VALIDATION OF A LOW COST SYSTEM FOR VIBRATION MONITORING

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Abstract. *Corrective maintenance cost has become a major concern in industries. The importance of predictive maintenance in manufacturing processes is getting greater every day. Predictive programs provide data about condition of the machine and operating efficiency of each system by monitoring production process variables (velocity, mass, power, strength) in real time. This program enables to identify the machine's problems before they become serious, since most of them can be avoided.One of the main symptoms that are monitored in predictive maintenance is the vibration of mechanical systems. The difficulty of this type of monitoring is the high cost of instrumentation accuracy. The instrumentation consists of acceleration sensors and a data acquisition system that contains a signal conditioner and an acquisition board.This paper seeks to validate a low cost system for vibration monitoring that consists of accelerometers, a signal conditioner and a data acquisition board for industrial applications. It was possible to analyze the accuracy, stability, system Frequency Response Function (FRF), transverse sensitivity in accelerometers and measuring range analysis of mounting a full instrumentation required to vibration monitoring. The developed low cost system was also validated through tests using a standard instrumentation constituted by accelerometers reference.*

Keywords*: validation, low cost system, vibration*

1. INTRODUCTION

Online monitoring of the vibration signals through accelerometers represents one of the main techniques used for the achievement of predictive maintenance, reducing the elevated expenses of the industries with the achievement of the other kinds of maintenance.

Many types of accelerometers exist, manufactured with different technologies, each with unique characteristics, advantages and disadvantages. The most common are the capacitive, piezoelectric and piezoresistive. However, the high cost of the accelerometers complicates the implementation of those signal acquisition systems, keeping its use restricted to the areas where cost is irrelevant, such as military and aerospace.

Recently, the mechanical accelerometers began to be replaced for a new kind, the microelectromechanical systems (MEMS). MEMS technology is one of the most promising in the field of analog technology. It explores the mechanical properties of silicon for creating mobile structures that, in the case of MEMS sensors, detect movement (acceleration), in different directions.

Thanks to MEMS technology, the accelerometers with sensitivity in 2 and 3 axes presently reduce themselves to a component of, approximately, 15 mm^3, few milligrams and low cost. Thus, these can add new capacities to the products, making them more functional and dependable.

In parallel to the evolution of the accelerometers are observed significant advances in electronic components, including computers, that allow to monitor diverse variables at the same time quickly and automated.

All of those factors tend to reduce costs significantly, since a same type of accelerometer can be used in various applications. However, for an accelerometer to be utilized in monitoring, acquisition and analysis of signals, experimental tests should be carried out in real time and in conformity with the technical standards, to validate the applicability and efficacy of those.

The reliability of the measurements carried out using accelerometers is guaranteed when these are performed by qualified personnel, using adequate and calibrated measurement and instrumentation approaches. The calibration of a vibration transducer has as main objective the determination of its sensitivity to mechanical vibrations in the amplitudes and frequencies of interest, with the level of movement freedom for which it was conceived and will be used (Ripper et al, 2006).

The calibration of vibration transducers is approached by the assembly of technical standards ISO 16063 and include primary calibration approaches, calibration methods and comparative tests to determine the additional characteristics of vibration and shock transducers (Ripper et al, 2006). ISO 16063-1 presents the basic concepts relative to the calibration of vibration transducers and orientation for the calculation of uncertainty. In turn, ISO 16063-11 specifies accelerometers' instrumentation and calibration procedures, which consists of obtaining the magnitude and angle of phase of the complex sensitivity utilizing sinusoidal excitement and laser interferometry. ISO 16063-21 describes the calibration of vibration transducers by comparison, mainly by straight comparison with a standard calibrated by primary approaches; it can also be applied to other levels of the metrological hierarchy. Finally, ISO 16063-22 specifies the instrumentation and procedures to be utilized for the secondary calibration of vibration transducers through shock excitement.

2. OBJECTIVE

The aim of this paper is to validate a low cost system for vibration monitoring, consisting of accelerometers, signal conditioners and an analog to digital conversion board. Validation will be performed through determination and analysis of different parameters, specifically: system stability, system Frequency Response Function (FRF), transverse sensitivity in accelerometers and system measuring range analysis.

