

# VALIDATION OF SIGNAL PROCESSING TECHNIQUES FOR VIBRATION MEASUREMENTS

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**Abstract:** A study is presented in this paper able to identify and to quantify the effects of sensor characteristics and of data processing aspects on the uncertainty of the features used for Condition Monitoring (CM) applications, based on a hybrid approach. The precision of the sensors and the modalities to perform the FFT and obtain the related features are evaluated, to improve the coherence of information deriving from the data obtained by means of a physics-based model and that gained from the experiments. Validation of the features related to both classes is expected to improve the fusion process of data and the accuracy of prognostic algorithms.

**Keywords:** condition monitoring, data processing, measurement uncertainty, hybrid approach, features.

## 1. INTRODUCTION

In the last few years, condition monitoring (CM) [1] is becoming more and more interesting for companies because of its great influence on the operational continuity of many processes: in some cases, the faulty of a system can cause a relevant financial loss due to the lack of production, in other cases it can protect an item from damage. Therefore, CM in industrial context helps to reduce maintenance costs and to increase the assets lifetime [2], [3].

In condition based maintenance, the maintenance strategies are supported by the application of a hybrid approach [4]. These CM techniques are based on a vibration analysis including the following steps:

1. Physics-based modelling: dynamic behavior of sub-systems and their interaction is analytically described by advanced simulation models;
2. Data acquisition: collection of vibration signals from some sensors (generally accelerometers) installed on the asset under testing;
3. Signal processing: data analysis to obtain some information useful for fault prediction;
4. Features extraction: meaningful features evaluation and extraction for fault condition identification by merging both physical and experimental data;
5. Fault prediction: detection and identification of faults and subsequent prediction, mostly made by neural network or machine learning algorithms.

Merging the physics-based modelling and the data-driven approaches into trustable algorithms, suitably trained with synthetic features able to reproduce both physics-based modelling and experimental data, is not a trivial task.

In this context, the need to make homogeneous as much as possible the informative content of features of both classes is an essential aspect to deal with, bearing in mind the different nature of physics-based data, on the one hand, and experimental ones, on the other hand. These differences may be interpreted in terms of variability, accuracy, effect of data validation and processing.

Supporting and reaching the fault prediction requires efficient signal processing algorithms, generally based on the evaluation of features in the frequency domain.

Fast Fourier Transform (FFT) is the basic tool for analyzing the signals in frequency domain and some of the most used features can be found in literature [5], [6], [7].

Furthermore, other specific techniques exist, in particular the following features are worthy of note, such as spectral envelope [8], [9] and spectral kurtosis [8], [10] which are the application in sequence of several data processing steps.

If accurate and coherent features have to be considered, with reference to the processing of physics-based modelling data and experimental ones, the effect of the selection of the related parameters (windowing, filter type, bandwidth, and so on) is difficult to accurately predict. For this reason, it is also important the choice of sensors, because the quality of these will affect the signal-to-noise ratio. The objective of this work is to realize a tentative procedure to take into account the difference between signals deriving from theoretical and experimental analysis.

The effects of the parameters choice are studied, taking into account the type of signals and the specific applications, merging the deterministic nature of models together with a gradually increasing random nature of the real monitored situations. In fact, in order to experimentally evaluate the difference between theoretical deterministic and real random data, an experimental analysis on the effect of type of signal in different conditions is carried out: numeric signal, electronic generated signal, real signal from a laboratory test bench, random industrial real data with noise. Different accelerometers are also used to consider their contribution to the variability. The final goal is to give evidence of the impact that sensors of different quality levels and different parameters have on the post-processing results.

The paper is organized as follows. In section 2 the methodology is explained and the materials used for the tests are described. In Section 3 the observations obtained are reported and discussed. Short conclusions and future works end the paper.

