Vibration Analysis of Bearing Mechanisms for Predictive Maintenance

Abstract

This report presents the results of a three-month group project conducted as part of the graduate program at Centrale Lille. The project focused on automating the process of failure detection in rolling-element bearings. The goal was to develop user-friendly software capable of reliable defect detection, thereby assisting other (PhD) students in their research.

Predictive maintenance plays a crucial role in industrial environments, ensuring the optimal operation and longevity of production lines. The objective of this project was to design a system for the efficient and automated analysis of mechanical vibrations in bearings, with the aim of improving preventive maintenance strategies. Using a dataset of vibration signals from a bearing test rig—both with and without known defects—we were able to validate theoretical analyses through practical experimentation.

Main Objectives

- Develop an automated defect detection system.
- Design an ergonomic user interface for ease of use.
- Provide comprehensive documentation of the approach.

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Theory

Spectral Approach to Gear Vibration Analysis

Amplitude and frequency modulation are key characteristics of gear signals. According to the model proposed by C. Capdessus [1], the gear signal can be expressed as a function that accounts for amplitude modulation caused by the rotation of the gear wheels.

$$s_e(t) = \sum_{n=-\infty}^{+\infty} s_c(t - n\tau_e) \cdot \left(1 + \sum_{m=-\infty}^{+\infty} s_{p_1}(t - m\tau_{p_1}) + \sum_{p=-\infty}^{+\infty} s_{r_1}(t - p\tau_{r_1})\right) \qquad (23)$$

avec

- τ_e : période d'engrènement
- $\tau_{p_1} = N_1 \tau_e$: période de rotation du pignon et N_1 est le nombre de dents du pignon
- $\tau_{r_1} = N_2 \tau_e$: période de rotation de la roue et N_2 est le nombre de dents de la roue
- $s_c(t)$: signal d'engrènement
- $s_{p_1}(t)$: signal périodique de période τ_{p_1} induit par la rotation du pignon
- $s_{r_1}(t)$: signal périodique de période τ_{r_1} induit par la rotation de la roue

Figure 1: Amplitude Modulation in Gear Signals

Manifestation of Defects

Defects in gears can be identified by analyzing changes in the vibration spectrum. When a tooth is damaged, a periodic shock occurs at the gear's rotational frequency, modulating the gear signal and increasing the amplitude of its sidebands [1].

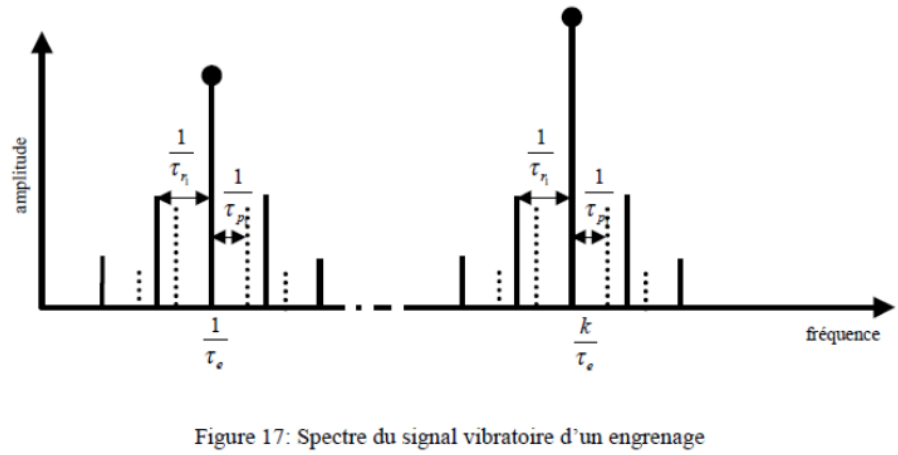


Figure 2: Vibration Spectrum of a Gear

In this study, we analyzed both defective and healthy signals, each characterized by specific frequencies. By examining the signal envelopes, these characteristic frequencies become clearly visible.

