A brief review of time-frequency applications in mechanical signal processing: state-of-the-art and challenges

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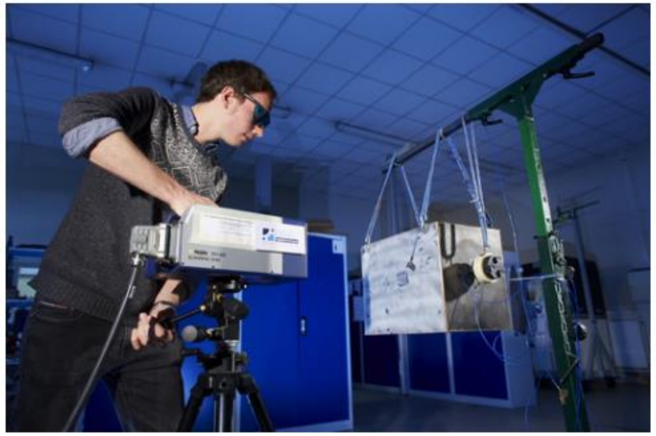
Laboratoire vibrations Acoustique

- 15 permanent researchers
- 25~30 PhD students + postdocs
- Axes of research
  - Vibro-acoustics
  - Source Identification
  - Sound Perception
  - Condition Monitoring/SHM/NDT



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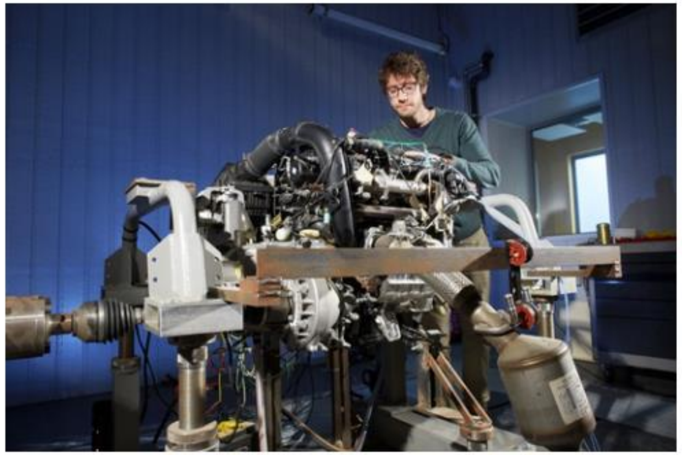
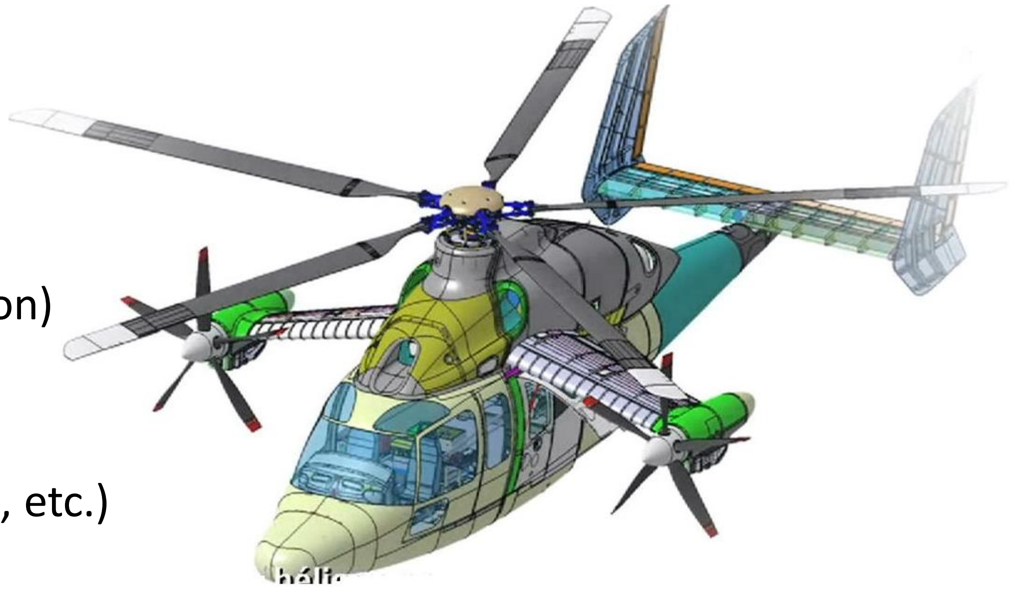
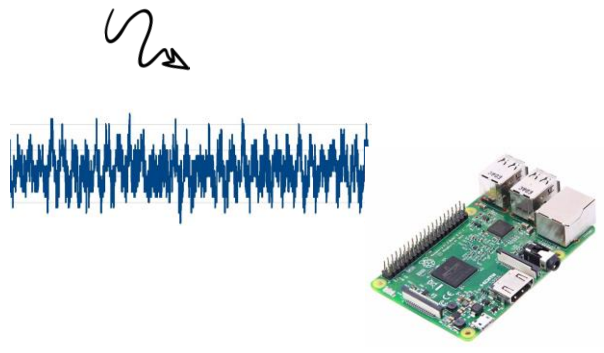


Signal processing in mechanical engineering

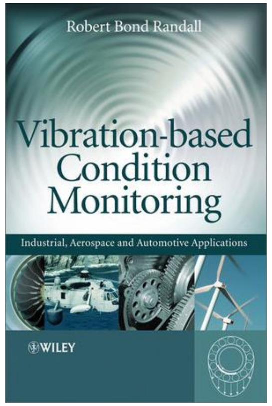
- Control
  - Process control
  - Acoustical comfort
  - Energy harvesting
- Structural health monitoring
  - Health status of elastic structures (civil engineering, transportation)
  - Lifetime extension, avoidance of catastrophic failures
- Machine health monitoring
  - Rotating machines in any application (transportation, production, etc.)
  - Cost-savings / breakdowns, lifetime extension
- Non-destructive testing
  - Inspection of materials
- Tribology
  - Surface of materials
  - Characterization of their functionality

