Detection and monitoring of bearings:

a hybrid approach based on vibration analysis and data

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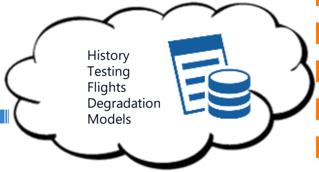
Agenda

Context and objectives

Predictive maintenance

Continuous Heath monitoring

Database



Expert assistance tool

Flights / Test benches

High frequency measurements

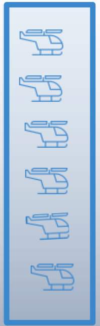
Vibrations
Acoustic signals
Load/Speed

Expert

Preprocessing
Advanced tools of vibration analysis
Decision

Challenges for the Safran Expert

Multiple engines
Multiple flights/tests



Which data to look at first ?

Big data

Search for suspicious signals

☹ Tedious individual analysis

A degradation model ?

~~Particle sensor~~

A mechanical system with a defect

Estimate the size of a defect for prognostic

☹ Sensor not always available

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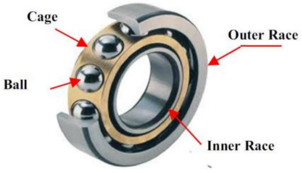
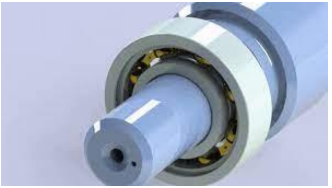
Predictive maintenance of bearings

- **Rotating mechanical component**
  - Support for gears, shafts, discs, etc.



A bearing

  - Equip helicopters, aircraft engines, landing gears, power transmissions systems (AGB, RGB, etc.)

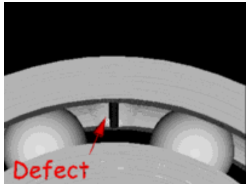


A bearing that is supporting the rotation of a shaft

- **Bearings are prone to failure**
  - Difficult environmental conditions (temperature), severe operating conditions (high speed and load)
  - Significant consequences: maintenance tools, engine failure

A bearing defect

- **Vibration health monitoring**
  - A defective bearing emits specific vibrations



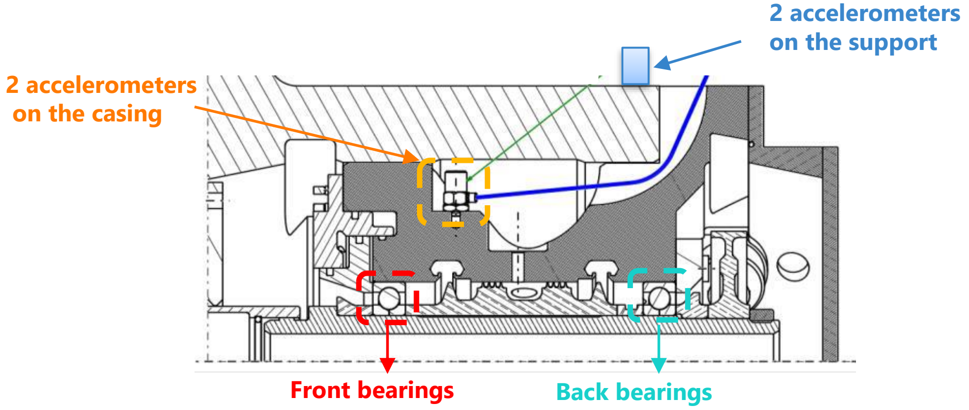
Vibrations caused by a bearing defect

Database

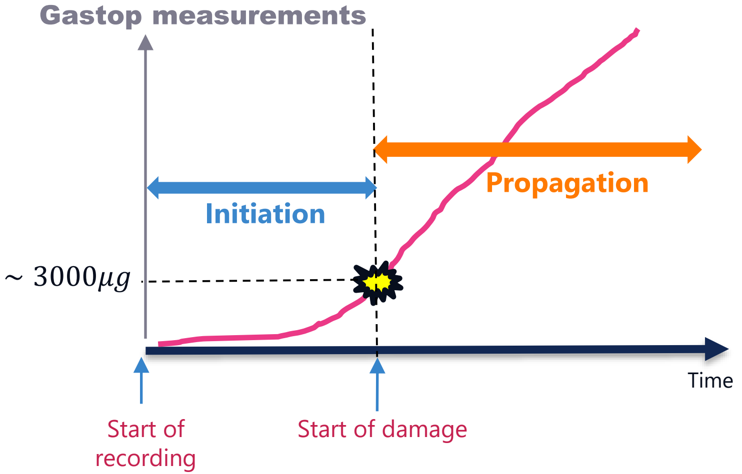
- A test bench in Safran Helicopter Engines (Bordes)
- Inner ring damage of a bearing
- **Number of tested bearings:** 10 bearings
- **Position**: 4 bearings Front/ 6 bearings Back