3. METHODOLOGY

For the achievement of this paper a vibration monitoring system set in the Laboratory of Vibrations and Acoustics, Federal University of Uberlandia was used, being composed by accelerometers, a signal conditioning system and an analog-to-digital converter.

Initial tests evaluated the stability of the system in continuous operation during 4 days being analyzed the statistical parameters given by mean, standard deviation and confidence interval, calculated with a confidence level of 95% for the sensitivity of the sensors and ANOVA analysis. Finally were carried out tests that evaluated the existence of crossover effects between the axes, the frequency response function and the dynamic resolution of the mounted system comparing with a standard system.

3.1. Evaluated measurement system

The low-cost measurement system developed for the monitoring of vibrations and evaluated in this paper consists of:

- 3 accelerometers mounted on structures with different geometries, and two of them possess sensitivity in two directions and another with sensitivity in one direction, with a total of 5 directions.
- Signal Conditioner composed by continuous voltage source responsible for supply the sensors (5.7 V) and the circuits of gain and filtering of the signals. This work opted for an analog tension gain of 5 times and a cutoff frequency of 6 kHz for the analog low-pass filter of two poles.
- A/D converter manufactured by Data Translation, Econ/USB series, model DT-9812, 12 bits, 8 channels, maximum amplitude of operation of 2.5 V, and maximum frequency of acquisition of 50 kHz (providing a amplitude resolution for the system in the order of 0.61 mV).

The reference used in this paper for the directions of the evaluated accelerometers are presented in Table 1, and the mounted sensors are presented in Figure 1:

Table 1: Description of evaluated accelerometers and channels.

Geometry	Cubic	Cubic	Cylindrical	Cylindrical	Cylindrical with hexagonal base
Description	Accel. 1-x1	Accel. 1-y1	Accel. 2-x2	Accel. 2-y2	Accel. 3-z1

Figure 1: Accelerometers used in the experiments.

To develop this work, it was used an accelerometer from Analog Devices type ADXL 321. In order to apply it on vibration monitoring of production process, held the sensor assembly in an aluminum frame, Figure 2, pasting the chip, Figure 3, parallel to the base with epoxy resin.

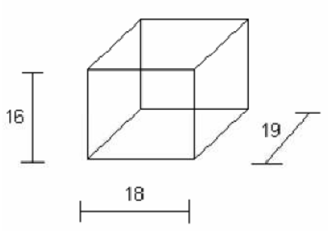

Figure 2: Aluminum frame.

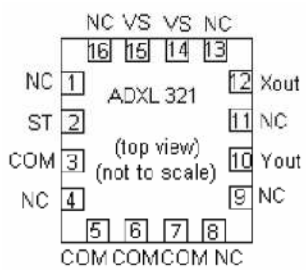

Figure 3: Chip ADXL 321 (Analog Devices).

In the assembly, were used the pins:
- Com: Pin 3
- VS: Pin 14
- Xout: Pins 7 and 12
- Yout: Pins 7 and 10

According to Analog Devices, the characteristics of ADXL 321 are:

Table 2: Specifications of ADXL 321

Parameter	Conditions	Min	Typ	Max	Unit
SENSOR INPUT	Each axis				
Measurement Range			18		g
Cross Axis Sensitivity			2		%
SENSITIVITY (RATIOMETRIC)	Each axis				
Sensitivity at Xout, Yout		51	57	63	mV/g
FREQUENCY RESPONSE					
Sensor Resonant Frequency			5.5		kHz
TEMPERATURE					
Operating Temperature Range		-20		70	°C

3.2. System stability analysis

For this tests, in order to evaluate the stability of the developed measurement system, the following equipment were utilized:
- Standard Exciter manufactured by the Bruel&Kjaer, model 4294, frequency of 159.15 Hz;
- Signal Conditioners developed with tension amplifiers and analog low-pass filters;
- Notebook manufactured by InfoWay, Intel ATOM N270 processor, 1.60 GHz, 800 MHz and 2 GB RAM.

Figure 3 shows the equipment employed in experiments.

Figure 3: Equipment employed.

A computational program was developed, in C++ language, especially for automated acquisition of the signals from the sensors. The signals were sampled with a frequency of 12500 Hz, during 20 s, obtaining 250000 points and a frequency resolution of 0.05 Hz for each test. For the achievement of the processing and analyzes of the spectrum of the signals, MatLab was used.