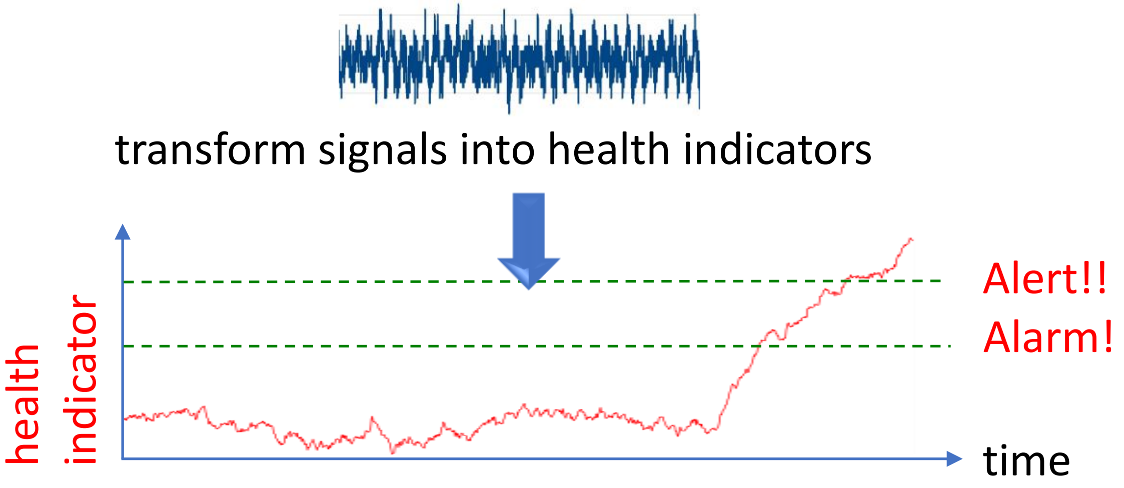


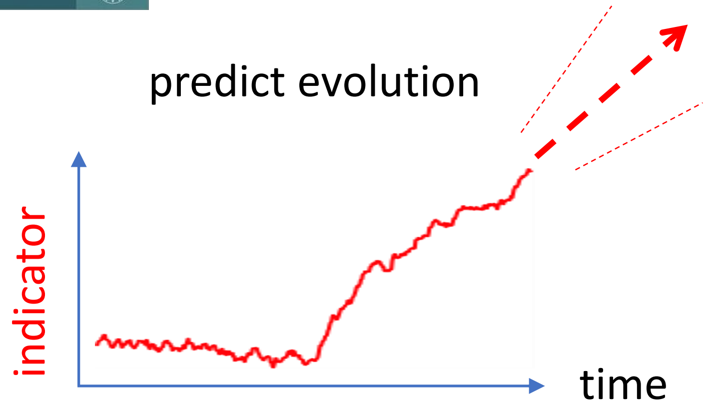


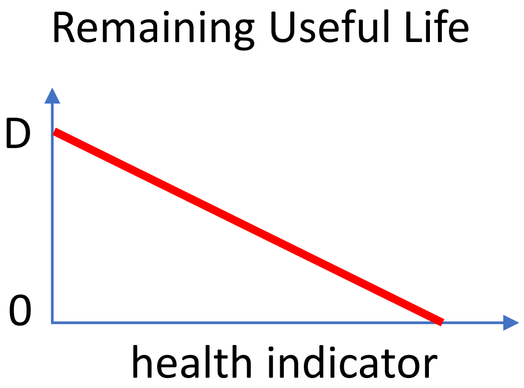
The health monitoring process

- **Monitoring:** is the machine in good condition?
- **Diagnostics:** what/where/how is the fault?
- **Prognostics:** how long can the machine still operate?



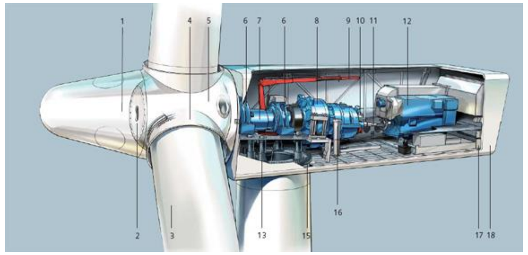




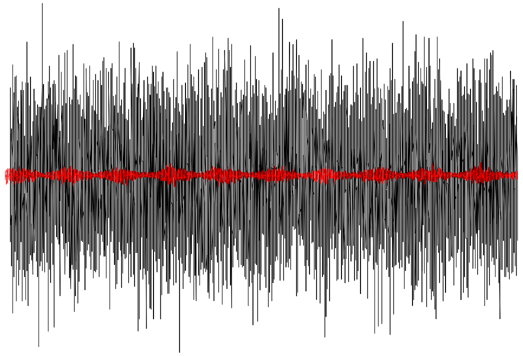


Particularities of rotating machine signals

- Signals produced by the operation of machines, involving the interconnection of many mechanical parts (gears, bearings, joints, cams, etc.)
  - Electrical, acoustical, vibrational, stresses, speeds of rotations, etc.
  - Responses of physical systems to internal excitations



- Properties
  1) Low SNR : superposition of the effects of many sources of excitations
  2) Polymorphic : combination of deterministic and random components
  3) Evolving : nonstationarities wrt different scales
     - Within cycles : evolution of properties inside a rotation (wrt angle of rotation)
     - Cycle-to-cycle : evolution wrt operational variables (e.g. speed)
     - Long-term : evolution wrt environmental variables (e.g. temperature)



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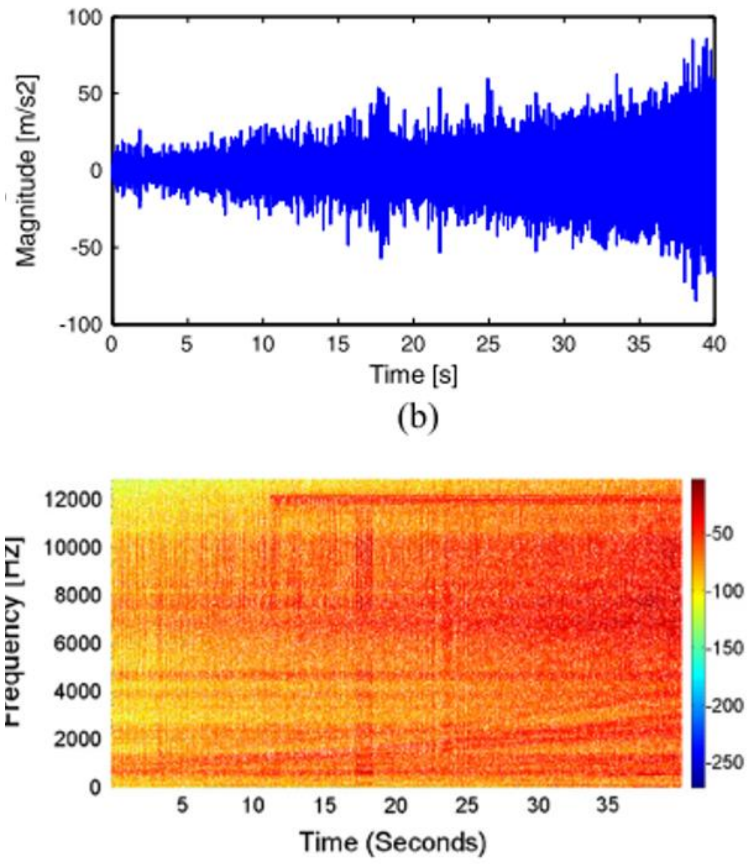

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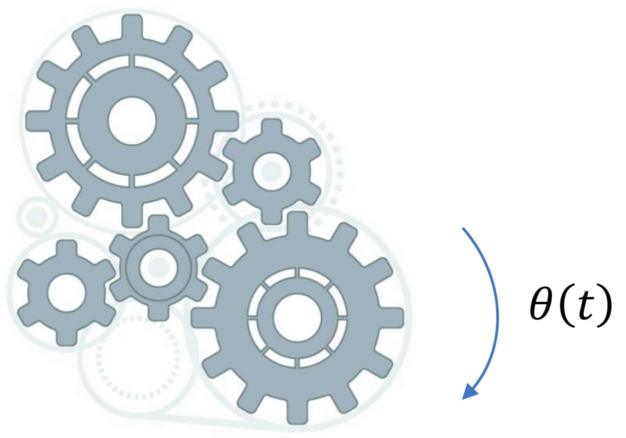
Tentative model

1) Additive model

$$x(t) = p(t) + r(t) + n(t)$$

$p(t)$: deterministic component
$r(t)$: nonstationary random component
$n(t)$: residual (e.g. external noise)

