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A robust detector for rolling element bearing condition monitoring, based on the modulation signal bispectrum, and its performance evaluation against the kurtogram

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&

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Contents

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1. Introduction

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- Bearings are at the heart of almost every rotating machine
  - they have received a lot of attention in the field of vibration analysis
  - because they are common sources of machine faults
- To keep machinery operating reliably many methods for bearing fault detection and diagnosis have been developed
  - vibration measurement and associated signal processing are the most widely used approach

1. Introduction

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A review of signal processing methods

- High frequency resonance technique
- Cyclostationary spectral analysis
- Cepstrum analysis
- Bispectrum analysis
- Time-frequency analysis
- Self-adaptive noise cancellation
- Minimum entropy deconvolution
- Empirical mode decomposition

Most methods are based on tracking the amplitude variations of characteristic fault frequencies

Only limited attention has been given to utilisation of modulation characteristics in extracting the diagnostic information

But the Modulation Signal Bispectrum can be used to extract fault features from envelope signals giving reliable bearing fault detection, diagnosis and severity assessment

1. Introduction

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Purpose of the research

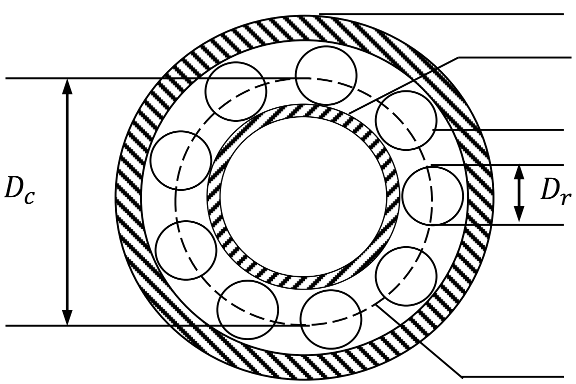
- **To develop and evaluate a robust detector for bearing fault diagnosis based on modulation signal bispectrum (MSB) analysis**

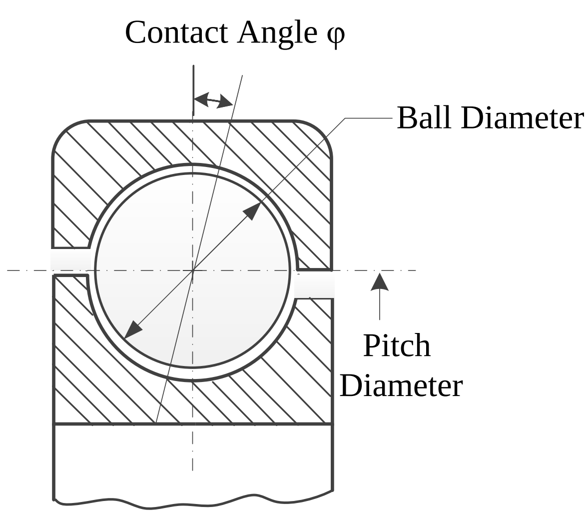
The modulation signal bispectrum

- **MSB analysis can be used to suppress random noise and to decompose nonlinear modulation components in a measured signal, eg vibration**
- **Advantages of the modulation signal bispectrum include:**

1) **Highly effective suppression of random noise**
2) **Revelation of the weak nonlinear characteristics of signals**

Bearing fault frequencies





Outer race fault frequency:

$$BPFO = \frac{N_r}{2} F_s (1 - \frac{D_r}{D_c} \cos \varphi)$$

Inner race fault frequency:

$$BPFI = \frac{N_r}{2} F_s (1 + \frac{D_r}{D_c} \cos \varphi)$$

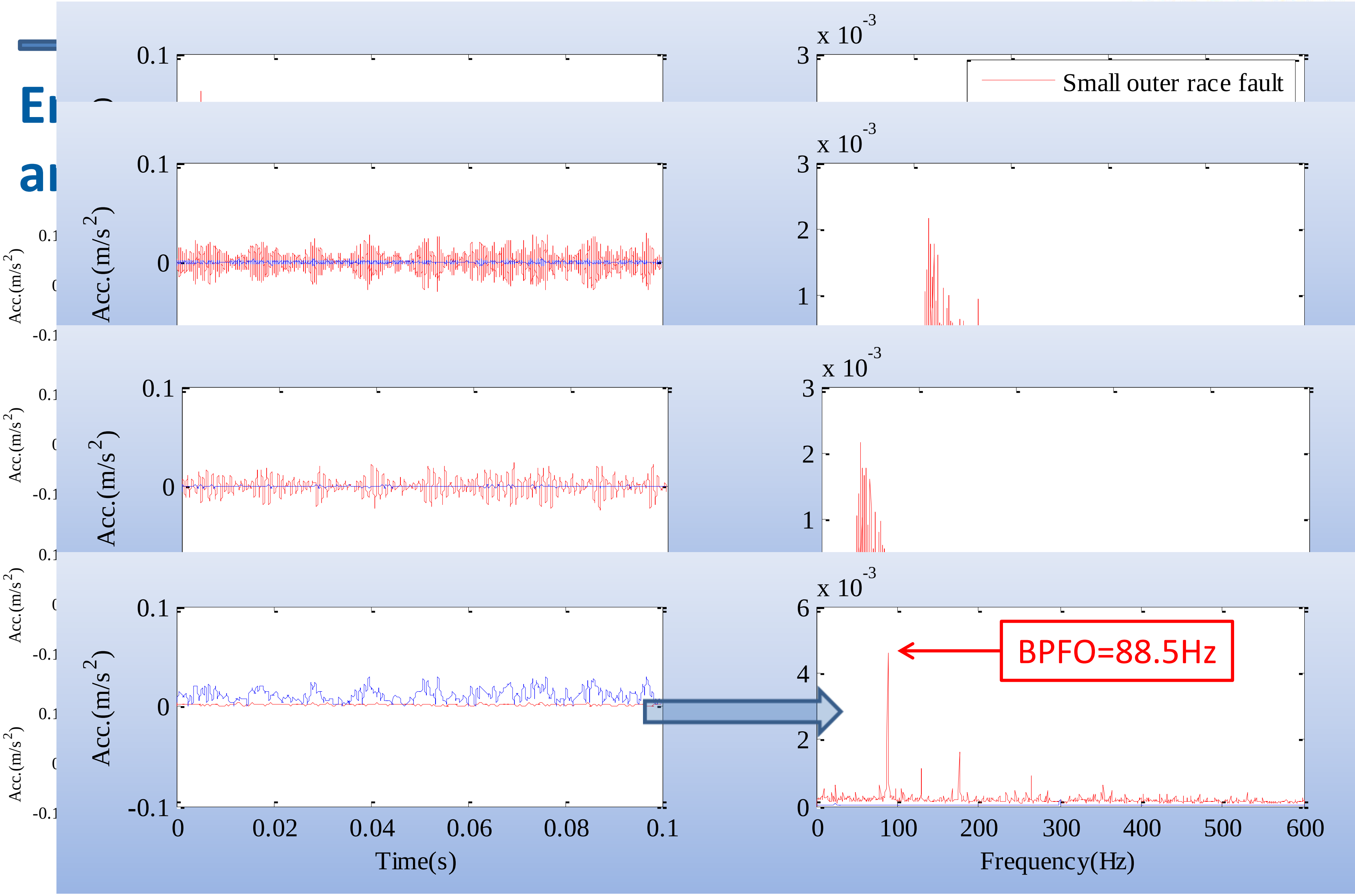
Ball fault frequency:

$$BSF = \frac{D_c F_s}{2 D_r} (1 - \frac{D_r^2}{D_c^2} \cos^2 \varphi)$$

Cage fault frequency
(often called the fundamental train frequency):

$$FTF = \frac{1}{2} F_s (1 - \frac{D_r}{D_c} \cos \varphi)$$

2. The modulation signal based detector



2. The modulation signal based detector

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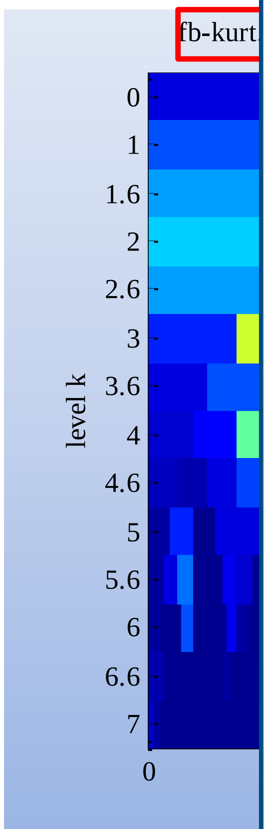

