Condition monitoring and diagnostics of gearboxes: Industrial case studies developed at Ferrara Technopole

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University of Ferrara

UNIONE EUROPEA
Fondo europeo di sviluppo regionale

POR FESR 2007-2013
OBIETTIVO COMPETITIVITÀ E OCCUPAZIONE
Regione Emilia-Romagna

COSTRUIAMO INSIEME IL FUTURO

MechLav
Laboratorio per la Meccanica Avanzata

RETE ALTA TECNOLOGIA
EMILIA-ROMAGNA
HIGH TECHNOLOGY NETWORK

PIATTAFORMA
MECCANICA
MATERIALI

UNIVERSITÀ DEGLI STUDI DI FERRARA
- EX LABORE FRUCTUS -

The Gear Day – UniMORE Dip. di Ingegneria «Enzo Ferrari»

Modena, 8 Marzo 2016

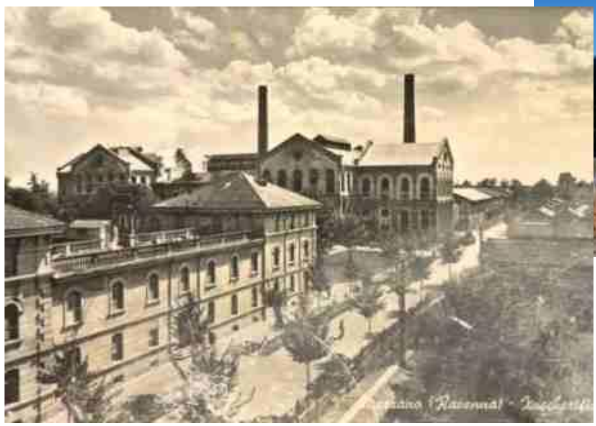
Outline

- Engineering Dept. & MechLav @ UniFE
- Condition Monitoring & Diagnostics of Gearboxes
- Case Studies
    - Faults in Gears / Rolling Bearings
    - Ordinary / Planetary Trains
    - Different Vibration Processing Techniques

ENDIF - Engineering Department In Ferrara

Science-Technology Center

Engineering Department
Head: prof Roberto Tovo



Engineering: over 2000 students

ENDIF - Engineering Department In Ferrara

- **3 RESEARCH AREAS:**
  Civil, Mechanical/Materials, ICT

- **STAFF**
- 63 professors and research associates
- 8 technicians / 6 administrative
- ≈ 60 research fellows (graduated and post-Doc)
- ≈ 60 Ph.D students

- **STUDENT: about 2.000 (400 new admissions each year).**

- **RESEARCH FUNDS (yearly):**
  - **EU and national projects > 1.316 k€**
  - **Private Companies > 1.370 k€**

- **RESEARCH LABS**
- ≈ 30 “light” labs (CAD and instrumentation)
- 3 “heavy” labs (Constructions/Hydraulics, Geotechnics, Mechanics)
- 2 anechoic chambers (acoustic and electromagnetic)

50Hz - >10kHz
(10.1 x 9.5 x 8.3 m)

up to 18GHz (9,10 x 5,80 x 5,55 m)

Mission

- **Organization completely dedicated to industrial research, technologic services and transfer for companies.**

- Dedicated **staff** of high qualification (20 people), coordinated by university staff (18 people).

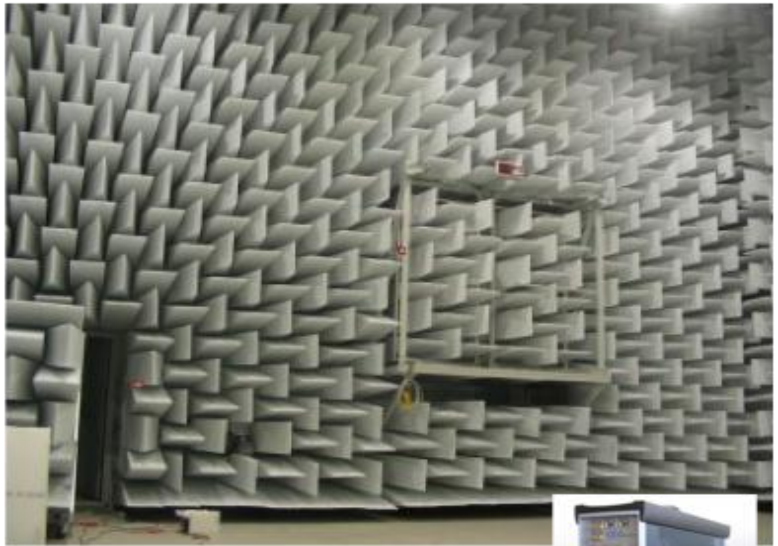
- **Activities** carried out with **industrial schedule and modalities**:
  - Technologic services;
  - Technologic transfer of advanced methodologies in industrial environment;
  - Training for company personnel;
  - Collaboration with companies in industrial research projects supported by regional, national and EU programs.

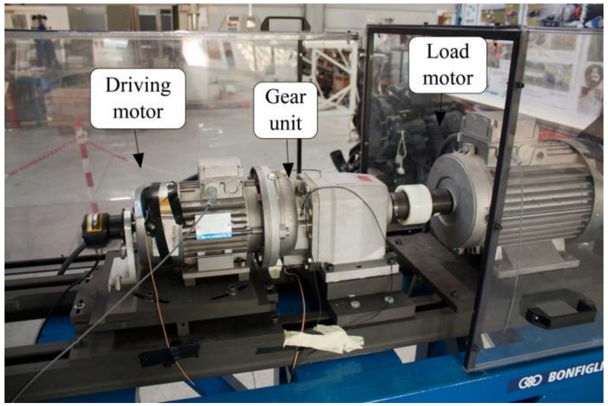
Integrated skills

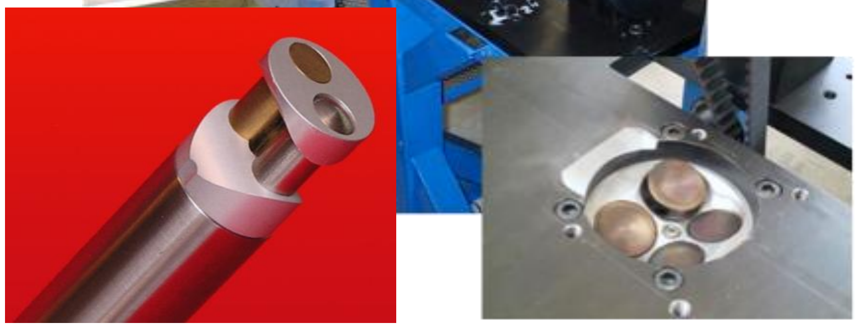
- Fluid-dynamics
- Structural integrity
- Materials
- Vibro-acoustics (NVH)
  - Vibro-acoustic design and optimization of products
  - CM & Diagnostics
  - Noise control (passive / active)
  - Porous materials
- Automation
- ICT for manufacturing > E-maintenance

Facilities at MechLav-UniFE

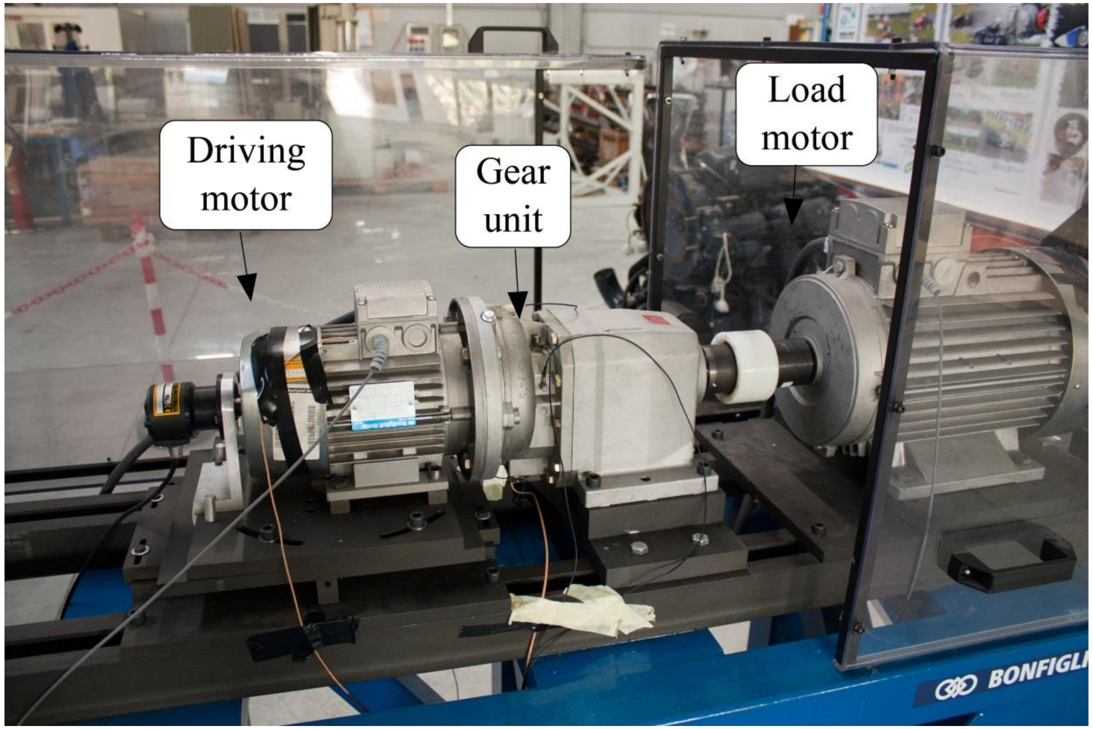
• Anechoic and hemi-anechoic chamber (50 Hz cut-off frequency)
•Complete instrumentation for acoustic and vibration measurements and modal analysis
•Test bench for rotating components (gears, bearings, joints)
•3-Axis Electro-Dynamic Vibration System
•Contactless sensors > Laser Doppler vibrometers, Microflown
•Software MB, FEM, BEM, psycoacoustic for simulation and optimization
•Model-Test correlation

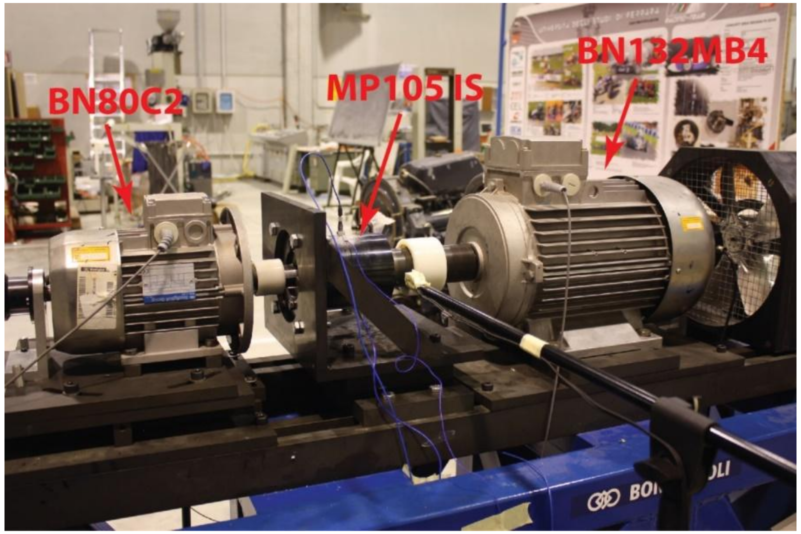




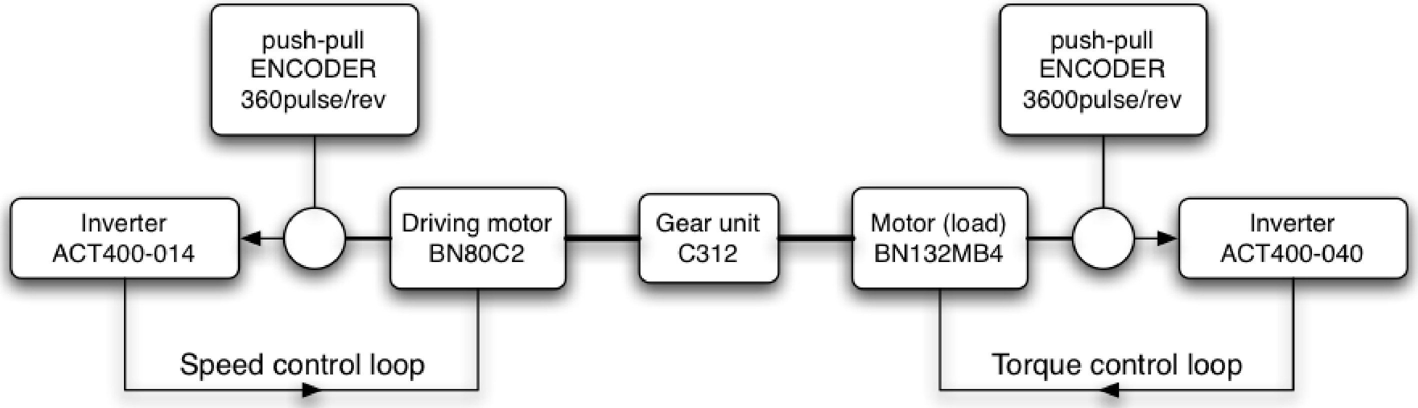


Gearbox test-rig @ University of Ferrara





	Driving motor	Loading motor
Nominal power [kW]	1.5	9.2
Nominal torque [Nm]	5.1	61
Nominal speed [rpm]	2800	1440
Number of poles per phase winding	2	4



Facilities at MechLav-UniFE

- Fully instrumented test rig for fluid machine testing
- Fatigue testing
- Reverse engineering tools
    - Portable 3D Scanner
    - Rapid Prototyping
    - Quality control and assessment
- Scientific cluster for high performance FEM/CFD computations

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L'ENERGIA CHE TI ASCOLTA.