2) Descriptive variable = angle of rotation of the machine $\theta(t)$

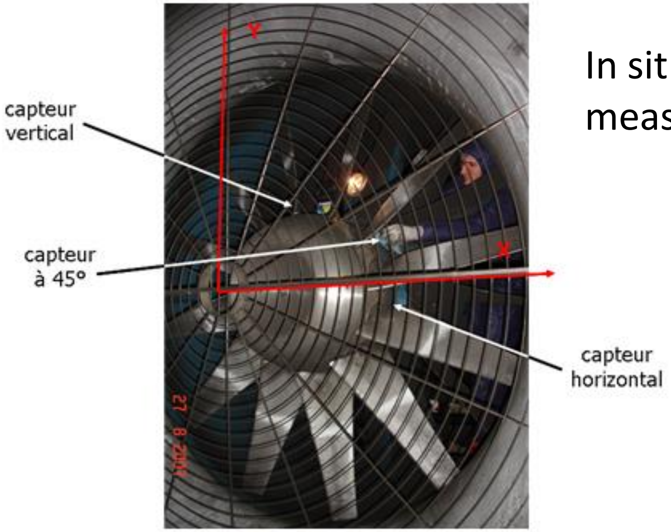


Deterministic part

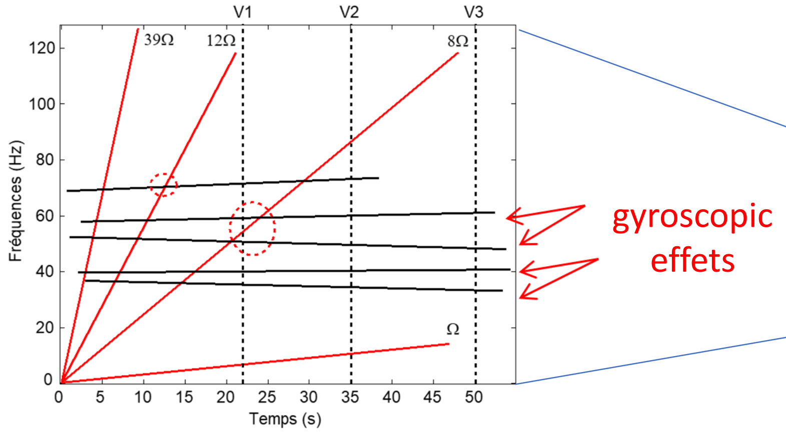
- $p(t) = \sum_k c_k e^{\alpha_k \theta(t)}$
  - c_k = constant under constant rotational speed ($\theta(t) = \Omega t$)
  - $c_k(\dot{\theta})$ under slow speed variations
  - $c_k(\dot{\theta}, \ddot{\theta})$ under fast speed variations (Fadi's presentation)
  - $c_k(\dot{\theta}, \ddot{\theta}, \xi)$ under environmental effects

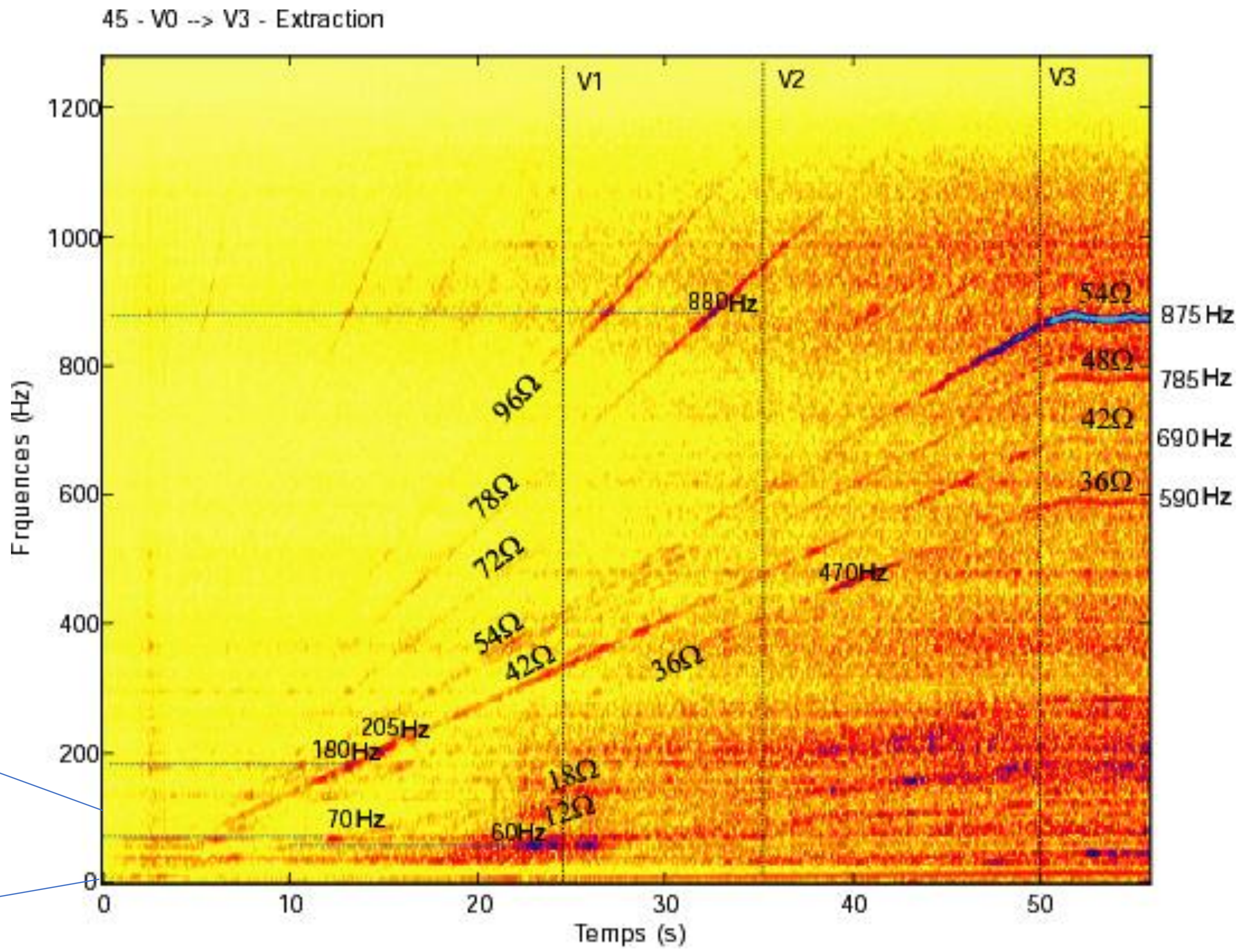
- Estimation of varying Fourier coefficients = order tracking
  - Gabor transform
  - Tracking filters : Vold-Kalman filter

