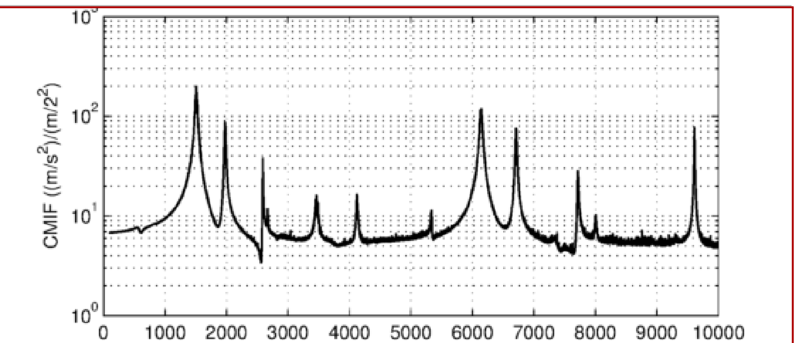
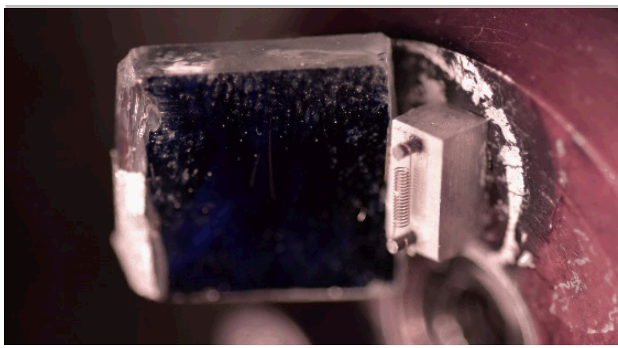
SAND2018-1326C





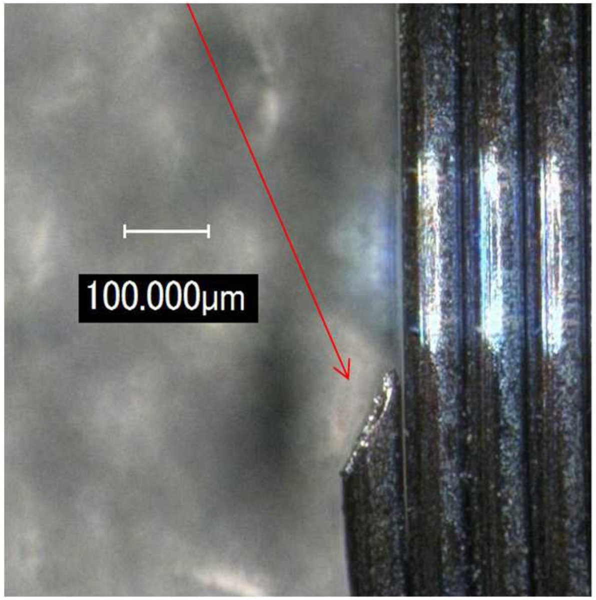
Dynamic Measurements on Miniature Springs for Flaw and Damage Detection

Dan Rohe

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

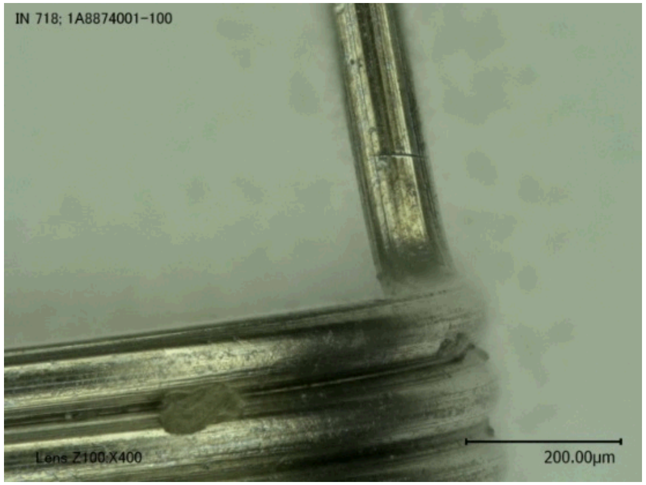
Motivation

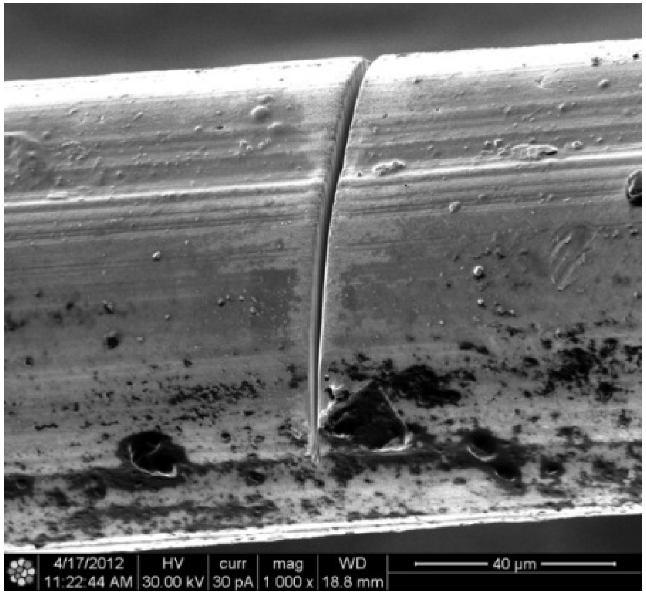
- Components used at Sandia contain very small springs
- These springs are at the limit of manufacturer's ability to produce and therefore have significant variability
- In a finite element model, small springs can't be meshed with any kind of fidelity, so reduced order modeling is likely necessary
- *Can we experimentally measure dynamic properties of the spring?*



Damage detection in small springs

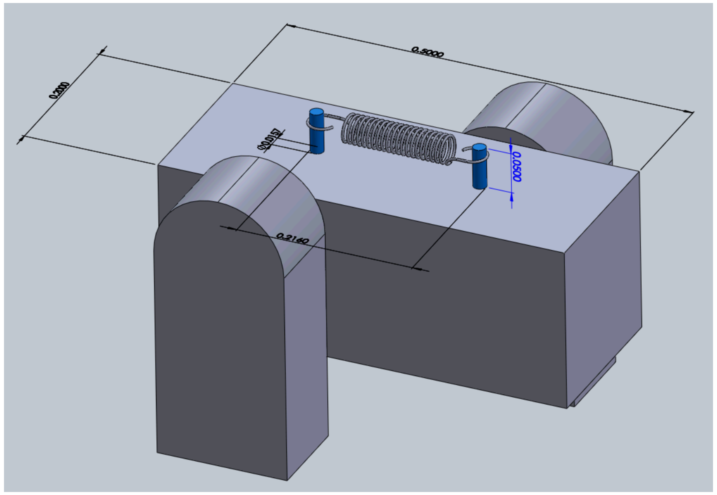
- Due to their size, flaws can be hard to detect
- A good deal of effort has gone into determining the health of a spring before it is placed in service including:
  - Visual inspection (microscopy)
  - CT scans
  - Thermal imaging while passing current through the spring
  - Force/displacement curve changes
- None of these techniques have been sensitive enough to find flaws in the springs
- *Can we use variation in dynamic properties to determine spring health?*

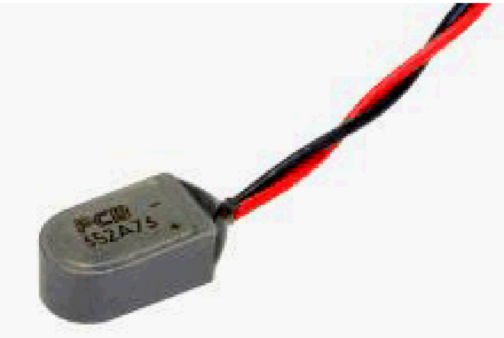




Dynamic Measurements on Springs

- Small structures create difficulties for traditional instrumentation techniques
- Spring is very light compared to test setup if traditional sensors are used:
  - Spring mass ~2 mg
  - Aluminum fixture mass ~900 mg
  - PCB 352A73 mass ~300 mg (not including cables)
- In pictured setup, spring is 0.13% of the test setup mass
- Spot size of laser vibrometer is approximately 25 µm at 144 mm standoff
  - Could measure on the spring itself, which is ~75 µm wide
  - Can reduce spot size with close-up module lenses
- Higher noise floor than accelerometer measurements





