

Envelope analysis for rolling bearing faults: steps and frequencies

This article shows how envelope analysis pulls repeating impacts out of a high-frequency vibration band, how to calculate the four defect frequencies, and how to read the result step by step.

In short

- A bearing defect produces short impacts, and envelope analysis reveals their repetition rate in a high-frequency band.
- The defect frequencies BPFO, BPFI, FTF and BSF follow from shaft speed and bearing geometry, so they can be calculated.
- Measured peaks sit near the calculated frequencies rather than exactly on them, because real bearings slip.

01 / Impacts, resonance and modulation

In a rolling-element bearing, a defect such as a scratch on the inner race or a pit on the outer race creates a short impact each time a rolling element passes over it. Each impact excites the structural resonances of the machine, so a high-frequency band rings. The result is a signal whose amplitude rises and falls at the rate of the impacts. This is amplitude modulation. The repetition rate of the impacts depends on the bearing geometry and the shaft speed, not on the size of the defect, so the measured rate can be matched against calculated values.

In a raw low-frequency spectrum, that repetition is often masked by the strong peaks of gears, unbalance and motor components. Envelope analysis aims to extract the modulation from the raw signal, so that only its repetition rate remains visible.

02 / Steps: filter, demodulate, FFT

The method has four steps. First, a band-pass filter isolates a band around a structural resonance. Second, the envelope is extracted by taking the magnitude of the analytic signal obtained from the Hilbert transform; this is demodulation. Third, the mean value, the DC component, is removed from the envelope. Last, the FFT of the envelope is computed and its peaks are compared with the defect frequencies.

The order of the steps and the band choice both matter. The sampling rate of the raw signal must also be high enough; otherwise the high-frequency resonance band has already folded before the envelope is taken. Check the sampling rate before you choose the band. A band that is too narrow can miss the impacts, and one that is too wide lets other impact sources into the envelope. For that reason, choose the band by inspecting the spectrum for resonance peaks, not at random. If resonances are hard to see, an impact hammer test or a comparison with a healthy machine's record can help.

03 / Defect frequencies and their formulas

Four defect frequencies follow from the bearing geometry and the shaft frequency f_r . N_b is the number of rolling elements, d the ball diameter, D the pitch diameter (the diameter of the circle through the rolling-element centres), and ϕ the contact angle.

- BPFO (outer race): $(N_b/2) \cdot f_r \cdot (1 - (d/D) \cos \phi)$
- BPFI (inner race): $(N_b/2) \cdot f_r \cdot (1 + (d/D) \cos \phi)$
- FTF (cage): $(f_r/2) \cdot (1 - (d/D) \cos \phi)$
- BSF (ball spin): $(D/(2d)) \cdot f_r \cdot (1 - ((d/D) \cos \phi)^2)$

These formulas assume no slip and an ideal geometry. Real bearings slip, so a measured peak sits near the calculated value rather than exactly on it.

04 / Worked example: a hypothetical bearing

Hypothetical example. Take a bearing with $N_b = 9$, $d/D = 0.2$, $\phi = 0$ and $f_r = 25$ Hz. Since $\cos 0 = 1$:

- $BPFO = 4.5 \times 25 \times (1 - 0.2) = 4.5 \times 25 \times 0.8 = 90$ Hz
- $BPFI = 4.5 \times 25 \times (1 + 0.2) = 4.5 \times 25 \times 1.2 = 135$ Hz
- $FTF = 12.5 \times (1 - 0.2) = 12.5 \times 0.8 = 10$ Hz
- $BSF = 2.5 \times 25 \times (1 - 0.2^2) = 2.5 \times 25 \times 0.96 = 60$ Hz

A peak near 90 Hz in the envelope spectrum, together with its harmonics, would be a reason to suspect an outer-race defect. Inner-race defects usually show sidebands spaced at f_r , so around the 135 Hz peak you would look for pairs 25 Hz apart. This is a first check only; it does not replace a diagnosis.

05 / Limits: wrong band, gears and speed changes

Envelope analysis does not work in every case. The most common error is a band centred on the wrong resonance. The envelope then shows impacts from another source, and the peaks are misread. Repeating gear-mesh impacts can also appear as peaks in the envelope spectrum. If shaft speed changes during the record, the fixed defect frequencies smear across the spectrum and the peaks widen.

The record length matters too: it should contain several periods of the defect frequency, otherwise the lines do not separate in the envelope spectrum. For that reason, one record is not enough. Compare several records from the same measurement point, taken under similar load and speed. Decide whether a peak comes from the bearing by weighing the speed, the load and the mounting information together.

06 / Data and first practice steps

Practising on open data helps before you apply the method to your own machines. The Case Western Reserve University Bearing Data Center is an openly available source of bearing records that include known defects. Before you start on your own plant, check the following:

- Record the measurement point and the direction of each sensor.
- Note the shaft speed with each record, and check whether it stays steady during the record.
- Choose the band after you have seen the resonance peak, not at random.

- Compare the calculated defect frequencies with the spectrum of a machine known to be healthy.

Start with one machine and one measurement point. If the method does not work in that narrow case, review the measurement direction and the band choice before widening the scope.

Try it

Open a built-in synthetic signal in spectra, run its envelope spectrum, and compare the strongest envelope peak with the BPFO, BPFI, FTF and BSF values calculated from the formulas in this article.

References and online guide

[Open the online guide](#)

[Rolling-element bearing \(Wikipedia\)](#)

[Hilbert transform \(Wikipedia\)](#)

[hilbert \(SciPy\)](#)

[Case Western Reserve University Bearing Data Center](#)

Proposed pilot steps do not claim field accuracy. Synthetic examples are not measurements from a production site.