Conference
Periodically correlated processes and their applications
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In recognition of Prof Harry Hurd contribution to the field

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ADVANCES IN VIBRATION-BASED FAULT DETECTION: CYCLOSTATIONARY ANALYSIS AND COMPARATIVE EVALUATION OF EMERGING TECHNIQUES FOR ROLLING ELEMENT BEARINGS DIAGNOSIS.

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Outline

- CONTEXT
- A COMPARATIVE STUDY BETWEEN CYCLOSTATIONARY ANALYSIS AND SQUARED ENVELOPE SPECTRUM
- CONCLUSION

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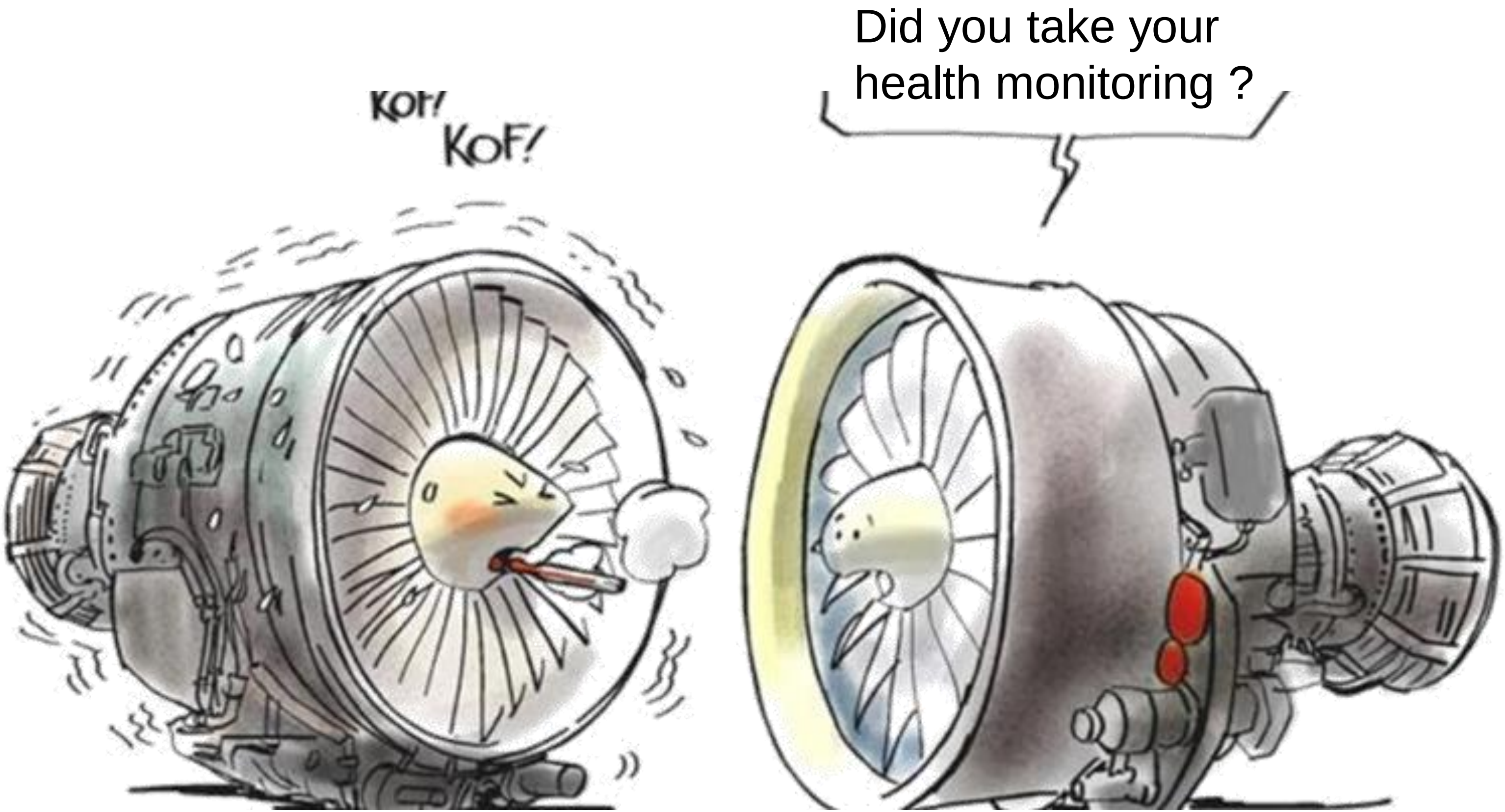
Why health monitoring ?



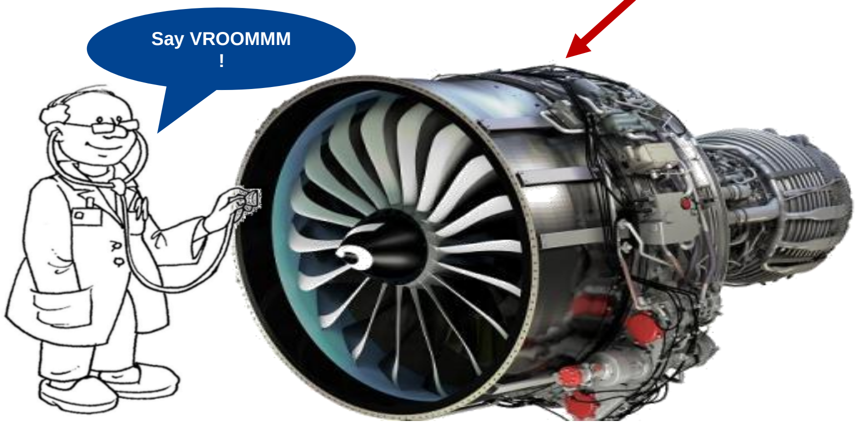
Issues and Challenges

- **Improve user safety**

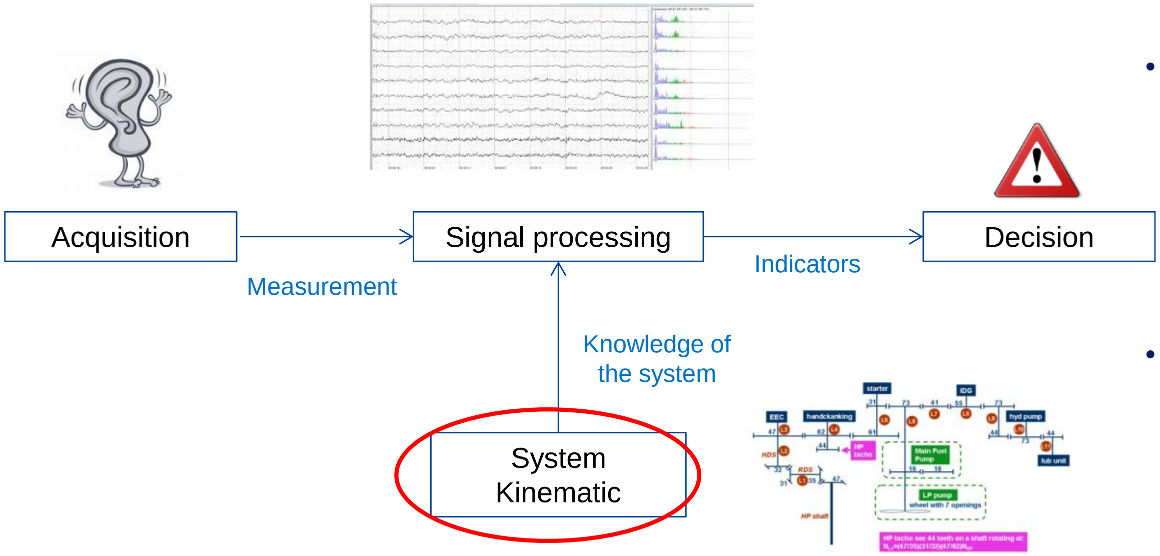
- **Optimize the operational reliability of the product**
  - The aircraft departs on time, arrives at the designated location on time
  - Reduction of operational events and unplanned maintenance operations