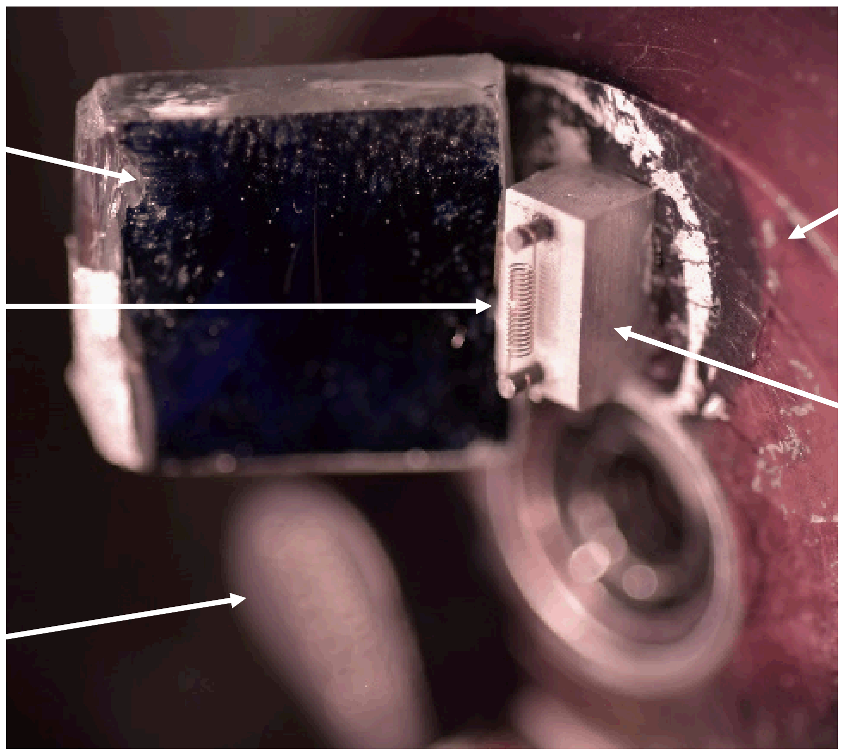
Test Setup

- Spring mounted to two dowels on a test fixture attached to shaker
- Accelerometer mounted to shaker surface measures the acceleration input
  - Laser measured the response of the fixture as well as the response of the spring to ensure fixture was "rigid" over the frequency band of interest.
- Mirror placed 45 degrees with respect to the shaker surface
  - By bouncing the laser off the mirror, the side of the spring could be measured as well, so 2D motion could be measured.

First-surface mirror

Laser Spot on Spring

Accelerometer mounted to shaker surface



Shaker Surface

Spring Fixture

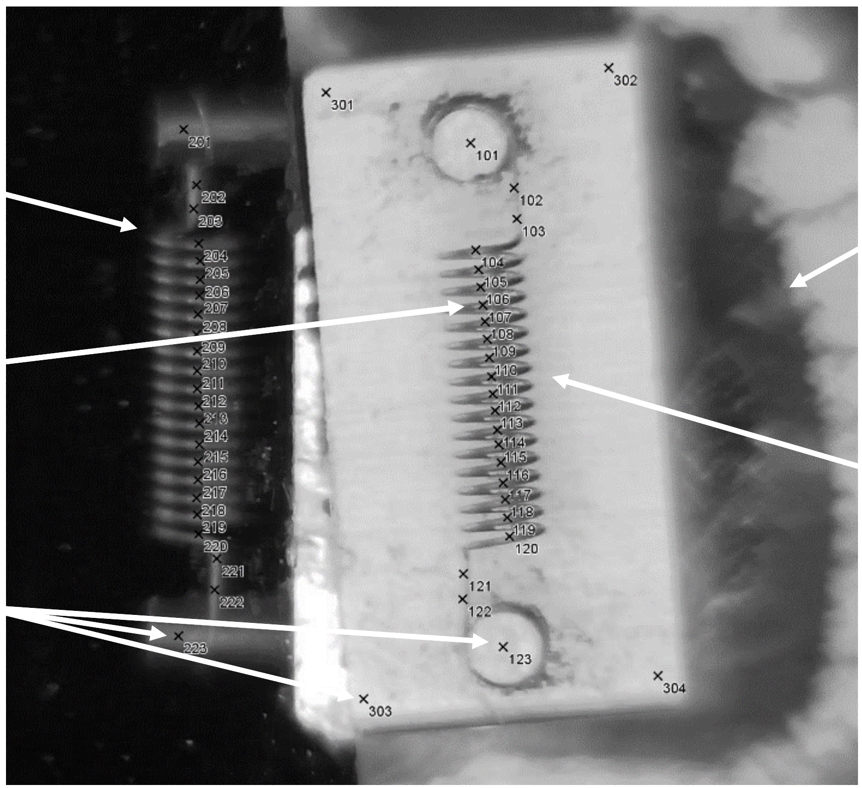
Test Setup

- Due to mirror, laser could see two views of the spring (top and side) allowing measurements perpendicular and parallel with the shaking direction.
- Laser measured 21 points on each visible surface of the spring, one measurement per coil plus points on hook and fixture.

View of spring through mirror

Xs represent laser measurement locations

Measurements on the fixture verify "rigid" motion, transfer function with reference accelerometer is 1.

