A MULTI-ORDER SYNCHRO-SQUEEZING TRANSFORM APPROACH FOR INSTANTANEOUS ANGULAR SPEED ESTIMATION

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Introduction

- In the context of condition monitoring, faults are mostly represented by its frequencies characteristics with respect to the reference shaft speed

- In non stationary conditions, estimating the Instantaneous Angular Speed (IAS) of rotating machines with high precision is mandatory.

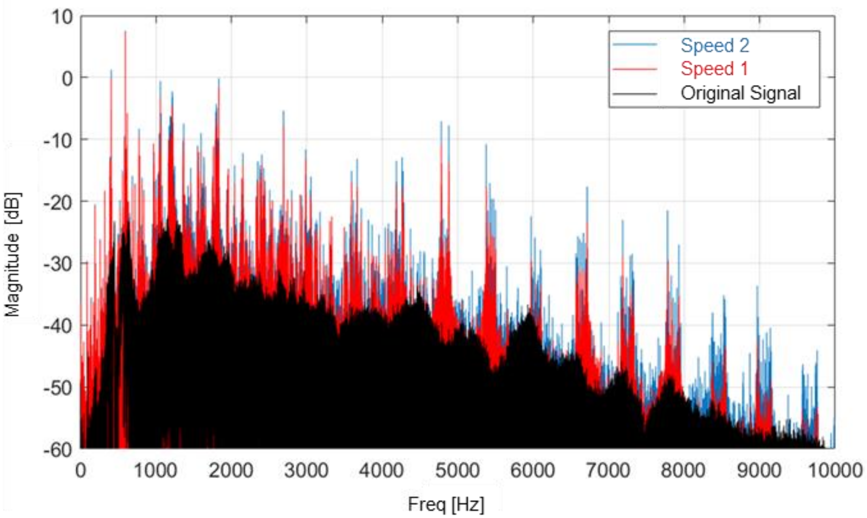
- While direct speed measurement via angle encoders offers accuracy, cost-effective vibration sensors provide an alternative, especially when standard encoders are impractical.

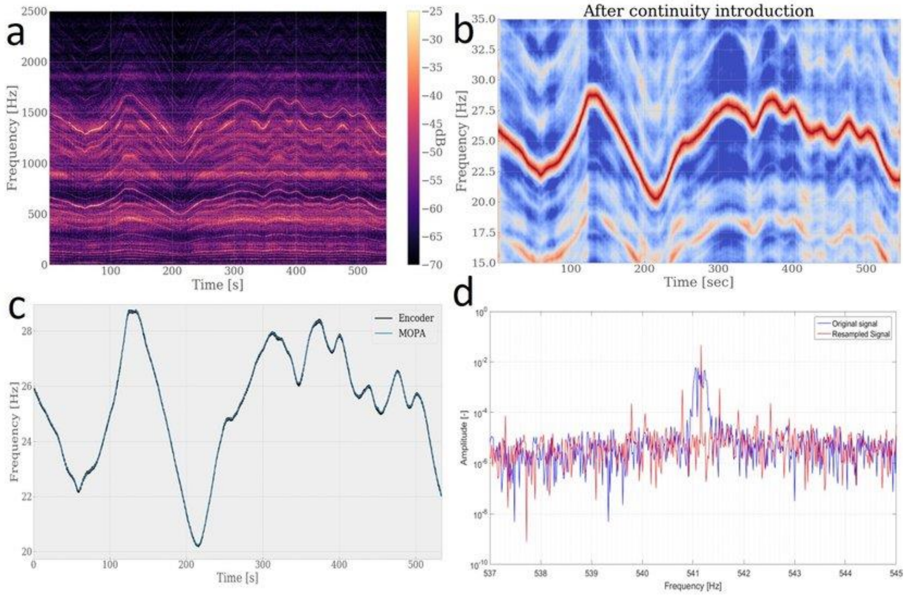
- Yet, utilizing vibration signals for IAS estimation presents challenges like low signal-to-noise ratios (SNR), harmonic interference, fading harmonics, and colored noise.

- How can we extract information from Time-Frequency Representations (TFR)? Is it sufficient to focus on one frequency band of the reference shaft? If not which harmonics should we choose? What if the noise distribution polluting the signal is unknown?