Industrial example : diagnosis of a fan with a craked blade



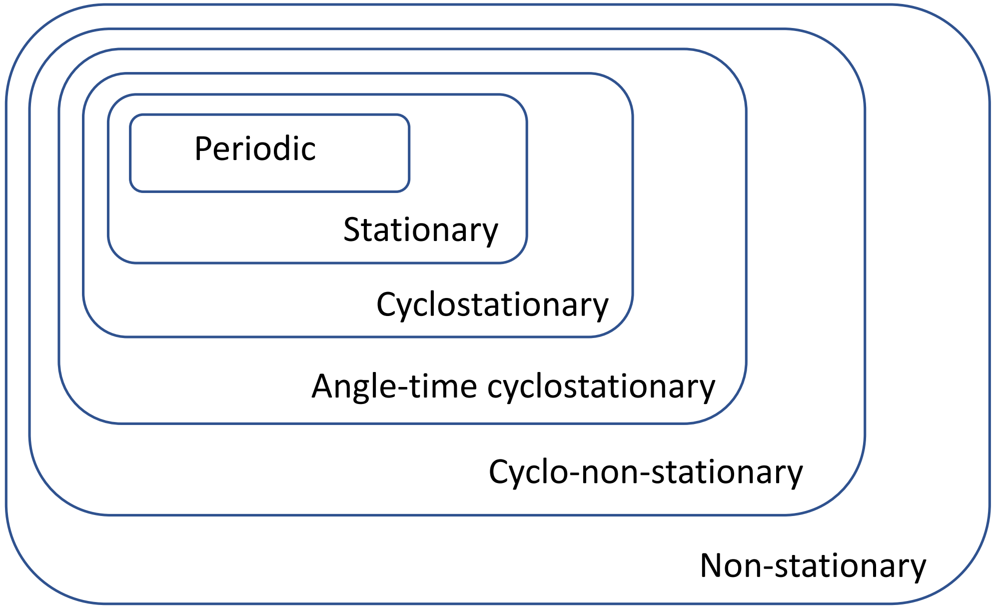
In situ acceleration measurements





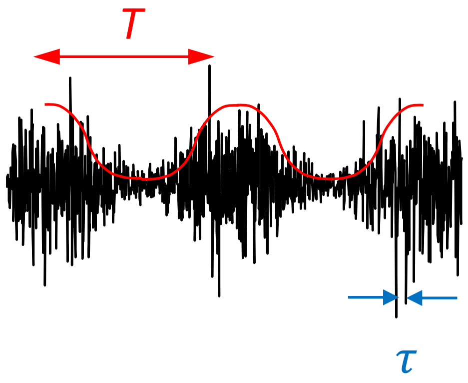
Random part

- $r(t) = \sum_k c_k(t) e^{\alpha_k \theta(t)}$
  - $\{c_k(t)\}$ are cross-dependend random processes
  - time-stationary under nearly constant rotational speed
    - exactly constant speed $(\theta(t) = \Omega t) \Rightarrow$ cyclostationary process
    - slight speed fluctuations $\Rightarrow$ angle-time cyclostationary process
  - $\{c_k(t, \dot{\theta})\}$ under slow speed variations
  - $\{c_k(t, \dot{\theta}, \ddot{\theta})\}$ under fast speed variations
  - $\{c_k(t, \dot{\theta}, \ddot{\theta}, \xi)\}$ under the effect of environemental effect

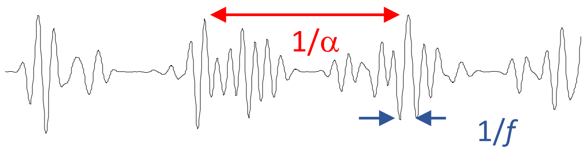


Random part : cyclostationary processes

- $r(t) = \sum_k c_k(t) e^{\alpha_k \Omega t}$
- Second-order properties
  - $R(t,\tau) = \mathcal{E}\{r(t+\tau)r(t)\}$
  - $< R(t,\tau)e^{-\alpha_k \Omega t} > \neq 0$
  - $\alpha_k = k\alpha_1 : \ R(t+T,\tau) = R(t,\tau)$



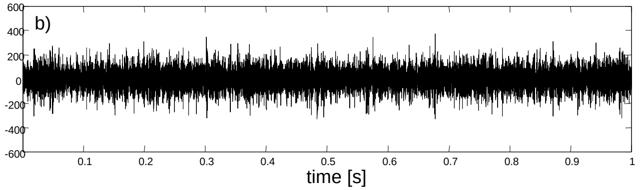
- Spectral correlation (OF-SC)
  - $S(\alpha, f) = \mathcal{F}_{t\to\alpha}\mathcal{F}_{\tau\to f}\{R(t,\tau)\}$

