Development of Diagnosis System for Rolling Bearings Faults on Real Time Based on FPGA

M. Kashiwagi[1], C. da Costa[2] and M. H. Mathias[1]

[1] Department of Mechanical
UNESP - Univ Estadual Paulista
Campus of Guaratinguetá – Guaratinguetá, São Paulo (Brazil)
Phone:+0055 12 31232849, e-mail: **masamori@ifsp.edu.br, mathias@feg.unesp.br**

[2] IFSP – Fedral Institute of Science Education and Technology
Campus of Cubatão – Cubatão, São Paulo (Brazil)
Phone:+0055 11 76407234, e-mail: **cost036@attglobal.net**

Abstract. The real-time monitoring of events in an industrial plant is an advanced technique that presents the real conditions of operation of the machinery responsible for the manufacturing process. A predictive maintenance program includes various rotating machinery condition monitoring techniques of the machine to determine the conditions of failure. To increase the operational reliability and to reduce preventive maintenance, it is necessary an efficient tool for analysis and process monitoring, in real time, enabling the detection of incipient faults for rolling bearings. Over the past few years there has been a major technological developments related to digital system, including innovations in both hardware and software. These innovations enable the development of new design methodologies that take into account the ease of future modifications, upgrades and expansions of the designed system. This paper presents a study of new design tools for embedded digital systems based on open hardware architecture with reconfigurable logic. Will be discussed a case study in the area of fault detection of rolling bearings, as well as its implementation and testing.

Key words

Mechanical vibration, Embedded system, Digital signal processing and FPGA.

1. Introduction

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 [1-8].

Machine vibration analysis is one of the important tools for rolling bearing faults identification. In fact, large rotating machinery systems are often equipped with sensors based on mechanical quantities. In many situations, vibration monitoring methods are used to detect the presence of incipient failures in rolling bearings [9].

In this context, a variety of sensors could be used to collect measurements from a rotating machine for the purpose of preemptive failure monitoring. These sensors might measure stator voltages and currents, air-gap and external magnetic flux densities, rotor position and speed, output torque, internal and external temperature and case vibrations, among others. In addition, a real time vibration measurement and analysis instrument could monitor a variety of failures.

For the purpose of detecting such fault-related signals, many diagnostic methods have been developed so far. These methods to identify faults in rotating machines, may involve several different types of fields of science and technology [10- 11].

The contribution of this paper is to present new design tools for embedded digital systems based on open hardware architecture with reconfigurable logic for real time vibration measurement and analysis. Besides, special purpose digital signal processing (DSP) hardware, implemented into a low-cost field programmable gate array (FPGA) is developed to provide on-line detection, measurement and data analysis for rolling bearing faults.

2. 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 [12].

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, Z is the number of balls. Assume the contact between balls and inner race and outer race is pure rolling contact [13].
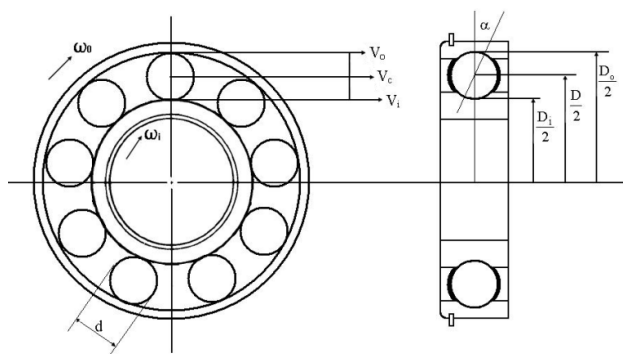

Fig. 1- Ball bearing geometry

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

Table 1- Characteristic fault frequencies

It is important that the measurements of vibration are taken to diagnose the state of the machine before it enters into a fault mode. It is further necessary to do so in real time by continuously monitoring the machine variables.