- **Optimize maintenance operations**
  - Reduce downtime
  - Reduce maintenance costs
  - Ensure product usage tracking
  - Quickly isolate defects

- **Build customer loyalty**
  - Offer high value-added services



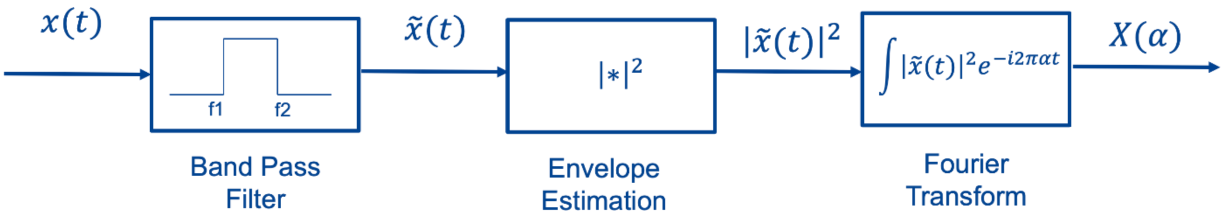
Health Monitoring principle



- **Vibration analysis is a well established technology**
  - ✓ Non-intrusive nature
  - ✓ Easy implementation and instrumentation
  - ✓ Allows incipient fault detection

- **Main bloc of a vibration analysis**
  - ✓ Acquisition (accelerometers, microphones, encoders, etc.)
  - ✓ Signal processing (de-noising, filtering, transformation, etc.)
  - ✓ Fault diagnosis through frequency signature analysis

Squared Enveloppe Spectrum (SES)



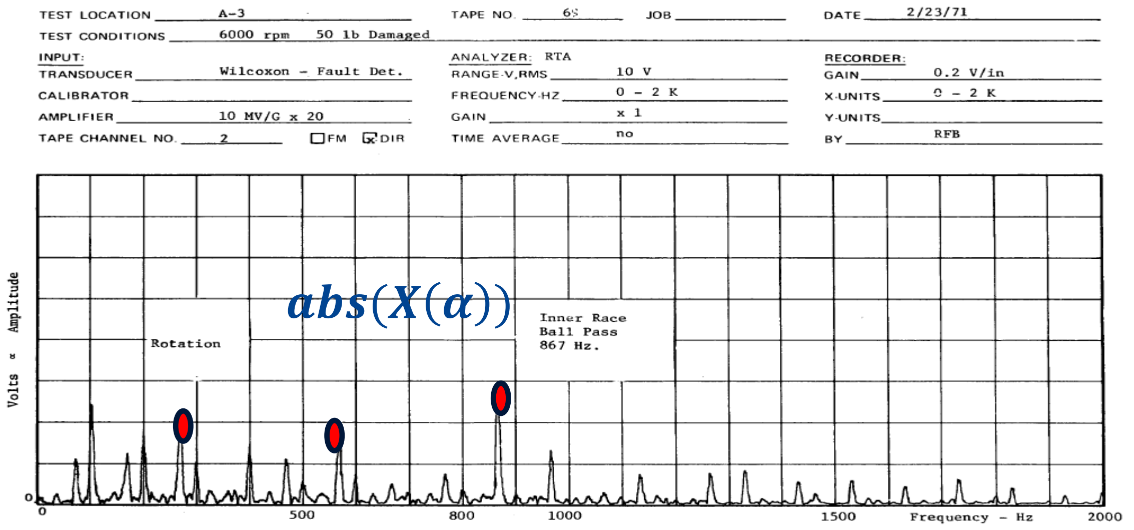


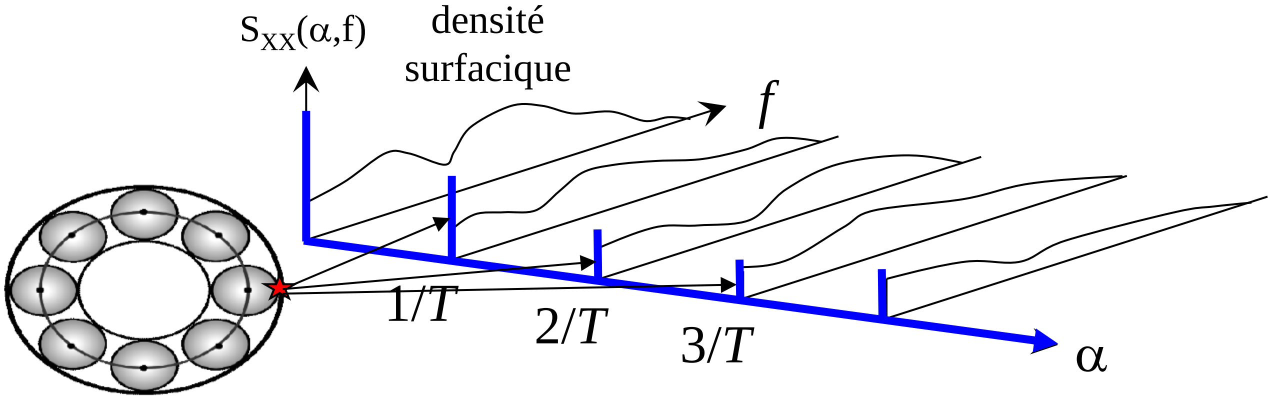
Fig. F-24 Fault Detector Frequency Spectrum, 50 lb. Thrust, 6000 rpm, Pitted

Design and Fabrication of prototype System for early warning of impending bearing failure, NASA design report June 1970

Squared Envelope Spectrum and Cyclostationarity Relationship (R.B Randall 2001, MSSP)

To see this, let us define $M_{xx}(\alpha)$ as the spectrum obtained after integrating $S_{xx}(\alpha, f)$ along f, that is,

$$M_{xx}(\alpha) = \int_R S_{xx}(\alpha, f)\, \mathrm{d}f.$$



$$M_{xx}(\alpha) = \int_R \lim_{W\to\infty} \frac{1}{W} \int_R \int_{-W/2}^{W/2} C_{xx}(t,\tau)\, \mathrm{e}^{-j2\pi(f\tau+\alpha t)}\, \mathrm{d}t\, \mathrm{d}\tau\, \mathrm{d}f. \quad = \lim_{W\to\infty} \frac{1}{W} \int_{-W/2}^{W/2} C_{xx}(t,0)\, \mathrm{e}^{-j2\pi\alpha t}\, \mathrm{d}t.$$

Cyclostationarity approach

$$C_{xx}(t,0) = E\{|x(t)|^2\}$$

$$X(\alpha) = \int |\tilde{x}(t)|^2 e^{-i2\pi\alpha t} dt$$

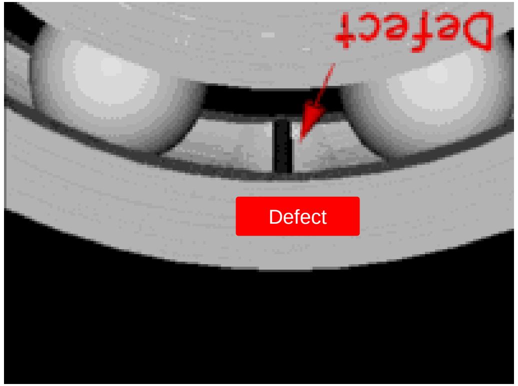
Squared Envelope Spectrum approach

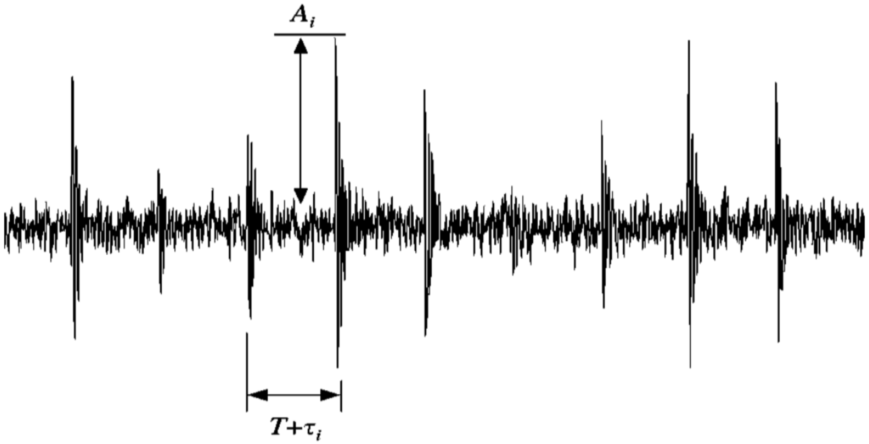
Cyclostationarity in bearings

- Faulty Bearings emit specific vibrations
  - When fault surface meet another surface
  - A shock is generated => transient waveform
  - Periodic patterns due to the rotation motion

