Development of an Instrumentation System Embedded on FPGA for Real Time Measurement of Mechanical Vibrations in Rotating Machinery

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Abstract—**The real-time monitoring of events in an industrial plant is vital, to monitor the actual conditions of operation of the machinery responsible for the manufacturing process. A predictive maintenance program includes condition monitoring of the rotating machinery, to anticipate possible conditions of failure. To increase the operational reliability it is thus necessary an efficient tool to analyze and monitor the equipments, in real-time, and enabling the detection of e.g. incipient faults in bearings. To fulfill these requirements some innovations have become frequent, namely the inclusion of vibration sensors or stator current sensors. These innovations enable the development of new design methodologies that take into account the ease of future modifications, upgrades, and replacement of the monitored machine, as well as expansion of the monitoring system. This paper presents the development, implementation and testing of an instrument for vibration monitoring, as a possible solution to embed in industrial environment. The digital control system is based on an FPGA, and its configuration with an open hardware design tool is described. Special focus is given to the area of fault detection in rolling bearings.**

Keywords-ball bearings; fault diagnosis; reconfigurable architectures; vibration monitoring;

I. INTRODUCTION

An ideal machine does not produce vibrations, because all energy is directed to perform the work to be done. However, the elements of machines, dissipated energy as heat, noise, and vibration, because of the actions of cyclic forces and the natural presence of trembles in moving machines.

Predictive maintenance by vibration monitoring of rotating machine is a scientific approach that becomes the new route to the maintenance management. Rotating machine, even new ones generate some level of vibration. Small levels of ambient vibrations are acceptable. However, higher levels and increasing trends are symptoms of abnormal machine performance. Many condition monitoring methods have been proposed for different type of rotating machine faults detection and localization [1–3].

Machine vibration analysis is one of the important tools for rolling bearing faults identification. In fact, large rotating machine systems are often equipped with sensors monitoring mechanical quantities. In many situations, vibration monitoring methods are used to detect the presence of incipient failures in electrical motors [4–6].

The contribution of this paper is to present the steps for designing a vibration monitoring instrument embedded on reconfigurable logic, for real time vibration measurement and analysis. Digital signal processing routines, implemented into a low-cost field programmable gate array (FPGA) were developed to provide on-line detection, measurement and data analysis for rolling bearing faults. The outputs of the system when monitoring a motor with inner and outer race faults in its bearings are discussed.

II. EMBEDDED INSTRUMENTATION

An embedded analysis instrument is a system where the processing unit is dedicated and performs a specific monitoring function, usually reporting in real time. In contrast to the use of a general purpose computer, which works with various devices and processes, embedded instruments are aimed at tasks requiring a fast processor dedicated to a single assignment.

A. Embedded systems

Embedded digital systems have grown tremendously in recent years, not only in their popularity, but also in their complexity. This complexity demands a new type of designer, one who can easily cross the traditional border between hardware design and software design.

Three important trends have made such a unified view possible. First, integrated circuit (IC) capacities have increased to the point that both software processors and custom hardware processors now commonly coexist on a single IC. Second, compilers and programming software has evolved, being now common the use of processor-independent C, C++, or Java compilers, and integrated design environments (IDEs) in embedded system design. Such developments significantly decreased the importance of the focus on microprocessor internals, and the full abstraction of assembly language. Third, synthesis technology has advanced to the point that synthesis tools have become commonplace in the design of digital hardware. Synthesis tools are, for hardware design, nearly at the same level as compilers in software design: they allow the designer to describe desired functionality in a high-level programming environment, and then automatically generate an efficient custom-hardware processor implementation.

B. *Modeling Instrumentation Systems*

The modeling of instrumentation systems requires the use of a set of tools for mounting a virtual simulation of physical systems. For design engineers these tools should allow the design of a simplified physical model, as close as possible to the real model, allowing its implementation in real time and within levels of accuracy required.

These tools should support, through hierarchical block libraries, dedicated to mathematical computation functions, the modeling of the whole instrumentation system. Digital signal processing routines, electronic components, mechanical elements, sensors, actuators and all other parts should be possible to model. From the modeling of the complete instrumentation system, a predictive control algorithm can be implemented optimize the operation of the monitored machine.