Importance of better speed estimation

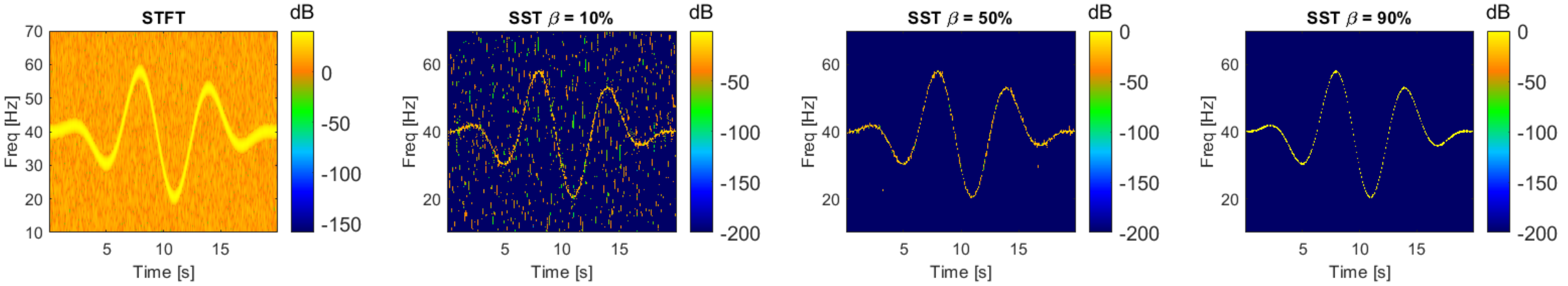
- Better speed estimation reduces the energy leakage
- The capacity of correctly estimating the high fluctuation of the speed will manifest high frequency spectrum components





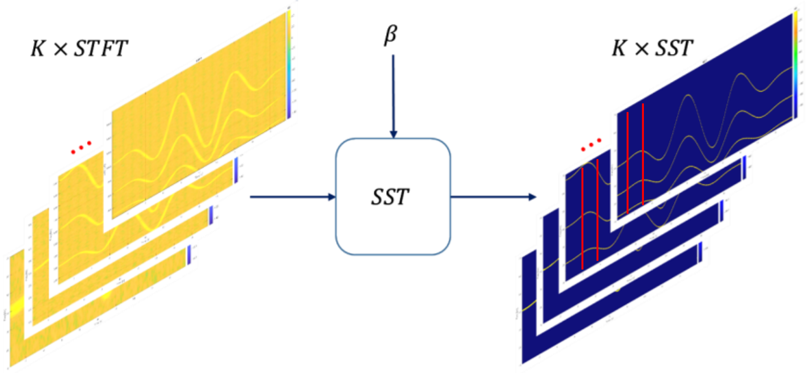
Short Time Fourier Transform (STFT) & Synchro-squeezing Transform (SST)

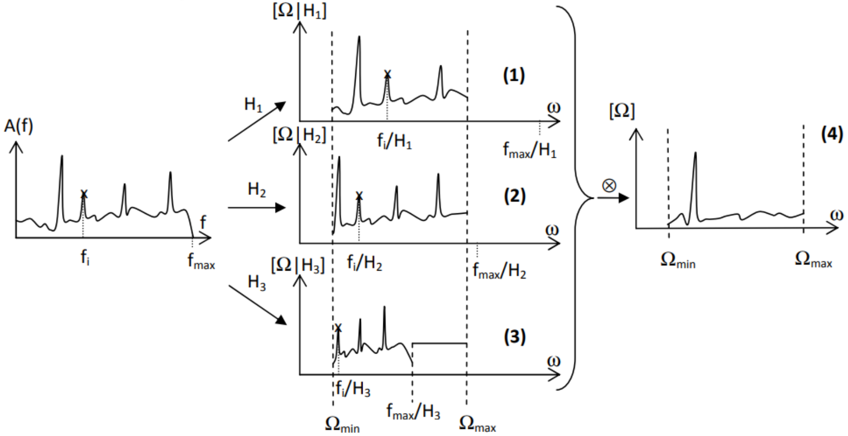
- STFT : $S_x^g(t,f) = \int_{\mathbb{R}} x(\tau) g(\tau - t) e^{-2\pi i f(\tau - t)} d\tau$
- SST : $\tilde{T}_x^\gamma(t,f) = \int_{|S_x^g(t,f)|>\gamma} S_x^g(t,f)\delta\big(f - \hat{\omega}_x(t,f)\big) df$
- Threshold : $\gamma(\tau) = \beta \times \sup_{f \in [\Omega_{min}\ \Omega_{max}]} \left|S_x^g(\tau,f)\right|$