- Fault type and location can affect their
  - ✓ frequency content
  - ✓ energy and shape
  - ✓ Statistical nature

- Challenges
  - ✓ Jitter phenomenon (rolling element slip)
  - ✓ Deviation of bearing frequency (cage slip)
  - ✓ Interference of other periodic/harmonic components (gears, shafts, turbines, etc.)





$$x(t) = \sum_i A_i s(t - iT - \tau_i) + n(t)$$

Cyclostationary models in mechanical systems

- Cyclostationary signals are random processes whose structure comprises some hidden periodicity

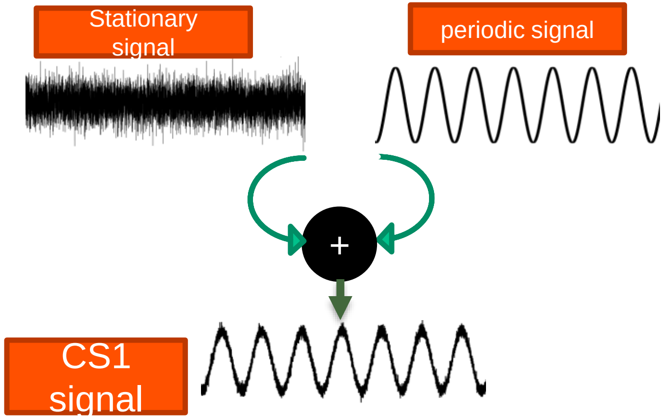
$$p_x(x_1, \dots x_n; \theta_1 \dots \theta_n) = p_x(x_1, \dots x_n; \theta_1 + \Theta \dots \theta_n + \Theta)$$

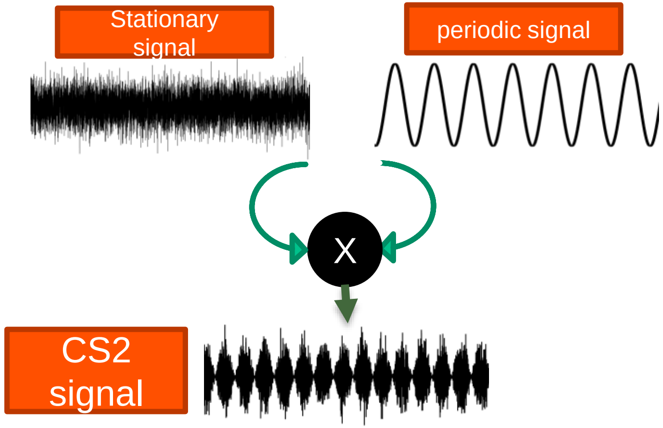
- The cyclostationary framework describes well machine signals
- First-order cyclostationarity (CS1)
  - ✓ Includes shaft imbalances, misalignments, fans, gears, and some bearings
  - ✓ Defined by the periodicity of the first-order moment:

$$M_1(\theta) = E\{x(\theta)\} = M_1(\theta + \Theta)$$

- Second-order cyclostationarity (CS2)
  - ✓ Interaction between periodic and random phenomena
  - ✓ Generated by turbulence, combustion forces and also faulty bearings as a result of rolling element slips
  - ✓ Defined by the periodicity of the second-order cumulants:

$$C_{2x}(\theta, \phi) = E\{\left(x(\theta) - m_x(\theta)\right)\left(x(\theta - \phi) - m_x(\theta - \phi)\right)\} = C_{2x}(\theta - \Theta, \phi)$$





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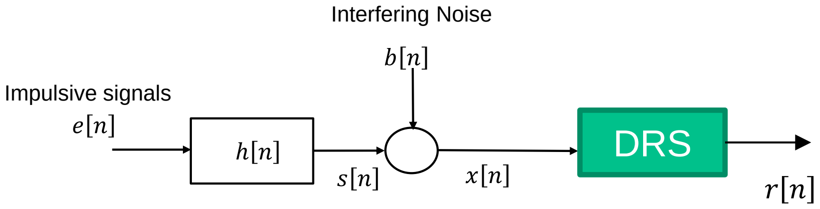
Algorithms of bearing faults detection

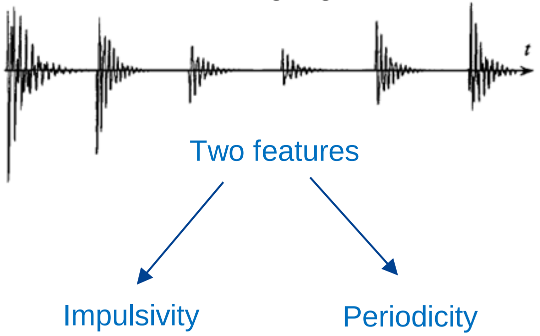
- Elimination of the déterministe component (deterministic/random separation techniques):
  - Synchronous average
  - Fourier domain analysis
  - Self-adaptative noise cancellation (and its frequency domain counterpart)
  - Linear prediction filter

- Promoting the bearing fault signature:
  - Impulsiveness-based approach (MED, SK, kurtogram, etc.)
  - Cyclostationary-based approach (spectral correlation, cyclic coherence WV spectrum, cyclic filtering, etc.)

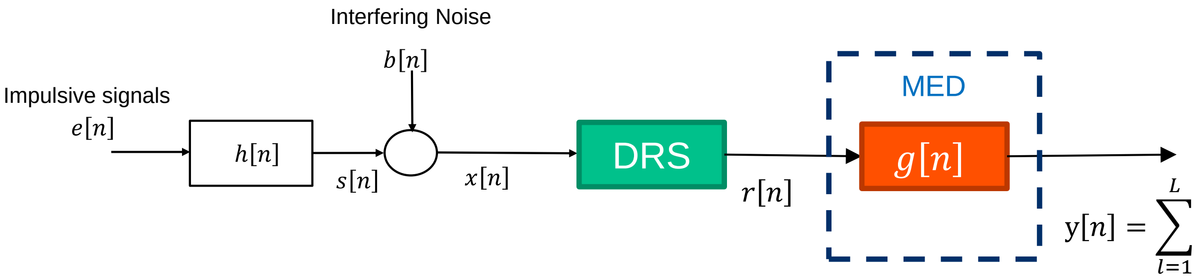
- This study aims at comparing two leading approaches:
  - Approach 1: Minimum entropy deconvolution (MED) combined with the spectral kurtosis (SK)
  - Approach 2: Spectral coherence based method



Bearing signal



First approach : Minimum Entropy Deconvolution (MED)