Theoretical signals	Experimental analysis	Validation	Post-processing parameters	Features (I level)	Features (II level)
Sinusoidal	(Numerical signal)	<ul style="list-style-type: none"> <li>• Variability</li> <li>• Accuracy</li> <li>• Uncertainty propagation</li> </ul>	<ul style="list-style-type: none"> <li>• Windowing</li> <li>• Filter Type</li> <li>• Bandwidth</li> <li>• ...</li> </ul>	<ul style="list-style-type: none"> <li>• RMS</li> <li>• Variance</li> <li>• Median</li> <li>• Standard deviation</li> <li>• Fast Fourier Transform (FFT)...</li> </ul>	<ul style="list-style-type: none"> <li>• Mean value of all amplitude peaks</li> <li>• Amplitude and frequency of the lower and greatest peaks</li> <li>• Distance between the frequencies of the two greatest peaks</li> <li>• Spectral Envelope</li> <li>• Spectral Kurtosis</li> <li>• Band power</li> <li>• ...</li> </ul>
Sinusoidal	Signal Generator				
Sinusoidal	3-axis accelerometer: • linear slide • rotary bench				
Complex, Random aspects	3-axis accelerometer: Industrial machine	<ul style="list-style-type: none"> <li>• Sensor precision</li> <li>• Signal-to-noise ratio</li> </ul>			

Figure 1. Methodological approach: main aspects

## 2. MATERIALS AND METHODS

As already stated, the behaviour of the real applications often involves disparate contributions to the measurement uncertainty, linked to the natural combination of aspects occurring throughout both the measurement and the operating processes.

Starting from a case that can be considered ideal, (i.e. limiting the sources of variability), the method is applied and the differences are observed both in a graphical and a quantitative manner. Flat top, Hanning and rectangular windows are applied for the FFT evaluated for the signals listed below:

1. sinusoidal waveforms digitally built in Matlab,
2. sinusoidal waveform from a signal generator,
3. acceleration signals of a three-axis accelerometer, measuring the sinusoidal wave motion of both a linear slide and a rotary bench, with a known motion law,
4. random vibration signals measured on a machine for industrial use.

The analysis will be carried out with reference to the theoretical data, the data from signal generators and the data from sensors, obtained with reference to the different applications of interest and characterized by different noise levels and signal shapes. Figure 1 highlights the methodological aspects taken into account in order to reach the expected improvement in the efficaciousness of the condition monitoring analysis and prognostics algorithms.

As far as for the acceleration signals, the output data from the three-axis accelerometers tested on different calibration benches will be used. The test benches that will be considered, produce a rotary motion [11] and a linear displacement [12], respectively.

The first test bench is based on a rotary device driven by a brushless servomotor, controlled by a Programmable Logic Controller by means of a high accuracy angular encoder, which allows to realize different motion laws

(sinusoidal, saw-tooth, ramp, etc.). The test bench is depicted in Figure 2 (a). The accelerometer is placed with an angle of inclination with respect to the horizontal plane: in this way, all the measuring axes will be subjected to a variable acceleration at a frequency depending on the repetition rate of oscillations.

The second test bench is based on a linear slide, which can be moved according to an assigned motion law. An inclined steel plate is installed on the test bench, with an inclination angle of 45° (Figure 2 (b)).

The sensors to be tested can be placed on the plate at different angles of rotation on the inclined plane: 0°, 30°, 45° and 60°. In this way, all the measuring axes will be subjected to accelerations with different amplitudes, at the same frequency of oscillation.

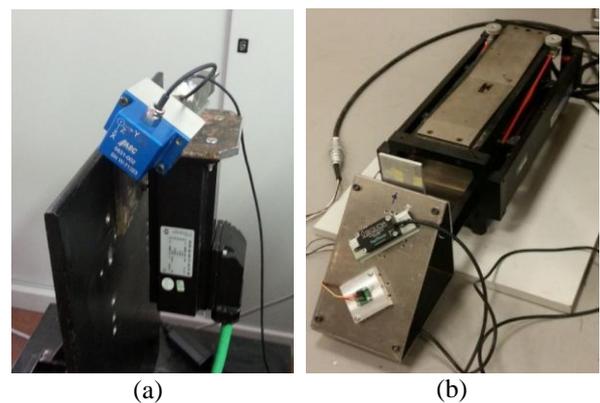


Figure 2. Calibration benches: (a) rotary test bench; (b) linear test bench.

## 3. PRELIMINARY RESULTS

Preliminary results show the effects of different window functions on data analysis and signal post-processing outcome, when different applications are considered. These

gradually approach the random monitored phenomena, towards those observables in practical industrial applications.

In the following, the four experimental cases, hint in the previous section, are reported and briefly analysed.

