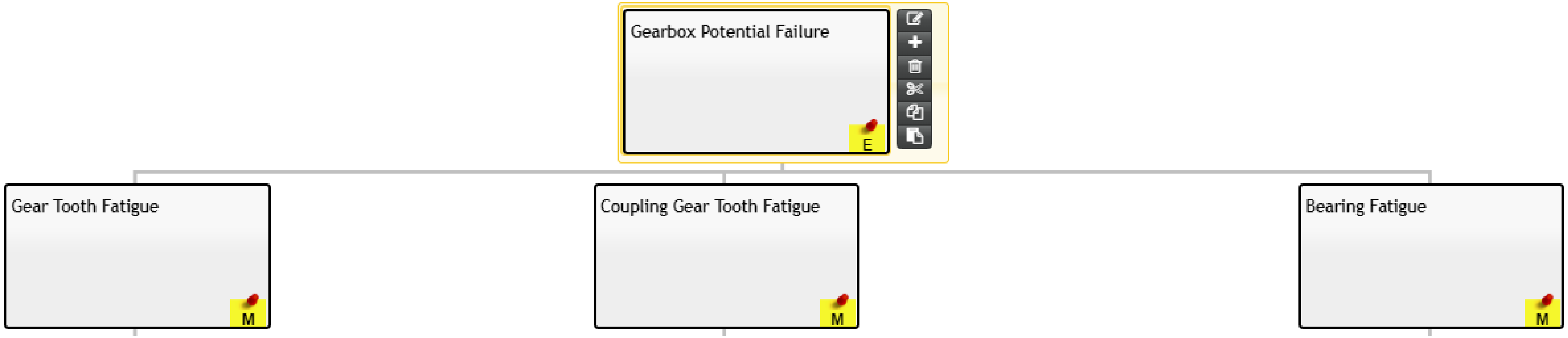
The gear coupling failure frequency and the shaft 2 gear tooth failure frequencies are shown again.

In the different spectral graphs, the frequency of the shaft 3 gear is also observed, which is the other frequency highlighted in the gearbox train simulation.

Spectrum Analysis Shaft N°4



Failure Modes Tags



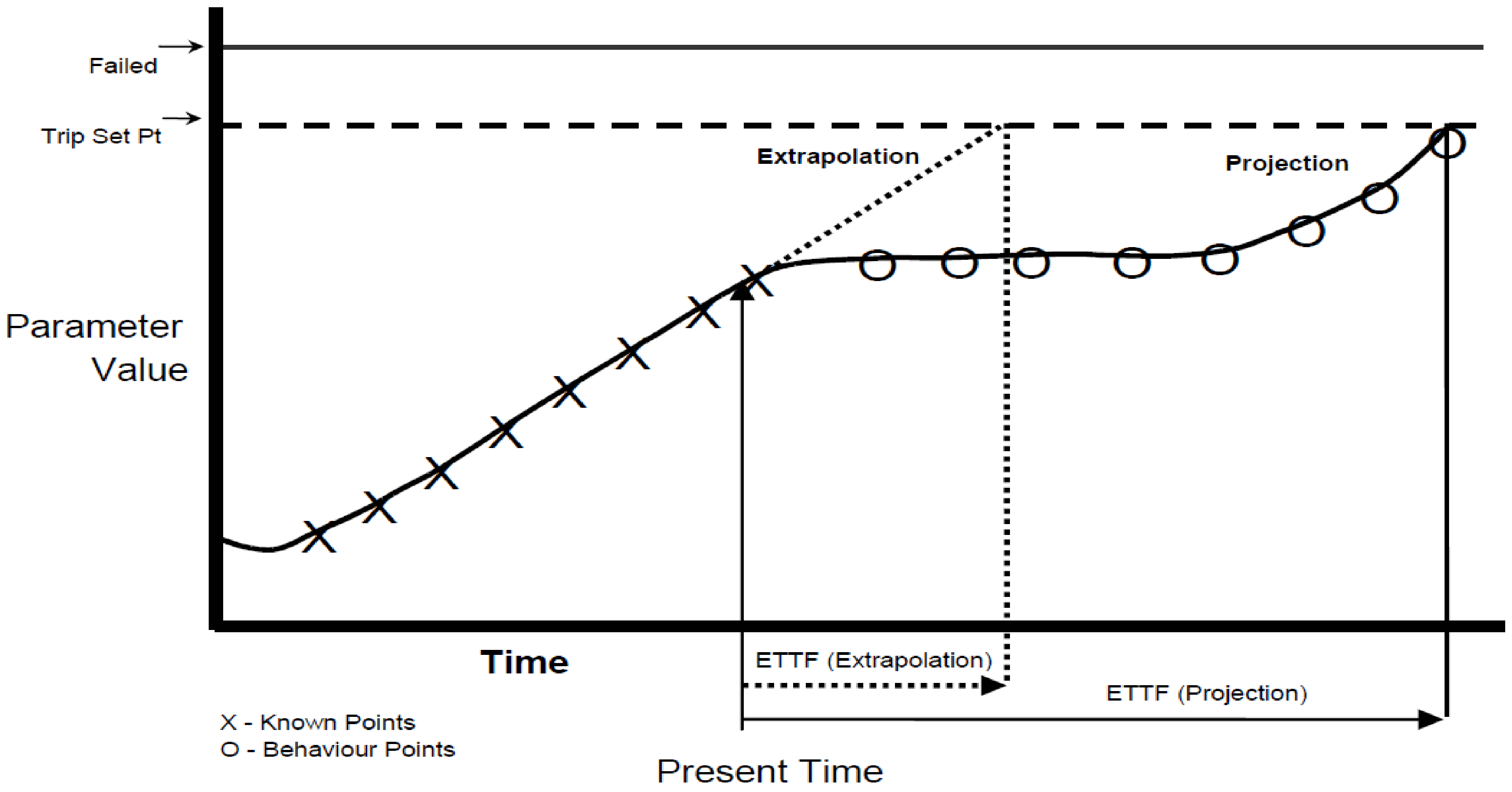
Three (3) failure modes identified:

<u>Failure Modes:</u>

- **Gear Coupling Fatigue.**
- **Gears Shaft Fatigue. (Shaft 2 and 3)**
- **SKF 22340 Bearing Fatigue. (Shaft 2).** This is the smallest and most susceptible bearing in the machinery train and is an effect of the inadequate clearance of Bearing TIMKEN HH234048 in the Shaft N°1.

Prognostics of Failure to Identify the Remaining Useful Life

ETTF: Estimated Time To Failure



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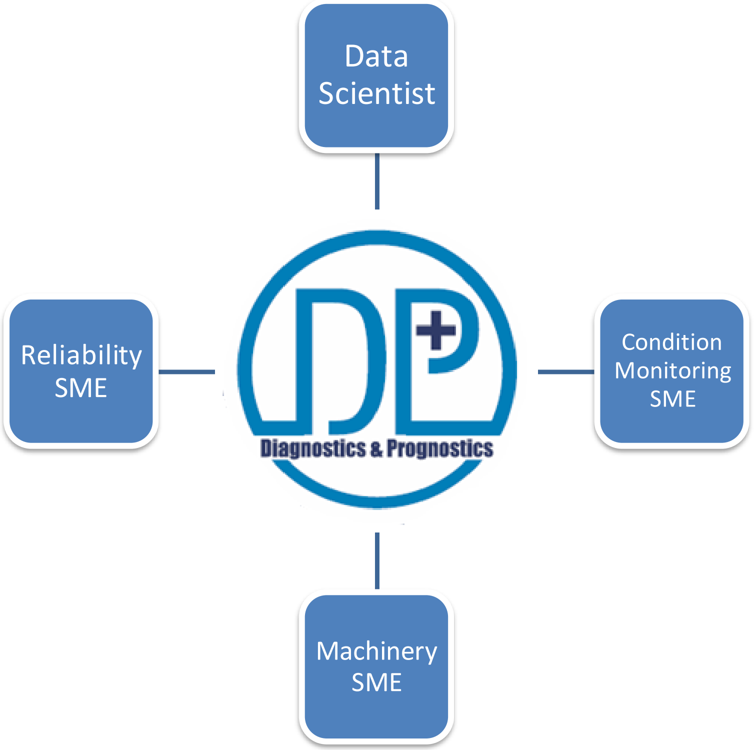
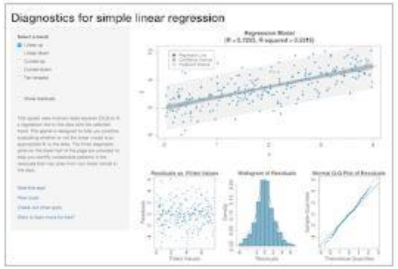
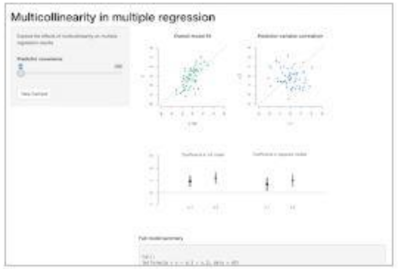
Prognostics of Failure to Identify the Remaining Useful Life





LINEAR REGRESSION DIAGNOSTICS

Explore the fit of a linear regression.

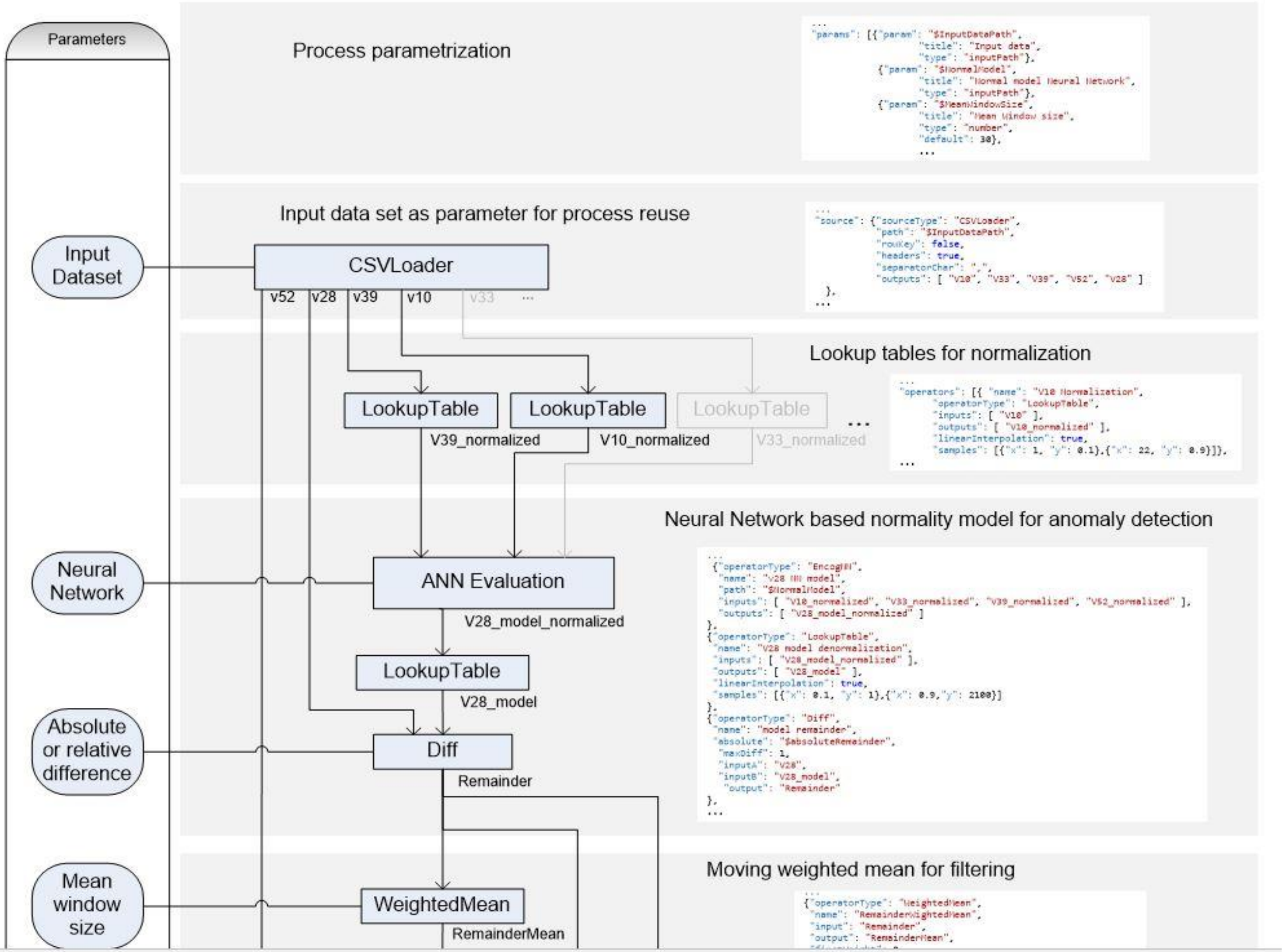


MULTICOLLINEARITY

Simulate correlation between model predictors.