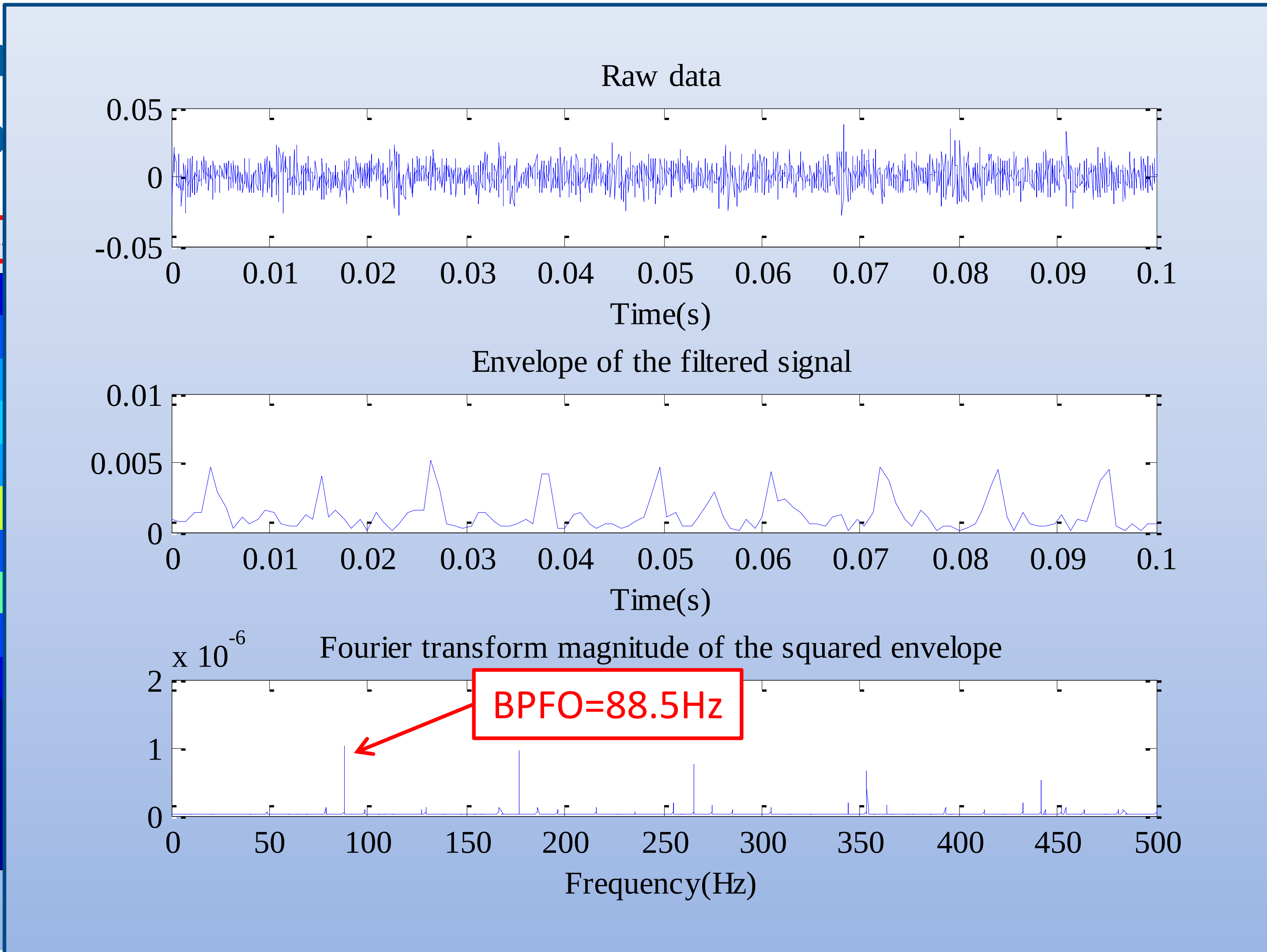

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[…]equency,
[…] regions
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The bearing vibration model

It was decided to use 2 ways of evaluating the new method: via simulated data and real data. To simulate bearing fault data, a bearing vibration model is needed.

The vibration signature x(t) of a faulty rolling element bearing is comprised of several components, and these are represented in the model as follows:

Machinery induced vibration

Noise

$$x(t) = x_f(t)x_q(t)x_{bs}(t) + x_s(t) + n(t)$$

Impulses produced by bearing fault

AM due to the non-uniform load distribution

Bearing-induced vibration determined by the bearing structural dynamics

The presence of modulation in the time data means that there will be **sidebands** in the frequency domain, and these **are key to bearing fault detection/diagnosis**

2. The modulation signal based detector

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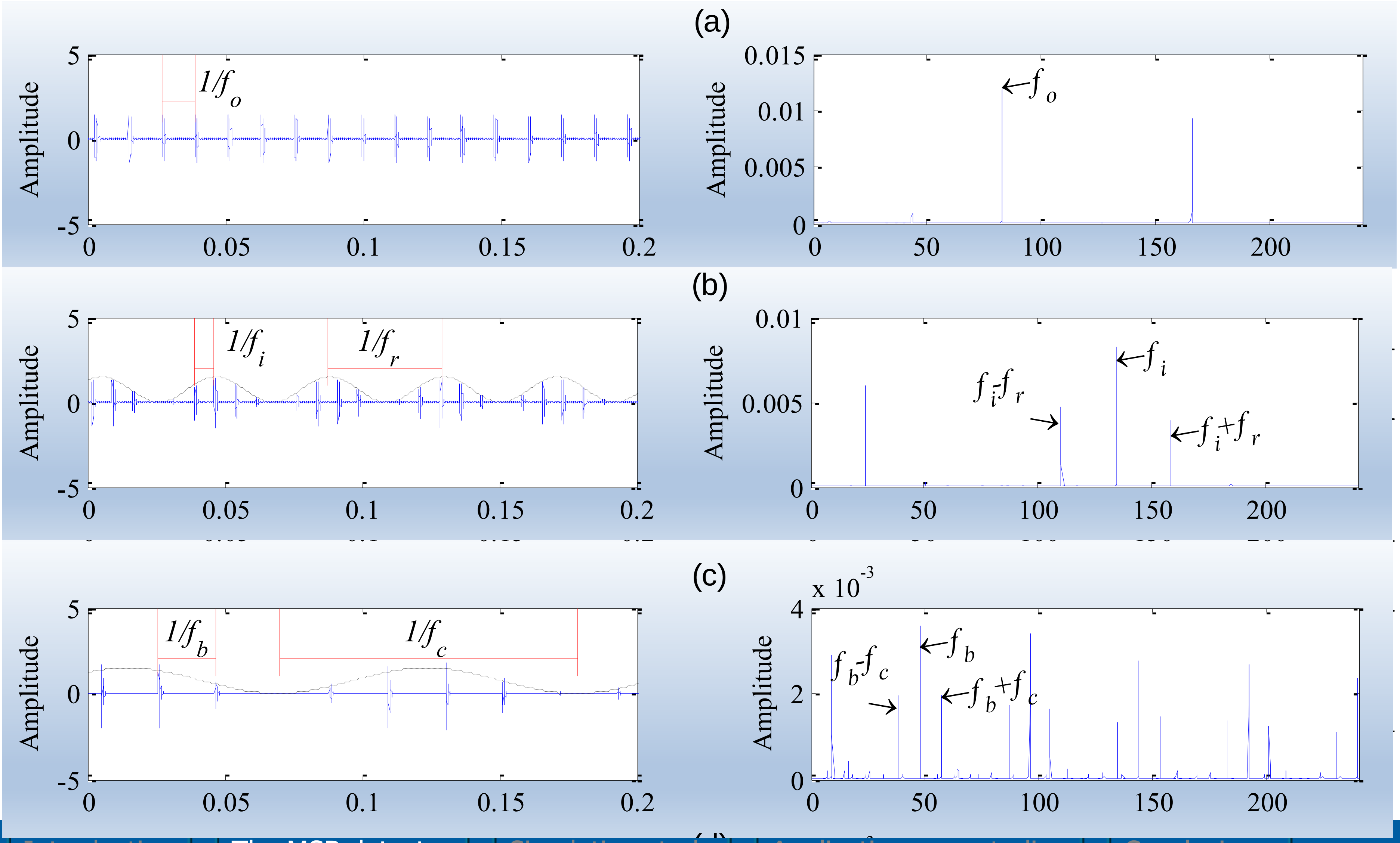

2. The modulation signal based detector

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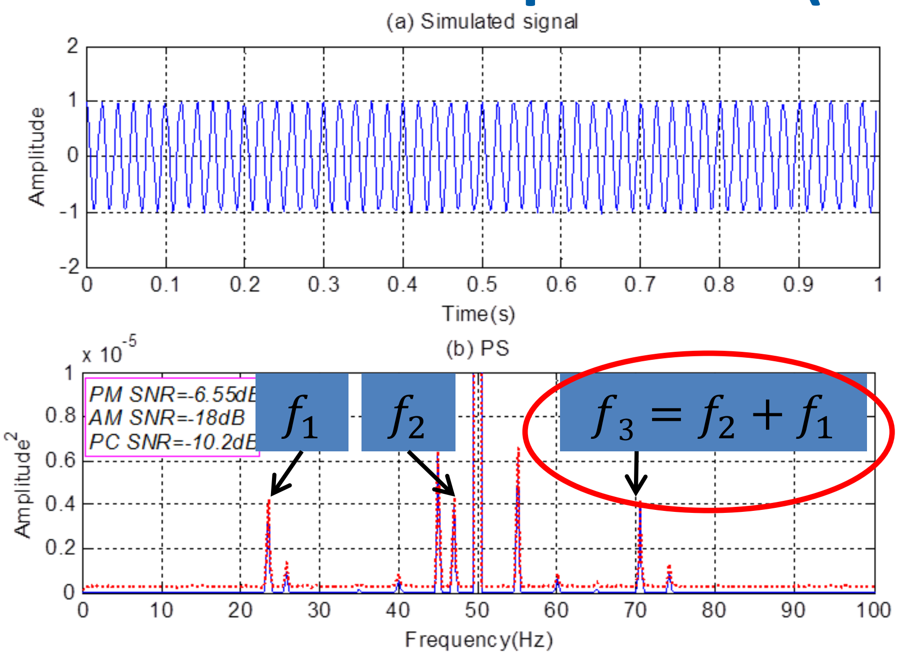
Conventional bispectrum (CB)



- Conventional bispectrum offers:
  - Nonlinear identification capability
  - Retention of phase information
  - Noise suppression capability

$$PS(f) = E\langle X(f)X^*(f)\rangle$$

Definition of CB:

$$B(f_1, f_2) = E\langle X(f_1)X(f_2)X^*(f_1+f_2)\rangle$$

Phase of CB:

$$\varphi_{CB}(f_1, f_2) = \varphi(f_2) + \varphi(f_1) - \varphi(f_2 + f_1)$$

Coherence of CB:

$$b^2(f_1, f_2) = \frac{|B(f_1, f_2)|^2}{E\langle |X(f_1)X(f_2)|^2\rangle E\langle |X(f_1+f_2)|^2\rangle}$$