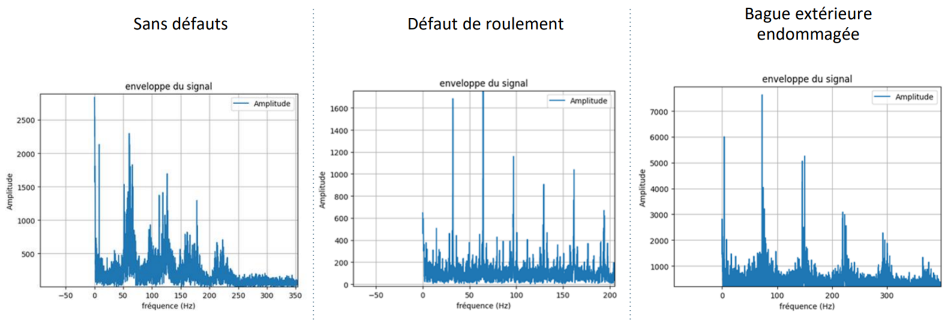


Figure 3: Comparison of Envelope Signals: Defective vs. Healthy

> Theoretically, it is possible to identify specific failures based on their associated frequencies.

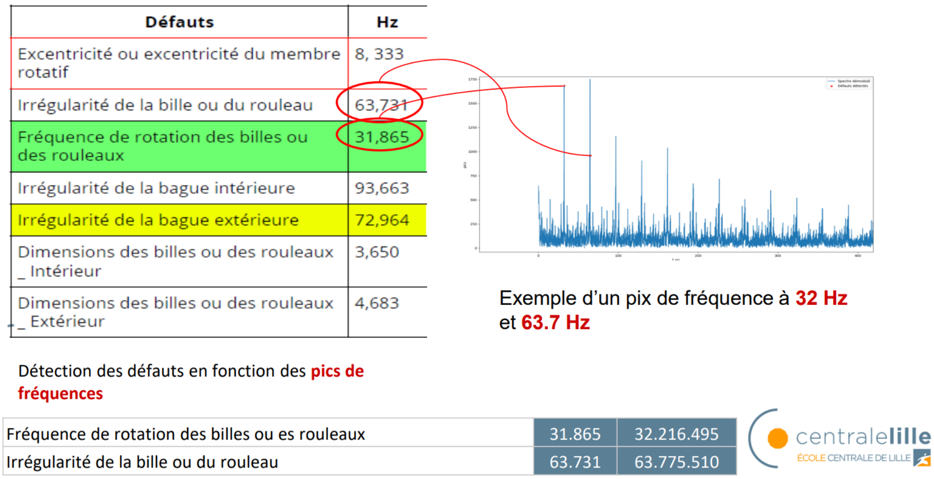
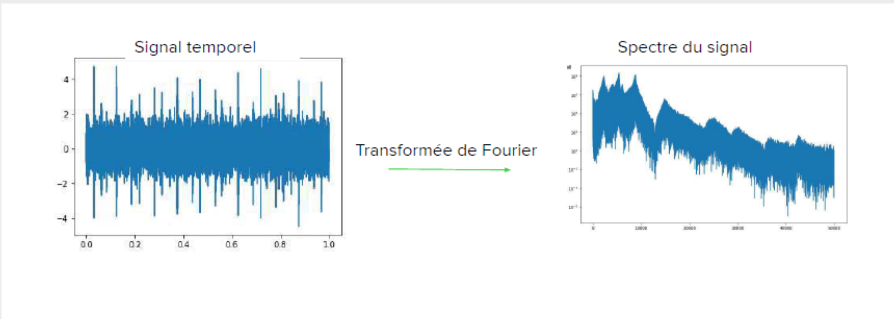


