IEEE PHM 2012 Prognostic challenge

Outline, Experiments, Scoring of results, Winners

Contents

1 Overview of the challenge

1.1 Prognostics of bearings' life duration

The IEEE Reliability Society and FEMTO-ST Institute were pleased to organize the IEEE PHM 2012 Data Challenge. The challenge was focused on the estimation of the remaining useful life (RUL) of bearings, a critical problem since most of failures of rotating machines are related to these components, strongly affecting availability, security and cost effectiveness of mechanical systems and equipment in industries such as power and transportation.
The challenge was open to all potential conference attendees. Both Academic (from University) and Professional teams (from Industry) were encouraged to enter. The two top scoring participants from both categories were invited to present at a special session of the 2012 IEEE International Conference on Prognostics and Health Management (`http://www.phmconf.org/`).

1.2 Challenge datasets

PHM challenge datasets were provided by FEMTO-ST Institute (Besançon - France, `http://www.femto-st.fr/`). Experiments were carried out on a laboratory experimental platform (PRONOSTIA) that enables accelerated degradation of bearings under constant and/or variable operating conditions, while gathering online health monitoring data (rotating speed, load force, temperature, vibration).
Regarding the PHM Challenge, data representing 3 different loads were considered (rotating speed and load force). Participants were provided with 6 run-to-failure datasets in order to build their prognostics models, and were asked to estimate accurately the RUL of 11 remaining bearings. Monitoring data of the 11 test bearings were truncated so that participants were supposed to predict the remaining life, and thereby perform RUL estimates. Also, no assumption about the type of failure to be occurred was given.
The challenge datasets were characterized by a small amount of training data and a high variability in experiment durations (from 1h to 7h). Thereby, performing good estimates was quite difficult and this made the challenge more exciting. Note also that theoretical framework (L10, BPFI, BPFE, etc.) mismatches the experimental observations.

1.3 Acknowledgment

The datasets are being made publicly available. Publications making use of these databases are requested to cite the following paper.

> Patrick Nectoux, Rafael Gouriveau, Kamal Medjaher, Emmanuel Ramasso, Brigitte Morello, Noureddine Zerhouni, Christophe Varnier. *PRONOSTIA: An Experimental Platform for Bearings Accelerated Life Test.* IEEE International Conference on Prognostics and Health Management, Denver, CO, USA, 2012.

2 The PRONOSTIA platform

2.1 Outline

PRONOSTIA is an experimentation platform (Fig. 1) dedicated to test and validate bearings fault detection, diagnostic and prognostic approaches. The platform has been designed and realized at AS2M department of FEMTO-ST Institute.
The main objective of PRONOSTIA is to provide real experimental data that characterize the degradation of ball bearings along their whole operational life (until their total failure). This