$E\langle\ \rangle$ **An average must be performed to suppress random noise**

But it is limited to $f_1 + f_2 = f_3$ …
…so it only shows the higher sideband

The modulation signal bispectrum (MSB)

The MSB is based on the CB, but is more attractive in this work because it contains both upper and lower sideband components

$$B_{MS}(f_c, f_x) = E\left\langle X(f_c + f_x) X(f_c - f_x) X^*(f_c) X^*(f_c) \right\rangle$$

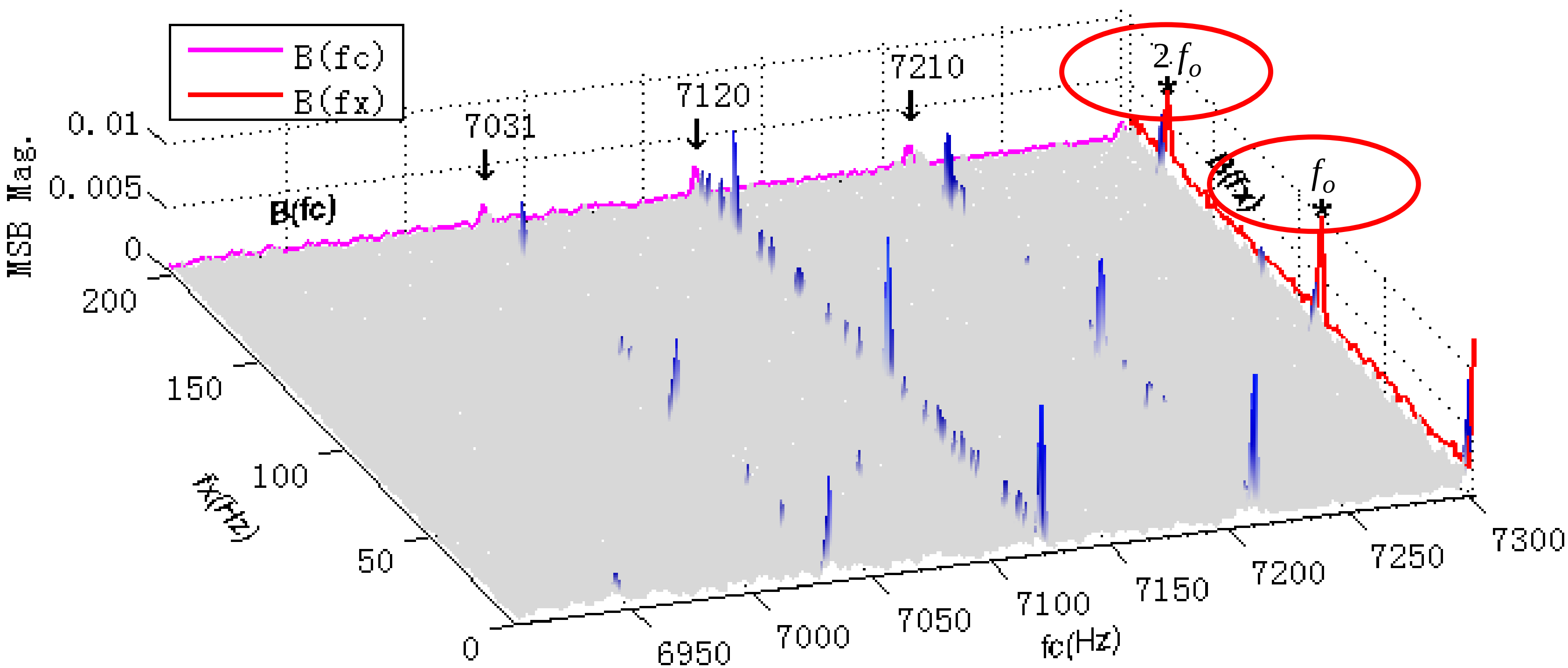
The MSB can itself be modified to enable precise quantification of sideband amplitudes, by removing the influence of the carrier frequency f_c. We call this the MSB sideband estimator (MSB-SE), defined as:

$$B_{MS}^{SE}(f_c, f_x) = \frac{B_{MS}(f_c, f_x)}{\sqrt{\left|B_{MS}(f_c, 0)\right|}}$$

The MSB-SE only includes the information of sidebands $(f_c + f_x)$ & $(f_c - f_x)$

2. The modulation signal based detector

Typical results of the MSB detector - $B(f_x)$ - formed from slices shown along $B(f_c)$, show that the optimal frequency band for detecting a bearing fault is at a specific value of f_c. Symptomatic features are labelled *.



2. The modulation signal based detector

Vibration signal

Calculate the MSB using

Calculate the MSB-sideband estimator using

Calculate the compound MSB slice using

Calculate the robust MSB detector using

$$B(f_x) = \frac{1}{K}\sum_{k=1}^{K} B_{MS}^{SE}\left(f_c^{k}, f_x\right) \quad f_x > 0$$

Flow chart of the robust MSB detector calculation

3. Simulation study

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Four different simulation scenarios were developed

They use different levels of random noise and different amounts of aperiodic interference, to represent the noisy in-field measurements typically encountered in the vibration-based condition monitoring of rolling element bearings

Scenario	White noise	Aperiodic impact interference	Type 1 SNR value	Type 2 SNR value
Low noise signal without impact interferences	Level 1	None	-15dB	n/a
High noise signal without impact interferences	Level 2	None	-30dB	n/a
Low noise signal with low level impact interferences	Level 1	Level 1	-15dB	-22dB
High noise signal with high level impact interferences	Level 1	Level 2	-22dB	-48dB

$$\boxed{Type\ 1\ SNR = 20\log_{10}\left(P_s / P_n\right)}$$

$$\boxed{Type\ 2\ SNR = 20\log_{10}\left(A_s / A_n\right)}$$

3. Simulation study

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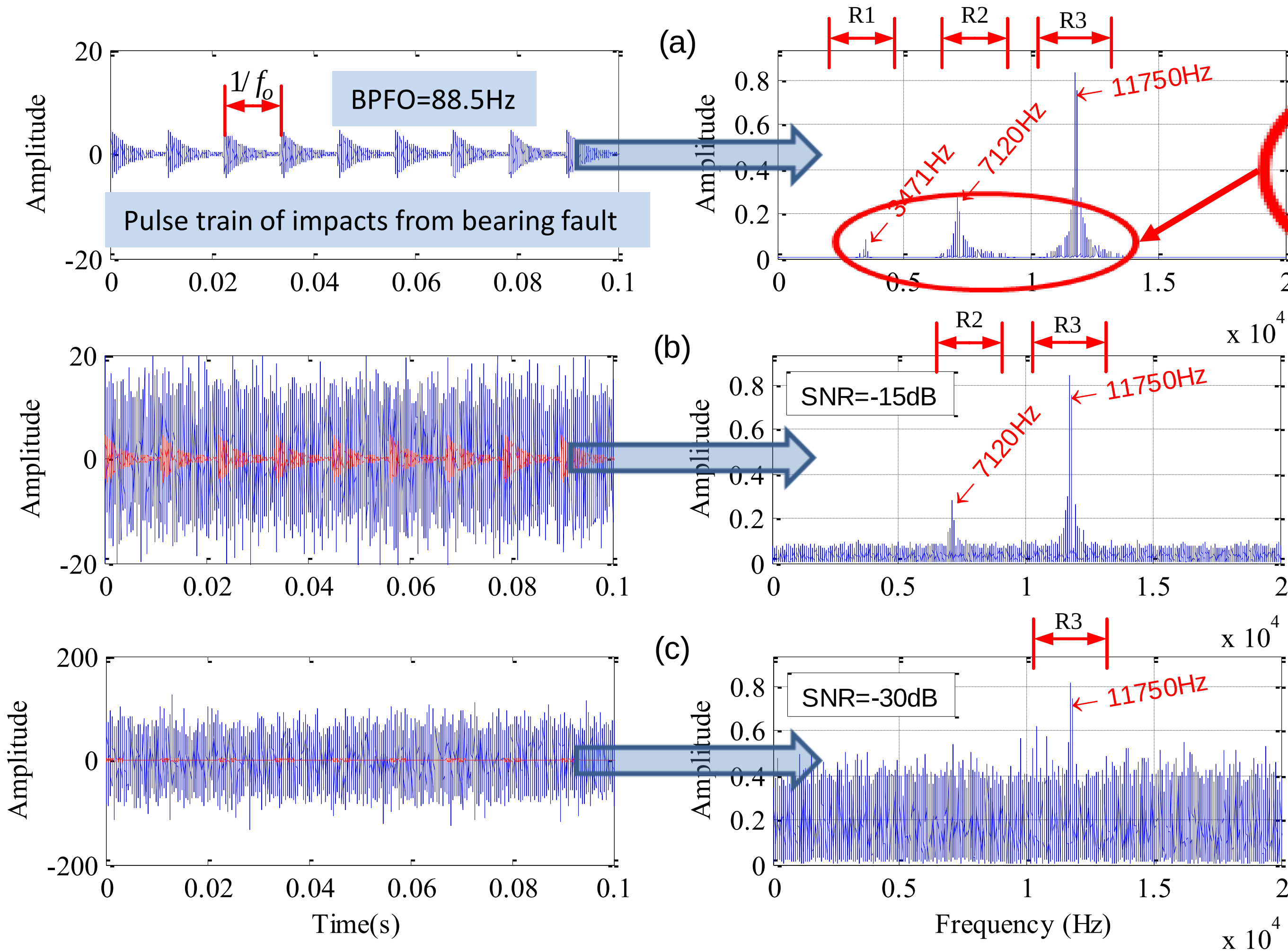
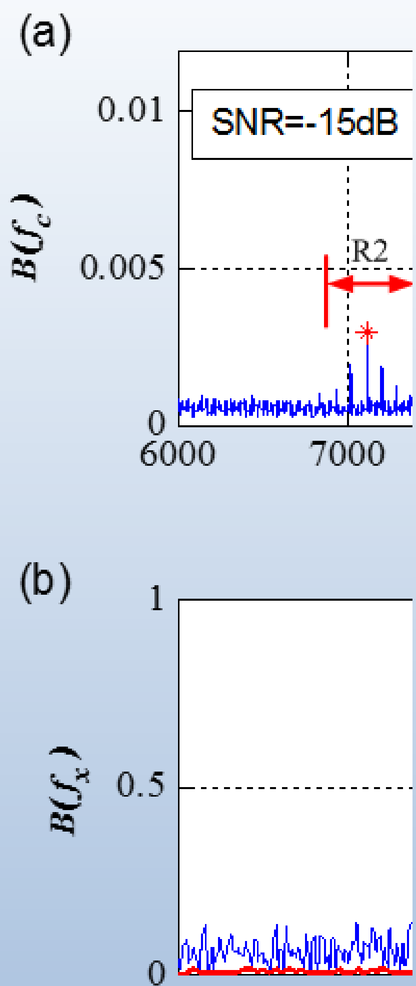
The extent of white noise contamination