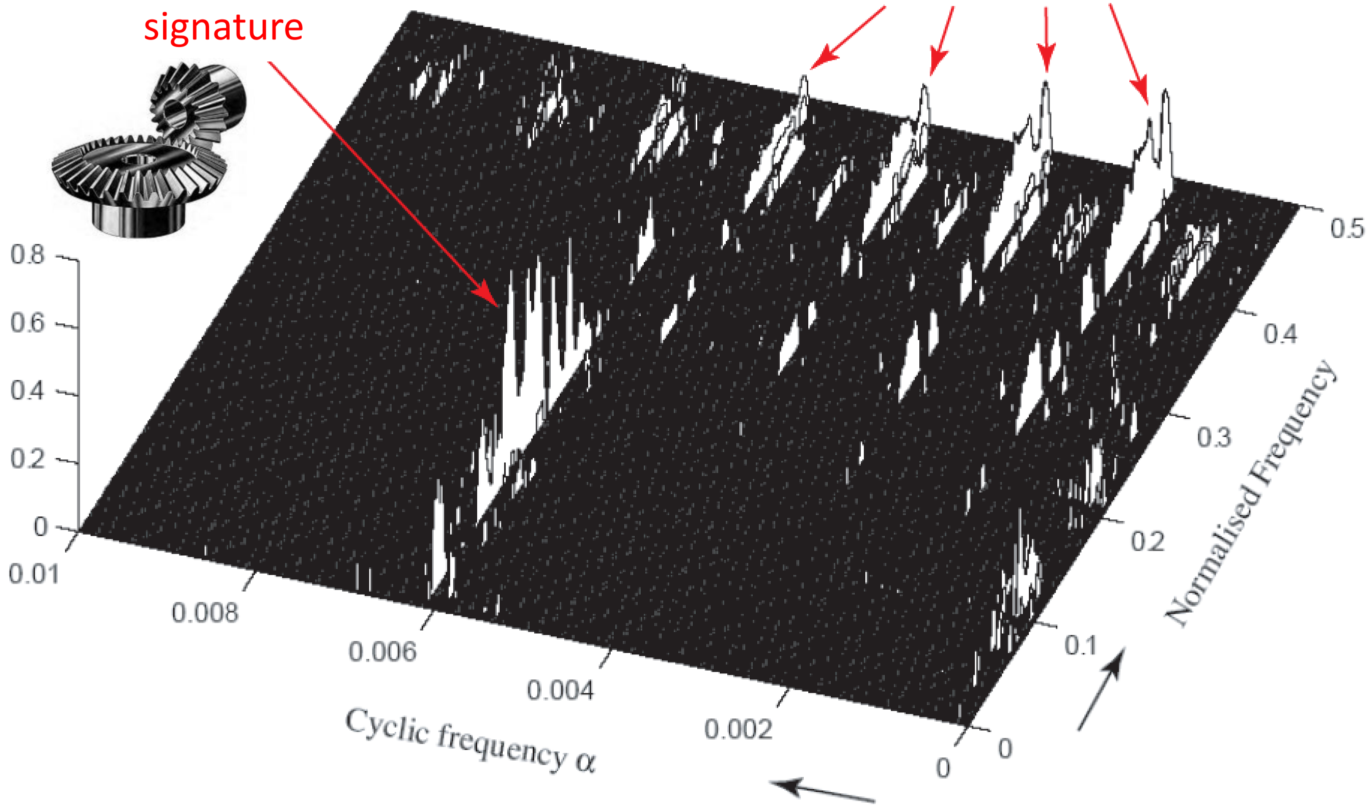


Lab experiment

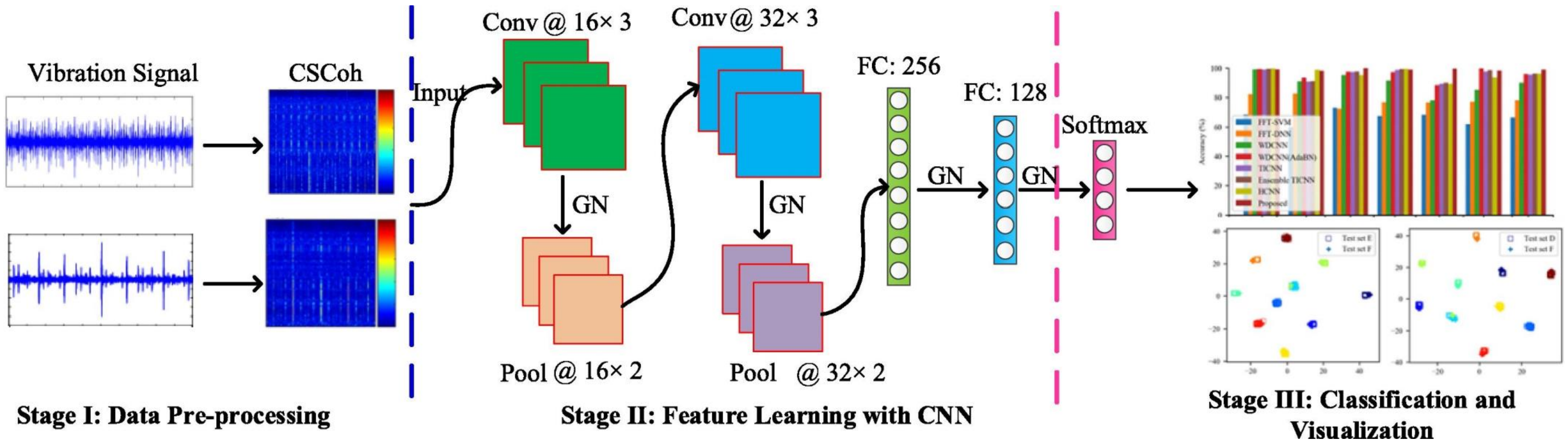
Test-bench: UNSW-Sydney (Prof. B. Randall)

- gear ratio = 1:1, 32 teeth
- bearings Koyo 125
  OR Ø 44.85,
  IR Ø 32.17, 12 ball





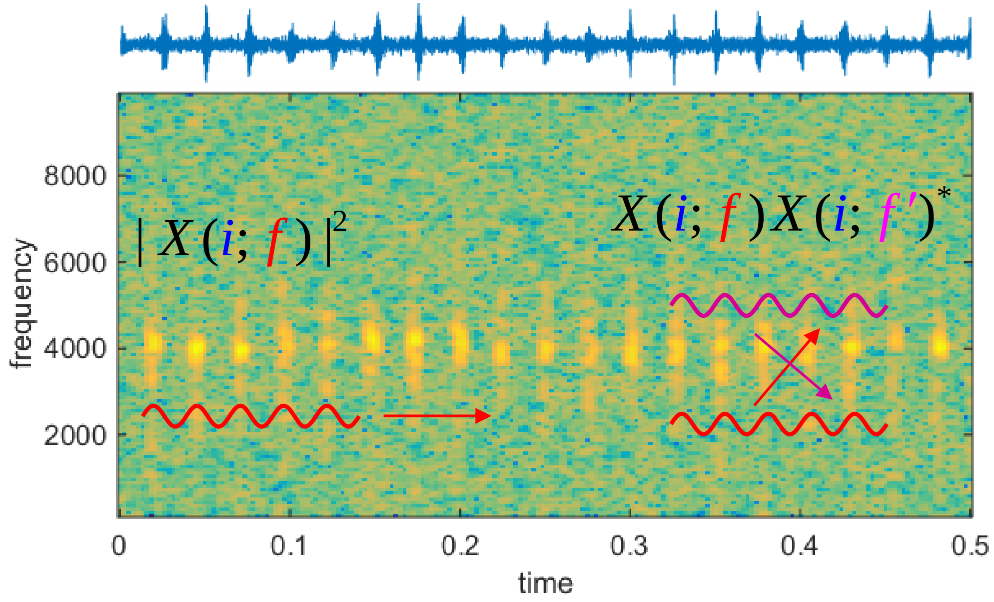
A proxy for CNN inputs



Zhuyun Chen, Alexandre Mauricio, Weihua Li, Konstantinos Gryllias, A deep learning method for bearing fault diagnosis based on Cyclic Spectral Coherence and Convolutional Neural Networks, *Mechanical Systems and Signal Processing*, 140, 2020

Random part : cyclostationary processes

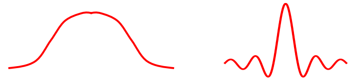
- Fast estimator
  - A CS signal has its energy flows periodically in the short-time Fourier transform (STFT)
    - through frequency channels of the STFT
    - across frequency channels of the STFT



Computational gain

$$\frac{C_{ACP}}{C_{Fast}} \sim \frac{L}{2R}$$

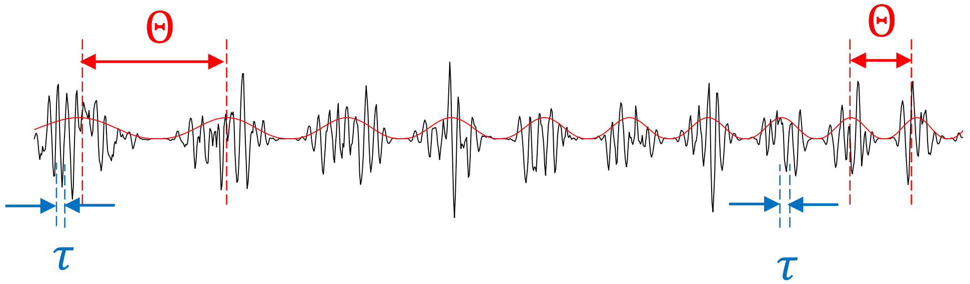
$$S_x(\alpha, f) = DFT_{i\to\alpha}\left\{X_{w_1}(i; f)X_{w_2}(i; f)^*\right\}$$



J. Antoni, G. Xin, Nacer Hamzaoui, Fast computation of the spectral correlation, *Mechanical Systems and Signal Processing*, 92, 2017, 248-277