The experimental tests were conducted in the Laboratory of Vibrations and Acoustics. Simultaneously, it was performed the measurement of room temperature, using a digital thermo-hygrometer with resolution of 0.1 °C and measurement interval of -20 to 60 °C.

The evaluation of stability was initiated with a punctual calibration of the system, in the nominal frequency of 159.15 Hz generated by the standard calibrator, as recommended by the ISO standard 16063-21.

During calibration it was performed the measurement of the calibrator excitation through each of the mounted accelerometers, with different geometries, for this work. For each direction three samples were collected.

Concluded the initial calibration the measurement system was coupled to a refrigerator, as in Figure 4, to be continuously excited. The experimental procedure extended itself during 4 days and data collection was performed automatically by the computer, through the developed software. Passed 24 h a new calibration was performed with the objective of evaluating the behavior of the system over time. The mean time of each measurement was thirty minutes.

Figure 4: Sensors attached to the refrigerator.

In order to verify the stability of the system it was utilized an ANOVA statistical calculation using MatLab. The sensitivity of the sensors in all directions were separated in daily samples, having been made three measurements daily for each of the five sensors, totaling up 15 values per treatment.

3.3. Frequency Response Function (FRF) analysis

Tests were carried out for determination of the resonance frequencies and of the linear response bandwidths of the sensors, evaluating the 5 directions considered. The utilized criterion was the analysis of the FRFs having as input the signals of a standard piezoelectric accelerometer from B&K, model 4371, and as output the signals of the sensors studied. The sensors were used simultaneously for the acquisition of a signal of the white noise kind.

The specifications of standard piezoelectric accelerometer from B&K are charge sensitivity (at 159.15 Hz) from 9.8 ± 2% pC/g, mounted resonance frequency from 42 kHz, frequency response from 0.1 to 12600 Hz $^{+-}$10%, transverse sensitivity <4% and temperature range from -55 to 250 °C (Bruel & Kjae).

For the tests it was used a Nexus signal conditioner linked to the standard system, a digital analyzer (Spectral Dynamics SD 380 Analyzer from Scientifics-Atlanda), a signal generator model 1049 (with operation bandwidth between 2 Hz and 20 kHz, and 1.25V of amplitude), an amplifier 2712 (up to 4 times gain, with low exit impedance) and a shaker, as Figure 5. The signals were sampled until 10 kHz with a resolution in frequency of 0.5 Hz.

The standard equipments were calibrated as recommended by the ISO, with measurement uncertainty ten times smaller than required for the equipment tested. It was observed during testing that the room temperature was 27 $^{+}_{-}$ 5 °C with relative humidity up to 40%, according to the ISO.

Figure 5: Equipments employed.

It were evaluated the graphics of amplitude, phase and coherence of the FRFs, and a table was mounted containing the resonance frequency values, length of linear operation, mean, standard deviation and interval of confidence considering the values obtained for the five directions of sensitivity.

3.4. Transverse sensitivity analysis

It is desired that a bidirectional sensor does not present response in a perpendicular direction to the excitation direction. So tests were performed to evaluate a possible crossover interference of the channels of the studied bidirectional sensors.

For a comparison effect, it were initially used 2 standard B&K sensors that performed the measurement of a white noise kind of signal applied over a standard block attached to the shaker, as shows Figure 6. It was possible to observe the spectrum of the signals in the perpendicular and main directions to the excitation through the standard system and subsequently compare them to the signals acquired by the bidirectional sensors studied.

Figure 6: Mounting the accelerometer and standard block on the shaker.

3.5. System measuring range analysis

Tests were carried out to evaluate the dynamic resolution of the system, in which were utilized a band-pass filter (2 kHz and 23%), model 1621 in the output of the signal generator. A white noise was generated, filtered, amplified and applied to the shaker in which were simultaneously positioned a standard sensor and one of the studied sensors, as shown in Figure 7. The tests were repeated for all the directions of the sensors.

Figure 7: Accelerometers placed on the shaker.

Finally were plotted the graphics with the signals acquired simultaneously considering as criterion for determination of the dynamic operation resolution of the system, the value in dB from which it is observed a difference higher than 1dB between the signals of the standard and studied sensors.