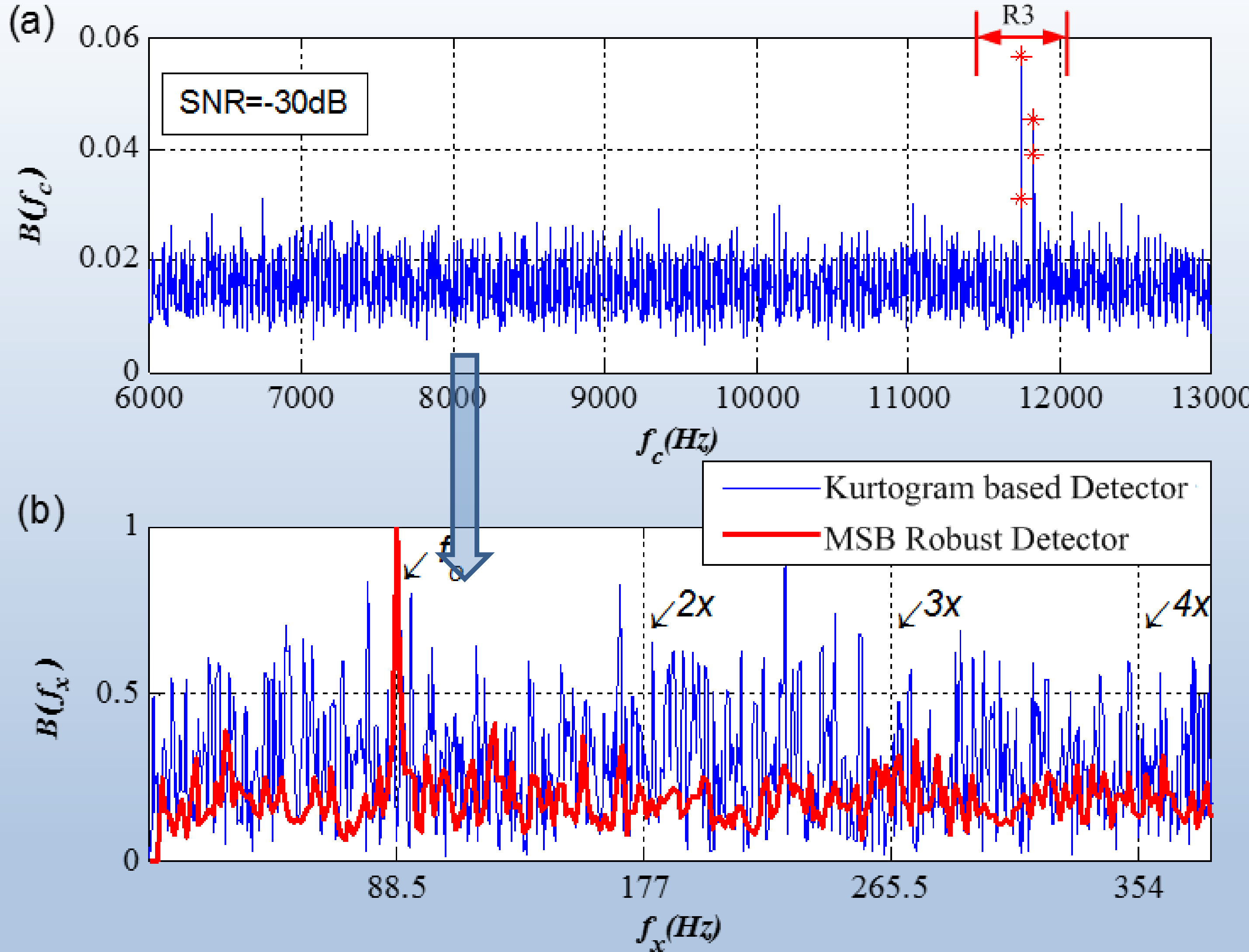


Simulated structural resonance regions which naturally amplify bearing frequency harmonics