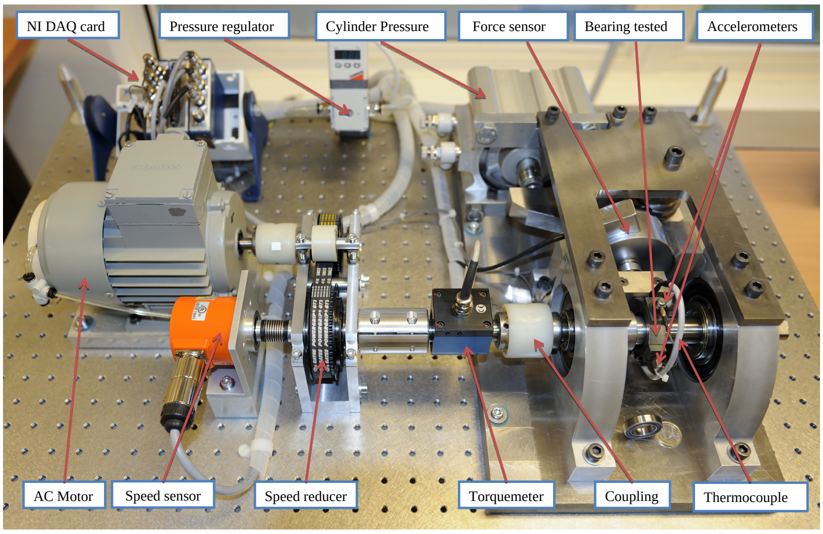


Figure 1: Overview of PRONOSTIA

experimental platform allows to conduct bearings' degradations in only few hours. Also, compared to other bearing test beds proposed in literature, the data provided by the PRONOSTIA platform are different in the sense that they correspond to "normally" degraded bearings. This means that the defects are not initially initiated on the bearings and that each degraded bearing contains almost all the types of defects (balls, rings and cage). Furthermore, even if the data provided for the challenge concern constant operating conditions for each realized experiment, the current design of PRONOSTIA enables to provide data related to bearings degraded under variable operating conditions.
PRONOSTIA is composed of three main parts: a rotating part, a degradation generation part (with a radial force applied on the tested bearing) and a measurement part, which are detailed hereafter.

2.2 Rotating part

This part includes the asynchronous motor with a gearbox and its two shafts: the first one is near to the motor and the second one is placed at the ride side of the incremental encoder.
The motor has a power equal to 250 W and transmits the rotating motion through a gearbox, which allows the motor to reach its rated speed of 2830 rpm, so that it can deliver its rated torque while maintaining the speed of the secondary shaft to a speed less than 2000 rpm. Compliant and rigid shaft couplings are used to create connections for the transmission of the rotating motion produced by the motor to the shaft support bearing.
The bearing support shaft (Fig. 2) leads the bearing through its inner race. This one is kept fixed to the shaft with a shoulder on the right hand and a threaded locking ring on the left hand. The shaft which is made of one piece is held by two pillow blocks and their large gearings. Two clampings allow the longitudinal blocking of the shaft between the two pillow blocks. A human machine interface allows the operator to set the speed, to select the direction of the motor's rotation and to set the monitoring parameters such as the motor's instantaneous temperature expressed in percentage of the maximum temperature of use.

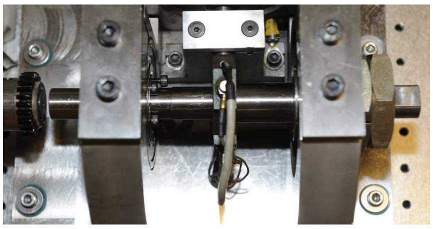


Figure 2: Shaft support bearing

2.3 Loading part

Components from this part are grouped in a unique and same aluminum plate partially isolated from the instrumentation part by a thin layer of polymer. The aluminum plate supports a pneumatic jack, a vertical axis and its lever arm, a force sensor, a clamping ring of the test bearing, a support test bearing shaft, two pillow blocks and their large oversized bearings. The force issued from the pneumatic jack is first amplified by a lever arm, and is then indirectly applied on the external ring of the test ball bearing through its clamping ring (Fig. 3).
This loading part constitutes the heart of the global system. In fact, the radial force reduces the bearing's life duration by setting its value up to the bearing's maximum dynamic load which is 4000 N (see Appendix A.1). This load is generated by a force actuator, which consists in a pneumatic jack, where the supply pressure is delivered by a digital electro-pneumatic regulator.