Figure 4: Characteristic Frequencies and Associated Defects

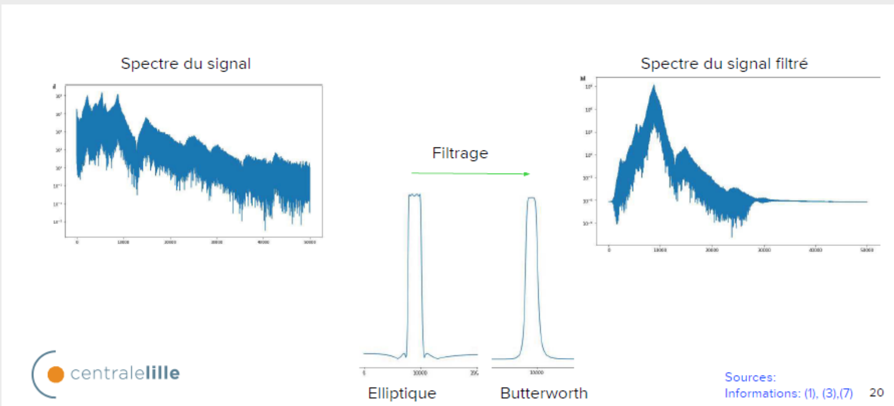
Envelope Frequency Analysis

The envelope detection process was implemented in Python and consists of the following stages [2]:

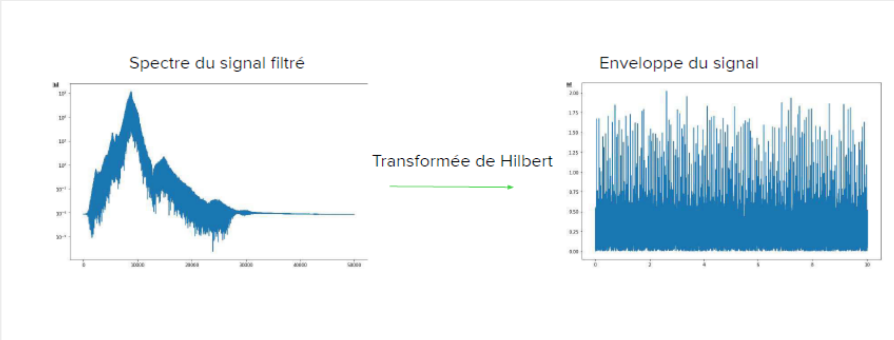
Step 1: Fourier transform of the input time signal and identification of the resonance frequencies of the machine.



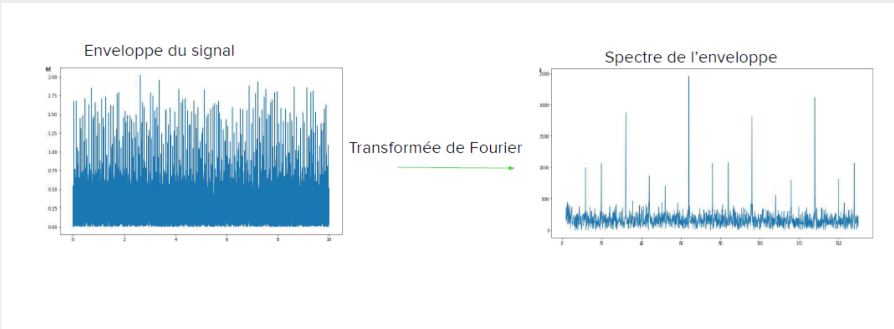
Step 2: Signal filtering.



Step 3: Hilbert transform.



Step 4: The Fourier transform of the envelope.



Without preprocessing the time-domain signal, it is possible to detect the most obvious defects, which manifest as high-amplitude peaks in the spectrum. This approach is particularly effective for identifying periodic faults.

The proposed solution combines envelope analysis with cepstral analysis, which highlights periodic frequencies with abnormally high energy levels.