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il clima per ogni tempo

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FAVA
impianti per pastifici

TECHNODRIVE

FCA

Condition Monitoring & Diagnostics

Aims:

- Avoiding abrupt failures
- Predictive maintenance
- Quality control in manufacturing

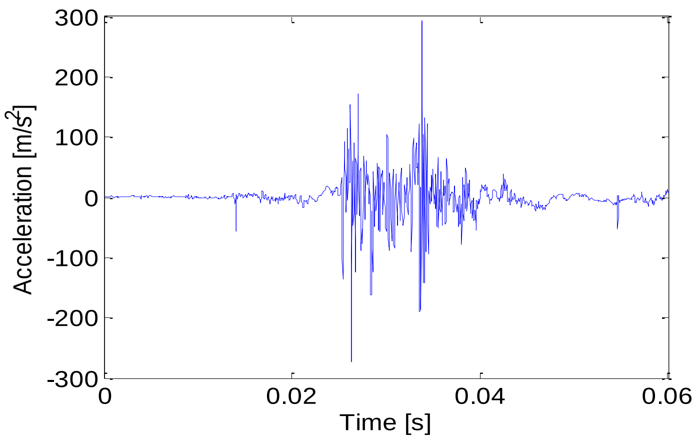
In **gearboxes**:

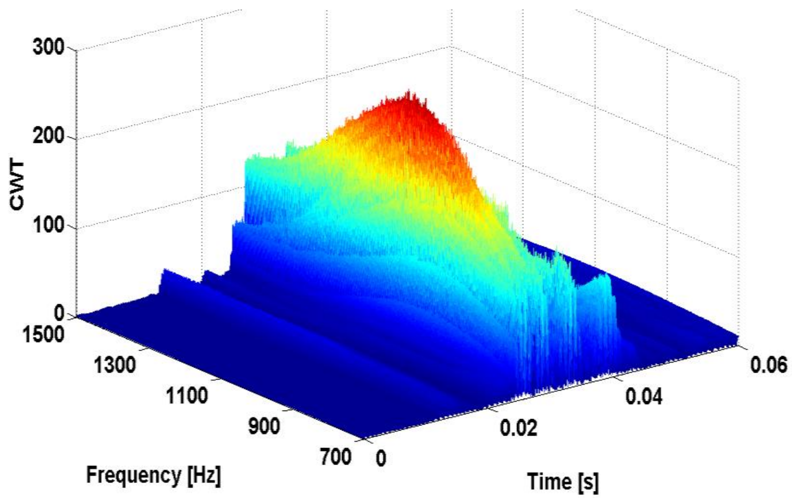
- **Gears**
    - Pitting > Spalling
    - Cracks
    - …
    - Eccentricity
    - Profile and geometrical errors
- **Rolling bearings**
    - Pitting
    - Distributed wear
    - …

Vibration analysis is the most effective tool …

Condition Monitoring & Diagnostics
Methodology

Development of new advanced techniques for faulty detection → Evaluation of the effectiveness of such techniques → Development of hw/sw systems – customized on the basis of specific requirements





Time Domain
statistical analysis

Angular Domain
TSA, Order tracking

Cyclostationary Analysis
Cyclic power, Cyclic modulation spectrum, spectral correlation density, Blind signal extraction

Time-Frequency Analysis
Short time Fourier transform, Countinous Wavelet transform, Discrete Wavelet transform, Wigner-Ville distribution

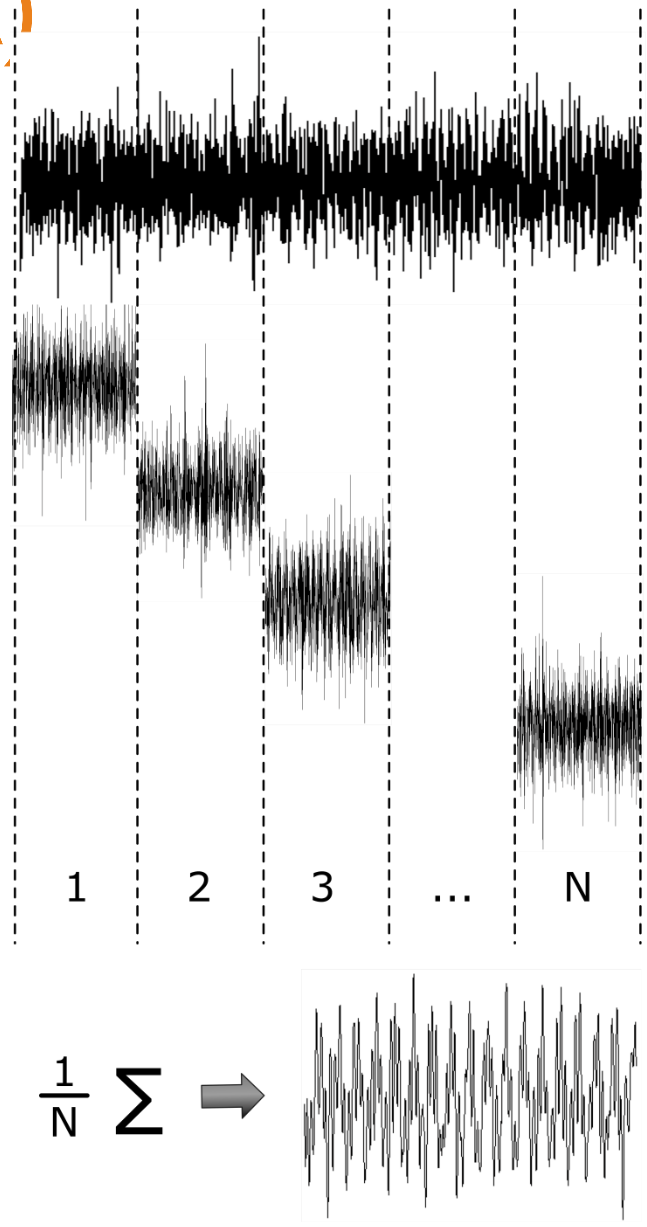
Gear diagnostics
Synchronous Average (SA)

Synchronous averaging is one of the most powerful techniques for the extraction of periodic signals from a composite signal. It is based on averaging periodic sections, necessitating an a-priori knowledge of the period sought. It is one of the most effective signal processing tools applied to rotating machinery, and has been known and used for decades

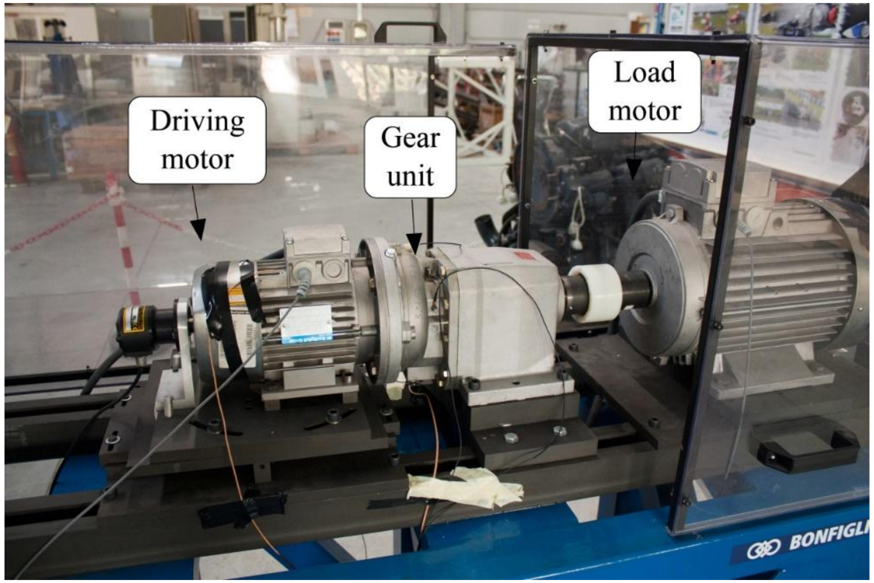
Resampling in angular domain at constant angular position, thanks to a tachometer signal.

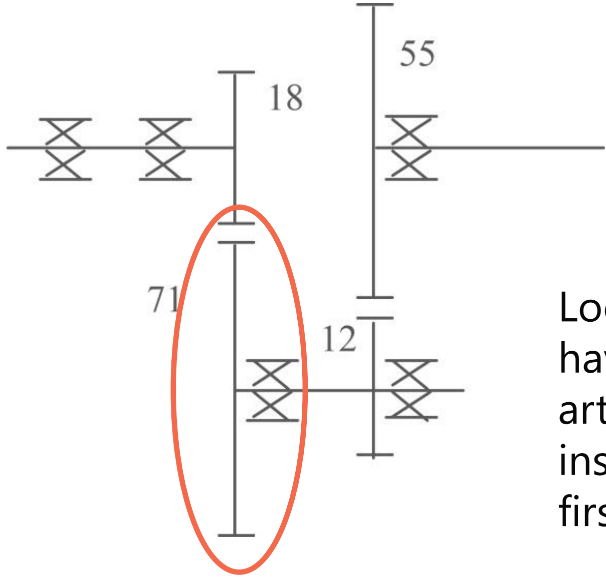
Averaging portions of signal exactly corresponding to **one revolution of the gear** of interest.

Periodic components - synchronous with that gear - are unchanged; **non-synchronous component are removed** (due to other gears and mechanical parts).



Ordinary Gearbox
Case study 1: Localised fault in gears

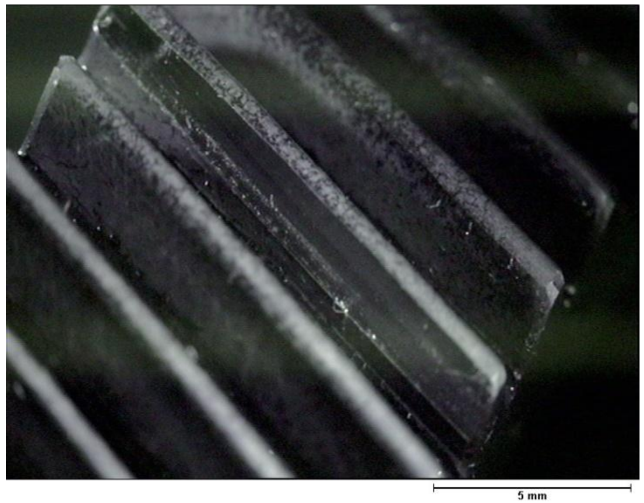




Localised faults have been artificially inserted in the first stage gear

Sp25%
[4mm x 2mm x 0.6mm]

Increasing fault dimension



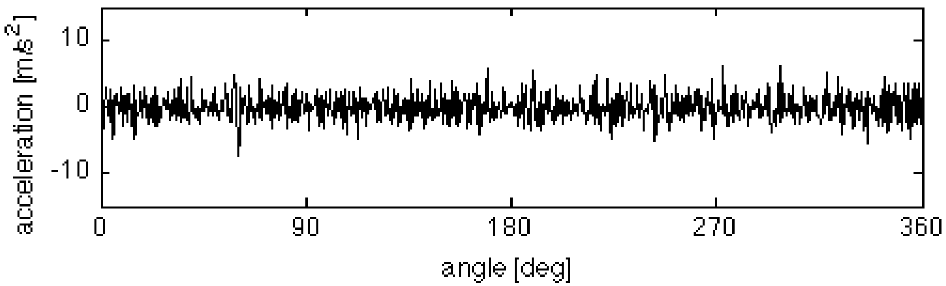
Sp100%
[15.5mm x 2mm x 0.6mm]

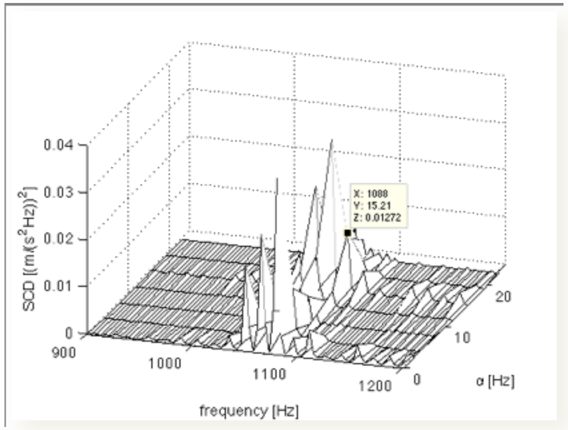
Case study 1: Localised fault in gears

Synchronous Average (SA)

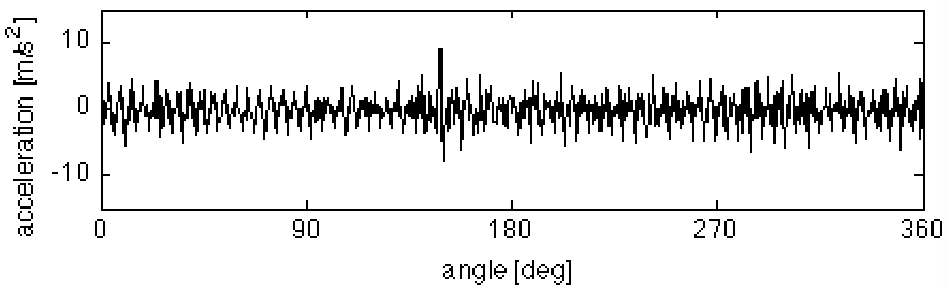
SCD – Spectral Correlation Density
Correlation between 'regular' components (meshing) and fault components

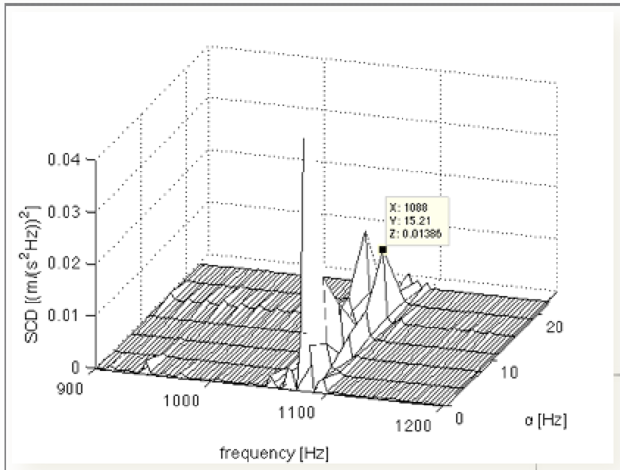
Sp 25%:



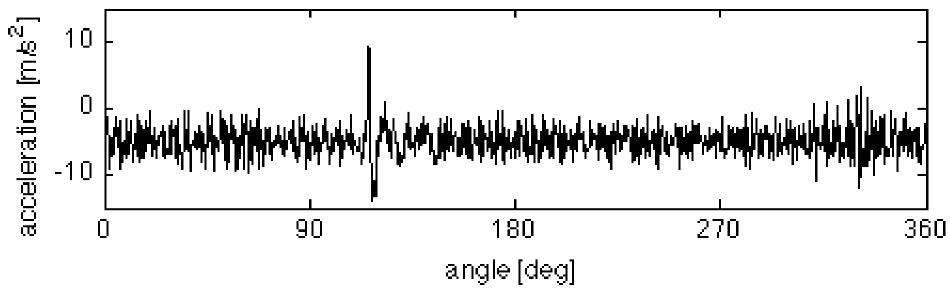


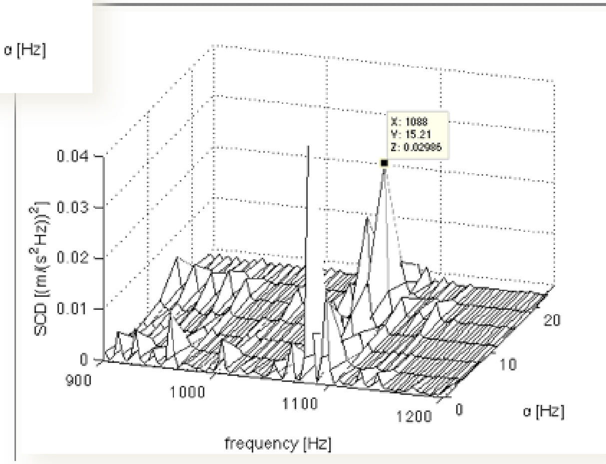
Sp 50%:





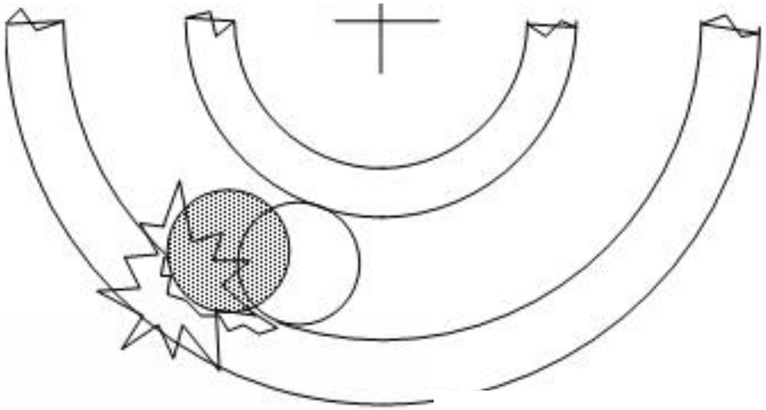
Sp 100%:

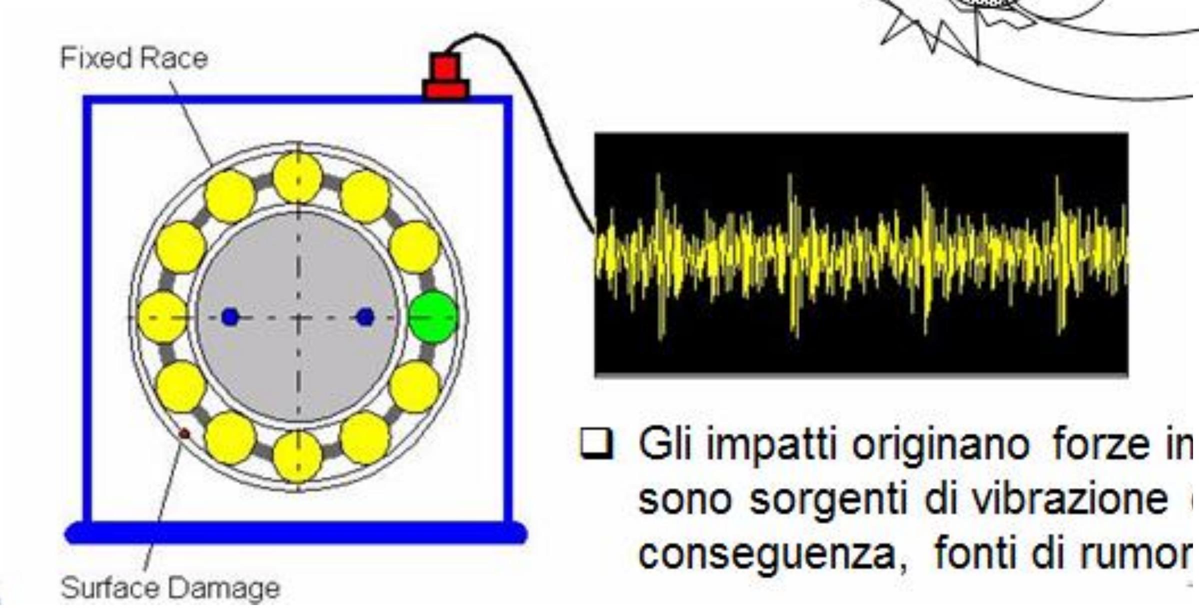


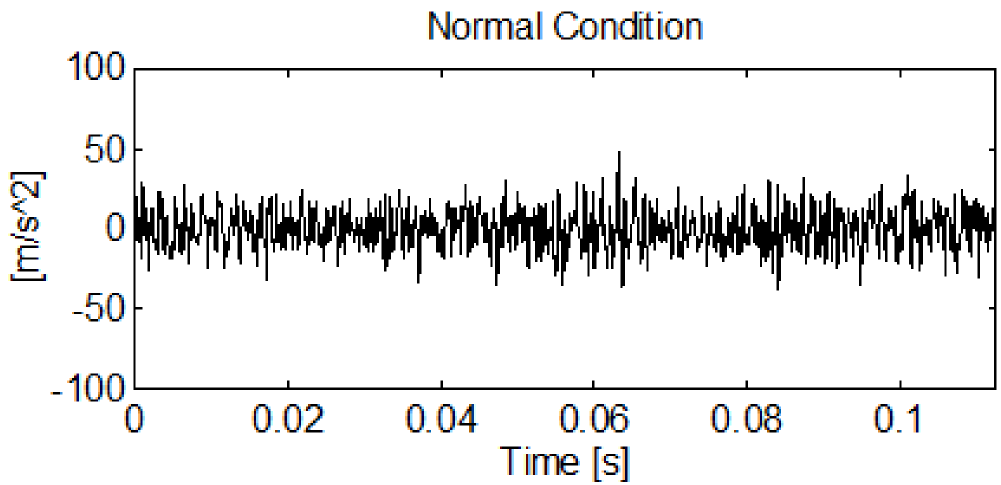


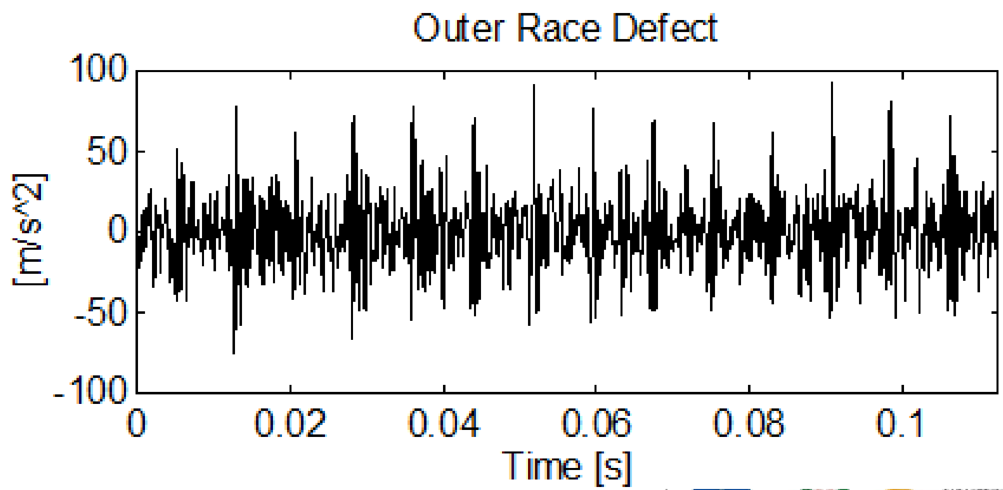
Rolling Bearings – Fault effects

- Avviene un impatto ogni volta che un elemento volvente attraversa un danno superficiale.



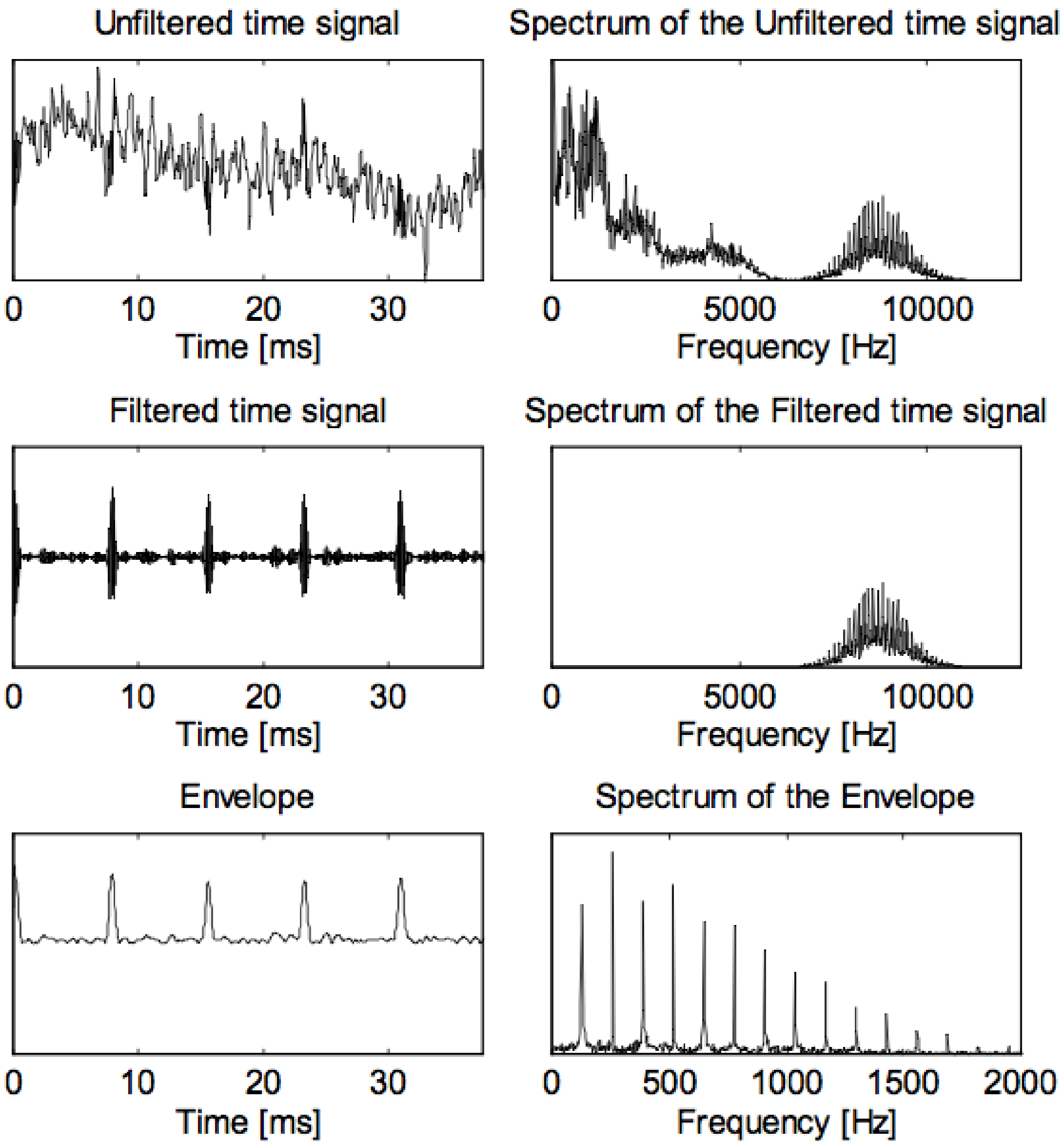






- Initial Pitting
- Periodic impacts between rolling elements and race
- Train of impulses at characteristic frequencies
- Excitation of resonances

Envelope analysis



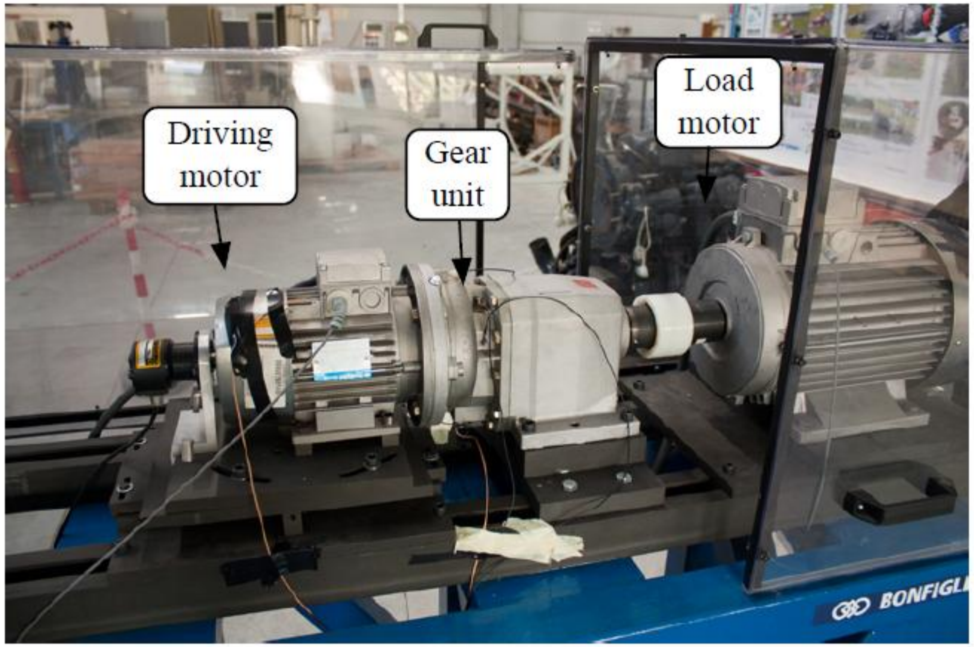
Cyclostationary analysis

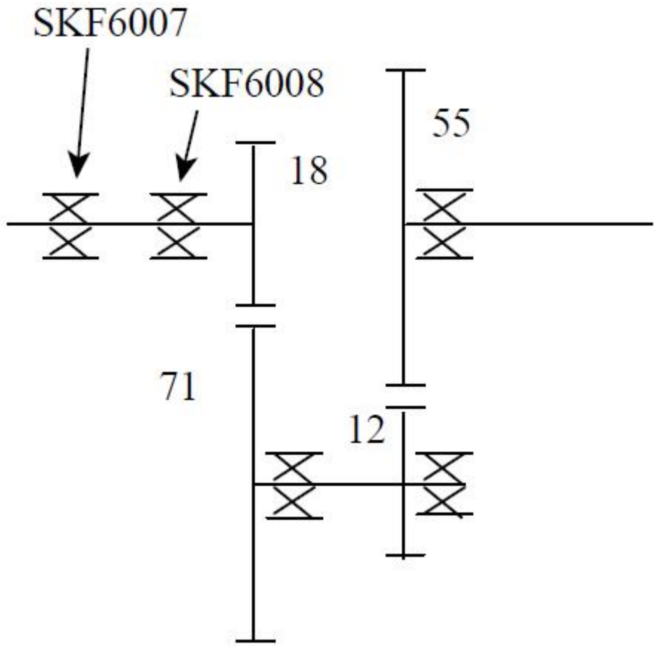
Generally speaking, a cyclostationary signal is a signal which exhibits **hidden periodicity, due to faults in rotating machinery**