Prognostics of Failure to Identify the Remaining Useful Life

Model and Programming



ML Applied in Rotating Machinery for Anomalies Detection and RUL estimation

Prognostics of Failure to Identify the Remaining Useful Life

Dataset

	Gearbox > Input Shaft Mesh Side > X				Gearbox > Input Shaft Mesh Side > Y			
2	Time (UTC)	Avg(in/s	Min(in/s	Max(in/	Time (UTC)	Avg(in/s	Min(in/s	Max(in/
3	7/5/2019 19:55	0.0939	0.0939	0.0939	7/5/2019 19:55	0.133	0.133	0.133
4	7/5/2019 19:56	0.1141	0.1141	0.1141	7/5/2019 19:56	0.1349	0.1349	0.1349
5	7/5/2019 19:57	0.0907	0.0907	0.0907	7/5/2019 19:57	0.1546	0.1546	0.1546
6	7/5/2019 19:58	0.0891	0.0891	0.0891	7/5/2019 19:58	0.1471	0.1471	0.1471
7	7/5/2019 19:59	0.1177	0.1177	0.1177	7/5/2019 19:59	0.1378	0.1378	0.1378
8	7/5/2019 20:00	0.1127	0.1127	0.1127	7/5/2019 20:00	0.1461	0.1461	0.1461
9	7/5/2019 20:01	0.1131	0.1131	0.1131	7/5/2019 20:01	0.162	0.162	0.162
10	7/5/2019 20:02	0.1256	0.1256	0.1256	7/5/2019 20:02	0.1307	0.1307	0.1307
11	7/5/2019 20:03	0.1023	0.1023	0.1023	7/5/2019 20:03	0.1405	0.1405	0.1405
12	7/5/2019 20:04	0.1062	0.1062	0.1062	7/5/2019 20:04	0.1467	0.1467	0.1467
13	7/5/2019 20:05	0.0961	0.0961	0.0961	7/5/2019 20:05	0.1441	0.1441	0.1441
14	7/5/2019 20:06	0.1212	0.1212	0.1212	7/5/2019 20:06	0.1387	0.1387	0.1387
15	7/5/2019 20:07	0.1143	0.1143	0.1143	7/5/2019 20:07	0.1411	0.1411	0.1411
16	7/5/2019 20:08	0.0882	0.0882	0.0882	7/5/2019 20:08	0.1669	0.1669	0.1669
17	7/5/2019 20:09	0.1271	0.1271	0.1271	7/5/2019 20:09	0.1355	0.1355	0.1355
18	7/5/2019 20:10	0.095	0.095	0.095	7/5/2019 20:10	0.1387	0.1387	0.1387
19	7/5/2019 20:11	0.1312	0.1312	0.1312	7/5/2019 20:11	0.1379	0.1379	0.1379
20	7/5/2019 20:12	0.1022	0.1022	0.1022	7/5/2019 20:12	0.1341	0.1341	0.1341
21	7/5/2019 20:13	0.1203	0.1203	0.1203	7/5/2019 20:13	0.1331	0.1331	0.1331
22	7/5/2019 20:14	0.1058	0.1058	0.1058	7/5/2019 20:14	0.1561	0.1561	0.1561
23	7/5/2019 20:15	0.1079	0.1079	0.1079	7/5/2019 20:15	0.1431	0.1431	0.1431
24	7/5/2019 20:16	0.104	0.104	0.104	7/5/2019 20:16	0.1401	0.1401	0.1401
25	7/5/2019 20:17	0.1184	0.1184	0.1184	7/5/2019 20:17	0.1316	0.1316	0.1316
26	7/5/2019 20:18	0.1056	0.1056	0.1056	7/5/2019 20:18	0.1402	0.1402	0.1402
27	7/5/2019 20:20	0.1047	0.1047	0.1047	7/5/2019 20:20	0.1405	0.1405	0.1405
28	7/5/2019 20:21	0.1284	0.1284	0.1284	7/5/2019 20:21	0.1486	0.1486	0.1486
29	7/5/2019 20:22	0.1242	0.1242	0.1242	7/5/2019 20:22	0.1454	0.1454	0.1454
30	7/5/2019 20:23	0.0982	0.0982	0.0982	7/5/2019 20:23	0.128	0.128	0.128
31	7/5/2019 20:24	0.1278	0.1278	0.1278	7/5/2019 20:24	0.1421	0.1421	0.1421
32	7/5/2019 20:25	0.1177	0.1177	0.1177	7/5/2019 20:25	0.1441	0.1441	0.1441
33	7/5/2019 20:26	0.1143	0.1143	0.1143	7/5/2019 20:26	0.1484	0.1484	0.1484
34	7/5/2019 20:27	0.107	0.107	0.107	7/5/2019 20:27	0.1464	0.1464	0.1464
35	7/5/2019 20:28	0.1253	0.1253	0.1253	7/5/2019 20:28	0.1416	0.1416	0.1416
36	7/5/2019 20:29	0.1137	0.1137	0.1137	7/5/2019 20:29	0.1316	0.1316	0.1316
37	7/5/2019 20:30	0.0912	0.0912	0.0912	7/5/2019 20:30	0.1451	0.1451	0.1451
38	7/5/2019 20:31	0.0993	0.0993	0.0993	7/5/2019 20:31	0.1447	0.1447	0.1447
39	7/5/2019 20:32	0.0973	0.0973	0.0973	7/5/2019 20:32	0.1338	0.1338	0.1338
40	7/5/2019 20:33	0.0988	0.0988	0.0988	7/5/2019 20:33	0.1355	0.1355	0.1355
41	7/5/2019 20:34	0.1015	0.1015	0.1015	7/5/2019 20:34	0.1392	0.1392	0.1392
42	7/5/2019 20:35	0.101	0.101	0.101	7/5/2019 20:35	0.1353	0.1353	0.1353
43	7/5/2019 20:36	0.1161	0.1161	0.1161	7/5/2019 20:36	0.1382	0.1382	0.1382
44	7/5/2019 20:37	0.0999	0.0999	0.0999	7/5/2019 20:37	0.1399	0.1399	0.1399
45	7/5/2019 20:38	0.1141	0.1141	0.1141	7/5/2019 20:38	0.134	0.134	0.134
46	7/5/2019 20:39	0.1052	0.1052	0.1052	7/5/2019 20:39	0.1397	0.1397	0.1397
47	7/5/2019 20:40	0.1172	0.1172	0.1172	7/5/2019 20:40	0.1341	0.1341	0.1341
48	7/5/2019 20:40	0.1019	0.1019	0.1019	7/5/2019 20:40	0.1362	0.1362	0.1362
49	7/5/2019 20:41	0.107	0.107	0.107	7/5/2019 20:41	0.1391	0.1391	0.1391
50	7/5/2019 20:43	0.1127	0.1127	0.1127	7/5/2019 20:43	0.1339	0.1339	0.1339
51	7/5/2019 20:45	0.114	0.114	0.114	7/5/2019 20:44	0.1488	0.1488	0.1488
52	7/5/2019 20:46	0.1239	0.1239	0.1239	7/5/2019 20:45	0.1332	0.1332	0.1332
53	7/5/2019 20:47	0.1005	0.1005	0.1005	7/5/2019 20:46	0.1424	0.1424	0.1424
54	7/5/2019 20:48	0.1027	0.1027	0.1027	7/5/2019 20:47	0.1531	0.1531	0.1531
55	7/5/2019 20:49	0.1156	0.1156	0.1156	7/5/2019 20:48	0.1437	0.1437	0.1437
56	7/5/2019 20:50	0.1022	0.1022	0.1022	7/5/2019 20:49	0.1397	0.1397	0.1397
57	7/5/2019 20:51	0.1003	0.1003	0.1003	7/5/2019 20:50	0.1551	0.1551	0.1551
58	7/5/2019 20:52	0.1189	0.1189	0.1189	7/5/2019 20:51	0.1474	0.1474	0.1474
59	7/5/2019 20:53	0.1055	0.1055	0.1055	7/5/2019 20:52	0.1463	0.1463	0.1463

	Gearbox > Input Shaft Input Side > Y				Gearbox > First Intermediate			
2	Time (UTC)	Avg(in/s	Min(in/s	Max(in/	Time (UTC)	Avg(in/s	Min(in/s	Max(in/
3	7/5/2019 19:55	0.0854	0.0854	0.0854	7/5/2019 19:55	0.0948	0.0948	0.0948
4	7/5/2019 19:55	0.079	0.079	0.079	7/5/2019 19:55	0.0933	0.0933	0.0933
5	7/5/2019 19:56	0.0793	0.0793	0.0793	7/5/2019 19:56	0.0702	0.0702	0.0702
6	7/5/2019 19:57	0.078	0.078	0.078	7/5/2019 19:57	0.0786	0.0786	0.0786
7	7/5/2019 19:58	0.0796	0.0796	0.0796	7/5/2019 19:58	0.0908	0.0908	0.0908
8	7/5/2019 19:59	0.0821	0.0821	0.0821	7/5/2019 19:59	0.0774	0.0774	0.0774
9	7/5/2019 20:00	0.0777	0.0777	0.0777	7/5/2019 20:00	0.0734	0.0734	0.0734
10	7/5/2019 20:01	0.0977	0.0977	0.0977	7/5/2019 20:01	0.0787	0.0787	0.0787
11	7/5/2019 20:02	0.0884	0.0884	0.0884	7/5/2019 20:02	0.08	0.08	0.08
12	7/5/2019 20:03	0.0831	0.0831	0.0831	7/5/2019 20:03	0.0766	0.0766	0.0766
13	7/5/2019 20:04	0.0779	0.0779	0.0779	7/5/2019 20:04	0.081	0.081	0.081
14	7/5/2019 20:05	0.0834	0.0834	0.0834	7/5/2019 20:05	0.0914	0.0914	0.0914
15	7/5/2019 20:06	0.071	0.071	0.071	7/5/2019 20:06	0.0832	0.0832	0.0832
16	7/5/2019 20:07	0.0873	0.0873	0.0873	7/5/2019 20:07	0.0778	0.0778	0.0778
17	7/5/2019 20:08	0.0998	0.0998	0.0998	7/5/2019 20:08	0.089	0.089	0.089
18	7/5/2019 20:09	0.0827	0.0827	0.0827	7/5/2019 20:09	0.0775	0.0775	0.0775
19	7/5/2019 20:10	0.0862	0.0862	0.0862	7/5/2019 20:10	0.0774	0.0774	0.0774
20	7/5/2019 20:11	0.0854	0.0854	0.0854	7/5/2019 20:12	0.0634	0.0634	0.0634
21	7/5/2019 20:12	0.0924	0.0924	0.0924	7/5/2019 20:13	0.0645	0.0645	0.0645
22	7/5/2019 20:13	0.0801	0.0801	0.0801	7/5/2019 20:14	0.0634	0.0634	0.0634
23	7/5/2019 20:14	0.0777	0.0777	0.0777	7/5/2019 20:15	0.0716	0.0716	0.0716
24	7/5/2019 20:15	0.0859	0.0859	0.0859	7/5/2019 20:16	0.0819	0.0819	0.0819
25	7/5/2019 20:16	0.0867	0.0867	0.0867	7/5/2019 20:17	0.0655	0.0655	0.0655
26	7/5/2019 20:17	0.0825	0.0825	0.0825	7/5/2019 20:18	0.0587	0.0587	0.0587
27	7/5/2019 20:18	0.0785	0.0785	0.0785	7/5/2019 20:20	0.0641	0.0641	0.0641
28	7/5/2019 20:20	0.0816	0.0816	0.0816	7/5/2019 20:21	0.0729	0.0729	0.0729
29	7/5/2019 20:21	0.0725	0.0725	0.0725	7/5/2019 20:22	0.0712	0.0712	0.0712
30	7/5/2019 20:22	0.0835	0.0835	0.0835	7/5/2019 20:23	0.0589	0.0589	0.0589
31	7/5/2019 20:23	0.0875	0.0875	0.0875	7/5/2019 20:24	0.0653	0.0653	0.0653
32	7/5/2019 20:24	0.0827	0.0827	0.0827	7/5/2019 20:25	0.0669	0.0669	0.0669
33	7/5/2019 20:25	0.0843	0.0843	0.0843	7/5/2019 20:26	0.0747	0.0747	0.0747
34	7/5/2019 20:26	0.0814	0.0814	0.0814	7/5/2019 20:27	0.0635	0.0635	0.0635
35	7/5/2019 20:27	0.0894	0.0894	0.0894	7/5/2019 20:28	0.0709	0.0709	0.0709
36	7/5/2019 20:28	0.0823	0.0823	0.0823	7/5/2019 20:29	0.0831	0.0831	0.0831
37	7/5/2019 20:29	0.0904	0.0904	0.0904	7/5/2019 20:30	0.0726	0.0726	0.0726
38	7/5/2019 20:30	0.0903	0.0903	0.0903	7/5/2019 20:31	0.0586	0.0586	0.0586
39	7/5/2019 20:31	0.0822	0.0822	0.0822	7/5/2019 20:32	0.0765	0.0765	0.0765
40	7/5/2019 20:32	0.0776	0.0776	0.0776	7/5/2019 20:33	0.0741	0.0741	0.0741
41	7/5/2019 20:33	0.0904	0.0904	0.0904	7/5/2019 20:34	0.0666	0.0666	0.0666
42	7/5/2019 20:34	0.0904	0.0904	0.0904	7/5/2019 20:35	0.0641	0.0641	0.0641
43	7/5/2019 20:35	0.0759	0.0759	0.0759	7/5/2019 20:36	0.0624	0.0624	0.0624
44	7/5/2019 20:36	0.0808	0.0808	0.0808	7/5/2019 20:37	0.0734	0.0734	0.0734
45	7/5/2019 20:37	0.0802	0.0802	0.0802	7/5/2019 20:38	0.0606	0.0606	0.0606
46	7/5/2019 20:38	0.0746	0.0746	0.0746	7/5/2019 20:39	0.0712	0.0712	0.0712
47	7/5/2019 20:39	0.0841	0.0841	0.0841	7/5/2019 20:40	0.0729	0.0729	0.0729
48	7/5/2019 20:40	0.0756	0.0756	0.0756	7/5/2019 20:40	0.0677	0.0677	0.0677
49	7/5/2019 20:40	0.082	0.082	0.082	7/5/2019 20:41	0.0599	0.0599	0.0599
50	7/5/2019 20:41	0.0947	0.0947	0.0947	7/5/2019 20:43	0.0546	0.0546	0.0546
51	7/5/2019 20:43	0.0882	0.0882	0.0882	7/5/2019 20:44	0.0607	0.0607	0.0607
52	7/5/2019 20:44	0.0799	0.0799	0.0799	7/5/2019 20:45	0.0658	0.0658	0.0658
53	7/5/2019 20:45	0.0839	0.0839	0.0839	7/5/2019 20:46	0.0673	0.0673	0.0673
54	7/5/2019 20:46	0.0805	0.0805	0.0805	7/5/2019 20:47	0.0565	0.0565	0.0565
55	7/5/2019 20:47	0.0995	0.0995	0.0995	7/5/2019 20:48	0.0657	0.0657	0.0657
56	7/5/2019 20:48	0.0837	0.0837	0.0837	7/5/2019 20:49	0.0645	0.0645	0.0645
57	7/5/2019 20:49	0.0863	0.0863	0.0863	7/5/2019 20:50	0.0736	0.0736	0.0736
58	7/5/2019 20:50	0.0916	0.0916	0.0916	7/5/2019 20:51	0.0695	0.0695	0.0695
59	7/5/2019 20:51	0.076	0.076	0.076	7/5/2019 20:52	0.0664	0.0664	0.0664