- **Main sensors**
  - Vibrations : 4 accelerometers (2 casing / 2 support)
  - Gastop: measures the amount of iron particles released by the defective bearing into the oil circuit
  - Test conditions: load, speed

- **Acquisition** : 2 phases
  - **Initiation**: the defect is created by artificially indenting the inner ring of the bearing
  - **Propagation** : The defect was detected (partially) by the gastop



Test bench



Test strategy

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Objectives and constraints

- **Develop an assistance tool to help Safran experts for predictive maintenance of bearings using vibration data**
  1. Indicate to the expert, the signals to be analyzed with priority
     - **A classification task :** target variable = phase either initiation (healthy) or propagation (faulty)
  2. When it comes to estimating the degradation of a bearing, provide the expert with a pre-trained model on previous bearings of the same type
     - **A regression task**: target variable=gastop
  3. Bonus: perform **pre-processing** steps, such as normalizing the data relative to the test conditions

- **A hybrid approach: ML/signal**
  - Leverage physics, expertise, and experts knowledge
  - Simple, reproducible and scalabe

Overview

Overview

Data preparation

Correction of bias caused by test conditions

Detection of healthy/faulty groups based on vibration signals

Estimation of defect size based on vibration signals

Data cleaning
Feature engineering

Preprocessing
Statistical tests
Signal preprocessing
Data driven preprocessing

Classification
Feature selection
Model selection

Regression
Feature selection
Model selection

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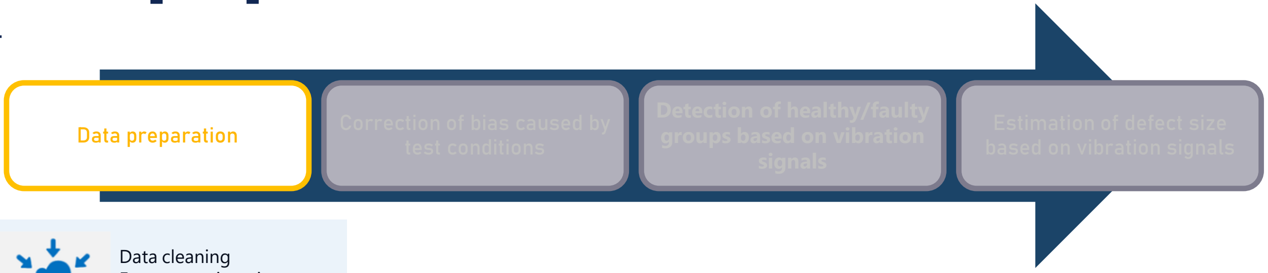
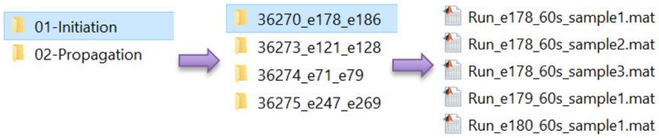
Step 1: Data preparation



Data cleaning
Feature engineering

- **Raw data**
  - 677 samples
  - Each sample is a time series of 3M data points

- **Data formatting**
  - Time series segmentation: 33,665 samples
  - Replace the time series with approximately 300 indicators
  - Load and Gastop are unavailable for multiple tests



	AbsMean	Peak	ZCR	Size	Spectrum_Mean	Spectrum_Peak	Spe
0	2.926541	23.948912	0.391512	409600	0.004283	0.455834	
1	3.579618	34.597335	0.386617	409600	0.005185	0.455920	
2	1.769216	12.204674	0.460372	409600	0.002519	0.451814	
3	4.000478	35.851585	0.394315	409600	0.006018	0.456674	