Multi Probability Density Functions

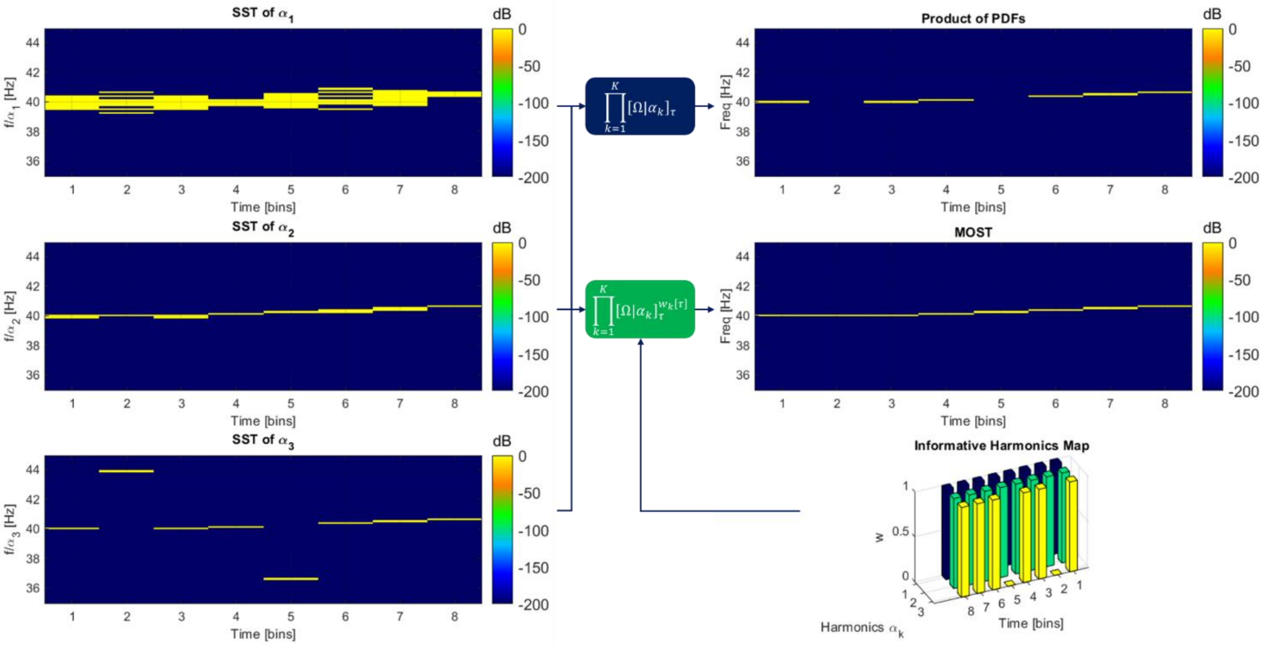
- Multi Order Probabilistic Approach (MOPA) based on multi PDFs to extract further information
- When the synchro-squeezed representation of a signal exhibits high amplitude at a specific frequency f, it implies a higher probability that the shaft frequency is equal to $\frac{f}{\alpha_k}$
- The 'most likely' trend will be the result of stacking multiple PDFs of the considered orders (from the kinematics)
- At a certain time bin τ, if the newly harmonic considered is noisy, the result is hindered instead of extracting information



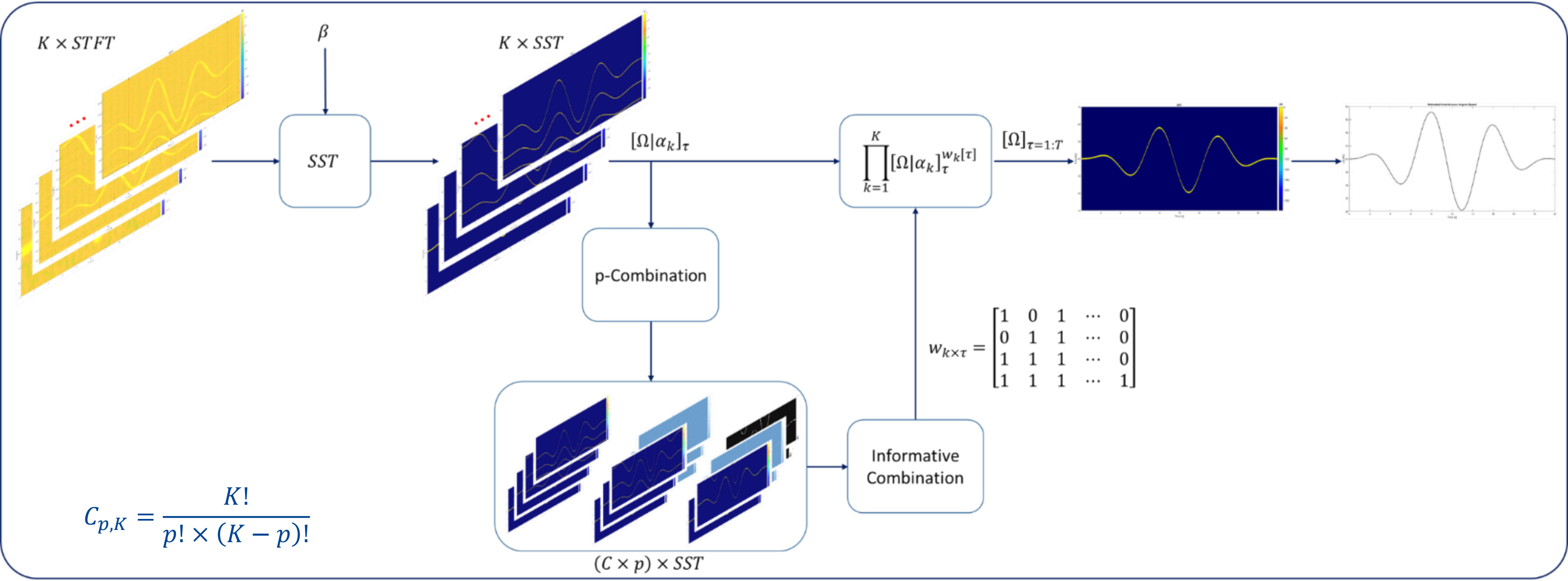


Methodology

- Thanks to the normalized threshold, as the PDF multiplication progresses, the interaction between informative and noisy harmonics becomes manifest
- The evaluation of informativeness is defined by the sum of the resulted product
- This allows to allocate binary weights for each considered harmonic such that the Informative Harmonics Map shows which harmonics hold relevant information from each combination of harmonics



