Bearing fault detection in brushless DC motors

A sensitivity study

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Institute
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Outline

Problem statement

Fault detection in brushless DC motors

- Design of algorithms for fault detection in electronically commutated (EC) motors
- Unknown quality limits
- Incipient faults – hard to distinguish between faulty and fault-free motor

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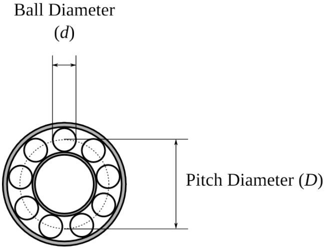
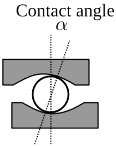
Bearing vibration model





$$BPFO = \frac{Zf_{rot}}{2}\left(1 - \frac{d}{D}cos\alpha\right) \quad BPFI = \frac{Zf_{rot}}{2}\left(1 + \frac{d}{D}cos\alpha\right)$$

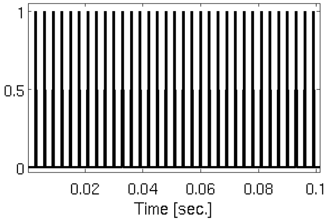
$$FTF = \frac{f_{rot}}{2}\left(1 - \frac{d}{D}cos\alpha\right) \quad BSF = \frac{Df_{rot}}{2d}\left(1 - \left(\frac{d}{D}cos\alpha\right)^2\right)$$

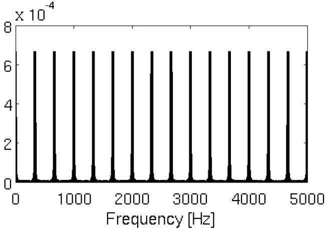
Localized bearing fault

Idealized periodic pulses

$$x(t) = \sum_{i=-\infty}^{+\infty} \delta(t - iT)$$

$$\mathcal{F}\{x(t)\}$$



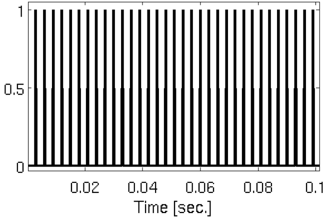


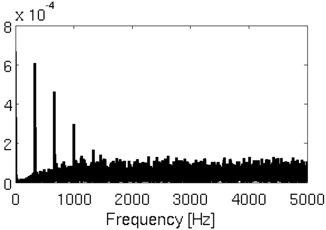
Localized bearing fault

Pulses with random lag

$$x(t) = \sum_{i=-\infty}^{+\infty} \delta(t - iT - \tau_i)$$

$$\mathcal{F}\{x(t)\}$$





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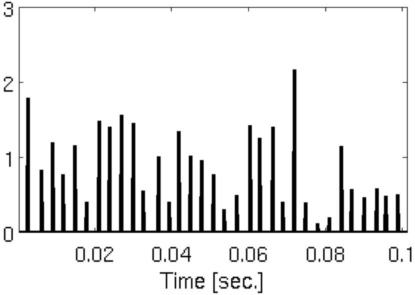
Localized bearing fault

Random amplitude Pulses with random lag

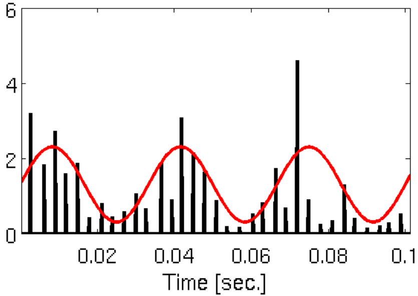
$$x(t) = \sum_{i=-\infty}^{+\infty} A_i \delta(t - iT - \tau_i)$$



Localized bearing fault

Periodic AM random amplitude Pulses with random lag

$$x(t) = \sum_{i=-\infty}^{+\infty} A_i q(T_p)\delta(t - iT - \tau_i)$$

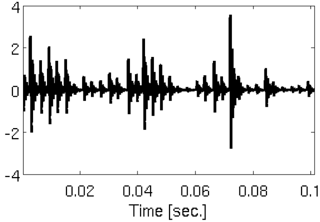


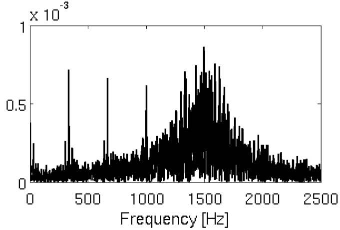
Localized bearing fault

Impulse responce

$x(t) = \sum_{i=-\infty}^{+\infty} A_i q(iT) s(t - iT - \tau_i)$

$\mathcal{F}\{x(t)\}$

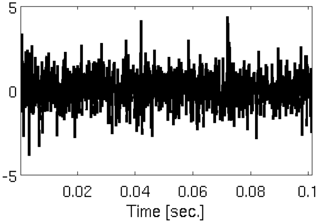


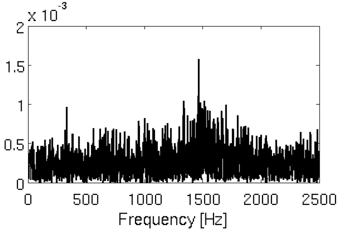


Localized bearing fault

Additive noise

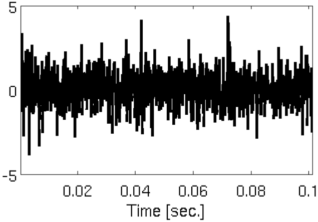
$$x(t) = \sum_{i=-\infty}^{+\infty} A_i q(iT) s(t - iT - \tau_i) + n(t)$$