	Gearbox > First Intermediate				Gearbox > Second Intermediate			
2	Time (UTC)	Avg(in/s	Min(in/s	Max(in/	Time (UTC)	Avg(in/s	Min(in/s	Max(in/
3	7/5/2019 19:55	0.0858	0.0858	0.0858	7/5/2019 19:55	0.0836	0.0836	0.0836
4	7/5/2019 19:55	0.0962	0.0962	0.0962	7/5/2019 19:55	0.0901	0.0901	0.0901
5	7/5/2019 19:56	0.0991	0.0991	0.0991	7/5/2019 19:56	0.0843	0.0843	0.0843
6	7/5/2019 19:57	0.0904	0.0904	0.0904	7/5/2019 19:57	0.075	0.075	0.075
7	7/5/2019 19:58	0.0912	0.0912	0.0912	7/5/2019 19:58	0.0762	0.0762	0.0762
8	7/5/2019 20:00	0.0847	0.0847	0.0847	7/5/2019 19:59	0.0933	0.0933	0.0933
9	7/5/2019 20:01	0.0892	0.0892	0.0892	7/5/2019 20:00	0.0724	0.0724	0.0724
10	7/5/2019 20:02	0.0892	0.0892	0.0892	7/5/2019 20:01	0.0919	0.0919	0.0919
11	7/5/2019 20:03	0.0901	0.0901	0.0901	7/5/2019 20:02	0.0848	0.0848	0.0848
12	7/5/2019 20:04	0.0963	0.0963	0.0963	7/5/2019 20:03	0.0842	0.0842	0.0842
13	7/5/2019 20:05	0.0999	0.0999	0.0999	7/5/2019 20:04	0.0937	0.0937	0.0937
14	7/5/2019 20:06	0.0951	0.0951	0.0951	7/5/2019 20:05	0.0854	0.0854	0.0854
15	7/5/2019 20:07	0.0852	0.0852	0.0852	7/5/2019 20:06	0.0756	0.0756	0.0756
16	7/5/2019 20:08	0.1005	0.1005	0.1005	7/5/2019 20:07	0.0877	0.0877	0.0877
17	7/5/2019 20:09	0.0833	0.0833	0.0833	7/5/2019 20:08	0.0802	0.0802	0.0802
18	7/5/2019 20:10	0.0843	0.0843	0.0843	7/5/2019 20:09	0.079	0.079	0.079
19	7/5/2019 20:11	0.3864	0.3864	0.3864	7/5/2019 20:10	0.0854	0.0854	0.0854
20	7/5/2019 20:12	0.1012	0.1012	0.1012	7/5/2019 20:11	0.0824	0.0824	0.0824
21	7/5/2019 20:13	0.1055	0.1055	0.1055	7/5/2019 20:12	0.0878	0.0878	0.0878
22	7/5/2019 20:14	0.1048	0.1048	0.1048	7/5/2019 20:13	0.0836	0.0836	0.0836
23	7/5/2019 20:15	0.1179	0.1179	0.1179	7/5/2019 20:14	0.1022	0.1022	0.1022
24	7/5/2019 20:16	0.1051	0.1051	0.1051	7/5/2019 20:15	0.0987	0.0987	0.0987
25	7/5/2019 20:17	0.0956	0.0956	0.0956	7/5/2019 20:16	0.0797	0.0797	0.0797
26	7/5/2019 20:18	0.1034	0.1034	0.1034	7/5/2019 20:17	0.0963	0.0963	0.0963
27	7/5/2019 20:20	0.1106	0.1106	0.1106	7/5/2019 20:18	0.0802	0.0802	0.0802
28	7/5/2019 20:21	0.1219	0.1219	0.1219	7/5/2019 20:20	0.0928	0.0928	0.0928
29	7/5/2019 20:22	0.1064	0.1064	0.1064	7/5/2019 20:21	0.0786	0.0786	0.0786
30	7/5/2019 20:23	0.1173	0.1173	0.1173	7/5/2019 20:22	0.1098	0.1098	0.1098
31	7/5/2019 20:24	0.1004	0.1004	0.1004	7/5/2019 20:23	0.0723	0.0723	0.0723
32	7/5/2019 20:25	0.1143	0.1143	0.1143	7/5/2019 20:24	0.0805	0.0805	0.0805
33	7/5/2019 20:26	0.0979	0.0979	0.0979	7/5/2019 20:25	0.1071	0.1071	0.1071
34	7/5/2019 20:27	0.0995	0.0995	0.0995	7/5/2019 20:26	0.1085	0.1085	0.1085
35	7/5/2019 20:28	0.101	0.101	0.101	7/5/2019 20:27	0.0923	0.0923	0.0923
36	7/5/2019 20:29	0.1039	0.1039	0.1039	7/5/2019 20:28	0.0813	0.0813	0.0813
37	7/5/2019 20:30	0.0974	0.0974	0.0974	7/5/2019 20:29	0.0826	0.0826	0.0826
38	7/5/2019 20:31	0.1018	0.1018	0.1018	7/5/2019 20:30	0.0888	0.0888	0.0888
39	7/5/2019 20:32	0.1057	0.1057	0.1057	7/5/2019 20:31	0.1038	0.1038	0.1038
40	7/5/2019 20:33	0.0972	0.0972	0.0972	7/5/2019 20:32	0.0907	0.0907	0.0907
41	7/5/2019 20:34	0.1104	0.1104	0.1104	7/5/2019 20:33	0.0847	0.0847	0.0847
42	7/5/2019 20:35	0.108	0.108	0.108	7/5/2019 20:34	0.1123	0.1123	0.1123
43	7/5/2019 20:36	0.1017	0.1017	0.1017	7/5/2019 20:35	0.0897	0.0897	0.0897
44	7/5/2019 20:37	0.1155	0.1155	0.1155	7/5/2019 20:36	0.0987	0.0987	0.0987
45	7/5/2019 20:38	0.1249	0.1249	0.1249	7/5/2019 20:37	0.0897	0.0897	0.0897
46	7/5/2019 20:39	0.115	0.115	0.115	7/5/2019 20:38	0.099	0.099	0.099
47	7/5/2019 20:40	0.1005	0.1005	0.1005	7/5/2019 20:39	0.101	0.101	0.101
48	7/5/2019 20:40	0.0981	0.0981	0.0981	7/5/2019 20:40	0.0842	0.0842	0.0842
49	7/5/2019 20:42	0.1071	0.1071	0.1071	7/5/2019 20:40	0.0918	0.0918	0.0918
50	7/5/2019 20:43	0.1176	0.1176	0.1176	7/5/2019 20:41	0.0763	0.0763	0.0763
51	7/5/2019 20:44	0.1031	0.1031	0.1031	7/5/2019 20:43	0.0813	0.0813	0.0813
52	7/5/2019 20:45	0.112	0.112	0.112	7/5/2019 20:44	0.0812	0.0812	0.0812
53	7/5/2019 20:46	0.1036	0.1036	0.1036	7/5/2019 20:45	0.0882	0.0882	0.0882
54	7/5/2019 20:47	0.1164	0.1164	0.1164	7/5/2019 20:46	0.0972	0.0972	0.0972
55	7/5/2019 20:48	0.1058	0.1058	0.1058	7/5/2019 20:47	0.1032	0.1032	0.1032
56	7/5/2019 20:49	0.1107	0.1107	0.1107	7/5/2019 20:48	0.0856	0.0856	0.0856
57	7/5/2019 20:50	0.1292	0.1292	0.1292	7/5/2019 20:49	0.0804	0.0804	0.0804
58	7/5/2019 20:51	0.1063	0.1063	0.1063	7/5/2019 20:50	0.0851	0.0851	0.0851
59	7/5/2019 20:52	0.1029	0.1029	0.1029	7/5/2019 20:51	0.1004	0.1004	0.1004