Multi Order Synchro-squeezing Transform (MOST)



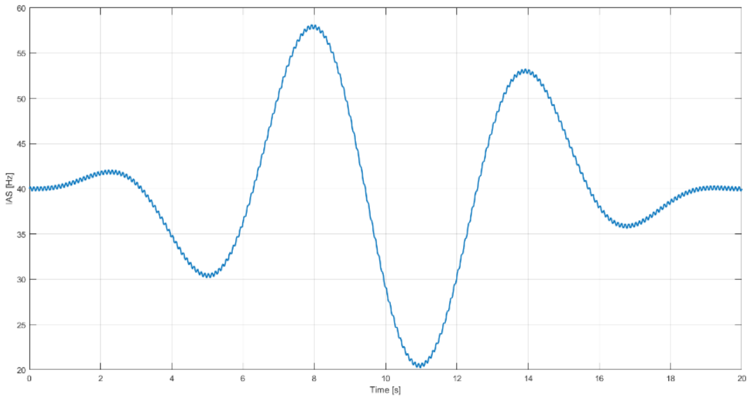
Results – Simulation

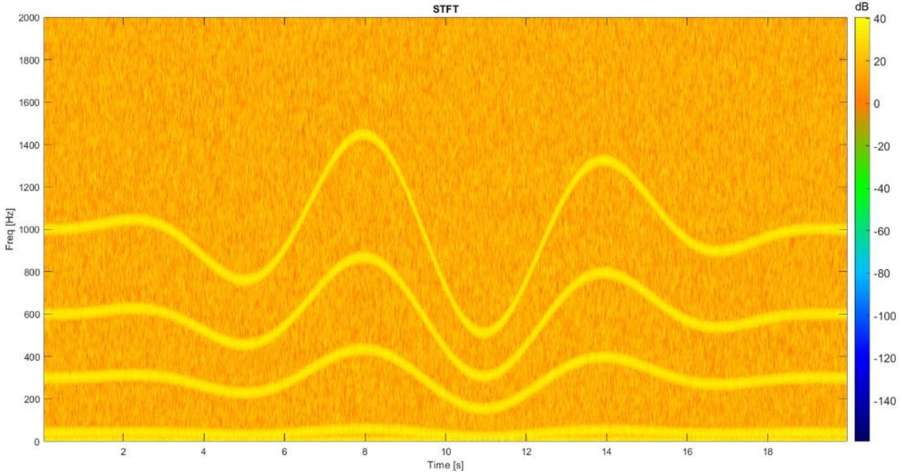
- Simulated Signal Model :

$$x[n] = \sum_{k=1}^{K} A_k[n] \sin(\alpha_k \times \theta[n] + \phi_k[n]) + \nu[n]$$

$$\nu \sim \mathcal{N}\left(0, \sigma_{\nu_k}^2\right) \;\&\; \phi_k \sim \mathcal{N}\left(0, \sigma_{\phi_k}^2\right)$$

- First Harmonic noisier than the other three
- Last three harmonics interfere between each other
- Comparing methods : PD, 4-SST, MOPA, MOST





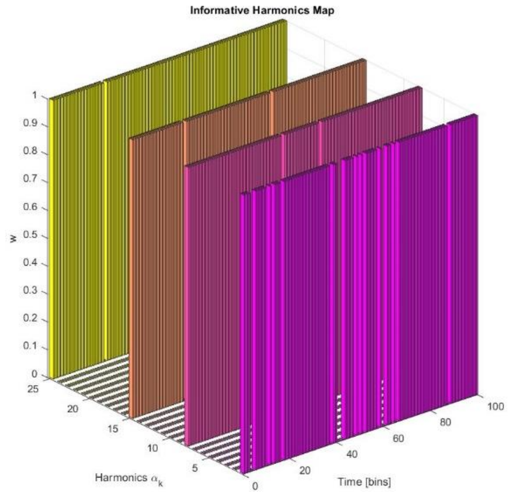
Results – Simulation

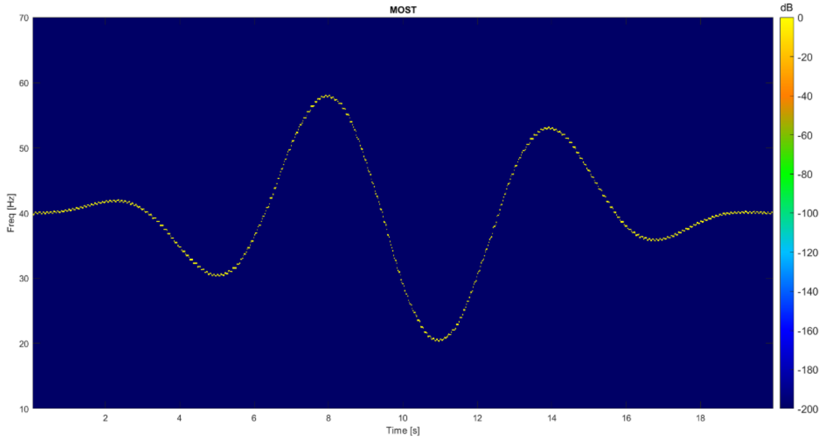
Table 1: Input Parameters for Different Methods

