Virtual Instruments Based Approach to Vibration Monitoring, Processing and Analysis

Mohammed Almaged
Nineveh University
Department of Systems and Control Engineering
Aljamaa Street, Mosul
Nineveh, Iraq
mohammed.younus@uoninevah.edu.iq

Jack Hale
Newcastle University
Department of Mechanical Engineering
Stephenson Building, Newcastle Upon Tyne
UK
jack.hale@ncl.ac.uk

Abstract: This paper shows the design procedures of a virtual system (VI) that is based on LabVIEW software with the aid of National Instruments (NI) Data Acquisition Devices (DAQ). The function of the system developed in this paper comprises data acquisition and generation operations. In addition, it also involves the implementation of several signal processing and analysis techniques such as Fast Fourier Transform (FFT) and Infinite Impulse Response (IIR) filters. The application of the proposed VI can be expanded according to the user requirements. For example, it can be used in the area of vibration monitoring, signal processing and analysis. This may include field dynamic balancing or fault detection and diagnosis. In this work, a measurement system, consisting of an integrated circuit piezoelectric (ICP) accelerometer and data acquisition device (DAQ) was prepared and assembled for the experiments. A shaker was used to produce a periodic vibration signal and hence simulates the most common vibration fault signatures experienced by rotating machines. A program in LabVIEW was designed to collect and analyse the simulated vibration signals in both time and frequency domains.

Key–Words: vibration monitoring, signal processing, signal analysis, virtual instruments (VI), LabVIEW, data acquisition and generation

1 Introduction

In recent years, the virtual instrument technology has made a significant development and been extensively used in the field of measurements allowing easy integration and flexible configuration [1, 2]. This is mainly owing to the vast development of powerful computers providing an excellent performance with a high processing speed. This is also due to the reduction in cost arises from eliminating the need for some hardware instruments such as filters, amplifiers and power analysers [3, 4]. The idea of Virtual Instrumentation (VI) involves utilizing personal computers equipped with a high-level programming software along with different types of measurement and control hardware to create systems that achieve the application requirements. Virtual programming simulates the real instruments making the use of its function more immediate and faster than working with the conventional hardware. One of the most commonly used software in virtual programming is LabVIEW. LabVIEW is a data-flow graphical programming language that has the advantages of being flexible and straightforward even to those who are not expert in writing complex programming codes. It is commonly used for designing a user-machine interface through several built-in toolkits that interact directly with the outside environment to perform a variety of functions such as testing, measuring and control [5, 7].

In this work, a PC-based VI for vibration measurement, processing and analysis was developed. Vibration monitoring offers the advantage of simple interpretation in identifying machinery conditions because variations in vibration amplitudes can be linked directly to the machine conditions change. Similarly, vibration analysis is an excellent sign to manifest the condition of rotating machines and detect potential failures as well as their sources. Those techniques are considered as the most efficient methods applied in predictive maintenance [8, 9]. Therefore, the advantages of this system can considerably decrease the cost of maintenance in rotating machines.

2 Experimental Setup

The experimental setup involved using an Integrated Circuit Piezoelectric (ICP) accelerometer fixed temporally on a shaker by the mean of adhesive mounting, as shown in Fig. 1. The shaker was utilized to simulate the induced vibration signal in rotating machines and hence considered as an experimental counterpart to any actual rotating system. The ICP accelerometer is a self-excited transducer that uses a piece of piezoelectric crystal configured in shear mode and encapsulated by a seismic mass. This configuration makes the accelerometer sensitive to the vibration in the axial direction only. Then, the NI compact DAQ-9178 chassis, shown in Fig. 2 below, was used for acquiring the shaker vibration signal via the NI 9234 c-series module. This module has four high-resolution ADC channels designed especially for powering and signal conditioning purposes of ICP accelerometers [10].