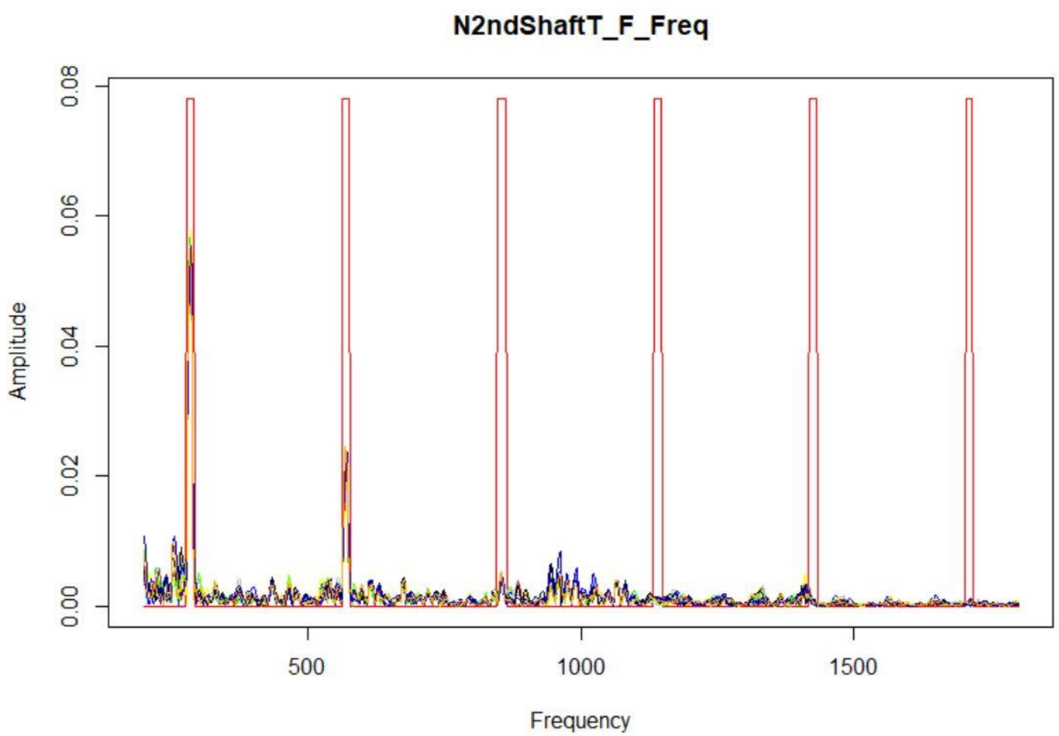
	Gearbox > Output Shaft Mesh Side				Gearbox > Final Output Shaft > X >			
2	Time (UTC)	Avg(in/s	Min(in/s	Max(in/	Time (UTC)	Avg(in/s	Min(in/s	Max(in/
3	7/5/2019 19:55	0.0538	0.0538	0.0538	7/5/2019 19:55	0.0987	0.0987	0.0987
4	7/5/2019 19:55	0.0567	0.0567	0.0567	7/5/2019 19:55	0.0996	0.0996	0.0996
5	7/5/2019 19:56	0.0644	0.0644	0.0644	7/5/2019 19:56	0.0965	0.0965	0.0965
6	7/5/2019 19:57	0.0547	0.0547	0.0547	7/5/2019 19:57	0.1173	0.1173	0.1173
7	7/5/2019 19:58	0.0631	0.0631	0.0631	7/5/2019 19:58	0.1008	0.1008	0.1008
8	7/5/2019 19:59	0.0515	0.0515	0.0515	7/5/2019 19:59	0.1061	0.1061	0.1061
9	7/5/2019 20:00	0.0535	0.0535	0.0535	7/5/2019 20:00	0.1042	0.1042	0.1042
10	7/5/2019 20:01	0.0495	0.0495	0.0495	7/5/2019 20:01	0.0987	0.0987	0.0987
11	7/5/2019 20:02	0.0551	0.0551	0.0551	7/5/2019 20:03	0.0915	0.0915	0.0915
12	7/5/2019 20:03	0.0543	0.0543	0.0543	7/5/2019 20:04	0.1049	0.1049	0.1049
13	7/5/2019 20:04	0.0547	0.0547	0.0547	7/5/2019 20:05	0.1134	0.1134	0.1134
14	7/5/2019 20:05	0.0512	0.0512	0.0512	7/5/2019 20:06	0.0961	0.0961	0.0961
15	7/5/2019 20:06	0.0508	0.0508	0.0508	7/5/2019 20:07	0.1421	0.1421	0.1421
16	7/5/2019 20:07	0.052	0.052	0.052	7/5/2019 20:08	0.0944	0.0944	0.0944
17	7/5/2019 20:08	0.0517	0.0517	0.0517	7/5/2019 20:09	0.0984	0.0984	0.0984
18	7/5/2019 20:09	0.0513	0.0513	0.0513	7/5/2019 20:10	0.105	0.105	0.105
19	7/5/2019 20:10	0.0595	0.0595	0.0595	7/5/2019 20:11	0.0943	0.0943	0.0943
20	7/5/2019 20:11	0.0645	0.0645	0.0645	7/5/2019 20:12	0.1015	0.1015	0.1015
21	7/5/2019 20:12	0.0533	0.0533	0.0533	7/5/2019 20:13	0.0914	0.0914	0.0914
22	7/5/2019 20:13	0.0518	0.0518	0.0518	7/5/2019 20:14	0.1154	0.1154	0.1154
23	7/5/2019 20:14	0.0462	0.0462	0.0462	7/5/2019 20:15	0.0988	0.0988	0.0988
24	7/5/2019 20:15	0.0478	0.0478	0.0478	7/5/2019 20:16	0.096	0.096	0.096
25	7/5/2019 20:16	0.0555	0.0555	0.0555	7/5/2019 20:17	0.0833	0.0833	0.0833
26	7/5/2019 20:17	0.0601	0.0601	0.0601	7/5/2019 20:18	0.1038	0.1038	0.1038
27	7/5/2019 20:18	0.0519	0.0519	0.0519	7/5/2019 20:20	0.1185	0.1185	0.1185
28	7/5/2019 20:20	0.057	0.057	0.057	7/5/2019 20:21	0.1086	0.1086	0.1086
29	7/5/2019 20:21	0.05	0.05	0.05	7/5/2019 20:22	0.0967	0.0967	0.0967
30	7/5/2019 20:22	0.0462	0.0462	0.0462	7/5/2019 20:23	0.0895	0.0895	0.0895
31	7/5/2019 20:23	0.0556	0.0556	0.0556	7/5/2019 20:24	0.1101	0.1101	0.1101
32	7/5/2019 20:24	0.0569	0.0569	0.0569	7/5/2019 20:25	0.1072	0.1072	0.1072
33	7/5/2019 20:25	0.0547	0.0547	0.0547	7/5/2019 20:26	0.1063	0.1063	0.1063
34	7/5/2019 20:26	0.0578	0.0578	0.0578	7/5/2019 20:27	0.0908	0.0908	0.0908
35	7/5/2019 20:27	0.0577	0.0577	0.0577	7/5/2019 20:28	0.1032	0.1032	0.1032
36	7/5/2019 20:28	0.0614	0.0614	0.0614	7/5/2019 20:29	0.0989	0.0989	0.0989
37	7/5/2019 20:29	0.0483	0.0483	0.0483	7/5/2019 20:30	0.0993	0.0993	0.0993
38	7/5/2019 20:30	0.0526	0.0526	0.0526	7/5/2019 20:31	0.101	0.101	0.101
39	7/5/2019 20:31	0.053	0.053	0.053	7/5/2019 20:32	0.102	0.102	0.102
40	7/5/2019 20:32	0.0561	0.0561	0.0561	7/5/2019 20:33	0.1036	0.1036	0.1036
41	7/5/2019 20:33	0.0462	0.0462	0.0462	7/5/2019 20:34	0.1142	0.1142	0.1142
42	7/5/2019 20:34	0.0533	0.0533	0.0533	7/5/2019 20:35	0.0967	0.0967	0.0967
43	7/5/2019 20:35	0.0529	0.0529	0.0529	7/5/2019 20:36	0.1042	0.1042	0.1042
44	7/5/2019 20:36	0.0469	0.0469	0.0469	7/5/2019 20:37	0.0917	0.0917	0.0917
45	7/5/2019 20:37	0.0656	0.0656	0.0656	7/5/2019 20:38	0.0927	0.0927	0.0927
46	7/5/2019 20:38	0.0584	0.0584	0.0584	7/5/2019 20:39	0.0929	0.0929	0.0929
47	7/5/2019 20:39	0.0597	0.0597	0.0597	7/5/2019 20:40	0.106	0.106	0.106
48	7/5/2019 20:40	0.0614	0.0614	0.0614	7/5/2019 20:40	0.1176	0.1176	0.1176
49	7/5/2019 20:40	0.0525	0.0525	0.0525	7/5/2019 20:41	0.0926	0.0926	0.0926
50	7/5/2019 20:41	0.0543	0.0543	0.0543	7/5/2019 20:43	0.1039	0.1039	0.1039
51	7/5/2019 20:43	0.0527	0.0527	0.0527	7/5/2019 20:44	0.0894	0.0894	0.0894
52	7/5/2019 20:44	0.0618	0.0618	0.0618	7/5/2019 20:45	0.0937	0.0937	0.0937
53	7/5/2019 20:45	0.0522	0.0522	0.0522	7/5/2019 20:46	0.108	0.108	0.108
54	7/5/2019 20:46	0.06	0.06	0.06	7/5/2019 20:47	0.0933	0.0933	0.0933
55	7/5/2019 20:47	0.0628	0.0628	0.0628	7/5/2019 20:48	0.1047	0.1047	0.1047
56	7/5/2019 20:48	0.0572	0.0572	0.0572	7/5/2019 20:49	0.1119	0.1119	0.1119
57	7/5/2019 20:49	0.057	0.057	0.057	7/5/2019 20:50	0.0975	0.0975	0.0975
58	7/5/2019 20:50	0.0565	0.0565	0.0565	7/5/2019 20:51	0.124	0.124	0.124
59	7/5/2019 20:51	0.0542	0.0542	0.0542	7/5/2019 20:52	0.0965	0.0965	0.0965