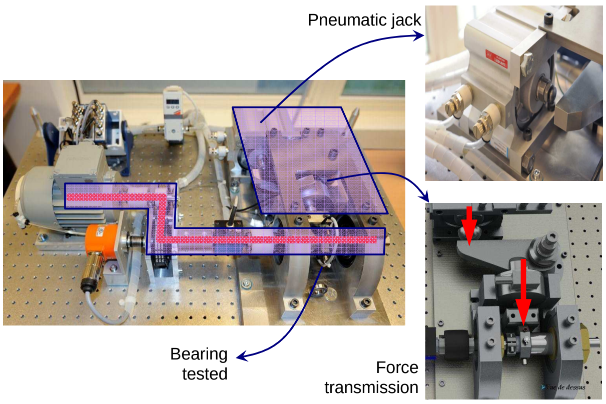


Figure 3: Details of the loading part

2.4 Measurements part

Operation conditions are determined by instantaneous measures of the radial force applied on the bearing, of the speed rotation of the shaft handling the bearing, and of the torque inflicted to the bearing. Each of these three analog measures is acquired at a frequency equal to 100 Hz.
The characterization of the bearing's degradation is based on two data types of sensors: vibration and temperature (Fig. 4). The vibration sensors (Appendix A.2) consists of two miniature accelerometers positioned at 90° to each other; the first is placed on the vertical axis and the second is placed on the horizontal axis. The two accelerometers are placed radially on the external race of the bearing. The temperature sensor (Appendix A.3) is an RTD (Resistance Temperature Detector) platinum PT100 (1/3 DIN class) probe, which is place inside a hole close to the external bearing's ring. The acceleration measures are sampled at 25.6 kHz and the temperature ones are sampled at 0.1 Hz.

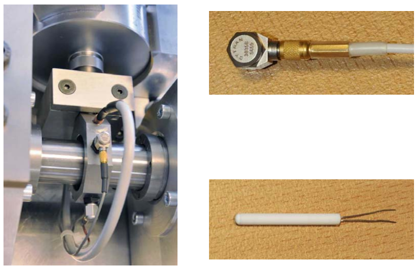


Figure 4: Measurement part: accelerometers and temperature sensor

3 Experimental datasets for the IEEE PHM 2012 challenge

3.1 Bearings degradation: run-to-failure experiments

PRONOSTIA platform enables to perform run-to failure experiments. In order to avoid propagation of damages to the whole test bed (and for security reasons), tests were stopped when the amplitude of the vibration signal overpassed 20g.
Figure 5 depicts an example of what one can observe on the ball bearing components before and after an experiment, as well as a vibration raw signal gathered during a whole experiment. Note that the degradation of bearings depict very different behaviors leading to very different experiment duration (until the fault).

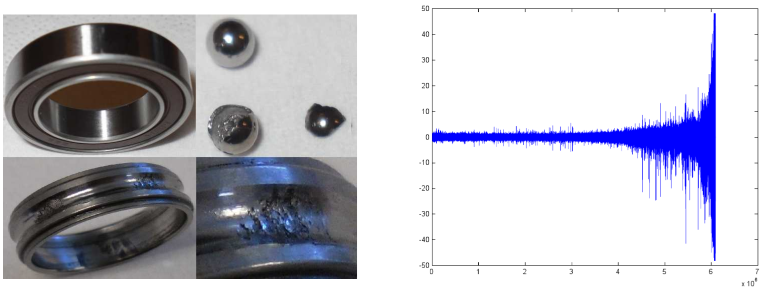


Figure 5: Normal and degraded bearings and vibration raw signal from an experiment

3.2 Challenge datasets

Regarding the PHM challenge, data representing 3 different loads were considered:
- First operating conditions: 1800 rpm and 4000 N;
- Second operating conditions: 1650 rpm and 4200 N;
- Third operating conditions: 1500 rpm and 5000 N.

Participants were provided with 6 run-to-failure datasets in order to build prognostics models, and were asked to estimate accurately the RUL of 11 remaining bearings (see Table 1). Vibration and temperature signals were gathered during all those experiments. Monitoring data of the 11 test bearings were truncated so that participants were supposed to predict the remaining life, and thereby perform RUL estimates. Also, no assumption on the type of failure to be occurred was given (nothing known about the nature and the origin of the degradation: balls, inner or outer races, cage...).