**1. Sinusoidal waveforms digitally built in Matlab:** A sinusoidal signal is numerically created in Matlab, simulating different amplitudes and frequencies in the ranges [1÷2] V and [20÷150] Hz, respectively. As a very simple and preliminary example, Figure 3 shows the behaviour of the FFT, when flat top (blue), Hanning (green) and rectangular (red) windows are applied on a signal with amplitude 2 and frequency 150 Hz.

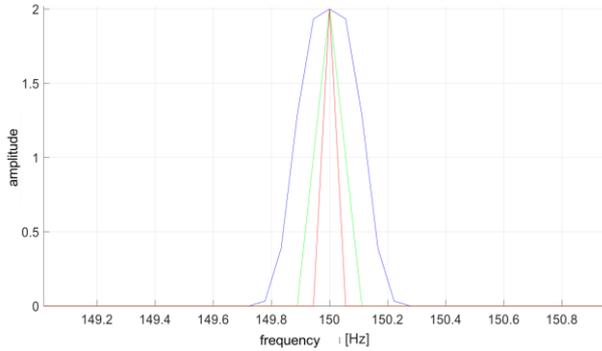


Figure 3. Comparison between flat top, Hanning and rectangular windows for a digital signal built in Matlab.

As might be expected, no remarkable differences can be noted in the effect of the windows on the signal analysed, being all able to catch the correspondent peak in the frequency domain.

**2. Sinusoidal waveform from a signal generator:** Table I shows the behaviour of the amplitude of the FFT, when the three windows are applied in the computation of the FFT for a sinusoidal wave realised by a signal generator (theoretical rms amplitude: 1,414  $V_{rms}$ ), at three different values of frequency (20, 50, 150 Hz). Mean differences are in the order of 10%.

	20 Hz	50 Hz	150 Hz
Flat Top	1,412	1,412	1,411
Hanning	1,405	1,368	1,313
Rectangular	1,394	1,300	1,166

**3. Acceleration signals of a three-axis accelerometer, measuring the sinusoidal wave motion of both a linear slide and a rotary bench:** If the same accelerometer is tested on the two systems, the temporal trend of the sensor output is different, due to the behaviour of the two test benches themselves.

In Figures 4, 5 and 6, the time behaviours of different sensors tested on the linear and the rotary benches are shown. In particular:

1. in Figures 4 and 5 the outputs of a MEMS accelerometer are shown, for tests on the linear and rotary bench respectively;

2. in Figure 6, the output of a piezoelectric accelerometer is shown, when it is tested on the rotary bench.

As for the linear calibration test bench (Figure 4), the frequencies of all acceleration components are the same; for the rotary bench (Figures 5 and 6), the frequency for the z-axis ( $\sim 6$  Hz) is twice that for x and y axes ( $\sim 3$  Hz), because the z-axis is excited by the centripetal acceleration.

Different noise levels of the acceleration signals can be noticed due to the different characteristics of the sensors.

The comparison of the amplitude values obtained applying the flat top, Hanning and rectangular windows for the spectrum analysis of the accelerometer signals is reported in Tables II, III, IV.

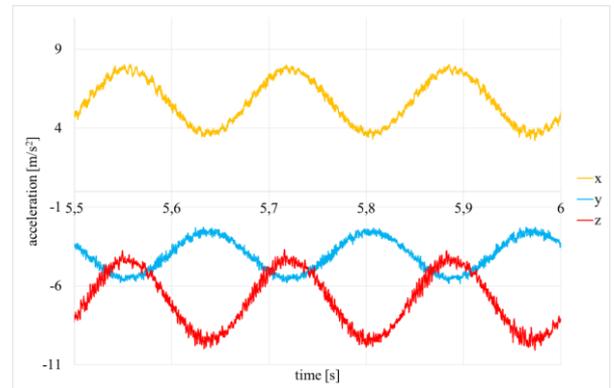


Figure 4. Time behaviour of the MEMS accelerometer on the linear bench.