4. RESULTS

4.1. System stability analysis

During the punctual calibration tests in 159.15 Hz it was observed the signals in time domain and the respective spectrum for the essays of the sensors in the 5 directions evaluated during the 4 days of tests. Figure 8 presents one of the samples obtained.

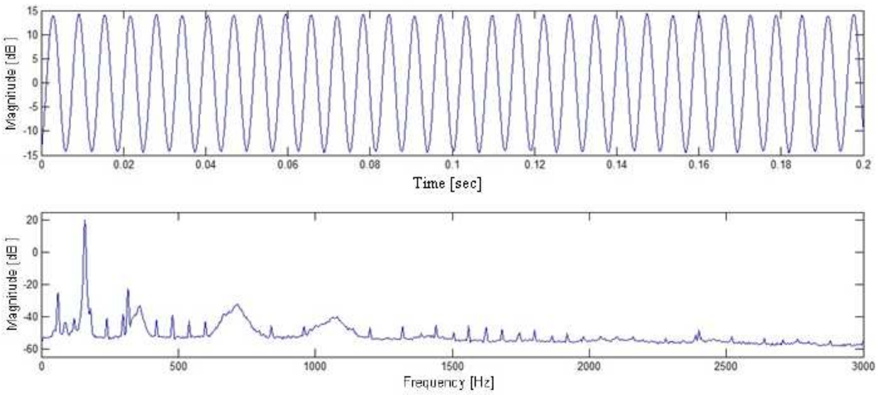

Figure 8: Time signal and signal spectrum generated by the exciter and acquired by the developed system.

It was observed that the system generated the spectrum of the signals with excitation frequency in 159.5 Hz for all essays over the 4 days of test. When compared with the reference frequency it presented a slightly superior value, of merely 0.35 Hz. This being, it is possible to say that the system presents good accuracy for the evaluated frequency. The variability of the measured frequency was zero, indicating good precision.

Table 3 presents the values of the calibration factors obtained during the 4 days of tests. Table 4 presents the statistical parameters of the ANOVA analysis.

Table 3: Sensitivity [V/ms^{-2}] grouped by day of testing.

Day 1	Day 2	Day 3	Day 4
5.89	5.85	5.82	5.82
5.89	5.85	5.82	5.82
5.90	5.85	5.82	5.82
5.69	5.72	5.70	5.68
5.69	5.72	5.70	5.68
5.69	5.72	5.70	5.68
6.18	6.15	6.19	6.18
6.19	6.15	6.19	6.17
6.19	6.15	6.19	6.18
6.17	6.20	6.18	6.19
6.18	6.20	6.19	6.19
6.18	6.20	6.19	6.19
6.12	6.20	6.20	6.18
6.13	6.19	6.20	6.18
6.13	6.17	6.20	6.18

Table 4: ANOVA analysis.

Source	SS	df	MS	F	Prob> F
Columns	0.001	3.000	0.000	0.010	0.999
Error	2.528	56.000	0.045		
Total	2.529	59.000			

The ANOVA table has six columns: The first shows the source of the variability. The second shows the Sum of Squares (SS) due to each source. The third shows the degrees of freedom (df) associated with each source. The fourth shows the Mean Squares (MS) for each source, which is the SS/df ratio. The fifth shows the F statistic, which is the ratio of the MSs. The sixth shows the p-value, which is derived from the cdf of F. As F increases, p-value decreases.

Regarding the sensitivity of the five axes of the evaluated accelerometers it can be observed that it had small variations between the values obtained between axes and between the calibrations, which was confirmed by the ANOVA analysis in which 99.9% of the samples can be considered as belonging to a same population. The variability observed can be justified due to variation of the environmental conditions over time and to random effects.

4.2. Frequency Response Function (FRF) analysis

In Table 5 are presented the results obtained after performing the tests that evaluated the frequency responses and the bandwidths of linear response of each sensor.

Table 5: Accelerometers' resonance frequency and sensors' linear response.

	Resonance Frequency [Hz]	Linear Response [Hz]
Direction x1	5400.0	3700.0
Direction y1	5400.0	3700.0
Direction z1	5300.0	3500.0
Direction x2	5200.0	3500.0
Direction y2	5200.0	3500.0
Mean	5300.0	3500.0
Standard Deviation	100.0	109.5
Confidence Interval	87.5	96.5

In Figure 9 it is presented the graphic with the FRF obtained for the direction y1.