The learning set was quite small while the spread of the life duration of all bearings was very wide (from 1h to 7h). Performing good estimates was thereby difficult and this made the challenge more exciting.

Datasets	**Operating Conditions**		
	Conditions 1	Conditions 2	Conditions 3
Learning set	Bearing1_1 Bearing1_2	Bearing2_1 Bearing2_2	Bearing3_1 Bearing3_2
Test set	Bearing1_3 Bearing1_4 Bearing1_5 Bearing1_6 Bearing1_7	Bearing2_3 Bearing2_4 Bearing2_5 Bearing2_6 Bearing2_7	Bearing3_3

Table 1: Datasets of IEEE 2012 PHM Prognostic Challenge

Note 1. As for the challenge, RUL was defined as time to accelerometer exceeding 20g.
Note 2. The theoretical models based on frequency signatures to detect bearings' faults (such as the inner and outer races and the cage faults) do not work. Indeed, frequency signatures are difficult to obtain due to the fact that the degradation may concern all the components of the test bearing at a same time.
Note 3. Existing reliability laws for bearings' life duration, such as the L_{10}, do not give same results than those obtained by the experiments (theoretical estimated life durations are different from those given by the experiments).
Note 4. For more equity during the competition, no member from FEMTO-ST applied to the challenge.

4 Organization of data

4.1 Data acquisition characteristics

Both learning and test datasets were given in "7z" compressed folders. Each one contains vibration ASCII files named "acc_xxxxx.csv", and temperature ASCII files named "temp_xxxxx.csv". The data acquisition parameters are given bellow and must be considered carefully.

- **Vibration signals (horizontal and vertical)**
  - Sampling frequency: 25.6 kHz
  - Recordings: 2560 samples (i.e. 1/10 s) are recorded each 10 seconds (see Fig. 6)
- **Temperature signals**
  - Sampling frequency: 10 Hz
  - Recordings: 600 samples are recorded each minute

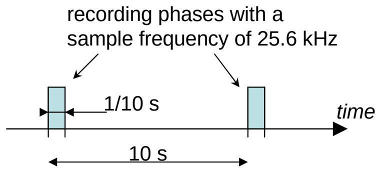


Figure 6: Illustration of acquisition parameters for vibration signals

4.2 ASCII files

For each ASCII file, the data were arranged as depicted in Table 2:

Column	**1**	**2**	**3**	**4**	**5**	**6**
Vibr. signal	Hour	Minute	Second	μ-second	Horiz. accel.	vert. accel.
Temp. signal	Hour	Minute	Second	0.x second	Rtd sensor	

Table 2: Arrangement of data within ASCII files

Characteristics of experiments from the learn and test sets are given in Appendix A.4 and A.5.

5 Scoring of results and top-scoring participants

5.1 Scoring of results

Teams were scored based on their RUL results that have been converted into percent errors of predictions. Let note $\widehat{RUL_i}$ and $ActRUL_i$ respectively the remaining useful life of the bearing estimated by a participant, and the actual RUL to be predicted (where $i \in [1, 11]$ states for the test bearings defined in Table 1). The percent error on experiment i was defined by:

$$\%Er_i = 100 \times \frac{ActRUL_i - \widehat{RUL_i}}{ActRUL_i} \tag{1}$$

Underestimates and overestimates have not be considered in the same manner: good performance of estimates related to early predictions of RUL (i.e. cases where $\%Er_i > 0$), with deduction to early removal, and more severe deductions for RUL estimates that exceeded actual component RUL (i.e. cases where $\%Er_i < 0$). The score of accuracy of a RUL estimates for experiment i was thereby defined as follows. Figure 7 depicts the evolution of this scoring function.

$$A_i = \begin{cases} exp^{-ln(0.5).(Er_i/5)} & \text{if } Er_i \leq 0 \\ exp^{+ln(0.5).(Er_i/20)} & \text{if } Er_i > 0 \end{cases} \tag{2}$$