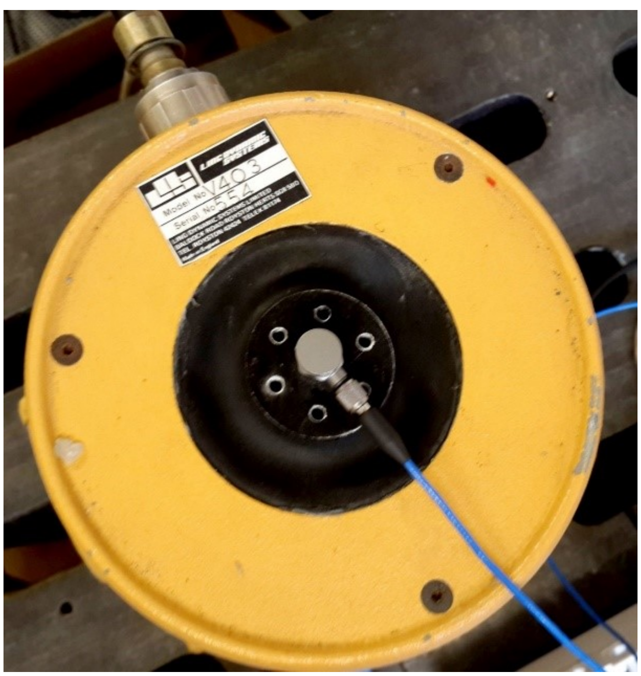

Fig. 1 ICP accelerometer fixed on the shaker

Fig. 2 NI cDAQ-9178 chassis with NI 9234 c-series module

In some applications such as dynamic balancing, it is also important to know the phase of the vibration signal in order to identify the heavy spot position on the rotor. For this purpose, a stroboscope was designed and implemented using a high-intensity LED capable of producing an extremely short and bright burst of light. The stroboscope was triggered by a series of TTL pulses generated by the computer in LabVIEW and transferred via the NI 9264 output module. The frequency of the flash is adjusted in LabVIEW so that it is equal to the speed of the rotating machine. To calculate the vibration phase, the vibration signal is compared with the strobe reference signal using correlation measure. The general architecture of the virtual instruments system is shown in Fig. 3.

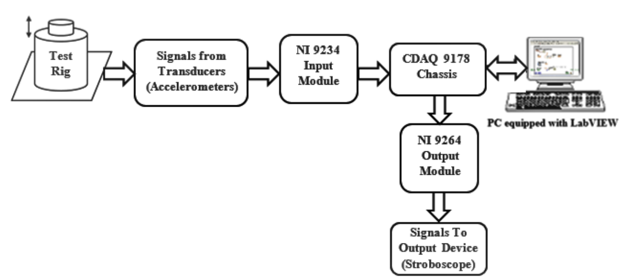

Fig. 3 Virtual instruments (VI) architecture

3 Program Design

LabVIEW was employed along with the hardware setup to perform the following functions:

- Acquire, record and display shaker vibration signal.
- Generate an analogue output to trigger the stroboscope.
- Perform signal processing and analysis to obtain amplitude and phase angle values of the vibration signal.

LabVIEW is a graphical programming language commonly used for creating engineering-design platforms that interact with real-world data and signals. Users interact with LabVIEW through two separate windows. These are the block diagram and control panel. The control function can be designed in the block diagram, while the front panel is used to input user-defined values through different types of controls and display output data via several graphs, charts and indicators. The designed program can be described through the following flowchart:

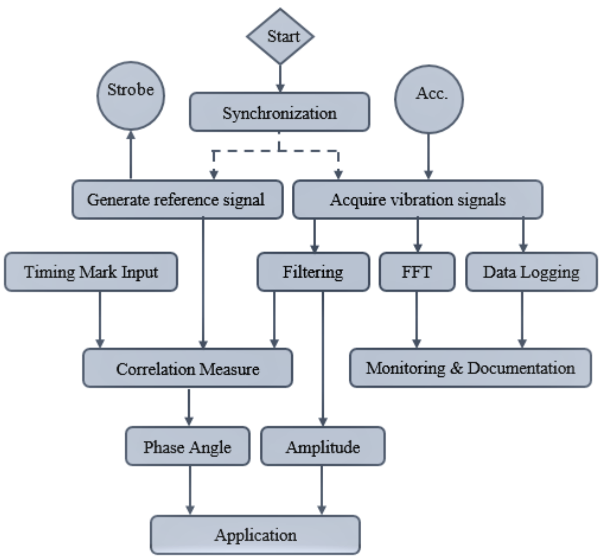

Fig. 4 Flowchart of the designed VI

3.1 Data acquisition task

DAQmx functions offer great flexibility in configuring acquisition parameters such as the sampling rate and number of samples. Furthermore, these functions provide an access to timing and triggering information as well as the ability to synchronize multiple tasks to run at the same time. The data acquisition task requires the main DAQmx functions shown in Fig. 5. Initially, the DAQmx create channel (1) function was employed to set the type of the channel to Analog Input (AI) Accelerometer channel. It also allows us to specify a number of vibration parameters such as range, unit and sensitivity depending on the sensor used. Then, the DAQmx timing (2) function was utilized to set the sampling rate (KS/s) and the number of samples (N) for a Finite acquisition process. After configurations, the DAQmx configure logging (3) function was employed to initialize a TDMS file that can be read via Excel to record the acquired data. To transfer the task to the running state, the DAQmx start task (4) function was called. Then, the DAQmx Read (5) function was utilized to read the acquired vibration signal, which is generated by the shaker at (50 Hz), through a waveform graph in the front panel as shown in Fig. 6.

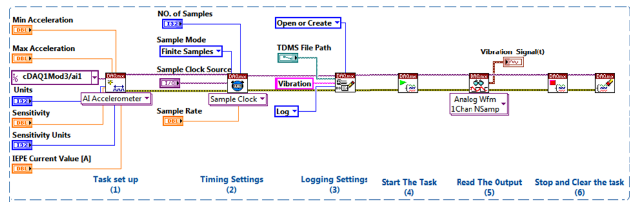

Fig. 5 Data acquisition task

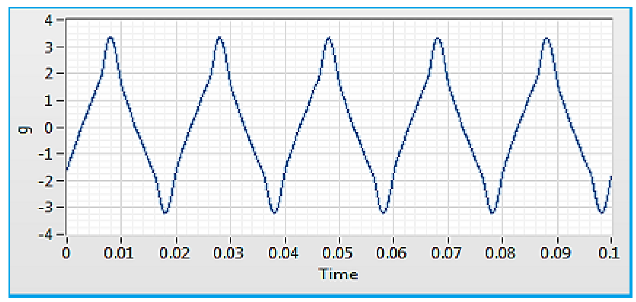

Fig. 6 Shaker vibration signal

3.2 Data generation task

Both analogue input and output tasks were implemented using the same set of DAQmx functions. Generating an analogue output is similar to the acquisition operation with some minor modifications. For example, the DAQmx read function was replaced by the DAQmx write VI. Also, unlike the acquisition process, a continuous sampling mode was chosen in order to trigger the stroboscope circuit for an unlimited amount of time. The block diagram of the trigger signal generation process is shown in Fig. 7.

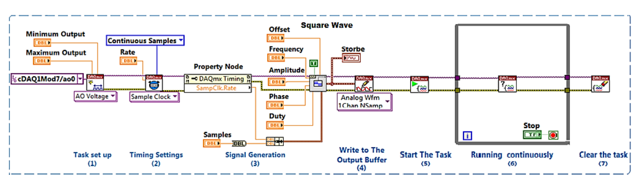

Fig. 7 Data generation task

To produce a continuous stream of short duration pulses for the stroboscope, the Square Waveform VI (3) was implemented to generate a series of a pulse train. This VI creates a square wave pattern according to the specified input voltage level, DC offset and phase angle value. It also defines the period of the square wave, duty cycle and signal sampling information. The sampling information is given as a bundle of the sampling rate and the number of samples in the waveform. The frequency of the generated square wave was equivalent to the fundamental frequency of the vibration signal. A view from the front panel is shown in Fig. 8.

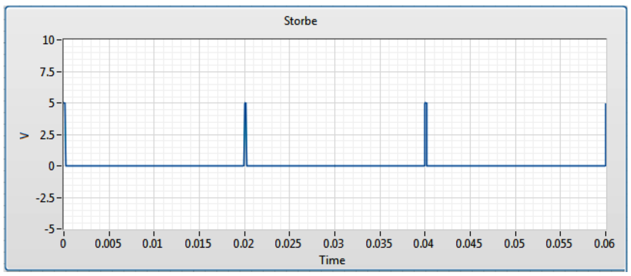

Fig. 8 Strobe reference signal

3.3 Data synchronization

The term synchronization refers to the idea of multiple tasks running exactly at the same time. Generally, data synchronization is difficult to implement as clock and trigger signals should be routed manually between devices required to be synchronized. However, the compact DAQ controller offers greater flexibility in sharing trigger and clock signals between several C-series modules. In addition, DAQmx is a multithreaded function. This means that multiple data acquisition and generation operations can be run together in the same VI.

