Bearing Prognostic method Based on Entropy Decrease at Specific Frequency

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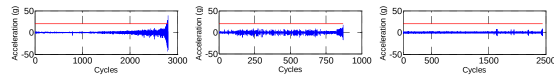
Motivation

- Vibration signal are generally measured for bearing fault diagnosis and prognosis.



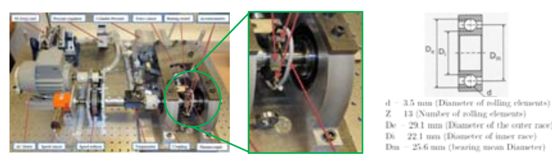
- Unfortunately, it is very challenge to extract damage feature.
  - Raw data (acceleration) are not consistent in a pattern of signal, life span, and threshold even if they are from the same systems and usage conditions.
  - There are many efforts to tackle this problem, e.g. methods based on frequency domain and entropy, but not mature yet.
- Therefore, this presentation proposes an improved method for bearing prognosis.

Outline

1. Introduction
2. Damage feature extraction
3. Prognosis
4. Issue on threshold
5. Conclusions

Introduction

- FEMTO bearing*

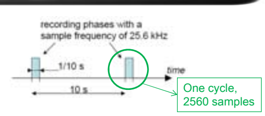


[Experimentation platform: PRONOSTIA]

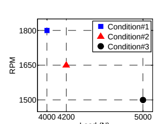
*P. Nectoux, R. Gouriveau, K. Medjaher, E. Ramasso, B. Morello, N. Zerhouni, C. Varnier. PRONOSTIA: An Experimental Platform for Bearings Accelerated Life Test. IEEE International Conference on Prognostics and Health Management, Denver, CO, USA, 2012.

Introduction

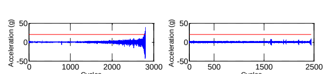
- Data acquisition (Acceleration)
  - Sampling frequency: 25.6 kHz
  - 2560 samples (during 1/10 secs.) are recorded every 10 secs.



- Three different operating conditions
  - Condition 1: 7 Sets
  - Condition 2: 7 Sets
  - Condition 3: 3 Sets



- Threshold: 20g



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Keywords
Specific Frequency & Entropy Decrease

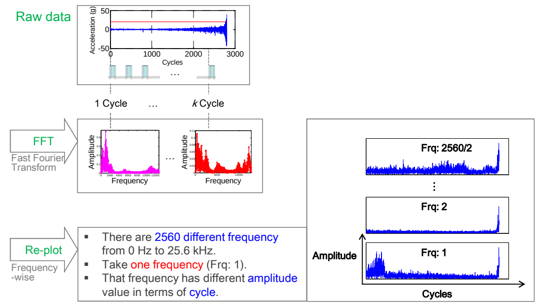
Damage feature extraction

Summary of feature extraction method

- The idea of this method is based on:
  - In most case, raw data don't give degradation information.
    - » Multiple/complex damage modes exist in a bearing system.
  - Certain changes in specific frequencies may contain degradation information.
    - » It is a kind of decomposed signal.
    - » Some of them represent noise part, and some of them catch a damage change.
- Procedure
  - Step 1: Reshape FFT results in frequency-wise
  - Step 2: Select specific frequencies having degradation information based on entropy decrease

Damage feature extraction

Step 1: Frequency-wise plot

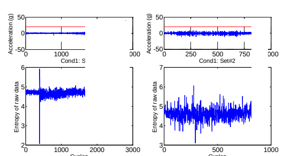


- There are 2560 different frequency from 0 Hz to 25.6 kHz.
- Take one frequency (Frq: 1).
- That frequency has different amplitude value in terms of cycle.

Damage feature extraction

Step 2: Select specific frequencies

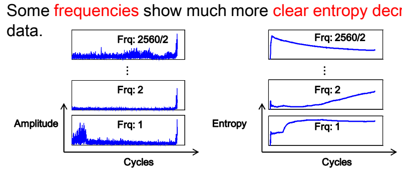
- Entropy (information theory), *H*
  - Equation: $H(X) = -\sum_{i=1}^{n} p(x_i)\log_2 p(x_i)$
  - Nature
    - » The entropy of an isolated system never decreases.
    - » The entropy of a system (A) decreases only when it interacts with some other system (B) whose entropy increases in the process.
- System A
  - » Bearing test system
- System B
  - » Microscopic damage in bearing
- Without B, entropy of A does not decrease.
- After B, entropy of A decreases.



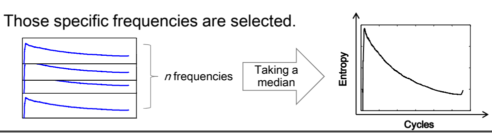
Damage feature extraction

Step 2: Select specific frequencies

- Some frequencies show much more clear entropy decrease than raw data.

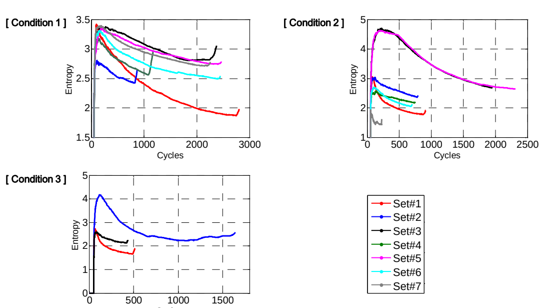


- Those specific frequencies are selected.