Time signal − **Time synchronous average** = **Residual signal**

Advanced cyclostationary processing on residual signal

Case study 2: Distributed fault on ball bearings





Description	Symbol	SKF6007	SKF6008
Rotation frequency [Hz]	f_r	45	45
Outer race fault frequency [Hz]	f_o	207	230
Inner race fault frequency [Hz]	f_i	288	310
Cage fault frequency [Hz]	f_c	18.8	19.2
Ball fault frequency [Hz]	f_b	268	300

Accelerated life-time test on degreased ball bearings

Case study 2: Distributed fault on ball bearings

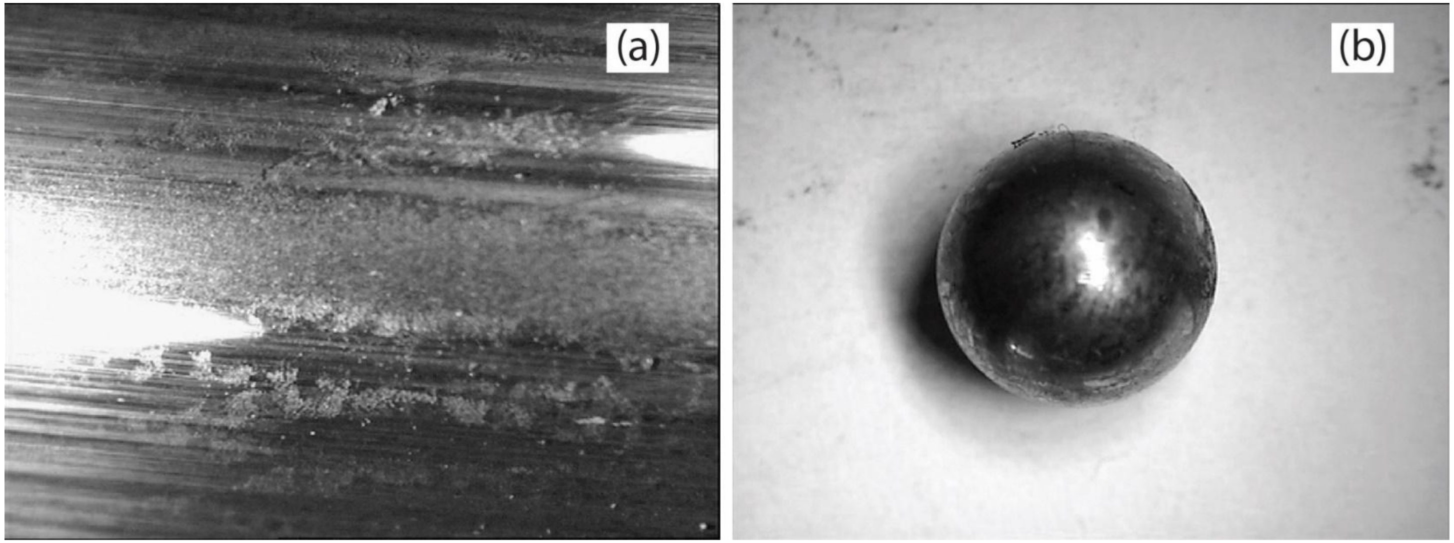
Tests were carried out over a time span of 12 days. During this period, in order to monitor the fault evolution, the time among acquisitions has been proportionally decreased, such as: 1 hour for day 1, 30 min for days 2 and 3, 15 min for days 4 and 5, 5 min for day 6 to 12, for 4728 acquisitions in total

day	1	2	3	4	5	6	7	8	9	10	11	12
# acquisition/day	24	48	48	96	96	288	288	288	288	288	288	288

Total number of acquisitions: 4728

# acquisition/day	2	4	4	4	6	6	6	6	6	6	8	5

# of presented acquisitions: 64

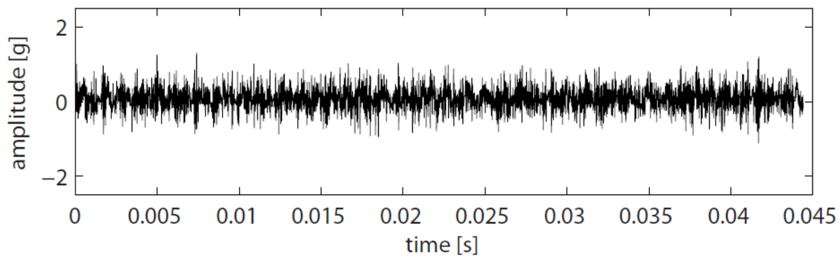


Distributed pitting can be seen on the **outer ring of SKF6007**, and on the **rolling element of SKF6008** at the end of the test.

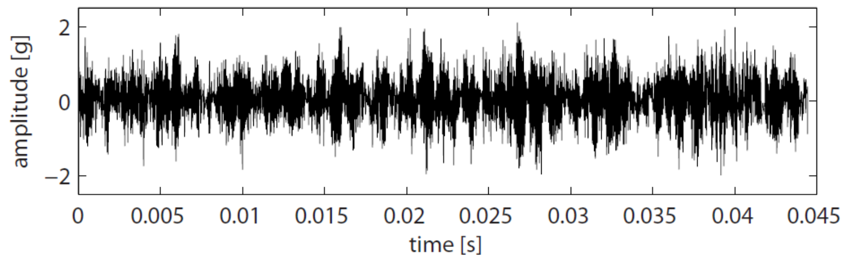
Case study 2: Distributed fault on ball bearings

Raw vibration signal >NO periodic impulses

- First acquisition

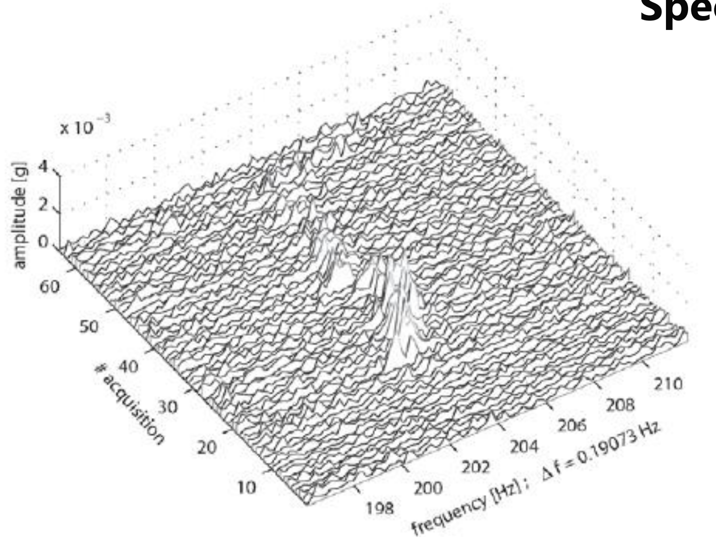


- Last acquisition



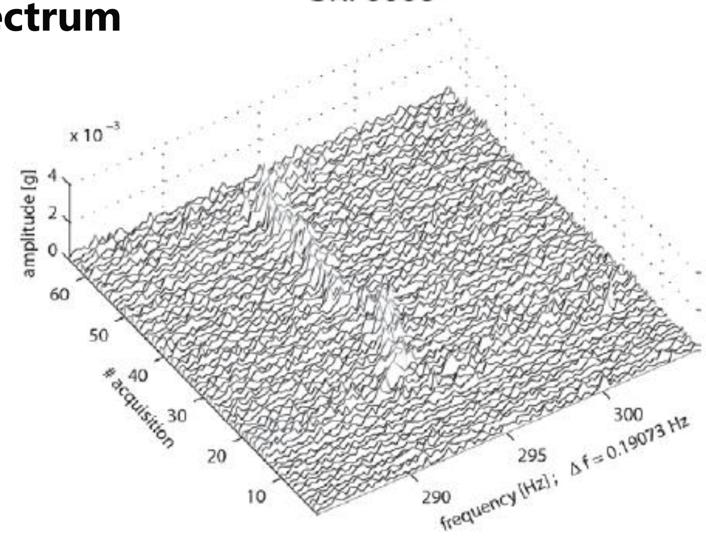
ENVELOPE SPECTRUM

Outher race fault frequency
SKF6007



Envelope Spectrum

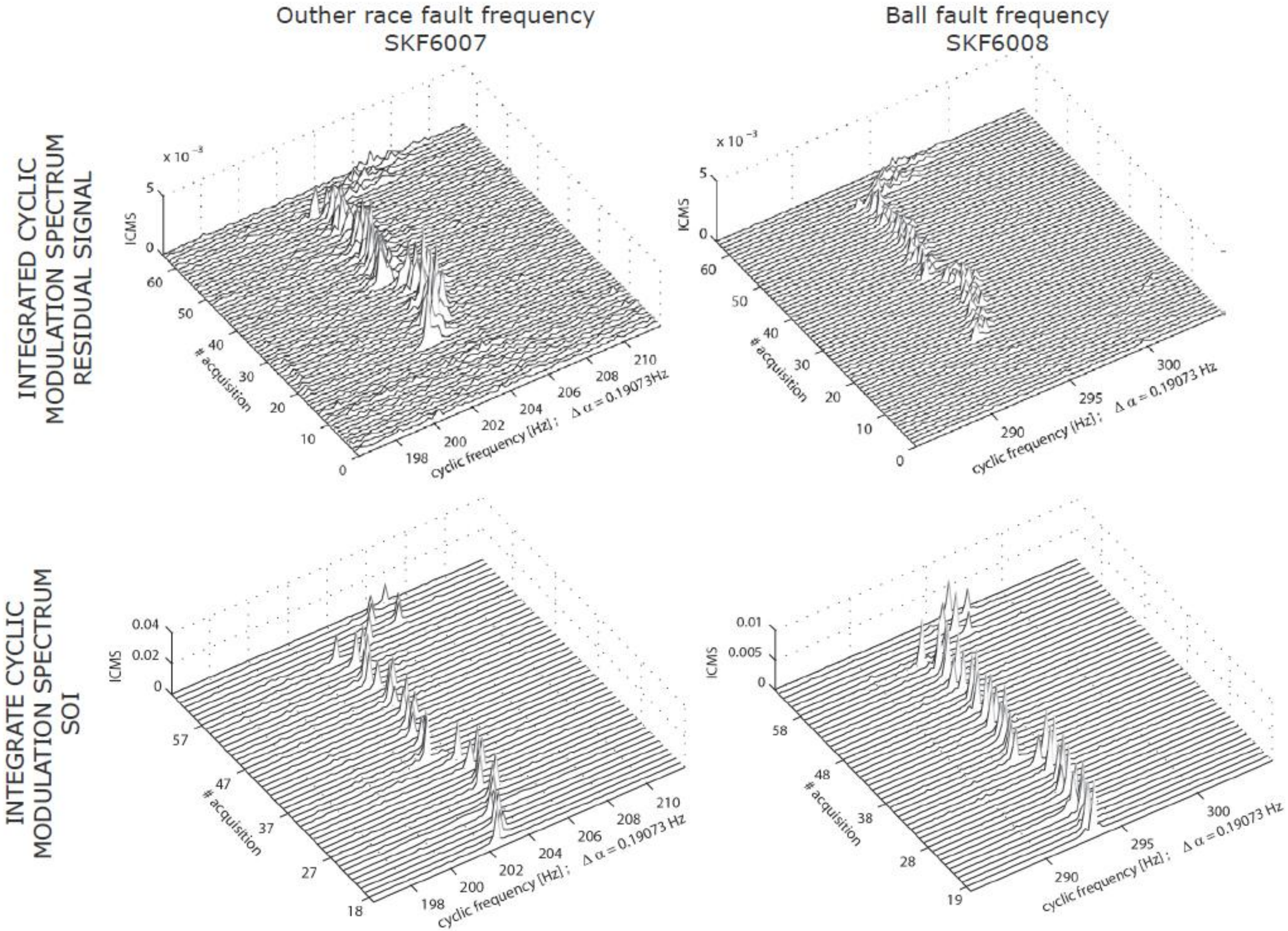
Ball fault frequency
SKF6008



Envelope Spectrum highlights the initial fault whilst it cannot supply further information concerning the extension of the wear. In fact, this technique is sensitive to the slight, but detectable, impacts originated at the beginning of the fault manifestation.