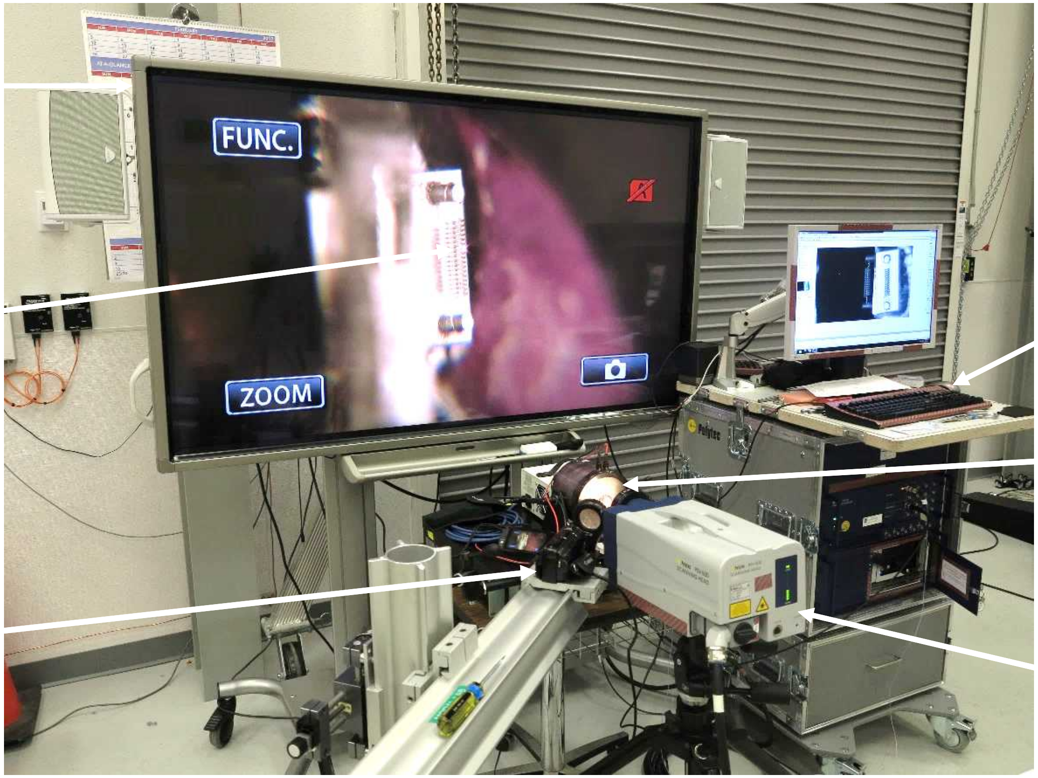


Shaker Surface

Direct view of spring

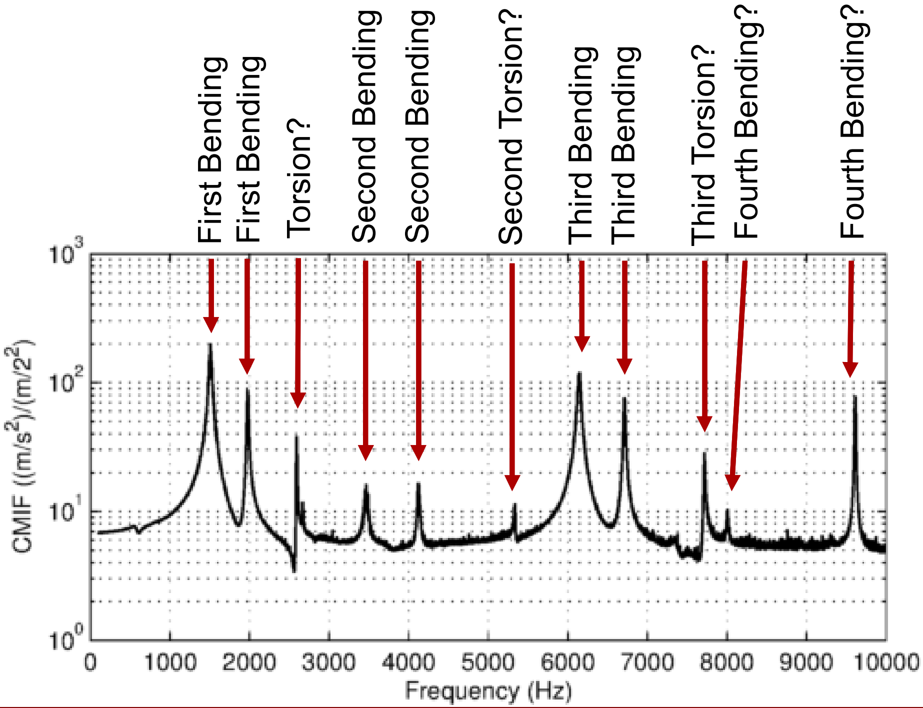
Test Setup

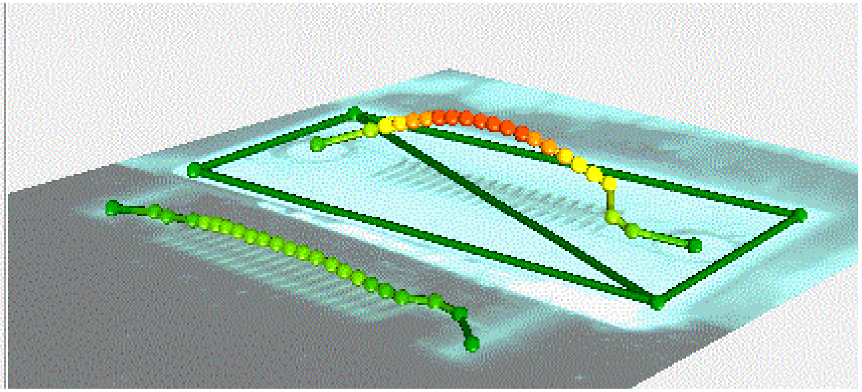
- Video from external camera was routed to large monitor to visualize laser spots



Vibration measurements

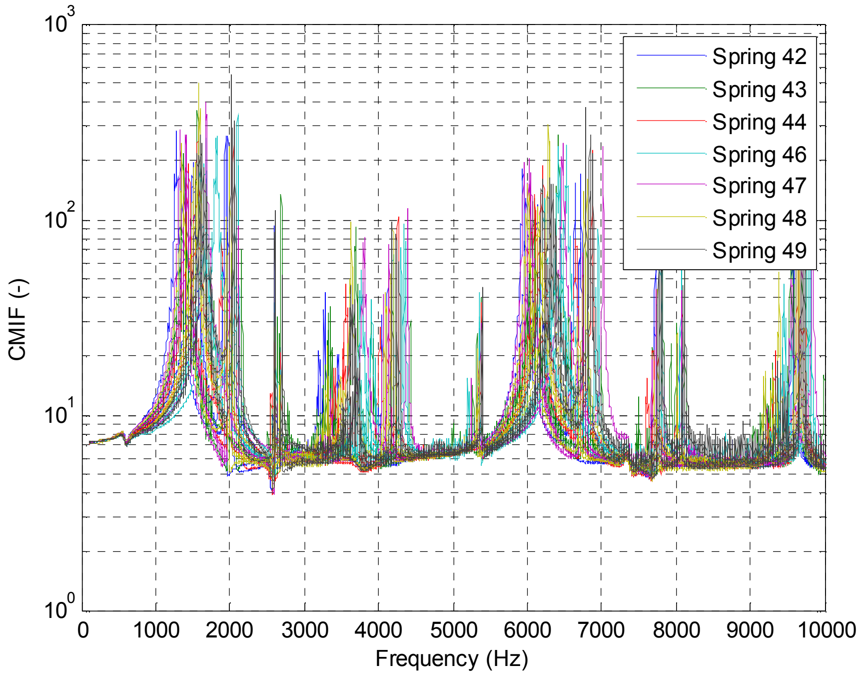
- Vibration measurements achieved, reasonable signal quality obtained
- Able to distinguish most mode shapes
  - “Even” (asymmetric) bending modes were not well excited, since both pins are nominally moving in the same direction.
  - Torsion modes not measured well with only one point per coil.

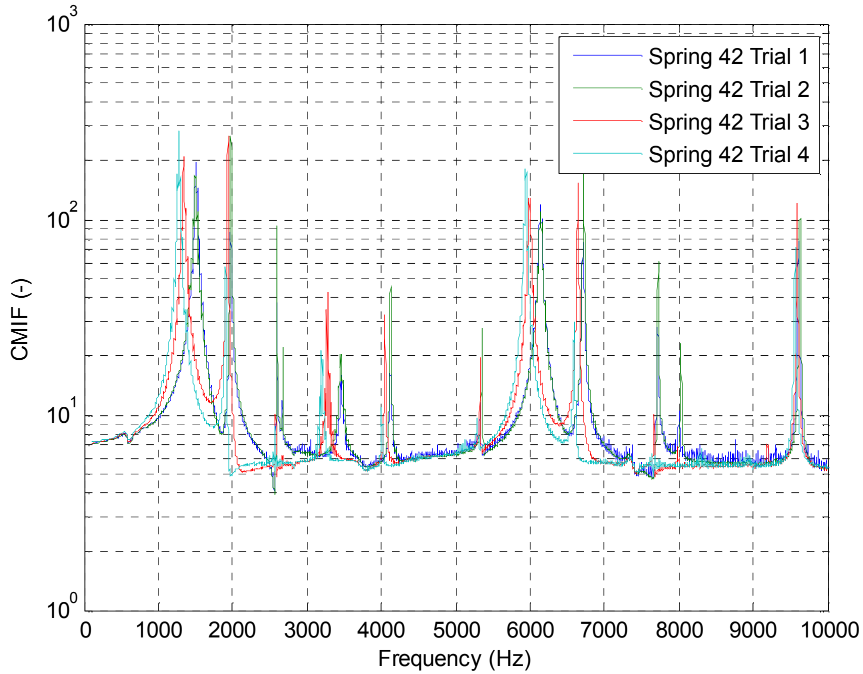




Understanding "healthy" springs

- In order to determine if we could see damage to a spring, we first had to understand what a health spring looked like.
- To get an idea of variability, 7 springs were tested, with each tested 4 times.
- Placing springs on the pins was somewhat inconsistent
  - Greater dexterity or more sophisticated tooling or fixture required for more consistent results