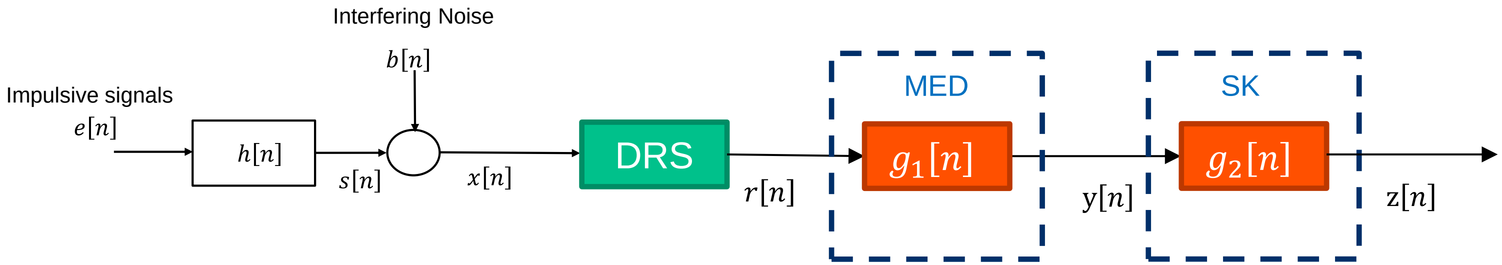
$$y[n] = \sum_{l=1}^{L} g[l]r[n-L]$$

- It finds the deconvolution filter that maximise the kurtosis of the output => maximizes the kurtosis

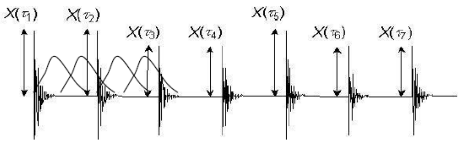
- the objective function method, originally proposed in Ref. [Lee 1999], objective function to maximize:

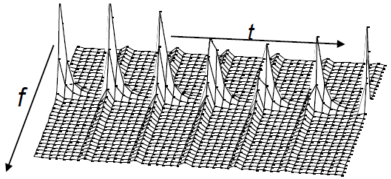
$$O_k(g) = \frac{\sum_{n=0}^{N-1} y[n]^4}{\left(\sum_{n=0}^{N-1} y[n]^2\right)^2}$$

First approach : Spectral Kurtosis (SK)



- The spectral kurtosis is a fourth order spectral moment,
- Can be seen as a the kurtosis of the signal filtered in multiple bands





$$K_y(f) = \frac{< |Y(t;f)|^4 >_t}{< |Y(t;f)|^2 >_t^2} - 2$$

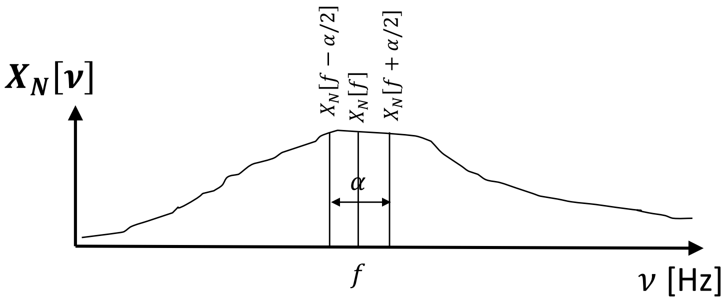
Second Approach:Cyclostationarity approach

Spectral correlation (SC)

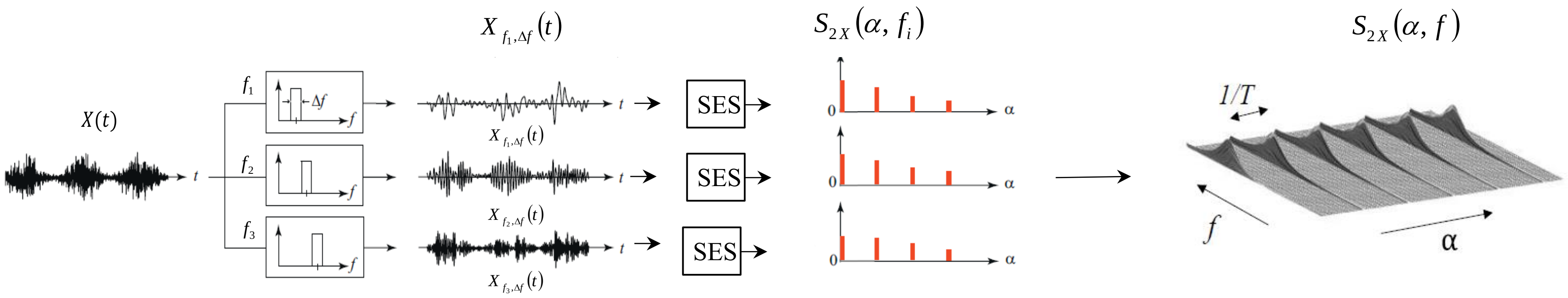
$$S_{2x}(f,\alpha) = \lim_{N\to\infty} \frac{1}{N\Delta_t} \mathrm{E}\left\{X_N[f-\alpha/2]\,X_N[f+\alpha/2]^*\right\}$$

- *f : spectral frequency*
- *α: cyclic frequency*

Fourier Domain



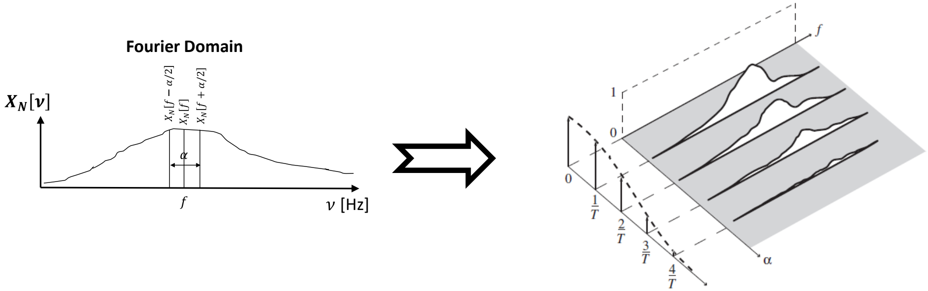
Intuitive explanation (Partial)



Second approach

***S**pectral **Coh**erence (SCoh)*

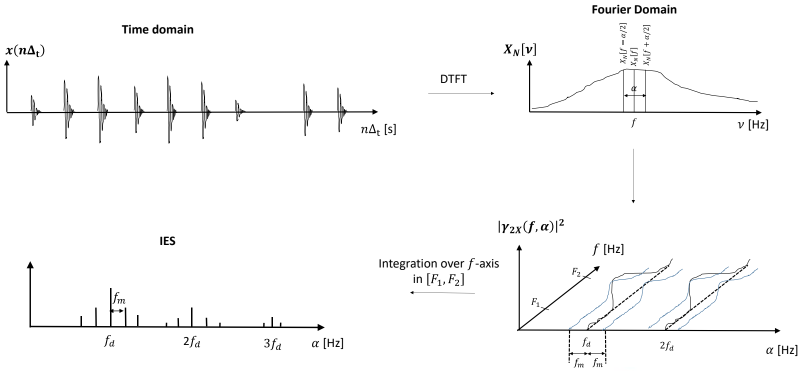
$$\gamma_{2x}(f,\alpha) = \lim_{N\to\infty} \frac{\mathrm{E}\left\{X_N[f-\alpha/2]X_N[f+\alpha/2]^*\right\}}{\left(\mathrm{E}\left\{\left|X_N[f-\alpha/2]\right|^2\right\}\mathrm{E}\left\{\left|X_N[f+\alpha/2]\right|^2\right\}\right)^{1/2}}$$



***I**mproved **E**nvelope **S**pectrum (IES)*

- An average of the squared-magnitude Scoh over the f-axis is made (possibly over a limited frequency band)

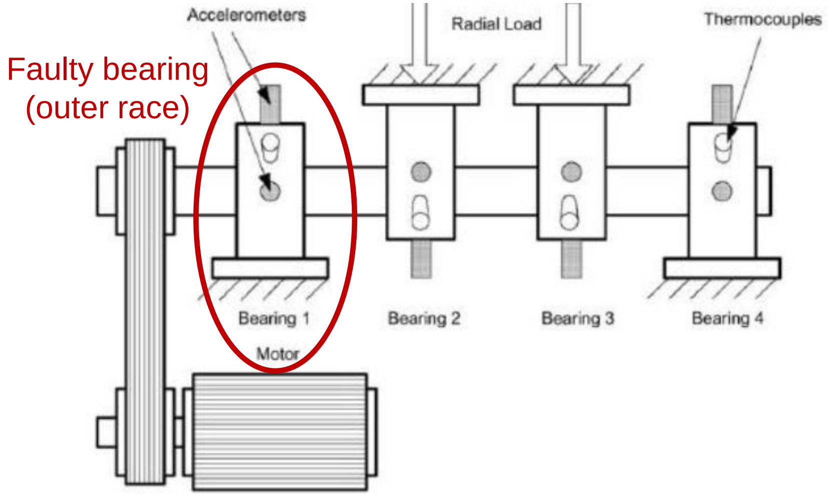
- Diagnostic indicators can then be constructed by summing up the harmonics at the suspected frequency faults