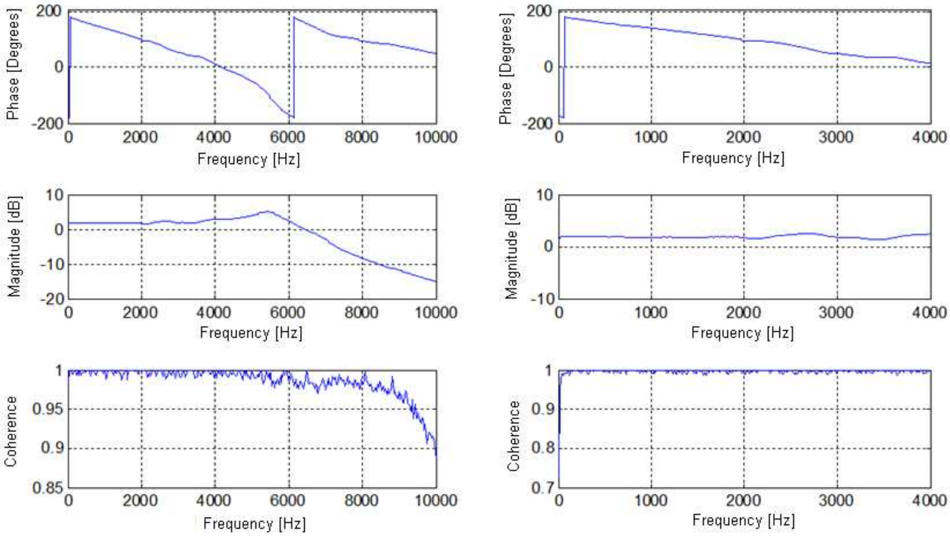

Figure 9: Frequency Response Function from direction y1.

It is observed through the analysis of the results that the studied sensors possess a resonance frequency with mean value of 5300 Hz, with standard deviation of 100 Hz and confidence interval of + /- 87.5 Hz, and a bandwidth of linear operation limited in 3500 Hz with standard deviation of 109.5 Hz and confidence interval of + /- 96.5 Hz calculated with a level of confidence of 95%.

By the analysis of the FRF one can observe the region of resonance and linear bandwidth for the direction y1 near the expected means with a coherence equal to 1 in frequencies up to 4 kHz.

4.3. Transverse sensitivity analysis

It was evaluated the transverse sensitivity for accelerometers 1 and 2 comparing with the results obtained by the standard system, obtaining Figure 10.

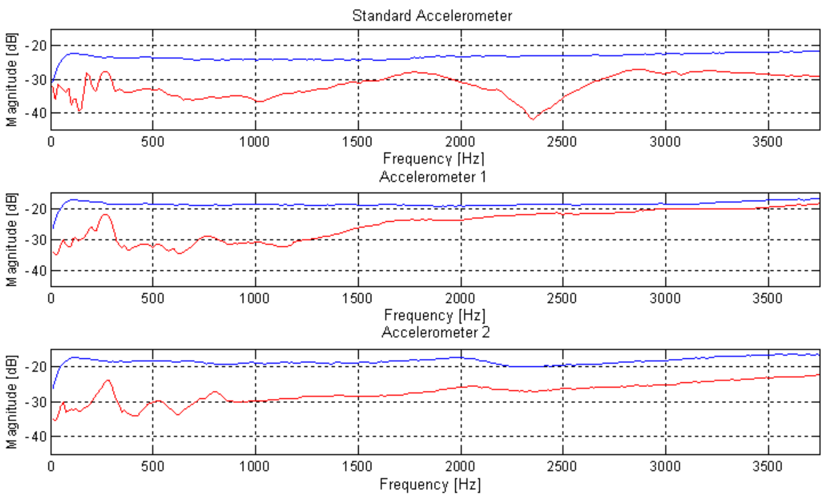

Figure 10: Transverse Sensitivity from accelerometers 1 and 2.

It is observed, through the analysis of the figures, that behavior of the spectrum in the principal and crossed directions is similar for the standard and studied accelerometers. It is able to note yet that the difference between the main and crossover signals for the standard sensor are very close to the differences between the main and crossover signals for the studied sensors, obtaining greater differences for the accelerometer 1 in high frequencies and better results in medium and low frequencies. For accelerometer 2 better results were obtained even in high frequencies.