The final score of all RUL estimates has been defined as being the mean of all experiment's score:

$$Score = \frac{1}{11}\sum_{i=1}^{11}(A_i) \tag{3}$$

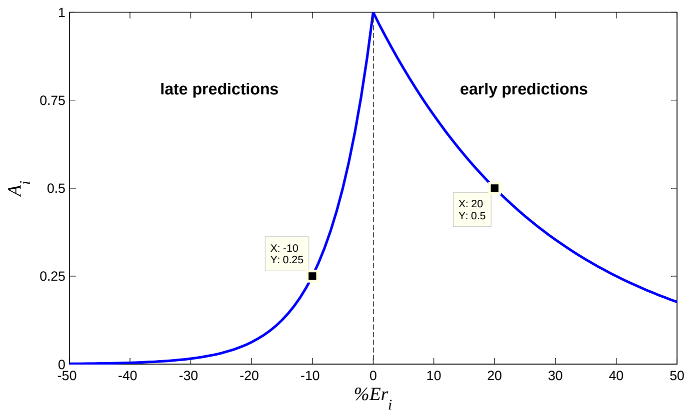


Figure 7: Scoring function of a RUL estimates according to its percent error

5.2 Actual RULs to be estimated

Test set	Actual RUL
Bearing1_3	5730 s
Bearing1_4	339 s
Bearing1_5	1610 s
Bearing1_6	1460 s
Bearing1_7	7570 s
Bearing2_3	7530 s
Bearing2_4	1390 s
Bearing2_5	3090 s
Bearing2_6	1290 s
Bearing2_7	580 s
Bearing3_3	820 s

Table 3: Actual RULs to be estimated

5.3 Top-scoring participants

Thanks to all participants and congratulations to the winners.

- **Industrials**
  - WINNER
    - A.L.D. Ltd. (Israel)
    - Contact: Sergey Porotsky (Chief Scientist) - `Sergey.Porotsky@ald.co.il`
  - RUNNER UP
    - GE Global Research (Niskayuna, NY)
    - Contact: Tianyi Wang (Information Scientist) - `wangty98@gmail.com`

- **Academics**
  - WINNER
    - enter for advanced life cycle engineering (CALCE), University of Maryland
    - Contact: Arvind Sai Sarathi Vasan (PhD student) - `arvind88@umd.edu`
  - RUNNER UP
    - Jođef Stefan Institute (Slovenia)
    - Contact: Matej GaŽperin (PhD student) - `matej.gasperin@ijs.si`

6 Contact point

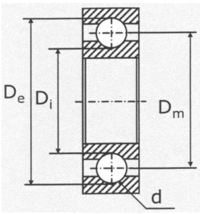
For any request please contact the local organizing committee (Rafael Gouriveau, Kamran Javed, Kamal Medjaher, Ahmed Mosallam, Patrick Nectoux, Emmanuel Ramasso, Noureddine Zerhouni) at:
`ieee-2012-PHM-challenge@femto-st.fr`

FEMTO-ST Institute
UMR CNRS 6174 - UFC / ENSMM / UTBM
24 rue Alain Savary, 25000 Besançon, France

A Appendix

A.1 Characteristics of tested bearings

- Fitted with two synthetic rubber seals to prevent leakage of lubricant as well as entry of dust, water and other harmful material
- Outside Race Diameter D=32 mm
- Inside Diameter d=20 mm
- Thickness B=7 mm
- Load Ratings Static: 2470 N
- Load Ratings Dynamic: 4000 N
- Maximum Speed : 13000 rpm



d = 3.5 mm (Diameter of rolling elements)
Z = 13 (Number of rolling elements)
De = 29.1 mm (Diameter of the outer race)
Di = 22.1 mm (Diameter of inner race)
Dm = 25.6 mm (bearing mean Diameter)

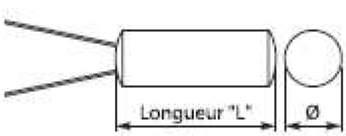
A.2 Characteristics of the accelerometers