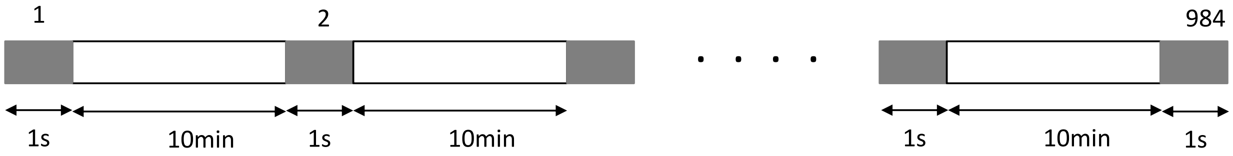


Application 1:Run-to-failure test on a laboratory benchmark

- The dataset are provided by the NSF I/UCR Center for Intelligent Maintenance Systems (available on the NASA Website)

- Acquisition program of the run-to-failure test records





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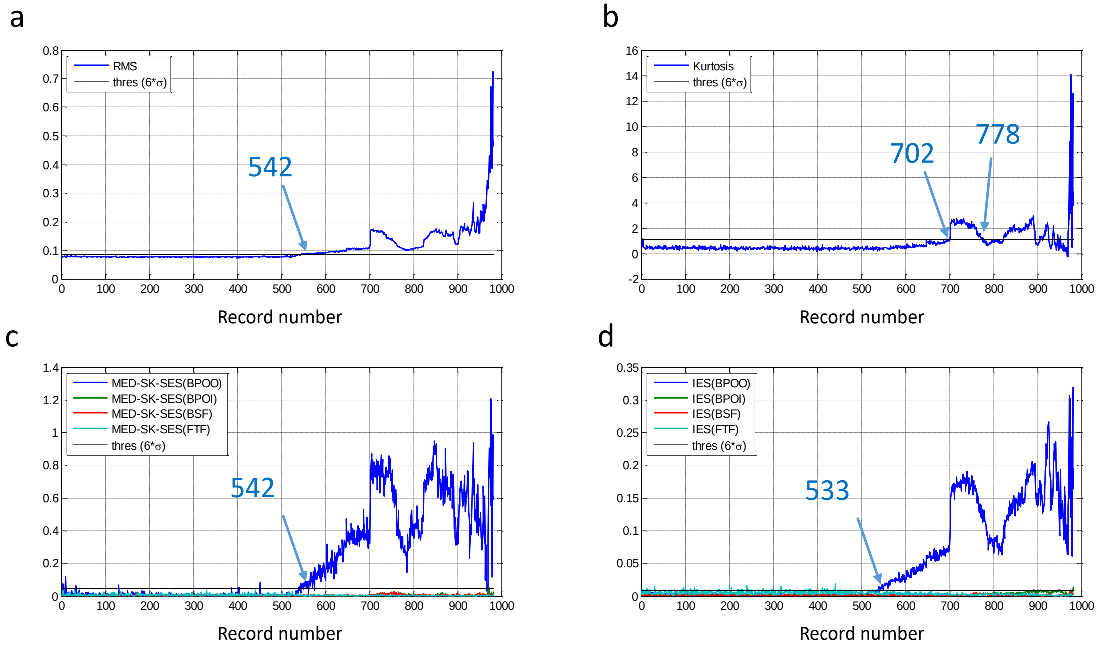
Application 1:Case 1: nearby accelerometer

- The aim is to assess the detection precocity
- Five harmonics are considered to build both estimators
- Statistical threshold were built using the first 200 acquisition assuming healthy operation
- The CS approach was able to detect the fault earlier



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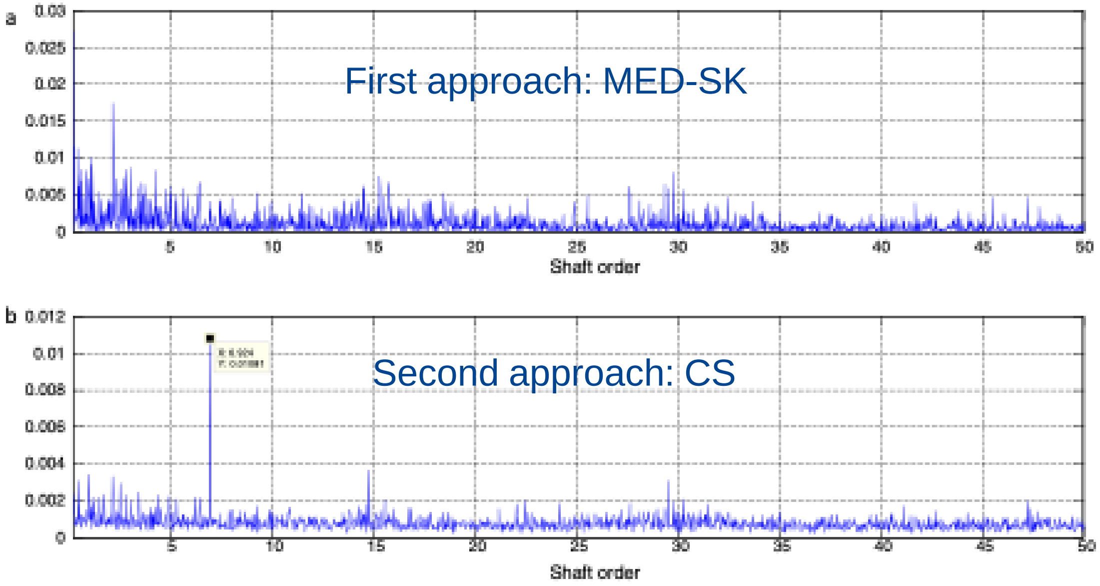
Application 1:Case 1: nearby accelerometer

- Envelope spectra computed by the two approaches at record 532 (very beginning the fault appearance)
- A BPFO harmonic is seen by the CS approach



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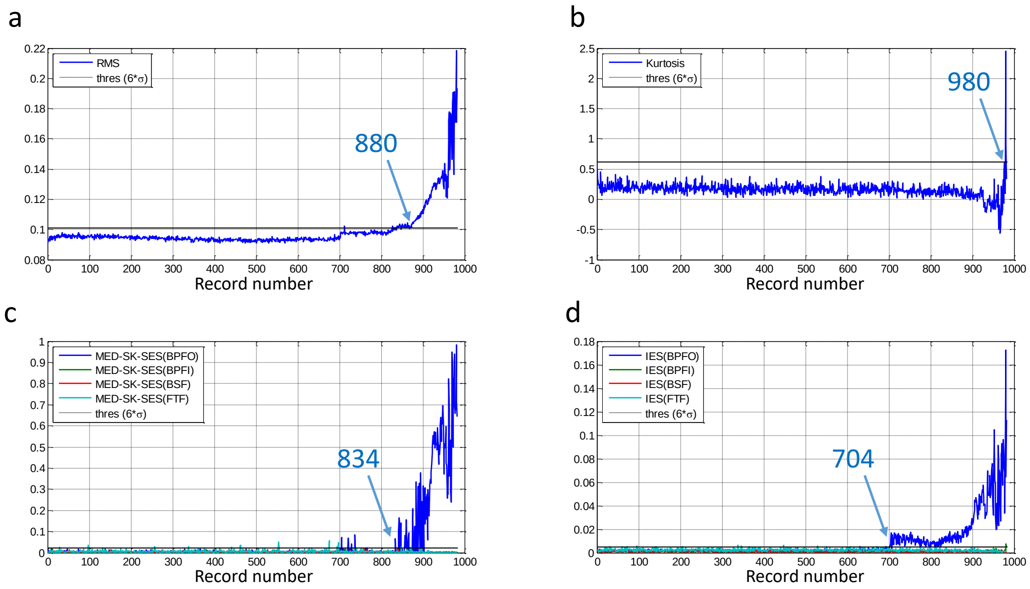
Application 1:Case 2: A remote accelerometer