Low noise, no impacts

High noise, no impacts

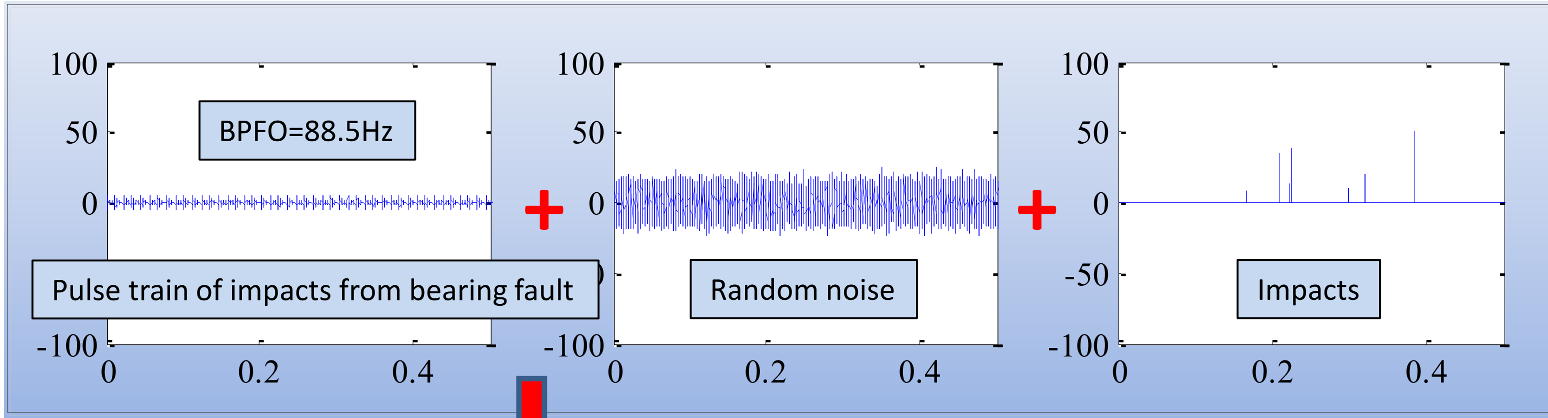




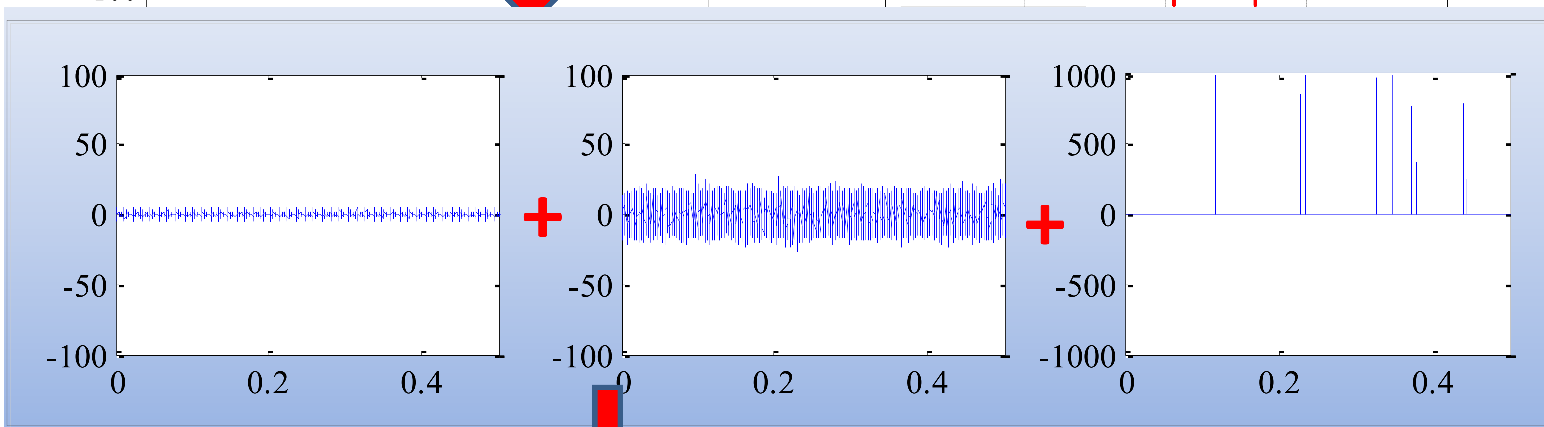
L

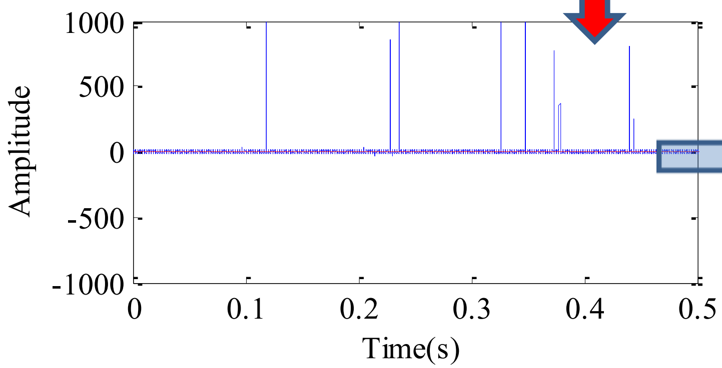
High noise, no impulses

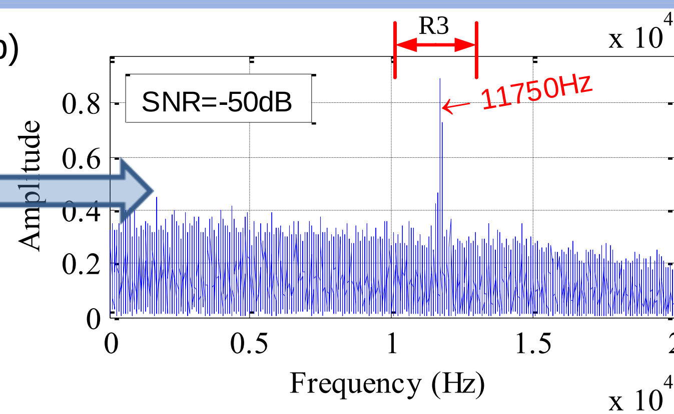
th white



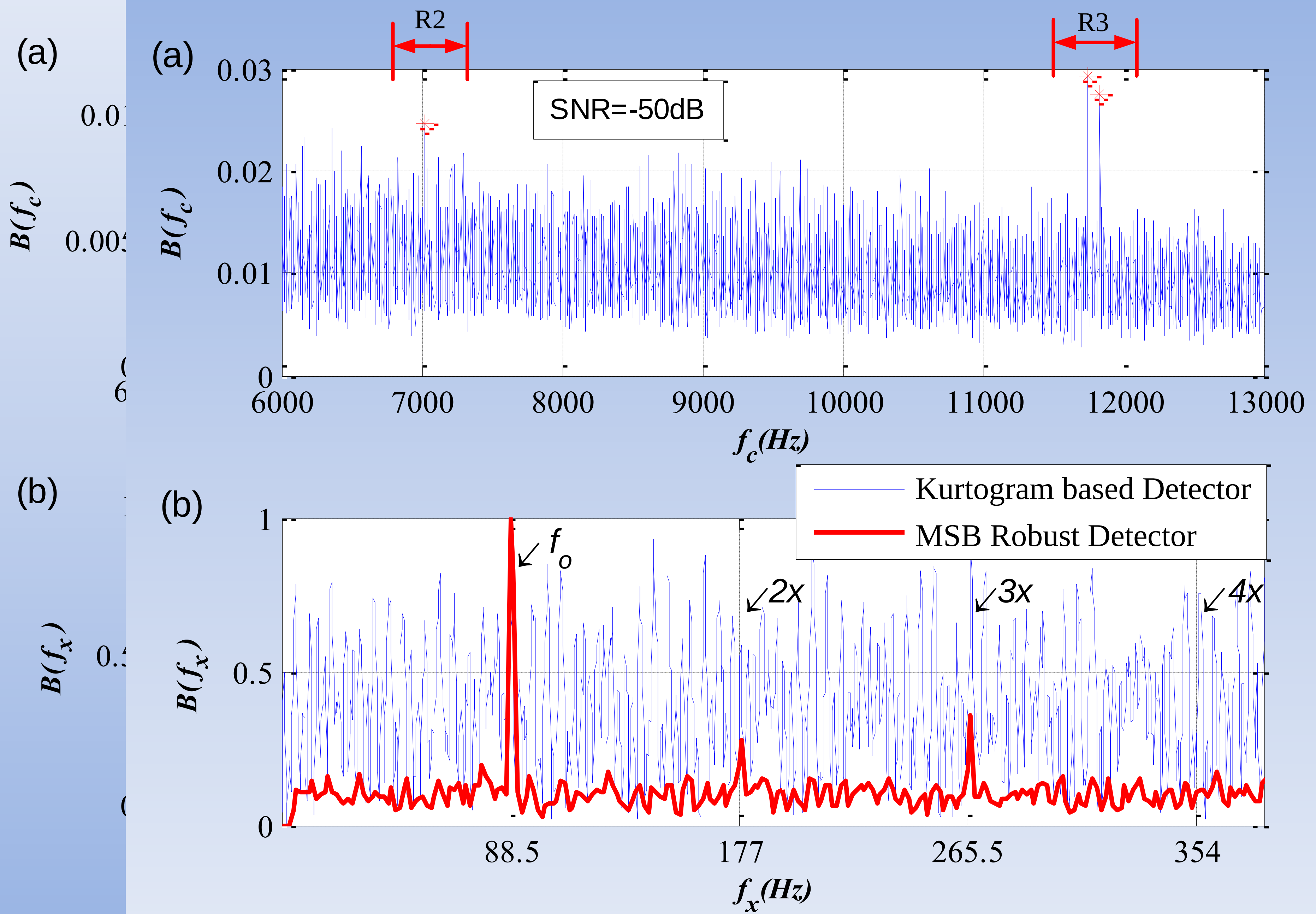
Low noise,
level impacts







Low noise,
high level impacts



(a)
R2
R3
SNR=-50dB
0.03
0.02
0.01
0
B(f_c)
6000
7000
8000
9000
10000
11000
12000
13000
f_c(Hz)
(b)
Kurtogram based Detector
MSB Robust Detector
1
0.5
0
B(f_x)
f_o
2x
3x
4x
88.5
177
265.5
354
f_x(Hz)

4. Application case studies

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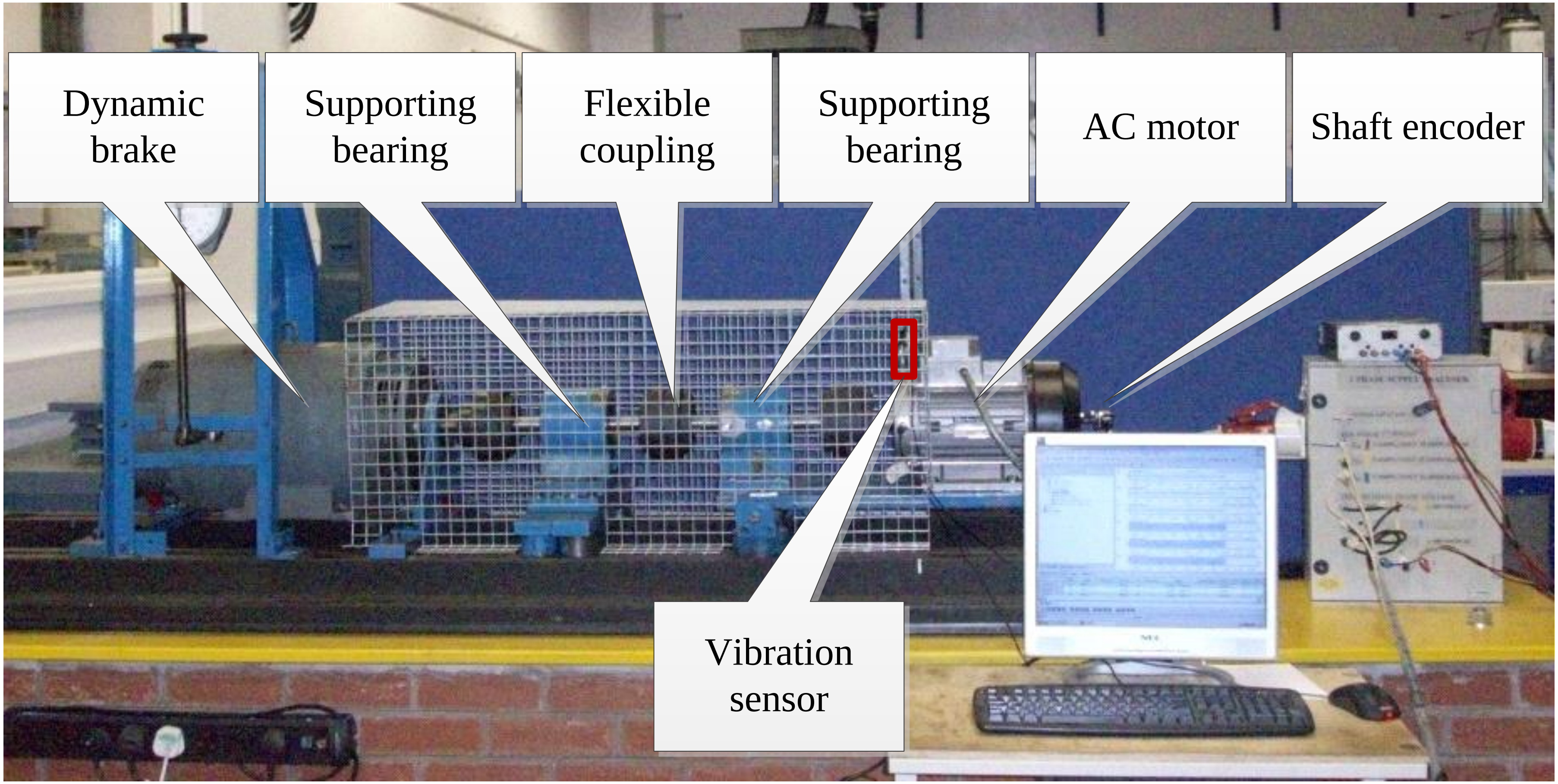
The first real application: motor bearing fault detection