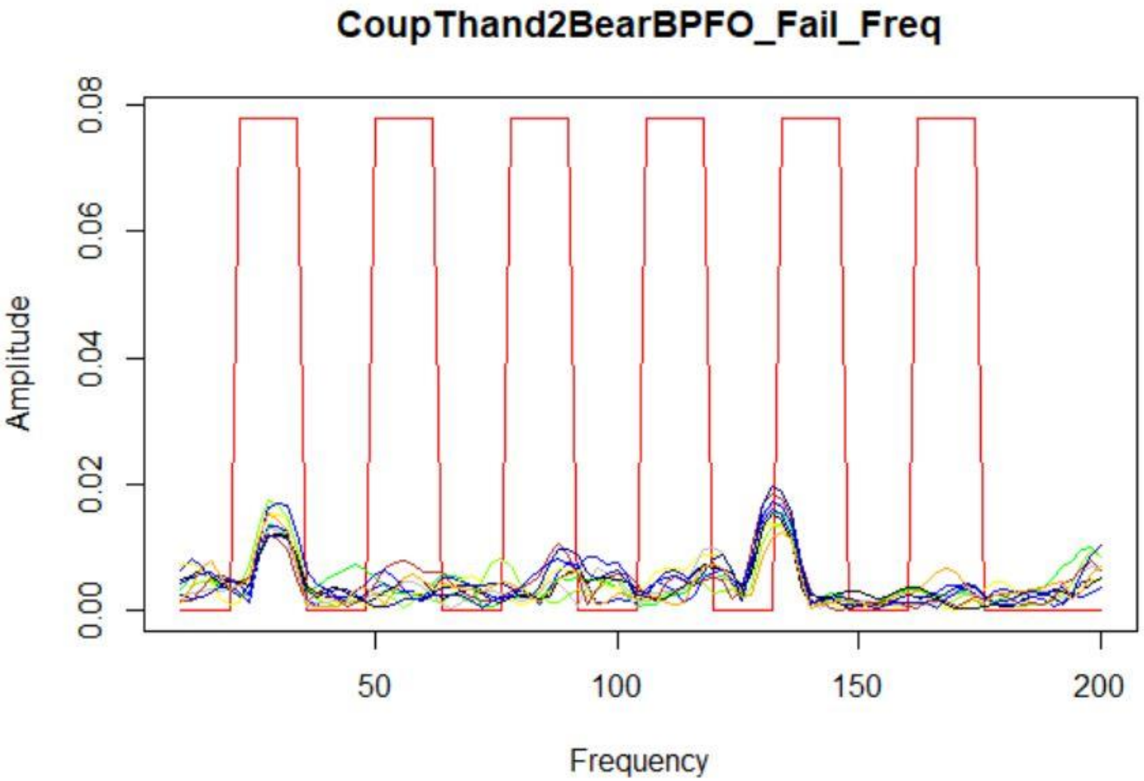
	Gearbox > Final Output Shaft > Y >				Gearbox > Second Intermediate			
2	Time (UTC)	Avg(in/s	Min(in/s	Max(in/	Time (UTC)	Avg(in/s	Min(in/s	Max(in/
3	7/5/2019 19:55	0.096	0.096	0.096	7/5/2019 19:55	0.0546	0.0546	0.0546
4	7/5/2019 19:55	0.0937	0.0937	0.0937	7/5/2019 19:55	0.0597	0.0597	0.0597
5	7/5/2019 19:56	0.0976	0.0976	0.0976	7/5/2019 19:56	0.0581	0.0581	0.0581
6	7/5/2019 19:57	0.1095	0.1095	0.1095	7/5/2019 19:57	0.057	0.057	0.057
7	7/5/2019 19:58	0.1015	0.1015	0.1015	7/5/2019 19:58	0.0527	0.0527	0.0527
8	7/5/2019 20:00	0.0965	0.0965	0.0965	7/5/2019 20:00	0.055	0.055	0.055
9	7/5/2019 20:01	0.0973	0.0973	0.0973	7/5/2019 20:01	0.0592	0.0592	0.0592
10	7/5/2019 20:02	0.0999	0.0999	0.0999	7/5/2019 20:02	0.0557	0.0557	0.0557
11	7/5/2019 20:03	0.0891	0.0891	0.0891	7/5/2019 20:03	0.048	0.048	0.048
12	7/5/2019 20:04	0.087	0.087	0.087	7/5/2019 20:04	0.0542	0.0542	0.0542
13	7/5/2019 20:05	0.0883	0.0883	0.0883	7/5/2019 20:05	0.0496	0.0496	0.0496
14	7/5/2019 20:06	0.0911	0.0911	0.0911	7/5/2019 20:06	0.0683	0.0683	0.0683
15	7/5/2019 20:07	0.1018	0.1018	0.1018	7/5/2019 20:07	0.0472	0.0472	0.0472
16	7/5/2019 20:08	0.1013	0.1013	0.1013	7/5/2019 20:08	0.0634	0.0634	0.0634
17	7/5/2019 20:09	0.0928	0.0928	0.0928	7/5/2019 20:09	0.0628	0.0628	0.0628
18	7/5/2019 20:10	0.0966	0.0966	0.0966	7/5/2019 20:10	0.0603	0.0603	0.0603
19	7/5/2019 20:11	0.0886	0.0886	0.0886	7/5/2019 20:11	0.0551	0.0551	0.0551
20	7/5/2019 20:12	0.0943	0.0943	0.0943	7/5/2019 20:12	0.0513	0.0513	0.0513
21	7/5/2019 20:13	0.0896	0.0896	0.0896	7/5/2019 20:13	0.0501	0.0501	0.0501
22	7/5/2019 20:14	0.0882	0.0882	0.0882	7/5/2019 20:14	0.0541	0.0541	0.0541
23	7/5/2019 20:15	0.1004	0.1004	0.1004	7/5/2019 20:15	0.0541	0.0541	0.0541
24	7/5/2019 20:16	0.095	0.095	0.095	7/5/2019 20:16	0.056	0.056	0.056
25	7/5/2019 20:17	0.0889	0.0889	0.0889	7/5/2019 20:17	0.061	0.061	0.061
26	7/5/2019 20:18	0.1026	0.1026	0.1026	7/5/2019 20:18	0.0507	0.0507	0.0507
27	7/5/2019 20:20	0.0927	0.0927	0.0927	7/5/2019 20:20	0.056	0.056	0.056
28	7/5/2019 20:21	0.0907	0.0907	0.0907	7/5/2019 20:21	0.0503	0.0503	0.0503
29	7/5/2019 20:22	0.0843	0.0843	0.0843	7/5/2019 20:22	0.0538	0.0538	0.0538
30	7/5/2019 20:23	0.117	0.117	0.117	7/5/2019 20:23	0.0609	0.0609	0.0609
31	7/5/2019 20:24	0.089	0.089	0.089	7/5/2019 20:24	0.0517	0.0517	0.0517
32	7/5/2019 20:25	0.1057	0.1057	0.1057	7/5/2019 20:25	0.0575	0.0575	0.0575
33	7/5/2019 20:26	0.0896	0.0896	0.0896	7/5/2019 20:26	0.0581	0.0581	0.0581
34	7/5/2019 20:27	0.0888	0.0888	0.0888	7/5/2019 20:27	0.0567	0.0567	0.0567
35	7/5/2019 20:28	0.0927	0.0927	0.0927	7/5/2019 20:28	0.0568	0.0568	0.0568
36	7/5/2019 20:29	0.0993	0.0993	0.0993	7/5/2019 20:29	0.0527	0.0527	0.0527
37	7/5/2019 20:30	0.0899	0.0899	0.0899	7/5/2019 20:30	0.0551	0.0551	0.0551
38	7/5/2019 20:31	0.0835	0.0835	0.0835	7/5/2019 20:31	0.0493	0.0493	0.0493
39	7/5/2019 20:32	0.1144	0.1144	0.1144	7/5/2019 20:32	0.0532	0.0532	0.0532
40	7/5/2019 20:33	0.0832	0.0832	0.0832	7/5/2019 20:33	0.059	0.059	0.059
41	7/5/2019 20:34	0.0916	0.0916	0.0916	7/5/2019 20:34	0.0622	0.0622	0.0622
42	7/5/2019 20:35	0.0853	0.0853	0.0853	7/5/2019 20:35	0.0646	0.0646	0.0646
43	7/5/2019 20:36	0.1031	0.1031	0.1031	7/5/2019 20:36	0.0562	0.0562	0.0562
44	7/5/2019 20:37	0.0983	0.0983	0.0983	7/5/2019 20:37	0.0529	0.0529	0.0529
45	7/5/2019 20:38	0.0918	0.0918	0.0918	7/5/2019 20:38	0.0551	0.0551	0.0551
46	7/5/2019 20:39	0.0879	0.0879	0.0879	7/5/2019 20:39	0.0647	0.0647	0.0647
47	7/5/2019 20:40	0.0893	0.0893	0.0893	7/5/2019 20:40	0.0517	0.0517	0.0517
48	7/5/2019 20:40	0.1078	0.1078	0.1078	7/5/2019 20:40	0.0595	0.0595	0.0595
49	7/5/2019 20:41	0.1172	0.1172	0.1172	7/5/2019 20:41	0.0644	0.0644	0.0644
50	7/5/2019 20:43	0.0981	0.0981	0.0981	7/5/2019 20:43	0.0525	0.0525	0.0525
51	7/5/2019 20:44	0.0998	0.0998	0.0998	7/5/2019 20:44	0.0506	0.0506	0.0506
52	7/5/2019 20:45	0.0863	0.0863	0.0863	7/5/2019 20:45	0.0571	0.0571	0.0571
53	7/5/2019 20:46	0.0964	0.0964	0.0964	7/5/2019 20:46	0.0618	0.0618	0.0618
54	7/5/2019 20:47	0.0934	0.0934	0.0934	7/5/2019 20:47	0.06	0.06	0.06
55	7/5/2019 20:48	0.0997	0.0997	0.0997	7/5/2019 20:48	0.0574	0.0574	0.0574
56	7/5/2019 20:49	0.0846	0.0846	0.0846	7/5/2019 20:49	0.06	0.06	0.06
57	7/5/2019 20:50	0.094	0.094	0.094	7/5/2019 20:50	0.0632	0.0632	0.0632
58	7/5/2019 20:51	0.1065	0.1065	0.1065	7/5/2019 20:51	0.0607	0.0607	0.0607
59	7/5/2019 20:52	0.084	0.084	0.084	7/5/2019 20:52	0.0598	0.0598	0.0598

	Gearbox > Output Shaft Mesh Side	
2	Time (UTC)	Avg(in
3	7/5/2019 19:55	0.084
4	7/5/2019 19:55	0.071
5	7/5/2019 19:56	0.09
6	7/5/2019 19:57	0.076
7	7/5/2019 19:58	0.08
8	7/5/2019 19:59	0.07
9	7/5/2019 20:00	0.089
10	7/5/2019 20:01	0.080
11	7/5/2019 20:02	0.080
12	7/5/2019 20:03	0.096
13	7/5/2019 20:04	0.089
14	7/5/2019 20:05	0.090
15	7/5/2019 20:06	0.085
16	7/5/2019 20:07	0.079
17	7/5/2019 20:08	0.091
18	7/5/2019 20:09	0.083
19	7/5/2019 20:10	0.086
20	7/5/2019 20:11	0.086
21	7/5/2019 20:12	0.097
22	7/5/2019 20:13	0.086
23	7/5/2019 20:14	0.080
24	7/5/2019 20:15	0.080
25	7/5/2019 20:16	0.090
26	7/5/2019 20:17	0.087
27	7/5/2019 20:18	0.084
28	7/5/2019 20:20	0.099
29	7/5/2019 20:21	0.07
30	7/5/2019 20:22	0.087
31	7/5/2019 20:23	0.077
32	7/5/2019 20:24	0.08
33	7/5/2019 20:25	0.093
34	7/5/2019 20:26	0.089
35	7/5/2019 20:27	0.076
36	7/5/2019 20:28	0.097
37	7/5/2019 20:29	0.090
38	7/5/2019 20:30	0.077
39	7/5/2019 20:31	0.098
40	7/5/2019 20:32	0.093
41	7/5/2019 20:33	0.070
42	7/5/2019 20:34	0.081
43	7/5/2019 20:35	0.101
44	7/5/2019 20:36	0.092
45	7/5/2019 20:37	0.088
46	7/5/2019 20:38	0.110
47	7/5/2019 20:39	0.072
48	7/5/2019 20:40	0.084
49	7/5/2019 20:40	0.095
50	7/5/2019 20:41	0.089
51	7/5/2019 20:43	0.089
52	7/5/2019 20:44	0.089
53	7/5/2019 20:45	0.082
54	7/5/2019 20:46	0.089
55	7/5/2019 20:47	0.082
56	7/5/2019 20:48	0.086
57	7/5/2019 20:49	0.099
58	7/5/2019 20:50	0.086
59	7/5/2019 20:51	0.088