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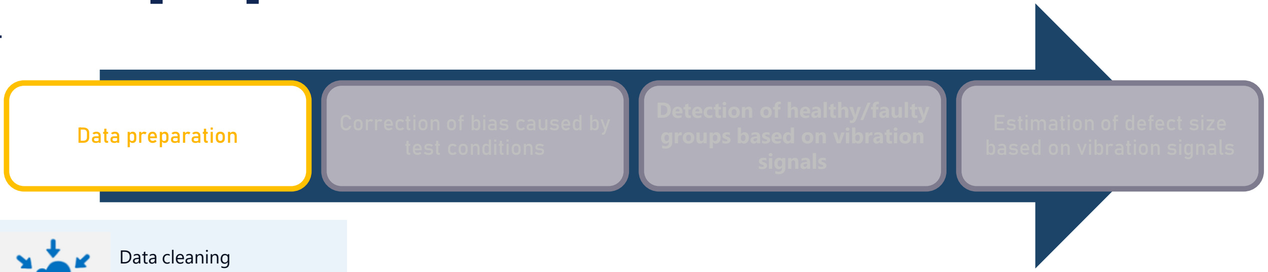
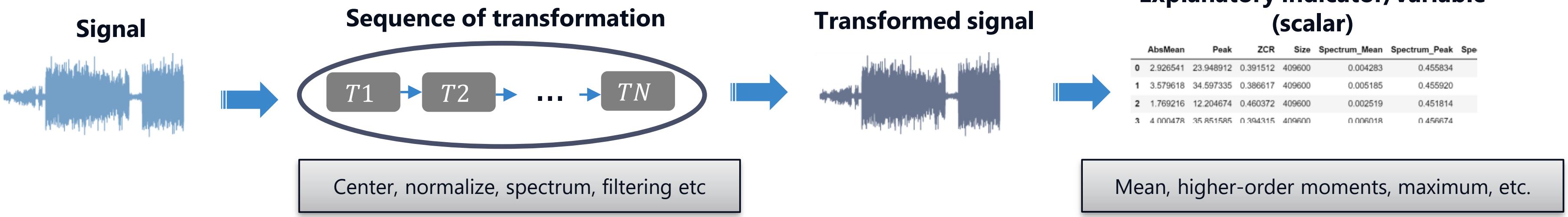
Step 1: Data preparation



Data cleaning
Feature engineering

- **Feature engineering**
  - **Semi-automatic generation**: a sequence of <u>transformations</u> followed by <u>a scalar indicator</u>
    - Transformations derived from signal processing techniques
    - Simple scalar indicators, statistical in nature



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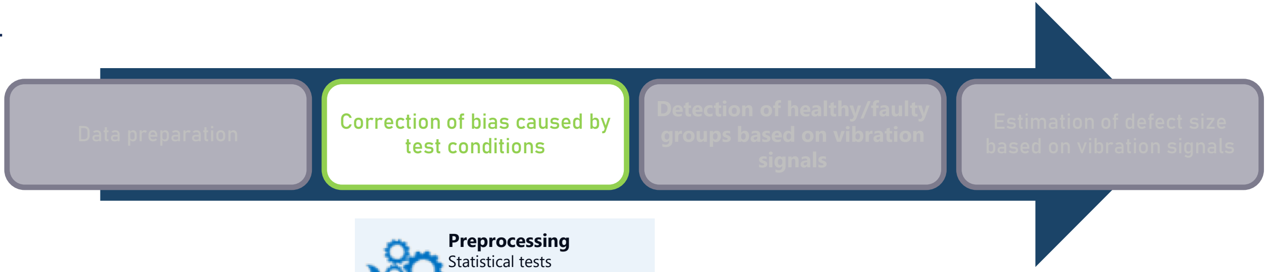
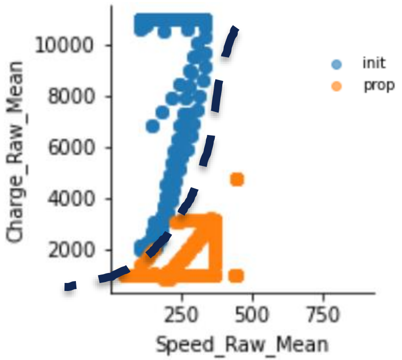
Step 2: Bias correction



Preprocessing
Statistical tests
Signal preprocessing
Data driven preprocessing

- ## Test conditions bias
  - High variability in speed and load
    - Load and speed are discriminative variables of the defect phase
    - Health indicators are sensitive to test conditions



- Consequences on the learning process
  - *Classification*: Learning the difference in test conditions rather than the defect
  - *Regression* : Model performance degrades when test conditions differ from training conditions
  - Iso-conditions : Loss of information/not always feasible