Case study 2: Distributed fault on ball bearings

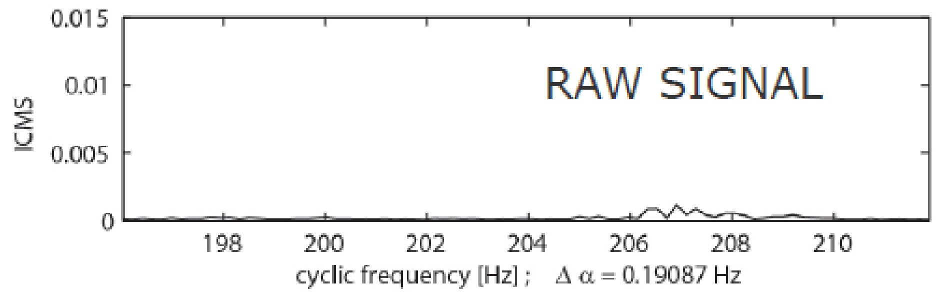
Advanced cyclostationary processing

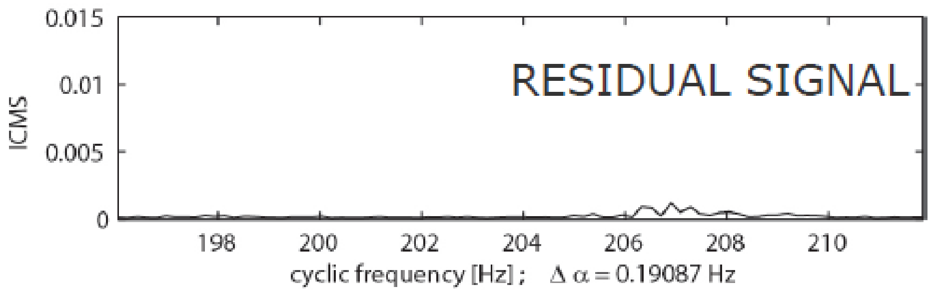


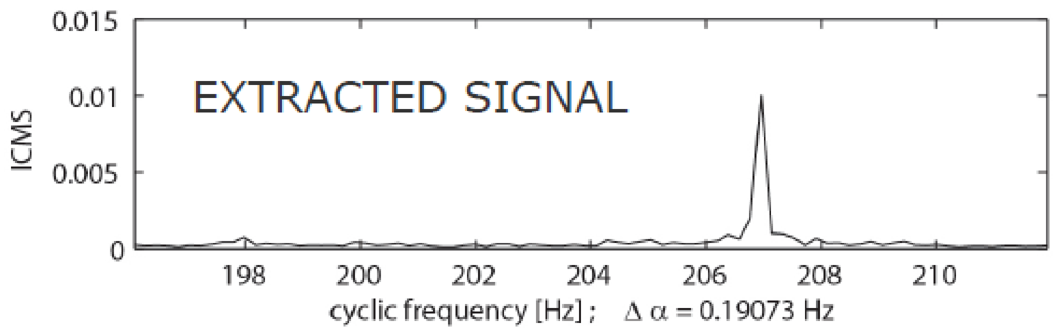
Blind signal extraction > extraction of the signal only due to the bearing

Case study 2: Distributed fault on ball bearings

Outher race fault frequency SKF6007
Last acquisition







Planetary gearbox diagnostics

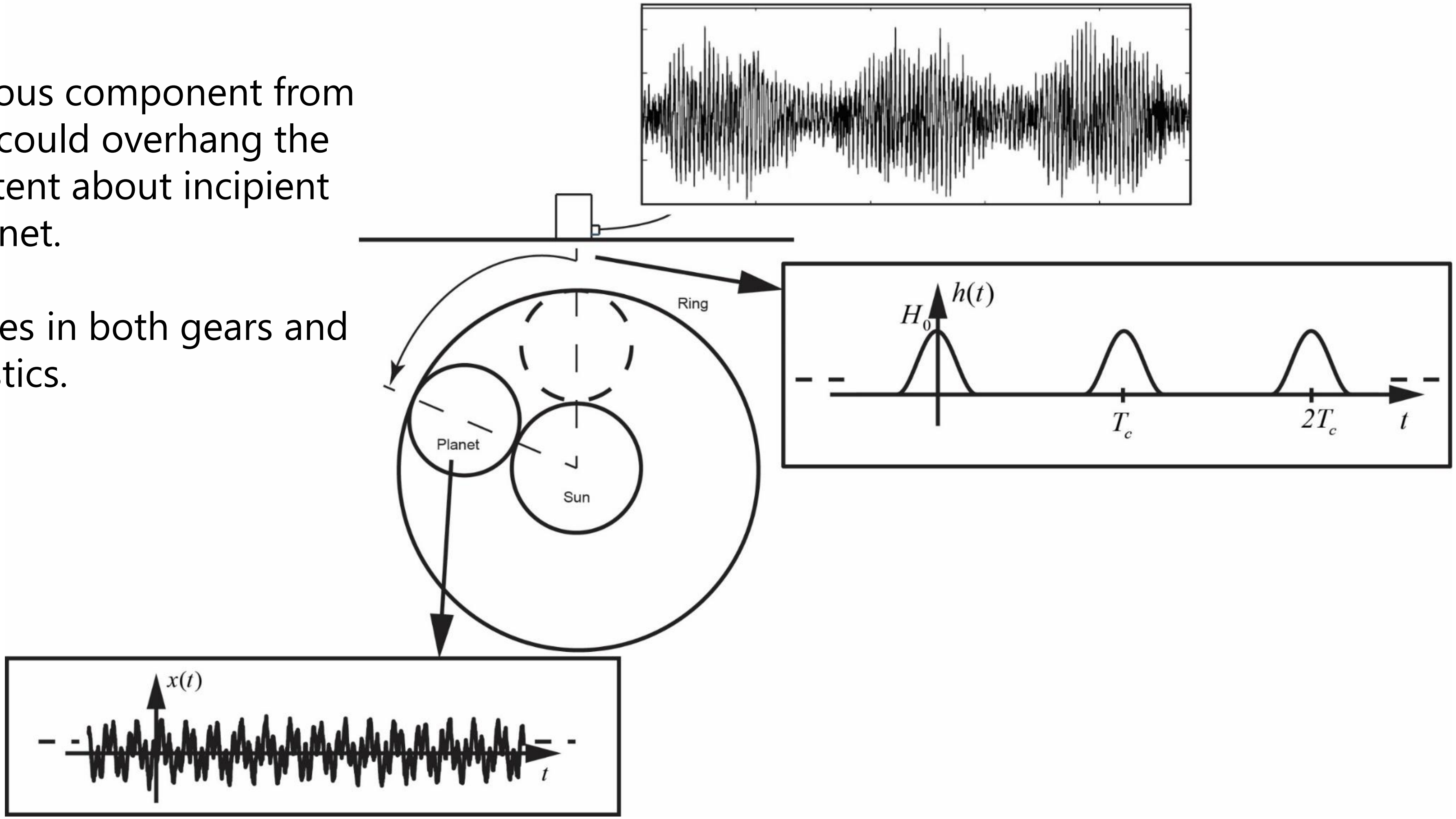
Generally, accelerometer is placed on the gearbox case near the ring gear.

Variable distance between one of the planet and the accelerometer.

Amplitude modulation of the vibration signal.

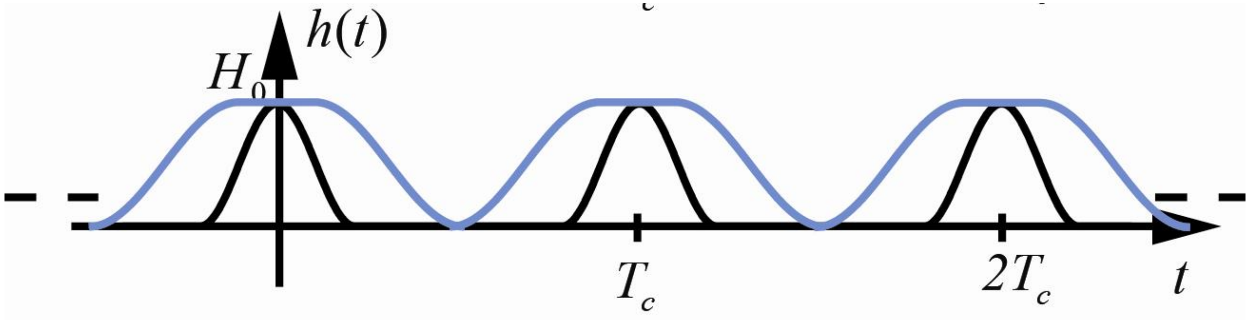
Noise and spurious component from healthy planets could overhang the informative content about incipient faults in one planet.

Serious difficulties in both gears and bearing diagnostics.

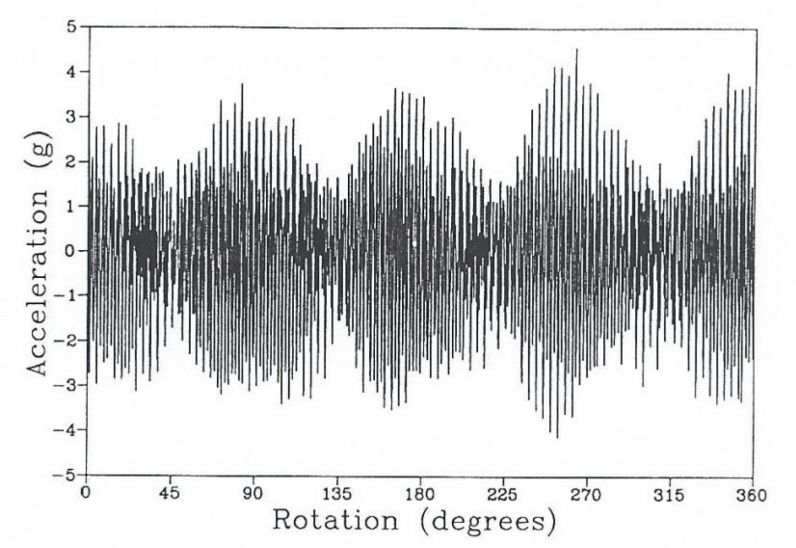


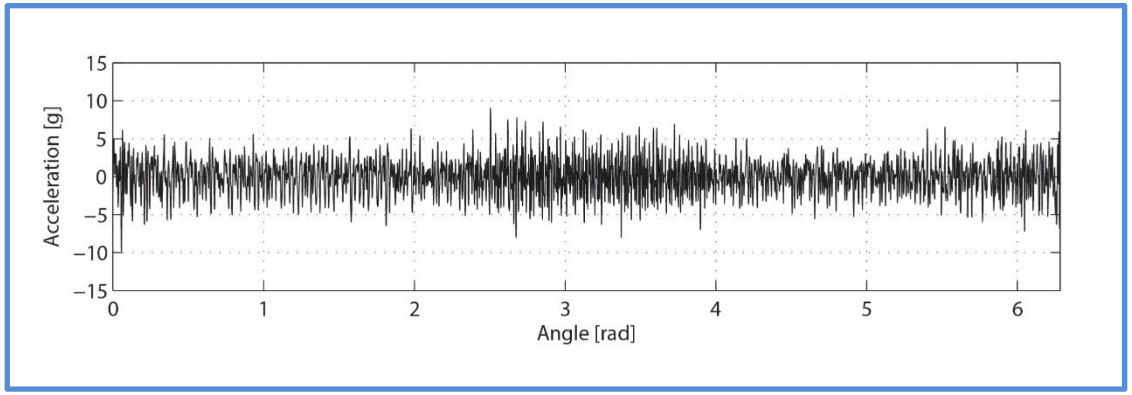
Planetary gearbox diagnostics

For diagnostics, it is necessary **to extract the vibration signal due to one specific planet**.
For this purpose, it is necessary to know **when the planet is meshing in correspondence of the transducer.**



Amplitude modulation can be used … but sometimes it is NOT clear





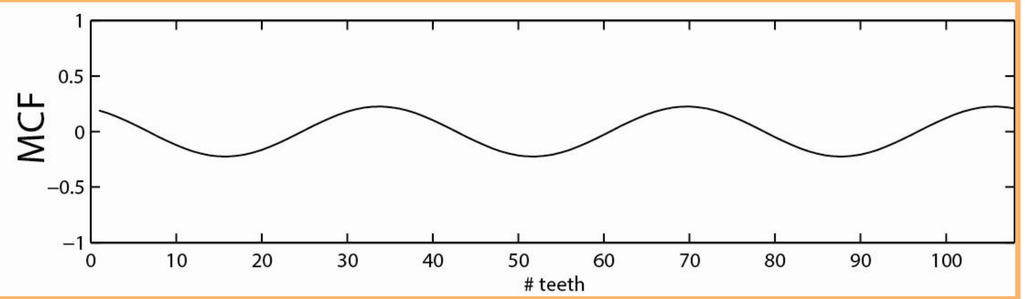
Extraction of Planet Synchronous Average

Evaluation of the planet-transducer position with a simple statistical parameter >obtaining hidden modulation

$$MCF = \frac{x_{peak-peak}(t)}{RMS(x(t))}$$

Filter the MCF function around the order which corresponds to the planet gear number