4. Application case studies

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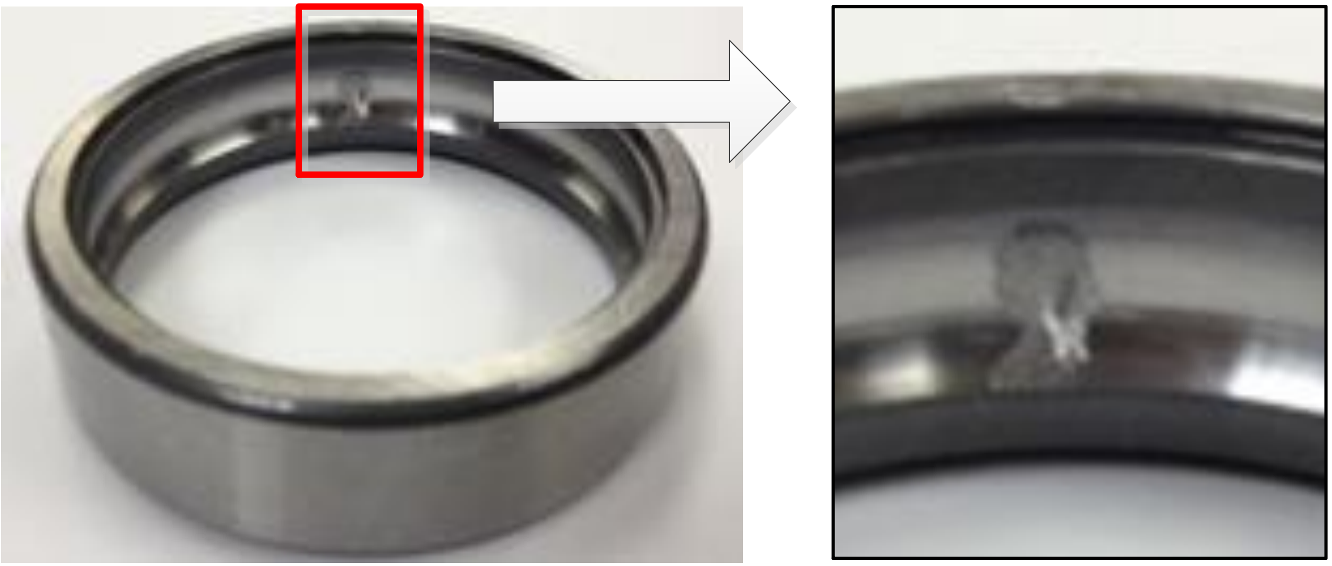

Electric motor bearing with a small seeded outer race fatigue defect (defect simulated by EDM)

Specification of NSK Type 6206ZZ deep groove ball bearing

Parameter	Measurement
Pitch Diameter	46.4mm
Ball Diameter	9.53mm
Ball Number	9
Contact Angle	0˚

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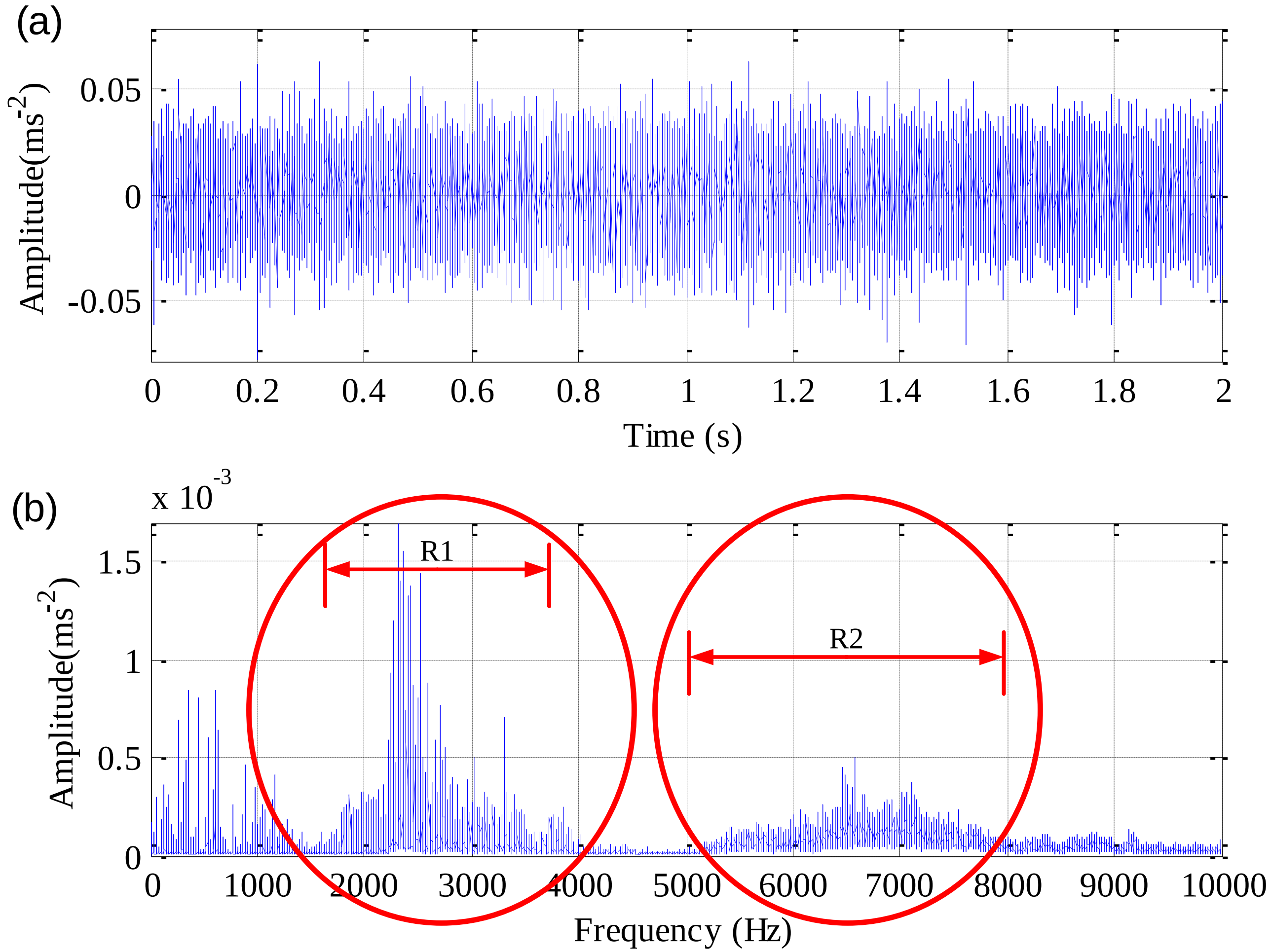
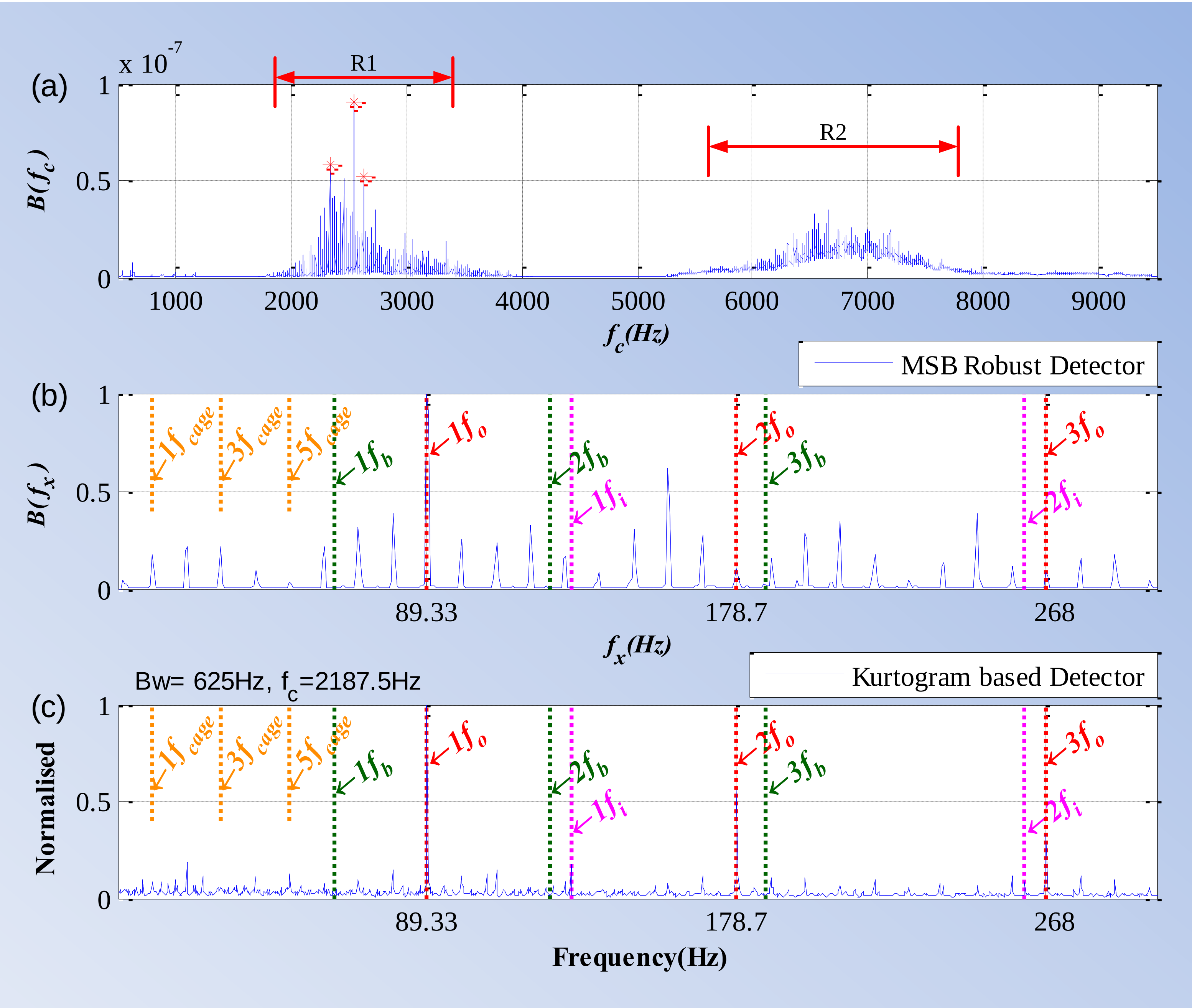
The motor data reveals 2 clear resonant regions