Method Name	PD	4-SST	MOPA	MOST
Parameters	$\omega_{init} = 40Hz$ $Bw = 5Hz$ $N_w = 400$	$\omega_{min} = 10Hz$ $\omega_{max} = 70Hz$ α_k $N_w = 400$ $N_{overlap} = 80\%$ $N_{FFT} = 8000$ $\beta = 50\%$	$\omega_{min} = 10Hz$ $\omega_{max} = 70Hz$ α_k $N_w = 400$ $N_{overlap} = 80\%$ $N_{FFT} = 8000$ $K_w = 10$ $\gamma = 0.5Hz/s$	$\omega_{min} = 10Hz$ $\omega_{max} = 70Hz$ α_k $N_w = 400$ $N_{overlap} = 80\%$ $N_{FFT} = 8000$ $\beta = 50\%$

- Less weights were allocated for the first harmonic which fits the simulated example since it was the noisier

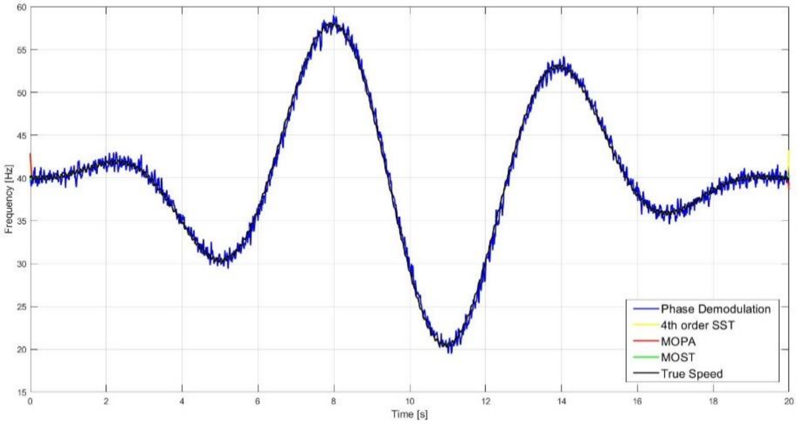
- Convergence to the IAS Map without any further continuity/cleaning

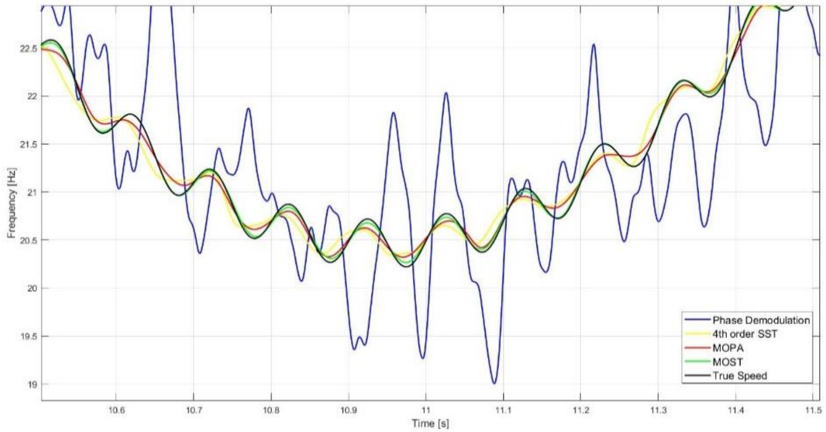


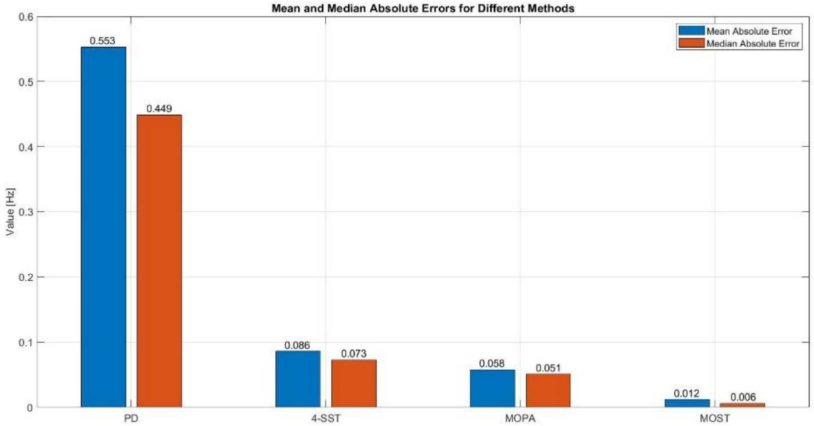


Results – Simulation

- Close convergence of MOST's trend to the actual speed with respect to other methods
- Outperformance of MOST after evaluating the mean and median absolute errors