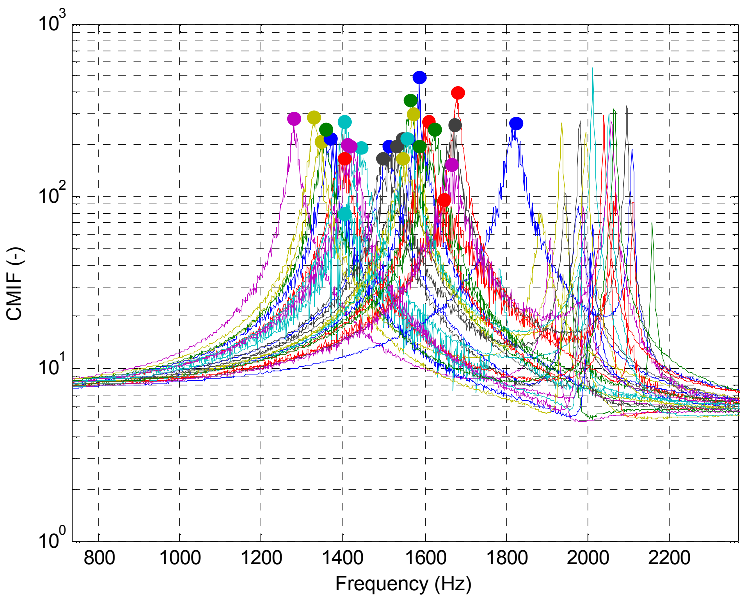


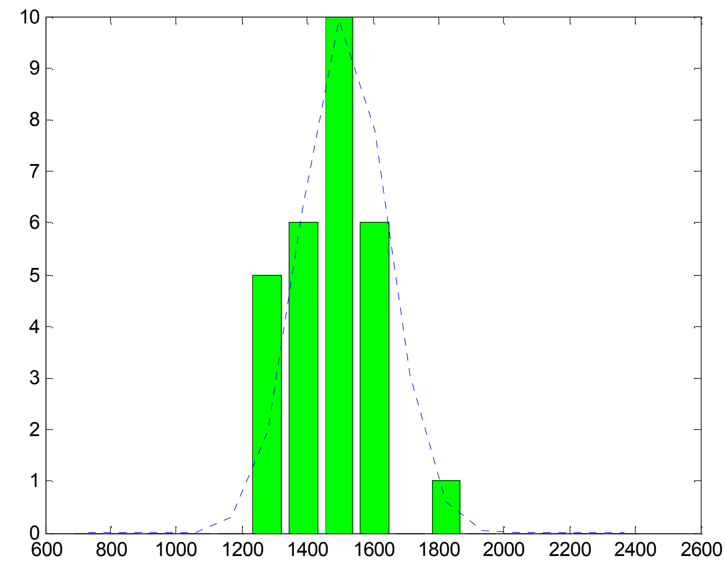


Detecting Flaws in Springs

Sandia National Laboratories

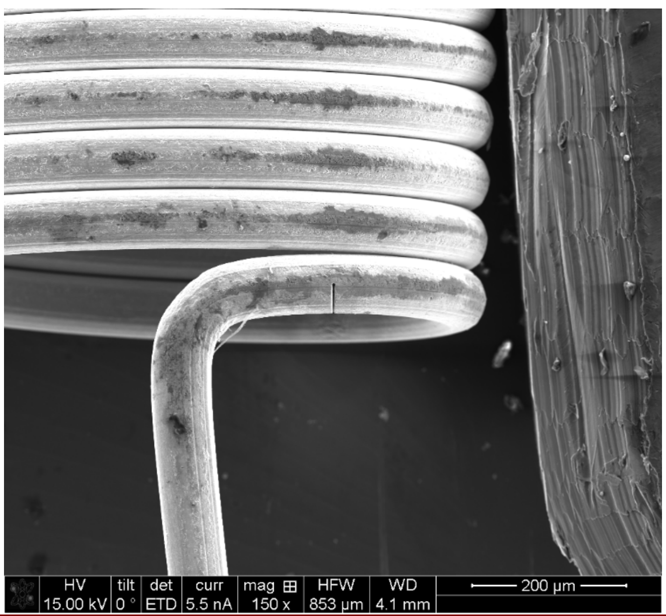
- Healthy springs were grouped by mode to create a distribution of natural frequencies
- Normal distributions were fit to the modal distribution
  - Some modes grouped very tightly: 15 Hz standard deviation
  - Some modes exhibited large spread: 165 Hz standard deviation

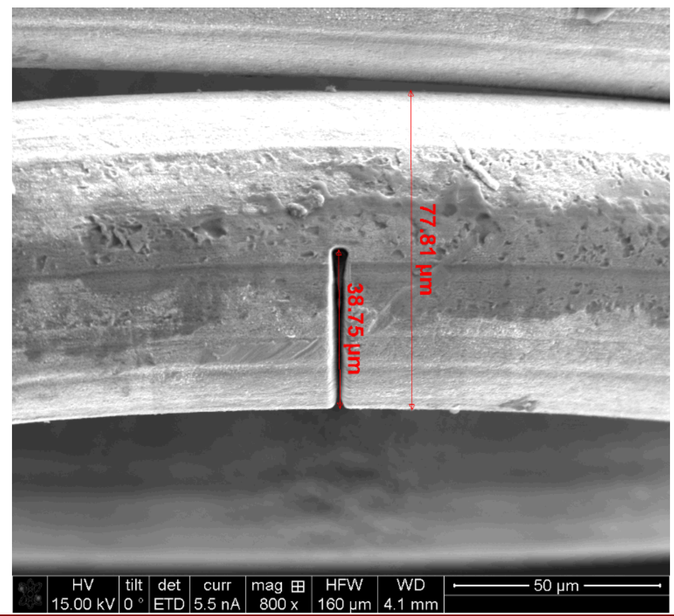




Blind Identification of Springs

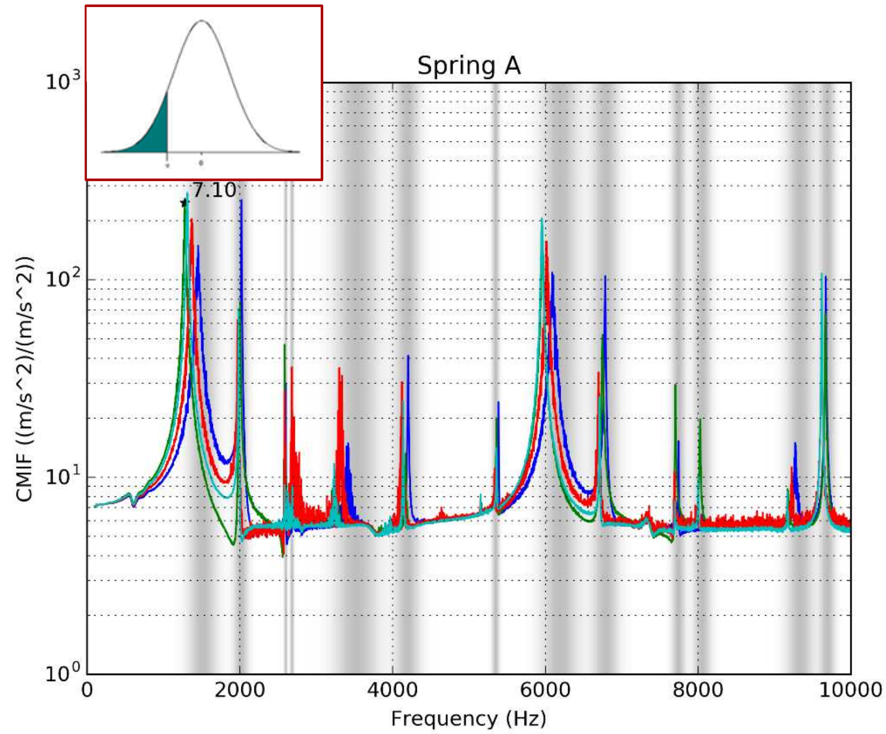
- From a selection of 9 springs, 6 springs were “damaged” and 3 springs were “healthy”
- Damage included permanent yield (from a ratchet yield test) and severe mechanical flaws (focused ion beam etching)
- Similar testing was performed on these springs to see if their modal properties became “out of character” with the healthy springs
- The 3 healthy springs were included at this step as well to give us a “blind” study.
- Use the normal distribution to figure out the likelihood that a given natural frequency would occur in the healthy distribution