Random part : AT-cyclostationary processes

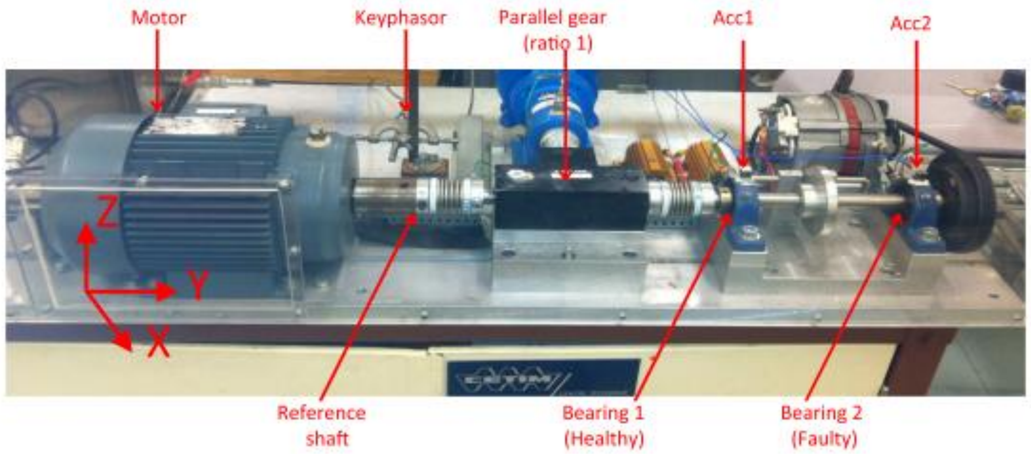
- Second-order angle-time cyclostationary processes (AT-CS2)
  - $R(\theta,\tau) = \mathcal{E}\{r(t(\theta)+\tau)r(t(\theta))\}$
  - $< R(\theta,\tau)e^{-\alpha_k\theta} > \neq 0$
  - $\alpha_k = k\alpha_1 : R(\theta+\Theta,\tau) \simeq R(\theta,\tau),\ |\tau|\ddot{\theta} \ll 1$



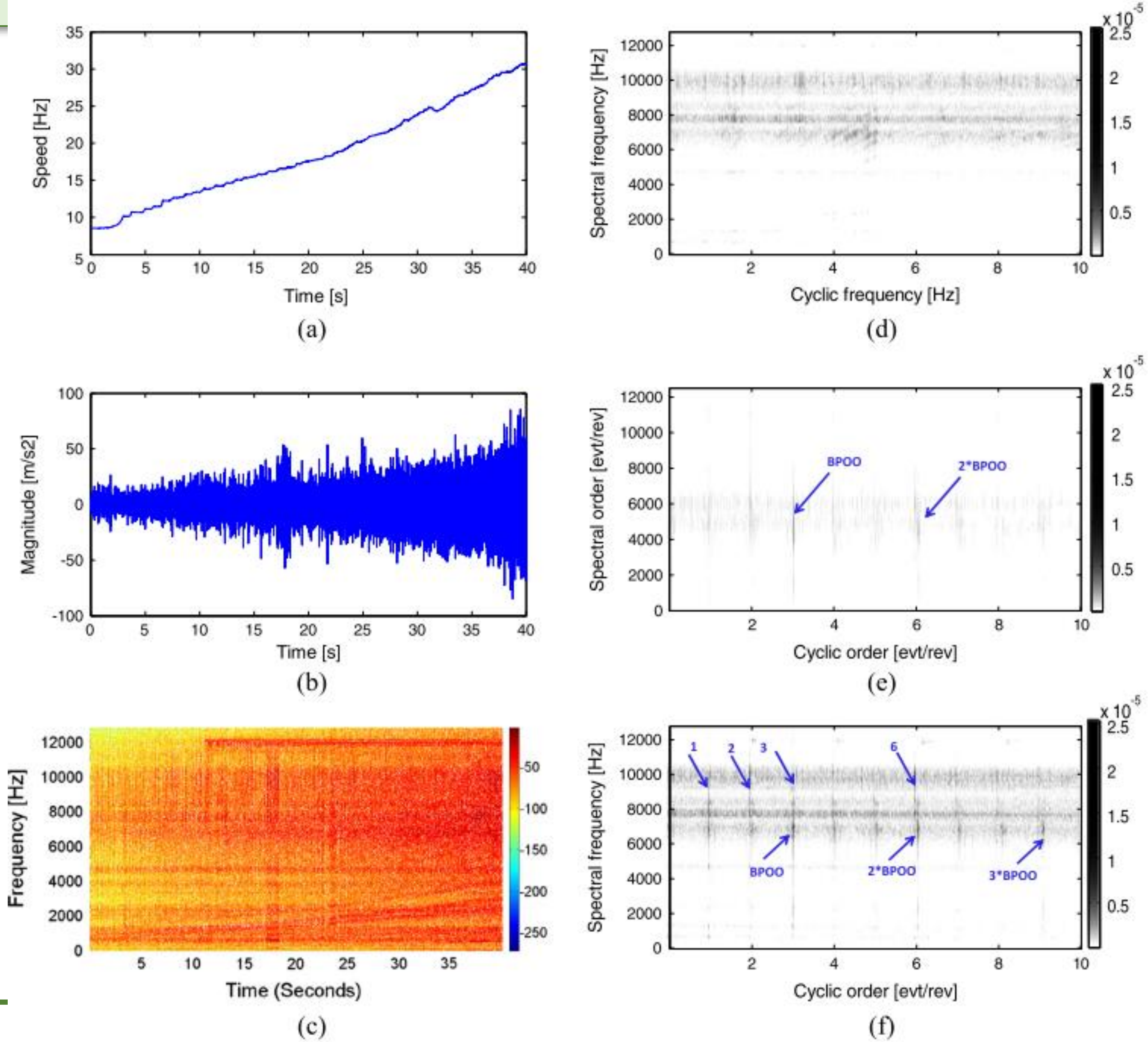
- Order-frequency spectral correlation (OF-SC)
  - $S(\alpha,f) = \mathcal{F}_{\theta\rightarrow\alpha}\mathcal{F}_{\tau\rightarrow f}\{R(\theta,\tau)\}$

Lab example

- Detection of a rolling element bearing fault under variable speed
- Comparison of approaches in
  - time domain $\Rightarrow$ frequency-frequency spectral correlation
  - angle domain $\Rightarrow$ order-order spectral correlation
  - angle-time domain $\Rightarrow$ order-frequency spectral correlation

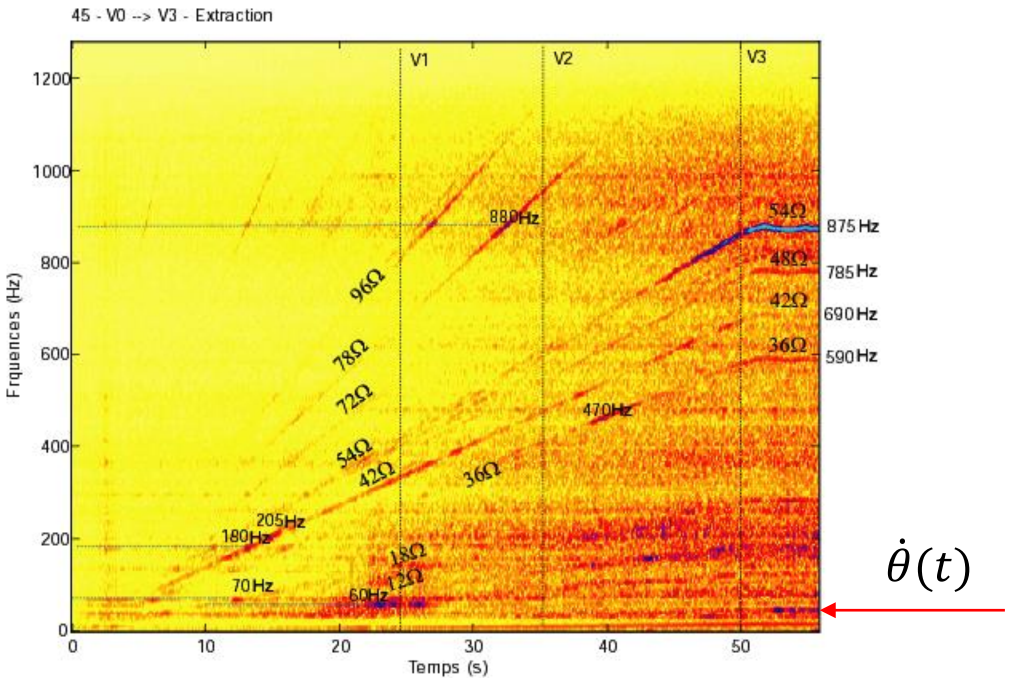


Dany Abboud, Jerome Antoni, Mario Eltabach, Sophie Sieg-Zieba, Angle/time cyclostationarity for the analysis of rolling element bearing vibrations, Measurement 75 (2015) 29–39