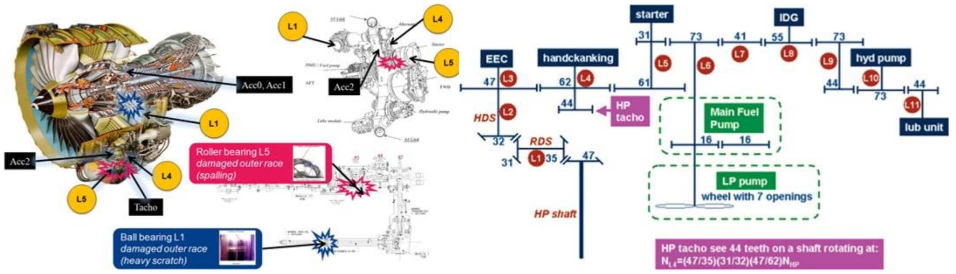






Results – Safran CFM56

- A whole set of kinematics is available to evaluate
- Choice of orders like IPD was made with respect to the resulting informative harmonics map



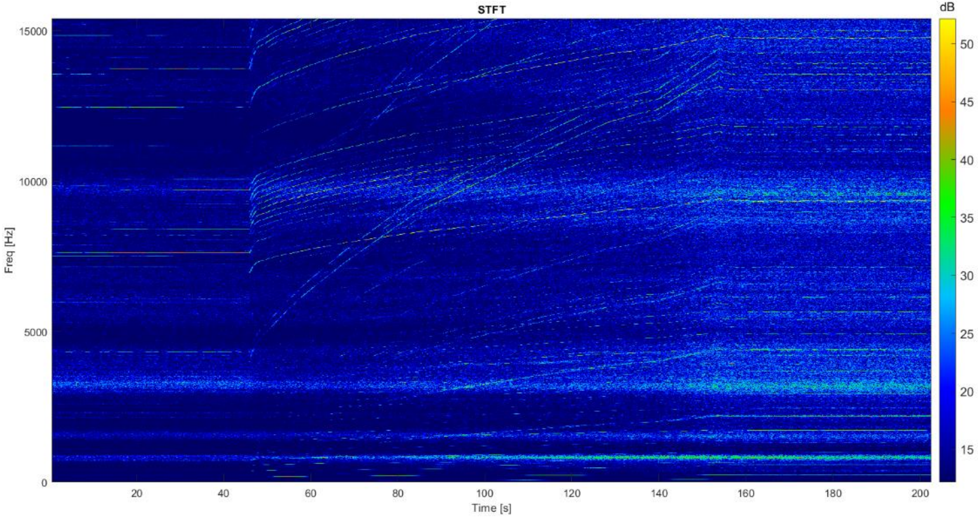


Table 2: Input Parameters for Different Methods

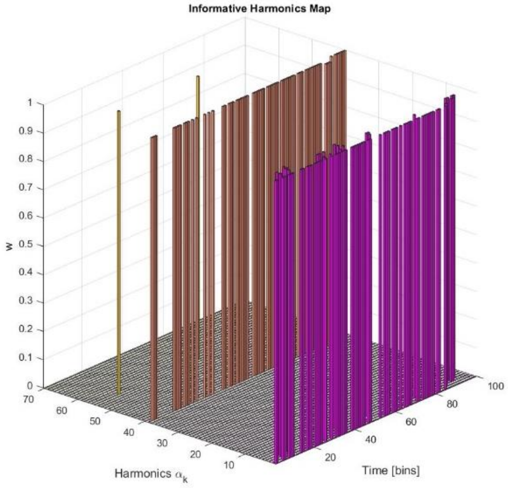
Method Name	PD	IPD	TKEO	MTVKF	MOPA	MOST
Parameters	$\omega_{init} = 6960Hz$ $Bw = 100Hz$ $N_w = 2^{14}$	$\omega_{init} = 6960Hz$ $Bw = 100Hz$ $N_w = 2^{14}$ $\{H\} = \{1.342, 38, 75\}$	$\omega_{init} = 6960Hz$ $Bw = 100Hz$ $N_w = 2^{14}$	$\omega_{init} = 6960Hz$ $Bw_{max} = 50Hz$ $N_w = 2^{14}$ $N_{FFT} = 2^{14}$ $N_{overlap} = 90\%$ $N_p = 1$ $N_m = 5$ $Bw_{VKF} = 4Hz$ $N_{VKF} = 2$	$\omega_{min} = 175Hz$ $\omega_{max} = 230Hz$ $\{\alpha\} = \{1, 1.342, 2, 2.684, 38, 58\}$ $N_w = 2^{14}$ $N_{FFT} = 2^{14}$ $N_{overlap} = 90\%$ $K_w = 20$ $\gamma = 0.4Hz/s$	$\omega_{min} = 175Hz$ $\omega_{max} = 230Hz$ $\{\alpha\} = \{1, 1.342, 2, 2.684, 38, 58\}$ $N_w = 2^{14}$ $N_{FFT} = 2^{14}$ $N_{overlap} = 90\%$ $\beta = 50\%$