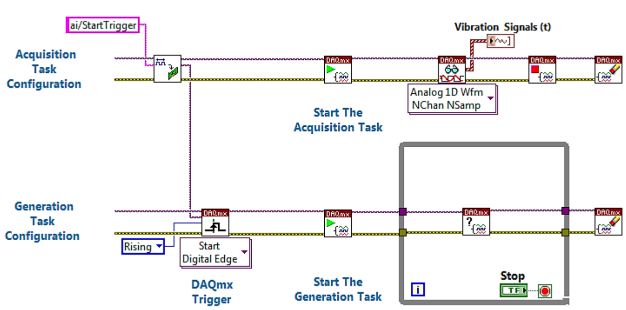

Fig. 9 Tasks synchronization

The data acquisition and generation tasks, explained earlier, are running asynchronously of each other. This is acceptable in most applications in which phase measurement is not an issue. However, when the phase difference between signals resulted from different tasks is a key concern, a tight synchronization between these tasks is required. To handle this, it is important to ensure that both tasks are initiated at the same instant of time using the same sampling clock in order to avoid clock signal drift and frequency mismatch. This was achieved by sharing a unified trigger signal (ai) built into the compact DAQ-1978 chassis. The block diagram, shown in figure 9, reveals the main functions used in the synchronization process of both tasks.

3.4 Signal analysis

Signal acquired in the time domain provides information about the vibration amplitude experienced by the machine at the instant of time during which it has been sampled. In many cases, it is also necessary to know the source of this vibration. In general, each fault in rotating machines has a unique power spectrum related to it. For example, rotor imbalance usually produces a high vibration amplitude at a frequency component equivalent to the rotor synchronous speed. To achieve a frequency domain representation of the vibration signal, the Fast Fourier Transform (FFT) was implemented using the FFT power spectrum VI, illustrated in Fig. 10.

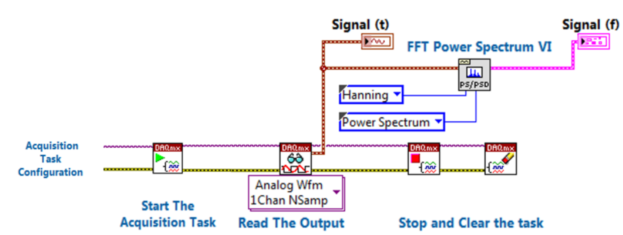

Fig. 10 Power spectrum VI

FFT algorithm is based on the assumption that the sampled signal is periodic. Therefore, if the signal is not periodic or the duration of the acquisition does not match an integer number of signal intervals, a leakage error will occur. This error can be reduced by using windowing. This VI offers several types of windows such as rectangular, Hanning, etc. Depending on the application, a certain window can be more effective than the others. The equivalent frequency representation of the acquired time-domain signal is shown in Fig. 11. It can be clearly seen that the peak amplitude appears at frequency component equal to the frequency of the vibration signal (50 Hz). Also, the harmonics are clearly visible, as is expected for the periodic but non-sinusoidal signal shown in Fig. 6.

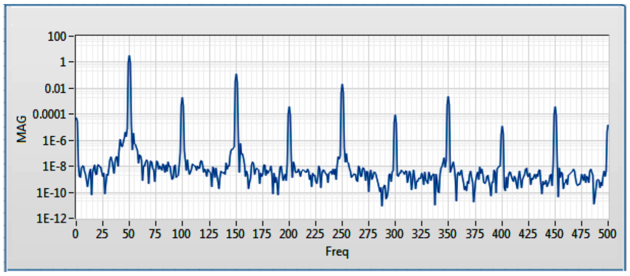

Fig. 11 Vibration signal power spectrum

3.5 Signal processing

Here, different types of Infinite Impulse Response filters were designed and implemented in LabVIEW using IIR Filter VI. This VI allows the user to choose, via filter specification, different topologies of IIR filters such as Butterworth, Bessel, Chebyshev, Inverse Chebyshev and Elliptic. For each topology, it is also possible to specify the order of the filter and its type, for instance, Lowpass, Highpass, Bandpass and Bandstop. A view of the block diagram is shown in Fig. 12.