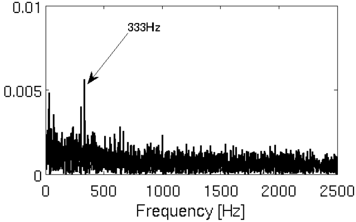


Envelope analysis of simulated fault

$x(t)$



$\mathcal{H}\{x(t)\}$



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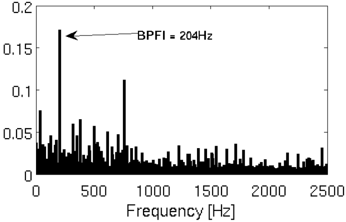
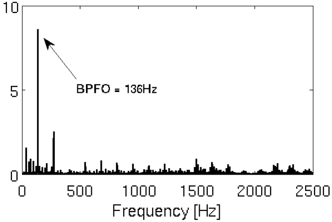
Envelope spectra of unfiltered signals

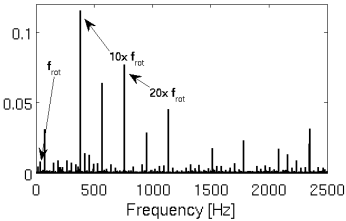


(a) Inner race fault

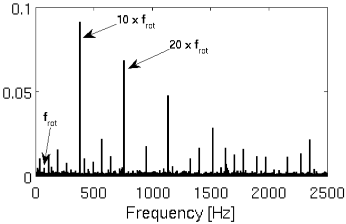


(b) Outer race fault

Envelope spectra of unfiltered signals



(a) Fault free



(b) Lack of lubrication

Sensitivity improvements

Ideas

- Select a frequency band where the impulses generated by the fault can be best detected
- Conditions for frequency band selection
  - where the signal-to-noise ratio (SNR) is the highest
  - around a structural resonance frequency excited by the impacts
  - spectrum comparison for determining the region with the biggest change

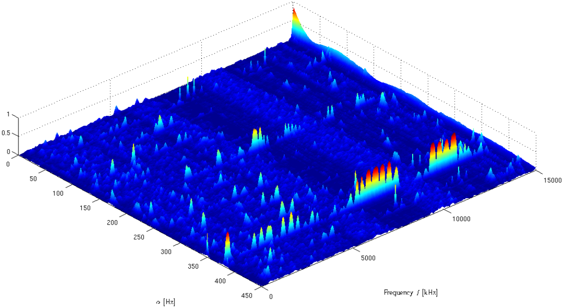
Cyclostationary processes

- Strict-sense CS process (SSCS)
  $F(x_1, x_2, \cdots, x_n; t_1, t_2, \cdots, t_n) =$
  $F(x_1, x_2, \cdots, x_n; t_1 + mT, t_2 + mT, \cdots, t_n + mT)$
- Wide-sense CS process (WSCS)
  $E\{x(t)\} = E\{x(t + mT)\}$
  $R_x(t_1, t_2) = R_x(t_1 + mT, t_2 + mT)$

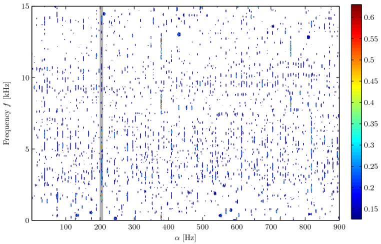
Spectral correlation density

- Wiener-Khinchin theorem for CS
  $S_x(\omega) = \int_{-\infty}^{+\infty} = R_x(\tau) e^{-j\omega t} dt$
  $S_x^\alpha(\omega) = \int_{-\infty}^{+\infty} = R_x^\alpha(\tau) e^{-j\omega t} dt$
- Spectral Coherence (correlation coefficient)
  $|\rho_x^\alpha(\omega)|^2 = \frac{|S_x^\alpha(\omega)|^2}{S_x(f-\alpha/2) S_x(f+\alpha/2)}, |\rho_x^\alpha(\omega)|^2 \in [0, 1]$