Prognostics of Failure to Identify the Remaining Useful Life

Spectrum Prognosis focused on Failure Modes Tags

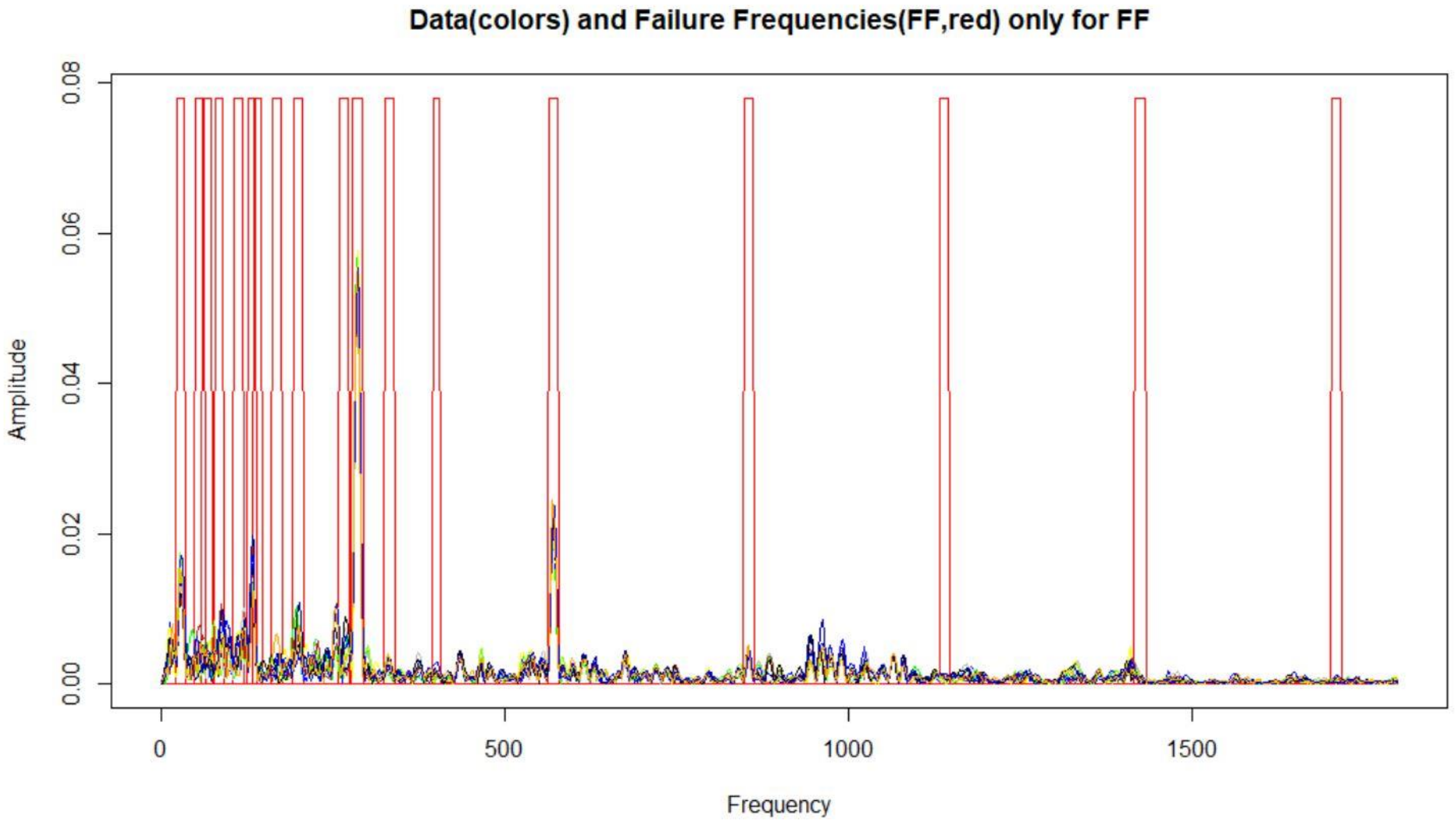




Prepared by: Ernesto Primera

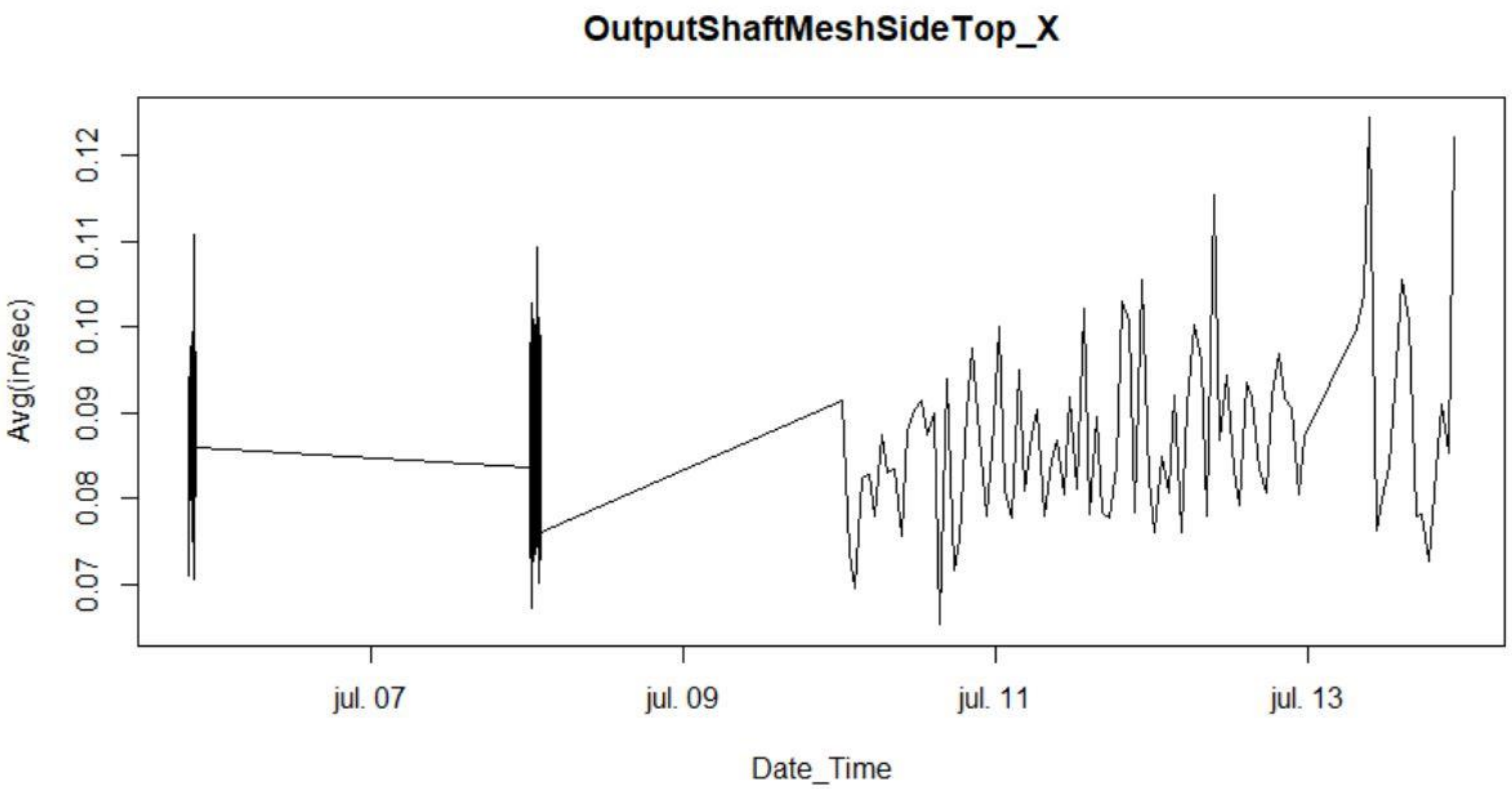
Prognostics of Failure to Identify the Remaining Useful Life

Spectrum Prognosis focused on Failure Modes Tags



Prognostics of Failure to Identify the Remaining Useful Life

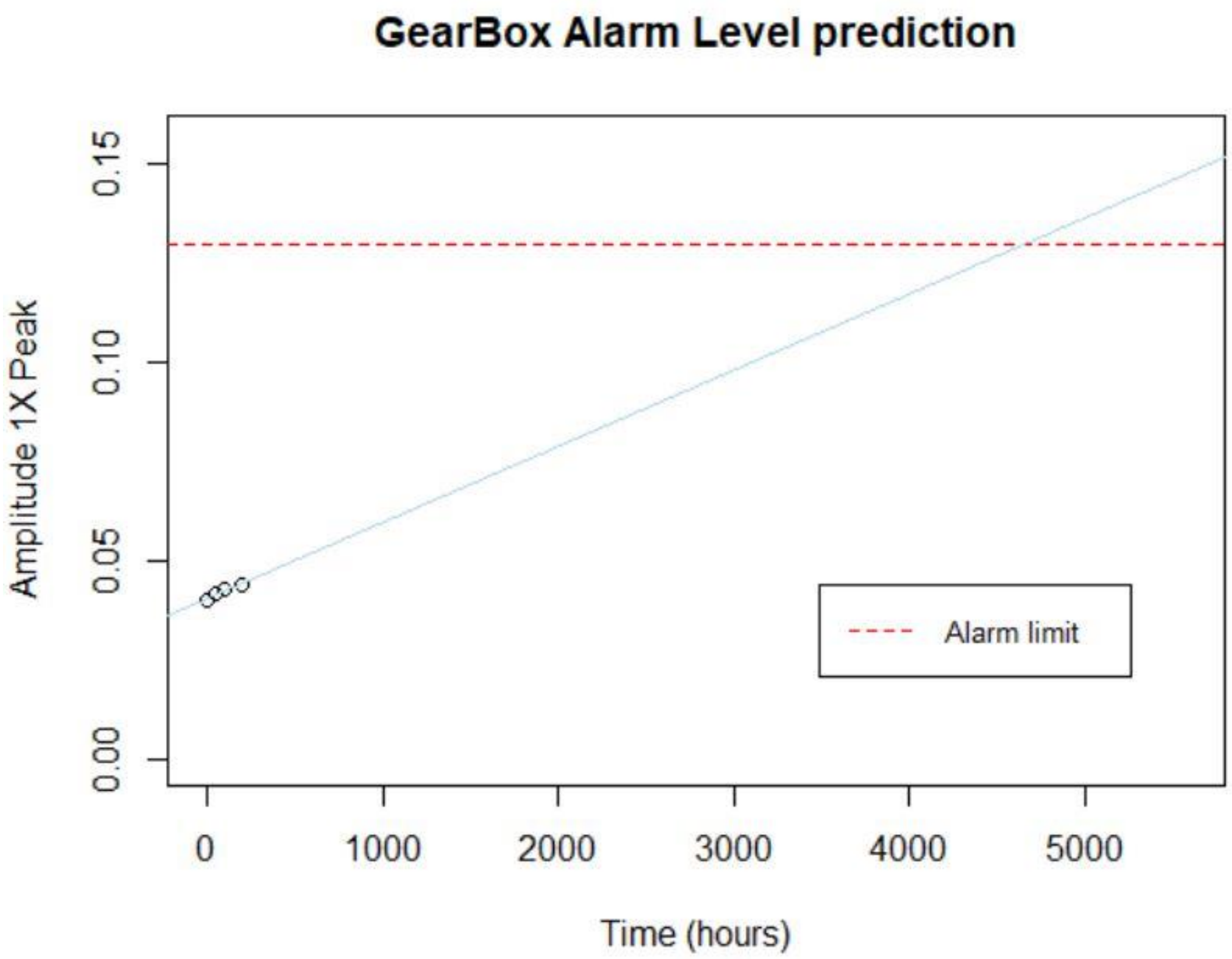
Gear Mech Projection



Prepared by: Ernesto Primera

Prognostics of Failure to Identify the Remaining Useful Life

Remaining Useful Life (RUL)



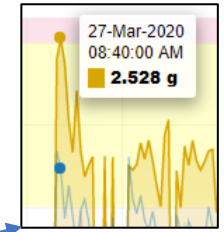
Conclusion:

The degradation process is slow, however the evolution of the 1X spectra allows to predict, with low level of confidence because we have very few spectrums and very close in time to each other, that around 1X the maximum amplitude of Failure frequency **will cross the alarm limit in 4647 hours.** There is not enough data to use Neural Networks, so we use linear regression.

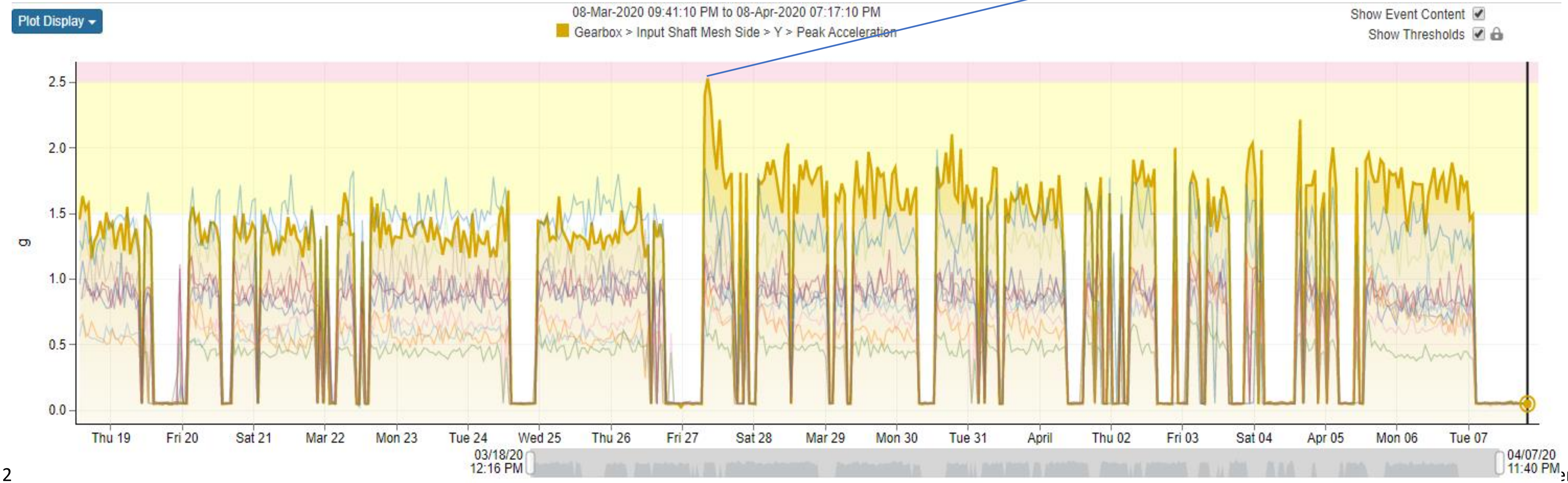
(Approximately March-Abril 2020)

Prognostics of Failure to Identify the Remaining Useful Life

Remaining Useful Life (RUL)



Observations:
The trend chart shows vibration in Velocity values, which are keeping within the alert limits.