Measurement of instantaneous angle of rotation $\theta(t)$

- Direct measurement
- Estimation of $\dot{\theta}(t)$ from signal itself
  - From deterministic part
    - Multi-order probabilistic approach (MOPA)
    - Iterated Adaptive Approach
    - Synchrosqueezing transforms
  - From random part



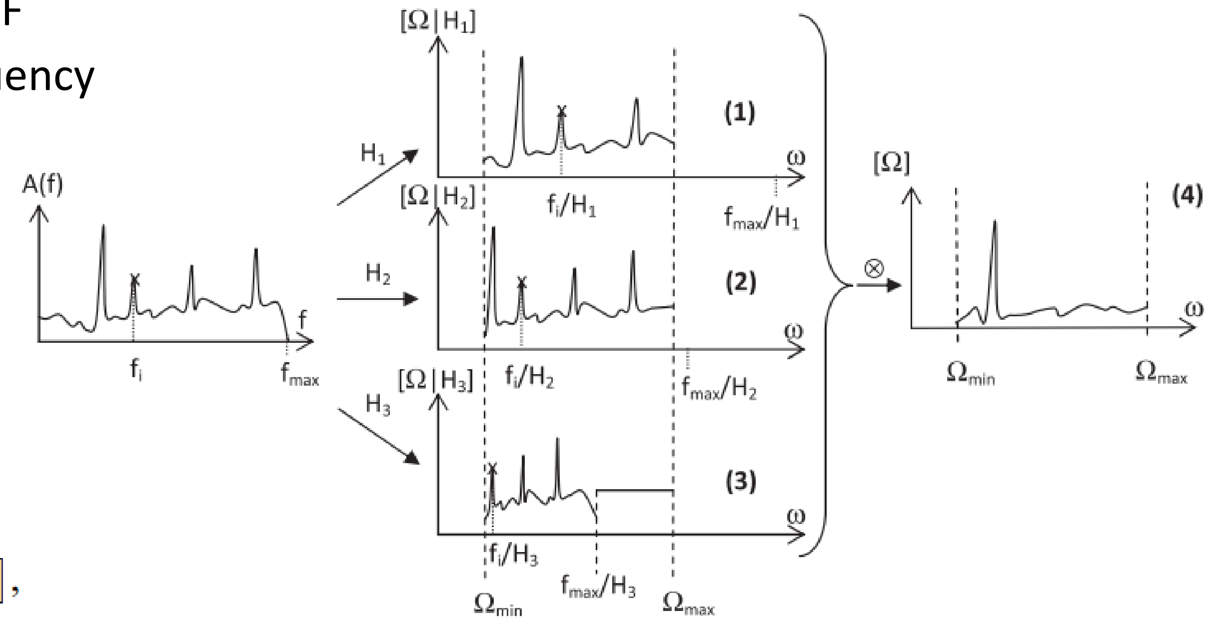
From deterministic part

- Multi-order probabilistic approach (MOPA)
  - retrieve instantaneous frequency of harmonically related components
  - see each spectrum of the normalized STFT as a PDF
  - calculate the posterior PDF of instantaneous frequency

$$[\Omega|H_i] = \frac{1}{\xi_i} A(H_i\omega) \quad \text{for } \Omega_{min} < \omega < \Omega_{max}$$

$$[\Omega|H_i] = 0 \quad \text{for } \omega < \Omega_{min} \mid \omega > \Omega_{max}$$

$$[\Omega] \propto \prod_{i=1}^{n} [\Omega|H_i],$$



  - assume continuity wrt time

$$[\Omega_j]_{j+k} = \int_{\Omega_{min}}^{\Omega_{max}} [\Omega_j|\Omega_{j+k}][\Omega_{j+k}] \, d\omega \propto \exp\left(\frac{-\omega^2}{2\sigma_k^2}\right) * [\Omega_{j+k}],$$

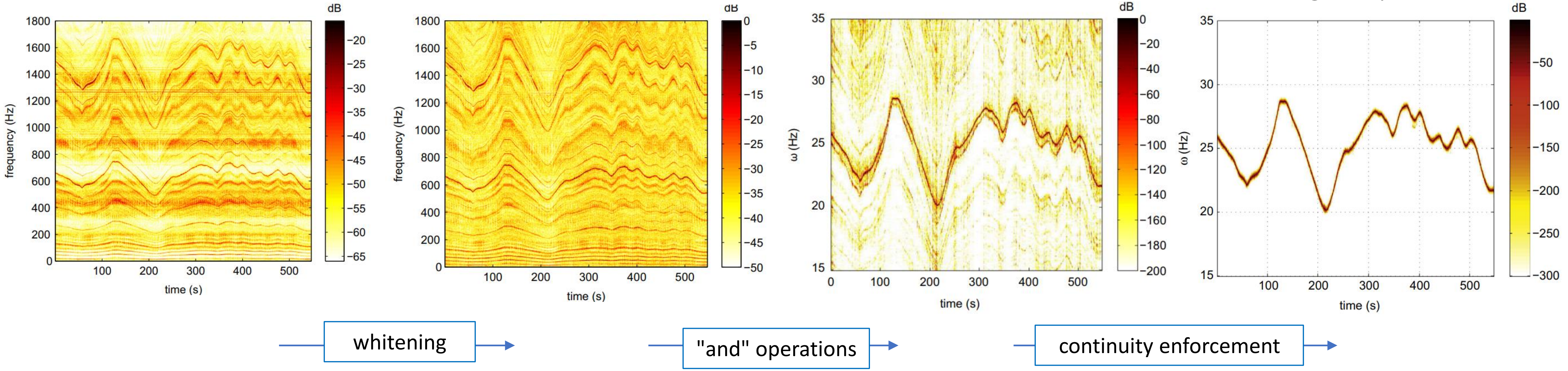
$$[\Omega_j]_s \propto \prod_{k=-K}^{K} [\Omega_j]_{j+k}$$

Quentin Leclère, Hugo André, Jérôme Antoni, A multi-order probabilistic approach for Instantaneous Angular Speed tracking debriefing of the CMMNO′14 diagnosis contest, *Mechanical Systems and Signal Processing*, 81, 2016, 375-386

Industrial application

- Windturbine monitored by Engie Green

Pdf of instantaneous angular speed



Adaptive TF representation

- Iterative Adaptive Approach
  - Model

$$\begin{cases} \boldsymbol{y}_N = \boldsymbol{F}_{N,K}\boldsymbol{\alpha}_K + \boldsymbol{e}_N \\ \boldsymbol{F}_{N,K} \triangleq [\boldsymbol{f}_N(\omega_0), \boldsymbol{f}_N(\omega_1), \ldots, \boldsymbol{f}_N(\omega_{K-1})] \end{cases}$$