Comparison to Healthy Springs: Spring A

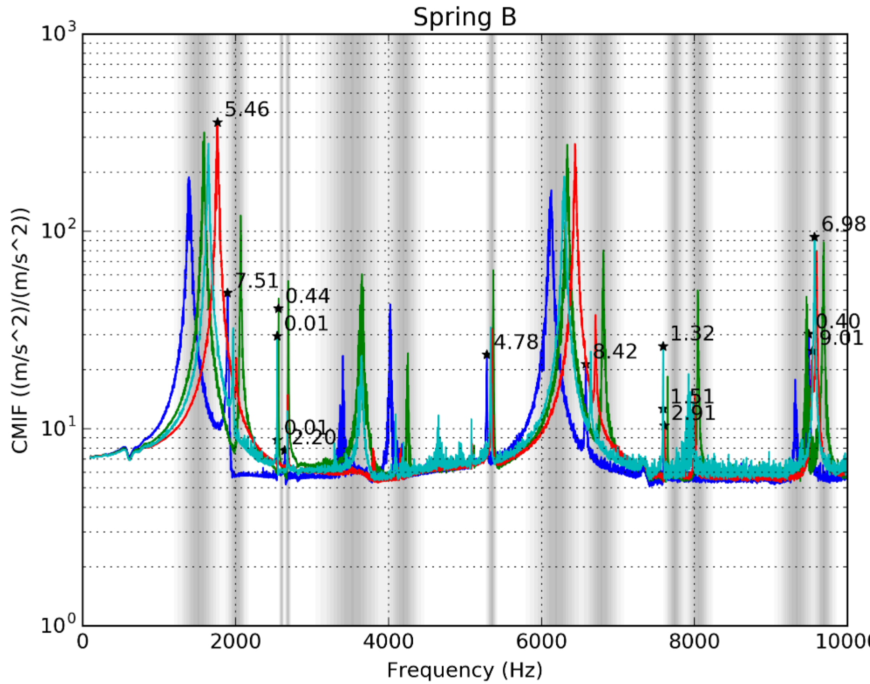
- Only one mode (first bending mode) had less than a 10% chance of occurring in a healthy spring.
- Some modes show bias, though none are particularly bad.



	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8	Mode 9	Mode 10	Mode 11	Mode 12	Mode 13
Healthy Mean:	1513	2012	2601	2682	3525	4192	5348	6190	6787	7742	8052	9335	9694
Healthy Std:	130.4	65.82	14.7	17.33	197.81	111.33	32.47	164.53	119.23	60.83	79.4	122.08	68.55
Spring Mean:	**1352**	1994	2588	2688	**3316**	4157	5360	**6005**	6734	7709	7997	9209	9642
Spring Std:	76.81	22.02	7.93	8.66	79.18	36.63	19.7	61.63	39.34	23.97	31.61	47.21	29.78
Spring Min:	1278	1970	2583	2680	3233	4120	5338	5953	6697	7694	7964	9170	9616
Spring Max:	1452	2020	2600	2700	3416	4203	5386	6088	6783	7744	8027	9269	9670

Comparison to Healthy Springs: Spring B

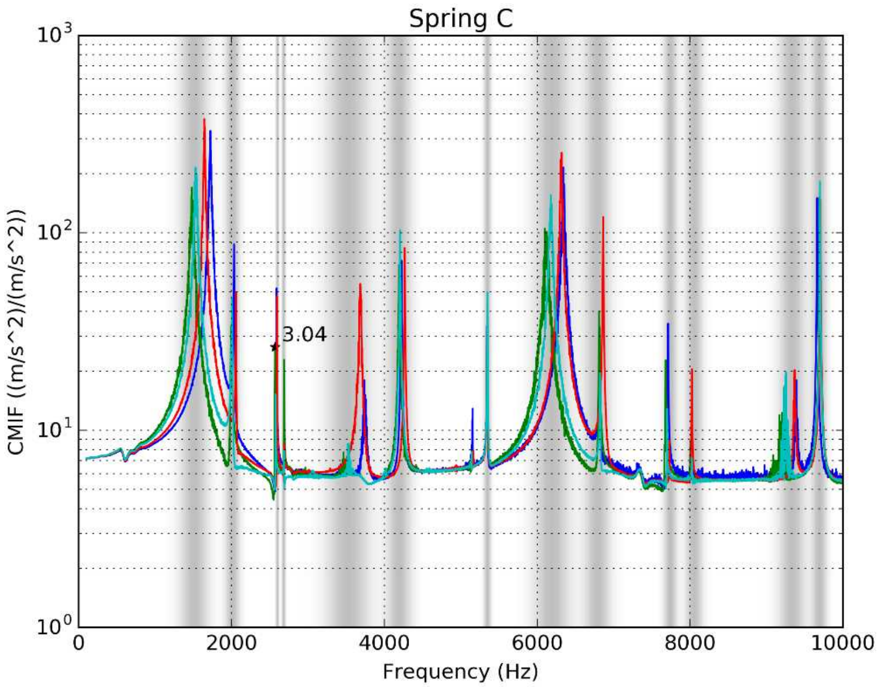
- The first group of tight modes near 2650 Hz show the largest variation from the healthy springs.



	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8	Mode 9	Mode 10	Mode 11	Mode 12	Mode 13
Healthy Mean:	1513	2012	2601	2682	3525	4192	5348	6190	6787	7742	8052	9335	9694
Healthy Std:	130.4	65.82	14.7	17.33	197.81	111.33	32.47	164.53	119.23	60.83	79.4	122.08	68.55
Spring Mean:	1596	1984	2548	2672	3627	4131	5335	6300	6686	7611	7991	9432	9589
Spring Std:	156.9	71.9	9.29	20.37	167.06	99.51	36.73	129.01	98.15	26.21	62.74	94.95	79.38
Spring Min:	1388	1895	2542	2642	3402	4020	5284	6128	6581	7591	7922	9319	9497
Spring Max:	1764	2066	2559	2688	3806	4253	5369	6438	6811	7648	8045	9542	9689

Comparison to Healthy Springs: Spring C

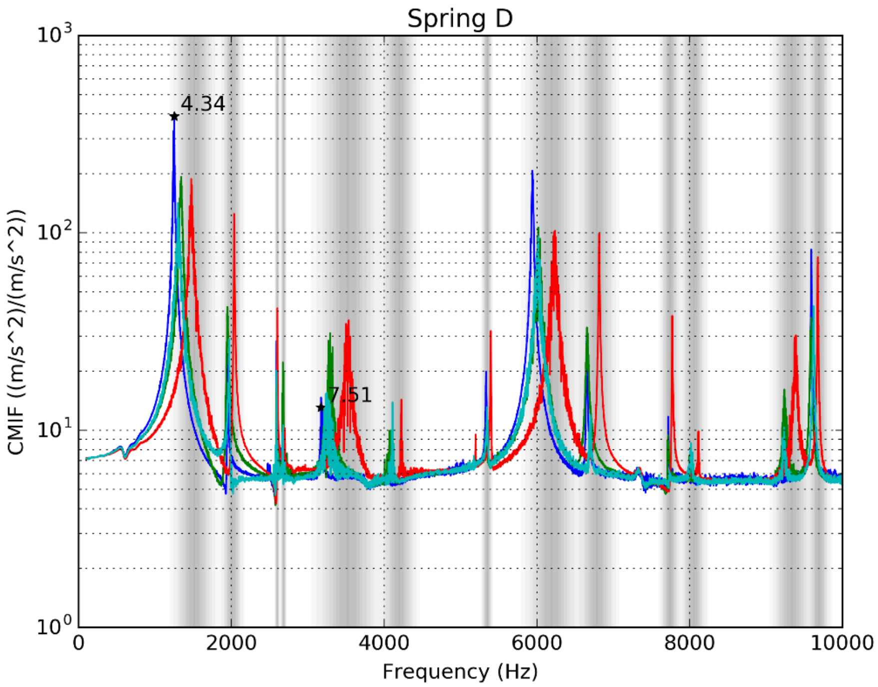
- Spring C generally fits within the healthy spring distributions.