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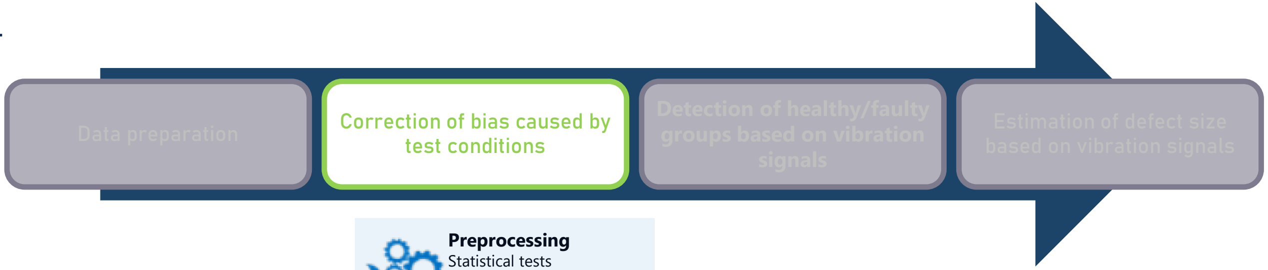
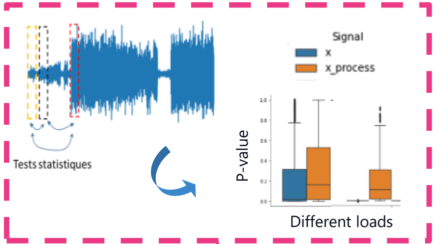
Step 2: Bias correction



Preprocessing
Statistical tests
Signal preprocessing
Data driven preprocessing

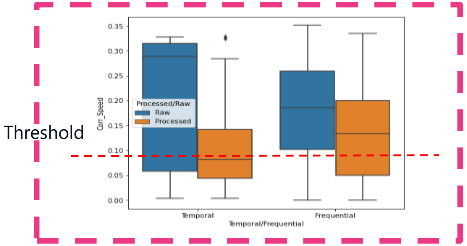
- ## Proposed regularization solutions
  - ### A signal-processing based approach
    - A preprocessing method: NAMVOC
    - Re-compute indicators on corrected data

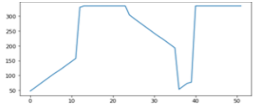
Validation of relevance of the pre-processing through statistical tests



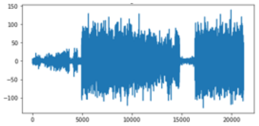
Different loads

Selection of indicators with the least correlation to test conditions



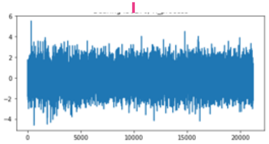


Speed



Raw vibration signal

NAMVOC



Pre-processed vibration data

	AbsMean	Peak	ZCR	Size	Spectrum_Mean	Spectrum_Peak	Spe
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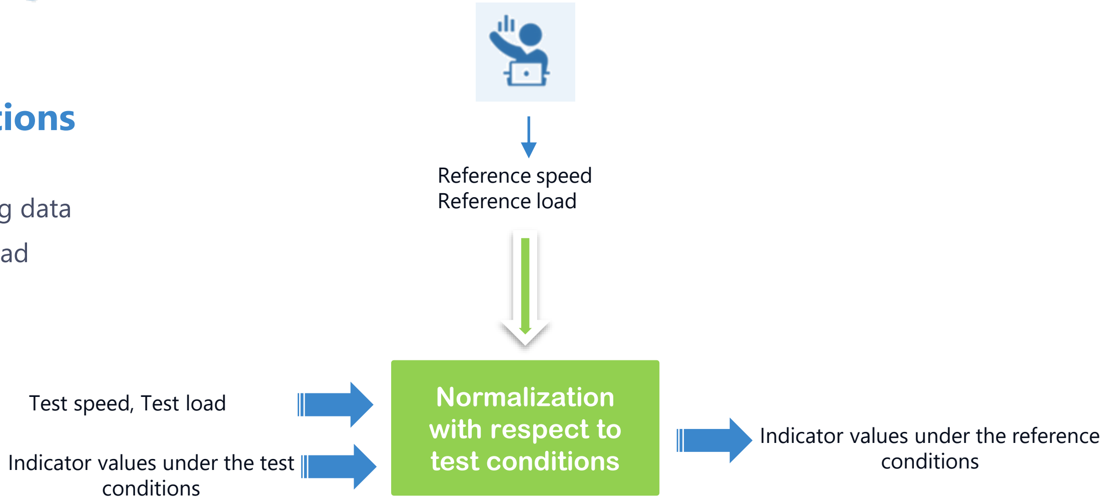
Indicators computed on pre-processed data

