APPLICATION OF VIBRATION & ACOUSTIC EMISSION ANALYSIS IN FAULT DETECTION OF ROTATING MACHINERY

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Maintenance is a MUST!

- Break down maintenance
  - Dangerous, very costly
- Preventive maintenance
  - Costly
- Condition based maintenance
  - Ideal

- The estimated cost of corrosion maintenance in the U.S. (Year 2002) > $276 billion.
- Corrosion maintenance expenditures over this 5 year period were approximately 3.1% of the U.S. GDP, and stimulated congress to enact the Corrosion Prevention Act in 2007.
OUTLINE

• Faults to Consider
• Experimental Procedure
• Diagnostics
  ▪ Vibration Analysis
  ▪ Statistical Analysis
  ▪ Signal Processing Techniques for AE Fault Detection
  ▪ Experimental Result
• Conclusions & Contributions
• Future Work
Faults to Consider
Overview of a Pressure Washer
FAULTS to CONSIDER (Cont.)

Crack Locations
Experimental Test Setup (Cont.)
Faults to Consider (Cont.):
Rolling Element Bearing Defects

Outer race
Inner race
Roller elements

Line Defect
Notch Defect
Experimental Test Setup

Sampling Frequency ($F_s$) = 2 MHz

NI USB 6366 X series DAQ card

Nano 30

AE Signal

20/40/60C, Preamp

LabView

USB cable

NOISE?!!
Experimental Test Setup (Cont.)
Experimental Test Setup (Cont.)
Diagnostic Using Vibration Measurements

FE Model Analysis Predicted Vibration Match ? No Crack Yes

FE Model with Crack Analysis Predicted Vibration Match ? Yes

Initial Guess of Crack Parameters

Crack Parameter Optimization

Crack Exists at Current Parameters
Diagnostic Using Vibration Measurements

Challenges

- Dynamic simulation of crack breathing
- Handling of noisy signals
- Optimization methods and procedures
- Introducing a specific crack
- Non-uniqueness of the solution

..............
Diagnostic Using Vibration Measurements (Cont.)

Meeting the Challenges: FE Modeling of Crack Breathing Behavior

Nodal Crack Force Approach

Superposition of the nodal crack forces used to simulate crack breathing.
Diagnostic Using Vibration Measurements

Meeting the Challenges:
FE Modeling of Crack Breathing Behavior

Original Design with Modifications
Diagnostic: Vibration Measurements

Meeting the Challenges: Use of Neural Networks Model

1. Experimental measurement
2. Perceptron Neural Network $N$
3. Crack Location $L$?
   - $L = 6$
   - Backpropagation Neural Network $N^6$
   - Corresponding Numerical signal
4. Experimental measurement
5. Crack Location $L$?
   - $L = 1$
   - Backpropagation Neural Network $N^1$
   - Corresponding Numerical signal
6. Backpropagation Neural Network $N^6$ and Crack size and location
7. Backpropagation Neural Network $N^1$ and Crack size and location
Diagnostic: AE Measurements

Challenges

- Dynamic simulation of faulty condition
- Handling of noisy signals
- Signal processing technique
- Introducing a specific fault
- Intense of measured data
Diagnostic: AE Measurements (Cont.)
Signal Processing: FFT vs. Wavelet

Fourier Transform

Wavelet Transform
Diagnostic: AE Measurements (Cont.)

Simulated Impulse-Like Signal

S + Noise

\[ f = 4 \text{ Hz} \]
Diagnostic: AE Measurements (Cont.)

Wavelet Method

- Shannon Entropy

\[ H(X) = - \sum_{i=1}^{n} p(x_i) \log(p(x_i)), \quad \sum_{i=1}^{n} p(x_i) = 1 \]

- Kurtosis

\[ K = \frac{1}{N} \frac{\sum_{i=1}^{N} (x_i - \bar{x})^4}{\sigma^4} \]

\[ \text{KER} = \frac{\text{Kurtosis}}{\text{Entropy}} \]
De-noising Utilizing the Proposed Method

Fourier Transform

Wavelet Transform

\[ f_o = 4 \text{(Hz)} \]
### Experimental Test Results

#### Table: Best Wavelet Function and Optimal Frequency Band

<table>
<thead>
<tr>
<th>Condition</th>
<th>Best Wavelet Function</th>
<th>Optimal Frequency Band (Hz)</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>S300</td>
<td>db39</td>
<td>7812.5-15625</td>
<td>5</td>
</tr>
<tr>
<td>S2200</td>
<td>db42</td>
<td>187500-250000</td>
<td>2</td>
</tr>
</tbody>
</table>
Experimental Test Results

<table>
<thead>
<tr>
<th>Condition</th>
<th>Theoretical Frequency (Hz)</th>
<th>Measured Frequency (Hz)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S300</td>
<td>23.55</td>
<td>24.02</td>
<td>2</td>
</tr>
<tr>
<td>S2200</td>
<td>172.72</td>
<td>173.93</td>
<td>1</td>
</tr>
</tbody>
</table>

\[ f_{or} = 24.02 \text{ (Hz)} \]

\[ f_{or} = 173.93 \text{ (Hz)} \]
Future Work

- Using the data of statistical analysis to train neural networks
  - Bearing condition monitoring
  - Crack propagation
  - Multiple fault detection

- Designing new wavelets to match a specified signal
  - Multiple fault detection
  - Feature extraction

- A complete dynamic modeling of a bearing with consideration of nonlinearities
  - Fault size estimation
  - Stability analysis of the rotating system
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Thank You
Objective ???