	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8	Mode 9	Mode 10	Mode 11	Mode 12	Mode 13
Healthy Mean:	1513	2012	2601	2682	3525	4192	5348	6190	6787	7742	8052	9335	9694
Healthy Std:	130.4	65.82	14.7	17.33	197.81	111.33	32.47	164.53	119.23	60.83	79.4	122.08	68.55
Spring Mean:	1595	2023	2582	2689	3608	4222	5347	6235	6828	7706	8017	9305	9691
Spring Std:	109.55	27.84	11.35	1.73	126.63	32.27	3	116.84	24.05	20.7	9.54	89.43	18.46
Spring Min:	1481	1997	2569	2688	3467	4192	5344	6098	6811	7681	8006	9205	9664
Spring Max:	1723	2058	2594	2691	3741	4266	5350	6344	6863	7730	8023	9391	9705

Comparison to Healthy Springs: Spring D

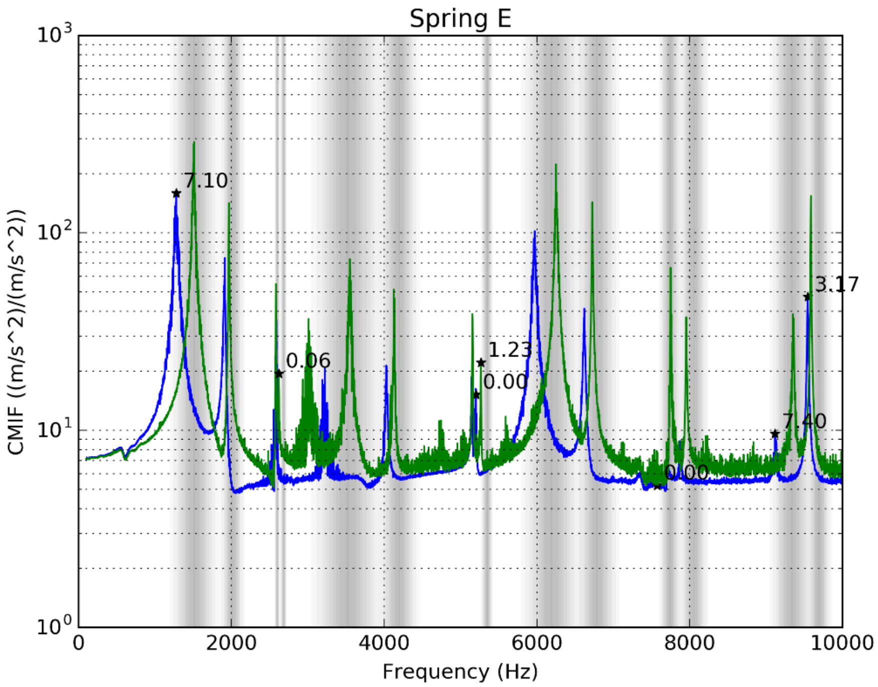
- Spring D generally fits within the healthy springs distribution
- Mode 8 shows a bit of bias.



	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8	Mode 9	Mode 10	Mode 11	Mode 12	Mode 13
Healthy Mean:	1513	2012	2601	2682	3525	4192	5348	6190	6787	7742	8052	9335	9694
Healthy Std:	130.4	65.82	14.7	17.33	197.81	111.33	32.47	164.53	119.23	60.83	79.4	122.08	68.55
Spring Mean:	1342	1975	2594	2679	3312	4137	5355	**6054**	6705	7735	8030	9289	9620
Spring Std:	95.56	41.87	5.5	12.18	155.83	77.49	27.24	129.07	75.8	25.73	58.24	88.64	41.27
Spring Min:	1250	1947	2591	2670	3173	4078	5334	5939	6652	7716	7991	9236	9589
Spring Max:	1473	2036	2602	2697	3534	4225	5395	6239	6814	7772	8116	9391	9678

Comparison to Healthy Springs: Spring E

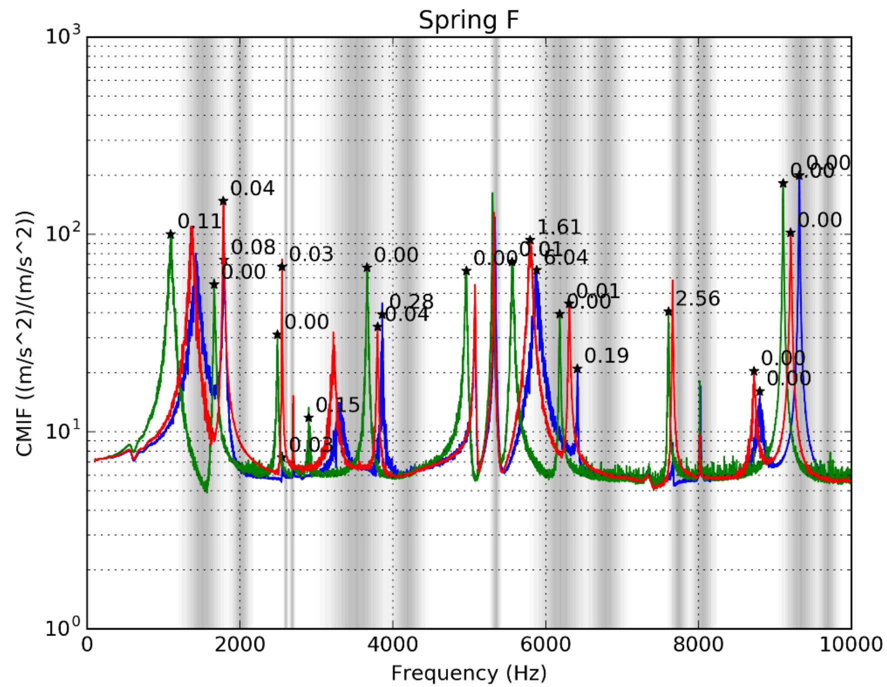
- Spring E unfortunately broke after only two tests.
- Variation from the healthy springs is seen in the modes with the smallest standard deviation.
- "Breaks after two tests" ends up being a pretty good indication of damage!