Matlab's Simulink was used for the prototyping of the digital signal processing application in terms of functional blocks, and the respective simulation. The DSP Builder software tool was used within Simulink, to support the design and direct compilation of the digital signal processing routines to FPGA's of Altera [8].

Therefore, using this approach, when the control algorithms are concluded, it is possible to replace the Simulink operation blocks by the ones compatible with the FPGA. Also it is possible to change between the actual machinery, its model, or previously recorded data.

C. *Reconfigurable FPGA device*

Reconfigurable computers offer a compromise between the performance advantages of fixed-functionality hardware and the flexibility of software-programmable substrates. Like ASICs, these systems are distinguished by their ability to directly implement specialized circuitry directly in hardware. Additionally, like programmable processors, reconfigurable computers contain functional resources that may be easily modified after field deployment in response to changing operational parameters and data sets. To date, the core processing element of most reconfigurable computers has been the field-programmable gate array (FPGA). These bit-programmable computing devices offer ample quantities of logic and register resources that can easily be adapted to support the fine-grained parallelism of many pipelined DSP applications. With current logic capacities exceeding one million gates per device, substantial logic functionality can be implemented on each programmable device. While appropriate for some classes of implementations, FPGA represent only one possible implementation in an embedded digital system.

III. ROLLING BEARING FAULTS

The common faults of rolling bearings include corrosion in inner race, outer race and rolling elements, fatigue pitting and cage damage. Any faults of inner race, outer race and rolling elements will cause modulation phenomenon. If there is a fault in either inner or outer race or rolling elements, mechanical impulse with higher amplitude will be incurred while shaft rotating. This impulse will motivate the nature frequency of inner, outer race and rolling elements [9].

A. *Geometry Dependence*

For a particular bearing geometry, inner race, outer race and rolling element faults generate vibration spectra with unique frequency components. These frequencies, known as the defect frequencies, are functions of the running speed of the motor and the pitch diameter to ball diameter ratio of the bearing. Outer and inner race frequencies are also linear functions on the number of balls in the bearing. Given the geometry of the bearing in Fig. 1, for an angular contact ball bearing in which the inner race rotates and the outer race is stationary, the four characteristic frequencies is presented in Table 1. Where the outer race is fixed, f_i is the rotation frequency of shaft in hertz, D is the pitch diameter, d is the ball diameter, α is the contact angle, and Z is the number of balls. Assume the contact between balls and inner race and outer race is pure rolling contact [2].

TABLE I. CHARACTERISTIC FAULT FREQUENCIES

Fault frequency of inner race	$f_{bi} = f_i \times \frac{Z}{2}(1 + \frac{d}{D}\cos\alpha)$
Fault frequency of outer race	$f_{bo} = f_i \times \frac{Z}{2}(1 - \frac{d}{D}\cos\alpha)$
Fault frequency of rolling elements	$f_{bs} = f_i \times \frac{D}{2d}(1 - (\frac{d}{D}\cos\alpha)^2)$
Fault frequency of cage	$f_c = f_i \times \frac{1}{2}(1 - \frac{d}{D}\cos\alpha)$

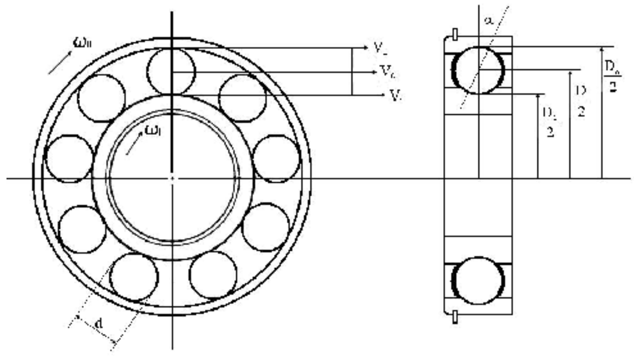

Figure 1. Ball bearing geometry

B. *Faults Identification Approaches*

On line vibration measurement and analysis instrument is one important tool for rolling bearing faults identification. There were explored two types of analysis: time domain and frequency domain. The frequency domain analysis is more attractive because it can highlight in more detail information about the status of the machine. Time domain analysis can give qualitative information about the machine condition.