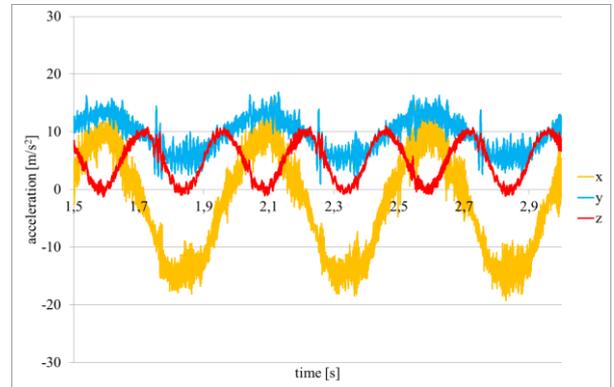


Figure 5. Time behaviour of the MEMS accelerometer on the rotary bench

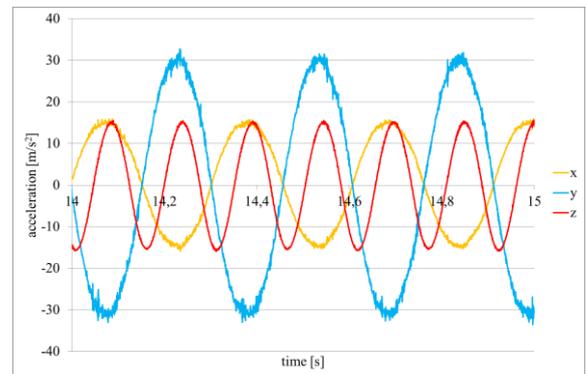


Figure 6. Time behaviour of the piezoelectric accelerometer on the rotary bench

**TABLE II.** MEMS accelerometer on the linear slide: Amplitude [ $m/s^2$ ]

	x-axis		y-axis		z-axis	
	6 Hz	10 Hz	6 Hz	10 Hz	6 Hz	10 Hz
Flat Top	1,660	2,554	1,683	2,585	2,667	4,132
Hanning	1,658	2,375	1,680	2,405	2,663	3,844
Rectangular	1,598	2,040	1,620	2,065	2,568	3,302

**TABLE III.** MEMS accelerometer on the rotary bench: Amplitude [ $m/s^2$ ]

	x-axis	y-axis	z-axis
	2 Hz	2 Hz	4 Hz
Flat Top	12,18	3,869	5,054
Hanning	12,18	3,868	5,054
Rectangular	12,18	3,869	5,054

**TABLE IV.** Piezoelectric accelerometer on the rotary bench: Amplitude [ $m/s^2$ ]

	x-axis	y-axis	z-axis
	3,3 Hz	3,3 Hz	6,6 Hz
Flat Top	15,31	31,42	15,33
Hanning	14,12	28,99	14,48
Rectangular	12,35	25,364	13,23

Depending on the windowing, significant differences can be noticed among the evaluated amplitudes; furthermore, the differences depend also on the calibration application and on the sensor performances.

This effect can affect the evaluation of the sensor sensitivity.

**4. Random vibration signals measured on a machine for industrial use:** If data from sensors used for CM on complex industrial systems are considered, the trends are obviously noisier (Figure 7) and the data processing may require special precautions.

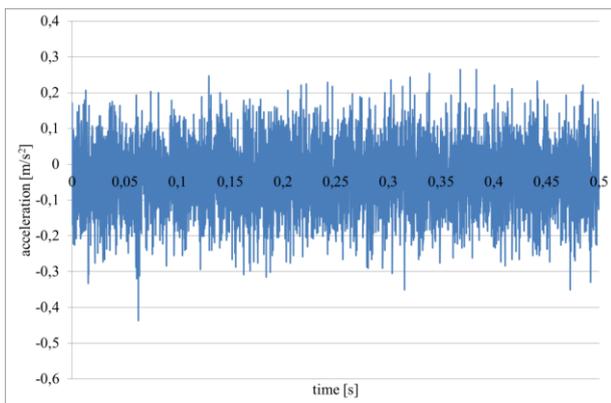


Figure 7. Output of an accelerometer used for the condition monitoring of an industrial system.

The analysis has to be carried out at different stages of use of the industrial machine, in order to detect damages. For roller bearing diagnostics, comparison of the band energy values in the interval 20 – 50 Hz is done. FFT results with different windows are reported in Table V.