	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8	Mode 9	Mode 10	Mode 11	Mode 12	Mode 13
Healthy Mean:	1513	2012	2601	2682	3525	4192	5348	6190	6787	7742	8052	9335	9694
Healthy Std:	130.4	65.82	14.7	17.33	197.81	111.33	32.47	164.53	119.23	60.83	79.4	122.08	68.55
Spring Mean:	1395	1941	2586	2622	3386	4078	5235	6111	6673	7730	7766	9235	9568
Spring Std:	164.76	37.48	3.54	0	231.93	70	45.96	196.58	74.25	28.99	267.29	166.88	28.99
Spring Min:	1278	1914	2583	2622	3222	4028	5202	5972	6620	7709	7577	9117	9547
Spring Max:	1511	1967	2588	2622	3550	4127	5267	6250	6725	7750	7955	9353	9588

Comparison to Healthy Springs: Spring F

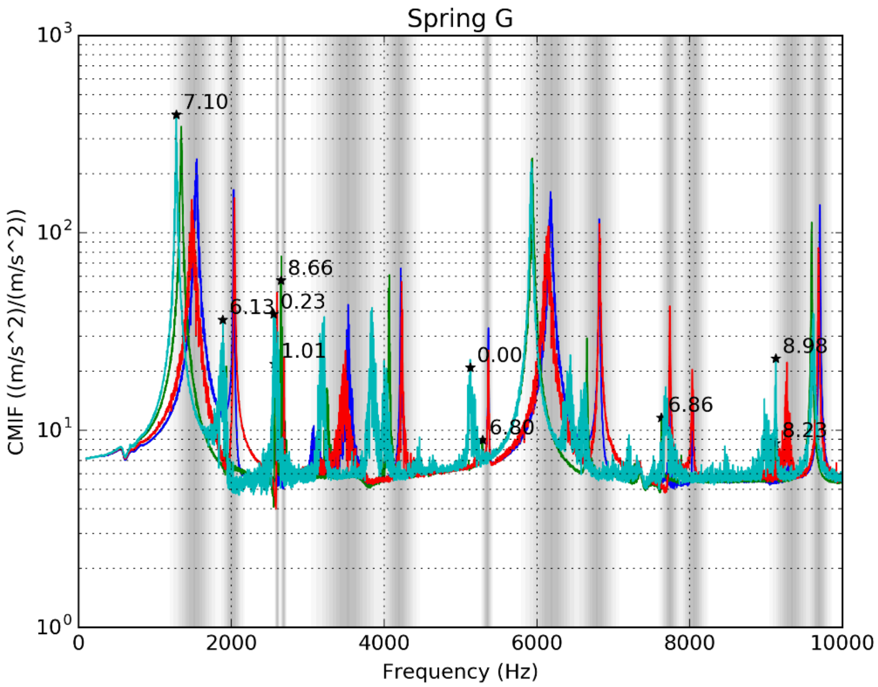
- Spring F is obviously damaged, with many modes outside of the healthy distributions.



	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8	Mode 9	Mode 10	Mode 11	Mode 12	Mode 13
Healthy Mean:	1513	2012	2601	2682	3525	4192	5348	6190	6787	7742	8052	9335	9694
Healthy Std:	130.4	65.82	14.7	17.33	197.81	111.33	32.47	164.53	119.23	60.83	79.4	122.08	68.55
Spring Mean:	**1289**	**1744**	2528	2696	**3141**	**3774**	**5207**	**5744**	**6302**	7643	8018	**8765**	**9210**
Spring Std:	175.78	73.82	34.06	2.08	214.69	100.55	211.7	167.13	117.66	32.35	7.81	53.74	106.57
Spring Min:	1089	1659	2489	2694	2898	3663	4963	5558	6181	7606	8013	8727	9106
Spring Max:	1419	1792	2548	2698	3305	3859	5336	5881	6416	7663	8027	8803	9319

Comparison to Healthy Springs: Spring G

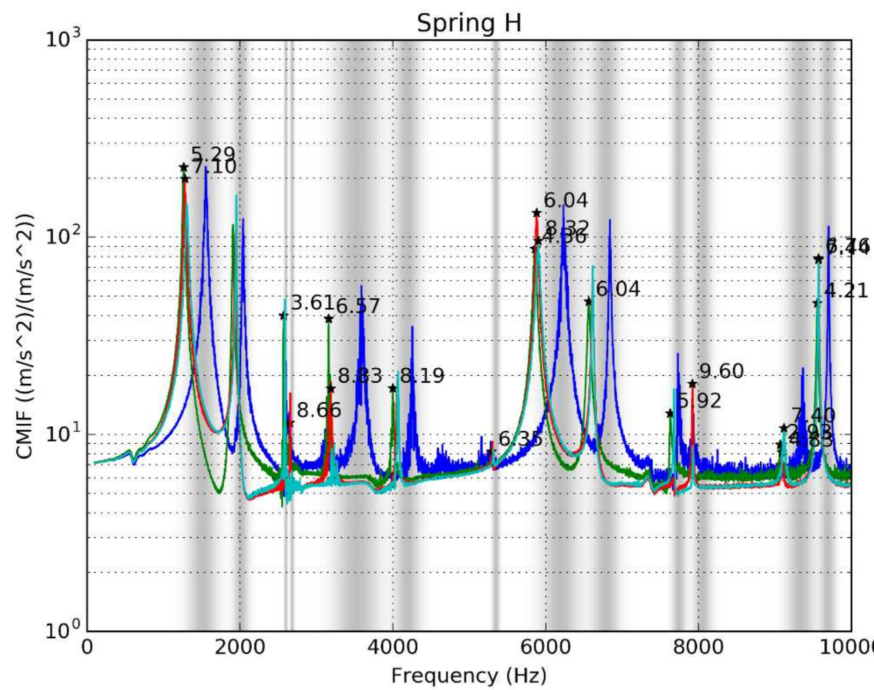
- Many modes show deviations from the healthy distributions.



	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8	Mode 9	Mode 10	Mode 11	Mode 12	Mode 13
Healthy Mean:	1513	2012	2601	2682	3525	4192	5348	6190	6787	7742	8052	9335	9694
Healthy Std:	130.4	65.82	14.7	17.33	197.81	111.33	32.47	164.53	119.23	60.83	79.4	122.08	68.55
Spring Mean:	**1413**	1973	2578	2677	**3372**	4173	5287	6048	6763	7699	8037	9211	9652
Spring Std:	123.24	73.44	21.28	21.96	161.7	89.95	112.67	134.55	93.83	51.4	5.66	99.59	51.54
Spring Min:	1278	1889	2556	2652	3216	4069	**5127**	5925	6655	7631	8033	9123	9598
Spring Max:	1547	2039	2597	2691	3528	4230	5366	6178	6819	7741	8041	9316	9705

Comparison to Healthy Springs: Spring H

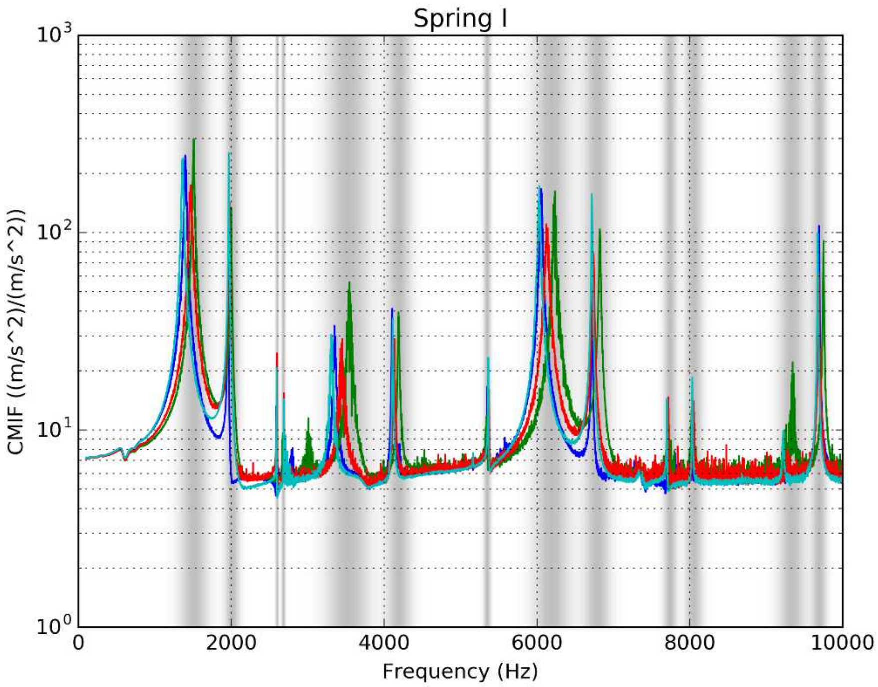
- Spring H has a number of modes that are outside the healthy distribution