Traditionally, fast Fourier transform (FFT) is used to perform frequency analysis. If the level of random vibrations and the noise are high, inaccurate information about the machine condition is obtained. Noise and random vibrations may be suppressed from the vibration signal using signal processing applications such FIR filters, averaging, correlation and convolution [10].

Some works [11–12] have used higher order spectra to detect the fault frequency from modulated frequencies. This approach is useful when there is a simple modulation. However, in complex modulations it is hard to get a good result in this way.

In this case study, a diagnostic system for identification of bearing failures was developed. In the first phase the virtual instrument system was developed in Matlab software. In the second phase, the model of the virtual instrument system was converted to VHDL code using Simulink/DSP Builder software and embedded on reconfigurable FPGA device.

IV. Virtual Instrument Developed

The proposed structure for the virtual instrumentation system consists of three stages: (i) calculation of the theoretical frequency characteristics of bearing failures; (ii) analysis of the time domain to calculate the RMS value, peak value, crest factor and kurtosis, (iii) analysis of high frequency bands (the technique of envelope) in the frequency domain, identifying the frequency of failures (peak values of the spectrum). The virtual instrumentation system was implemented in Matlab. Fig. 2 shows the graphical representation of the virtual instrument system implemented.

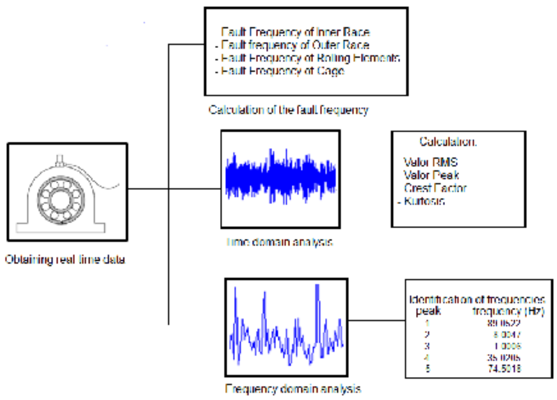

Figure 2. Schematic diagram of the virtual instrument system

TABLE II. Geometrical Parameters of the 6205 NSK

Geometrical Parameters	Value
Number of balls	9
Ball diameter	7.96 mm
Inner raceway diameter	31.04 mm
Outer raceway diameter	46.72 mm

A computational routine calculates the theoretical fault frequency, using the geometric data of the rolling bearing. In the analysis in time domain, routine calculates the parameters that demonstrate the existence of faults in rolling bearings, such as RMS value, peak value, crest factor and kurtosis. In the analysis of high frequency bands, the technique of envelope is obtained through four steps: (i) filtering the signal with an elliptic filter (band pass) in order to eliminate some noise, (ii) correction signal in the time domain, which consists of removing the negative part of the signal, (iii) application of fast Fourier transform to obtain the spectrum, (iv) identification of the five largest amplitude peaks of the spectrum to locate the frequency of failure.

A. *Methodology*

The experimental procedure was performed so that the virtual instrumentation system acquired data online, at a frequency of 10 kHz, at intervals of 4 seconds, comprise a total of 40,000 samples for processing and analysis by computer routines developed, operating with Matlab software. The bearing NSK 6205 was used to test, with previously known faults and generated in the laboratory by the manufacturer NSK. The bearings were classified by the manufacturer according to the location of the fault (inner and outer race). Table 2 shows the geometric data of the 6205 NSK bearing, which were used for the theoretical calculations of the frequency characteristics of bearing failures.

B. *Prototype Setup*

A laboratory set was prepared to examine theoretical results, which has been focused on the development and testing of algorithms and methods suitable for on line detection of rolling bearing faults identification. A test bench was created to provide a representative model of a real situation where the bearing could be mounted in its housing and the active forces and velocities were similar to those found in actual situations of the industrial environment. The vibration sensor is an accelerometer, with a bandwidth of more than 10 kHz, the selected data acquisition card, is a 16 bit card with a maximum sampling rate of 1.25 MS/s. Fig. 5 shows the laboratory set that illustrates the test environment used for the development of computational algorithms for virtual instrumentation system proposed. Basically, it consists of a microcomputer, a data acquisition board, an amplifier, a signal conditioner, an accelerometer and a three-phase induction motor.