- The aim is evaluate the robustness of these methods in a low SNR scenario and a significant alteration of the system transfer function

- The kurtosis has barely evolved in the test
  - Low SNR => attenuate impulsivity
  - Long transmission path has led to a nonlinear transfer function that has compensated the signal impulsivity for specific excitation forces)

- The CS approach was able to detect the fault earlier at record 704 (more consistently)



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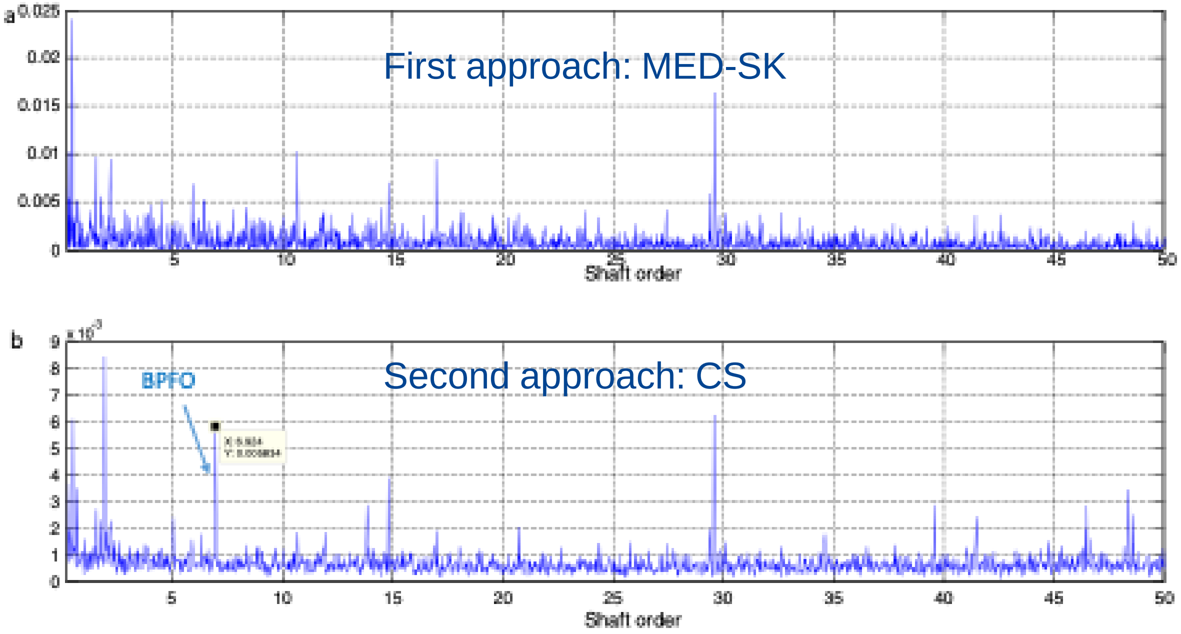
Application 1:Case 2: Remote accelerometer

- Envelope spectra computed by the two approaches at record 734 (very beginning pf the fault detection)

- A BPFO harmonic is seen by the CS approach



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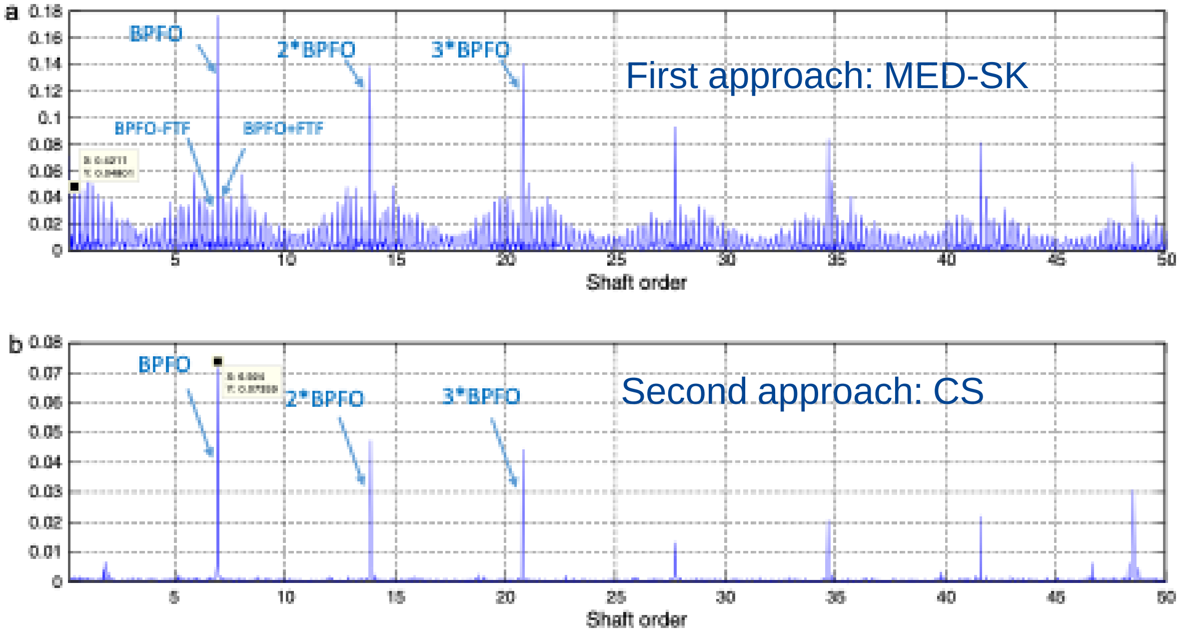
Application 1:Case 2: Remote accelerometer

- Envelope spectra computed by the two approaches at record 982 (fault is already very impulsive
- In the MED-SK case, the BPFO is modulated by the cage frequency, contrary to the CS approach where only BPFO related harmonics are present
  - ➢ MED-SK filtering is likely to favor a modulated impulse response series over an unmodulated one
  - ➢ MED-SK seems better when the signal is already impulsive