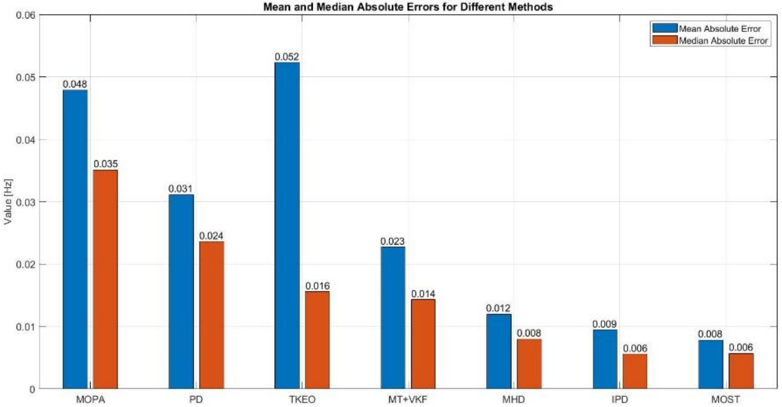
Results – Safran CFM56

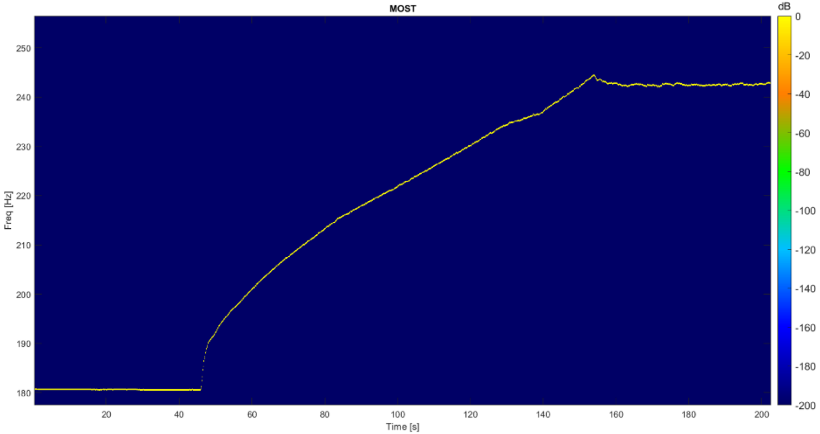
- Weights distribution concentrated around orders 1.342 and 38

- Convergence to the IAS Map without any further continuity/cleaning

- Outperformance of MOST after evaluating the mean and median absolute errors







Results – Wind Turbine

- Highly complex wind turbine signal
- Many interferences between harmonics

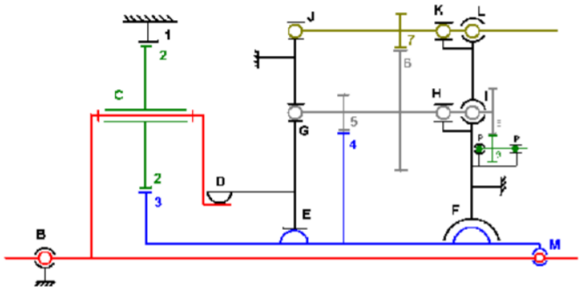
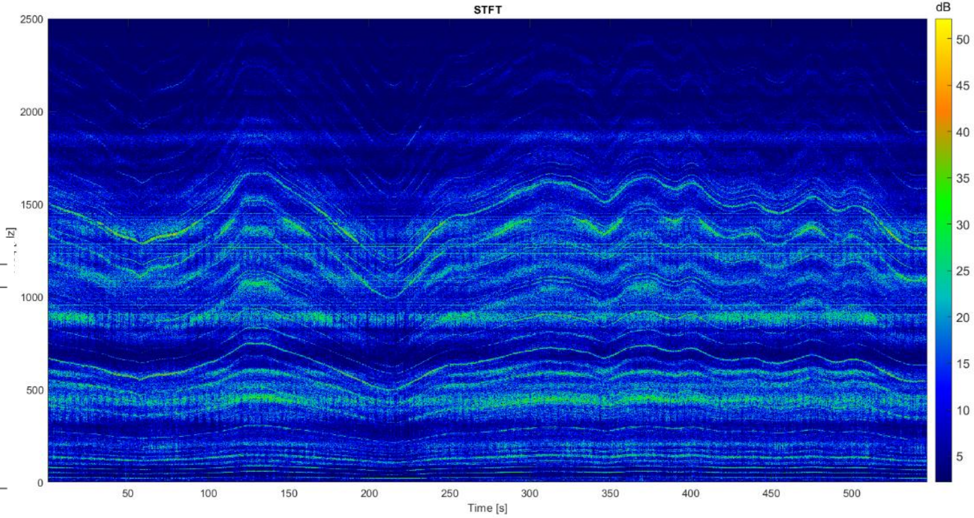


Table 3: Fundamental orders related to high-speed shaft

Gear Pair	Order Value
1	1
2/3, 1/2	1.025459229
4/5	5.316666667
6/7	29
8/9	15.225
10/11	6.619565217