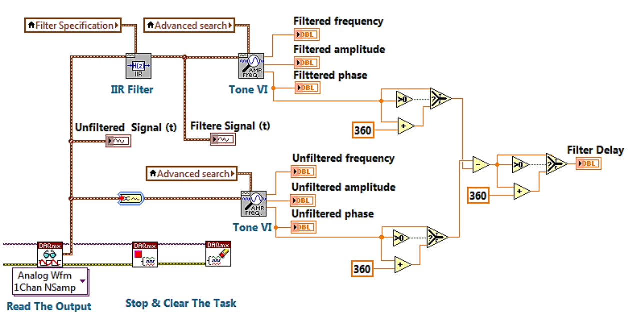

Fig. 12 Digital filter VI

Generally, delay represents a major drawback of all types of filters. The amount of delay depends on the type and order of the filter itself. In applications where phase measurement is crucial, it is important to account for this delay. To cope with filter delay, Tone extraction VI was utilized. This VI searches inside a specified frequency range in the signal and returns the highest component's amplitude, phase and frequency. Therefore, to know the amount of delay introduced by the filter, it is simply obtained by subtracting the phase of the filtered signal from the phase of the unfiltered signal. In addition, the filter transient response is another issue that should be considered while using digital filters. The response of a 6th order Butterworth bandpass filter applied to the acquired vibration signal is illustrated in Fig. 13.

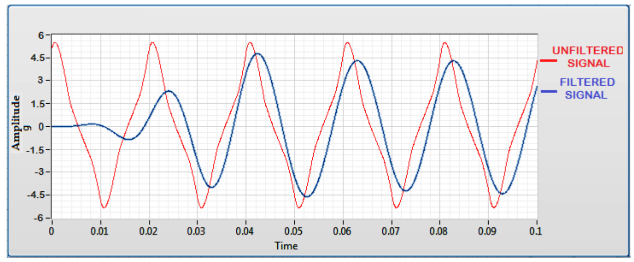

Fig. 13 Filter input / output signals

3.6 Correlation measure

Correlation is a measure of the degree of similarity between two signals. In its discrete form, correlation is the sum of a sample by sample multiplication of a series of data points (N) [11]. This can be expressed as:

$$Rxy[j] = \sum_{K=0}^{N-1} X[k] \cdot Y[k+j]$$

X[k] , Y[k]: Input sequences

The correlation measure between the vibration and strobe reference signals was used to calculate the vibration phase angle with respect to the fixed reference position on the frame of the rotating machine. In LabVIEW, cross-correlation is performed by initially shifting the reference signal by the number of samples (N), while the vibration signal is moved across it. Then, the sum of products of the two signals, which represents the cross-correlation measure at each lag position, is calculated. The plot of the cross and auto correlation sequences against the lag positions are shown in figures 14 and 15 respectively

The basic idea behind this designed VI, shown in Fig. 16 , is to find the lag position of the maximum value (Peak) in each sequence. Then, the difference between these positions gives the best match of the vi-