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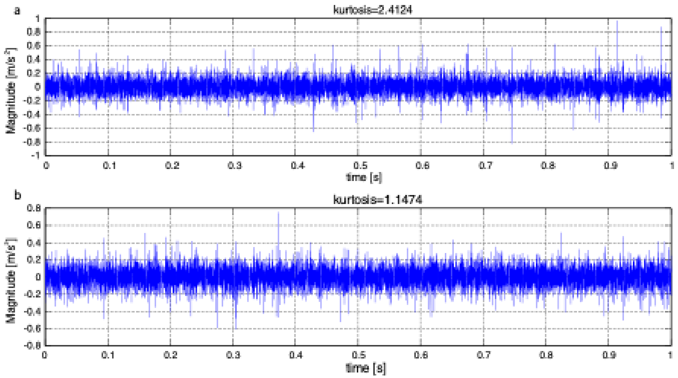
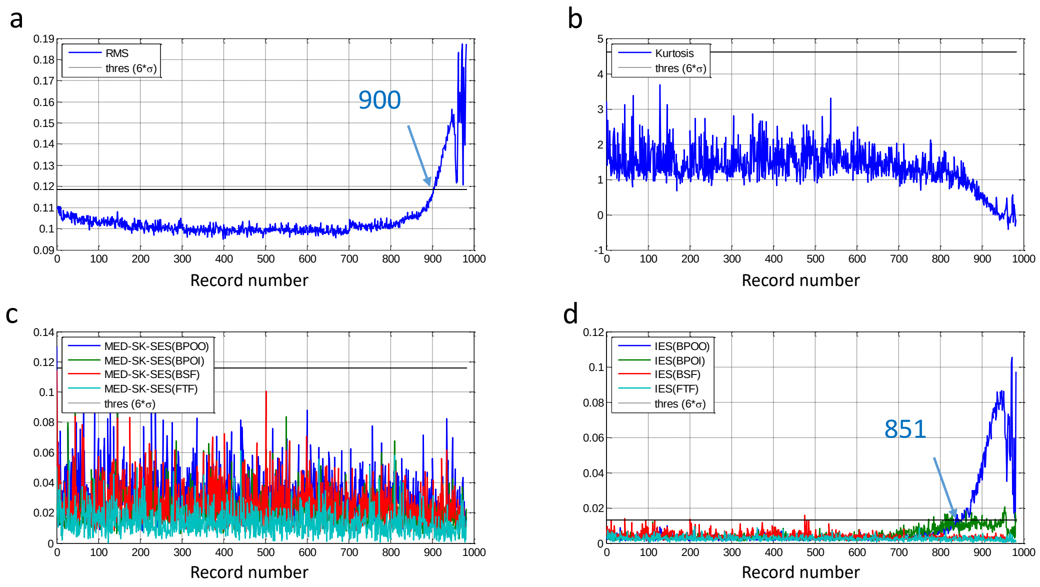
Application 1:Case 3: a remote accelerometer with non-stationary interferences

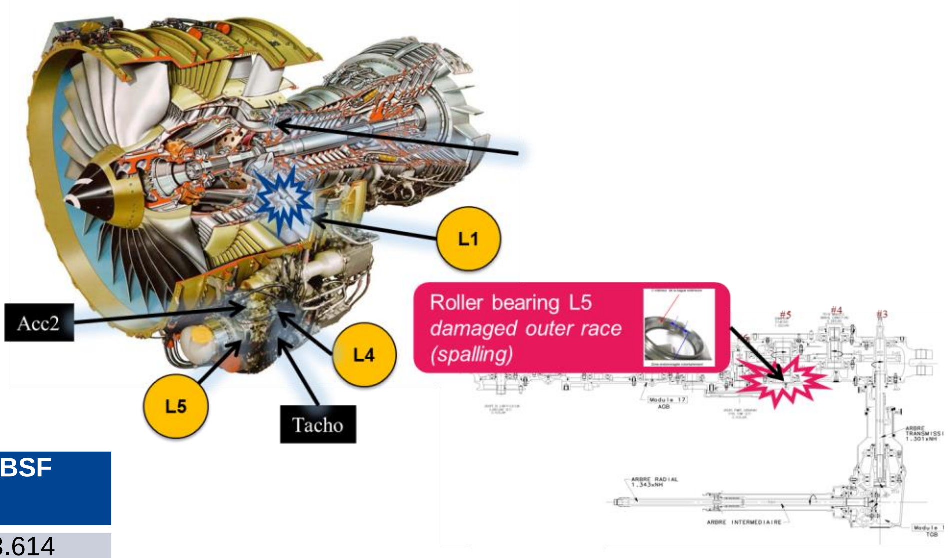
- This is the most challenging case as the defect source is remote from the sensor and the measurements contain some nonstationary impulsive interferences
- Presence of random impulses





Application 2:Safran contest (Surveillance 8): An Aircraft engine

- A tachometer measuring the shaft speed at L4 is given
- Characteristic frequencies of the faulty bearing



f_{L5}	FTF	BPFO	BPFI	BSF
1.0163	0.438	7.8855	10.408	3.614

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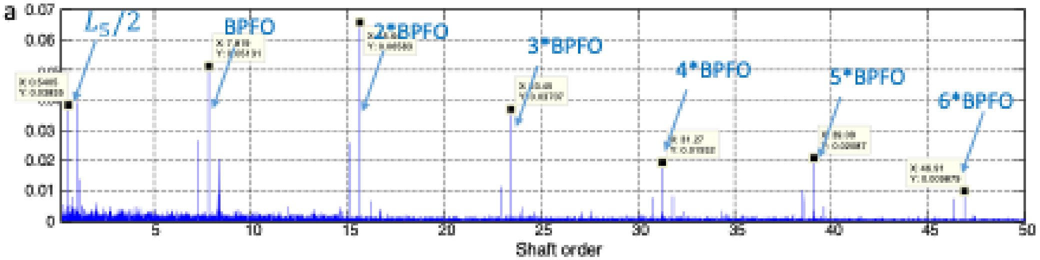
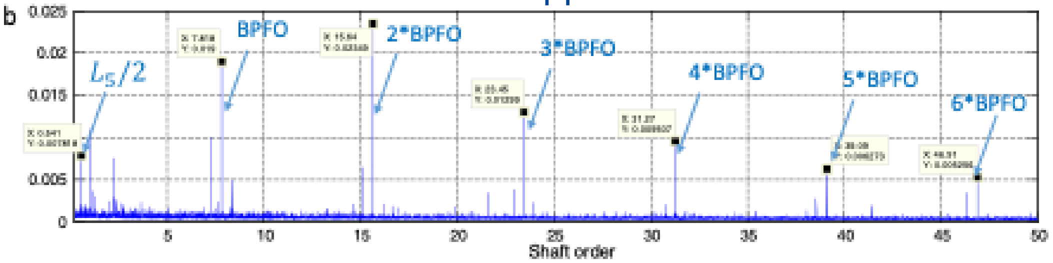
Application 2:Safran contest (Surveillance 8). An Aircraft engine

(a) The MED-SK-NES and (b) the IES applied on the 2 s signal acquired from a jet engine operating under regime R1 (Safran data; f_{L4} = 181 Hz).

