Introduction to condition monitoring of roller bearings

Geir Kulia

images/logo-wb.png

University of Agder
27 October 2021

Motivation

Rolling element bearings are widely used in rotating machines. Their failure is one of the most frequent reasons for machine breakdown.

This keynote will show the calculation of an elementary envelope spectrum to identify faults by monitoring for abnormalities in a bearing's

- Outer race
- Inner race
- Fundamental train
- Rolling elements

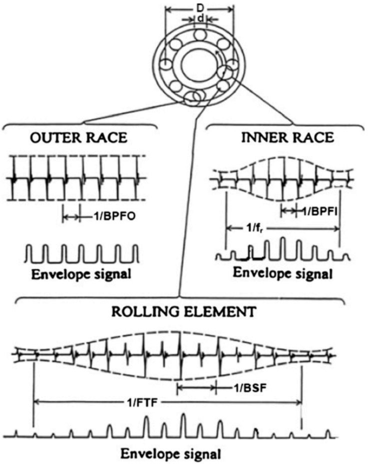

Figure: Typical signals and envelope signals from local faults in rolling element bearings. [1].

Measurement

A high density accelerometer is used to monitor the roller bearing. The accelerometer can be either permanently mounted or a portable device.

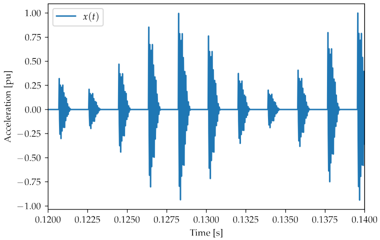

Figure: Example of a fingerprint of a damaged roller bearing.

The sampling rate, f_s is usually around $f_s \in [50 \text{ kHz}, 100 \text{ kHz}]$.

The analytic signal

The acceleration signal is high-pass filtered to remove unwanted machine noise. The design of these filters are outside the scope of this presentation. The resulting acceleration signal $x(t)$ is then used to generate an analytic signal, $z(t)$. It is defined as

$$z(t) = x(t) + jy(t) = a(t)e^{j\theta} \tag{1}$$

where $j^2 = -1$ and $y(t)$ is the Hilbert transform of $x(t)$ can conceptually be considered as the convolution $x(t) * \frac{1}{t}$. and where the amplitude is

$$a(t) = \sqrt{x^2(t) + y^2(t)} \tag{2}$$

and the phase (not to be confused with phase shift is

$$\theta(t) = \arctan\left(\frac{y}{x}\right) \tag{3}$$

The analytic signal

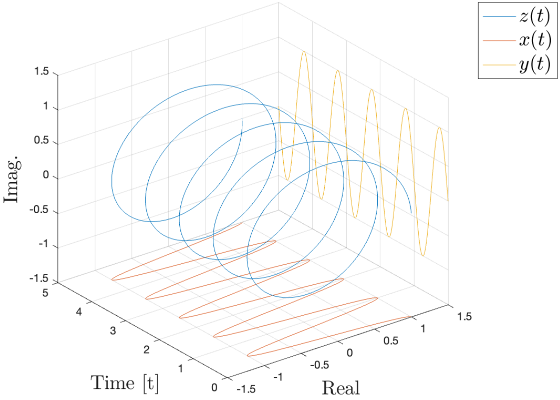

Figure: Analytic signal $z(t)$ of a real signal $x(t) = \cos(2\pi t)$, so that $z(t) = \cos(2\pi t) + j\sin(2\pi t) = 1\ e^{j2\pi t}$

The envelope and order spectrum

Using the analytic signal

$$z(t) = x(t) + jy(t) = a(t)e^{j\theta} \tag{4}$$

we can define the envelope as

$$e(t) = |z(t)| = |x(t) + jy(t)| = a(t) \tag{5}$$

The envelope spectrum is thus defined as the fourier spectrum of the envelope, $a(t)$

$$E_f(\omega) = \mathscr{F}\{a(t)\} = \int_{-\infty}^{\infty} e(t)e^{-j\omega t}dt \tag{6}$$