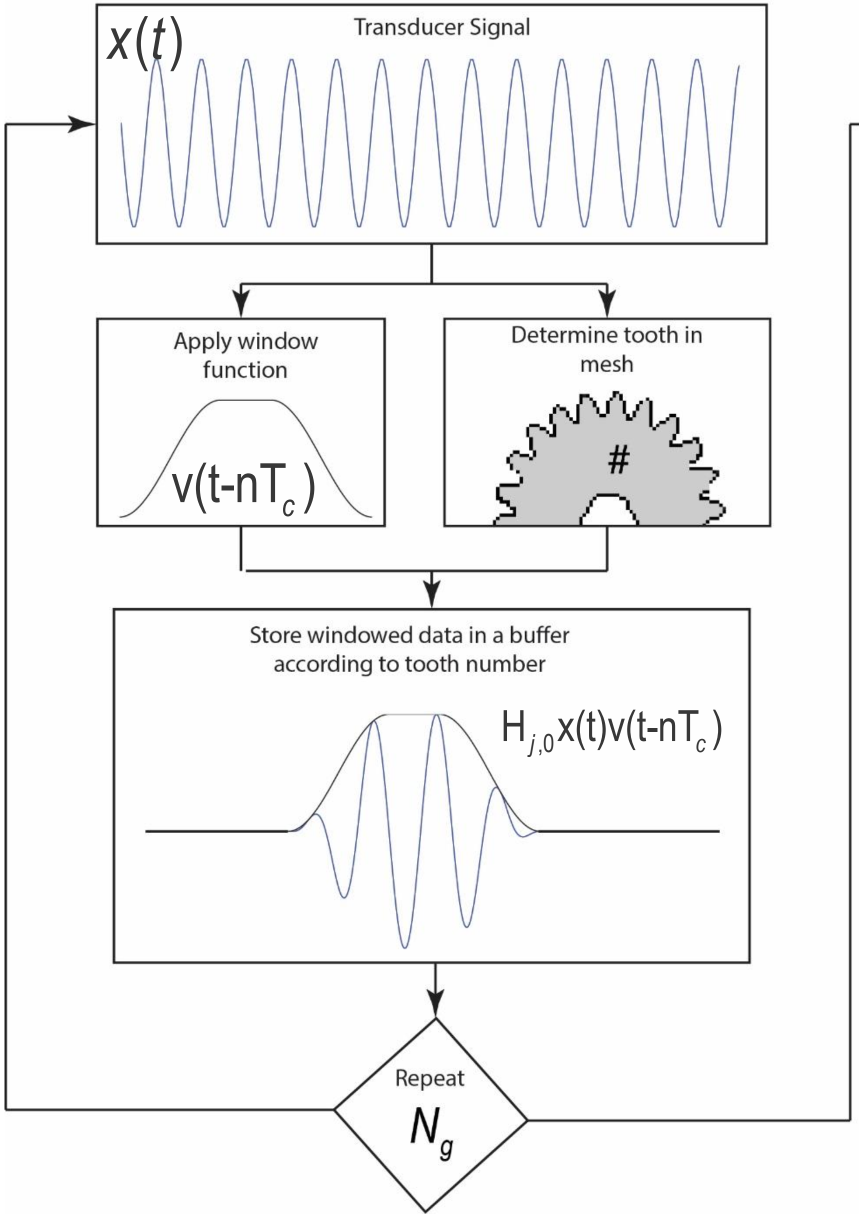
Modified crest factor MCF

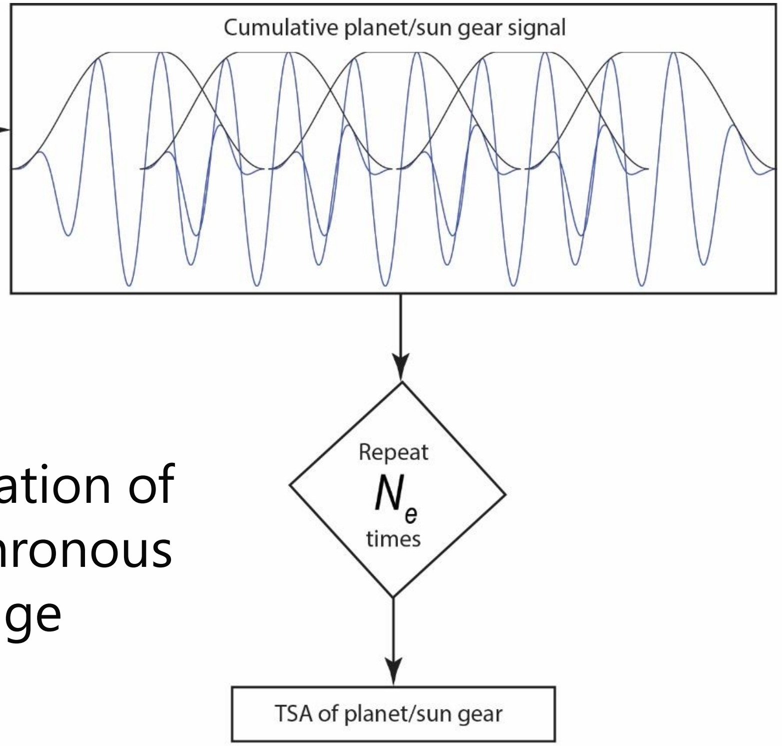


Extraction of Planet Synchronous Average

Recovering the planet vibration signal - tooth by tooth - as it would be if the planet was always the same distance from the transducer

$$[H_{j,0}x(t)v(t-nT_c)]*g(t) \qquad g(t) = g(t-nT_g)$$





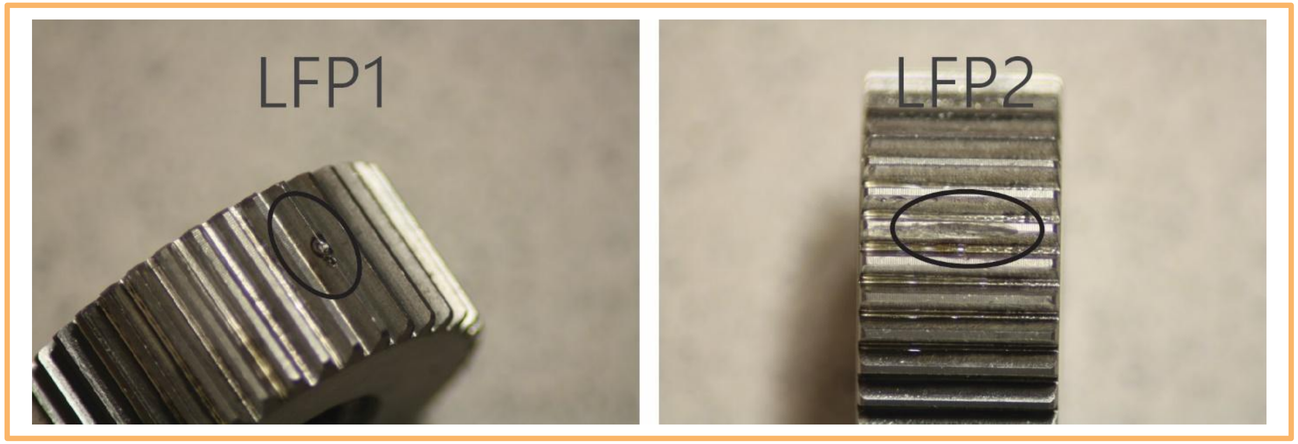
Evaluation of Synchronous Average

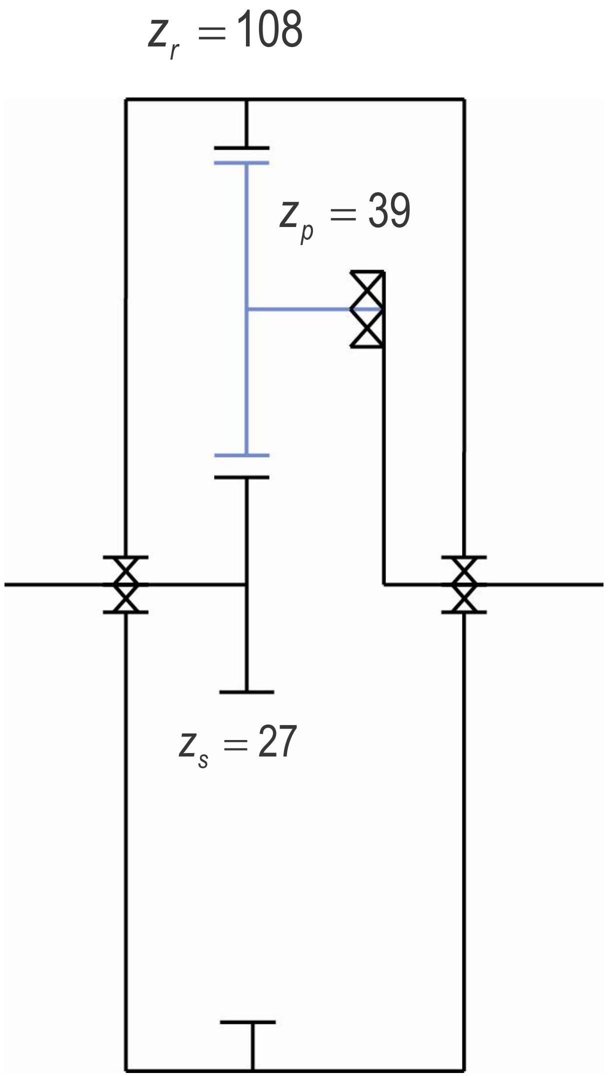
$$x_g(t) = \frac{1}{N_e N_v} \sum_{n=0}^{N_e N_g - 1} [H_{j,0}x(t)v(t\text{-}nT_c)] * g(t)$$

P.D. McFadden,
A technique for calculating the time domain averages of the vibration of the individual planet gears and sun gear in an epicyclic gearbox,
Journal of Sound and Vibration, Vol. 144, No. 1, 1991