Step 2: Bias correction

Preprocessing
Statistical tests
Signal preprocessing
Data driven preprocessing

- **Proposed regularization solutions**
  - **A data-driven approach**
    - Train a correction model using training data
      - ➤ Need information on speed and load



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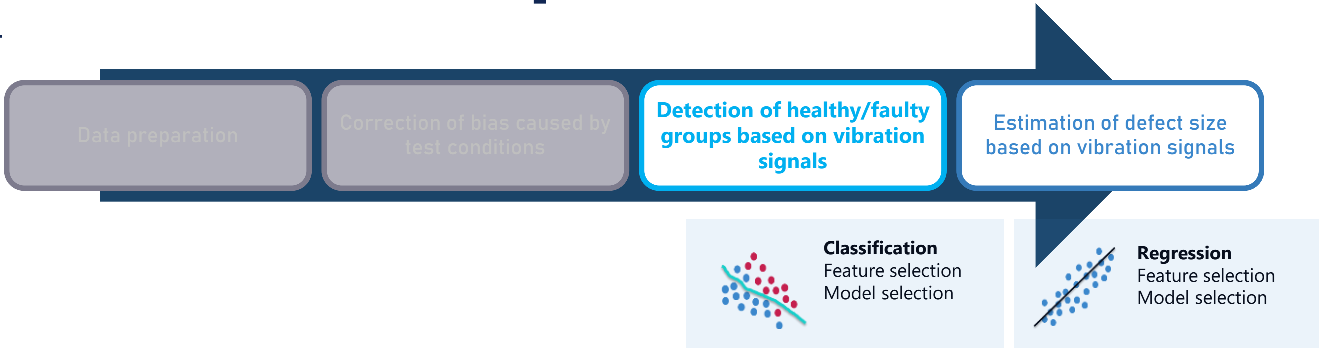
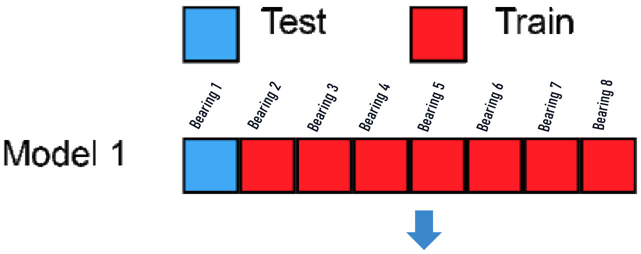
Step 3: construction of expert assistance models



- ## Choice of the database
  - **Data with iso-conditions**: fewer samples
  - **Selected indicators**: fewer variables (indicators)
  - **Corrected indicators**: need for load and speed data
- ## Model choice
  - **One model = One estimator + A set of indicators**
  - Experiments with multiple estimators
  - Search for the best parameters through cross-validation
  - Search for the best model with progressive feature selection (model with 1 variable, 2 variables, multiple variables, etc.).
- ## Validation choice
  - **Leave-One-Bearing-Out :** Validate the model 's ability to generalize to new bearings