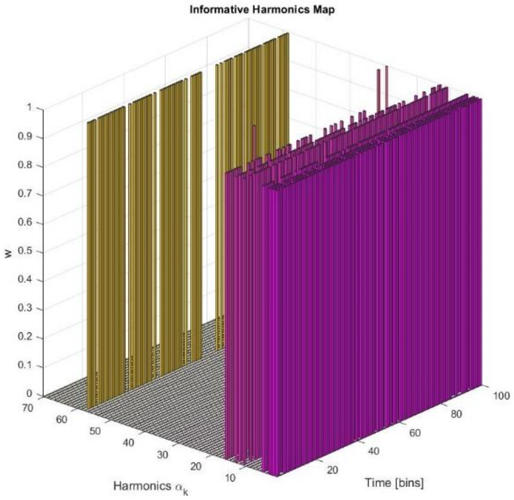
Table 4: Input Parameters for Different Methods

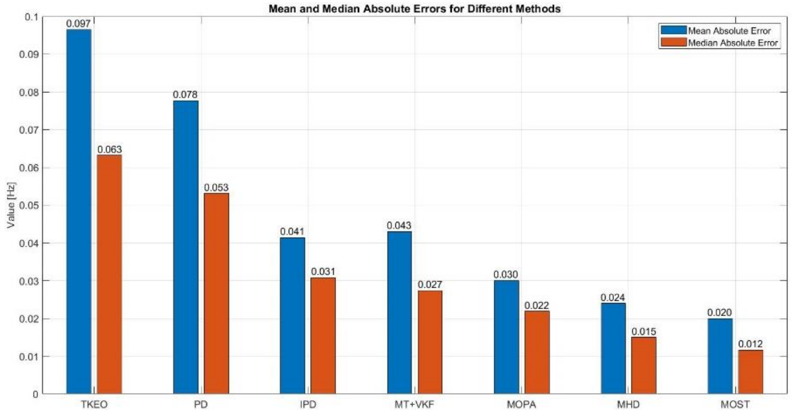
Method Name	PD	IPD	TKEO	MTVKF	MOPA	MOST
Parameters	$\omega_{init} = 53Hz$ $Bw = 8Hz$ $N_w = 50000$	$\omega_{init} = 53Hz$ $Bw = 8Hz$ $N_w = 50000$ $\{\alpha\} = \{2, 10.62\}$	$\omega_{init} = 53Hz$ $Bw = 8Hz$ $N_w = 50000$	$\omega_{init} = 75Hz$ $Bw_{max} = 2Hz$ $N_w = 5000$ $N_{FFT} = 10^4$ $N_{overlap} = 95\%$ $N_p = 1$ $N_m = 5$ $Bw_{VKF} = 4Hz$ $N_{VKF} = 2$	$\omega_{min} = 15Hz$ $\omega_{max} = 35Hz$ $\{\alpha\}$ $N_w = 5000$ $N_{FFT} = 10^4$ $N_{overlap} = 95\%$ $K_w = 20$ $\gamma = 0.4Hz/s$	$\omega_{min} = 15Hz$ $\omega_{max} = 35Hz$ $\{\alpha\}$ $N_w = 5000$ $N_{FFT} = 10^4$ $N_{overlap} = 95\%$ $\beta = 50\%$

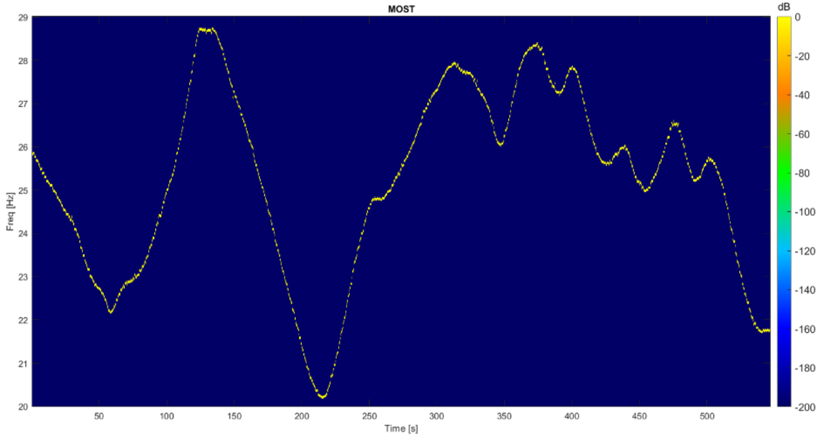


Results – Wind Turbine

- Weights distribution concentrated around low orders and the 58th
- Convergence to the IAS Map without any further continuity/cleaning
- Outperformance of MOST after evaluating the mean and median absolute errors







Conclusion

- Mechanical challenging task
  - Relevant speed information
  - Unknown harmonic state
- MOST
  - Normalized threshold
  - Multi PDFs
  - Informative Harmonics Map
- Convergence towards the most likely speed
  - Most orders highlighting same frequencies
  - Redundant harmonics from considered combinations

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