Case study 3: Localised faults in planet gear

Artificial spalls





Signal acquisition parameters

$$f_s = 102kHz \longrightarrow f_s = 12kHz$$

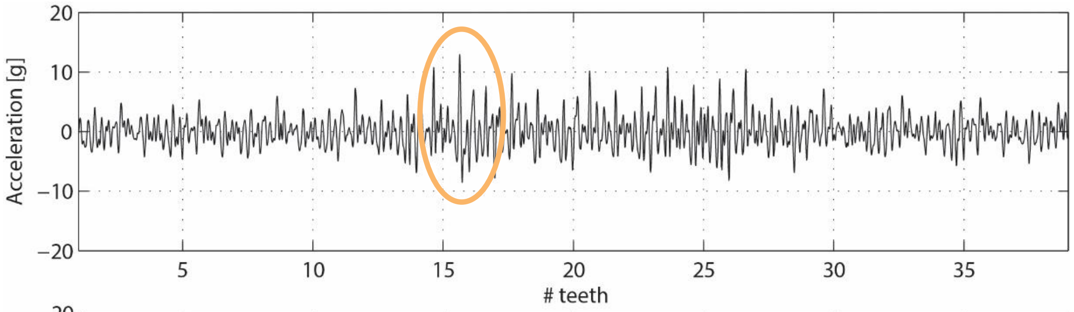
$$T = 60s$$

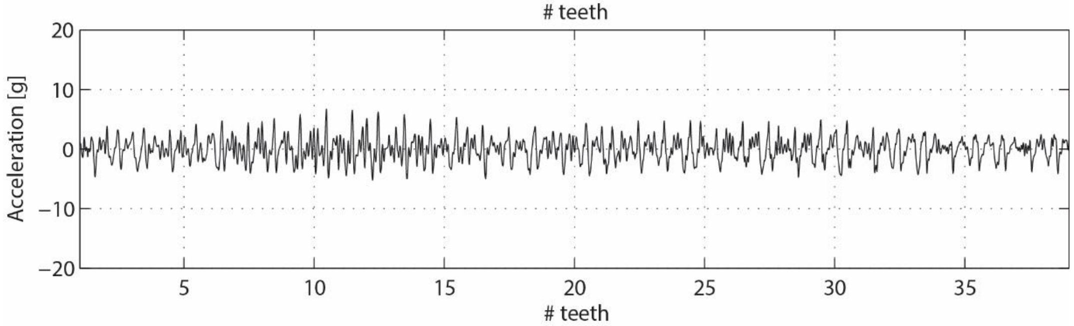
Nominal driving motor speed $= 20Hz$

Nominal output shaft torque $= 12Nm$

Case study 3: Localised faults in planet gear

Planet Synchronous Average

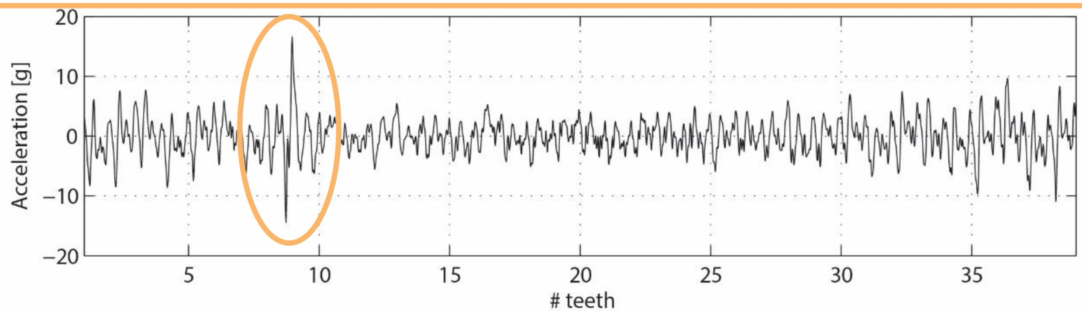


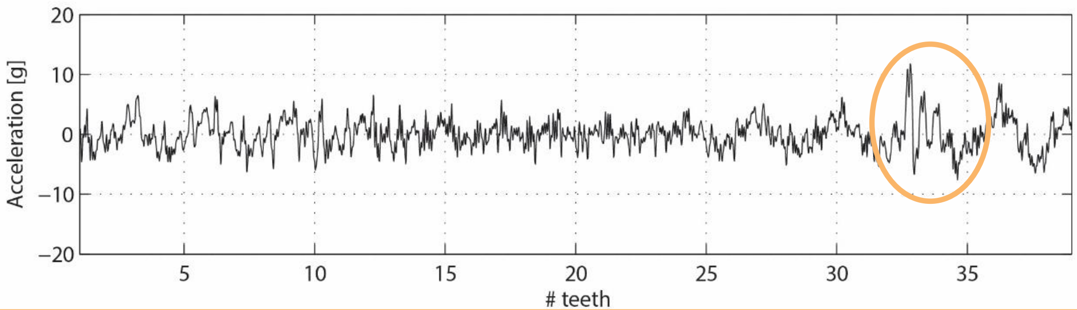


Closest position: 34th tooth

LFP1

Farthest position: 88th tooth





Closest position: 10th tooth

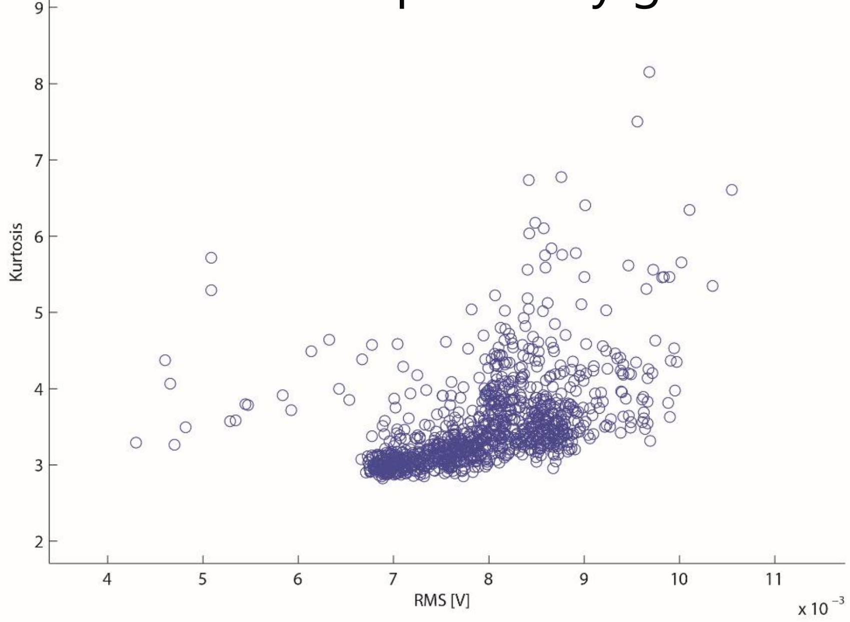
LFP2

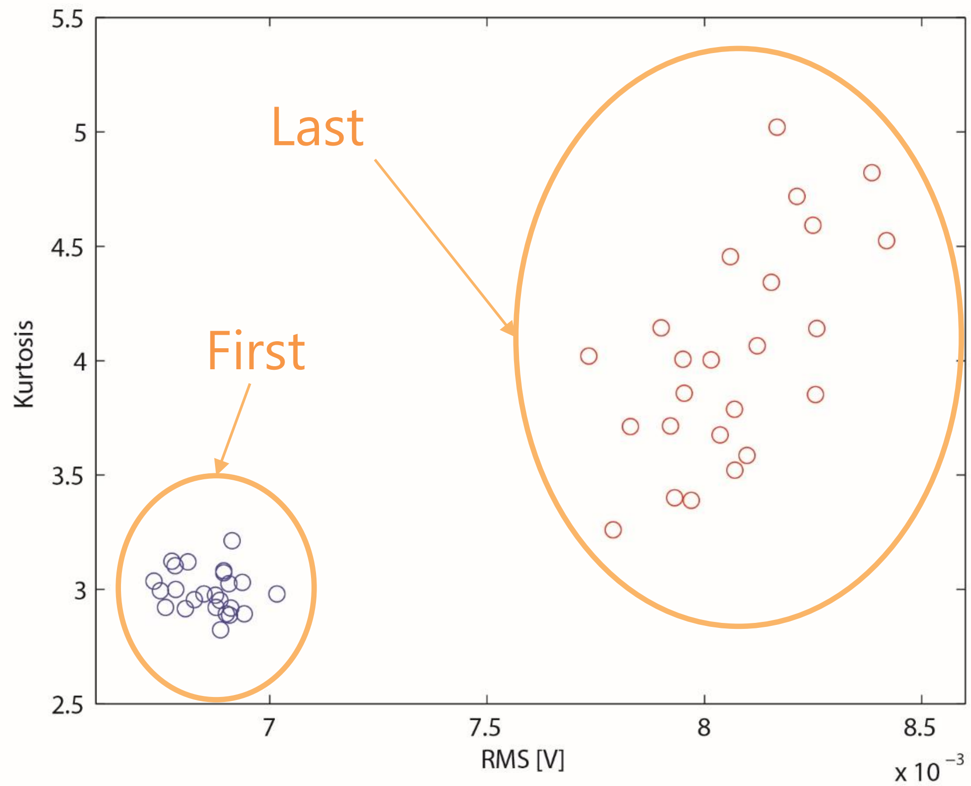
Farthest position: 64th tooth

Case study 4: Localised fault in planet gear Pitting – wear in operation

Simple statistical parameters could be used in an **automated procedure** for monitoring the evolution of faults

Statistical parameters – RMS and kurtosis - evaluated during a life-time test of planetary gearbox



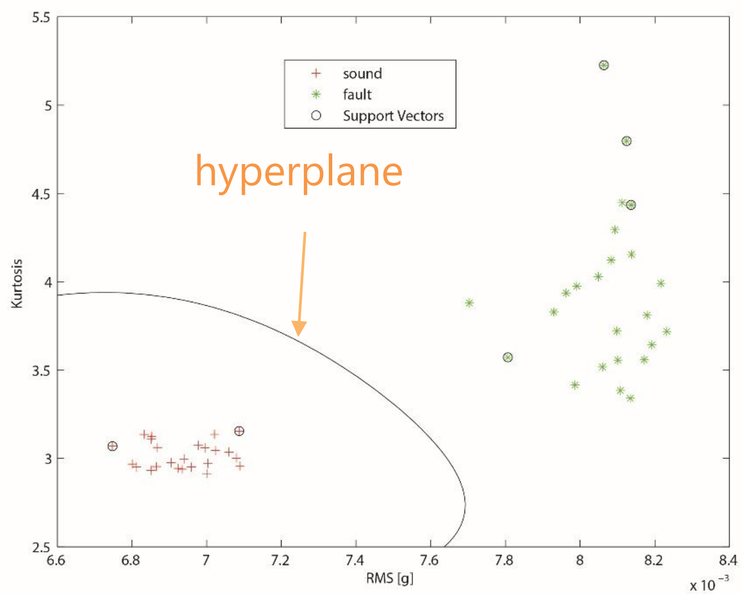


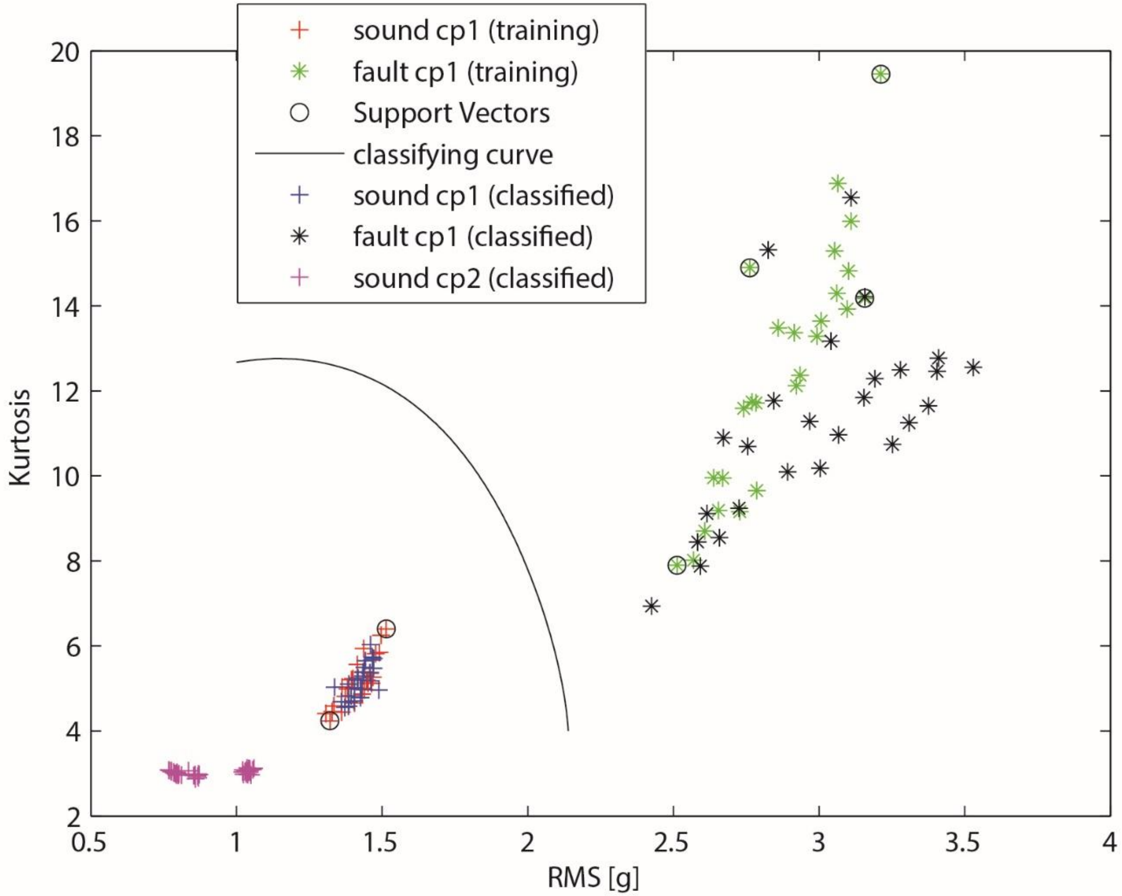
Case study 4: Localised fault in planet gear Pitting – wear in operation

Automatic classification tool: Support vector machines (SVM) are supervised learning models with associated learning algorithms that analyze data and recognize patterns

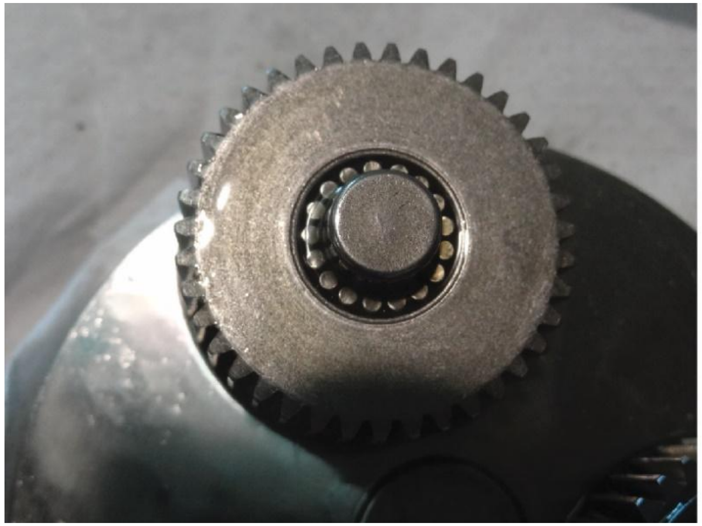
- Optimal hyperplane for linearly separable patterns
- Extend to patterns that are not linearly separable by transformations of original data to map into new space – Kernel function

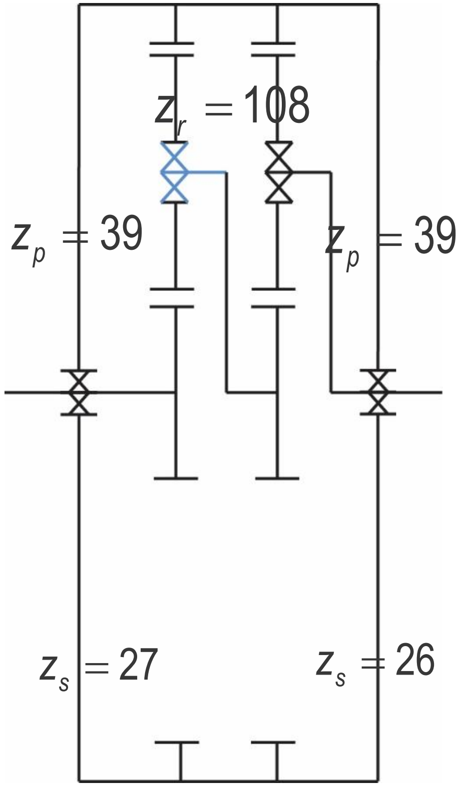
SVMs maximize the margin around the separating hyperplane





Case study 5: Planet bearing diagnostics





Full complement needle roller bearing

Artificial localized fault in the inner ring

Characteristic fault frequency = 11 Hz

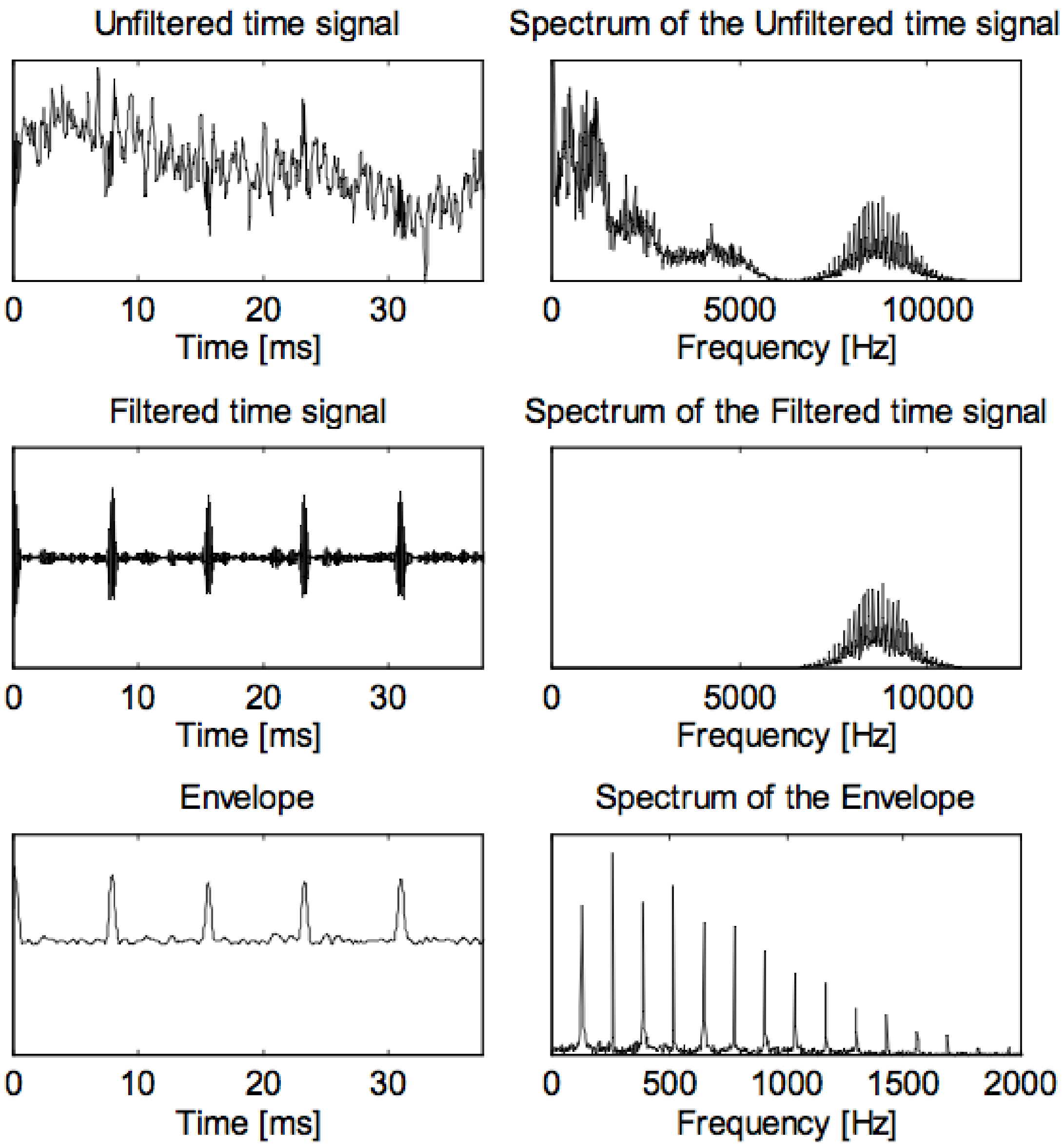
Signal acquisition parameters $f_s = 51.2kHz$, $T = 60s$

Nominal driving motor speed $= 45Hz$

Nominal output shaft torque $= 12Nm$

Case study 5: Planet bearing diagnostics

Envelope analysis:



Cyclostationary analysis:

Generally speaking, a cyclostationary signal is a signal which exhibit hidden periodicity