Damage feature extraction

Results of all test sets



Outline

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3. **Prognosis**
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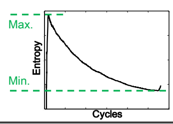
Keywords
Threshold

Prognosis

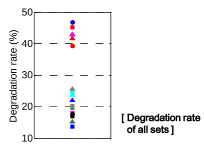
Model selection and threshold

- Model: $\text{Entropy} = \beta_1 \exp\left(\beta_2 \sqrt{\text{Cycle}}\right)$
  - Estimate beta 1 and beta 2 based on entropy data given up to current time.
- Threshold
  - Degradation rate:

$$1 - \frac{\text{min. entropy}}{\text{max. entropy}}$$



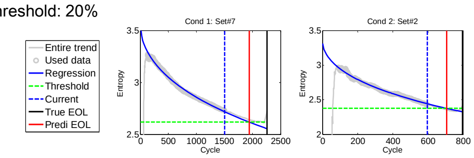
  - There are two groups for threshold.
    - » Faded by 20% and 45%



Prognosis

Prediction results of degradation

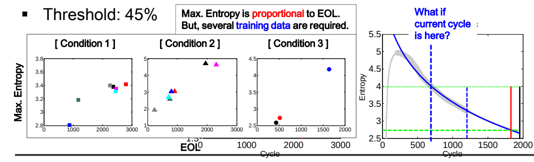
- Threshold: 20%



- Threshold: 45%

Max. Entropy is proportional to EOL.
But, several training data are required.

What if current cycle is here?



Prognosis

Prediction results RUL

- Current cycle
  - For set 1 and 2: 75% of lifespan
  - For set 3~set 7: given in challenge problem (IEEE PHM 2012)

		Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7
Cond#1	Current cycle	2101	652	1801	1138	2301	2301	1501
	RUL_True	701	218	573	34	161	146	757
	RUL_Prediction	87	475	460	34	133	976	442
	Error (%)	87.65	-117.97	19.64	-0.38	17.34	-568.54	41.61
Cond#2	Current Cycle	682	597	1201	611	2001	571	171
	RUL_True	228	199	753	139	309	129	58
	RUL_Prediction	98	109	627	21	201	90	44
	Error (%)	57.17	45.20	16.75	84.75	34.91	29.94	24.83
Cond#3	Current cycle	385	1227	351				
	RUL_True	129	409	82				
	RUL_Prediction	84	388	5				
	Error (%)	34.87	5.11	94.20				

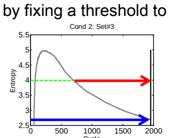
Score based on the competition criterion: 0.3605
(When **all** prediction results of RUL is the **exactly same** as true ones, the **score=1**.)

Outline

Issue on threshold

True EOL is unknown

- True EOL is unknown in real problems because it should be repaired before failure.
- Wasted life by fixing a threshold to 20%



[FEMTO Bearing failure]

  - Ratio of wasted life and true EOL

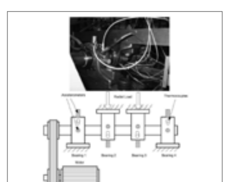
unit (%)	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7
Cond#1	84	4	16	6	11	50	5
Cond#2	80	15	64	7	63	29	52
Cond#3	76	84	8				

Half of bearings represent below 16% waste rate.

Issue on threshold

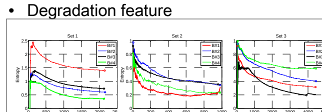
Threshold 20% is not an absolute value

- IMS bearing*



- Four double row bearings (16 rollers) were installed on a shaft.
- Three sets of test data are available.

- Degradation feature



By applying the same method,
- Damage feature is found.
- Max. Entropy is proportional to EOL.

But, the level of threshold is different.
- Faded by around 70%
- FEMTO: accelerated test
- IMS: nominal conditions

*J. Lee, H. Qiu, G. Yu, J. Lin, and Rexnord Technical Services (2007). 'Bearing Data Set', IMS, University of Cincinnati. NASA Ames Prognostics Data Repository, [http://ti.arc.nasa.gov/project/prognostic-data-repository], NASA Ames, Moffett Field, CA.

Conclusions

- Future work
  - Apply this method to other bearing problems under different level of (accelerated) loading conditions.
  - Hope there is a relation between threshold (degradation rate) and level of loading conditions.
  - Uncertainty caused by taking median of entropy from different frequencies, model parameter estimation, and threshold will be considered.
- This method can be widely applicable if certain relation (threshold-loading) is found or if several training data sets are available in each bearing problem.
  - Procedure summary of the method
    - » Reshape FFT results in frequency-wise
    - » Select specific frequencies showing entropy decrease
    - » Take a median of those entropies as a damage feature
    - » Model selection for prognosis, and estimate model parameters
    - » Setting a threshold (degradation rate based on the max. entropy)

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Thank you for your attention!!