	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8	Mode 9	Mode 10	Mode 11	Mode 12	Mode 13
Healthy Mean:	1513	2012	2601	2682	3525	4192	5348	6190	6787	7742	8052	9335	9694
Healthy Std:	130.4	65.82	14.7	17.33	197.81	111.33	32.47	164.53	119.23	60.83	79.4	122.08	68.55
Spring Mean:	1348	1961	2586	2655	3292	4094	5302	5969	6658	7678	7922	9162	9600
Spring Std:	137.1	57.3	11.73	4.24	198.44	109.7	13.2	175.88	123.13	42.16	1.53	138.23	68.73
Spring Min:	1261	1908	2570	2652	3161	3998	5288	5858	6563	7627	7920	9069	9555
Spring Max:	1552	2042	2598	2658	3586	4252	5314	6231	6839	7730	7923	9367	9702

Comparison to Healthy Springs: Spring I

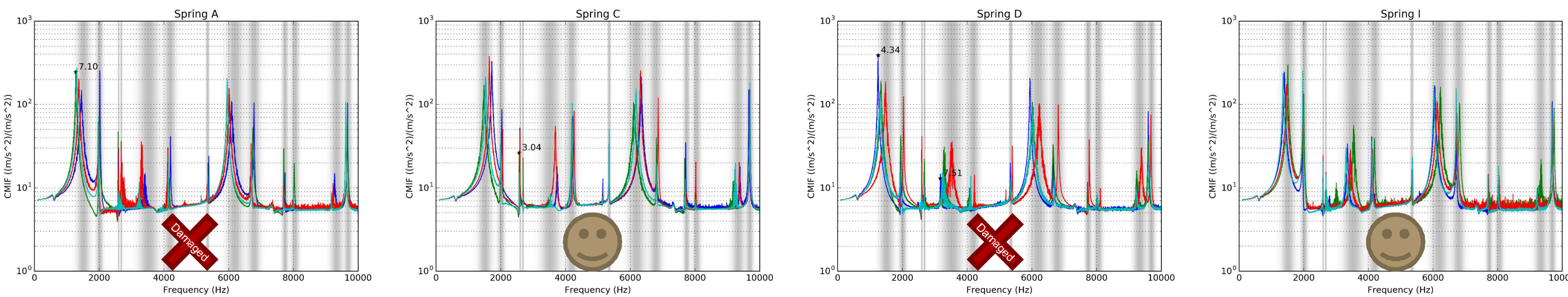
- Spring I is completely in character with the rest of the healthy.



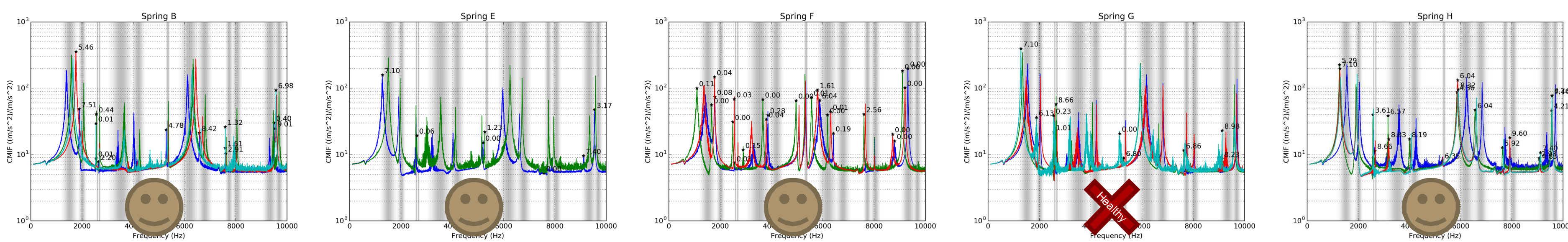
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8	Mode 9	Mode 10	Mode 11	Mode 12	Mode 13
Healthy Mean:	1513	2012	2601	2682	3525	4192	5348	6190	6787	7742	8052	9335	9694
Healthy Std:	130.4	65.82	14.7	17.33	197.81	111.33	32.47	164.53	119.23	60.83	79.4	122.08	68.55
Spring Mean:	1435	1974	2592	2683	3413	4135	5356	6110	6750	7712	8039	9283	9701
Spring Std:	65.93	16.68	3.4	6.24	107.02	37.21	14.49	92.68	48.94	13.77	15.55	88.39	32.29
Spring Min:	1364	1958	2589	2675	3306	4105	5339	6028	6719	7698	8019	9220	9675
Spring Max:	1508	1997	2597	2689	3545	4188	5372	6236	6822	7727	8052	9345	9748

Which springs are flawed?

- Judging by the previous analysis, Springs I, A, C, and D are healthy springs. Damaged springs are B, E, F, G, and H.



Healthy



Damaged

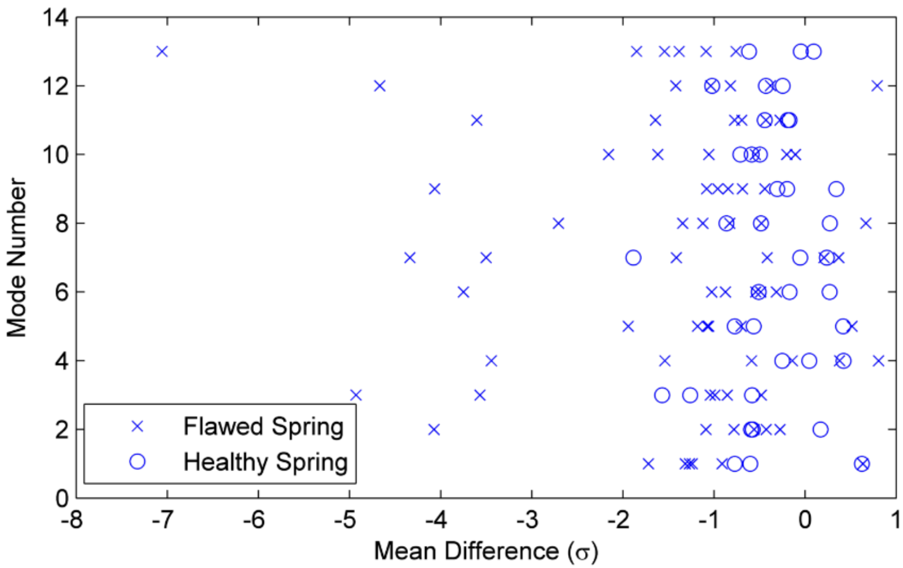
Which springs are flawed?

- Judging by the previous analysis, Springs I, A, C, and D are healthy springs. Damaged springs are B, E, F, G, and H.
- 3 of the 9 springs were incorrectly identified

Spring Letter	Spring Number	Our Guess?	Actual Flaw
A	**28**	**Healthy**	**5 coils from hook, out of hook plane**
B	29	Flaw	6 coils from hook, out of hook plane
C	22	Healthy	None
D	**27**	**Healthy**	**6 coils from hook, out of hook plane**
E	21	Flaw	6 coils from hook, in hook plane
F	23	Flaw	Yielded Spring
G	**25**	**Flaw**	**None**
H	26	Flaw	End coil next to hook
I	30	Healthy	None

Other Possible Metrics

- Data was re-examined (now with knowledge of which springs were healthy and which were flawed) to determine if other metrics might be more suitable.
- The mean first natural frequency of springs A and D, which were though healthy but actually flawed, were both over one standard deviation away from the healthy mean natural frequencies.
- On average, the flawed springs have lower mean natural frequencies that the healthy springs, but there are still exceptions
  - Flawed spring B would be accepted while healthy spring G would be rejected.



Conclusions

- Laser vibrometry proved a good way to get dynamic responses from these small components, and could be used to validate reduced order models of the springs in larger system models.
- No definitive metric was found that correlated natural frequency to spring damage with 100% accuracy.
  - Trends exists where natural frequencies of damaged springs tend to be lower, but there are exceptions to this rule.
- The spread of natural frequencies in the healthy springs due to test-to-test variation may be reducing the effectiveness of this technique.
- A more sophisticated damage identification technique that includes shape information could be used; however the shapes were already slightly noisy due to suboptimal laser signal return.
  - A photogrammetric approach may provide better full-field shapes