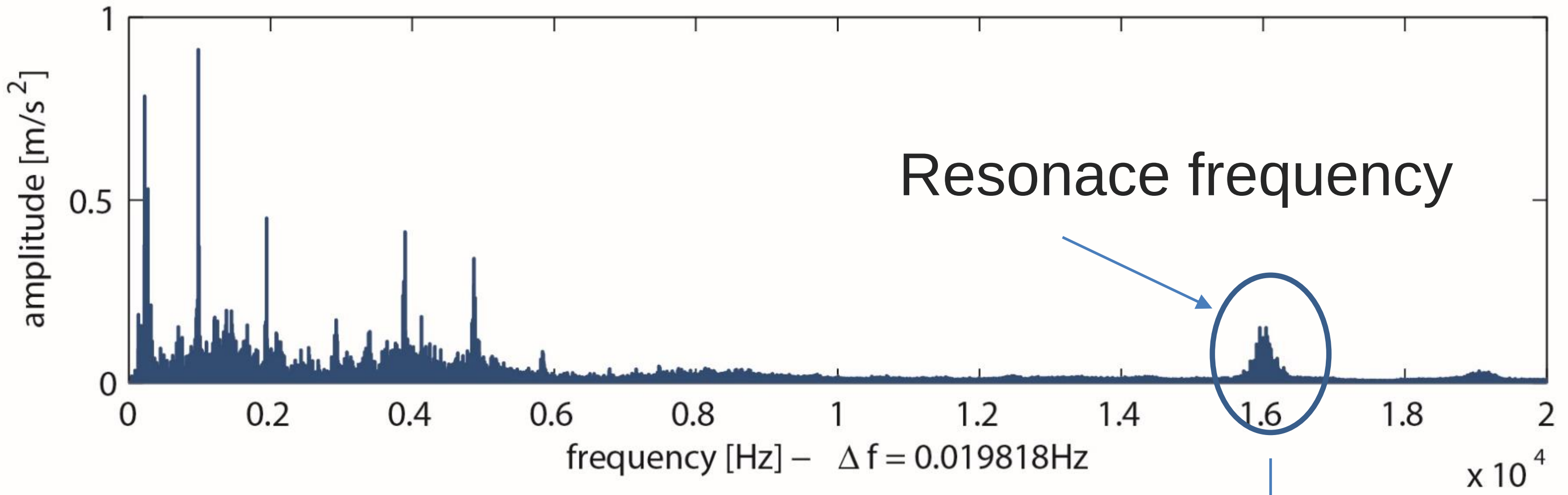
$$\text{Time signal} - \text{Time synchronous average} = \text{Residual signal}$$

Cyclic Power: period energy due to fault

$$CS(k) = FFT\left(\left|\text{residual signal}\right|^2\right)$$

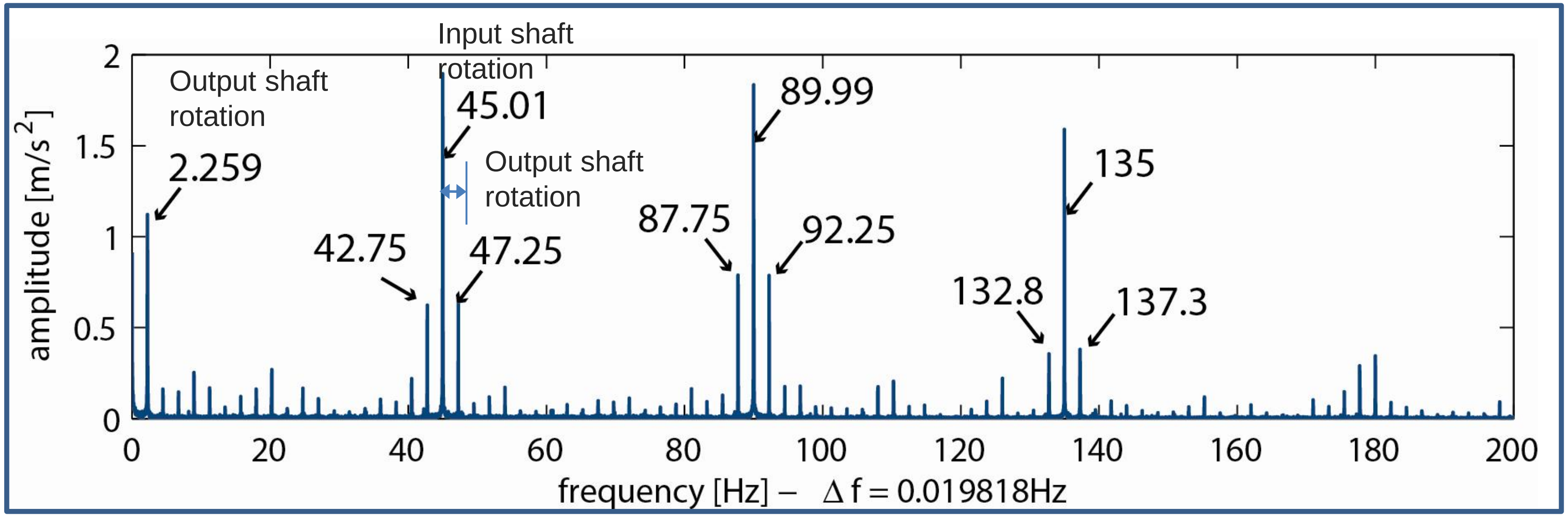
Case study 5: Planet bearing diagnostics

Raw Signal Spectrum



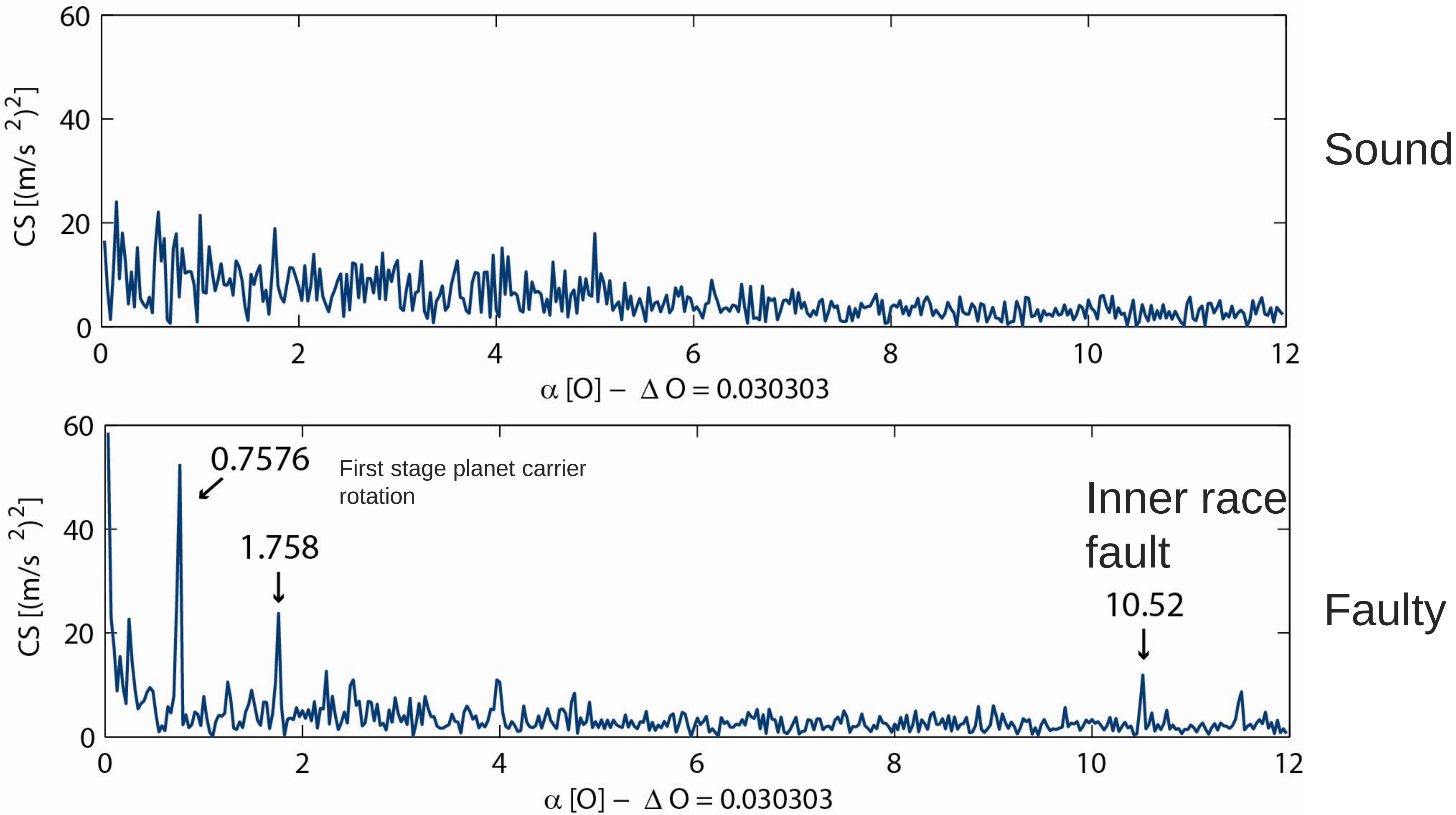
Faulty

Envelope Spectrum: no fault detection



Case study 5: Planet bearing diagnostics

Cyclic Power computed on the **planet extracted signals**



Customized CM & Diagnostic Systems: HARDWARE

Development of hw/sw systems – customized on the basis of specific requirements

Example:

- **ACQUISITION BOARD** NATIONAL INSTRUMENTS NI 9234, 24-Bit Sigma-Delta ADCs, 51.2 kS/s Max SampRate, 4 Input Simultaneous, Software Selectable IEPE AC/DC Coupling, Anti-Aliasing Filters, 102 dB Dynamic Range cDAQ-9174, CompactDAQ chassis (4 slot USB)

- **ACCELEROMETER** MODEL 623C00, ICP ACCELEROMETER IMI SENSITIVITY: 9.7 mV/g,   weght 30-40 g - sensibility 10mV/g - ICP – frequency range 0.5Hz-10kHz

- **TACHOMETER TRANSDUCER** PCB

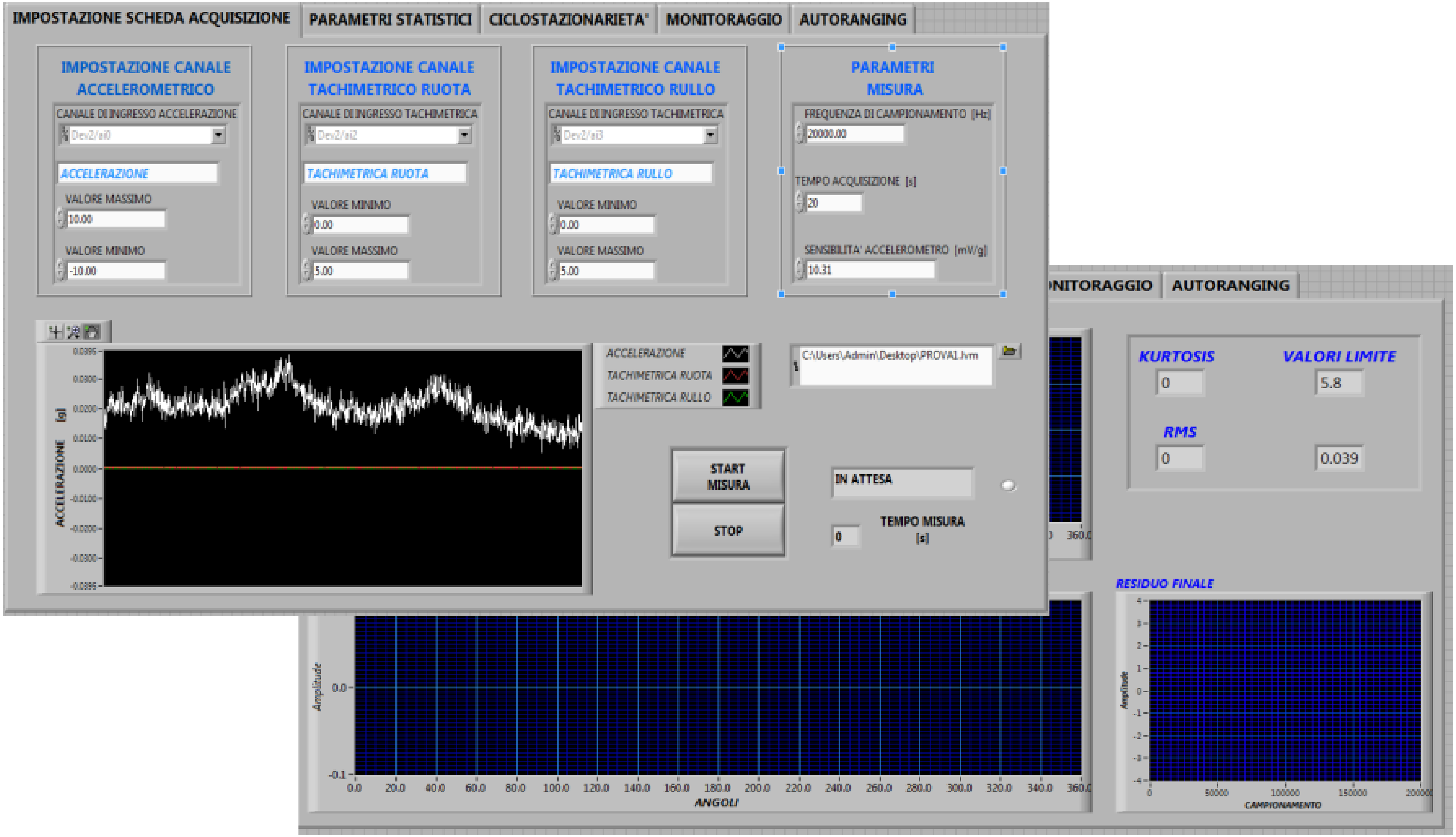
ACQUISITION BOARD

INDUSTRIAL ACCELEROMETER

TACHOMETER

Customized CM & Diagnostic Systems: SOFWARE

Esempio:



Conclusions

- Depending on the type of gearbox and the type of faults, specific **vibration processing techniques** have been developed and applied.
- Common and simple techniques are applied, when possible, but **advanced techniques** are required in some difficult cases.
- Among advanced techniques, **cyclostationary analysis** is very effective for rotating machinery.
- For the detection of planet faults in planetary gearboxes, a special technique for the **extraction of planet SA** is available.
- If required, **low cost hw/sw systems** can be developed, customized on specific requirements and applications.

Thanks for the attention

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