Mean score +/- standard deviation

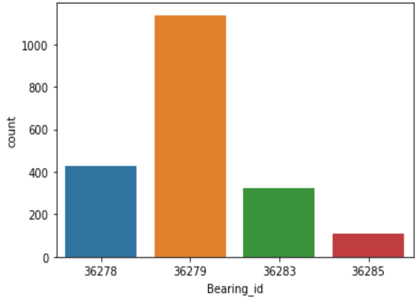
Model construction

Focus on the regression task

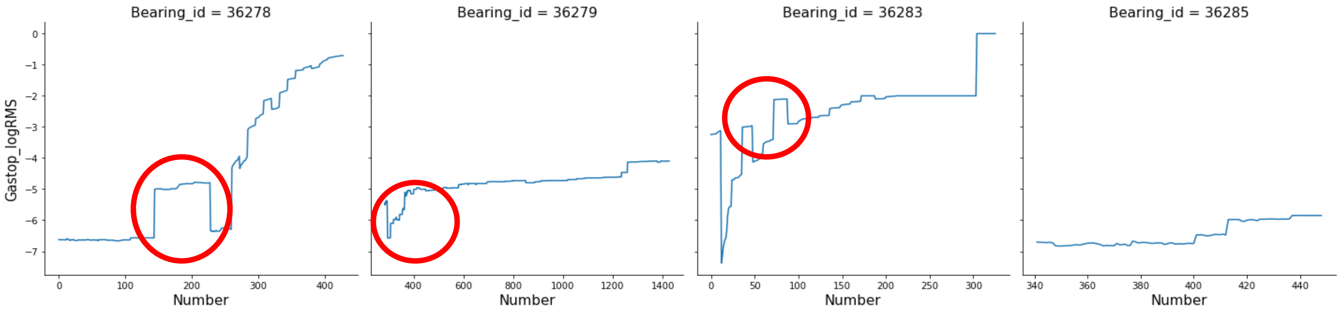
Description (1/2)

- **In/Out**
  - *Inputs* : Indicators computed on vibration data
  - *Target* : RMS of gastop (in log scale)

  - Anomaly ⇒ data in the **propagation phase**
  - Gastop ⇒ only available for 4 bearings
  - Some errors in the gastop measurements are currently being ignored



Database with available gastop variable



Target variables

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Description (2/2)

- ## Models
  - **Estimators**: linear regression, SVR (Support Vector Regression), decision tree, random forest
  - **Parameter tuning**: cross-validation
  - **Metric**: mean absolute error
  - **Validation** : Leave-One-Bearing-Out

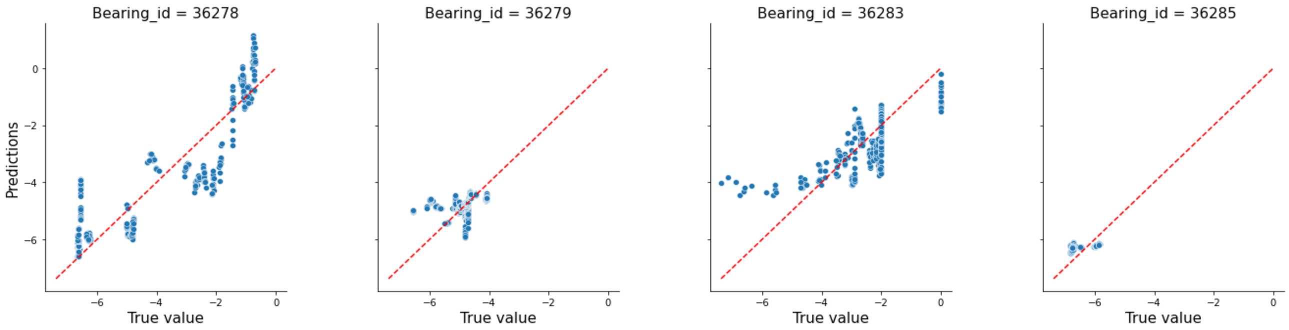
- ## Experiments
  - **Experiment 1:** data with iso-conditions (Not possible)
  - **Experiment 2:** selected indicators with the least correlation to test conditions (from the ones computed on pre-processed vibration with NAMVOC)
  - **Experiment 3**: corrected indicators using data-driven method

Main results

- **Best model** with 3 explanatory variables
- **Best indicators**: moments on amplitude and frequency spectrum
- Results consistent with expert analysis of some signals
  - ✓ The spectrum becomes richer with the progression of the defect
  - ✓ The characteristic defect frequencies change as the defect progresses
- The proposed correction step provides better variables
- Importance of choosing the sensor

Score (MAE +/- std)

	Selected indicators	Selected indicators + Corrected indicators
Sensor casing	0.85±0.45	0.62 ±0.21
Sensor support	0.75±0.13	**0.52 ±0.20**



Predicting the gastop value from vibrations

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Conclusion and perspectives

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Conclusion

- **Development of an Expert assistance tool for bearing monitoring**
  - **Preprocess** to normalize the data with respect to test conditions
  - **Classify** signals as suspicious/healthy in a dataset
  - **Infer** the size of defects from vibrations in the presence of an anomaly

- **Challenges encountered and Proposed solutions**

Task	Challenge	Proposed solution	Limitation/To be improved
Classify/ Infer	Biased database	Correction through signal processing/expert knowledge/statistical learning	How accurate is the database ?
Infer	New problem	Using gastop as a measurement correlated to defect size	Sensitivity of gastop/Source of defect (multiple components)/Gastop measurement errors
Preprocess	Open problem	An assumption and a model learned from the data	The speed and load are measurements that could be modulated by the defect

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