3. Faults Identification Approaches

Real time vibration measurement and analysis instrument is one important tool for rolling bearing faults identification. There are two types of analysis: time domain and frequency domain. The frequency domain analysis is more attractive because it can give more detailed information about the status of the machine. Time domain analysis can give qualitative information about the machine condition. Generally a machine vibration is a stationary signal composed of random vibration and noise. Traditionally, fast Fourier transform (FFT) is used to perform such 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 [14]. According to property of convolution, the convolution in time domain is equal to the product in frequency domain, so the fault signal becomes modulated signal after through accelerator sensor.

Some works [15], [16] 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 stage the virtual instrument system was developed in MATLAB software. In the second stage, the model of the virtual instrument system was converted to VHDL code using SIMULINK/DSP Builder software and embedded on FPGA. The design issues was captured and presented in a way that allowed the VHDL code to be generated automatically

4. Virtual Instrument System

The proposed structure for the virtual instrumentation system consists of three steps: (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 technical envelope or HFRT) 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.

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 the envelope is obtained through four stages: (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.

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 in the 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.

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

Table 2- Geometrical Parameters of the 6205 NSK bearing.
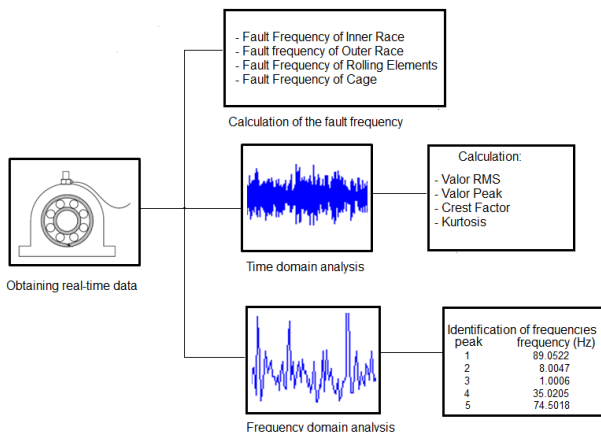

Fig. 2 - Schematic diagram of the virtual instrument system.

A. Laboratory Test Setup

A laboratory test setup was prepared to examine theoretical results, which has been focused on the development and testing of algorithms and methods suitable for real-time 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. 3 shows the laboratory test setup 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.

B. Experimental 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.

Fig. 3 – Mounting structure for bearing and related motor.

Fault Frequency (Hz)	Harmonic 1X	Harmonic 2X	Harmonic 3X
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

Table 3- Characteristic frequencies of bearing failures.

Fig. 4 shows the graphic of the vibration signal in time domain and spectral components produced by bearing defect (inner race). In the vibration spectrum presented in Fig. 4 it is not so ease the identification of the bearing failure.

In the analysis of high frequency bands, the technique of the envelope is obtained. Fig. 5 shows a 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.
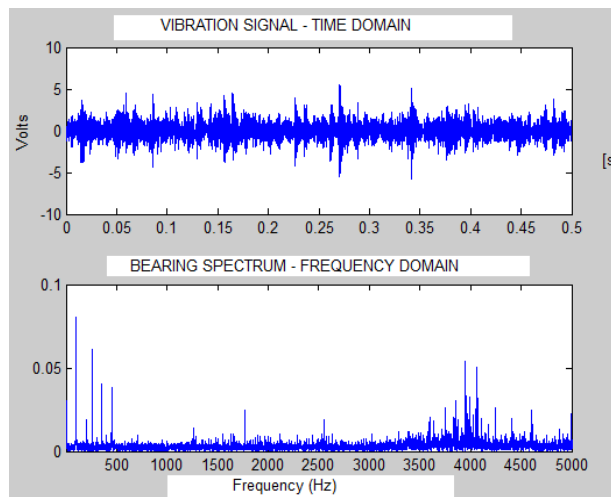

Fig. 4 – Vibration signal and the vibration spectrum of the bearing failure (inner race).
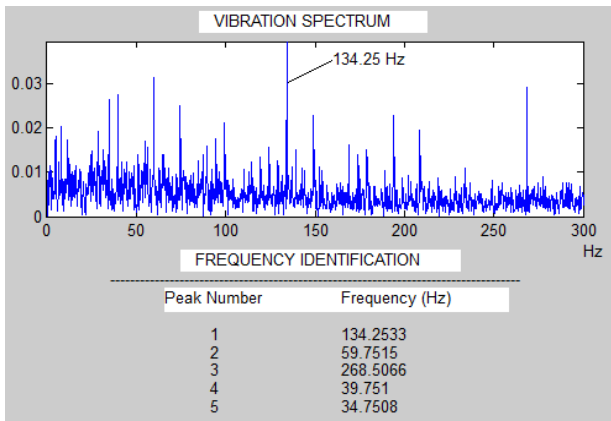
Fig. 5 – Spectrum of vibration signal demodulated with the identification of the characteristic frequency.