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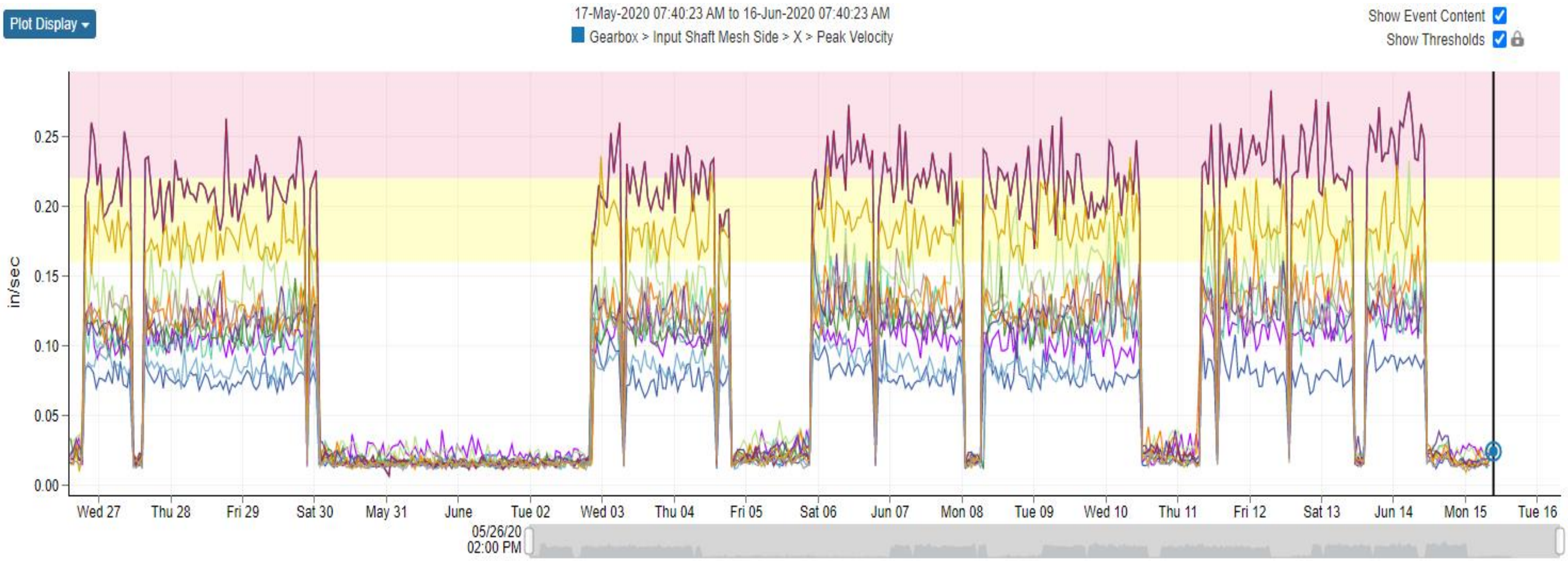
Prognostics of Failure to Identify the Remaining Useful Life

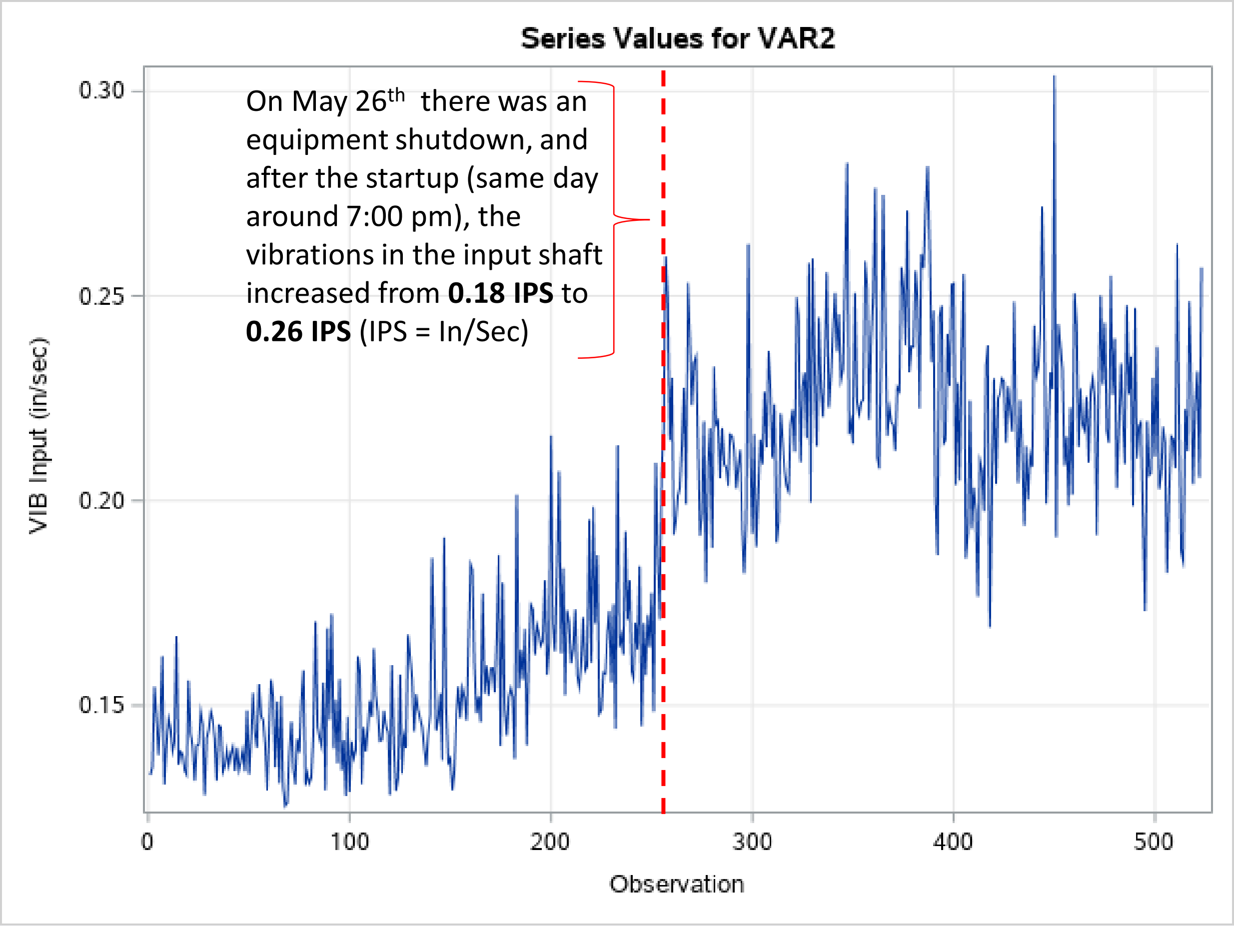
Remaining Useful Life (RUL)

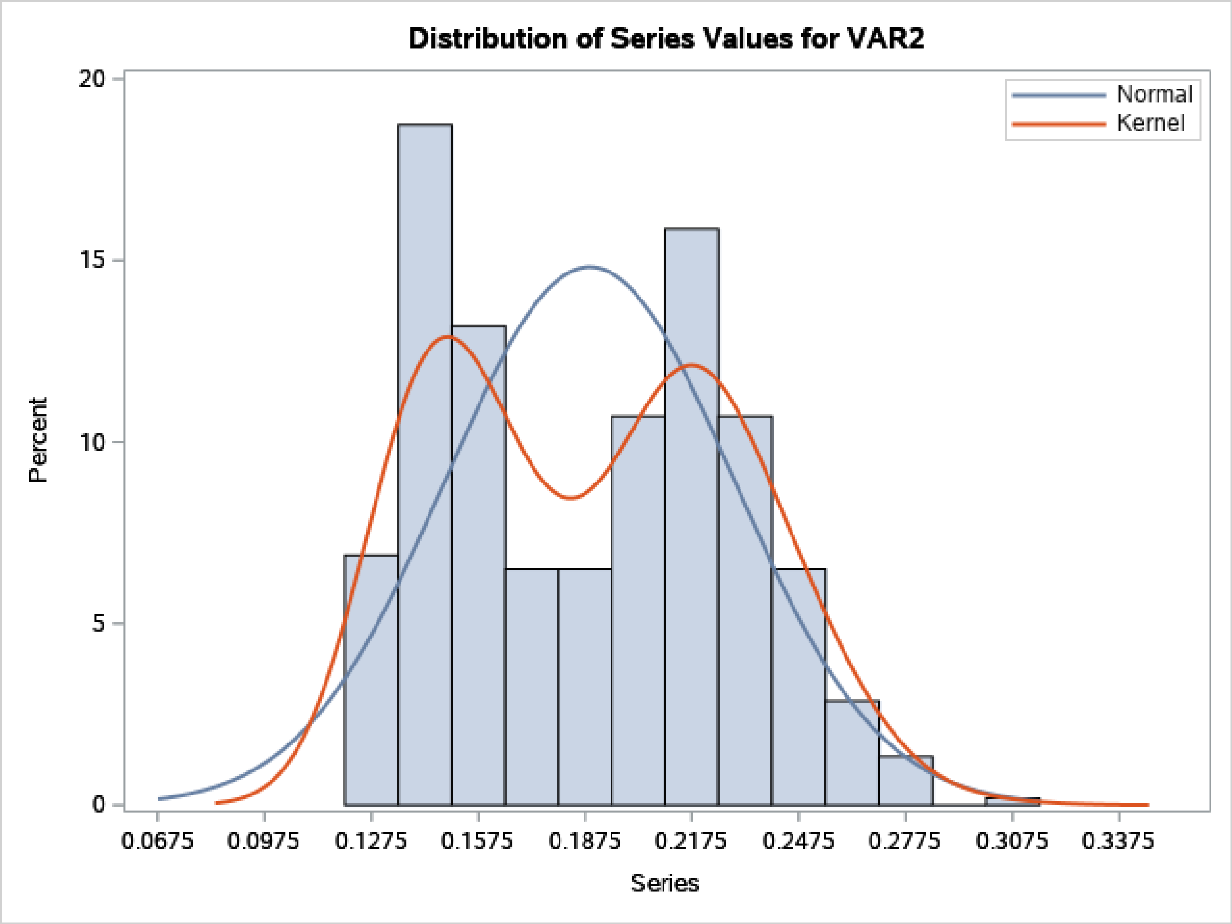


ML Applied in Rotating Machinery for Anomalies Detection and RUL estimation

Observations:

1. Two cycles are clearly observed. Before and after the event that occurred on May 26th where the vibrations increased.
2. The two cycles are clearly observed on the orange curve in the frequency distribution histogram as well.
3. Based on what is described in the two previous paragraphs, the forecast will be made only with the data of the second cycle, which begins on May 26th.





ML Applied in Rotating Machinery for Anomalies Detection and RUL estimation

Prognostics of Failure to Identify the Remaining Useful Life

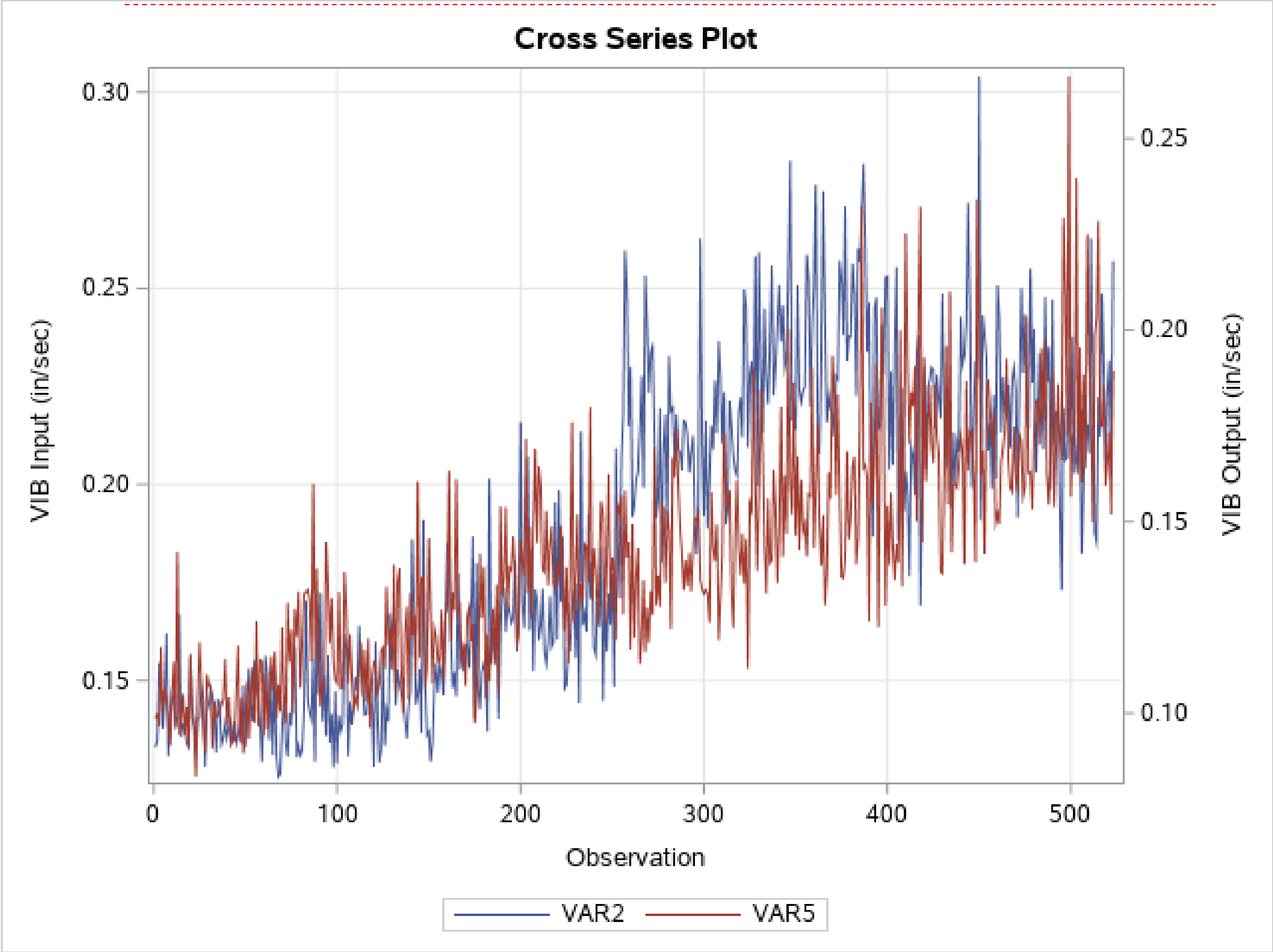
Vibration Trend:

Variables:
- **Input Shaft**
- **Output Shaft**

Vibration Unit:
In/Sec

Vibration Alarm Limit:
0.30 in/Sec

Timeframe:
July 2019 to July 2020



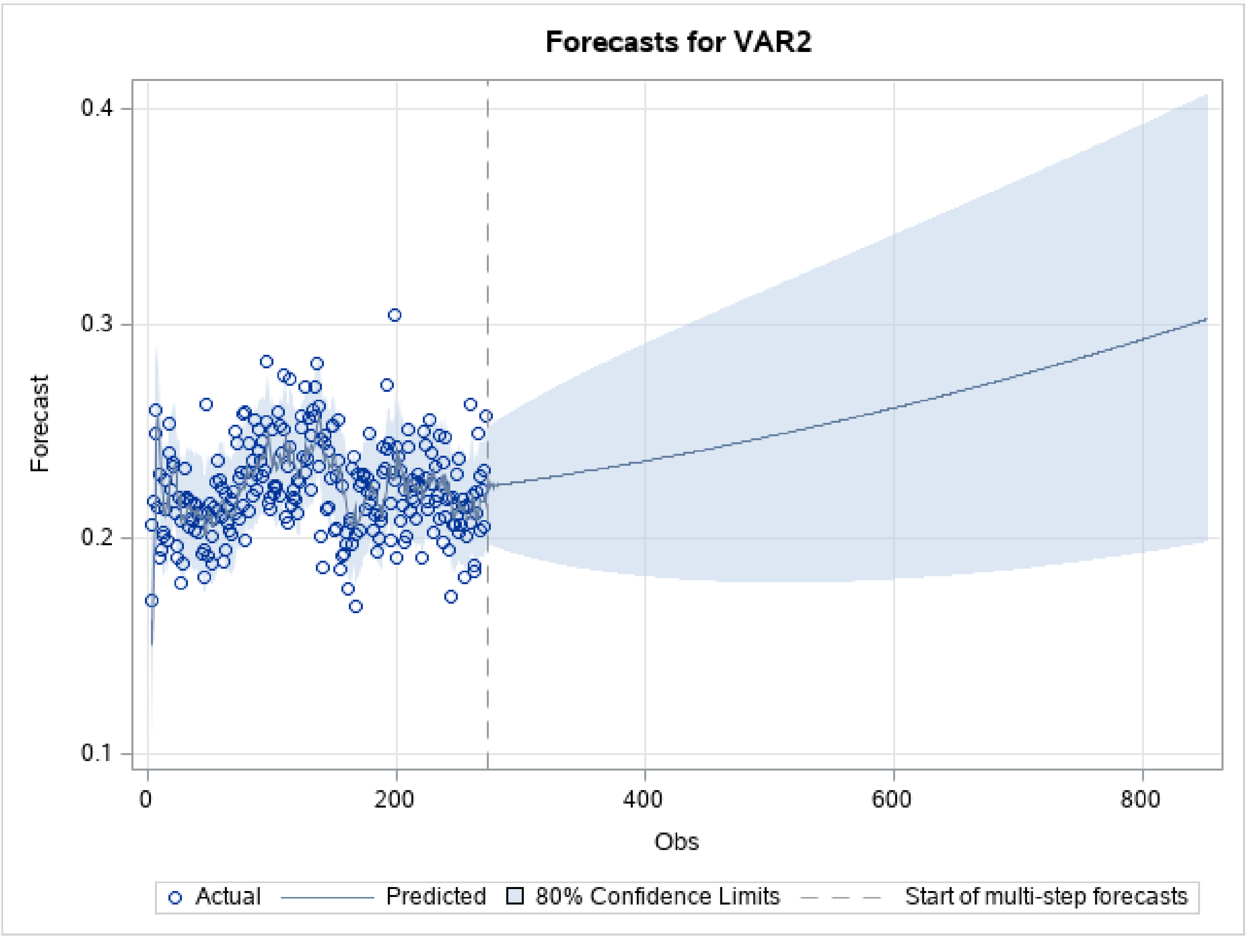
ML Applied in Rotating Machinery for Anomalies Detection and RUL estimation

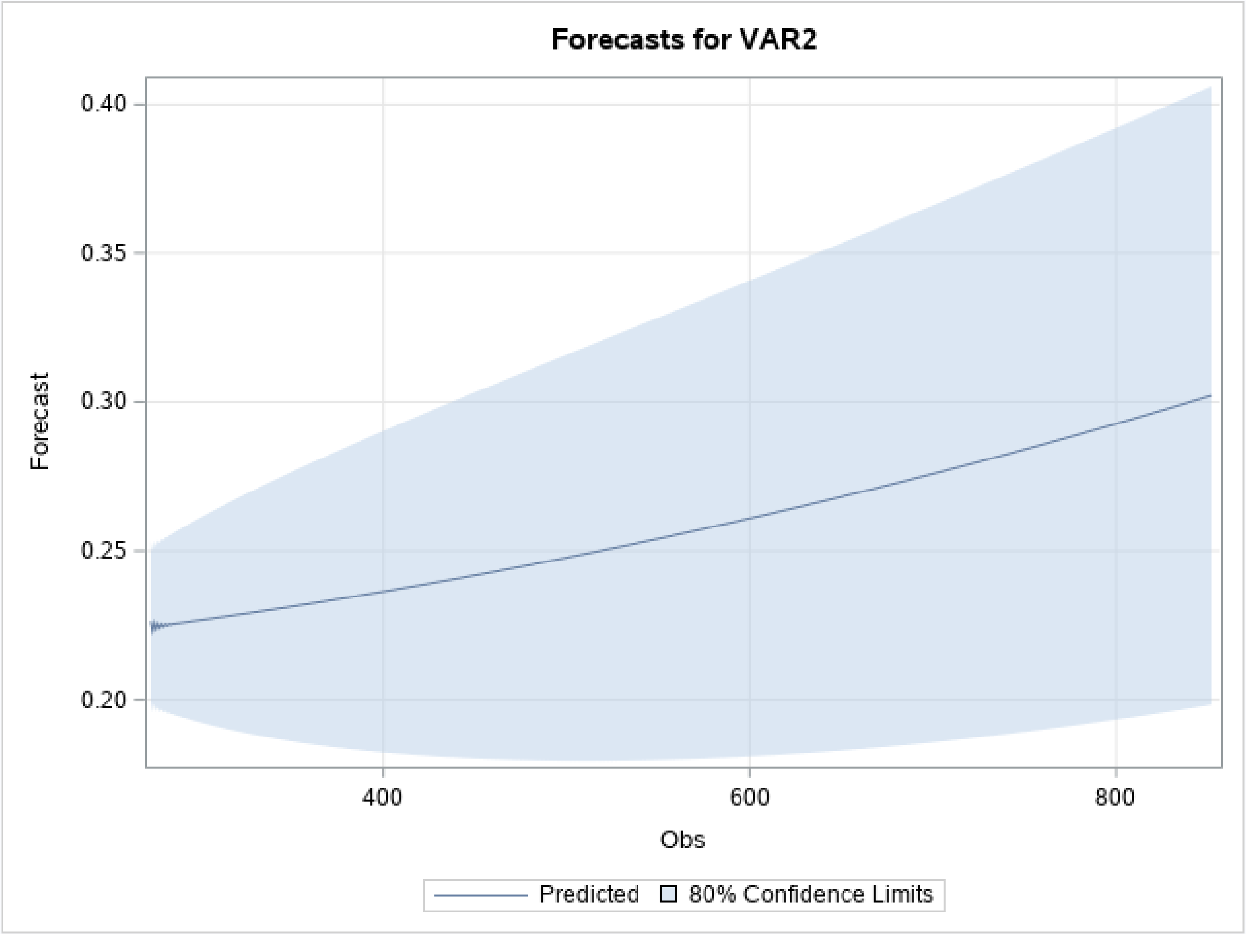
Prognostics of Failure to Identify the Remaining Useful Life

Summary:

The observations (Obs) are carried out every 1 hour, for that reason 950 Obs are approximately 950 Hours ≈ 40 Days.

Vibration Prognosis ≥ 0.40 IPS ≈ August 9, 2020.

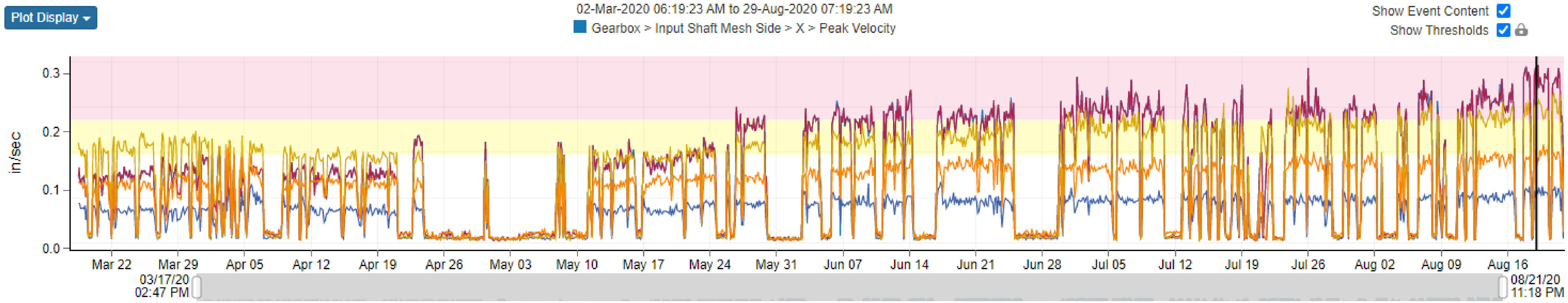




Prognostics of Failure to Identify the Remaining Useful Life

Timeline

- Wireless Sensor Installation — 7/5/2019
- 1st Email Notification & report — 7/15/2019
- 2nd Email Notification & report — 9/8/2019
- 3rd Email Notification & report — 10/15/2019
- 4th Email Notification & Report — 5/20/2020
- 5th Email Notification & Report — 6/15/2020
- Microsoft TEAM Meeting — 06/19/2020
- Emails Answers — 6/30/2020
- Last Report — 7/1/2020
- **Failure** — 8/22/2020



Prepared by: Ernesto Primera

Conclusions

Three (3) failure modes and two (2) potential causes are identified:

Failure Modes:

- Gear Coupling Fatigue.
- Gears Shaft Fatigue. (Shaft 2 and 3)
- Bearing Fatigue. (Shaft 2)

Root Causes:

- An inadequate bearing clearance (Shaft 1) has created gear overload. (validated)
- Improper assembly and installation of the coupling has caused the coupling to fail, and the Gear Coupling Failure has created dynamic loads on the gears train.

The case shows the success of applying advanced models and algorithms for equipment failure diagnosis and prognosis with time series variables such as vibrations. It was essential to have multiple vibrational variables through the shaft train of the gearbox, as well as the identification of failure modes to ensure their observability. One of the keys of the model was the application of identification of patterns of vibration frequencies in the vibrational spectrum and the projection of the amplitude of these frequency peaks through the regression model, which shows a straightforward combination of traditional knowledge about vibration analysis, and the application of data science models.