C. *Modeling Virtual Instrument System in Simulink Software*

A functional block is a basic structure that can represent a function, or a specialized system, with defined input and output ports and customized parameters [7], see Fig. 4.

Simulink allowed the modeling and simulation of the proposed diagnostic system for identification of bearing failures. The libraries of functional blocks of Simulink allowed the construction of the basic structure of the functional virtual instrumentation system, which was divided into three stages:

- **Stage 1**: measurement of the statistical parameters in time domain.
- **Stage 2**: frequency analysis of Fourier transform in the frequency domain.
- **Stage 3**: theoretical calculation of the frequencies of failures and display of geometric data of the bearing.

The system designer has to do the mapping of the electronic hardware to symbolic representation in Simulink. A voltage signal is coming from the vibration sensor. The selected data acquisition card is a 16-bit card with a maximum sampling rate of 1.25 MS/s. The model consists of one analog input block to drive the signal sensor, a subsystem of normalization of the signal block, a 6th order low-pass Butterworth filter block with a cut-off frequency of 5 kHz, a FFT calculating block implemented in Matlab and graphical display block which produces a graph of amplitude versus frequency of the band frequency of input signal. A functional block representing the block diagram of stage 2 is shown in Fig. 3.

D. Modeling Virtual Instrument System in DSP Builder Software

Figure 3 shows the block diagram of stage 2 modeled on the DSP Builder software. The block normalization of the signal was implemented using the library Altera DSP Builder Advanced Block set/Model Prim and Block set/Arithmetic. The block Filter was implemented using the library Altera DSP Builder Block set/Mega Core FIR_Compiler_v10_0. The block FFT was implemented using the library Altera DSP Builder Block set/Mega Core FFT_v10_0.

Once installed, along with the Matlab / Simulink, the DSP Builder allowed: (i) modeling system developed in Simulink; (ii) simulation of the model created; (iii) once the development phase has been completed, the conversion model for the RTL code in VHDL; (iv) simulation of VHDL code, using the same test vectors used in the simulation with Simulink; (v) transfer to FPGA hardware and final test of the complete system. After verifying the results obtained in the simulation environment in Simulink / DSP Builder, it was possible to generate the VHDL code for all models built.

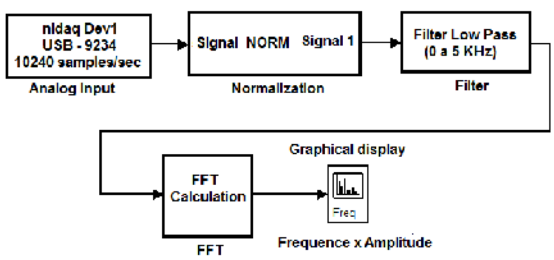

Figure 3. Schematic diagram of stage 2: frequency analysis of Fourier transform in the frequency domain.

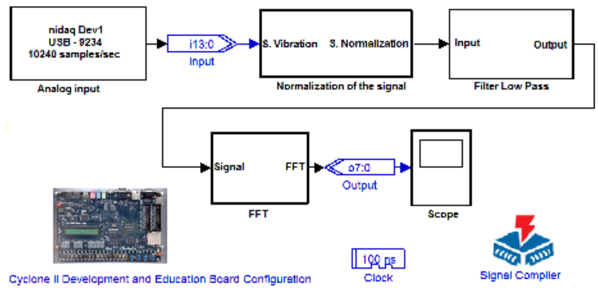

Figure 4. Block diagram of stage 2 modeled in DSP Builder.

V. EXPERIMENTAL INSTRUMENTATION SYSTEM RESULTS

Table 3 shows the fault frequencies and harmonics calculated by the virtual instrumentation system, considering the rotation axis as 25 Hz (1500 rpm) and the geometric parameters of the NSK 6205 bearing.