  - Least-square solution

$$||\boldsymbol{y}_N - \boldsymbol{f}_N(\omega_k)\alpha_k||^2_{\boldsymbol{Q}_N^{-1}(\omega_k)}, k = 0, 1, \ldots, K-1$$

$$\boldsymbol{Q}_N(\omega_k) = \boldsymbol{R}_N - p_k \boldsymbol{f}_N(\omega_k)\boldsymbol{f}_N^H(\omega_k)$$

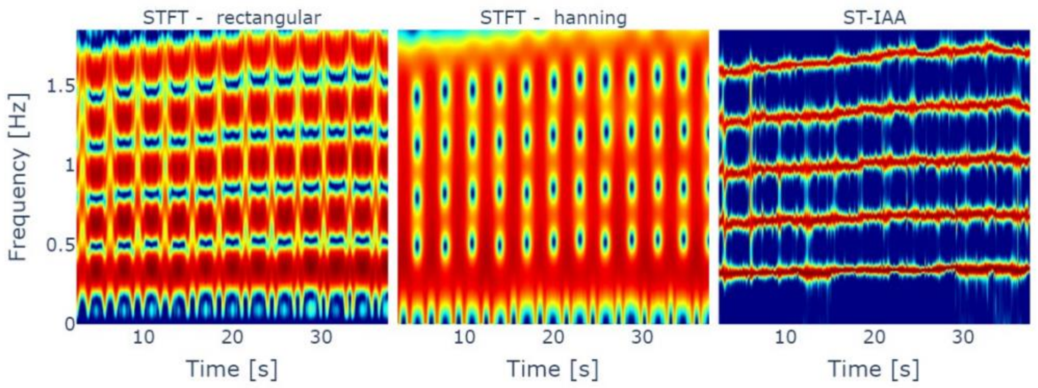
$$\boldsymbol{R}_N = \boldsymbol{F}_{N,K}\boldsymbol{P}_K\boldsymbol{F}_{N,K}^H$$

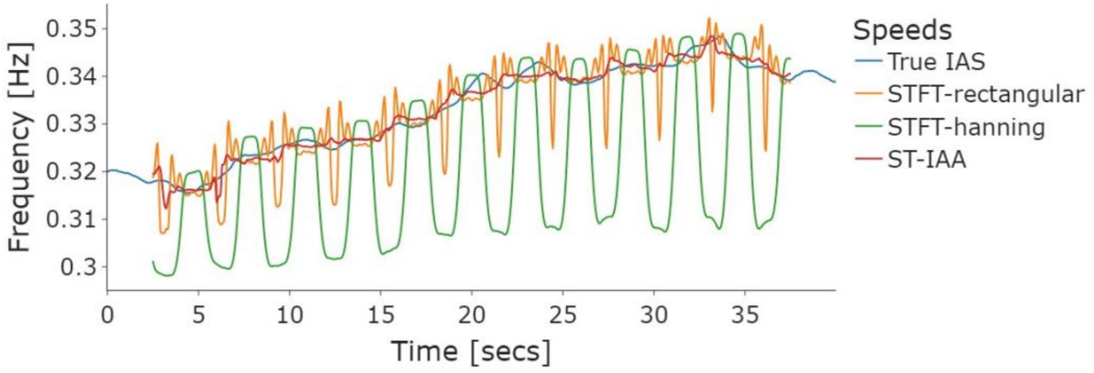
$$\alpha_k^{IAA} = \frac{\boldsymbol{f}_N^H(\omega_k)\boldsymbol{Q}_N^{-1}(\omega_k)\boldsymbol{y}_N}{\boldsymbol{f}_N^H(\omega_k)\boldsymbol{Q}_N^{-1}(\omega_k)\boldsymbol{f}_N(\omega_k)}, \quad k = 0, 1, \ldots, K-1.$$

C. Peeters, A. Jakobsson, J. Antoni, J. Helsen, The short-time Iterative Adaptive Approach: an effective analysis tool for complex non-stationary vibrations, *ISMA-USD Noise and Vibration Engineering Conference*, Sept. 12-14, 2022

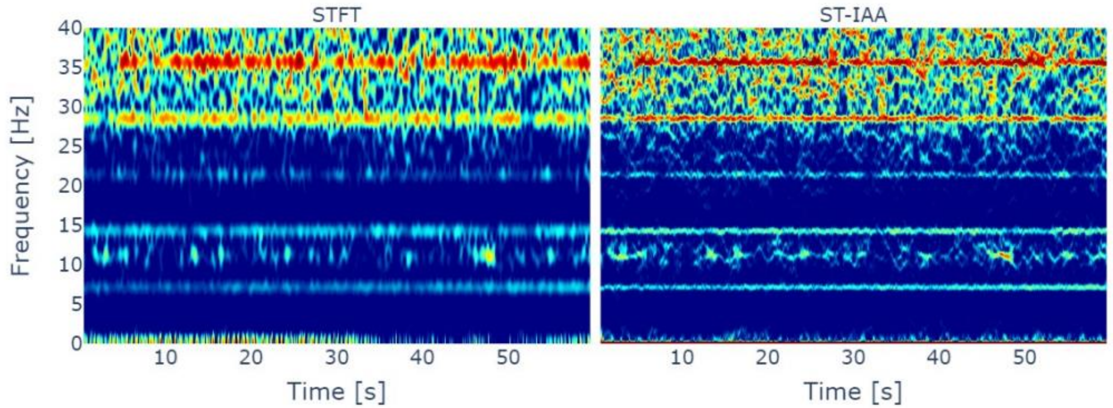
Adaptive TF representation

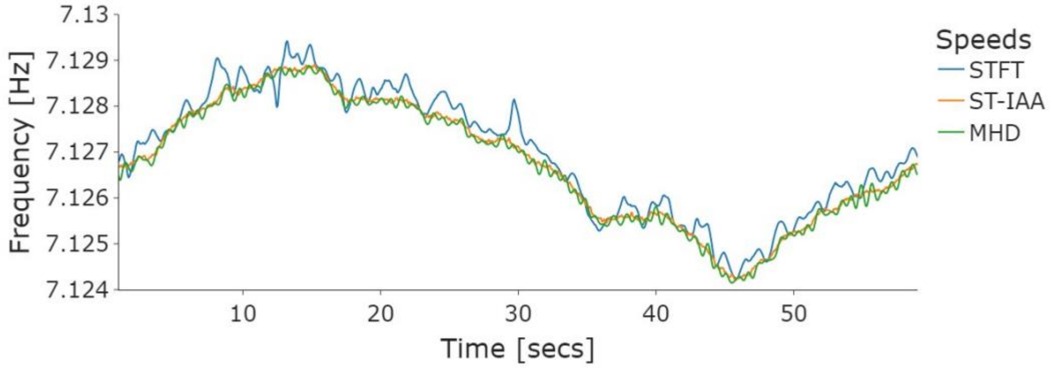
Synthetic signal





Gearbox vibration in large industrial multi-megawatt pump





Bottlenecks

- Time-frequency analysis of random signals
  - how to design estimators under nonstationary regime ?
- Estimation of instantaneous angular speed in random signals (time-warping)
  - e.g. frequency-modulated noise
- Interactions between varying deterministic components and nonstationary random signals
  - deterministic $\Rightarrow$ random
  - random $\Rightarrow$ deterministic ?