**TABLE V.** Industrial machine: Band acceleration content 20 – 50 Hz [ $m/s^2$ ]

	Condition 1	Condition 2	C1 / C2
	Flat Top	0,131	0,027
Hanning	0,094	0,018	5,222
Rectangular	0,085	0,014	6,024

Windowing affects the results in a not negligible way. Differences in the ratio between Condition 1 (C1) and Condition 2 (C2) for the considered windows are found; ratio of a specific band content is useful in order to evaluate the possible occurring of defects, in this case defects of roller bearings.

The effects of windowing impact also on the evaluation of the features of II level. As an example, tables VI-VII show the results obtained, when the band power is evaluated in correspondance of the main harmonics of interest for the phenomenon analysed, applying flat top, Hanning and rectangular windows. Being the signal random, band power evaluation is of interest. The same algorithm is performed for different conditions.

**TABLE VI.** Industrial machine: Band power content [W]

	Condition 1	Condition 2	C1 / C2
	Flat Top	13,04	6,595
Hanning	11,66	6,149	1,896
Rectangular	9,831	5,532	1,777

**TABLE VII.** Industrial machine: Band power content [%]

	Condition 1	Condition 2	C1 / C2
	Flat Top	67,7	59,1
Hanning	60,5	54,6	1,108
Rectangular	51,1	49,3	1,037

## 4. CONCLUSIONS

In this paper the effect of some aspects concerning the acceleration measurement and processing has been evaluated. The quality of acceleration transducer and the setting of data processing techniques in different operating conditions as for the signal to noise ratio have been taken into account.

In particular, the differences among the vibration indicators are studied with reference not only to parameters, which are measured directly, but also with respect to features which are evaluated by repeated data processing in the frequency domain.

The analysis has been carried out with reference to some data processing parameters (windowing) and features of I level (frequency rms amplitude) and of II level (power spectral content and ratio of it with respect to the total power content) in order to study the propagation of differences.

This approach is believed to be useful in order to evaluate how much hardware and data processing settings influence the results with reference to the value of high selectivity features that are proposed in literature.

The awareness about these effects could help in merging features obtained by theoretical and experimental data, in comprehensively evaluating the uncertainty of features and in understanding the resolution of CM techniques.

## 5. REFERENCES

- [1] R. B. Randall, *Vibration-based condition monitoring*. Jhon Wiley & Sons, 2011.
- [2] ISO 13373:2016: Condition monitoring and diagnostics of machines - Vibration condition monitoring.
- [3] ISO 55001:2014: Asset management - Management systems – Requirements.
- [4] U. Leturiondo, M. Mishra, D. Galar, O. Salgado, "Synthetic data generation in hybrid modelling of rolling element bearings." *Insight: Non-Destructive Testing and Condition Monitoring*, vol. 57 no. 7 pp.395-400.
- [5] I. Khelf et al. "Adaptive fault diagnosis in rotating machines using indicators selection." *Mechanical Systems and Signal Processing*, vol. 40 no. 2, pp. 452-468, 2013.
- [6] P. Henriquez, et al., "Review of automatic fault diagnosis systems using audio and vibration signals.", *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 44, no. 5, pp. 642-652, 2014.
- [7] J. K. Sinha and K. Elbhah, "A future possibility of vibration based condition monitoring of rotating machines.", *Mechanical Systems and Signal Processing*, vol. 34, no. 1, pp. 231-240, 2013.
- [8] R. B. Randall and J. Antoni, "Rolling element bearing diagnostics—a tutorial." *Mechanical Systems and Signal Processing*, vol. 25 no. 2, pp. 485-520, 2011.
- [9] R. B. Randall, "Modern envelope analysis for bearing diagnostics." *International Journal of COMADEM*, vol. 19, no. 3, pp. 5-11, 2016.
- [10] J. Antoni, and R. B. Randall, "The spectral kurtosis: application to the vibratory surveillance and diagnostics of rotating machines." *Mechanical Systems and Signal Processing*, vol. 20 no. 2 pp. 308-331, 2006.
- [11] G. D'Emilia, A. Gaspari, and E. Natale. "Dynamic calibration uncertainty of three-axis low frequency accelerometers." *ACTA IMEKO* vol 4, no. 4, pp. 75-81, 2015.
- [12] G. D'Emilia, D. Di Gasbarro, A. Gaspari, and E. Natale, "Calibration and identification of operating limits of a low-cost embedded system with MEMS accelerometer", XXIV A.I.V.E.L.A. National Meeting proceedings, 2016.