A envelope periodogram is then defined as

$$E(\omega) = |E_f(\omega)|^2 \tag{7}$$

The envelope of a signal

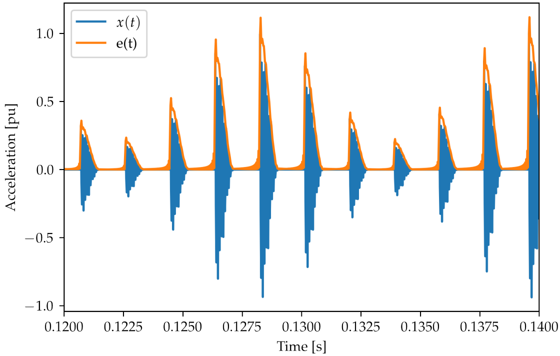

Figure: Example of a fingerprint of a damaged roller bearing with its envelope

Order spectrum

In the envelope spectrum, $E(\omega)$, the frequencies will scale with the shaft speed, f_r.
The order spectrum is an envelope spectrum where the frequencies are normalized with the rotation speed, denoted as order, so that

$$E(\text{order}) = E\left(\frac{\omega}{f_r}\right) \tag{8}$$

where in the order domain one get that $1 = f_r$.

The envelope spectrum

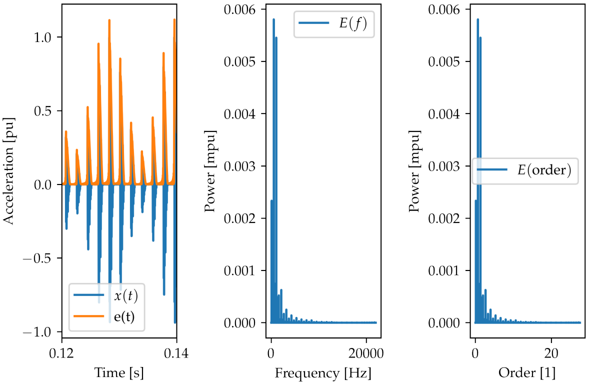

Figure: Example of a fingerprint of a damaged roller bearing $x(t)$ with its envelope $e(t)$, its envelope spectrum $E(f)$ and its order spectrum $E(\text{order})$

Order spectrum

One can now define fault orders corresponding to fault modes of the roller bering element:

- Outer race: $\mathrm{BPFO} = \frac{nf_r}{2}\left(1 - \frac{d}{D}\cos(\phi)\right)$
- Inner race: $\mathrm{BPFI} = \frac{nf_r}{2}\left(1 + \frac{d}{D}\cos(\phi)\right)$
- Fundamental train: $\mathrm{FTF} = \frac{f_r}{2}\left(1 - \frac{d}{D}\cos(\phi)\right)$
- Ball spin: $\mathrm{BSF} = \frac{D}{2d}\left(1 - \frac{d}{D}\cos^2(\phi)\right)$

where d is the diameter of a roller element, D is the diameter of bearing, n is the number of rolling elements, ϕ is the angle of the load from the radial plane. Hei

Thank you!

geir@sal.no

Give anonymous feedback on
https://www.admonymous.co/geir

Find the presentation and code at
https://github.com/kulia/uia-cm-2021-10-26

References

[1] Robert B. Randall and Jérôme Antoni. Rolling element bearing diagnostics—a tutorial. *Mechanical Systems and Signal Processing*, 25(2):485–520, 2011.

The Hilbert Transform

The analytic signal is defined as

$$z(t) = x(t) + jy(t) = a(t)e^{j\theta} \tag{9}$$

where $j^2 = -1$ and $y(t)$ is the Hilbert transform of $x(t)$ so that

$$y(t) = \frac{\text{pv}}{\pi} \int_{-\infty}^{\infty} \frac{x(\tau)}{t - \tau} d\tau \tag{10}$$

where pv denotes the Cauchy principal value. The Hilbert transform can conceptually be considered as the convolution $x(t) * \frac{1}{t}$.