Accelerometers Type DYTRAN 3035B
- 50 g range
- 100 mV/g

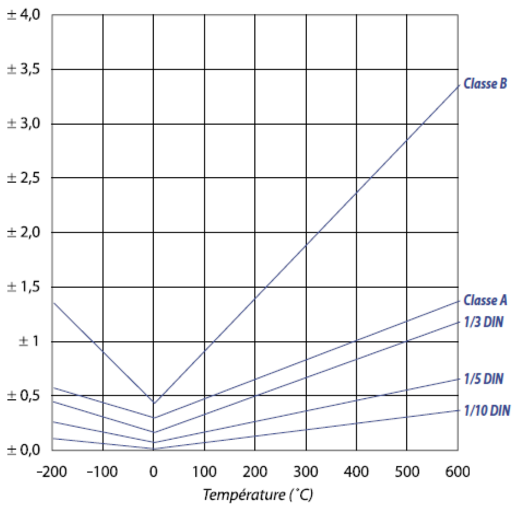
SPECIFICATION	VALUE	UNITS
PHYSICAL		
WEIGHT	2.5	grams
SIZE, HEX x HEIGHT	.281 (9/32) x .33	inches
MOUNTING PROVISION, 3035B	5-40 integral stud	
MOUNTING PROVISION, 3035BG	flat surface for adhesive mount	
CONNECTOR, RADIALLY MOUNTED	5-44 coaxial	
MATERIAL, HOUSING AND CONNECTOR	300 Series Stainless Steel	
PERFORMANCE		
FREQUENCY RANGE, ± 5%	0.5 to 10k	Hz
RESONANT FREQUENCY, NOM.	45	kHz
EQUIVALENT ELECTRICAL NOISE FLOOR	.007	g rms
LINEARITY [2]	± 1%	% F.S.
TRANSVERSE SENSITIVITY, MAX.	5	%
STRAIN SENSITIVITY	.002	g/με @ 250με
ENVIRONMENTAL		
MAXIMUM VIBRATION/SHOCK	600/3000	± g pk
TEMPERATURE RANGE, 3035B/BG, 3035B2/B2G	-60 to +225	°F
3035B1/B1G, 3035B3/B3G	-60 to +250	°F
SEAL, HERMETIC	Glass-to-metal and TIG welded	
COEFFIEICNT OF THERMAL SENSITIVITY	.04	%/°F
ELECTRICAL		
SUPPLY CURRENT [3]	2 to 20	mA
SUPPLY COMPLIANCE VOLTAGE RANGE	+18 to +30	Volts
OUTPUT IMPEDANCE, TYP.	100	Ω
BIAS VOLTAGE	+11 to +13	Vdc
DISCHARGE TIME CONSTANT	0.5 to 1.2	seconds
OUTPUT SIGNAL POLARITY FOR ACCELERATION TOWARD TOP	Positive	
CASE GROUNDING	Case is grounded to electrical power ground	

A.3 Characteristics of the temperature sensor

Temperature sensor Type platinum RTD PT100 PROSENSOR
- Class 1/3 DIN norm IEC 751
- Nominal resistance : 100 ohms
- Usage range : -200 to +600 řC
- Diameter : 2.8 mm
- Length : 25 mm