Note on Cepstral Analysis

The primary goal of cepstral analysis is to automate the detection of periodic defects. This allows us to distinguish between:

- Random high-frequency components without associated harmonics, which are not related to any specific defect.
- Periodic peaks indicative of either normal bearing operation or defective operation.

While effective, this method could be further enhanced by incorporating modern AI-based techniques.

Cepstrum Analysis

Originally developed for echo detection, the cepstrum is particularly useful for analyzing rotating machinery, where defects generate periodic echo-like patterns [1]. The energy cepstrum effectively highlights both harmonics and fundamental frequencies, enabling the automatic detection of periodic defects. The cepstrum is mathematically defined as:

$$\text{Cepstrum} = \left| \mathcal{F}^{-1} \left\{ \log \left(|\mathcal{F}\{x(t)\}|^2 \right) \right\} \right|^2$$

This method allows us to focus exclusively on periodic defects.

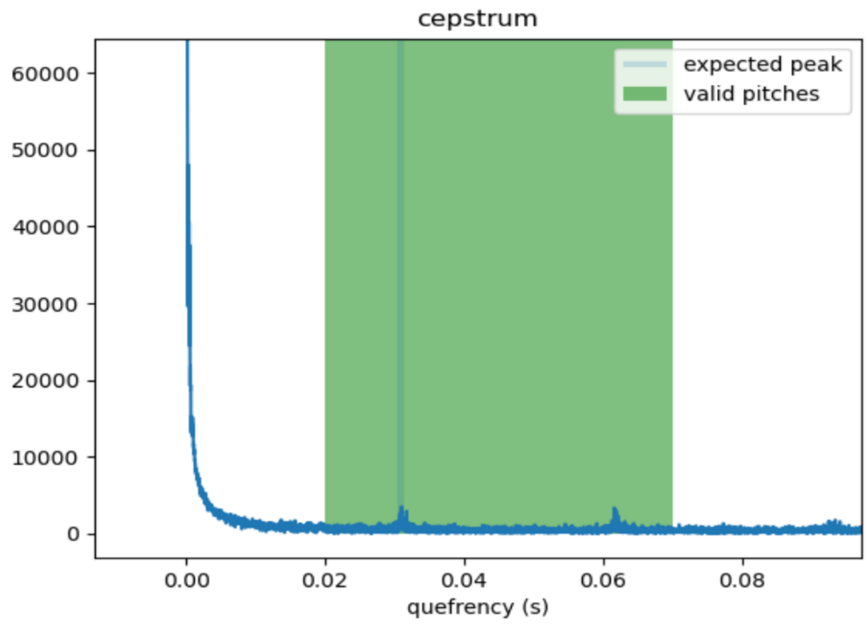


Figure 5: Quefrency Spectrum with Highlighted Defect-Related Quefrencies

Distinguishing Defects from Normal Behavior

The final step involves differentiating between actual defects and normal operational characteristics. This is achieved by evaluating the curvature of frequency peaks [2, 3]. The curvature of each potential defect is analyzed to eliminate false positives and accurately identify true defects. Additionally, kurtosis analysis is applied to detect impulsive signals, providing both temporal and spectral insights.

Software Workflow

The detection algorithm follows these steps:

- Compute the envelope spectrum of the time-domain signal.
- Identify potential defects using cepstral analysis and compare them to known defect frequencies.
- Evaluate the curvature of each candidate defect.
- Output the confirmed defects and their curvature for further analysis.

For more information, the software is available on GitHub: GitHub Repository.

References

[1] Mohamed El Badaoui, *Contribution au Diagnostic Vibratoire des Réducteurs Complexes à Engrenages par l'Analyse Cepstrale*, 2008.

[2] K. Belaid, A. Miloudi, M. Silmani, *Utilisation du Kurtosis dans le diagnostic des défauts combinés d'engrenages par la transformée continue en ondelettes.*

[3] M. Merzoug, A. Miloudi, *Amélioration de la sensibilité du Kurtosis en utilisant le débruitage par ondelettes.*