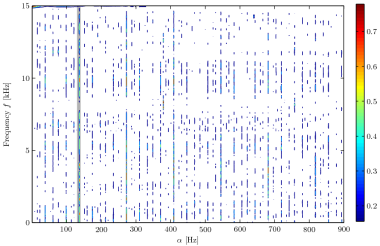
Cyclic coherence



Cyclic spectral coherence (SCOH) for vibration signal

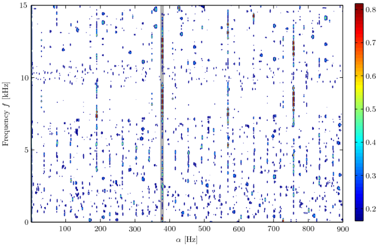


(a) Inner race fault

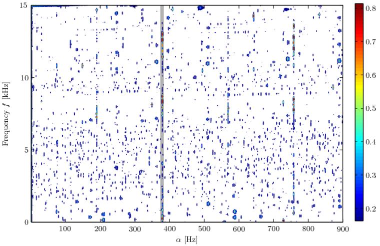


(b) Outer race fault

Cyclic spectral coherence (SCOH) for vibration signal

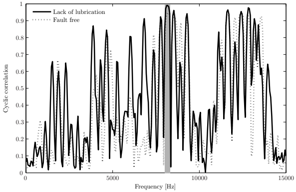


(c) Fault free

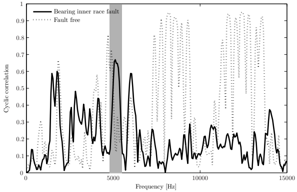


(d) Lack of lubrication

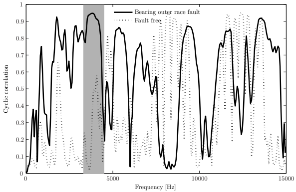
SCOH for selected cyclic frequencies



(a) Lack of lubrication

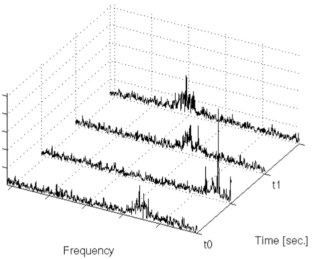


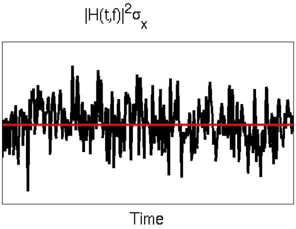
(b) Inner race fault



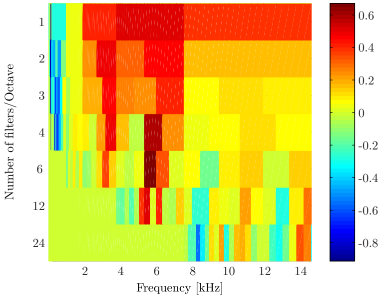
(c) Outer race fault

Definition of spectral kurtosis





Fast kurtogram



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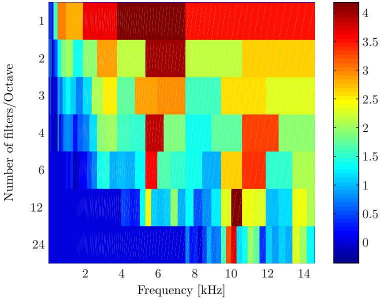
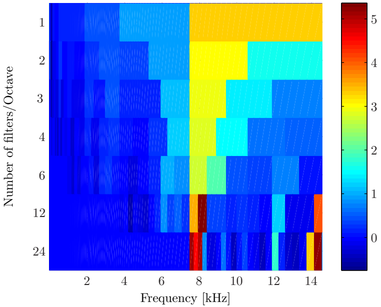


(b) Outer race fault

Fast kurtogram



(c) Lack of lubrication

Selected frequency bands

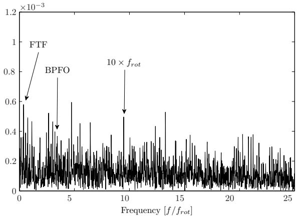
- Filter parameters determined by SK method

Fault	Central frequency	Bandwidth
Lack of lubrication	8180 Hz	1000 Hz
Bearing inner race fault	5600 Hz	900 Hz
Bearing outer race fault	5000 Hz	2000 Hz

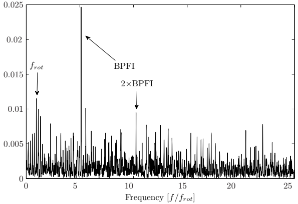
- Filter parameters determined by CS method

Fault	Central frequency	Bandwidth
Lack of lubrication	8150 Hz	600 Hz
Bearing inner race fault	5100 Hz	800 Hz
Bearing outer race fault	3700 Hz	1400 Hz

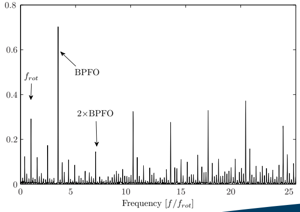
Results of filtering



(a) Lack of lubrication



(b) Inner race fault



Conclusion

- Envelope frequency analysis is capable in detecting majority of bearing faults
- Blind selection of band-pass filter parameters without the need of any historical data
- Increase in sensitivity of the feature extraction procedure

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Future work

- Non-stationary operating conditions
- Estimation of the remaining useful life