Condition Monitoring

- Does not provide the fault location
- No prognostics
- No modeling
- Which WPT?

Fault Diagnostics

Statistical Analysis

Signal Processing
Sensitivity Analysis Using DOE Method to Detect Incipient Faults

<table>
<thead>
<tr>
<th></th>
<th>(-)</th>
<th>(+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defect Size</td>
<td>0 (mm)</td>
<td>1 (mm)</td>
</tr>
<tr>
<td>Speed</td>
<td>300 (rpm)</td>
<td>1100 (rpm)</td>
</tr>
<tr>
<td>Load</td>
<td>0 (N)</td>
<td>100 (N)</td>
</tr>
</tbody>
</table>

AE Counts
PV
CF
R.M.S
Kurtosis
Burst Time
Skewness

<table>
<thead>
<tr>
<th></th>
<th>Counts</th>
<th>PV</th>
<th>RMS</th>
<th>Kurtosis</th>
<th>Duration</th>
<th>CF</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defect Size</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>Speed</td>
<td>0.32</td>
<td>0.92</td>
<td>0.99</td>
<td>0.51</td>
<td>-0.58</td>
<td>0.24</td>
<td>-0.03</td>
</tr>
<tr>
<td>Load</td>
<td>-0.01</td>
<td>0.19</td>
<td>0.08</td>
<td>0.17</td>
<td>-0.06</td>
<td>0.17</td>
<td>0.16</td>
</tr>
</tbody>
</table>
Sensitivity Analysis Using DOE Method to Detect Fault Growth

<table>
<thead>
<tr>
<th></th>
<th>(−)</th>
<th>(+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defect Size</td>
<td>1 (mm)</td>
<td>2 (mm)</td>
</tr>
<tr>
<td>Speed</td>
<td>300 (rpm)</td>
<td>1100 (rpm)</td>
</tr>
<tr>
<td>Load</td>
<td>0 (N)</td>
<td>100 (N)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Counts</th>
<th>PV</th>
<th>RMS</th>
<th>Kurtosis</th>
<th>Duration</th>
<th>CF</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defect Size</td>
<td>0.87</td>
<td>0.02</td>
<td>-0.27</td>
<td>0.46</td>
<td>0.54</td>
<td>1</td>
<td>-0.32</td>
</tr>
<tr>
<td>Speed</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>0.66</td>
<td>-0.09</td>
</tr>
<tr>
<td>Load</td>
<td>-0.04</td>
<td>0.20</td>
<td>0.09</td>
<td>0.14</td>
<td>-0.01</td>
<td>0.43</td>
<td>1</td>
</tr>
</tbody>
</table>
Intense of Data: Fault Frequencies

- Outer race defect $f_{or}$
  - $P_D = $ Pitch Diameter
  - $B_D = $ Ball Diameter
  - $\beta = $ Contact Angle
  - $n = $ Number of Rollers
  - $f_s = $ Shaft Frequency

$$f_{or} = \frac{n}{2} f_s \left(1 - \left(\frac{B_D}{P_D}\right) \cos \beta \right)$$

ERROR %
Objective

Condition Monitoring

Fault Diagnostics

Statistical Analysis

Signal Processing

Data Acquisition

Data Processing (Diagnostics)

Maintenance Decision Making

Detection of the faults

Identifying the causes

Estimate machine life

• Statistical Analysis
• Signal Processing
• Optimization
• FE Modeling
Faults to Consider (Cont.)

- Spoke Supports
- Gusset Plates
- Daisy-Wheel Modification
- Ring Support
Experimental Test Setup (Cont.)

- Fatigue Cracking Techniques:
  - 1. Bolt Removal method

Simulating a crack at the inner hub location by removing two bolts from the circumference.
Experimental Test Setup (Cont.)

- Fatigue Cracking Techniques:
  - 3. Real Fatigue Crack
Diagnostic: Vibration Measurements (Cont.)
Meeting the Challenges: Experimental vs. FEA
Diagnosis Using Vibration Measurements (Cont.)

Comparison of Results Using Various Techniques

Crack size identification using several techniques
Diagnostic: AE Measurements

Signal Processing: Statistical Parameters

- Kurtosis
- Root Mean Square (RMS)
- Crest Factor
- Skewness
- Ringdown Count
- Maximum Amplitude
- Time Duration

Condition Monitoring

Diagnostics

Statistical Analysis

Signal Processing

Single Fault
Fault Size
Multiple Fault

Amplitude

Time Duration

Maximum amplitude
Ringdown Count
Threshold
Experimental Test Results

L200N, S300 (rpm)

L200N, S2200 (rpm)