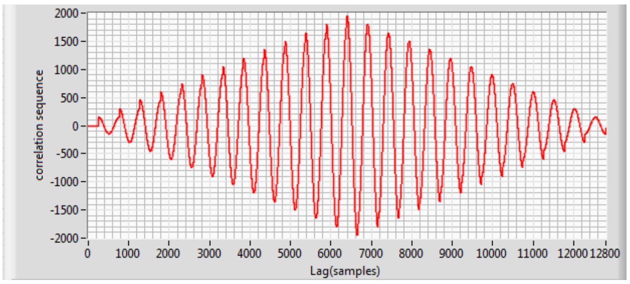

Fig. 14 Cross correlation of the two signals

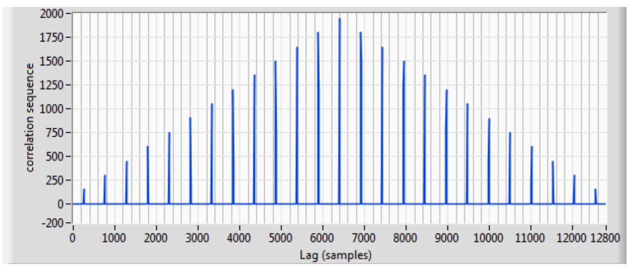

Fig. 15 Reference signal autocorrelation sequence

bration signal to the strobe reference signal which represents the vibration phase angle with respect to the given reference position. However, prior to the correlation measure, it is important to clarify that the filter transient response can affect the cross-correlation measure of both signals. This problem can be avoided by removing the transient response from the filtered vibration signal. However, to maintain phase information constant, the same number of samples should be removed from the strobe square wave. This can be accomplished by using the Delete from Array function.

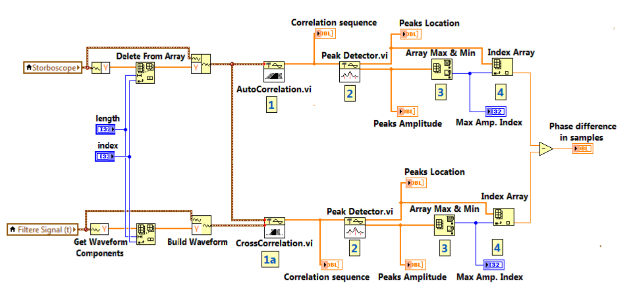

Fig. 16 Correlation measure VI

4 EXPERIMENTAL WORK

Initially, the software system presented in this paper is successfully employed in a following work to perform field dynamic balancing. A test rig, shown in Fig. 17, was designed and manufactured with two balancing discs to simulate the common shaft balancing problem. Two accelerometers were mounted on the bearings and aligned according to the fixed reference direction to measure the unbalance-induced vibrations. The stroboscope was positioned opposite to the 1st balancing disc and pointed towards the rotating timing mark, which was tapped on plane one disc.

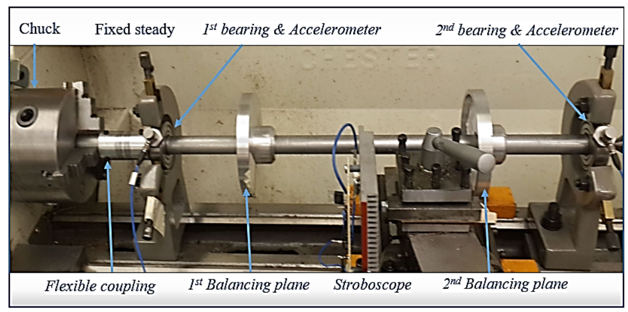

Fig. 17 Balancing test rig

The designed VI must be configured from the front panel according to the requirement and specification of the physical system. For the data acquisition task, the configuration may involve selecting the name of the physical channel in which the accelerometers are actually connected to. It also includes specifying additional properties of the channel such as range, unit, sensitivity, etc. In addition, it is necessary to set the source of the sample clock, sampling rate, sampling mode and the number of samples to acquire. For this particular task, finite sampling mode was chosen to acquire 12800 samples at 12.8 KS/s. In this way, the acquisition process will last for one second only. The user also needs to input filter specifications and FFT windowing Parameters. For example, a 6th order Butterworth bandpass filter was selected with a centre frequency equivalent to the vibration signal frequency. Furthermore, Hanning window was selected because its pattern seems to be the best match with the vibration signal.

Likewise, the same procedure required to be accomplished for the generation task of the strobe signal. Initially, the name of the channel was specified according to the actual output pin connected to the stroboscope. Then, a continuous sampling mode was chosen for this task so that the strobe is triggered continuously until the termination of the execution. This gives the operator a sufficient amount of time to visually read the position of the timing mark with respect to the fixed reference point. Also, it is essential to specify the amplitude, frequency, phase and duty cycle of the generated trigger signal. It is important to note that the frequency of the trigger signal must match the speed of the rotating machine so that the stroboscope generates one pulse per revolution. Moreover, a short duty cycle (1 percent) was chosen in order to illuminate a timing mark, which is painted on the 1st disc of the test rig, for only a short period of time during each revolution.