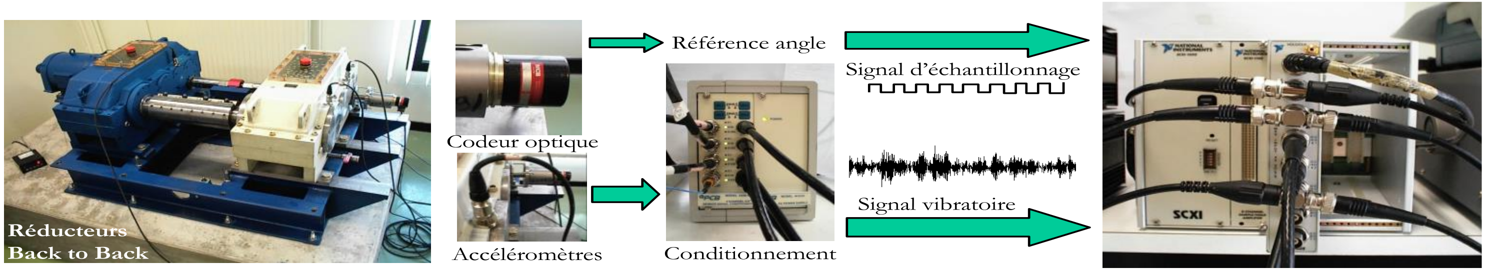
First approach: MED-SK

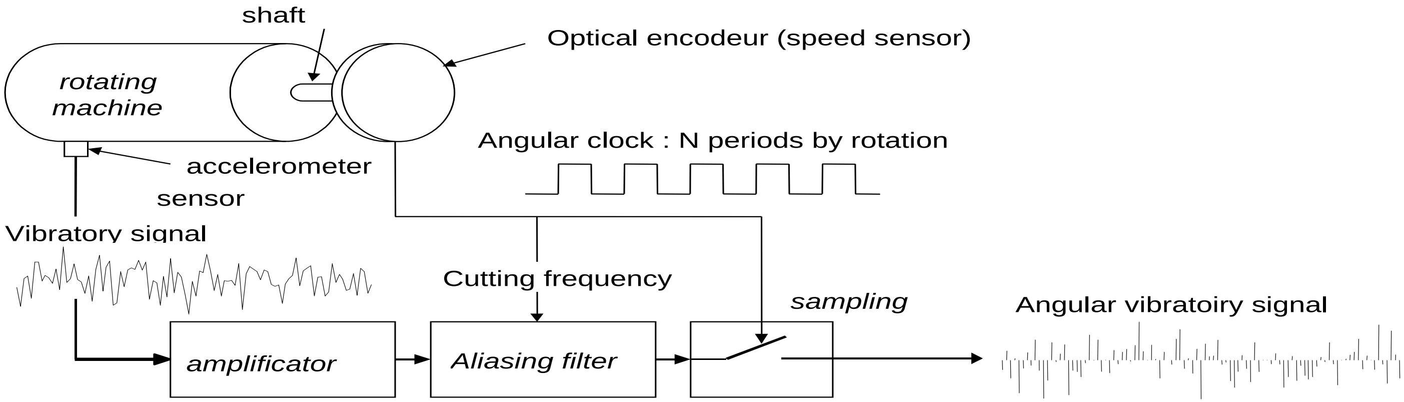


Second approach: CS



Extension to the variable speed case : Order tracking and synchronous sampling



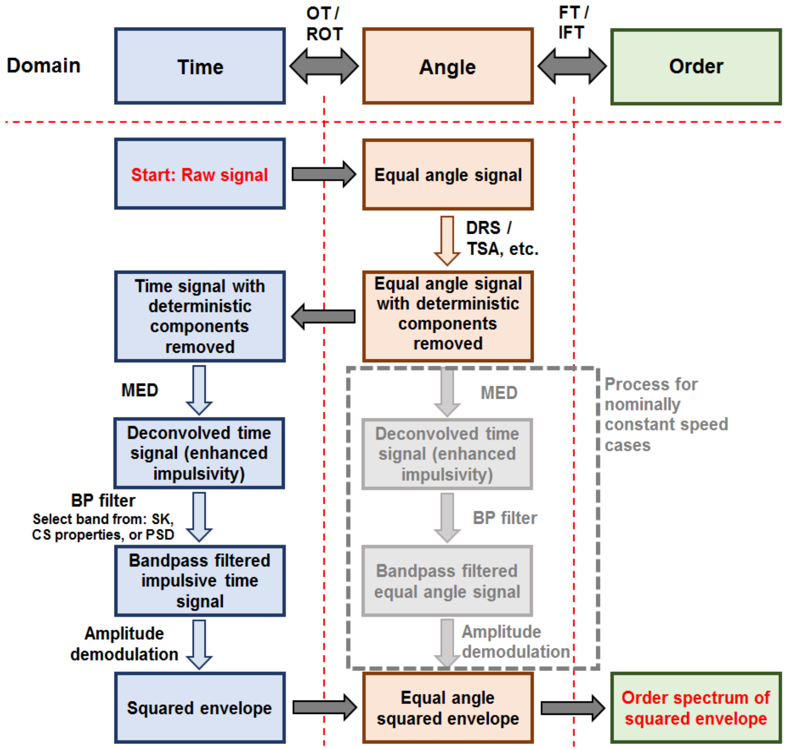


Extension to the variable speed case

- Extension of the first approach to the variable speed

- The Deterministic/random separation is better to be made in the angular domain

- The MED-SK filtering must be made in the time domain



- [Randall 2014] R. Randall , W. Smith , M. Coats, Bearing diagnostics under widely varying speed conditions, In: Proceedings of the 4th Conference In Condition Monitoring of Machinery in Non-stationary Operations, 14–16 December, Lyon, France, 2014.

- [Smith 2017] Wade A. Smith, Robert B. Randall, Xavier de Chasteigner du Mée, Zhongxiao Peng, “Use of Cyclostationary Properties to Diagnose Planet Bearing Faults in Variable Speed Conditions”, Tenth DST Group International Conference on Health and Usage Monitoring Systems (HUMS), Melbourne, Australia, 2017.

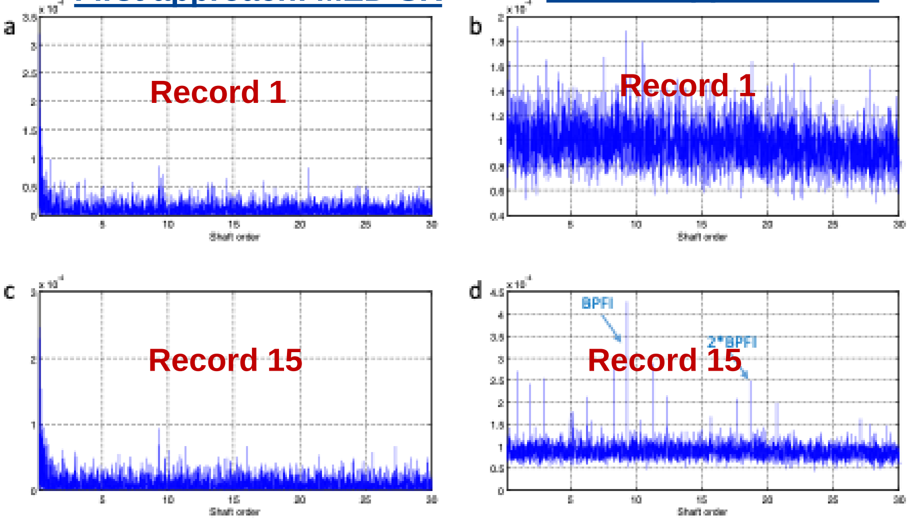
Application 3: Wind turbine

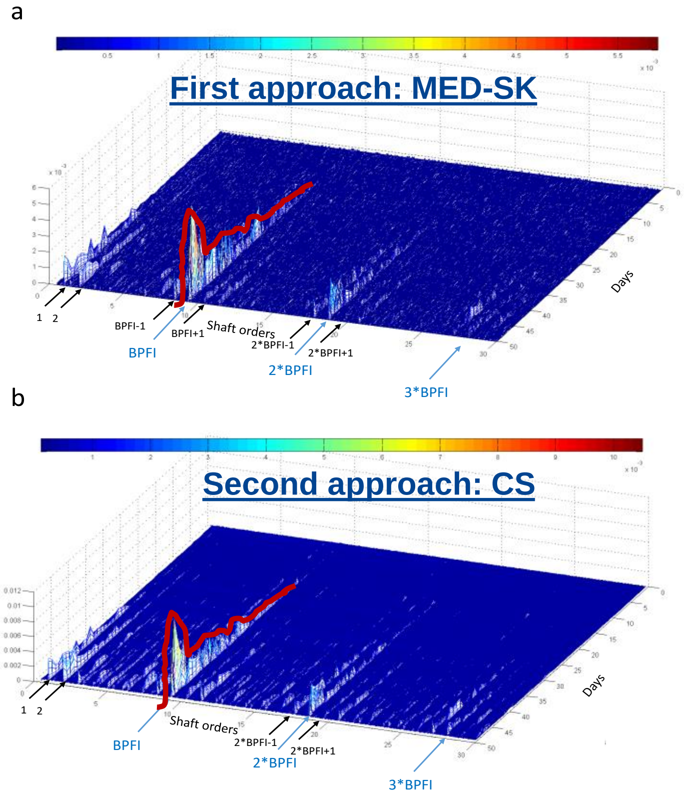
Application 3

- Evolution of (a) the MED-SK and (b) the IES throughout the days applied on a real wind turbine's gearbox
- Both approaches can be generalized to the variable speed case and detect an inner race fault

First approach: MED-SK

Second approach: CS





Conclusion

The CS approach demonstrates clear advantages over MED-SK, particularly in:

- **Detection precocity**: It enables earlier fault detection, crucial for predictive maintenance.
- **Robustness in noisy environments**: The CS approach effectively enhances the signal-to-noise ratio, making it more resilient against background noise.
- **Source separation**: Unlike SES, which may struggle with overlapping spectral components, the CS method allows for better distinction between fault sources (e.g., bearings vs. gearbox).

Thank you for your attention

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