The crossover effects of the evaluated accelerometers occur to the extent that the chips are not mounted perfectly parallel to the metallic structures of the sensors.

4.4. System measuring range analysis

Figure 11 shows the white noise signals, filtered in 2 kHz, which upon excitation by the shaker were acquired simultaneously by the standard sensor and by the sensor in the direction x1.

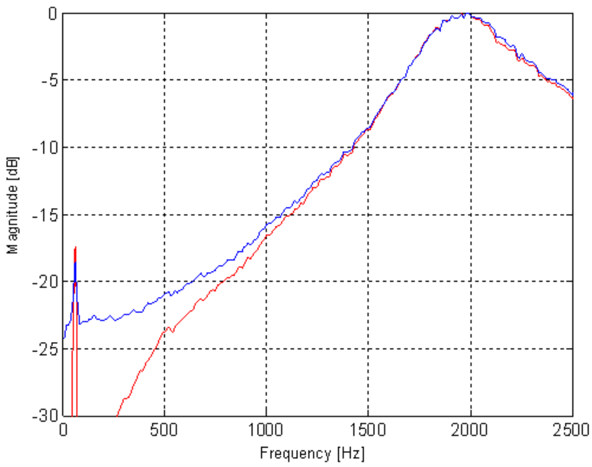

Figure 11: Measuring range from direction x1.

Observing Figure 11 it is able to notice a difference greater than 1 dB between the signals acquired by the standard and studied systems from -21 dB.

It is expected that the behavior of the studied system, upon acquiring a filtered signal, maintains itself like that of the standard system in its dynamic resolution of operation.

It is concluded that in a monitoring performed by the studied accelerometers, signals below 20 dB, in relation to the maximum value of the spectrum, are considered negligible.

The tests were repeated for the other directions. The results are presented in Table 6.

Table 6: System measuring range.

	Measuring range [dB]
Direction x1	21.3
Direction y1	19.1
Direction z1	17.4
Direction x2	19.1
Direction y2	26.7
Mean	19.1
Standard Deviation	3.7
Confidence Interval	3.2

Observing Table 6 it can be concluded that the dynamic resolution of the evaluated system is of 19.1 dB on mean, with standard deviation of 3.7 dB and confidence interval of + /- 3.2 dB, calculated with a confidence level of 95%.

5. CONCLUSIONS

With this work it was possible to conclude that:

- The evaluated system has mean sensitivity practically constant over 4 days of continuous operation being classified as stable for this period, and 99.9% of the obtained samples can be considered as belonging to a same population according to the ANOVA analysis. It was used an A/D converter 12-bit, providing an amplitude resolution for the system in the order of 0.61 mV.

- The system presents good accuracy for the frequency evaluated in the punctual essays in 159.15 Hz, obtaining 159.5 Hz in all of the essays, considering that signals were analyzed with a frequency resolution of 0.05 Hz. The variability of the measured frequency was zero, indicating good precision.

- The mean resonance frequency of the studied sensors is of 5300 Hz with standard deviation of 100 Hz and a confidence interval of + /- 87.5 Hz. The linear answer is limited in 3500 Hz with standard deviation of 109.5 Hz and confidence interval of + /- 96.5 Hz, calculated with a level of confidence of 95%, what guarantees the application of this system in the monitoring of the machining processes and performing of predictive maintenance.

- The behavior of the spectrum in the principal and crossover excitation directions of the signals acquired by the evaluated accelerometers is similar to the behavior of the spectrum of the standard accelerometer with greater differences in the high frequencies. The crossover effects of the evaluated accelerometers occur to the extent that the chips are not mounted perfectly parallel to the metallic structures of the sensors.

- The dynamic resolution of the evaluated system is of 19.1 dB on average, with standard deviation of 3.7 dB and confidence interval of + /- 3.2 dB, calculated with a confidence interval of 95%.

- The values for measuring range and frequency response of the system were consistent with those presented by the sensor manufacturer ADXL, considering that the whole acquisition system was calibrated consists by the sensor, the signal conditioning and acquisition board, thus obtaining the sensitivity and resolution of the entire system.

6. ACKNOWLEDGEMENTS

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