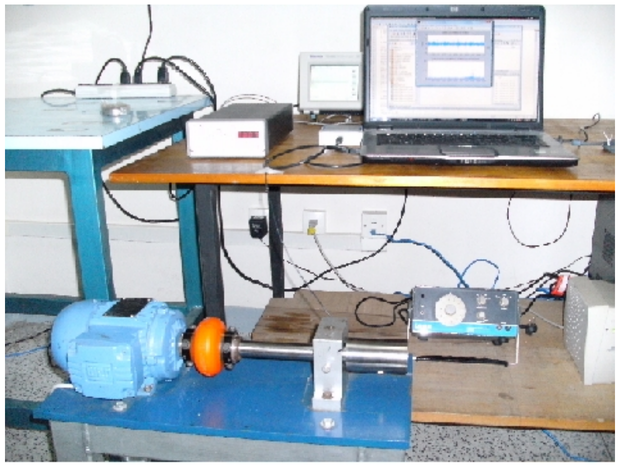

Figure 5. Mounting structure for bearing and related motor

TABLE III. CHARACTERISTIC FREQUENCIES OF BEARING FAILURES

Fault frequency (Hz)	Fundamental	2nd harmonic	3rd harmonic
Inner race	135.40	270.80	406.20
Outer race	89.60	179.20	268.80
Ball	58.87	117.74	176.61
Cage	9.95	19.90	29.85

In Fig. 6 it is plotted the vibration signal in time domain, and also the frequency composition of the signal, when a bearing defect (inner race) is presented. In the vibration spectrum presented in Fig. 6 it is not immediate the identification of the bearing failure.

In the analysis of high frequency bands, the technique of the envelope is obtained. Fig. 7 shows the spectrum of vibration signal demodulated with the identification of the characteristic frequency of inner race fault. It can be seen that the desired frequency components can be distinguished easily.

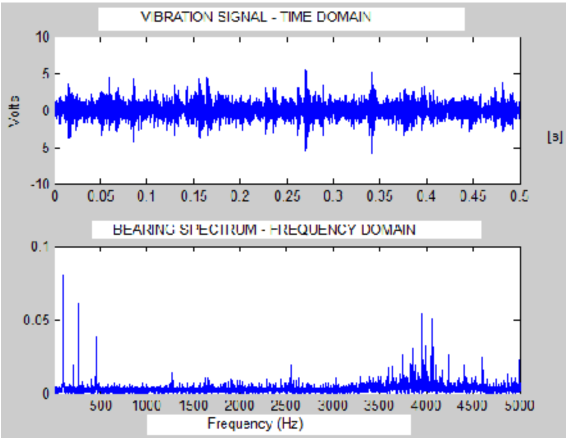

Figure 6. Vibration signal and the vibration spectrum of the bearing failure (inner race).

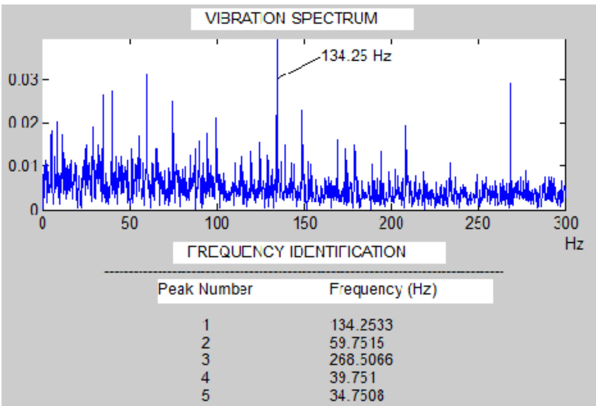

Figure 7. Spectrum of vibration signal demodulated with the identification of the characteristic frequency.

VI. CONCLUSION

A complete approach for modeling, simulation and development of an on-line vibration measurement and analysis digital instrument based in reconfigurable FPGA device was presented. FPGAs provide the highest digital signal processing performance available on a programmable platform, but optimizing a DSP algorithm in an FPGA can be difficult. Until recently, the algorithm needed to be ported to HDL and then RTL functional simulation would be verified to using the high-level simulation test vectors. The set of design tools used, Simulink and its package DSP Builder provided a higher level of design abstraction, adaptability, and productivity, and deliver a level of performance comparable to traditionally optimized HDL. This approach uses a high-level behavioral description of the DSP algorithm.

The implementation was simulated and then deployed into an FPGA based vibration analysis hardware set up. The results obtained were coherent with the faults generated on an NSK 6205 bearing, and therefore validate the proposed approach and implementation, which can be replicated and deployed on industrial plants.

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