	Tolérances									
Temp (°C)	Classe B		Classe A		1/3 DIN		1/5 DIN		1/10 DIN	
	± °C	± Ohms	± °C	± Ohms	± °C	± Ohms	± °C	± Ohms	± °C	± Ohms
-200	1,30	0,56	0,55	0,24	0,44	0,19	0,26	0,11	0,13	0,06
-100	0,80	0,32	0,35	0,14	0,27	0,11	0,16	0,06	0,08	0,03
0	0,30	0,12	0,15	0,06	0,10	0,04	0,06	0,02	0,03	0,01
100	0,80	0,30	0,35	0,13	0,27	0,10	0,16	0,05	0,08	0,03
200	1,30	0,48	0,55	0,20	0,44	0,16	0,26	0,10	0,13	0,05
300	1,80	0,64	0,75	0,27	0,60	0,21	0,36	0,13	0,18	0,06
400	2,30	0,79	0,95	0,33	0,77	0,26	0,46	0,16	0,23	0,08
500	2,80	0,93	1,15	0,38	0,94	0,31	0,56	0,19	0,28	0,09
600	3,30	1,06	1,35	0,43	1,10	0,35	0,66	0,21	0,33	0,10
650	3,60	1,13	1,45	0,46	1,20	0,38	0,72	0,23	0,36	0,11
700	3,80	1,17								
800	4,30	1,28								
850	4,60	1,34								



A.4 Characteristics of experiments from the learning dataset

Bearing1_1	- Experiment date: 2010-12-01 - Recording duration: 7h47m00s	- Nb. of files / channels: 3269 / 3 - Signals: vibration and temperature
Bearing1_2	- Experiment date: 2011-04-06 - Recording duration: 2h25m00s	- Nb. of files / channels: 1015 / 3 - Signals: vibration and temperature
Bearing2_1	- Experiment date: 2011-05-06 - Recording duration: 2h31m40s	- Nb. of files / channels: 1062 / 3 - Signals: vibration and temperature
Bearing2_2	- Experiment date: 2011-06-17 - Recording duration: 2h12m40s	- Nb. of files / channels: 797 / 2 - Signals: vibration
Bearing3_1	- Experiment date: 2011-04-07 - Recording duration: 1h25m40s	- Nb. of files / channels: 604 / 3 - Signals: vibration and temperature
Bearing3_2	- Experiment date: 2011-06-28 - Recording duration: 4h32m40s	- Nb. of files / channels: 1637 / 2 - Signals: vibration

A.5 Characteristics of experiments from the test dataset

Bearing1_3	- Experiment date: 2010-11-17 - Recording duration: 5h00m10s	- Nb. of files / channels: 1802 / 2 - Signals: vibration
Bearing1_4	- Experiment date: 2010-12-07 - Recording duration: 3h09m40s	- Nb. of files / channels: 1327 / 3 - Signals: vibration and temperature
Bearing1_5	- Experiment date: 2011-04-13 - Recording duration: 6h23m30s	- Nb. of files / channels: 2685 / 3 - Signals: vibration and temperature
Bearing1_6	- Experiment date: 2011-04-14 - Recording duration: 6h23m29s	- Nb. of files / channels: 2685 / 3 - Signals: vibration and temperature
Bearing1_7	- Experiment date: 2011-04-15 - Recording duration: 4h10m11s	- Nb. of files / channels: 1752 / 3 - Signals: vibration and temperature
Bearing2_3	- Experiment date: 2011-05-19 - Recording duration: 3h20m10s	- Nb. of files / channels: 1202 / 2 - Signals: vibration
Bearing2_4	- Experiment date: 2011-05-26 - Recording duration: 1h41m50s	- Nb. of files / channels: 713 / 3 - Signals: vibration and temperature
Bearing2_5	- Experiment date: 2011-05-27 - Recording duration: 5h33m30s	- Nb. of files / channels: 2337 / 3 - Signals: vibration and temperature
Bearing2_6	- Experiment date: 2011-06-07 - Recording duration: 1h35m10s	- Nb. of files / channels: 572 / 2 - Signals: vibration
Bearing2_7	- Experiment date: 2011-06-08 - Recording duration: 0h28m30s	- Nb. of files / channels: 200 / 2 - Signals: vibration
Bearing3_3	- Experiment date: 2011-04-08 - Recording duration: 0h58m30s	- Nb. of files / channels: 410 / 3 - Signals: vibration and temperature