(a)
x 10^-7
R1
R2
B(f_c)
f_c(Hz)
MSB Robust Detector
(b)
B(f_x)
1f_cage
3f_cage
5f_cage
1f_b
1f_o
2f_b
1f_i
2f_o
3f_b
3f_o
2f_i
89.33
178.7
268
f_x(Hz)
Kurtogram based Detector
Bw= 625Hz, f_c=2187.5Hz
(c)
Normalised
Frequency(Hz)

4. Application case studies

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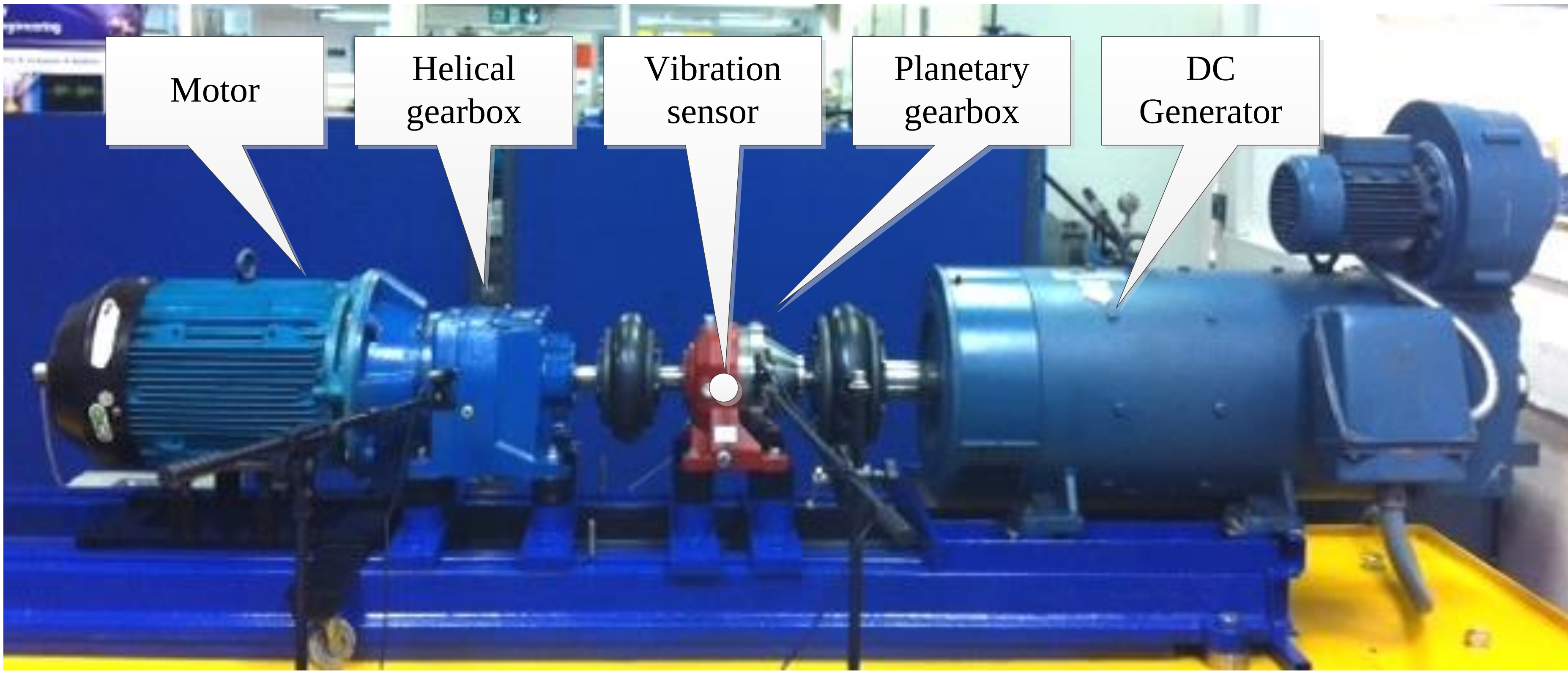
The second real application - planetary gearbox bearing fault detection



4. Application case studies

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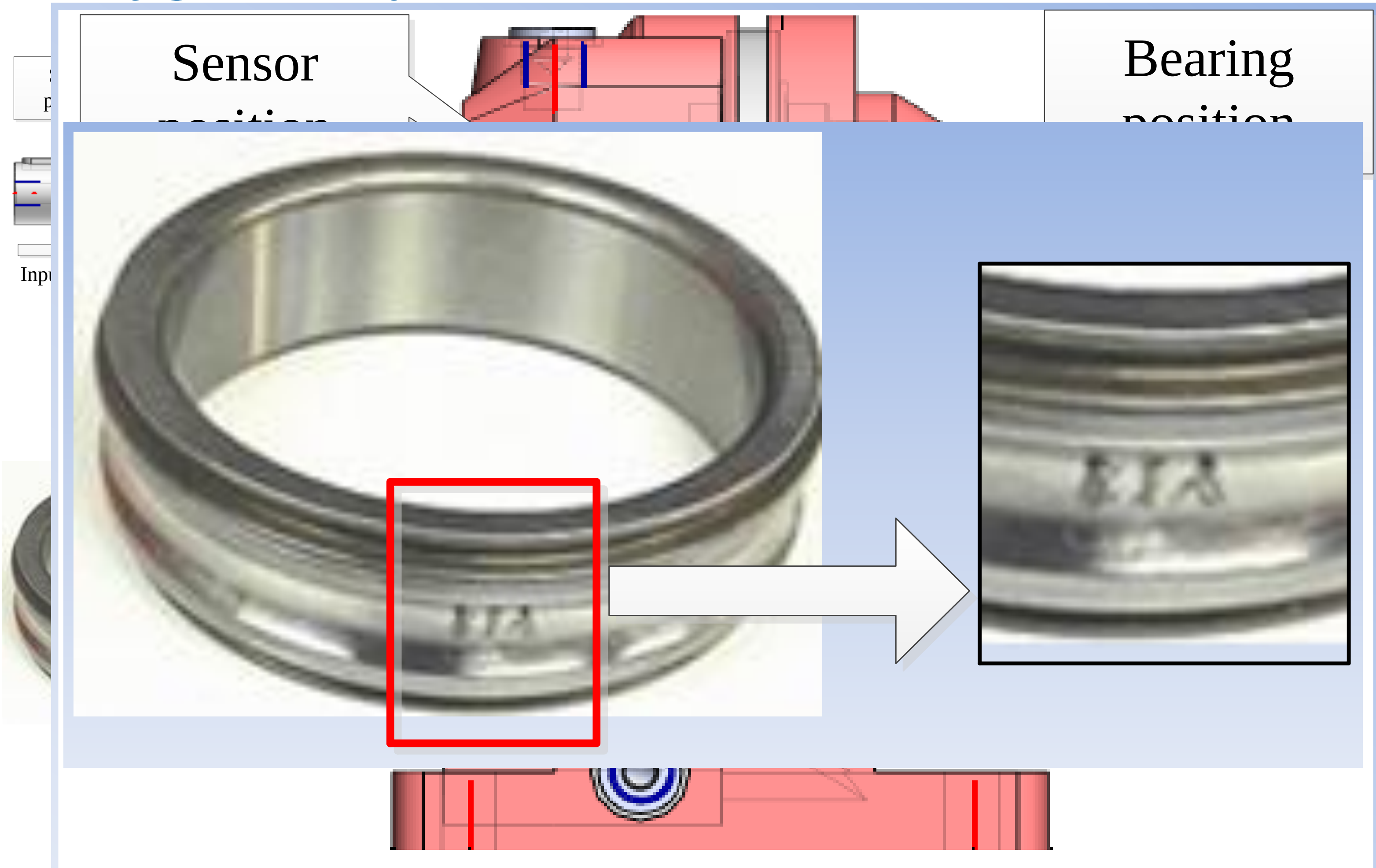
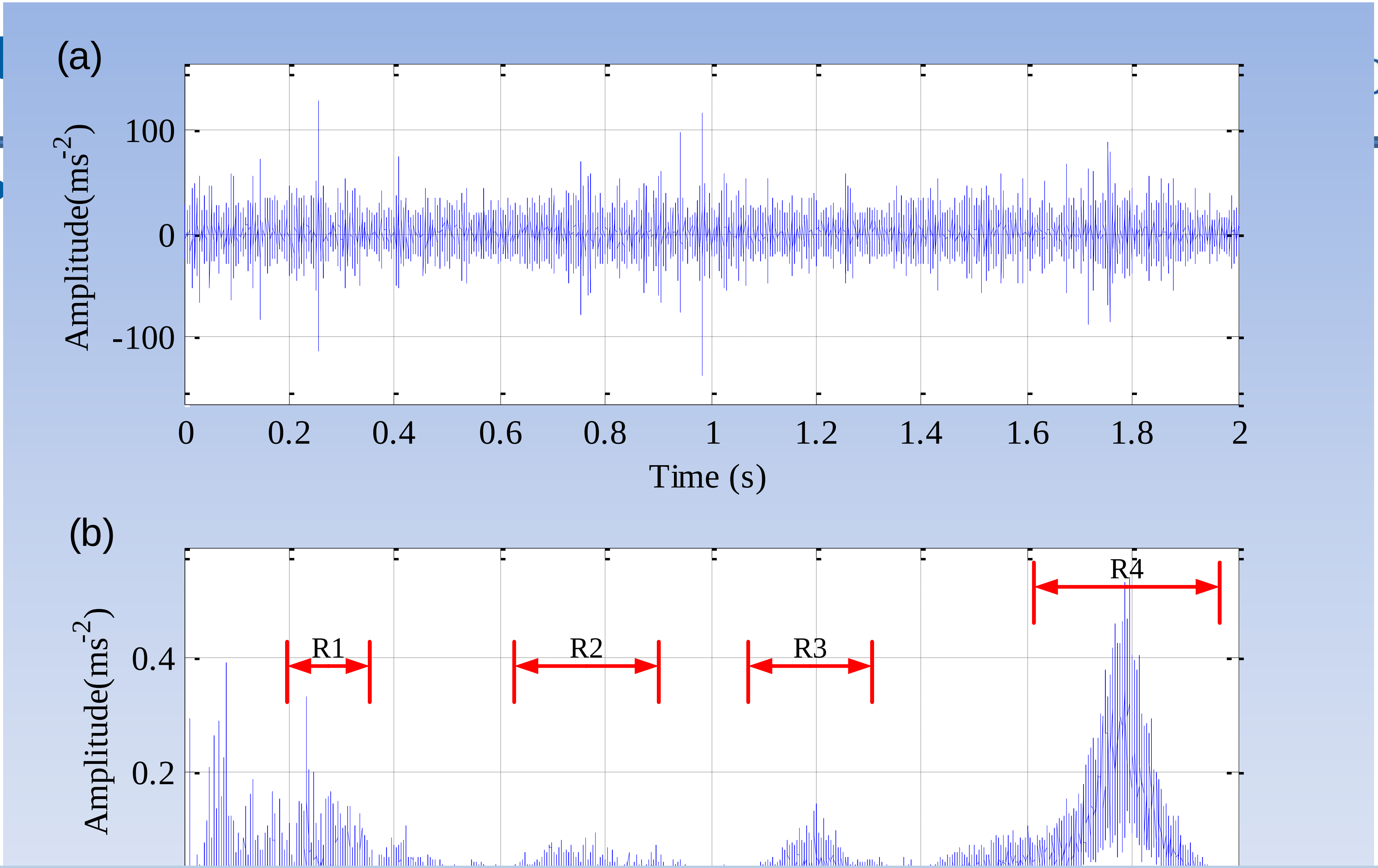
Planetary gearbox specification