The calculated percentage of the unbalance reduction shows that the vibration amplitude at the first measurement plane was reduced by 65 percent, while further improvement was obtained at the second measurement station where a reduction of 82 percent was achieved. The response of the initial vibration amplitude before balancing (Blue) and the final reduced vibration response achieved after balancing (Red) is shown in the Fig. 18.

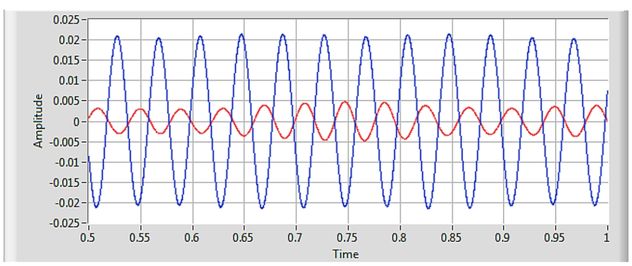

Fig. 18 Initial and final vibration amplitudes at bearing two

5 Conclusion

A vibration-based monitoring system has been developed in this paper. Initially, a shaker was used to simulate the most common vibration signal experienced by rotating machines. In addition, a group of instruments, such as accelerometers, DAQ device and stroboscope, was designed and assembled for the experiments. The ICP accelerometer was absolutely compatible with the compact DAQ device offering a direct interface without a need for any signal conditioning circuit. Furthermore, using compact DAQ internal timing engines reduced the complexity of data synchronization and provided very precise phase measurements. Although, the stroboscope was designed and implemented using readily available components in the lab, it worked properly to fulfill the required function. In overall, the experimental work has proved to be successful. The balancing results were satisfactory where the rotor unbalance was reduced by approximately a factor of eight.

Several VIs were designed in LabVIEW in order to acquire, process and analyse shaker vibration signals. In overall, a perfect representation of vibration patterns has been obtained. The system response was robust and fast enough to preserve phase information accurately. Furthermore, virtual instrumentation can be considered as a flexible system due to the easy and simple adjustment of the software parameters, for instance, filter specifications. Also, transducers are exchangeable which means that different types of measurements can be achieved with only minor software modifications.

References:

[1] G.R. Gillich, D. Frunzaverde, N. Gillich, and D. Amariei, ”The use of virtual instruments in engineering education,” Procedia-Social and Behavioral Sciences, vol. 2, pp. 3806-3810, 2010.

[2] H. J. Spoelder, ”Virtual instrumentation and virtual environments,” Instrumentation and Measurement Magazine, IEEE, vol. 2, pp. 14-19, 1999.

[3] G. Bingkun, L. Yanjia, S. Zhaoyun, and X. Mingzi, ”Vibration testing and analysis of motor based on virtual instrument,” in Mechanic Automation and Control Engineering (MACE), 2010 International Conference on, 2010, pp. 2373-2375.

[4] D. Ganeshkumar, T. Manigandan, and S. Palaniswami, ”Virtual Instrumentation based intelligent vibrobench for bearing testing,” in Industrial and Information Systems, 2007. ICIIS 2007. International Conference on, 2007, pp. 473-478.

[5] J. Y. Beyon, LabVIEW programming, data acquisition and analysis: Prentice Hall PTR, 2000.

[6] S. Sumathi and P. Surekha, LabVIEW based advanced instrumentation systems: Springer Science and Business Media, 2007.

[7] J.-H. Teng, S.-Y. Chan, J.-C. Lee, and R. Lee, "A LabVIEW based virtual instrument for power analyzers," in Power System Technology, 2000. Proceedings. PowerCon 2000. International Conference on, 2000, pp. 179-184.

[8] A. Gani and M. Salami, "Vibration faults simulation system (VFSS): A lab equipment to aid teaching of mechatronics courses," International journal of engineering education, vol. 20, pp. 61-69, 2004.

[9] I. Lită, D. A. Vişan, and I. B. Cioc, "Virtual instrumentation application for vibration analysis in electrical equipments testing," in Electronics Technology (ISSE), 2010 33rd International Spring Seminar on, 2010, pp. 216-219.

[10] NI. (2009). User guide and specifications For NI cDAQ-9178 Chassis. Available: http://www.ni.com/en-lb.html.

[11] P. F. Dunn, Measurement and data analysis for engineering and science: CRC press, 2014.