5. Modeling Virtual Instrument System in SIMULINK

SIMULINK is a dynamic system and simulation software that offers an interactive scientific and engineering environment for system modeling, analysis, and simulation. This environment is useful for the rapid prototyping of a digital signal processing application in terms of functional blocks, and provides a high-level simulation. 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 [17, 18 e 19].

The 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 models:

Model 1: measurement of the statistical parameters in time domain;
Model 2: frequency analysis of Fourier transform in the frequency domain;
Model 3: theoretical calculation of the frequencies of failures and displays of geometric data of the bearing.

The system designer has to do the mapping the behavioral of electronic hardware to symbolic representation in SIMULINK model. The signal is coming of 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 a model 2 is shown in figure 6.

6. Modeling Virtual Instrument System in DSP Builder Software

The DSP Builder is a software tool to support the design of systems based on digital signal processing (DSP), developed by Altera Inc., which provides a library of special blocks for use with SIMULINK, which are directly compiled into logic configurable to FPGA devices [20].
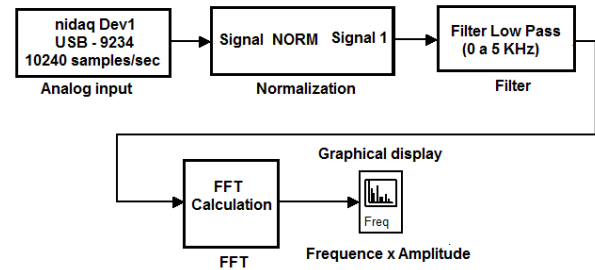

Fig. 6 – Schematic diagram of model 2: frequency analysis of Fourier transform in the frequency domain.

Fig. 7 shows the block diagram of model 2 modeled on the DSP Builder software.
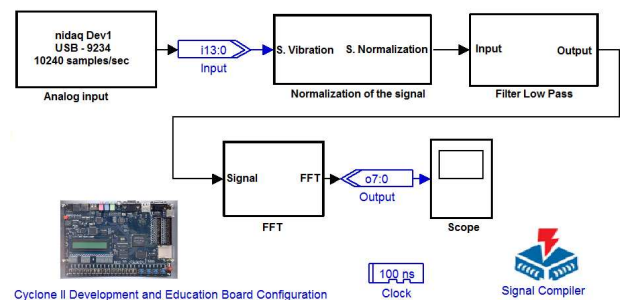

Fig. 7 – Block diagram of model 2 modeled in DSP Builder.

The block normalization of the signal was implemented using the library Altera DSP Builder Advanced Blockset/ModelPrim and Blockset/Arithmetic. The block Filter was implemented using the library Altera DSP Builder Blockset/MegaCore FIR_Compiler_v10_0. The block FFT was implemented using the library Altera DSP Builder Blockset/MegaCore 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, as well as the synthesis and configuration of the FPGA VHDL code.

7. Conclusion

A new approach for modeling, simulation and development of a real time vibration measurement and

analysis digital instrument based in FPGA was presented. FPGAs provide the highest DSP performance available on a programmable platform, but optimizing a DSP algorithm in a 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. Modern design tools as SIMULINK based package called DSP Builder, provide a higher level of design abstraction and productivity and deliver the performance of traditional optimized HDL. This approach uses a high-level behavioral description of the DSP algorithm. The design can be simulated and deployed into FPGA hardware. It is not required to use HDL for programming. It is only required to build system model under MATLAB/SIMULINK, and then the design can be completed after the parameters of each model are set.

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