08)



But when choosing the resonant region(s) to use in the calculation of the MSB-SE, it is always wise to check the coherence…

4. Application case studies

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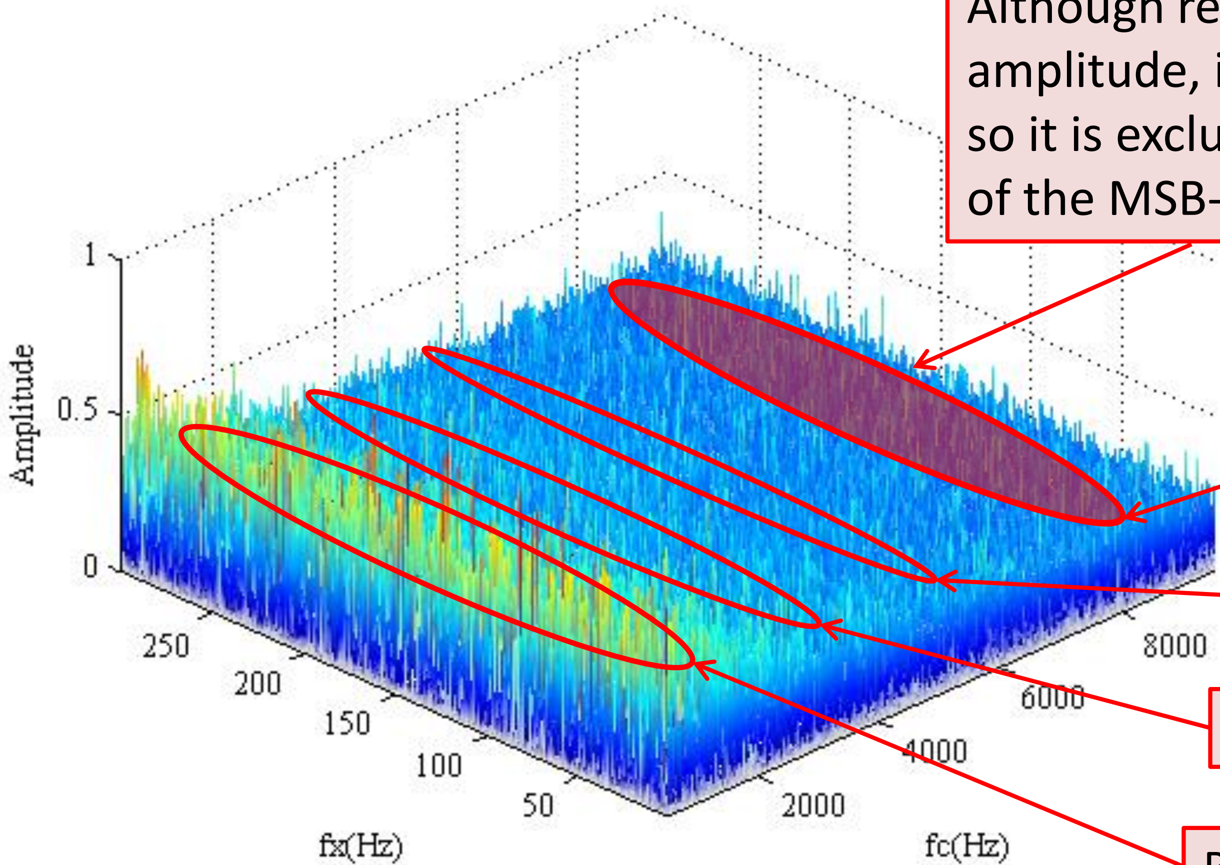
MSB-SE coherence for the planetary gearbox



Although resonance R4 has high MSB amplitude, it has low coherence and so it is excluded from the calculations of the MSB-SE detector

R4 (around 9kHz)

R3 (around 6kHz)

R2 (around 4kHz)

R1 (1kHz-2kHz)

4. Application case studies

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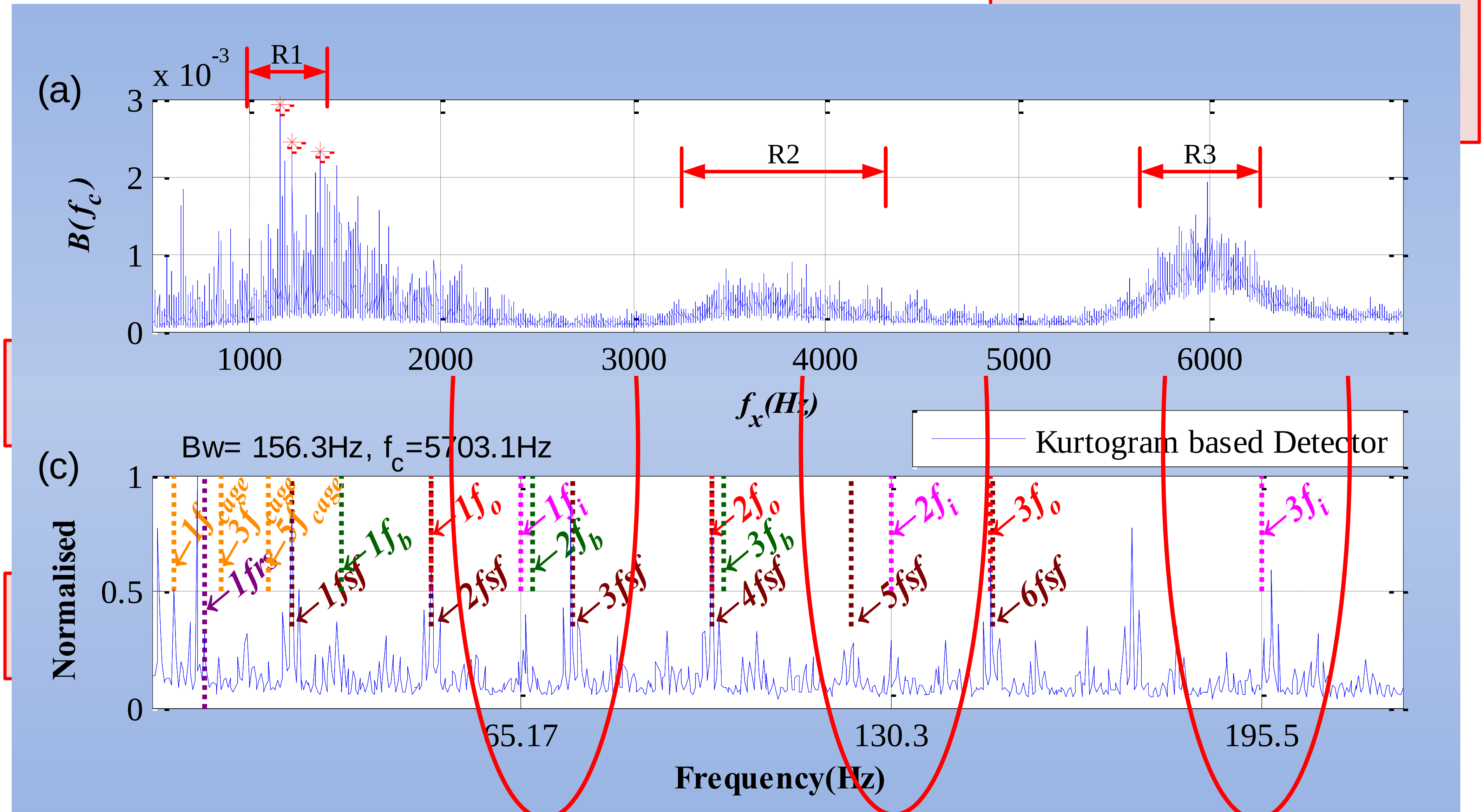

Conclusions

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- The MSB is demonstrably effective in suppressing noise and decomposing the nonlinear modulation components
  - The MSB-SE is effective in the suppression of both stationary white noise and aperiodic impact impulses.
- Simulated signal and real data studies shows that the capability of the MSB-SE exceeds that of a kurtogram-based detector.
- The application to signals from a planetary gearbox shows that the new approach can successfully detect bearing faults in circumstances where no other method is able to do so.